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
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

- 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°F

- Interior Radiation Analysis Group
  - Cone, inner MLI surfaces and tank
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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• 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

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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, % Full by Mass

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

Max Skirt Temp

Min Skirt Temp

Scaled Temp

Time, hrs

Test Data TC08  
Model Data TC08

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

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TC09 Test/Model Correlation

Increased ΔT due to LN2 still in fill line

TC09 (Located within 1" of Fill Line)

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

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TC11 Test/Model Correlation

Max Skirt Temp

Scaled Temp

Min Skirt Temp

Time, hrs

Test Data TC11  Model Data TC11

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

Test Data Boil Off Rate  Model Data Boil Off Rate
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Boil Off vs. LN2 Fill Level

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 - Correlation - Skirt Material Properties

TC07 Correlation - Skirt Material Properties

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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^* = \frac{1}{(1/e_0 + 1/e_i -1) \times [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?