CRYogenic Orbital TEstbed
Ground Test Article Thermal Analysis

TFAWS
August 13th-17th, 2012

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Agenda

- Introduction
- GTA Analysis Goals
- Test Facility
- Post-Test Modeling
- Post-Test Results/Correlation Efforts
- Questions/Discussion
Introduction

- **CRYogenic Orbital TEstbed**

  **Ground Test Article**

  - Multi Layer Insulation designed and applied to GTA to simulate Tank/LN2 on-orbit radiation-only environments
    - KSC Cryogenics Test Laboratory
  - Purpose of GTA test is to measure heat loads on tank/fluid during unsteady and steady state
  - GTA fitted with thermocouples at various locations
  - Unique opportunity to anchor thermal model against test data
  - Testing at MSFC in progress

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GTA Thermal Analysis Goals

• Objectives:
  - Provide thermal performance analysis on CRYOTE GTA (e.g. analytical prediction of LN$_2$ boil off rates)
    - Correlate heat loads to LN$_2$
    - Correlate temperature responses throughout GTA
    - Evaluate MLI performance
Thermal Networks

- MLI and Cone
- ESPA Ring and Cone
- MLI and Tank
- Cone and Tank
  - 4 titanium attach points

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Environments

- **Vacuum Chamber Environments**
  - Temp proposed to be held at a constant 292K
  - Pressure proposed to be held constant
  - Effective emissivity associated with MLI surfaces
    - \( e^* = \frac{1}{1/e_o + 1/e_i - 1} \times \frac{1}{N+1} \) = theoretical \( e^* \)

2 Radiation Analysis Groups in TD Model

- **Exterior Radiation Analysis Group**
  - ESPA ring and outer MLI surface only
  - Exposed to vacuum chamber environments
    - Temperature set to BC of 292°K (60°F)
- **Interior Radiation Analysis Group**
  - Cone, inner MLI surfaces and tank

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Test Facility

Exploration Systems Test Facility (ESTF) at MSFC
Test Facility

Vacuum Chamber
9' diam. X 20' long
10-8 Torr

Cryogenic
Test Bed
6' x 6'

Multipurpose Hydrogen Test Bed
10' x 10'

Test Tank Pressure Ctrl
& Boil Off Measurement

LN2 Feed, Drain, Vent

LN2 Dewar
240 Liter

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Test Facility

- Testing commenced 11-18-2011
- CRYOTE GTA was initially filled to ~90% full w/LN2
- LN2 was conditioned to 18psia before steady state measurements (tank @ 14.7psia during fill)
- Received ‘Fill’ and ‘Steady State’ data sets from test team on 12-1-2011
Post-Test Thermal Desktop Modeling
Post-Test TD Modeling

• Pre-test modeling very useful for finding heat loads to LN2 but not necessarily much else
  – Due to low fidelity nature of baseline model
  – Extremely difficult to assign broad surface temperatures to thermocouple locations

• Refined goals were to capture thermal gradients along:
  – Skirt surfaces
  – Tank surfaces

• Refined goals required refined modeling
Post-Test Modeling

Thermal Mesh Quality Refinements - Skirt

Pre-Test Model:
- 72 TD/RC Nodes
- 6 Angular Sections

Post-Test Model:
- 1504 TD/RC Nodes
- 32 Angular Sections
Post-Test Modeling

Thermal Mesh Quality and Surface Refinements - MLI

Pre-Test Modeling:
- Represented as a single surface
- "Overall" effective emissivity value used
- 72 TD/RC Nodes

Post-Test Modeling:
- Represented as 4 separate sub-blankets (per Johnson's MLI blanket sketches)
- 5024 TD/RC Nodes
Fill and Vent Lines Added:
- Use of FLOWCAD Pipes
- Set to BCs for fill modeling

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Post Test Modeling

Pre-Test Tank Model:
- 24 TD/RC Nodes
- 2 Lumps (liquid/vapor)

Post-Test “Fill” Tank Model:
- 704 TD/RC Nodes
- Divided into 20 equal sections/surface areas
- 20 Lumps (Core)
- AKA “The Beast”

Post-Test “Steady State” Tank Model:
- 704 TD/RC Nodes
- Divided into 20 equal sections/surface areas
- Reduced to 2 Lumps (Liquid/Vapor) to decrease analysis time

Vent to BC at room T and P
‘Set Flow’ Path
Fill from BC at Sat LN2 @ 14.7 psi

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Post-Test Results/Correlation Efforts

1.) Fill Operations
   a.) Tank Temperature Gradients
   b.) Fill Data
   c.) Skirt Temperature Gradients

2.) ‘Steady State’ Operations
   a.) Boil Off Rate of LN2
   b.) Skirt Temperature Gradients

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Tank Gradients

- Located in this directory, open the .avi file named: "Tank Temperature Gradients - 75% Fill"
LN2 Mass in CRYOTE Tank

LN2 Mass in CRYOTE Tank

Test Data - % Full by Mass
Fill Model - % Full by Mass

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• Located in this directory, open the .avi file named:
  “Skirt Temperature Gradients - 75% Fill”
TC07 Test/Model Correlation

Note: Min/max skirt temps correspond to min/max temps seen from TC07-TC11

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TC08 Test/Model Correlation

TC08 Correlation

Max Skirt Temp

Scaled Temp

Min Skirt Temp

Time, hrs

Note: Min/max skirt temps correspond to min/max temps seen from TC07-TC11

TC08

Bottom View

Thermocouples Lines

Thermocouple 15A & 17
Thermocouple 15B & 17
Thermocouple 15C & 17
Thermocouple 15D & 17
Thermocouple 15E & 17

TC08

Test Data TC08

Model Data TC08

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TC09 Test/Model Correlation

Increased $\Delta T$ due to LN2 still in fill line

Note: Min/max skirt temps correspond to min/max temps seen from TC07-TC11

TC09 (Located within 1" of Fill Line)

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TC11 Test/Model Correlation

Note: Min/max skirt temps correspond to min/max temps seen from TC07-TC11

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Skirt Gradients

• Located in this directory, open the .avi file named: “Skirt Temperature Gradients - Fill to Steady State”
LN2 Boil Off Correlation

Percent Boil Off Rate of LN2 in CRYOTE GTA Tank

![Graph showing the percent boil off rate of LN2 over time. The x-axis represents time in hours ranging from 0 to 60, and the y-axis represents the boil off rate in percent mass/hour. The graph includes two lines: one for test data boil off rate and another for model data boil off rate. The data includes test results from August 13th to 17th, 2012.]

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Analytical Trade Study:
Steady State Boil Off vs. Percent Full by Liquid Volume

Point where LN2 level reaches tank-to-skirt interface (~40% full by volume)

Surface area wetted at tank – skirt interface

Darkest blue represents liquid level

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Skirt Material Props Parametric

TC07 Correlation - Skirt Material Properties

Note: Min/max skirt temps correspond to min/max temps seen from TC07-TC11

Test Data TC07  G-10 Skirt Material Props  IM7/977-2 Skirt Material Props  Mx: k = G-10 Props and Cp = IM7/977-2 Props

TC07

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Conclusions & Recommendations

• Pre-test modeling gave accurate prediction for steady state heat loads to tank and LN2
  – Due to granularity of model surfaces, not appropriate for correlating temperature at specified thermocouple locations
• Post-test modeling provided fidelity necessary to make appropriate correlations throughout CRYOTE GTA
  – Should use caution when looking at unsteady state predictions
    • Thermophysical properties used for composite skirt were approximated as G10 props
    • Actual skirt was constructed out of a LOX compatible resin – combination of G-10 and IM7-977-2 props
• As long as fill level stays above ~35% by volume, steady state heat leak should remain relatively the same
Conclusions & Recommendations

• Modeling 4 separate MLI sub-blankets proved successful
  e* values used were based on: e* = 1/(1/e_o + 1/e_i -1) x [1/(N+1)]
  • e* value used for inner 3 blankets was lower
  • e* value used for outer blanket was higher
    – Due to outer Beta cover (assumed to be part of 4th outer blanket)

• Validated contact conductance coefficients used for tank flange-to-composite skirt interfaces
  Pre-test modeling assumed contact surface areas were rough in texture
  • Estimated contact conductance values were between 0.02 to 0.15 BTU/hr-R
  Final correlated contact conductance value was in above range
  Final HTC from tank to composite skirt to was slightly higher
  • Additional conductance from length of tank flange to tank
Questions?