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
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**

- **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
- **TIS10.** Heat Switch & Miscellaneous Thermal H/W
- **E17 ETU ISIM TB TEST**

**Final ISIM Thermal Design**

**IS8 FLIGHT ISIM TB TEST**

Deliver FLT ISIM

Deliver ETU 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

\[
T = f(t)
\]

\begin{align*}
\text{mass} & : \text{measured pre test} \\
\text{specific heat capacity} & : \text{theoretical*} \\
\text{temperature} & : \text{measured test data} \\
\text{time} & : \text{measured test data} \\
\text{Stephan-Boltzmann constant} & : 5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4 \\
\text{sample radiating area} & : \text{measured pre test} \\
\text{lead wire+residual gas loss} & : \text{calculated} \\
\text{emittance} & : \text{determined from above equation}
\end{align*}
Second Analytical Method

• Steady State Warm-Up

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

- \( T \): temperature, measured test data
- \( \sigma \): Stephan-Boltzmann constant, \( 5.67 \times 10^{-8} \) W/m\(^2\)/K\(^4\)
- \( A \): sample radiating area, measured pre test
- \( Q_{loss} \): lead wire+residual gas loss, calculated
- \( Q_{heater} \): heater power, measured test data
- \( \varepsilon \): 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’ (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 $1 \times 10^{-2}$ to $1 \times 10^{-9}$ 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 HK5174R82.312B
  – 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

A1100 Al or M55J Substrate

Suspension holes (4)
Heaters (4)
SD Sensors (2)
**Test Sample Configuration**

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

**Liquid Helium Shroud**

- Transient Sample
- Steady State Sample

**Samples**
- 20.32cm x 20.32cm (8” x 8”)

**Thermal Desktop™ Model**

- 196cm (77 in)
- 119cm (47 in)
- 148cm (58 in)
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

Diagram showing the Test Sample setup with:
- HP 44705 Mux +/−
- HP 44727 DAC +/− Shunt
- HP 44705 Mux +/−
- 82.3Ω
- Lake Shore 218S
- TVDS
- HP VEE GUI

Graph showing sample temperature vs. heater dissipation, with a maximum heater dissipation of 10 mW at 50 K.
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

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

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

- \( A_s \) = area of the test sample
- \( A_{\infty} \) = area of the shroud
- \( \alpha_{eff} \) = 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
- \( R_{He} \) = Helium gas constant

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

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

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

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

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

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

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

- \( Q_{\text{wire}} \) = 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

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

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

Emissivity Error Contributions

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

<table>
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<th>Total</th>
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<th>Asample</th>
<th>Pshroud</th>
<th>Eshroud</th>
<th>Ewire</th>
<th>Kwire</th>
<th>Dwire</th>
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<td>1.00E-03</td>
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</tr>
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</table>
Sample Emissivity, & Emissivity Error

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

Graph showing sample emissivity and emissivity error as a function of sample temperature (K)
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)

Time

Cryochamber Average
Facility 225 Shroud Average
Cryochamber Temperature Profile

Cryochamber Average Temperature Versus Time

Temperature (K)

Time

9/17/2004 0:00 9/18/2004 0:00 9/19/2004 0:00 9/20/2004 0:00 9/21/2004 0:00 9/22/2004 0:00 9/23/2004 0:00 9/24/2004 0:00
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?