Thermal Design Overview of the Mars Exploration Rover Project

Glenn Tsuyuki
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA
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Agenda

- Mission Overview
- Thermal Environments
- Driving Thermal Requirements
- Thermal Design Approach
- Thermal Control Block Diagram
- Thermal Design Description
- Thermal Analysis Results Summary
- Testing Plans
- Issues & Concerns
Flight System Configuration

Cruise Stage

Backshell

Heat Shield

Rover

Lander

Flight System

1.7 m

2.65 m
**MER-A Cruise Scenario**

**View from Ecliptic North Pole**

**MER-A**
Launch Date = 5/30/03
Arrival Date = 1/4/04

**MER-B**
Launch = 6/25/03
Arrival = 1/25/04

- **-z axis**
  - antenna boresight
  - panel normal axis
  - spin axis

90° cone around -z axis
- ±45° offset antenna
- ±45° panel normal axis

**Launch**
- Earth at launch
  - 6/3/03

**Post-injection attitude**
- 6/3/03
  - -z to Earth = 58°
  - -z to Sun = 40°

**Entry attitude**
- 1/4/04
  - -z to Earth = 24°
  - -z to Sun = 63°

**Mars at landing**
- 1/4/04

**Mars at launch**
- 6/3/03

**SPE and SEP**
- 6/3/03 SPE = 60°
- 7/9/03 SPE = 60°
- 8/26/03 SPE = 2°
- 1/4/04 SPE = 42°
- 1/4/04 SEP = 88°
- 1/25/04 SEP = 176°

**Vernal equinox**
- 8/26/03 SEP = 176°
Entry, Descent & Landing (EDL) Scenario

**Entry Turn & HRS Freon Venting:** E- 70m

**Cruise Stage Separation:** E- 15m

Entry: E- 0 s, 125 km, 5.7 km/s, γ = -11.5 deg.

Parachute Deployment: E+ 295 s, 11.8 km, 430 m/s

Heatshield Separation: E+ 315 s

Lander Separation: E+ 325 s

Bridle Deployed: E+ 335 s

Radar Ground Acquisition: L- 18 s

**TCM-5:** E- 12 hrs. Concurrent with EDL, but commanded from ground.

Airbag Inflation: 355 m, L - 10.1 s

Rocket Firing: L- 7 s, ~150 m, 90 m/s

Bridle Cut: L- 3 s, ~20 m

Bounces

Landing: ~E+420 s

Roll-Stop: L+2 min

Deflation: L+20 min

Petals & SA Opened: L+90 min

Airbags Retracted: L+74 min

**Landing Times (Mars local solar time):**

MER-A: ~2:30PM

MER-B: ~12:30PM

Earthset: ~3:30PM

**EDL Communication to Earth Communication with FSK tones:**

**EDL Direct to Earth Communication via UHF to MGS Orbiter:**
Impact to Egress Scenario

**Sol 1**
Solar Array Deploy
PMA Deploy & Imaging
HGA Deploy

**Sol 2-3**
Petal / Airbag Adjustments
Pancam/Mini-TES

**Sol 4**
Drive Petals to final Configuration
Release Middle Wheels & Fire 3rd Cable Cutter
Turn-in Place
Drive Off Lander Deck

GTT- 5
Surface Scenario

Location 4

Location 3

Location 2

Location 1

Landing Site


Sols 5-8: Approach soil target. Perform spectroscopy on soil target.

Sols 17-21: Drive to new location.

<40 m diameter

Reference:
2S Hematite Scenario for MERB

GTT-6
Spacecraft Cruise Configuration

- Cruise Stage (shown transparent)
- Medium Gain Antenna (MGA)
- Low Gain Antenna (LGA)
- Solar Panels (transparent)
- Sun Sensors
- Thruster Cluster (2 places)
- Prop Tank (2 places)
- Lander (stowed)
- HRS Radiators (1 of 12)
- RAD Motor (3 places)
- Aeroshell (Backshell/Heatshield) (backshell shown transparent)
- Sun Sensor Electronics Module
- Cruise Electronics Module (CEM)
- Star Scanner
Cruise Stage Configuration

Mars Exploration Rover

- Cruise Shunt Radiator
- LGA
- 2X Sun Sensors
- MGA rotated ~90°
- Thruster Cluster
- Sun Sensor Electronics
- CEM
- Star Scanner
- PDM Location
- Integrated Pump Assembly
- HRS Radiators
- Solar Array
- (2) Composite Tanks
- Shunt Limiter

Not shown:
- Lighting Suppression Assembly
Lander Assembly - Deployed

ARA (4 Places, Typ.)
Power LEM
Rover Wheel Tiedown (6 Places)
Rover Cabling
Rover Lift Mechanism
DRL Bridle
Bridle
Parachute Roller (3 Places, Typ.)
Shear Panel
LPA (3 Places, Typ.)
Radar Electronics
Radar Altimeter Bracket
Gas Generator (3 Places, Typ.)
BIP/Lander Sep Nut (6 Places, Typ.)
Primary Battery Packages
Avionics LEM
LPSA
LPA Electronics (3 Places, Typ.)
Rover - Stowed Configuration

- Low Gain Antenna
- Stowed Solar Arrays
- Rover Equipment Deck
- Rear Bulkhead
- Forward Bulkhead
- Rover Lift mechanism
- Cable retraction Mechanism
- Wheel Restraints (typical)
Shaded Isometric Views of the Stowed Rover
Deployed Rover on the Lander

- Low Gain Antenna Stack
- Deployed PMA with New Mast Deployment Drive
- Solar Arrays with 5 deployed Panels
- UHF Monopole Antenna
- Deployed Rover with New Mast Deployment Drive
- Pancam Calibration Target
- Low Profile Wheel Restraints
- High Gain Antenna Gimbal
- Solar Arrays with 5 deployed Panels
Isometric View of the WEB

- UHF Radio
- IMU
- REM Structure and Electronic Slices
- X-Band Waveguide to HGA
- X-Band SSPA
- Rear Cable Tunnel and Bulkhead
- 1/2" Sepnut WEB Restraint to Lander
- X-Band SDST
- Differential Shaft Connection to the Starboard Rocker Bogie
- Forward Cable Tunnel and Bulkhead
Remote Sensing Science Instruments

Pancams - Mast mounted stereo panoramic cameras with color filters on pan/tilt gimbal
  - 1024x1024x12bit CCD
  - ~16deg FOV

Mini-TES - Miniature Thermal Emission Spectrometer
  - Near and mid-IR point spectrometer (6 to 25 μm with resolution of 10 cm⁻¹) to determine mineralogy of Martian surface
  - 20/8mrad FOV raster scanned to produce thermal emission “images”
In situ Science Instruments

- Instrument Deployment Device (IDD) - a 5 DOF robotic arm for deployment of 3 in situ science instruments and a Rock Abrasion Tool (RAT) against rock and soil targets
  - Microscopic Imager (MI)- 1024x1024x12bit camera with 30 μm/pixel resolution with 3 mm depth of field
  - Alpha Particle X-ray Spectrometer (APXS) - determine elemental chemistry of target
  - Moessbauer Spectrometer (MB) - detects nanophase and amorphous hydrothermal Fe minerals, identifies Fe carbonates, sulfates, nitrates, and determines oxidation state of Fe minerals
- The front HAZCAMs provide imaging of workspace for ground planning of instrument deployments
Instrument Deployment Device (IDD)
Rock Abrasion Tool (RAT)
- Penetrates through dust & surface alteration that might be present on rocks, exposing materials more likely to preserve evidence of environmental conditions at the time of their formation
Thermal Environment

- **Off-sun during cruise requirements:**
  - Continuous: $0^\circ$ to $51^\circ$ off-sun cone angle
    - Launch to Launch + 21 days: up to $51^\circ$
    - Launch + 22 day to Mars turn-to-Entry: $0^\circ$ to $46^\circ$
  - Transient off-sun cone angles & durations
    - TCM1: $90^\circ$ for up to 110 minutes at 1.02 AU
    - Mars turn-to-Entry: $83^\circ$ for up to 70 minutes
Mission requirements (encompasses MER-A & MER-B):
- Cruise Heliocentric distance: 1.01 AU to 1.52 AU
- Areocentric longitude during surface operations ($L_s$): 328 to 40°
- Landing site: 15S to 10N
- Surface operations duration: 90 Sols

Mars surface environmental requirements (MER ERD, Rev A):
- Surface temperature (min/max): -97°C / 26°C
- Atmosphere temperature (min/max): -95°C / 2°C
- Solar flux at the surface (min/max): 0 / 600 W/m²
- Sustained wind speed at 1 m above surface:
  - 8:00 LST to 17:00 LST: 3 to 15 m/s
  - 17:00 LST to 8:00 LST (next day): 0 to 15 m/s
  - Wind speed at elevations below 1m will be less
Key Driving Level 3 Requirements

- Driving allowable flight temperature (AFT) requirements:
  - REM avionics/telecom maximum (op & non-op) AFT limit: 50°C
    - Limiting factor for DTE requirement & nighttime battery energy usage
    - Drives need for heat rejection system (HRS)
    - Drives EDL thermal design

  - Rover battery - operating AFT limits: -20/30°C
    - Tighter temperature limits than REM governed RHU & thermal switch usage for Martian surface operation

  - Lander battery - cruise storage (non-op) AFT limits: -40/10°C
    - Tightest limits of all non-HRS controlled hardware

  - Backshell IMU maximum operating AFT limit: 51°C
    - Constrains operation at launch (for calibration purposes) & during EDL

  - Propellant line minimum (op & non-op) AFT limit: 15°C
• **Surface communication requirements:**
  - 2 hours of continuous DTE operation per Sol and up to 3 total hours per Sol

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<th>DOORS ID</th>
<th>Requirement</th>
<th>Status</th>
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</thead>
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<td>888</td>
<td>The Thermal Control System shall maintain all specified flight hardware within the limits listed in the Temperature Requirements Table for 2 hrs of continuous DTE X-band per sol, starting no later than 11:00am and for 3 hr total of DTE X-band transmission per sol, subject to availability of power</td>
<td>Comply by design &amp; analysis</td>
</tr>
</tbody>
</table>

- Capability to operate the HGA actuators at 10 am Mars local time without additional warm-up heater

<table>
<thead>
<tr>
<th>DOORS ID</th>
<th>Requirement</th>
<th>Status</th>
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<tr>
<td>607</td>
<td>The Flight System shall be capable of operating the HGA actuators at 10 am Mars local time without additional warmup.</td>
<td>Comply by design &amp; analysis</td>
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</table>
Cruise Stage Thermal Design Overview

Sun Sensors:
Ag/FEP tape on top

MGA:
S13-GLO (white) paint on back

Solar Array:
Ag/FEP tape on inner ring, S13-GLO (white) paint on substrate backside

Cruise Shunt Radiator:
M1 (white) paint including sep. spring covers, anodized L/V spring pads

HRS Radiators:
M1 (white) paint on both sides

LVA:
S13-GLO (white) paint on lateral side
HRS Overview

IVSR consists of:
- IVSR structure
- IPA
- 2 Pyro valves
- Filter in parallel with a relief valve
- Vent outlet
- Pressure transducer
- CSL heat exchanger
- CSL “shark fin” radiator

Rover cable cutter
HRS flex tubing
BIP cable cutter
HRS radiator (12)

Mars Exploration Rover

GTT-28
• Mars Pathfinder IPA shown

• MER adopted a Mars Pathfinder build-to-print approach for the IPA
IPA Schematic

GAS FLOW THROUGH PYRO VALVE TO PURGE LIQUID CFC 11 FROM HRS

GAS FILL PORT
ACCUMULATOR
INLET
PURGE PORT

CFC 11 TO PYRO VALVE FOR VENT TO SPACE

THERMAL VALVE

PUMP/MOTOR “A”

CHECK VALVE

OUTLET

PUMP/MOTOR “B”

FILL PORT

BYPASS OUTLET

GTT-31
Aeroshell Thermal Design Overview

RAD Motors (3)
MLI & thermostatic heaters

TIRS Motors (3)
MLI & thermostatic heaters

Mounting plate mass

Heat Shield
Interior MLI
Exterior radiation shield

BS IMU
Thermostatic heaters
Mounting plate mass

BPSA
Thermostatic heaters
High ε finish

Thermal Battery (hidden)
MLI & thermostatic heaters
Rover Thermal Design Overview

PMA
- Mast actuator warm-up heaters
- Camera electronic warm-up heaters
- Camera filter wheel warm-up heaters
- Low $\alpha_\varepsilon$ finish on mast & camera actuators

SHAG
- Actuator warm-up heater
- Low $\alpha_\varepsilon$ finish on actuator

IDD
- Actuator warm-up heaters

Mobility
- Actuator warm-up heaters
WEB DESIGN FEATURES
- Aerogel attached to interior of WEB structure
- Thermostatic heaters on battery, REM, & mini-TES
- Thermal switches for battery
- HRS tubing on REM for cruise

Battery Radiators (2)  HRS tubing on REM

RHU holder

Thermal Switches (2)  Battery Assembly
Thermal Switch

- **Heat switch assembly:**
  - **Heat switch unit**
    - Passive, variable thermal conductance mechanism which is mounted between the radiator & RHU holder on Rover battery
    - Variable conductance achieved via temperature activated paraffin wax which expands/contracts to mechanically close/open the switch
  - **Wobblefram seal**
    - Teflon PFA diaphragm used to seal off hole in WEB wall
## Cruise Thermal Analysis - Cruise Stage

### TEMPERATURE (°C)

<table>
<thead>
<tr>
<th>CRUISE STAGE</th>
<th>ALLOWABLE FLIGHT</th>
<th>PREDICTED FLIGHT</th>
<th>Margin</th>
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<tbody>
<tr>
<td></td>
<td>OP min</td>
<td>OP max</td>
<td>NOP min</td>
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<tr>
<td>Cruise Solar Array average</td>
<td>-50 90</td>
<td>-70 110</td>
<td>-17 71</td>
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<tr>
<td>Cruise Shunt Limiter Assembly</td>
<td>-25 40</td>
<td>n/a 50</td>
<td>-12 2</td>
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<tr>
<td>Propellant Tanks (includes gas service valves)</td>
<td>15 30</td>
<td>15 30</td>
<td>23 23</td>
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<tr>
<td>Tanks during ground operations</td>
<td>n/a n/a</td>
<td>n/a 40</td>
<td>n/a n/a</td>
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<tr>
<td>Thruster Valve, 1 lbf</td>
<td>20 110</td>
<td>20 50</td>
<td>23 23</td>
</tr>
<tr>
<td>PDM</td>
<td>15 50</td>
<td>15 50</td>
<td>23 23</td>
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<td>service valve outside PDM make it a unit</td>
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<td>n/a n/a</td>
<td>n/a n/a</td>
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<td>filter</td>
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<td>latch valve</td>
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<td>n/a n/a</td>
<td>n/a n/a</td>
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<tr>
<td>pressure transducer</td>
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<td>n/a n/a</td>
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<td>CEM Assembly</td>
<td>-40 50</td>
<td>-40 50</td>
<td>3 22</td>
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<td>Star Scanner head &amp; electronics</td>
<td>-14 50</td>
<td>n/a n/a</td>
<td>0 27</td>
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<td>Sun Sensor electronics</td>
<td>-30 50</td>
<td>n/a n/a</td>
<td>3 22</td>
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<td>Sun Sensor Heads (2 on Z, 3 on XY)</td>
<td>-25 85</td>
<td>n/a n/a</td>
<td>-3-22 28/67</td>
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<tr>
<td>5/8&quot; Ti Bolt, Bushing &amp; Sep. Spring</td>
<td>-60 60</td>
<td>-60 60</td>
<td>-20 51</td>
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<tr>
<td>IPA</td>
<td>-20 40</td>
<td>-20 40</td>
<td>-3 6</td>
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<td>IPA electronics</td>
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<td>-3 6</td>
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<td>Pyro valve-HRS purge</td>
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<td>-30 66</td>
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<td>HRS radiator</td>
<td>-90 n/a n/a</td>
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<td>-40/-65 -7/-16</td>
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<tr>
<td>Cruise Shunt Radiator</td>
<td>-40 100</td>
<td>-40 100</td>
<td>-14 67</td>
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<tr>
<td>LVA</td>
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<td>n/a n/a</td>
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### Cruise Thermal Analysis - Aeroshell

**TEMPERATURE (°C)**

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<th>ALLOWABLE FLIGHT</th>
<th>PREDICTED FLIGHT</th>
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<tr>
<td><strong>OP</strong></td>
<td><strong>NOP</strong></td>
<td><strong>OP</strong></td>
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<tr>
<td>min</td>
<td>max</td>
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#### AEROSHELL

**BIP:**

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<tr>
<th>Component</th>
<th>OP Min</th>
<th>OP Max</th>
<th>NOP Min</th>
<th>NOP Max</th>
<th>Margin OP</th>
<th>Margin NOP</th>
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<tr>
<td>5/8&quot; Cable Cutter (BIP)</td>
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<td>1&quot; Cable Cutter in (BIP)</td>
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<td>-45</td>
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**Backshell:**

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<th>NOP Max</th>
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<td>n/a</td>
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<td>-47</td>
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<td>Lander Primary Battery (LiSO2)</td>
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<tr>
<td>Cruise (non-op)</td>
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<td>-40</td>
<td>10</td>
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<td>Lander Pyro Switch Assembly (LPSA)</td>
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<td>-50</td>
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<td>Lander Structure</td>
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### Cruise Thermal Analysis - Rover

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<td>IMU-Litton LN 200S (Rover &amp; Backshell)</td>
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<td>-47</td>
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</table>
Rover 2 Hour of Continuous DTE

SSPA, SDST, IMU, Battery Case, Mini-TES Temperatures - 4hr off, 2hr on DTE, No LHP, Batt Wax Switches (SP = 18°C), Hot Environment (Ls = 328, Lat = -15°, T1 = 250, Tau = 0.2, Albedo = 0.14), 4hr DTE Early MER A Power Profile

Max SSPA Interface Temp = 51°C
Max UHF Interface Temp = 52°C
Max Battery Temp = 26°C
Rover Cold Surface Scenario

MER_D Model - SSPA, SDST, IMU, Battery Case, Mini-TES Temperatures:
SSPA LHP (Sp=20.0C), Batt Wax Switches (SP=190C), Cold Environment
(Ls=16, Lat=-158, Tt=250, Tau=0.2, Albedo=0.28), Minimum "Loss of
Communication" Power Profile (373W/hr)
Subsystem Test Plans

- **Rover/HRS Thermal Characterization Test Overview**
  - Test start delayed (11/15/01 → 2/23/02) due to EM H/W delivery slip (10/1/01 → 1/18/02)
  
  - 30 day test is performed in Bldg. 248 10-foot vertical chamber

  - Test article is a combination of EM & TMM H/W (no flight H/W)

  - This is a preview of the integrated system thermal performance
    - Identify & correct potential thermal design defects prior to system thermal test
    - Examine HRS performance during cruise
    - Examine WEB/RED & thermal switch performance for Mars landed environment
Subsytem Test Plans (cont’d)

- System T/B Test Overview
  - S/C Cruise 1  9/10/02  B150 25’ chamber  12 days
  - S/C Cruise 2  11/5/02  B150 25’ chamber  5 days
  - Rover 1  1/10/03  B248 10’ chamber  12 days
  - Rover 2  1/22/03  B248 10’ chamber  5 days

- First & third tests are thermal design verification
  - No thermal margin testing planned

- Second & fourth tests are workmanship tests

- IR lamps used in B150 25’ chamber for off-sun environmental heating during cruise

- IR lamps used in B248 10’ for Mars solar environmental heating during landed operations
<table>
<thead>
<tr>
<th>Issue/Concern</th>
<th>Resolution Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difficult to quantify uncertain parameters for BS IMU thermal analysis.</td>
<td>Review analysis &amp; assumptions to determine if a realistic worst-case can be confidently established. If so, determine if IMU operational time is acceptable. If not, inform Systems that only 60 minutes of operation is permissible.</td>
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</table>
## Issues & Concerns: Thermal Testing

### Issue/Concern

<table>
<thead>
<tr>
<th>Schedule for Rover thermal vacuum/thermal balance tests too close to one another to permit assessment of test data &amp; to institute design fixes, if necessary</th>
<th>Work with ATLO to inject sufficient margin between both Rover tests.</th>
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</thead>
<tbody>
<tr>
<td>Separate flight lander test not part of ATLO thermal test baseline</td>
<td>Currently carried as a reserve request. Consider a descoped test where: Lander is tested in a smaller chamber OR only critical elements are tested.</td>
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</tbody>
</table>