MARS SCIENCE LABORATORY
ROVER SYSTEM THERMAL TEST

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Agenda

- Mission Overview
- MSL Spacecraft
- MSL Rover Configuration
- MSL Rover System Thermal Test
  - Test Objectives
  - Test Results
  - Model Correlation
  - Flight Predictions
- Major Conclusions
Mission Overview

ENTRY, DESCENT, LANDING
- Guided entry and powered “sky crane” descent
- 20 × 25-km landing ellipse
- Access to landing sites ±30° latitude, <0 km elevation
- 900-kg rover

CRUISE/APPROACH
- 8½-month cruise
- Arrive August 5, 2012

SURFACE MISSION
- Prime mission is one Mars year (669 Sols)
  - Latitude-independent and long-lived power source
  - Ability to drive out of landing ellipse
  - 72 kg of science payload
  - Direct (uplink) and relayed (downlink) communications
  - Fast CPU and large data storage

- Launched Nov. 26, 2011
- Atlas V (541)
Rover Side View

Ø 500 mm

660 mm

1120 mm

2260 mm
Test Summary

- The 15-day MSL Rover System Thermal Test was conducted from March 9-24, 2011 in the B-150, 25-ft Space Simulator at JPL.

- All primary test objectives were successfully met.

- The rover thermal design performed extremely well during this test and no violations of Allowable Flight Temperatures were observed.
System Thermal Test Objectives Were Met

- **Primary Objectives**
  - Gather sufficient data from multiple landed environments to permit analytical thermal math model correlation
    - All thermal balance and transient environment cases completed
  - Verify functionality of thermal hardware (heaters, thermostats, PRTs, SLI blanket, rover HRS system)
    - Thermal system performance better than conservative model predicts
  - Verify that the Rover functions properly within specified performance requirements in the simulated Mars surface environment
    - No AFT limit violations during functional tests
  - Extrapolate a correlated analytical model to flight environment to validate Rover thermal design post test
    - Completed
    - Worst-case flight predicts generated for Gale Crater landing site show plenty of temperature margin
      - Hot case RAMP predict = 42C (8C margin to max AFT of 50C)
      - Cold Case RAMP predict = -13C (27C margin to min AFT of -40C)
Why Can’t We Validate the Rover Thermal Design in Test?

- This test was **not** a direct validation of the rover surface thermal design. There are many elements of the Mars thermal environment that we cannot simulate inside a thermal chamber on the Earth.
  - Mars acceleration due to gravity is 3/8G,
    - free convection coefficients in the chamber will be higher than those experienced on Mars
  - Chamber backfilled with 10 Torr GN2, not 10 Torr CO2 (Mars atmosphere)
    - GN2 (k = 0.026 W/m*K at 300K)
    - GN2 has a 50% higher thermal conductivity than CO2 (k= 0.017 W/m*K at 300 K)
    - gas conduction and free convection in the chamber will be greater than what is experienced on Mars
  - No dust coverage or degraded thermal paints on the outside of the vehicle
    - white paint properties will be at their BOL values,
  - Solar simulator in the 25 foot chamber will not track (in elevation and azimuth) across the sky and it will not have a diffuse component
  - No wind simulation
  - No independent sky, ground and atmosphere temp control in chamber
    - chamber wall and floor shrouds will be controlled to same temp
    - atmosphere temperatures will be monitored but not controlled
Tests of Design Sensitivity

• Effect of GN2 versus vacuum
  – Compare cases #5 (Cold Thermal Balance at -105C) and #7 (Cold Vacuum Test at -105C)

• Effect of RTG Power (Q = 1315 W to 1821 W)
  – Compare case #5 (Cold Thermal Balance at -105C) to case #11B (Functional #5 at -80C)

• Effect of Solar Flux (Q" = 0 W/m^2 to 700 W/m^2)
  – Compare case #10 (Functional Test #4 Env’t at -80C) and Case #11A (Hot Thermal Balance at -80C)

• Effect of Shroud Temp (+20C to -105C)
  – Multiple cases
Test Article Description

- Rover consists of the following flight hardware:
  1. All Rover structures, and mechanisms: chassis, RAMP, mobility, actuators
  2. Entire Surface HRS thermal system: RIPA, HX Plates, RAMP
  3. Avionics components: flight computer, power boxes, battery, telecom
  4. All engineering cameras: HazCams, NavCams
  5. Science instruments: MAHLI, MastCams, ChemCam, APXS, REMS, RAD, CheMin, SAM, DAN
  6. Sample Acquisition/Sample Processing and Handling (SA-SPaH) hardware: Robotic Arm, Drill, CHIMRA, 3 Inlet Covers, 2 Contact Sensors, 2 Bit Boxes
  7. RTG simulator
Rover Thermal Hardware

- 58 Flight Heater Circuits Controlled by Rover
  - Custom designed Kapton film heaters from Tayco
  - FSW commandable or mechanical thermostat controlled
  - Primary and secondary heater circuits

- 22 Flight Mechanical Thermostats
  - Internal to RAMP: RBAU (8), CCBU (2), RIPA fault protection (4)
  - External: CCMU (4), RPFA (4)
  - Honeywell TS 700 Series

- 219 Honeywell, 1000-ohm, 2-wire PRTs
  - Data was piped from GDS to TDAS for thermal use
  - Nearby thermocouple measurements used to validate PRT measurements
  - Primary and backup PRTs

- Rover Heat Rejection System (HRS)
  - RAMP, Hot & Cold Plates, RIPAS, bypass valves
Test Instrumentation

- Thermal Data Acquisition System (TDAS) - LabView
  - 5 TDAS computers (2 for TCs and GSE power supplies, 1 for computed channels, 2 as view-only systems)
  - Scan and record intervals set at 1 minute
  - Connected to UPS & back-up generator
- Heaters powered & controlled by GSE Power Supplies
  - 2 shunt (FLT), 3 CCBU decontamination (FLT), 2 near RAMP too-hot thermostats (TEST)
- 386 Type E, 26-gage Thermocouples
  - 357 on Rover, 11 for chamber atmosphere, 18 on GSE
  - Used for AFT limit and PRT flight sensor verification, near flight thermostat and heater locations, to determine temperature gradient across interfaces, to aid in model correlation
- Additional 150 Thermocouples for Chamber Facility Measurements
Test Setup – Rover in Chamber

Rover Surface Configuration
Mounted on I-beam support frame 6 in. above chamber floor
Powered by Umbilical GSE Power Supply
9 Pyro firings during STT
- HGA, 3x HazCam Covers, RSM, Mobility Bogie Pose, Robotic Arm turret and elbow, Bit Box
- Other pyros fired in B-144 & B-150 prior to chamber installation

- Deployments
  - Hazcam covers, HGA, RA, RSM

- Solar simulator lens created a hexagonal spot – 15 feet, flat to flat
Surface System Environmental Test
As-Planned STT Thermal Profile Plot

MSL Rover STT Timeline

- Shroud temp (°C)
- RAMP Avg. Temp (°C)
- MMRTG (W)

Temperature (deg C)

MMRTG Power (W)

Time (hours)

Case 1A Pumpdown
Case 1B CO2M
Case 3 Funct #1 at -55°C
Case 5 Cold Thermal Balance at -105°C
Case 6A Funct #2 at -105°C
Case 6B Warm up Htr Char & High Avionics Pwr
Case 7 Cold Vac at -105°C
Case 8 Funct #3 Cold Vac at -105°C
Case 10 Funct #4 at -80°C Actuator Heat-to-Use
Case 11A Hot Thermal Balance at -80°C
Case 12 Funct #5 Backfill & Open Chamber
Case 13 Funct #6 Cold
Case 14 Funct #7 to DC & Camera
Case 15 Funct #8 SAM
Case 16 Hot Diurnal

SOLAR SIM: OFF
SOLAR SIM: 700 W/m²
SOLAR SIM: OFF
SOLAR SIM: Varies 0-500 W/m²
Vacuum
10 torr GN2
Vacuum
10 torr GN2
100 torr GN2

ICES 2012
Steady State Thermal Environments

- **Steady State Thermal Balance Cases**
  - **Case 1A** – Pumpdown & Rover Outgas
    - hot case with shrouds at +20C, vacuum environment, low RTG power (500W) and high RAMP power (363W)
  - **Case 5** – Cold Thermal Balance at -105C
    - cold case with shrouds at -105C, moderate RTG power (1315W) and low RAMP power (30W)
  - **Case 7** – Cold Vacuum Test at -105C
    - cold case with shrouds at -105C, moderate RTG power (1315W) and low RAMP power (30W)
  - **Case 11A** – Hot Thermal Balance at -80C
    - Hot case with shrouds at -80C, solar sim on at 700W/m^2, high RTG power (1600W) and high RAMP power (230W)
  - Additional Functional cases that went to steady state due to long duration (Case 3 – Functional #1 went for 23 hours)
Transient Thermal Environments

- **Transient Cases:**
  - **Case 2** – Accelerated Cooldown to -55C:
    - Global cooldown with shrouds ramping from 0C to -110C
  - **Case 4** – Accelerated Cooldown to -105C:
    - Global cooldown with shrouds ramping from -55C to -125C
  - **Case 6B** – Warmup Htr Thermal Char. & Step Change in RAMP Avionics Power:
    - Actuator & Camera Warmup with shrouds held at -105C; RAMP response to step change in power from 30W to 200W
  - **Case 9** – Accelerated Warmup to -80C:
    - Global warmup with shrouds ramping from -105C to -60C
  - **Case 10** – Actuator & Camera Heat–to–Use:
    - Actuator & camera warmups with shrouds held at -80C
  - **Case 11A** – Hot Thermal Balance –
    - External rover hardware exposure to step change in solar load from 0 W/m^2 to 700 W/m^2
  - **Case 12** – Accelerated Warmup to 0C:
    - Global warmup with shrouds ramping from -80C to +20C
HRS performance in Rover STT

- In the worst-case cold tested conditions, the RAMP component interfaces were ~3-10°C warmer than predicted.

- In the hot thermal balance test conditions, the hottest RAMP component interfaces were ~0.2°C cooler than predicted.

- The temperature difference between HRS fluid inlet & outlet (in RAMP) during test was smaller than predicted.

- RAMP was very uniform in temperature during STT (~2°C gradient in STT vs. ~7°C predicted).
Overview of RAMP Temperatures

**MSL Rover STT**

- **AFT MAX=50°C**
- **AFT MIN= -40°C**
- H/W stayed within AFT range during entire test

**X-axis:** Time

**Y-axis:** Temperature(°C)

- RAMP HRS Inlet
- RAMP HRS Outlet
- RAMP near RCE/RMCA

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Actuator/Camera Results

- **Actuator and camera warmup heaters have been adequately sized:**
  - Capable of warming up actuators and cameras above AFT in cold environment (-105C shroud, no solar) within expected time duration;
  - Capable of maintaining temperatures with proper duty cycle.

- **Verified Rover’s capability to do warmup heater control:**
  - Verified heater switches controlled by both RPAM-A and RPAM-B;
  - Verified FSW heater control in auto mode with selected control PRT’s and setpoints;
  - Pre-heat durations were consistent with pre-STT predicts.

- **Actuators and cameras operated within allowable temperatures:**
  - Target temperatures and pre-heat duration followed pre-STT model predicts;
  - Actuators and cameras were warmed up above the min op temperatures (min op Qual, FA, or AFT limits) before the functional (motion or imaging) tests were conducted.

- **Obtained thermal data for thermal model correlation:**
  - Actuators: Mobility, HGA, and Inlet Covers.
  - Cameras: MAHLI and MastCams.

- **Obtained thermal data for checking previously correlated models:**
  - Actuators: RSM, CHIMRA, Drill, and RA.
  - Cameras: HazCams and NavCam (MER).
Overview of External Temperatures

Overview of External Temperatures

MSL Rover STT

AFT MAX = 50°C

H/W stayed within AFT range during entire test

AFT MIN = -128°C

Mob. Drive Mtr Rt. Front
MastCam +Y Barrel
Thermal Model Correlation

- Parameters which were modified to improve rover system-level model correlation with test results included:
  - Thermo-optical Properties
    - Emissivity
    - Absorptivity
  - Radiation Blockage
  - Thermal Conductances
    - Interfaces
    - Cables
    - CO₂ thickness for Gas Conduction
  - Convection Coefficients
  - Effective Thermal Mass
Flight Predictions

**Predicted RAMP Temperatures at Gale Crater**

- **Summer Solstice (LS 270), 40% Dust:**
  - Summer, Science, no wind: 42°C

- **Winter Solstice (LS 90), No Dust, 15 m/s wind:**
  - Winter, Sleep, 15m/s Wind: -13°C

**Margin to Max AFT Limit: 50°C**

**Margin to Min AFT Limit: -40°C**
Major Conclusions

- It was a very successful test

- All primary test objectives were met.

- Rover thermal design performed well during this test and no violations of Allowable Flight Temperatures were observed.

- Model correlation work has been done for rover thermal system, actuator & camera thermal models

- Flight predicts have been done
  - Thermal performance predicts for Gale Crater Landing Site (4.5 degrees South latitude) are excellent

- Looking forward to an exciting and successful surface mission –
  Landing on Aug. 5, 2012, 10:30PM PDT
  Sol 0, 3:03PM LMST in Gale Crater
Acknowledgements

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• The authors wish to acknowledge the many engineers and scientists who worked collaboratively on the Mars Science Laboratory System Thermal Test and brought it to a successful conclusion.
# 23RD Thermal & Fluids Analysis Workshop (TFAWS)

Promoting Excellence in all Aspects of Design, Analysis, Build, and Test  
August 13-17, 2012 • Westin Pasadena Hotel • Pasadena, CA

**Purpose:** to encourage knowledge sharing, professional development, and networking throughout the thermal and fluids engineering community within NASA and the aerospace industry at large.

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<th>Topics</th>
<th>Program Includes</th>
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<td>Active thermal/life support</td>
<td>Paper sessions</td>
<td>Industry</td>
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<td>Hands-on software training</td>
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<td>Interdisciplinary thermal/fluids</td>
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<td>Tours of NASA JPL</td>
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<td>Banquet &amp; guest speakers</td>
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Hosted by NASA Jet Propulsion Laboratory (JPL)  
Registration is free, sponsored by NASA Engineering and Safety Center (NESC)

Abstracts due: May 18  
Papers due: July 20
# As-Run Test Timeline

## MSL Rover STT Status

<table>
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<tr>
<th>MSL Rover STT</th>
<th>Test Description</th>
<th>Estimated Duration (hrs)</th>
<th>Actual Duration (hrs)</th>
<th>From: mjd/11 h:mm AM</th>
<th>To: mjd/11 h:mm AM</th>
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<td>Late Start - Planned time was 8:00am</td>
<td>0.0</td>
<td>0.4</td>
<td>3/9/11 8:00 AM</td>
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<td>Pumpdown, Rover Outgas &amp; Backup Pump Fault Protection Checkout</td>
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<td>Test Case 1B</td>
<td>CQCM Measurement</td>
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<td>Accelerated Cool Down to -55C</td>
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<td>Functional #1: Deployment Verification at -55C</td>
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<td>Accelerated Cool Down to -105C Environment</td>
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<td>3/13/11 5:00 PM</td>
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<td>Cold Thermal Balance at -105C Survival Heater/Theret CheckOut, HGA Warmup Hr Char Test</td>
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<td>Functional Test #2: Environment @ -105C, E@-0°C (Hot Case)</td>
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<td>Cold Vacuum Test at -195C</td>
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<td>Functional #3 - Cold Vacuum Test at -195C</td>
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Initial Estimated Total Test Duration (days): 13.1 (hours) 216.0

Current Total Test Duration (days): 15.1 (hours) 240.0

Delta in Hours (negative is behind): -48.8
Gale Crater

Landing Ellipse
System Test Bed Drills