Home

James Webb Space Telescope (JWST) Integrated Science Instrument Module (ISIM) Cryogenic Component Test Facility

Presented by
Edward A. Packard

23rd Space Simulation Conference
November 8-11, 2004

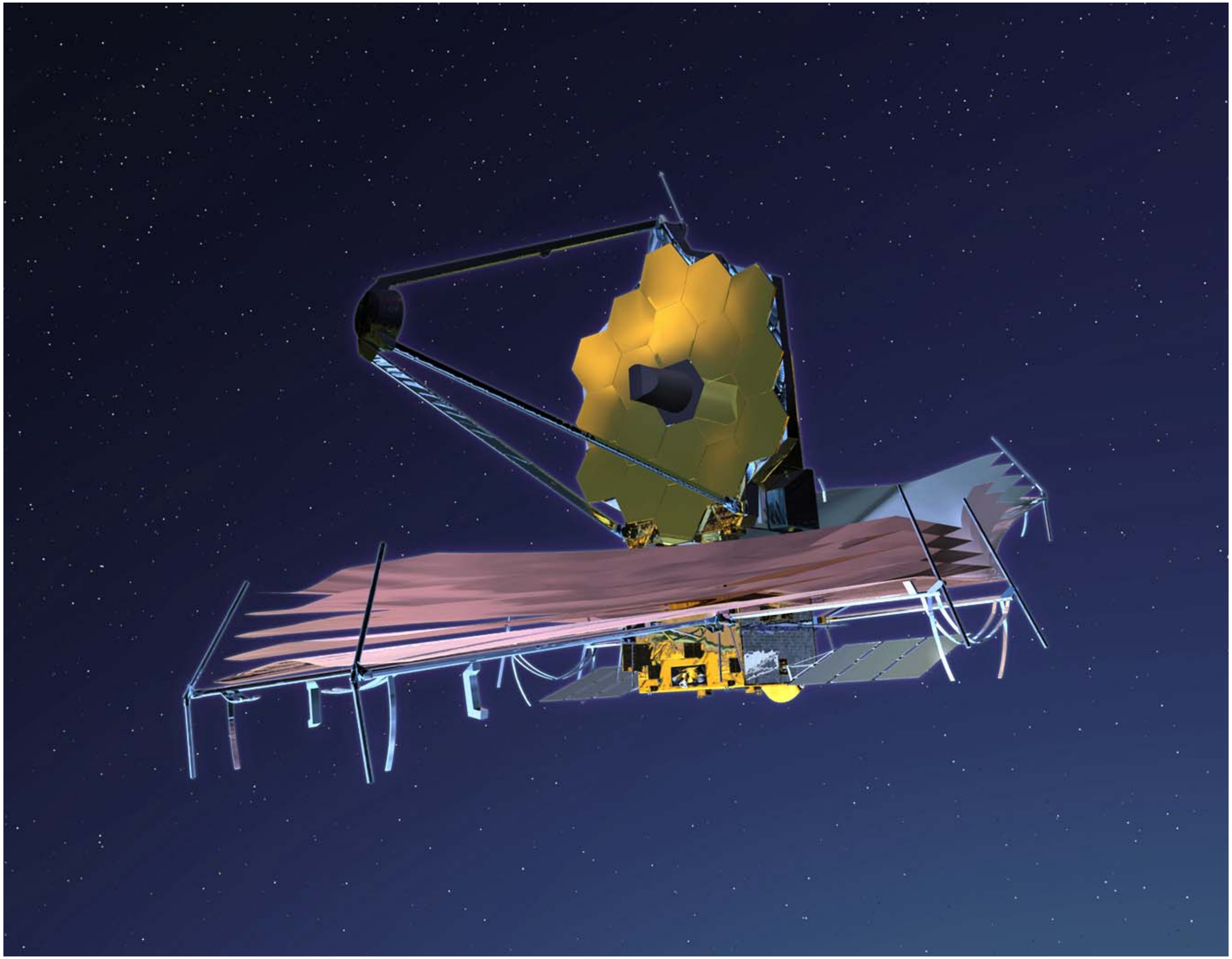
Presentation Overview

- JWST / ISIM Overview
- ISIM Thermal Verification Requirements
  - Emittance Test Objectives
- Cryochamber Design Requirements
- Cryochamber Construction
- Emittance Test Sample Selection and Configuration
- Error Sources and Error Mitigation
- Cryochamber Operation
- Cryochamber and Emittance Sample Test Results
- Future Considerations

JWST Overview

- Large infrared observatory positioned at L2
- Proposed launch date: August 2011
- Mission goals:
  - Understand the birth and formation of stars
  - Determine how planetary systems form
  - Explain galaxy formation
  - Determine the shape of the universe
  - Provide a better understanding of the intriguing dark matter problem

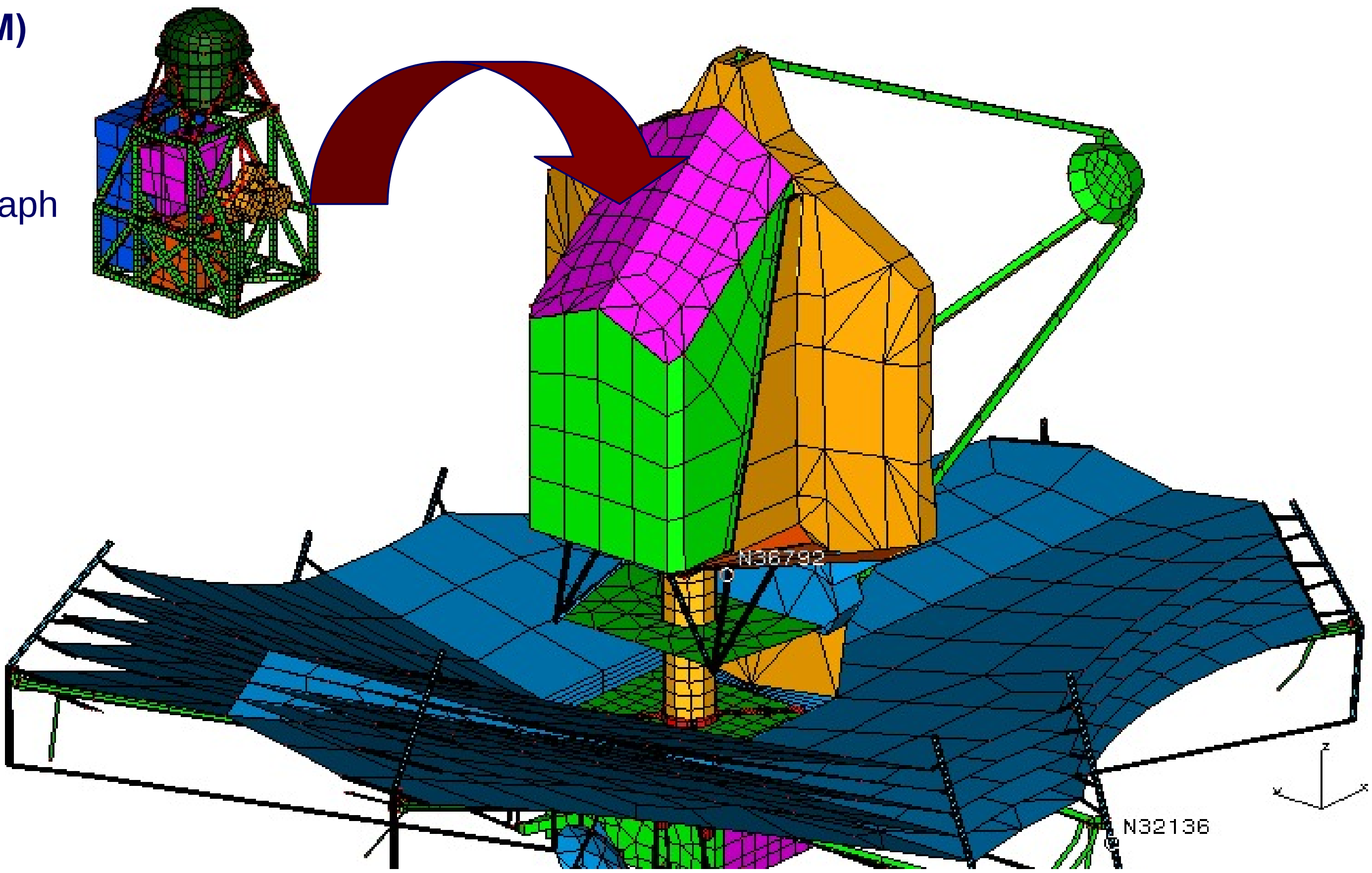
JWST Conceptual Illustration



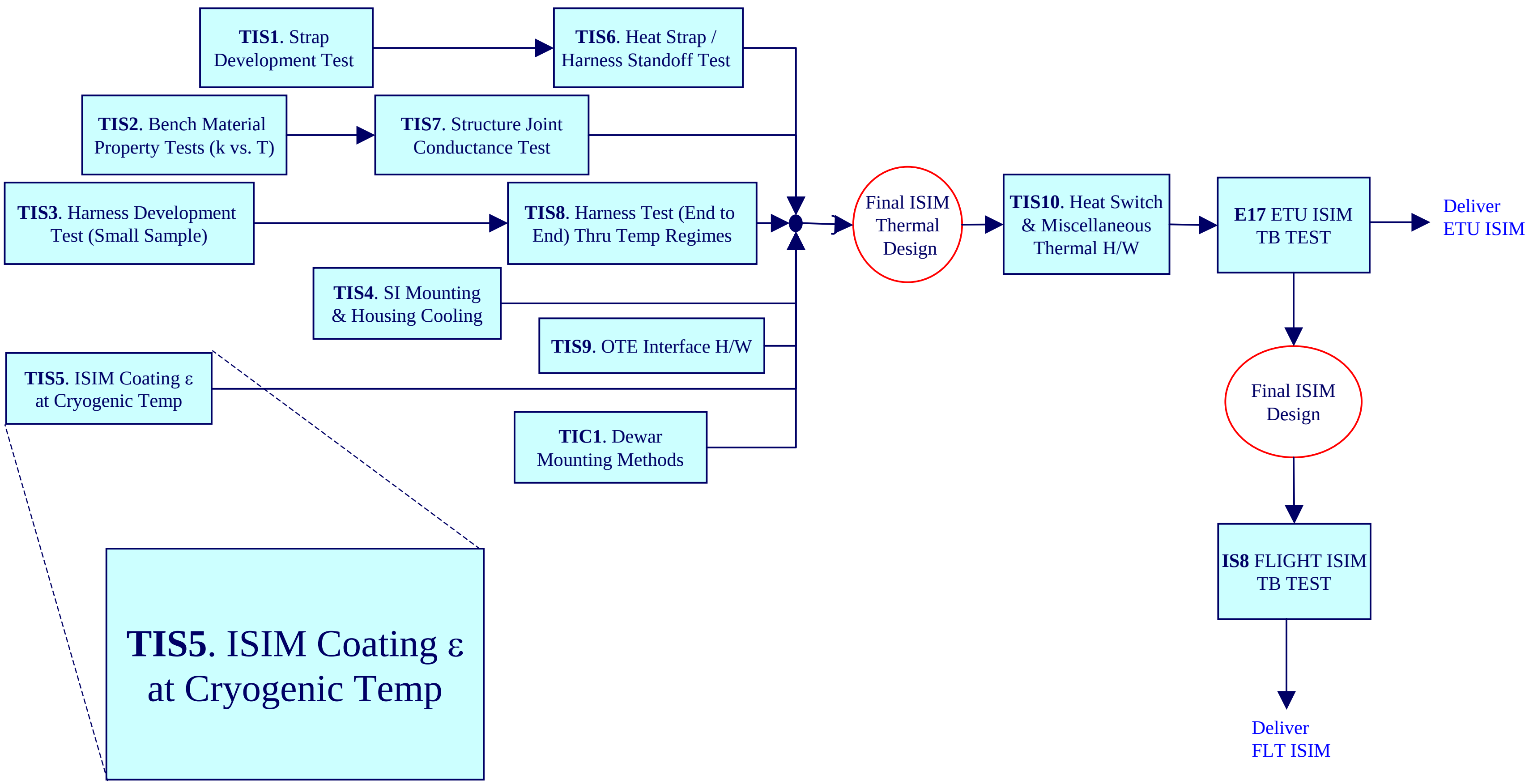
ISIM & Enclosure on JWST

Integrated Science Instrument Module (ISIM)

- Near Infrared Camera (NIRCam)
- Near Infrared Spectrograph (NIRSpec)
- Mid Infrared Instrument (MIRI)
- Fine Guidance Sensors (FGS)

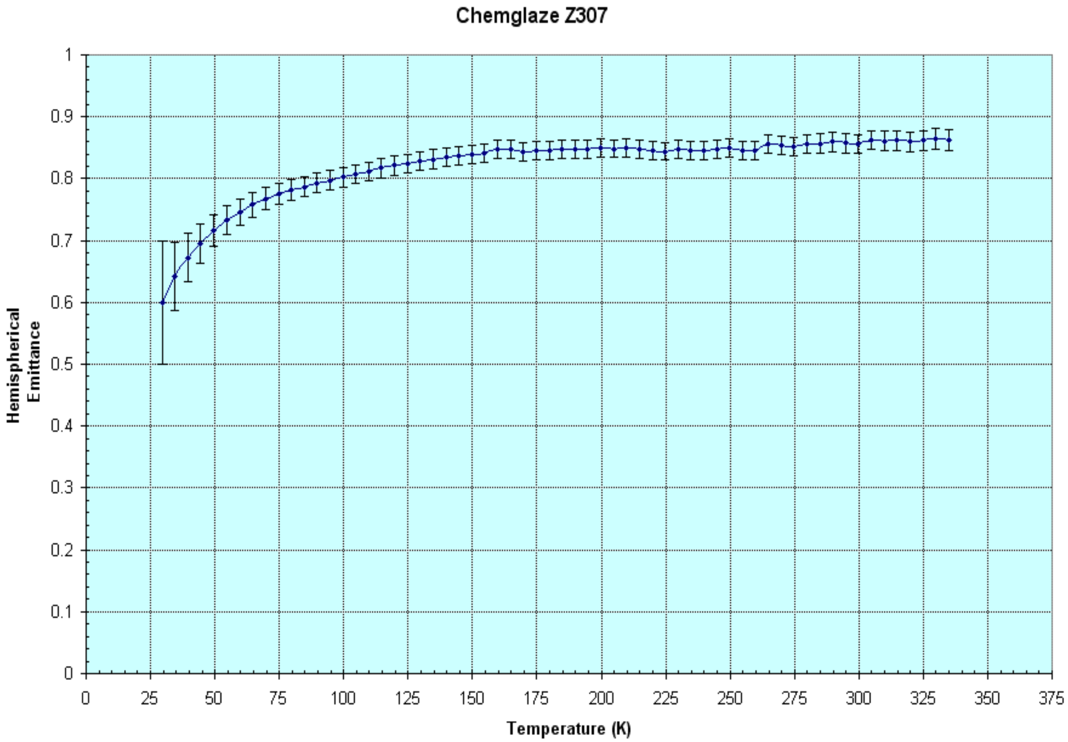


ISIM Thermal Verification Flow



TIS5 Test Objective

- To determine the emittance of candidate thermal control coatings for the JWST/ISIM Instrument Assembly from 30K to 293K
- To minimize associated error bars in determining emittance values (goal <5%) at 30K



First Analytical Method

- **Transient Cool-Down**

$$\left(mC_p dT/dt\right)_{sample} = \sigma\left(A\varepsilon\right)_{sample}\left(T^4_{sample} - T^4_{LHeShroud}\right) + Q_{loss}$$

where $$\left(mC_p\right)_{sample} = \sum\left(mC_p\right)_{substrate+coating+sensors}$$

and $$T = f\left(t\right)$$

m	mass	measured pre test
C_p	specific heat capacity	theoretical*
T	temperature	measured test data
t	time	measured test data
σ	Stephan-Boltzmann constant	= 5.67×10^{-8} W/m^2/K^4
A	sample radiating area	measured pre test
Q_{loss}	lead wire+residual gas loss	calculated
ε	emittance	determined from above equation

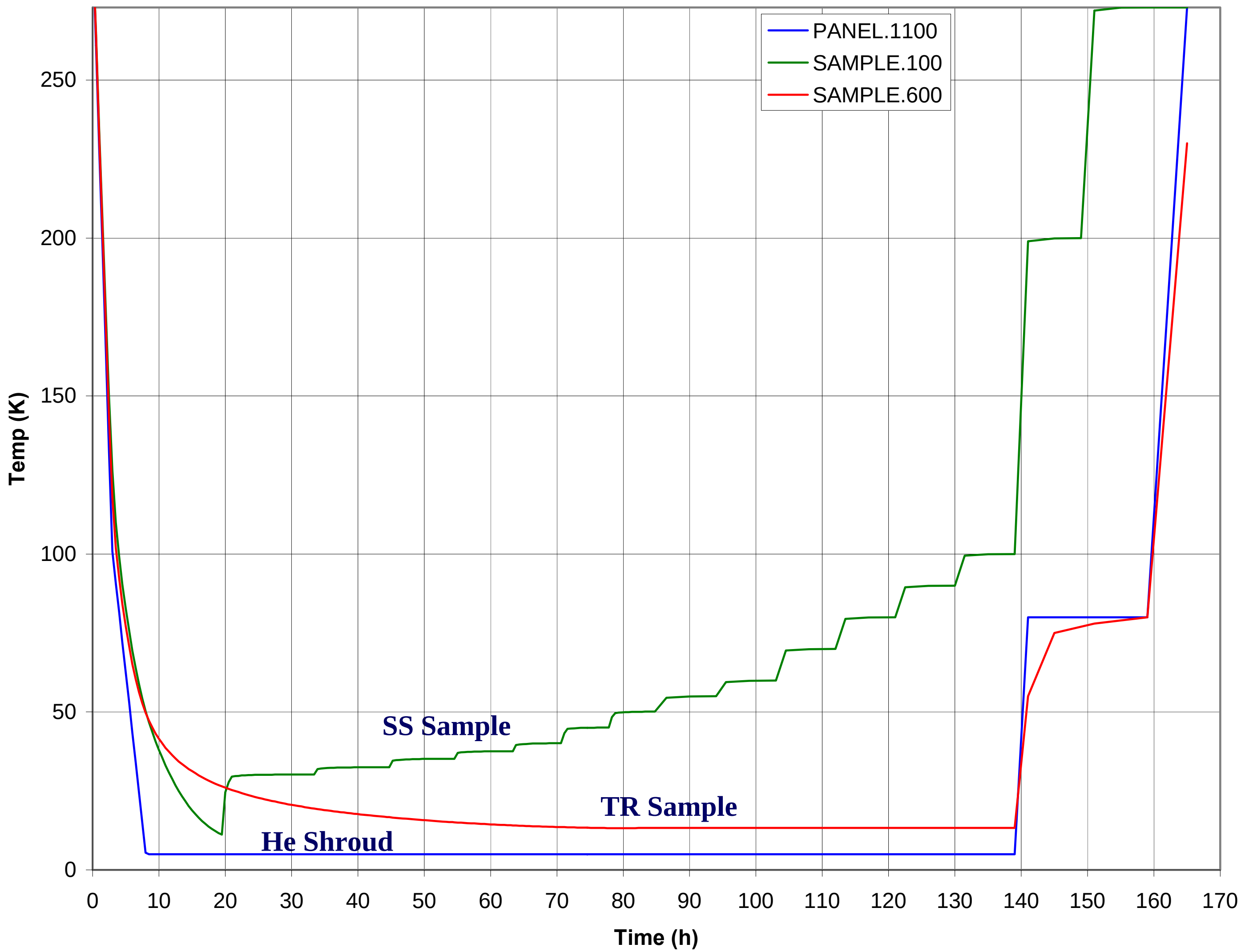
Second Analytical Method

- **Steady State Warm-Up**

$$Q_{heater} = \sigma\left(A\varepsilon\right)_{sample}\left(T_{sample}^4 - T_{LheShroud}^4\right) + Q_{loss}$$

T	temperature	measured test data
σ	Stephan-Boltzmann constant	= 5.67×10^{-8} W/m^2/K^4
A	sample radiating area	measured pre test
Q_{loss}	lead wire+residual gas loss	calcluated
Q_{heater}	heater power	measured test data
ε	emittance	determined from above equation

Test Profile – Overview Timeline



Cryochamber Design Requirements

- **Relatively large: $A_{\infty} >> A_s$ (chamber area >> sample area) and at least 3'x3'x3' ($1m^3$)**
- **Cool-down from 295K to < 7K in < 8 hours**
- **Thermal gradient < 1K**
- **Thermal stability < 0.1K/hr**
- **Chamber pressure < $1x10^{-7}$ Torr**
- **Cheap (to build and operate)**

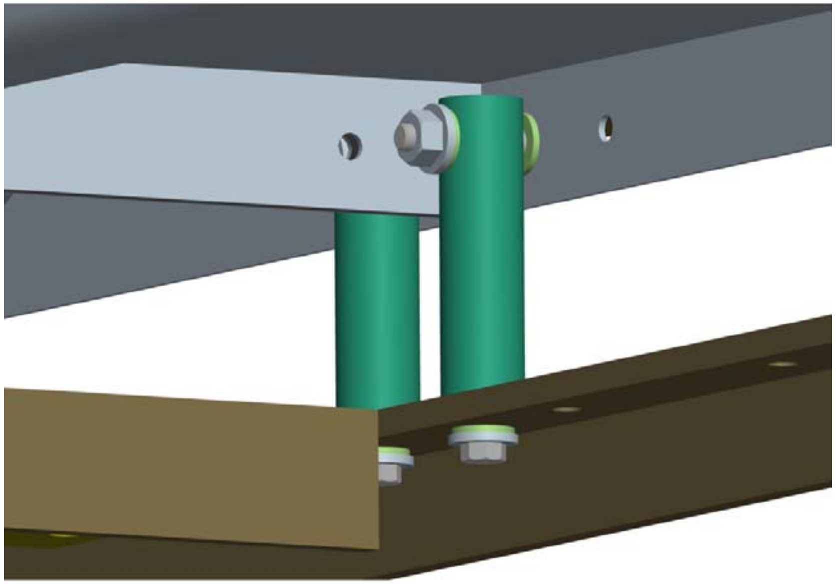
Cryochamber on Facility 239 Payload Cart

Cryochamber Design Overview

- **Volume: 6'L x 4'W x 5'H (1.9m x 1.2m x 1.5m)**
- **Utilized 11 existing cryopanels**
  - (5) 76" x 29"
  - (2) 76" x 23"
  - (2) 61.5" x 29"
  - (2) 54" x 23"
- **Cryopanels painted with Aeroglaze Z307**
- **Supported by an "exoskeleton" frame**
- **Plumbed in four parallel circuits**
- **Covered with single-layer, two-sided VDA**

Cryochamber Thermal Isolation

- Cryopanels supported by G-10 isolators with L/W=3.6

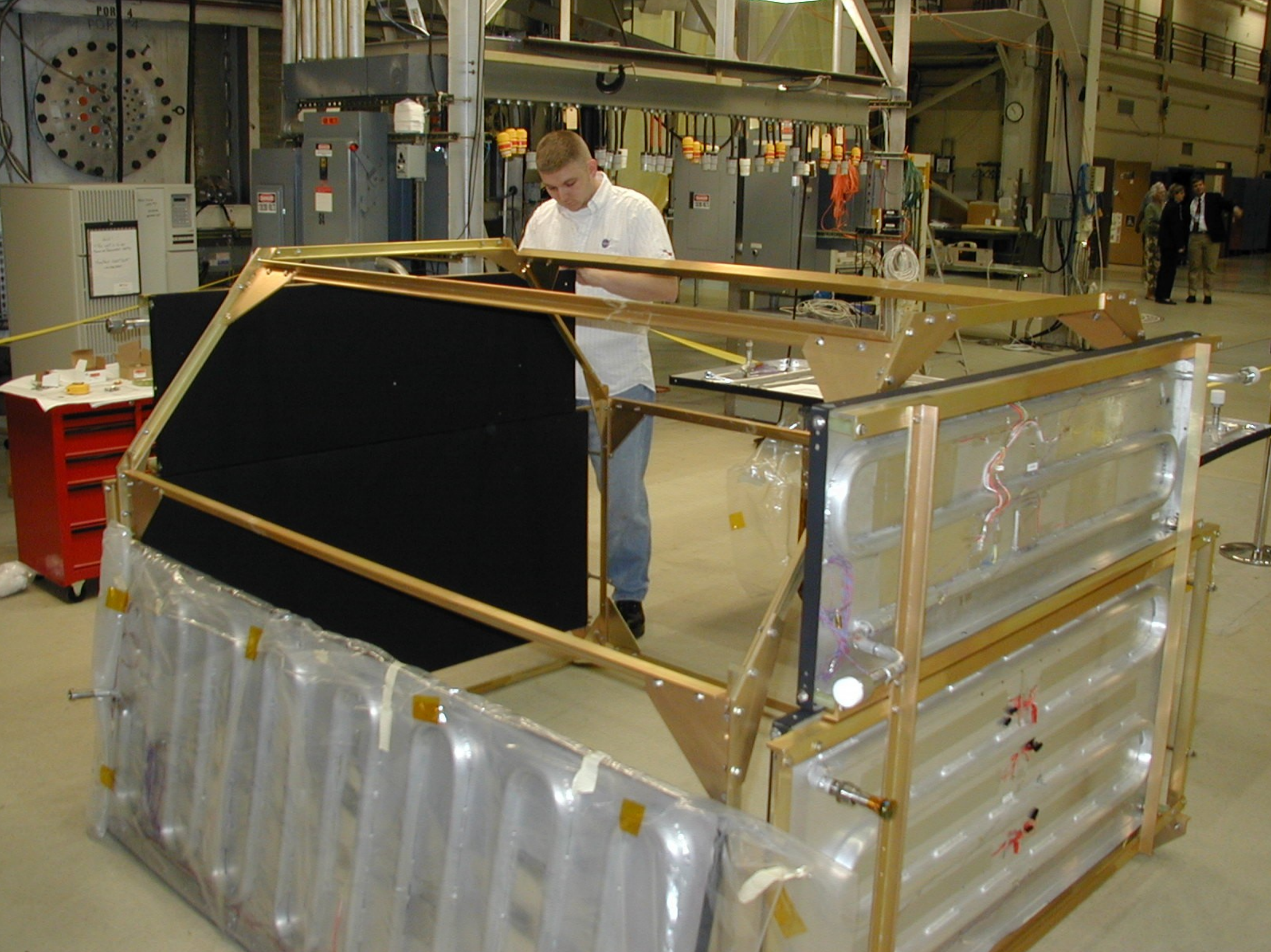


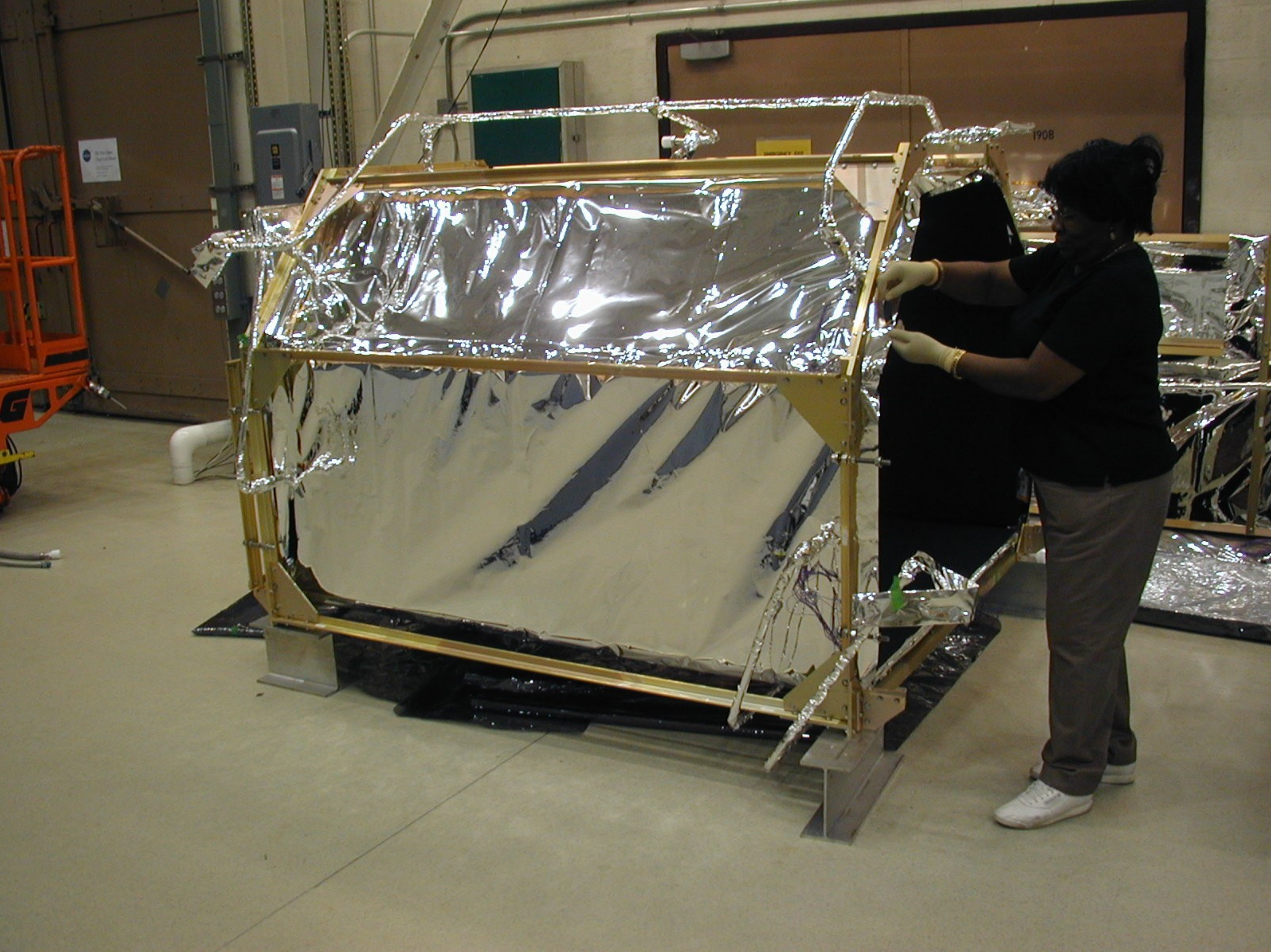
- Three mil double sided VDA over gaps between panels
- Three mil double sided VDA over all panels
- Four-layer MLI wrapped around all tubing

Calculated conduction and radiation heat loss = 10.7W

Cryochamber Instrumentation

- **Temperature**
  - (15) LakeShore DT-470-CU-13 standard curve silicon diodes used for panel and tube monitoring to LHe temperatures
    - ±1K accuracy
  - (20) Type T thermocouples used for fixture and tube monitoring down to LN_2 temperatures
- **Pressure**
  - NIST traceable calibrated Granville Phillips Stabil-Ion Gauge on Chamber
    - ±4% accuracy per decade from $1x10^{-2}$ to $1x10^{-9}$ Torr




1908

Test Samples

- **Sample selection**
  - (2) Bare 8” x 8” x 0.024” (8 ply) M55J-954-6 Composite
  - (2) Black Kapton (2 mil) on 8” x 8” x 0.020” A1100 Aluminum Substrate
  - (2) Z306 Black Paint on 8” x 8” x 0.020” A1100 Aluminum Substrate
- **One transient (without heaters) and one steady state (with heaters) sample for each sample type**

Test Sample Description

- **Steady State Sample Heaters**
  - (4) 3” x 3” Minco HK5174R82.3l12B
  - 82.3 Ohms each wired in series
- **Temperature Sensors**
  - (2) LakeShore DT-470-SD-13 silicon diodes per sample
  - Calibrated from 4K-100K within at least +/-50mK
- **Wiring**
  - Heater to heater: 40AWG Cu; PTFE insulation; Aluminum tape overlay
  - Power leads: 30 AWG Manganin; Formvar insulation; VDA overcoat
  - Voltage leads: 36 AWG Manganin; Formvar insulation; VDA overcoat
  - Silicon diodes: 36 AWG Phosphor bronze; 2 twisted pairs; Formvar insulation

Steady State Test Sample Configuration

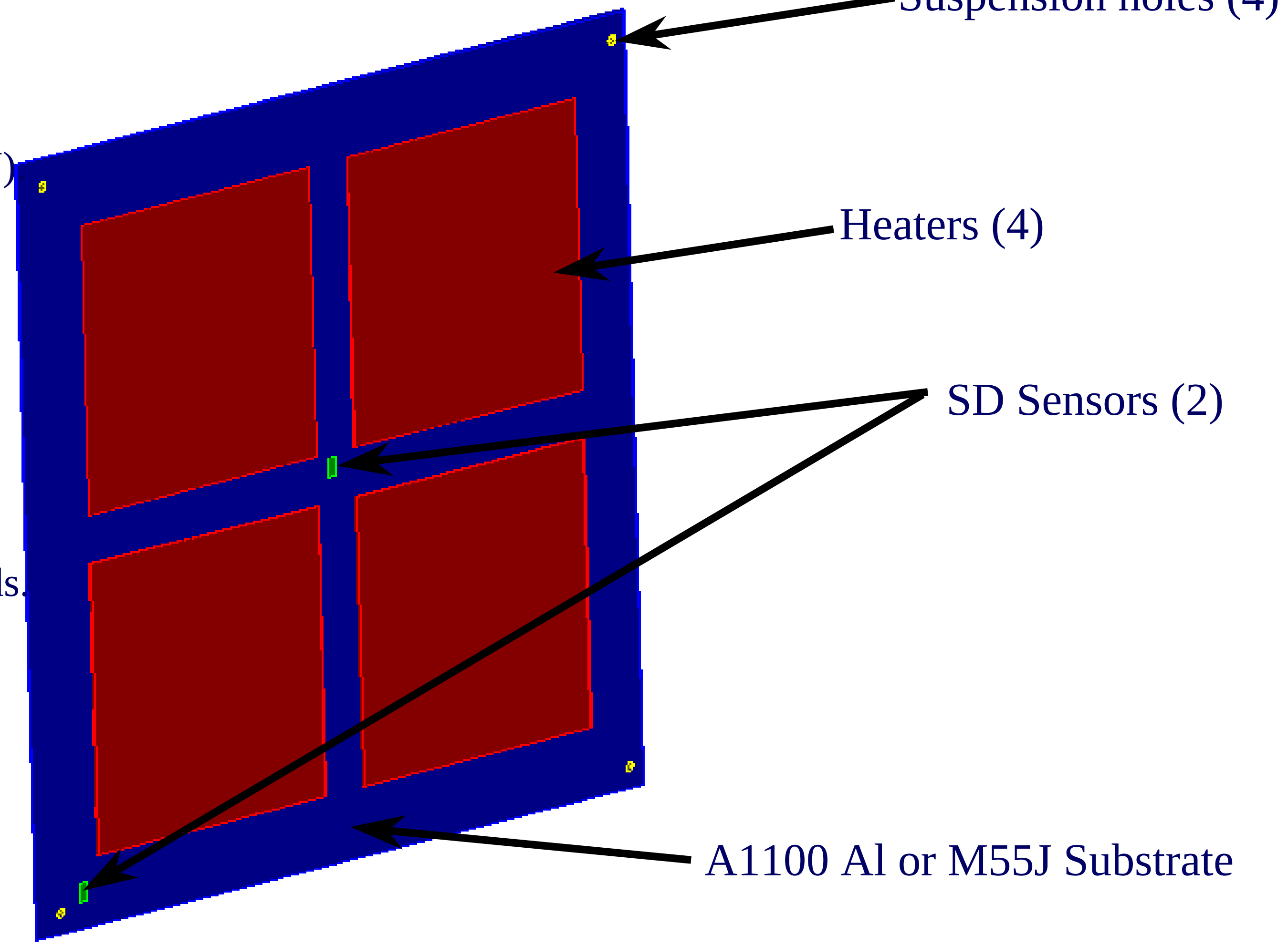
-Thermal control coating applied over heaters (except M55J)

-For M55J sample heaters covered with Aluminum tape.

- Heaters for steady state samples only.

-Al tape over SD sensors & heater leads.

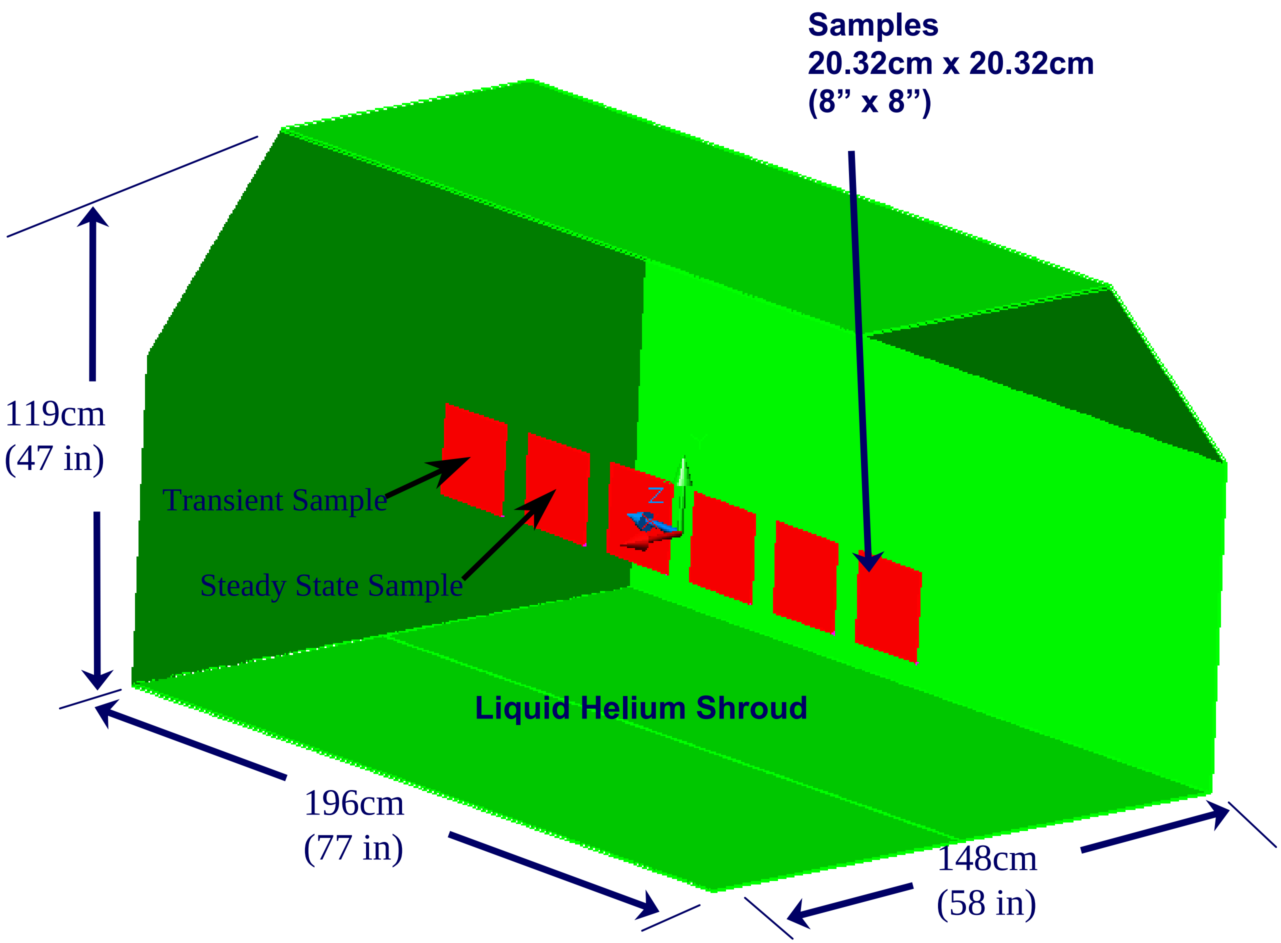
-Sensor/heater lead wires not shown



Test Sample Configuration

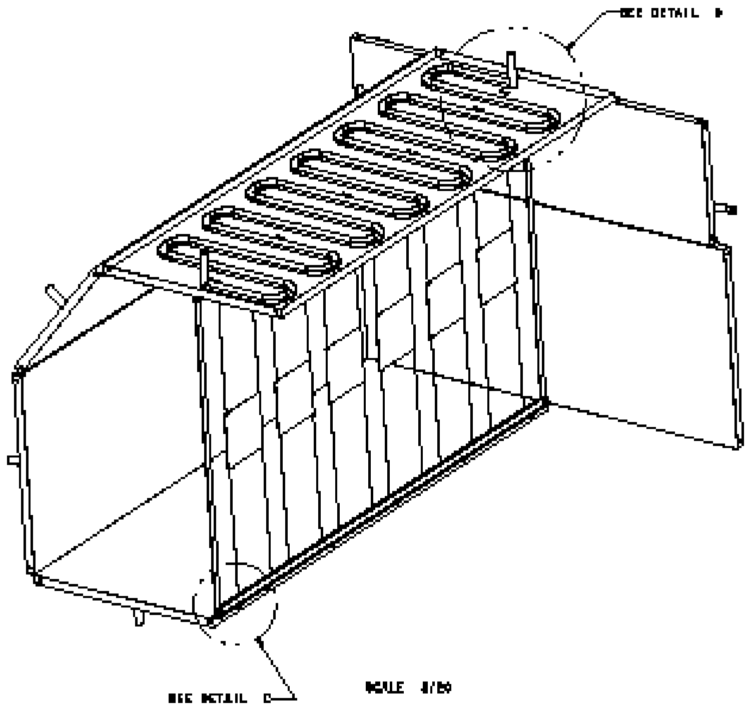
-Alternating transient / steady state samples

-Kevlar suspension not shown

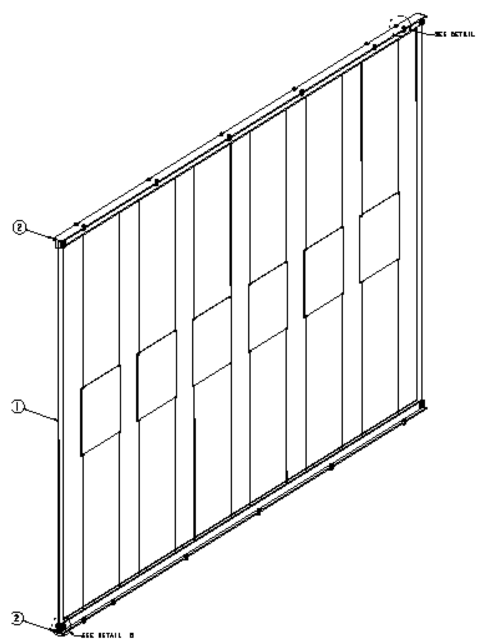


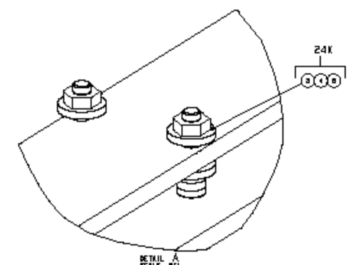
Thermal Desktop™ Model

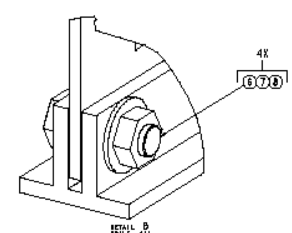
Test Sample Support Frame

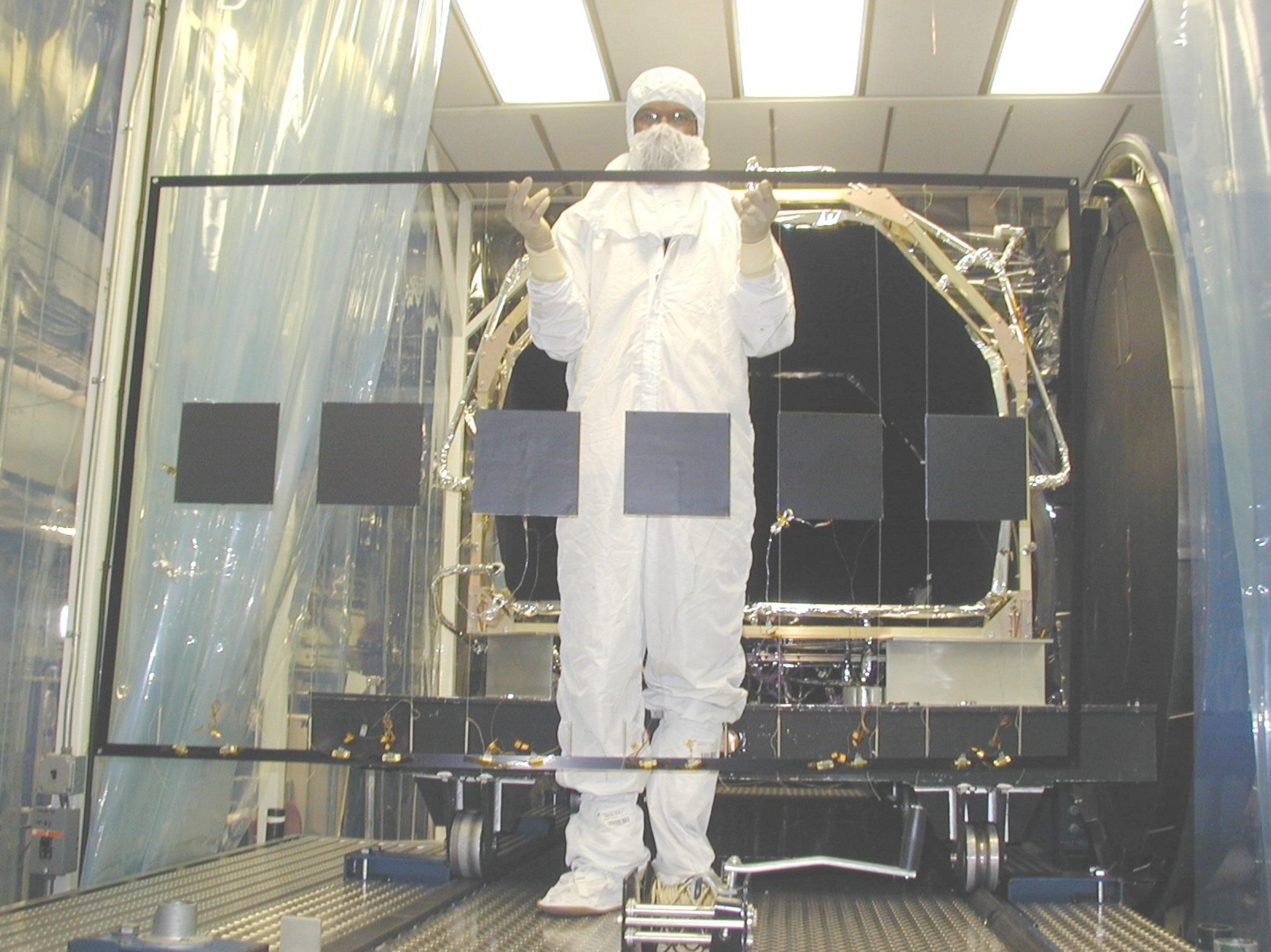


- •Black anodized
- •Conductively coupled to He shroud
- •Tension springs to attach Kevlar to frame

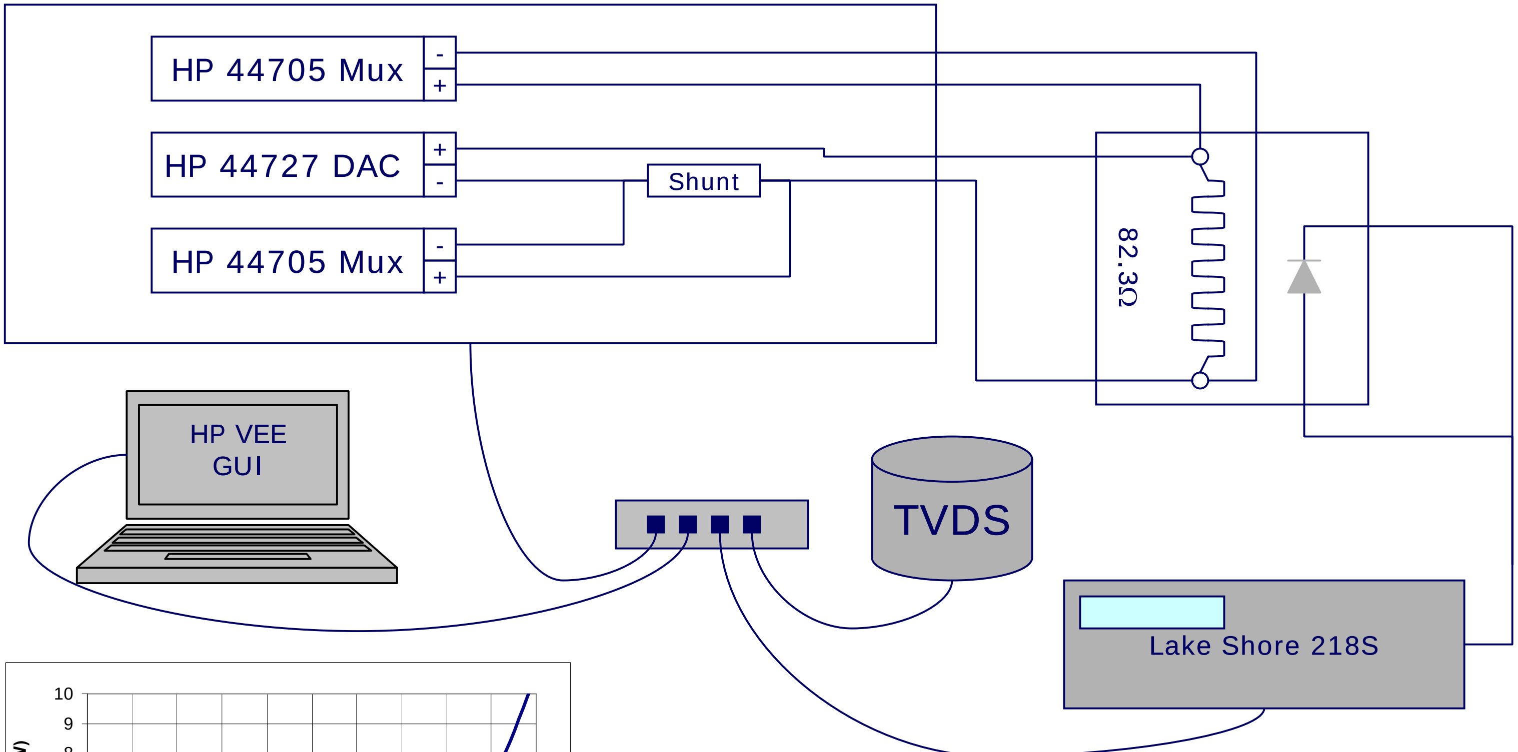


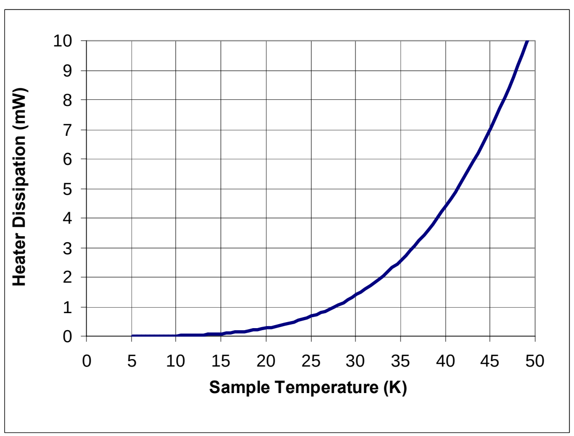






Test Sample Control & Measurement





System Accuracy

Power: <0.001mW

Temperature: ±50mK

Emissivity Determination

- **Thermal Balance Equations**
  - Transient

$$Q_c = \left(mC_p dT / dt\right)_{sample} = Q_{rad} + Q_{gas} + Q_{wire}$$

  - Steady State

$$Q_{htr} = Q_{rad} + Q_{gas} + Q_{wire}$$

where:

Q_c	sample internal energy rate of change
m	mass
C_p	Specific heat capacity
T	temperature
t	time
Q_{rad}	radiation to He shroud
Q_{gas}	residual gas conduction to He shroud
Q_{wire}	heater / sensor lead wire loss
Q_{htr}	heater dissipation

Emissivity Determination

- **Radiation Heat Loss**

$$Q_{rad} = \sigma A_s \varepsilon_{eff} (T_s^4 - T_\infty^4)$$

where

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_s} + \frac{A_s}{A_\infty} \left(\frac{1}{\varepsilon_\infty} - 1 \right) \right]^{-1}$$

for

$$A_s << A_\infty \qquad \varepsilon_{eff} = \varepsilon_s$$

- σ = Stefan-Boltzmann constant
- A_s = area of the test sample
- A_∞ = area of the shroud
- ε_{eff} = effective emissivity
- ε_s = emissivity of test sample
- ε_∞ = emissivity of shroud
- T_s = sample temperature
- T_∞ = shroud temperature

Emissivity Determination

- **Residual Helium Gas Heat Loss**

$$Q_{gas} = \alpha_{eff} XYP_{\infty} A_s (T_s - T_{\infty})$$

where $$\alpha_{eff} = \left[\frac{1}{\alpha_s} + \frac{A_s}{A_{\infty}} \left(\frac{1}{\alpha_{\infty}} - 1 \right) \right]^{-1}$$

$$X = \frac{\gamma_{He} + 1}{\gamma_{He} - 1}$$

$$Y = \left(\frac{R_{He}}{8\pi T_{\infty}} \right)^{1/2}$$

for $A_s << A_{\infty}$ $\quad \alpha_{eff} = \alpha_s$

- A_s = area of the test sample
- A_{∞} = area of the shroud
- α_{eff} = effective accommodation coefficient (ac)
- α_s = ac of He @ sample temperature
- α_{∞} = ac of He @ shroud temperature
- T_s = sample temperature
- T_{∞} = shroud temperature
- P_{∞} = pressure @ He shroud
- g = C_p / C_v
- C_p = specific heat @ constant pressure
- C_v = specific heat @ constant volume
- R_{He} = Helium gas constant

Ref: “Cryogenic Engineering”, T.M. Flynn, p372 (7.9)

Emissivity Determination

- **Lead Wire Heat Loss – Sensor Wires**
  - Assumptions
    - Ohmic dissipation insignificant
    - Wire radiation significant
    - Long lead wires

$$Q_{wire} = \pi\left(0.1\sigma\right)^{\frac{1}{2}}\left(k^{\frac{1}{2}}D^{\frac{3}{2}}\varepsilon^{\frac{1}{2}}\right)_{wire} T_s^{\frac{5}{2}}$$

- Q_{wire} = lead wire loss
- σ = Stephan-Boltzmann constant
- k_{wire} = Lead wire thermal conductivity (weighted average)
- D_{wire} = Lead wire outer diameter (includes insulation)
- ε_{wire} = lead wire insulation emittance
- T_s = sample temperature

Emissivity Determination

- **Lead Wire Heat Loss / Gain – Heater Wires**
  - Assumption
    - Ohmic dissipation significant (heater wires)
    - Wire radiation insignificant

$$Q_{wire} = \left(\frac{\pi D^2 k}{4L} \right)_{wire} \left(T_s - T_\infty \right) + \left(\frac{2 I^2 \rho L}{\pi D^2} \right)_{wire}$$

- Q_{wire} = heater lead wire loss/gain
- k_{wire} = Lead wire thermal conductivity (weighted average)
- D_{wire} = Lead wire outer diameter (includes insulation)
- L_{wire} = Lead wire length
- I_{wire} = Lead wire current
- ρ_{wire} = Lead wire electrical resistivity

Error Bar Determination

- All quantities in the aforementioned equations are known or measured except for the sample emissivity, ε_s. For either the steady-state or transient case, we can isolate this term and derive an expression in terms of the other variables.

$$\varepsilon_s = f\left(A_s, A_\infty, A_{wx}, A_{ws}, L, T_s, T_\infty, \varepsilon_w, \varepsilon_\infty, \alpha_{He}, \alpha_\infty, P_\infty, Q_{heater}, m, C_p, \frac{dT}{dt} \right)$$

- The variance of ε_s is then given by

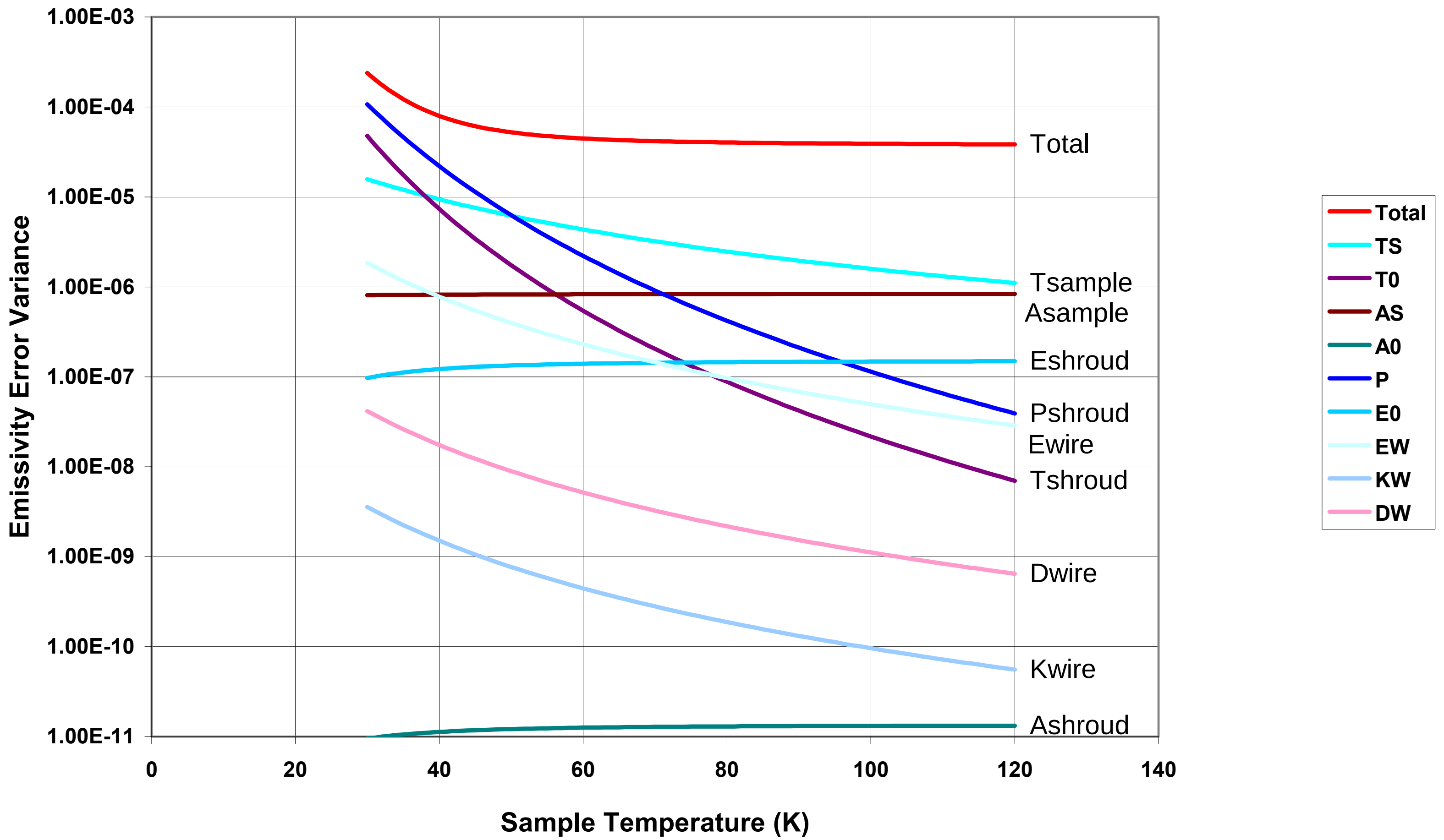
$$E_{\varepsilon_s}^2 = \left(\frac{\partial \varepsilon_s}{\partial A_s} \right)^2 E_{A_s}^2 + \left(\frac{\partial \varepsilon_s}{\partial A_\infty} \right)^2 E_{A_\infty}^2 + \ldots\ldots + \left(\frac{\partial \varepsilon_s}{\partial Q_{heater}} \right)^2 E_{Q_{heater}}^2$$

Ref: “Physics Quick Reference Guide”, American Inst. of Physics, p198

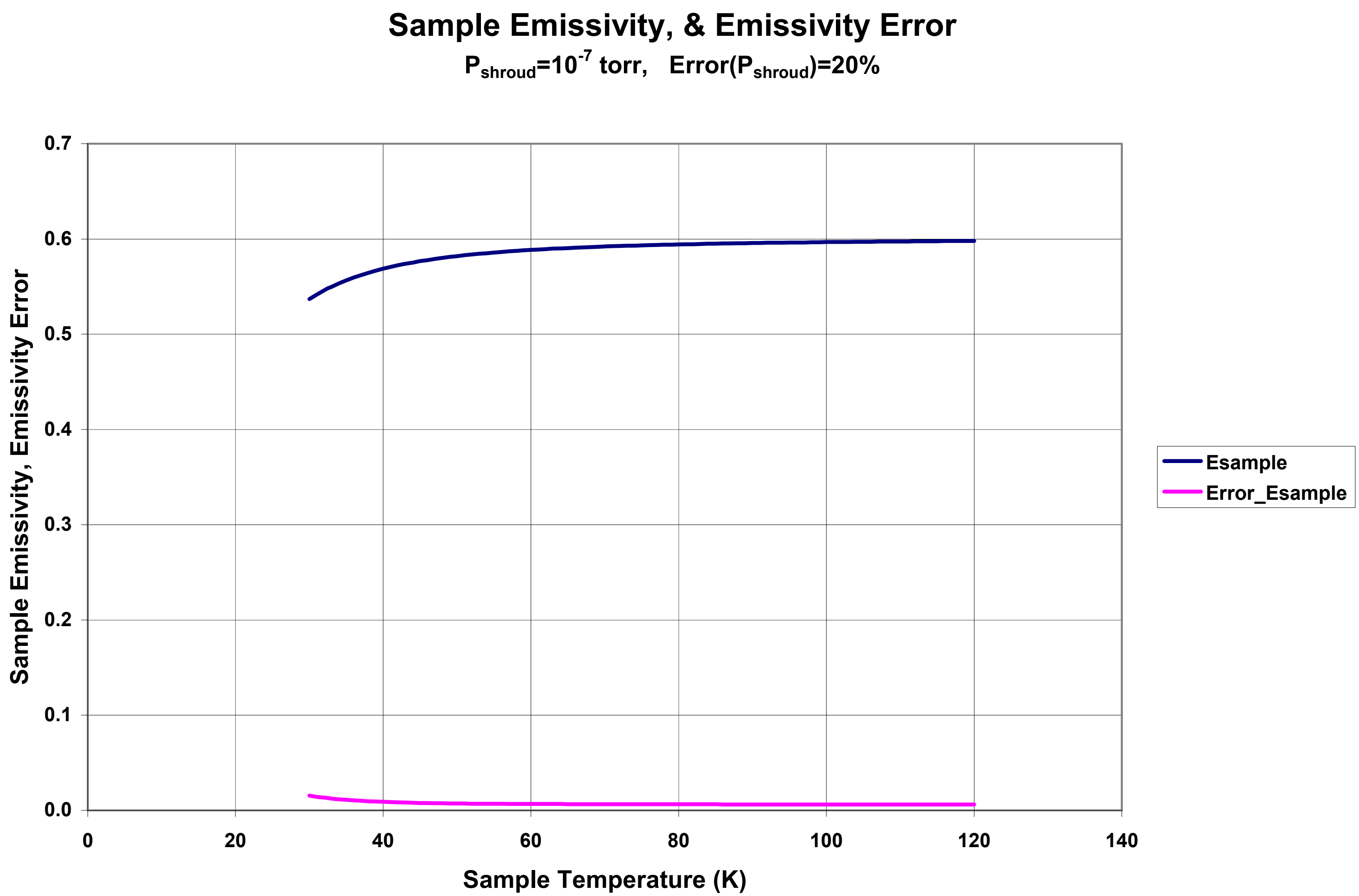
Error Bar Determination

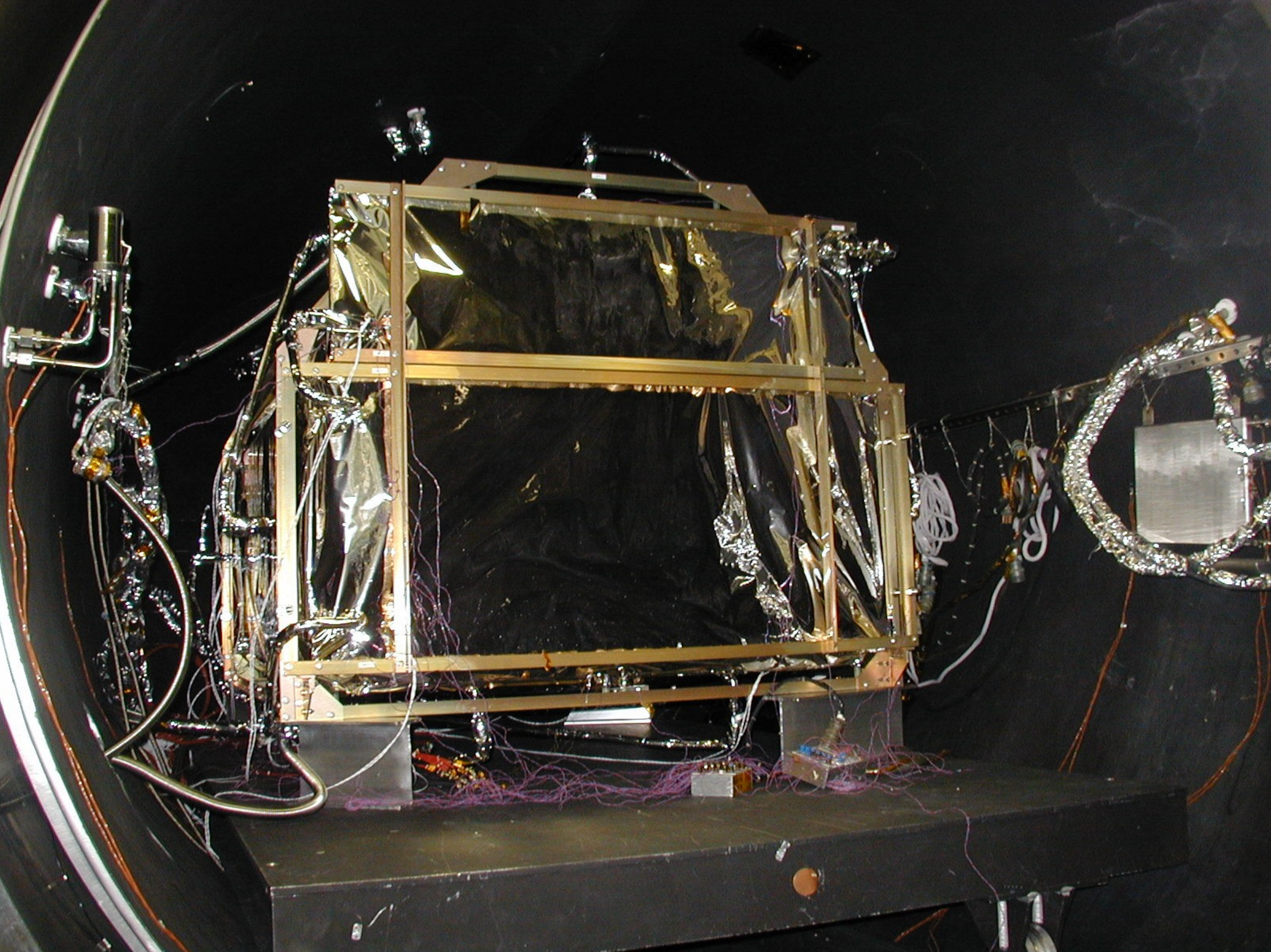
Emissivity Error Contributions

$P_{shroud}=10^{-7}$ torr, Error(P_{shroud})=20%



Error Bar Determination

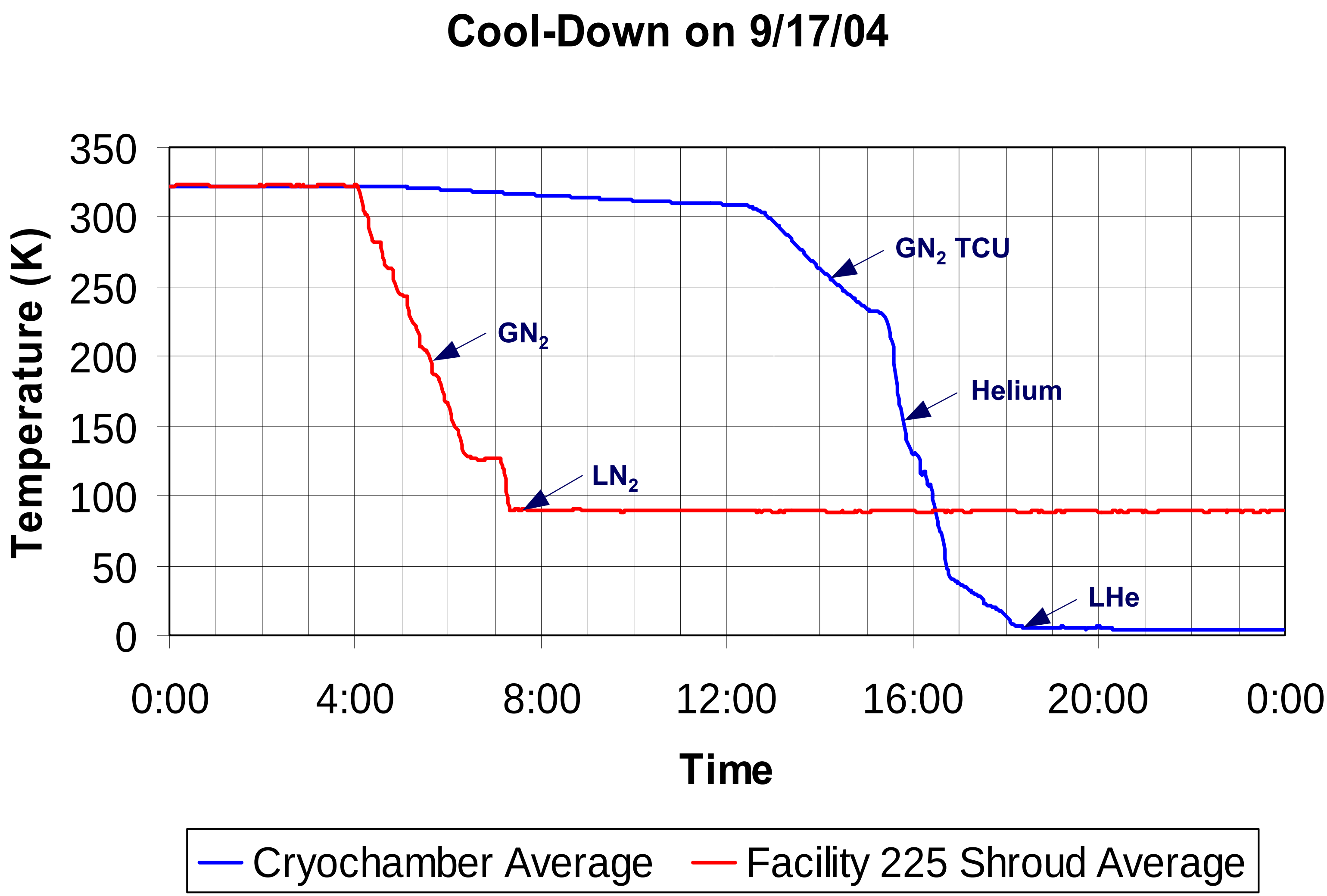




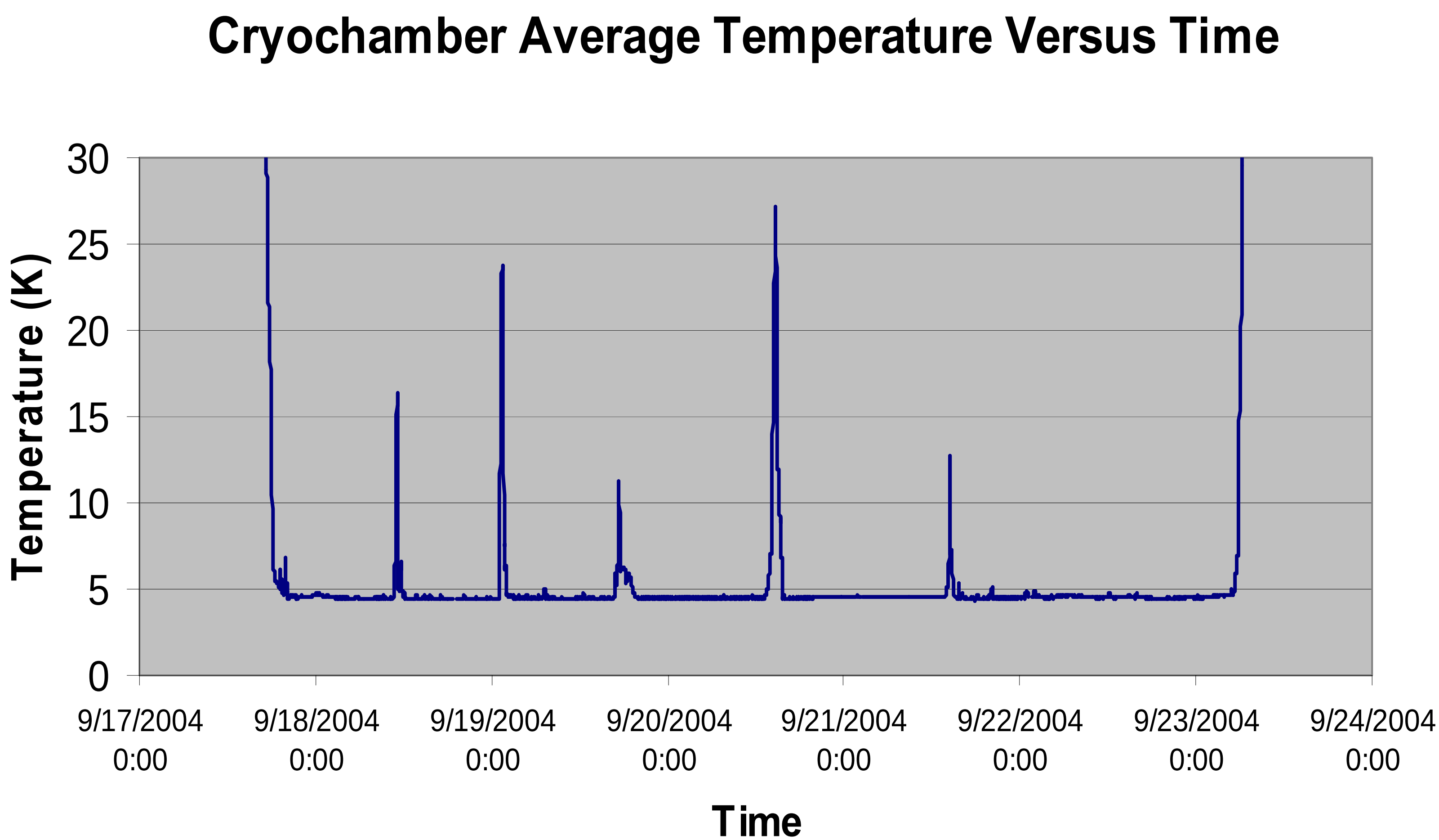
Cryochamber Operation

- **Baked-out cryochamber and emittance samples at 323K (50°C)**
- **Flooded Facility 225 chamber shroud with LN_2**
- **Pre-cooled cryochamber to 233K (-40°C) with GN_2 TCU**
- **Purged cryochamber with GHe**
- **Cooled cryochamber to 4.5 K with LHe**

Cryochamber Cool-Down



Cryochamber Temperature Profile



Cryochamber Test Results

- **All cryochamber test objectives were met**
  - **Cooled-down from >300K to 4.5K in less than 6 hours**
  - **Thermal gradient < 0.5K**
  - **Thermal stability < 0.1K/hr**
  - **Chamber pressure < $5x10^{-8}$ Torr**
- **Total cost of cryochamber was $77,738 which included**
  - **Design, fabrication and construction**
  - **Helium transfer lines**
  - **Instrumentation**
  - **Thermal blanketing**
- **Helium consumption was as predicted – about 500 liters/day**

Test Sample Results

- **Emittance test samples**
  - **M55J and Z306 sample results look good**
  - **Black Kapton delaminated from A1100 substrate**
  - **Steady state approach superior – less error than transient approach**
- **Emittance data not released**
  - **Parasitic losses and error bars being characterized**
  - **Emittance data to be published soon**

Future Considerations and Improvements

- **Cryochamber**
  - **Improve GN_2 TCU pre-cooling**
  - **Eliminate GHe purge during dewar changes**
    - **Plug inlet instead**
  - **Procure second helium transfer line**
    - **Improve time to change-out helium dewars**
- **Test Samples**
  - **Eliminate transient samples – pending analysis**
  - **Perform emittance testing of external radiator coating candidates:**
    - **Ball Infrared Black (BIRB)**
    - **Ball S13GLO**
    - **Black anodized aluminum**

Questions?