SUMMARY OF 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

• 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

**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

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

- Launched Nov. 26, 2011
- Atlas V (541)
Rover Traverse Configuration

- Remote Sensing Mast (RSM)
- Bridle Exit Guide (3)
- RPFA and Enclosure
- RUHF Antenna
- MMRTG
- Heat Exchangers
- RTG Windbreaker
- RLGA Antenna
- High Gain Antenna System (HGAS)
- Rover Chassis
- SA-SPaH
  - Robotic Arm
  - Bit Box
  - Inlet Covers
  - Cal Targets
- Mobility System
Rover Side View
Test Summary

- The 15-day MSL Rover System Thermal Test was conducted 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 spacecraft 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 = 42°C (8°C margin to max AFT of 50°C)
      – Cold Case RAMP predict = -13°C (27°C margin to min AFT of -40°C)
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) 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 #11A (Hot Thermal Balance 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 to create 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)

Case 1A Pumpdown
Case 1B CQC
Case 3 Funct #1 at -55°C
Case 4 Cold Thermal Balance at -105°C
Case 5 Cold Thermal Balance at -105°C
Case 6 Warm up Htr Char & High Avionics Pwr
Case 6B Warm up Htr Char & High Avionics Pwr
Case 7 Cold Vac at -105°C
Case 8 Cold Vac at -105°C
Case 9 Cold Vac at -105°C
Case 10 Funct #4 at -80°C Actuator Heat-to-Use
Case 11 Funct #5 -SAM
Case 11A Hot Thermal Balance at -80°C
Case 12 Accel Warmup to 0°C & Camera Funct #6
Case 13 Funct #7 at 0°C
Case 14 Hot Diurnal
Case 15 Hot Diurnal
Case 16 Backfill & Open Chamber
Case 17 Backfill & Open Chamber
Case 18 Backfill & Open Chamber

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

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Steady State Thermal Environments

- **Steady State Thermal Balance Cases**
  - **Case 1A** – Pumpdown & Rover Outgas
    - hot case with shrouds at +20°C, vacuum environment, low RTG power (500W) and high RAMP power (363W)
  - **Case 5** – Cold Thermal Balance at -105°C
    - cold case with shrouds at -105°C, moderate RTG power (1315W) and low RAMP power (30W)
  - **Case 7** – Cold Vacuum Test at -105°C
    - cold case with shrouds at -105°C, moderate RTG power (1315W) and low RAMP power (30W)
  - **Case 11A** – Hot Thermal Balance at -80°C
    - Hot case with shrouds at -80°C, 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 -55°C:
    - Global cooldown with shrouds ramping from 0°C to -110°C
  - **Case 4** – Accelerated Cooldown to -105°C:
    - Global cooldown with shrouds ramping from -55°C to -125°C
  - **Case 6B** – Warmup Htr Thermal Char. & Step Change in RAMP Avionics Power:
    - Actuator & Camera Warmup with shrouds held at -105°C; RAMP response to step change in power from 30W to 200W
  - **Case 9** – Accelerated Warmup to -80°C:
    - Global warmup with shrouds ramping from -105°C to -60°C
  - **Case 10** – Actuator & Camera Heat–to–Use:
    - Actuator & camera warmups with shrouds held at -80°C
  - **Case 11A** – Hot Thermal Balance –
    - External rover hardware exposure to step change in solar load from 0 W/m² to 700 W/m²
  - **Case 12** – Accelerated Warmup to 0°C:
    - Global warmup with shrouds ramping from -80°C to +20°C
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 temps. during STT (~ 2 C gradient in STT vs. ~7 C predicted)
Overview of RAMP Temperatures

Overview of RAMP Temperatures

_H/W stayed within AFT range during entire test_

AFT MAX = 50°C

AFT MIN = -40°C
Health of RHRS during STT

**No leaks observed**

**No evidence of accumulator bellows sticking**

Operating pressures in system were maintained within the nominal expected range throughout the test

- Min pressure during STT = 67 psia (Min Yellow Alarm = 55 psia)
- Max pressure during STT = 153 psia (Max Yellow Alarm = 180 psia)

Note: Gaps in data occur when Rover is sleeping
Thermal Interface Check

- All Electronics well coupled to RAMP
- Largest $\Delta T$ to RAMP is 7.4°C (UHF-A)

<table>
<thead>
<tr>
<th>Electronics</th>
<th>Electronics to RAMP $\Delta T(^{\circ}C)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case 8: Vacuum</td>
</tr>
<tr>
<td>CCBU</td>
<td>5.2</td>
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<tr>
<td>CheMin</td>
<td>3.4</td>
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<tr>
<td>DEA</td>
<td>2.0</td>
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<tr>
<td>RIMU-A</td>
<td>7.0</td>
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<tr>
<td>RIMU-B</td>
<td>6.4</td>
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<tr>
<td>RAD</td>
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<tr>
<td>RCE-A</td>
<td>5.8</td>
</tr>
<tr>
<td>RCE-B</td>
<td>6.3</td>
</tr>
<tr>
<td>REMS</td>
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</tr>
<tr>
<td>RIPA</td>
<td>1.4</td>
</tr>
<tr>
<td>RMCA</td>
<td>4.2</td>
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<tr>
<td>RPA</td>
<td>2.8</td>
</tr>
<tr>
<td>RPAM-A</td>
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</tr>
<tr>
<td>RPAM-B</td>
<td>4.7</td>
</tr>
<tr>
<td>SAM</td>
<td>-0.9</td>
</tr>
<tr>
<td>SDST</td>
<td>2.0</td>
</tr>
<tr>
<td>SSPA</td>
<td>5.1</td>
</tr>
<tr>
<td>UHF-A</td>
<td>7.4</td>
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<tr>
<td>APXS</td>
<td>1.1</td>
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<tr>
<td>UHF-B</td>
<td>6.2</td>
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</table>

* Box was not on during Case 6B
Rover Survival and Warm-up Heater Performance

<table>
<thead>
<tr>
<th>Heater Location</th>
<th>Heater Type</th>
<th>% Duty Cycle @ 29.5V</th>
<th>Est. % Duty Cycle @ 22V</th>
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</thead>
<tbody>
<tr>
<td>Battery - Primary</td>
<td>Survival</td>
<td>32.7</td>
<td>58.7</td>
</tr>
<tr>
<td>Battery - Back-up</td>
<td>Survival</td>
<td>TBD via model correlation</td>
<td></td>
</tr>
<tr>
<td>Battery - Primary</td>
<td>Warm-up</td>
<td>57.0</td>
<td>N/A</td>
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<tr>
<td>Battery - Back-up</td>
<td>Warm-up</td>
<td>45.1</td>
<td>N/A</td>
</tr>
<tr>
<td>RPFA - Primary</td>
<td>Survival</td>
<td>15.8</td>
<td>28.4</td>
</tr>
<tr>
<td>RPFA - Back-up</td>
<td>Survival</td>
<td>15.8</td>
<td>28.4</td>
</tr>
<tr>
<td>CCMU O-Box - Primary</td>
<td>Survival</td>
<td>33.3</td>
<td>59.9</td>
</tr>
<tr>
<td>CCMU E-Box - Primary</td>
<td>Survival</td>
<td>33.3</td>
<td>59.9</td>
</tr>
</tbody>
</table>

Extrapolated Values

All tested rover heater duty cycles are well under the 80% design requirement.

Two Warm-up heaters were able to warm the battery from -20°C to 0°C using 224 W-hrs of energy.

The battery can be maintained at 0°C with one warm-up heater on.

The maximum gradient observed across the battery with primary survival, primary warm-up, and back-up warm-up heaters on was less than 3°C meeting the spatial gradient temperature requirement of ≤ 5°C.
Actuator/Camera Results

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

- **Verified Rover’s capability of 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

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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 – Starting on Aug. 5, 2012
Backup
## As-Run Test Timeline

### MSL Rover STT Status

<table>
<thead>
<tr>
<th>MSL Rover STT</th>
<th>Test Description</th>
<th>Estimated Duration (hrs)</th>
<th>Actual Duration (hrs)</th>
<th>From: m/d/11 h:mm AM</th>
<th>To: m/d/11 h:mm AM</th>
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</thead>
<tbody>
<tr>
<td></td>
<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>
<td>3/9/11 8:23 AM</td>
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<tr>
<td>Test Case 1A</td>
<td>Pumpdown, Rover Outgas &amp; Backup Pump Fault Protection Checkout</td>
<td>21.0</td>
<td>29.1</td>
<td>3/9/11 8:23 AM</td>
<td>3/10/11 1:30 PM</td>
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<tr>
<td>Test Case 2</td>
<td>Accelerated Cooldown to -55C</td>
<td>24.0</td>
<td>23.3</td>
<td>3/10/11 1:30 PM</td>
<td>3/11/11 6:45 PM</td>
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<tr>
<td>Test Case 3</td>
<td>Functional #1: Deployment Verification at -55C</td>
<td>12.0</td>
<td>22.7</td>
<td>3/11/11 6:45 PM</td>
<td>3/12/11 5:30 PM</td>
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<tr>
<td>Test Case 4</td>
<td>Accelerated Cooldown to -105C Environment</td>
<td>24.0</td>
<td>23.5</td>
<td>3/12/11 5:30 PM</td>
<td>3/13/11 5:00 PM</td>
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<tr>
<td>Test Case 5</td>
<td>Cold Thermal Balance at -105C, Survival Heater Test, HGA Warmup HT Char Test</td>
<td>12.0</td>
<td>13.1</td>
<td>3/13/11 5:00 PM</td>
<td>3/14/11 6:07 AM</td>
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<td>Test Case 6A</td>
<td>Functional Test #2 Environment @ -105oC [Cold Case]</td>
<td>29.0</td>
<td>39.2</td>
<td>3/14/11 6:07 AM</td>
<td>3/15/11 5:18 PM</td>
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<td>Test Case 7</td>
<td>Cold Vacuum Test at -105C</td>
<td>16.0</td>
<td>13.0</td>
<td>3/17/11 12:00 AM</td>
<td>3/17/11 1:00 PM</td>
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<td>Test Case 8</td>
<td>Functional #3 - Cold Vacuum Test at -105C</td>
<td>6.0</td>
<td>8.5</td>
<td>3/17/11 1:00 PM</td>
<td>3/17/11 9:30 PM</td>
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<td>Test Case 9</td>
<td>Accelerated Warmup to -80C</td>
<td>24.0</td>
<td>15.0</td>
<td>3/17/11 9:30 PM</td>
<td>3/18/11 12:30 PM</td>
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<td>Test Case 10</td>
<td>Functional Test #4: Environment @ -80C Actuator Heat-to-Use &amp; Articulate</td>
<td>8.0</td>
<td>21.5</td>
<td>3/18/11 12:30 PM</td>
<td>3/19/11 10:00 AM</td>
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<td>Test Case 11A</td>
<td>Hot Thermal Balance Test at -80C</td>
<td>12.0</td>
<td>13.5</td>
<td>3/19/11 10:00 AM</td>
<td>3/19/11 11:30 PM</td>
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<tr>
<td>Test Case 11B</td>
<td>Functional #5 - SAM on 20C RAMP</td>
<td>19.0</td>
<td>32.0</td>
<td>3/19/11 11:30 PM</td>
<td>3/21/11 7:30 AM</td>
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<tr>
<td>Test Case 12</td>
<td>Accelerated Warmup to 0C &amp; Camera Functional #6 at -40C during Transition</td>
<td>24.0</td>
<td>16.5</td>
<td>3/21/11 7:30 AM</td>
<td>3/22/11 12:00 AM</td>
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<td>Test Case 13</td>
<td>Functional Test #7: Environment @ 00C [Hot Case]</td>
<td>10.0</td>
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<td>Test Case 16</td>
<td>Hot Diurnal Test</td>
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<td>Test Case 16B</td>
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<td>3/23/11 6:00 PM</td>
<td>3/23/11 6:00 PM</td>
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<td>Test Case 17</td>
<td>Backfill and Open Chamber</td>
<td>14.0</td>
<td>17.5</td>
<td>3/23/11 6:00 PM</td>
<td>3/24/11 11:30 AM</td>
</tr>
</tbody>
</table>

Initial Estimated Total Test Duration (days): 13.1  
(hours): 315.0

Current Total Test Duration (days): 15.1  
(hours): 363.5

Delta in Hours (negative is behind): -48.5
GDS Fixed Pages

Spacecraft Thermal Control Workshop 2012
Gale Crater

Landing Ellipse
Gale Crater

Mound is ~5 km high

notional traverse

landing site

Gale Crater
System Test Bed Drills