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Gravity Probe B Relativity Mission

Dewar Lifetime & TAO Assessment following Thermal Vacuum Test 2

S0917, Rev. -

August 15, 2003

Prepared by:

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Approved by:

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Approved by:

Systems Engineering	**Date**

Approved by:

Quality Assurance	**Date**

ITAR Assessment Performed ____________________
Tom Langenstein

ITAR Control Req'd? ☐ **Yes** ☐ **No**

Purpose:

This document formally releases the presentation material prepared for the June 12, 2003 review of the Thermal Vacuum Test #2.

The attached charts show that the Dewar predicted on-orbit lifetime is 18.8 months, and that this value is supported by a host of test and analytical data.
Additionally, the effect known as Thermal Amplitude Oscillation (TAO) has been shown to be a ground concern only, and will not occur on orbit.

For U. S. Export control reasons, pages which show the Lockheed Martin thermal model details have been omitted.

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12 June 2008

Dewar Lifetime Prediction

John Mester

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Dewar Lifetime Outline

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- GP-B Dewar On-Orbit Lifetime Requirements
- Dewar TVAC II Measurement Overview
- Thermal Model Projected Lifetime
- MSFC Independent Thermal Model
- Thermal Model Correlation with Test Data
- Thermal Vac II Dewar Analysis
- Dewar Lifetime Conclusions
- Request Log Items

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Dewar Lifetime Summary

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- GP-B dewar on-orbit lifetime requirement
  - Level 1 (program commitment agreement) is >16 months
  - Stanford imposed >16.5 month requirement on LM in payload contract

- Nominal initial on-orbit state:
  - Main Bath Superfluid
  - 95% Full (2319 Liters of liquid)
  - Guard Tank depleted
- Current projected lifetime
  - LM model predicting = 18.8 months
  - Supported by Suite of Ground Measurements

GP-B meets the dewar lifetime requirement

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TVAC II Dewar Measurements

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- Mitigation of GSE helium leakage in TVAC II test successful
  - No He Leakage into Chamber
- Goal of TVAC II dewar measurements successfully met
  - Boil off and temperature profile measurements made for further validation of Dewar Thermal Model
- TVAC II dewar measurements complete the suite of Thermal Model ground test correlation checks
- TVAC II dewar measurements adds to confidence in Thermal Model prediction of on orbit lifetime = 18.8 months

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LM Science Mission Dewar/Probe C Thermal Model

EM N0. TCS 342 B S0600 Rev A January 2002

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- **Based on Dewar and Probe drawings and material thermal properties**
  - Audit of Probe C drawings performed to reflect as built configuration
    - » **Includes copper pins between the Probe Heat Stations and Probe HEXs**
    - » **Measured infrared reflectance values of Probe heat station baffles**
- **Thermal Model is run in SINDA V1.6 and Thermal Analyzer Library computer codes**
  - 571 nodes
- **Model predictions are correlated with ground test temperature profile and boil off measurements - tests model's fidelity**
- **On Orbit Lifetime Prediction obtained using SF He properties and dewar boundary conditions derived from orbit environment**

LM Thermal Model Predicts On Orbit Lifetime of 18.8 Months

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Details of LM Thermal Model Assumptions

SD
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- The Belleville Pre-load system modeled with a 1000 pounds of pre-load
- Heat load from the QBA incorporates detailed SIA model
- Spacecraft Environment for Solar, Earth Albedo, and Earth IR heating is averaged over GP-B orbit
- Mission averaged optical properties are used for Spacecraft surfaces

Component Boundary Temperatures

Location	Kelvin
Probe/Top Hat	243K
Window 4	238K
Dewar Vacuum Shell Conic	228K
Vacuum Shell Cylinder	231K
Vacuum Shell Aft Dome	232K
Attitude Reference Platforms	246K

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MSFC Independent Thermal Model

Report No.: MG-02-359 August 2002

12 June 2003

- Independent Thermal Model based on 370 dewar and 375 probe drawings
- Developed Geometric Math Model consisting of 840 surfaces representing 6919 corresponded nodes
  - Material Conductance and Emissivity Properties Used
  - Includes Science Mission heat loads
- Thermal Model is run in SINDA/FLUINT and Thermal Desktop computer codes
- Contact conductances are tuned to match NBP test data
- On Orbit Lifetime Prediction obtained using SF He properties and dewar boundary conditions derived from orbit environment

MSFC Thermal Analysis Predicts On Orbit Lifetime of 17.2 Months

Post TVAC II Review - 7

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Details of MSFC Thermal Model Assumptions

[illegible]
12 June 2003

- The Belleville Pre-load system modeled with a 1000 pounds of pre-load
- Heat load from the QBA applied to Probe station 200
- Spacecraft Environment for Solar, Earth Albedo, and Earth IR heating are averaged over GP-B orbit
- EOL (end of life) optical properties are used for Spacecraft surface properties - yields worst case boundary temperatures
- Some Differences in amount of 2nd surface aluminized Teflon and 2nd surface Kapton between model and current vehicle as-built

Component Boundary Temperatures

Location	Kelvin
Window 4	234.2
Dewar Vacuum Shell Conic	236.5
Dewar Vacuum Shell Cylinder	236.8
Dewar Vacuum Shell Aft Dome	238.4
Attitude Reference Platform	267.9

MSFC Thermal Analysis Uses Worst Case Boundary Temperatures

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LM Thermal Model Ground Test Correlation Cases

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- Probe without Dewar @ room temperature

    Probe-B heater test
    Probe-C heater test

- Probe and Dewar

    Probe-C in Dewar and heat station rings disconnected
    Probe-C in Dewar and heat station rings connected using copper pins
        Main Tank Normal Boiling Point, Guard Tank Empty of Liquid
        Main Tank Superfluid, Guard Tank Normal Boiling Point
        Main Tank Superfluid, Guard Tank Empty of Liquid
        TVAC I and II - Main Tank NBP, Dewar Boundary Temp Reduced

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Thermal Model Ground Test Correlation

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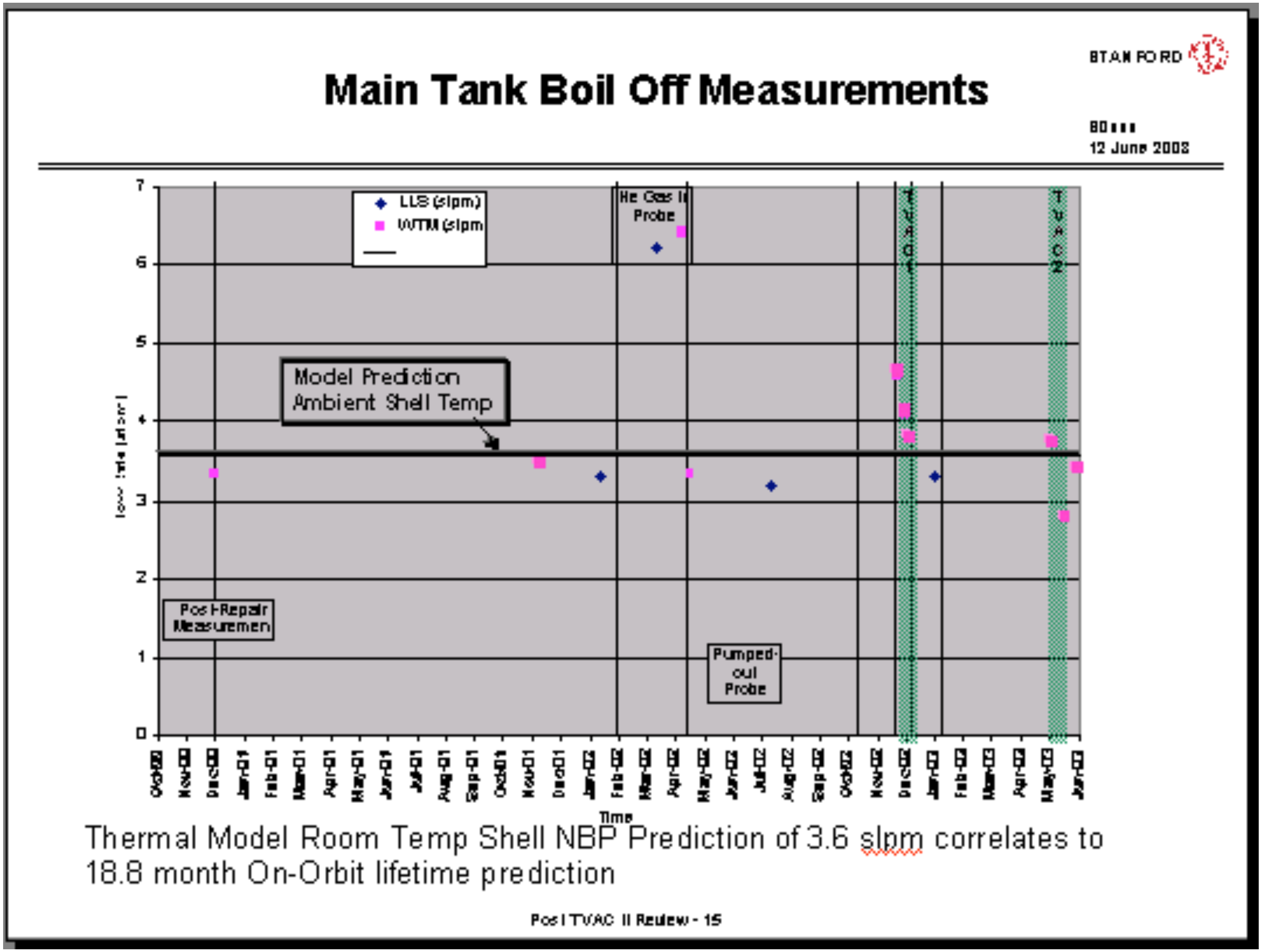
- Main Tank NBP, Guard Tank Empty:
  - Predicted Temperatures within 7 K
  - Predicted MT He boil off within 0.2 mg/sec of measured 12.5 mg/sec
  - Other He boil off measurements over last 2 years are consistent
- Main Tank Superfluid, Guard Tank NBP:
  - Predicted Temperatures within 3 K
  - Predicted GT He boil off within 0.5 mg/sec of measured 18.6 mg/sec
- Main Tank Superfluid, Guard Tank Empty:
  - Predicted GT Temperature within 3.5 K
  - Predicted MT He boil off within 0.1 mg/sec of measured 3.1 mg/sec
- TVAC I:
  - Boil Off in TVac at Room Temp was 25-35% higher than outside nominal
    - Likely Cause TAO (Measurements made post TVAC I strengthen likelihood)
  - Boil off rates decreased as dewar shell cooled
    - delta consistent with thermal model within (large) measurement error
- TVAC II:
  - TAO impact characterized
  - Measured Boil off rates decreased as shell cooled
    - Temperatures and Boil Off consistent with thermal model including TAO impact

Based on All Available Data Thermal Model Is Well Correlated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Main Tank Boil Off Measurements
12 June 2003
LLS (slpm)
WTM (slpm
He Gas In Probe
TVAC 1
TVAC 2
Model Prediction
Ambient Shell Temp
Post-Repair Measuremen
Pumped-out Probe
Time
Thermal Model Room Temp Shell NBP Prediction of 3.6 slpm correlates to 18.8 month On-Orbit lifetime prediction
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Thermal Vac II Dewar Measurement Scheme

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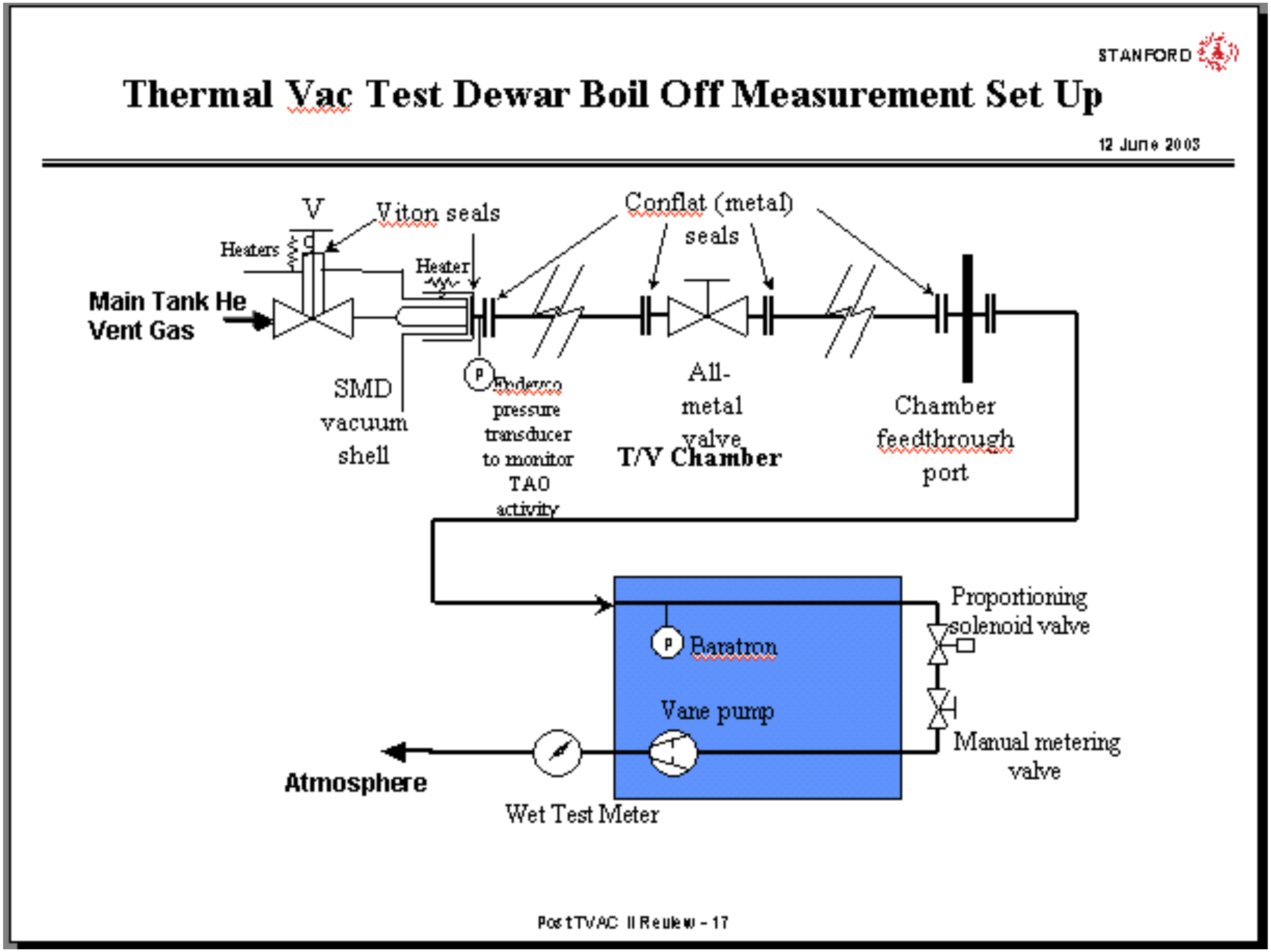
- During TVac test dewar is in horizontal - liquid level sensor not valid
  - Other ground tests confirm no boil off rate difference between horizontal and vertical
- Dewar heat rate is determined from He vent rate
  - He vent rate is measured with wet test meter
  - Main Tank temp residual slope is accounted for
- Atmospheric pressure variations generally prevent steady state from being achieved
  - A technique for isolating the main tank from atmospheric pressure is used
- Conversion of vent rate to boil off rate
  - Wet Test Meter yields volume flow at room pressure, temperature
  - Correct for ambient water vapor pressure
    - » Bubbler used to ensure saturation
  - Use gas law to convert from ambient to STP
  - Only 86.5% of boiloff gas actually vents
  - Assumes unit volume of NBP liquid is replaced by unit volume of NBP vapor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Thermal Vac Test Dewar Boil Off Measurement Set Up
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V
Viton seals
Heaters
Heater
Conflat (metal)
seals
Main Tank He
Vent Gas
SMD
vacuum
shell
Endevco
pressure
transducer
to monitor
TAO
activity
All-
metal
valve
T/V Chamber
Chamber
feedthrough
port
Proportioning
solenoid valve
Baratron
Vane pump
Manual metering
valve
Atmosphere
Wet Test Meter
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TVAC II Dewar Measurements

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- **May 1 Measured Boil Off = 3.7 slpm**
  - Dewar boundary at Room Temperature
  - In TVAC, Chamber and Guard Tank Evacuated
  - Slightly Higher than 3.6 slpm Thermal Model Prediction
  - Higher than average boil off measurements since 12/00 of 3.45 slpm
  - TAO observed with Endevco, Amplitude = 0.7 Torr, Freq = 1 Hz
- **May 16 Measured Boil Off = 2.9 slpm**
  - Dewar boundary temperature simulating on orbit conditions at end of 2nd cold cycle
  - Includes effects of – 1.0×10^{-4} K/hr main bath temperature slope
  - Confirmed by measurement 23 hr later with – 4.9×10^{-5} K/hr main bath temperature slope
  - TAO monitored, same freq and amplitude as May 1 measurement

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TVAC II Dewar Measurements 2

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TVAC cold soak achieved orbit like dewar boundary temperatures

Top Hat	237 K
Conic Section	228 K
Top Plate	256 K
Window 4	211 K
Supt Ring/for&aftCyl	246 K
Aft Dome	247 K
ARP Post	236 K

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TVAC II Data Thermal Model Correlation With TAO Heat Load

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Method 1) Sink Model Guard Tank Temp to Match Measured Boil Off
– Check Correlation between predicted and measured temps

Method 2) Experimentally determine TAO heat Load
– Check Correlation between predicted Main Tank Heat Load and measured Main Tank Heat Load

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TVAC II Data Thermal Model Correlation With TAO Heat Load

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Method 1)

- **Thermal Model Run with Guard Tank Temp fixed to 28 K**
  - Sets Boil Off close to measured 2.9 slpm during cold soak
- **Dewar/Probe Temperature Profile predictions within 5 K of measurements**
  - ECU Si Diode Thermometer Measurements include recent gain calibration Completed by Bob Farley

Thermal Model Temperature Profile Closely Matches TVAC Measurements

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TVAC II Data Thermal Model Correlation With TAO Heat Load

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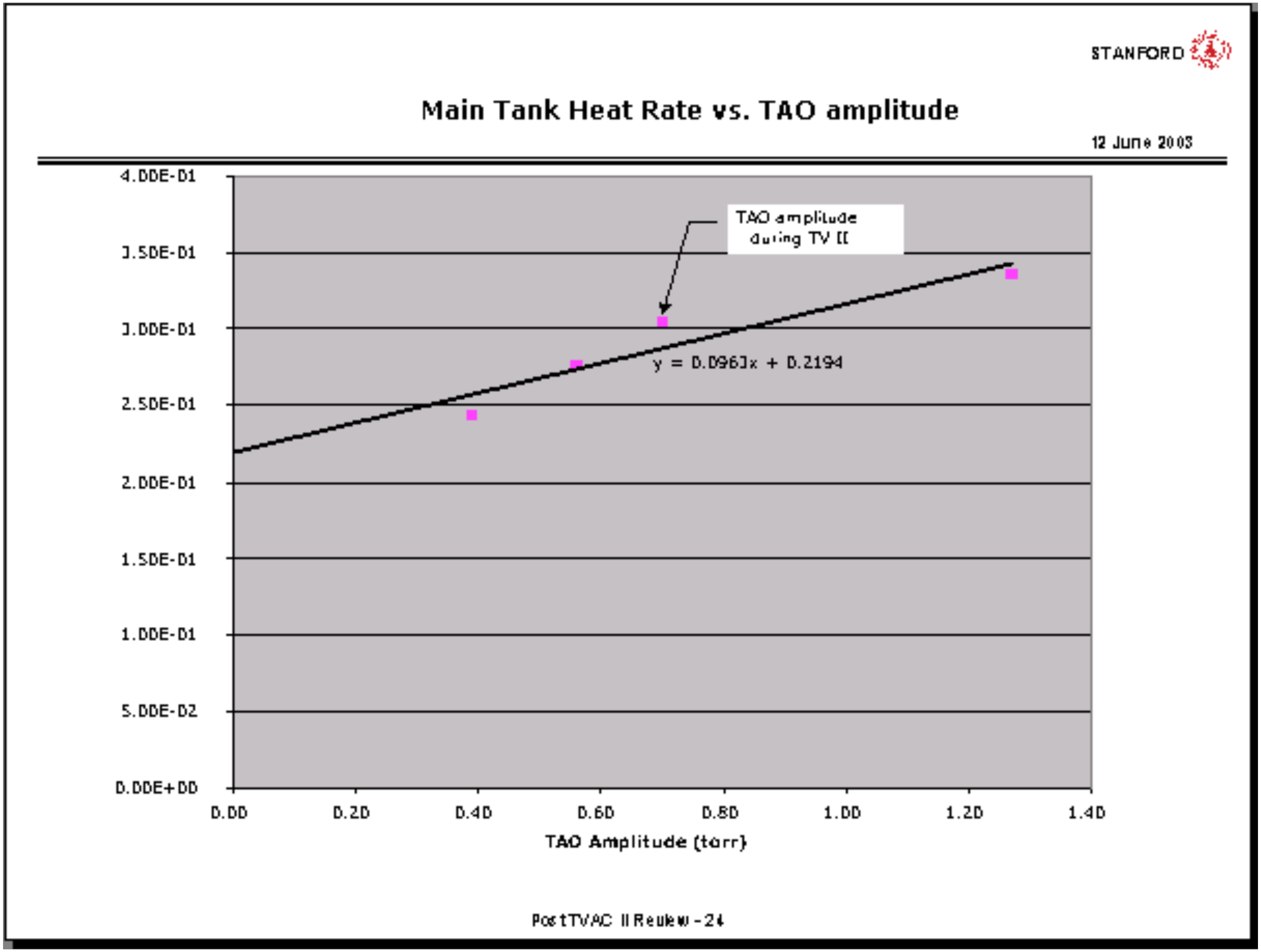
Method 2)

- **TAO heat load determined from measurements in pre and post TVAC II Tests**
  - TAO Amplitude modified by adding ballast volumes and throttling valve in GSE vent line in accordance with TAO analysis
  - Heat load into main tank scales with TAO amplitude
  - Guard tank temperature increases with to TAO amplitude, in spite of increased cooling from the main tank vent
  - Difference of main tank heat load for TVAC II TAO amplitude with lowest measured TAO amplitude, 0.304W - 0.244W = 0.06W (similar result is obtained from linear fit)

- **Subtracting TAO heat load from TVAC II cold soak measurement yields a residual main tank heat load of 0.145 W**

- **Thermal Model Prediction for the orbit like dewar shell temperature achieved in TVAC II is 0.159 W**

Thermal Model Predicted Heat Load Closely Matches TVAC Measurements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Main Tank Heat Rate vs. TAO amplitude
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TAO amplitude during TV II
y = 0.0963x + 0.2194
4.00E-01
3.50E-01
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
TAO Amplitude (torr)
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TAO Analysis

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- TAO analysis by Sidney Yuan
  - Finding for TVAC configuration w/ added GSE Predicts Oscillations in 2 Hz frequency Range - as measured
- Analysis concludes TAO should appear in ground test only with added GSE required for TVAC operation
  - 10s of feet of vent line added
  - Measurements confirm analysis
- Analysis concludes TAO will not occur in orbit configuration
  - Measurements have confirmed analysis

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TAO Analysis On-Orbit Case

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- GP-B SMD tested in on-orbit configuration
  - Main Tank Superfluid
  - Vented through porous plug into thruster plenum with one thruster
  - Vacuum maintained on vent side of thruster
  - Measured heat rate agrees with Thermal Model
  - Vent pressure monitored
    - » Resolution sufficient to measure fluctuations of liquid vapor interface in porous plug
    - » No TAO detected

- Independent TAO analysis performed based on dewar geometry and temperature profile (Sidney Yuan S0391)
  - Analysis updated May 03 to include as built thruster vent plumbing
  - Concludes SMD venting under space conditions is "unconditionally stable"

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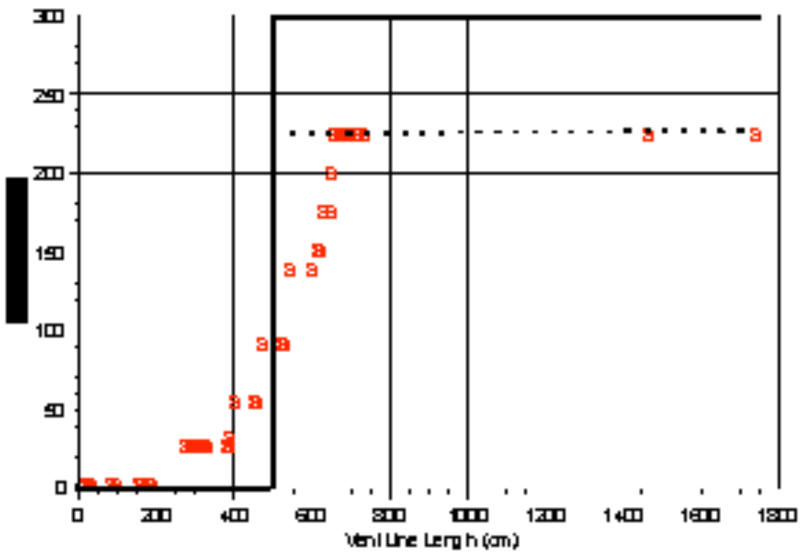
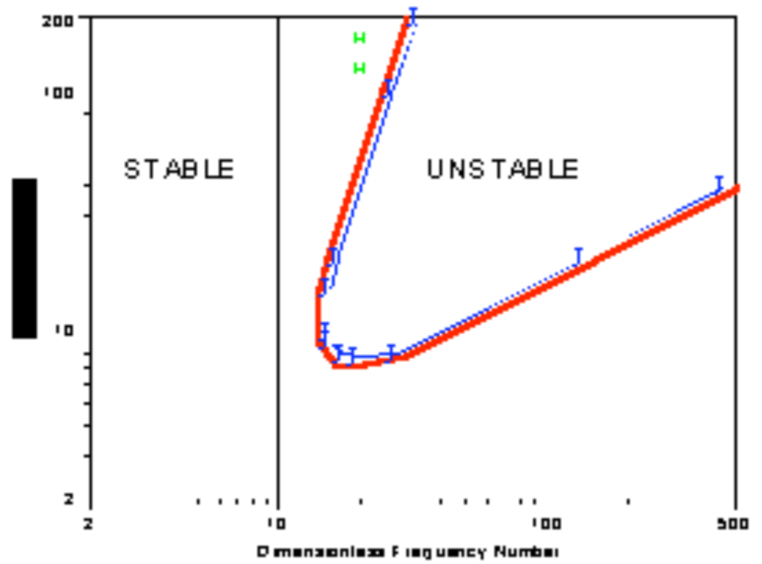
TAO Analysis On-Orbit Case

12 June 2003

S.Yuan





Temperature profile within the vent line during ground test and in space. A step function is assumed which represents the worse case.

Stability Curve Blue inner curve includes as built corrections. Green points represent parameter r $(C_c / l_c \nu_c)^{1/2}$, where r is the radius of the vent line, C_c is the sound velocity of the cold gas, l_c is the cold end plumbing length and ν_c is the viscosity of cold gas. "As one can see, both the ground and space conditions are unconditionally stable,"

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TAO Analysis On-Orbit Case 2

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- Further possibility considered at request of Steve Castles

  "Assume vent line has a partial air ice plug in it ... just inside the inner vapor cooled shield [i.e., below HEX1]. This partial plug could alter the characteristics of the vent line and potentially increase the possibility of a TAO on orbit. I do not consider this a likely...",

- Consideration of risk of occurrence concludes blockage is highly unlikely

- Analysis concludes that a blockage (even with allowing for temperature profile changes) moves the stability curve to the right "It can be concluded that the system remains stable with Steve's hypothesis."

Both analysis and test confirm TAO's are not an on-orbit risk

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TAO Analysis: Risk of Blockage

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During NBP operations (a vast majority of the time):

1) The MT is kept at a positive pressure. The vent plumbing is leak checked.

2) Main tank pressure is monitored by the DAS with alarm

3) Vent flow is always in the viscous regime - leaks cannot diffuse rapidly enough to propagate far upstream

4) The main tank is not susceptible to pressure collapse in the same way as the guard tank

During pumping operations:

1) Vent flow is still in the viscous regime. As long as the main tank is being actively pumped, air will be swept away from the dewar.

2) All plumbing involved in pumping on the main tank is leak checked. Valves close on power failure.

After closeout of the main tank:

1) GSE vent is leak checked and has redundant closure.

2) Thruster vent has redundant closure (parallel valves RAV4A, 4B in series with manual valve SV-12) until closeout of the FEE before solar array installation.

3) RAVs 4A/4B are check for through leakage at time SV-12 is opened.

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TAO Analysis: Blockage Results

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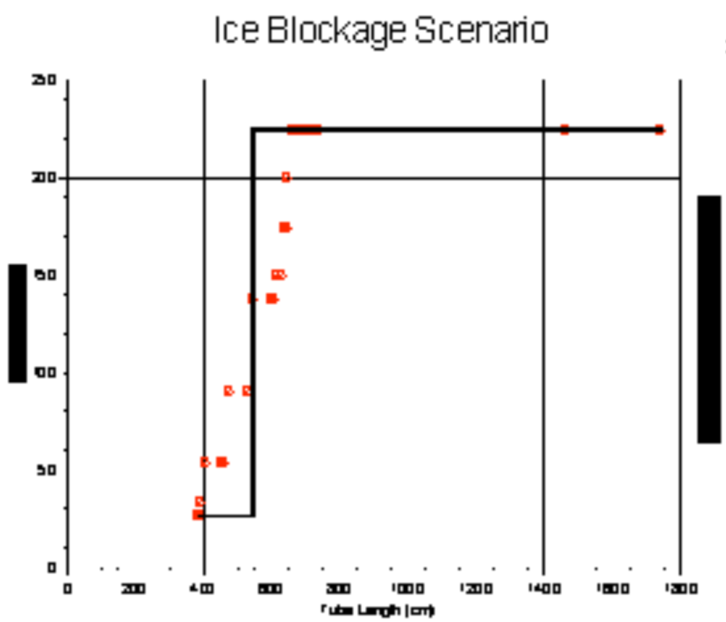
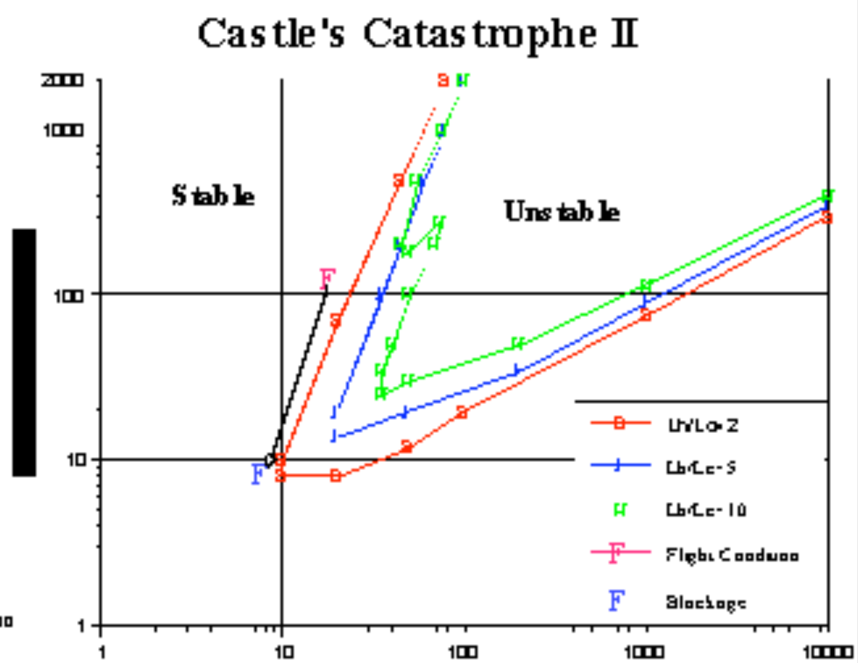


Temperature profile with partial vent line blockage.



As vent line blocks the Stability Curve moves up and toward the right, dimensionless parameter done and left. The system become more stable.

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Dewar Lifetime Conclusions

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- TVAC II adds to ground test thermal model correlation checks, in particular for reduced dewar shell temperature
  - Measured boil off rate and temperatures are consistent with Thermal Model when TAO impact is included
- TAOs are not an On-Orbit Risk
- Consideration of all available ground test correlation data gives high confidence in Thermal Model validity
- Independent MSFC model also predicts the 16 month lifetime requirement is met with margin

Thermal Model is supported by suite of ground tests
Prediction of on orbit lifetime = 18.8 months