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

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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
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

- TIS1. Strap Development Test
- TIS2. Bench Material Property Tests (k vs. T)
- TIS3. Harness Development Test (Small Sample)
- TIS4. SI Mounting & Housing Cooling
- TIS5. ISIM Coating $\varepsilon$ at Cryogenic Temp
- TIS6. Heat Strap / Harness Standoff Test
- TIS7. Structure Joint Conductance Test
- TIS8. Harness Test (End to End) Thru Temp Regimes
- TIS9. OTE Interface H/W
- TIC1. Dewar Mounting Methods
- Final ISIM Thermal Design
- TIS10. Heat Switch & Miscellaneous Thermal H/W
- E17 ETU ISIM TB TEST
- Deliver ETU ISIM
- Final ISIM Design
- IS8 FLIGHT ISIM TB TEST
- Deliver FLT ISIM
**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

\[ \left( mC_p \frac{dT}{dt} \right)_{\text{sample}} = \sigma \left(A\varepsilon\right)_{\text{sample}} \left(T_{\text{sample}}^4 - T_{\text{LHeShroud}}^4\right) + Q_{\text{loss}} \]

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

and \[ T = f(t) \]

- \( m \) mass measured pre test
- \( C_p \) specific heat capacity theoretical*
- \( T \) temperature measured test data
- \( t \) time measured test data
- \( \sigma \) Stephan-Boltzmann constant = 5.67x10^{-8} W/m^2/K^4
- \( A \) sample radiating area measured test data
- \( A \) sample radiating area measured test data
- \( Q_{\text{loss}} \) lead wire+residual gas loss calculated
- \( \varepsilon \) emittance determined from above equation
Second Analytical Method

• Steady State Warm-Up

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

\[ T \quad \text{temperature} \quad \text{measured test data} \]
\[ \sigma \quad \text{Stephan-Boltzmann constant} \quad 5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4 \]
\[ A \quad \text{sample radiating area} \quad \text{measured pre test} \]
\[ Q_{loss} \quad \text{lead wire+residual gas loss} \quad \text{calculated} \]
\[ Q_{heater} \quad \text{heater power} \quad \text{measured test data} \]
\[ \varepsilon \quad \text{emittance} \quad \text{determined from above equation} \]
Test Profile – Overview
Timeline

- SS Sample
- TR Sample
- He Shroud

Temperature (K) vs Time (h)
Cryochamber Design Requirements

• Relatively large: $A_{\infty} >> A_s$ (chamber area >> sample area) and at least 3’x3’x3’ (1m³)
• 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
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

Suspension holes (4)
Heaters (4)
SD Sensors (2)
A1100 Al or M55J Substrate
Test Sample Configuration

- Alternating transient / steady state samples
- Kevlar suspension not shown

Liquid Helium Shroud

196 cm (77 in)

148 cm (58 in)

119 cm (47 in)

Samples
20.32 cm x 20.32 cm (8” x 8”)

Transient Sample

Steady State Sample

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

\[ Q_c = \left( m C_p \frac{dT}{dt} \right)_{\text{sample}} = Q_{\text{rad}} + Q_{\text{gas}} + Q_{\text{wire}} \]

  – Steady State

\[ Q_{\text{htr}} = Q_{\text{rad}} + Q_{\text{gas}} + Q_{\text{wire}} \]

where:

- \( Q_c \): sample internal energy rate of change
- \( m \): mass
- \( C_p \): Specific heat capacity
- \( T \): temperature
- \( t \): time
- \( Q_{\text{rad}} \): radiation to He shroud
- \( Q_{\text{gas}} \): residual gas conduction to He shroud
- \( Q_{\text{wire}} \): heater / sensor lead wire loss
- \( Q_{\text{htr}} \): 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 \[ A_s \ll A_\infty \]

\[ \varepsilon_{eff} = \varepsilon_s \]

- \( \sigma \) = Stefan-Boltzmann constant
- \( A_s \) = area of the test sample
- \( A_\infty \) = area of the shroud
- \( \varepsilon_{eff} \) = effective emissivity
- \( \varepsilon_s \) = emissivity of test sample
- \( \varepsilon_\infty \) = emissivity of shroud
- \( T_s \) = sample temperature
- \( T_\infty \) = shroud temperature
Emissivity Determination

• Residual Helium Gas Heat Loss

\[
Q_{\text{gas}} = \alpha_{\text{eff}} X \gamma_{\text{He}} P_{\infty} A_s (T_s - T_{\infty})
\]

where

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

\[
X = \frac{\gamma_{\text{He}} + 1}{\gamma_{\text{He}} - 1}
\]

\[
Y = \left( \frac{R_{\text{He}}}{8 \pi T_{\infty}} \right)^{\frac{1}{2}}
\]

for \( A_s \ll A_{\infty} \) \( \alpha_{\text{eff}} = \alpha_s \)

- \( A_s \) = area of the test sample
- \( A_{\infty} \) = area of the shroud
- \( \alpha_{\text{eff}} \) = effective accommodation coefficient (ac)
- \( \alpha_s \) = ac of He @ sample temperature
- \( \alpha_{\infty} \) = ac of He @ shroud temperature
- \( T_s \) = sample temperature
- \( T_{\infty} \) = shroud temperature
- \( P_{\infty} \) = pressure @ He shroud
- \( g = \frac{C_p}{C_v} \)
- \( C_p \) = specific heat @ constant pressure
- \( C_v \) = specific heat @ constant volume
- \( R_{\text{He}} \) = 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

\[
Q_{\text{wire}} = \pi \left(0.1\sigma\right) \frac{1}{2} \left(\frac{1}{k_{\text{wire}}^2 D_{\text{wire}}^2 \varepsilon_{\text{wire}}^2}\right) T_s^{\frac{5}{2}}
\]

- \(Q_{\text{wire}}\) = lead wire loss
- \(\sigma\) = Stephan-Boltzmann constant
- \(k_{\text{wire}}\) = Lead wire thermal conductivity (weighted average)
- \(D_{\text{wire}}\) = Lead wire outer diameter (includes insulation)
- \(\varepsilon_{\text{wire}}\) = 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

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

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

• All quantities in the aforementioned equations are known or measured except for the sample emissivity, \( \varepsilon_s \). 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 \( \varepsilon_s \) is then given by

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

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

Emissivity Error Contributions

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

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Sample Temperature (K)

Emissivity Error Variance
Error Bar Determination

Sample Emissivity, & Emissivity Error

\[ P_{\text{shroud}} = 10^{-7} \text{ torr}, \quad \text{Error}(P_{\text{shroud}}) = 20\% \]
Cryochamber Operation

• Baked-out cryochamber and emittance samples at 323K (50°C)
• Flooded Facility 225 chamber shroud with LN₂
• Pre-cooled cryochamber to 233K (-40°C) with GN₂ TCU
• Purged cryochamber with GHe
• Cooled cryochamber to 4.5 K with LHe
Cryochamber Cool-Down

Cool-Down on 9/17/04

Temperature (K)

0:00 4:00 8:00 12:00 16:00 20:00 0:00

Time

Cryochamber Average
Facility 225 Shroud Average

GN₂ TCU
Helium
LN₂
LHe
Cryochamber Temperature Profile

Cryochamber Average Temperature Versus Time

![Graph showing temperature profile over time](image-url)
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 GN₂ 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?