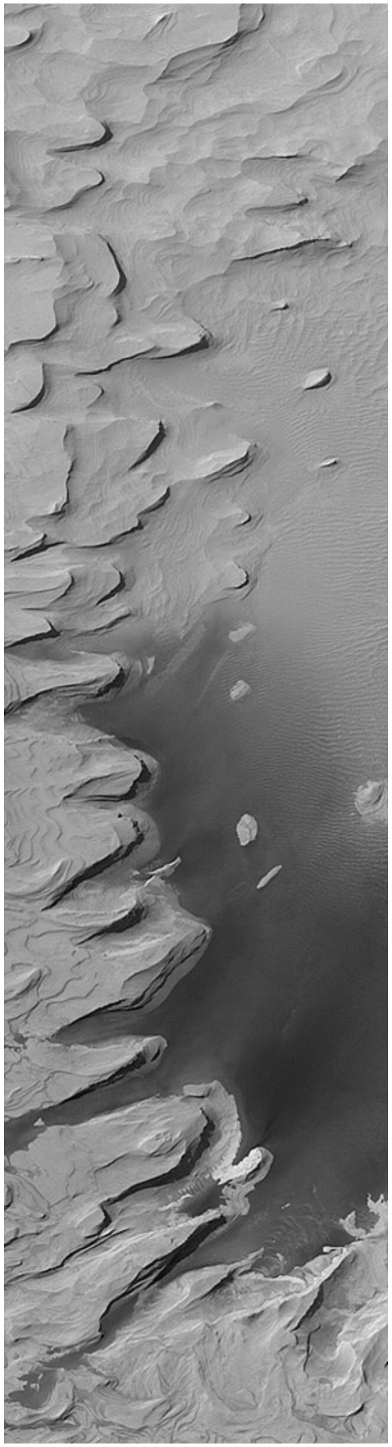

SUMMARY OF MARS SCIENCE LABORATORY ROVER SYSTEM THERMAL TEST

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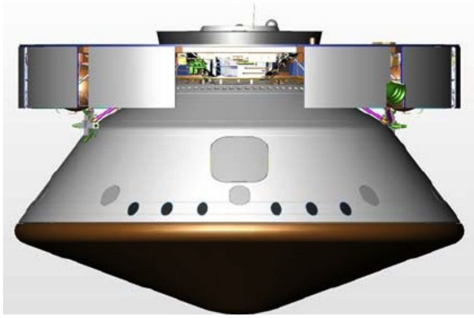
Jet Propulsion Laboratory/California Institute of Technology
Spacecraft Thermal Control Workshop, Aerospace Corp.
March 20-22, 2012

Agenda

- Mission Overview
- MSL Spacecraft
- MSL Rover Configuration
- MSL Rover System Thermal Test
  - Test Objectives
  - Test Results
- Major Conclusions

Mission Overview

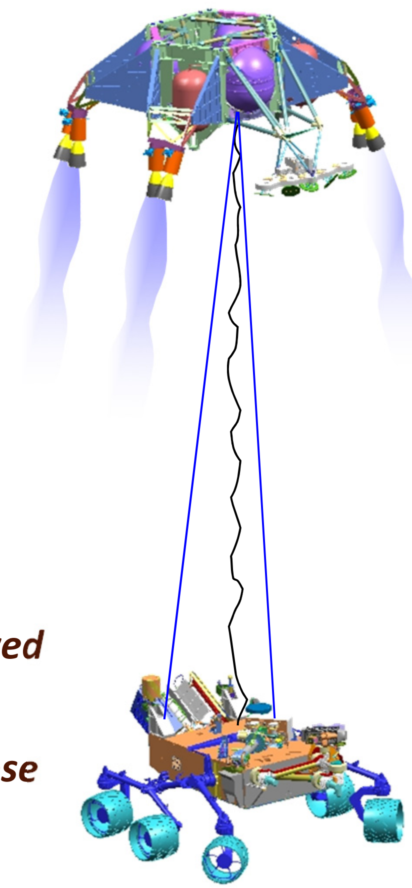


CRUISE/APPROACH

- *8½-month cruise*
- *Arrive August 5, 2012*

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*

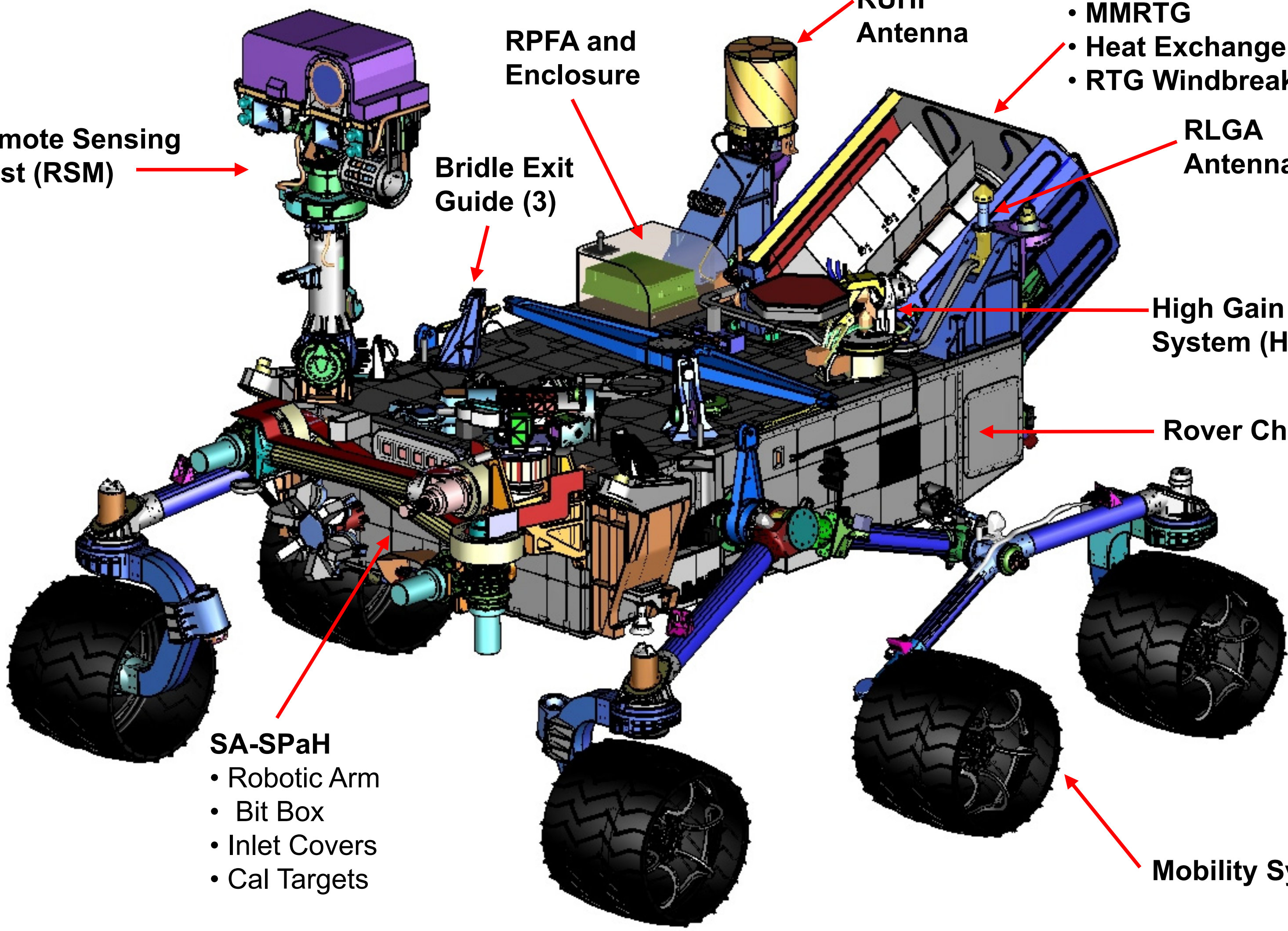


- *Launched Nov. 26, 2011*
- *Atlas V (541)*

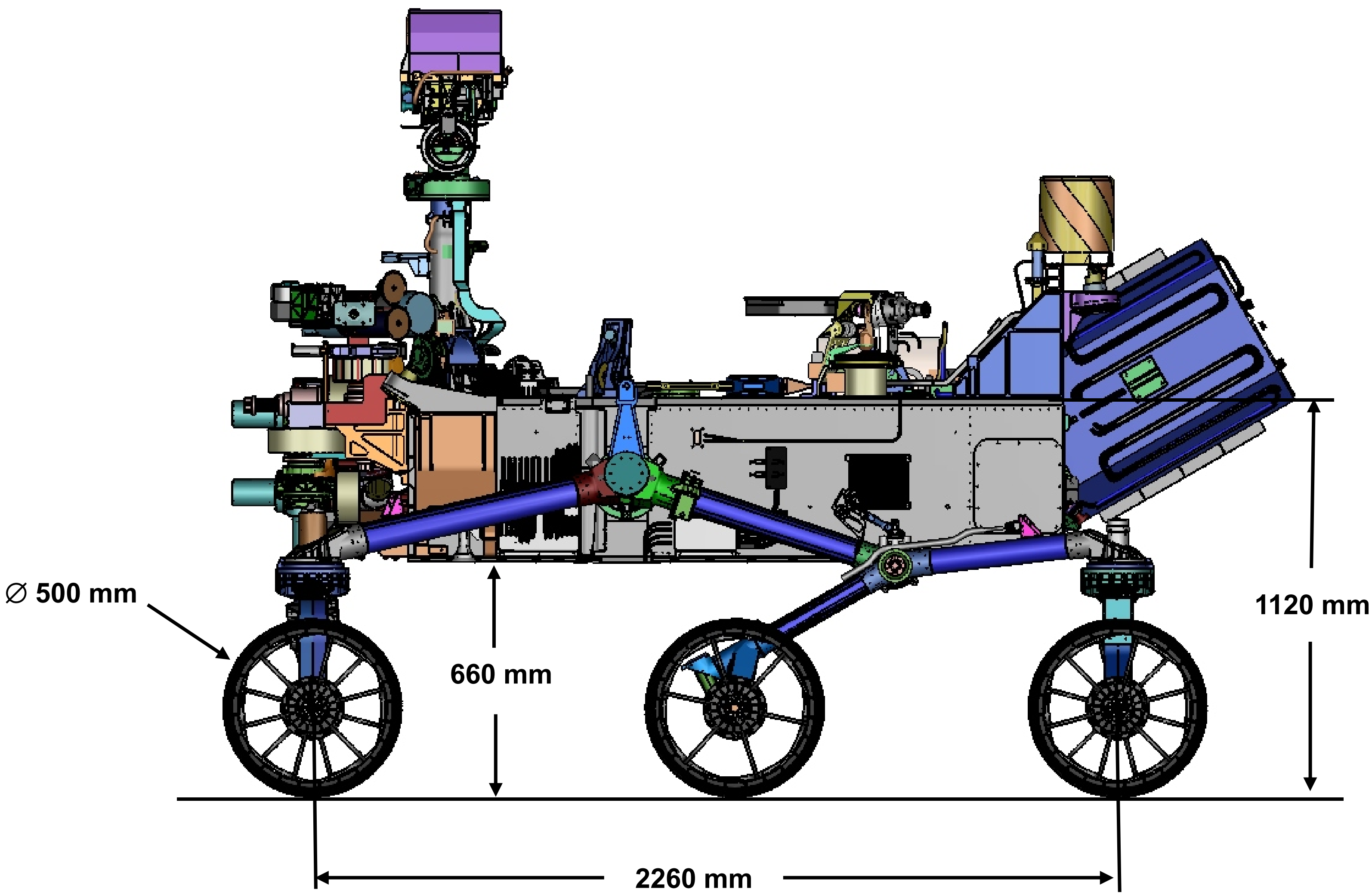
SURFACE MISSION

- *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*

Rover Traverse Configuration

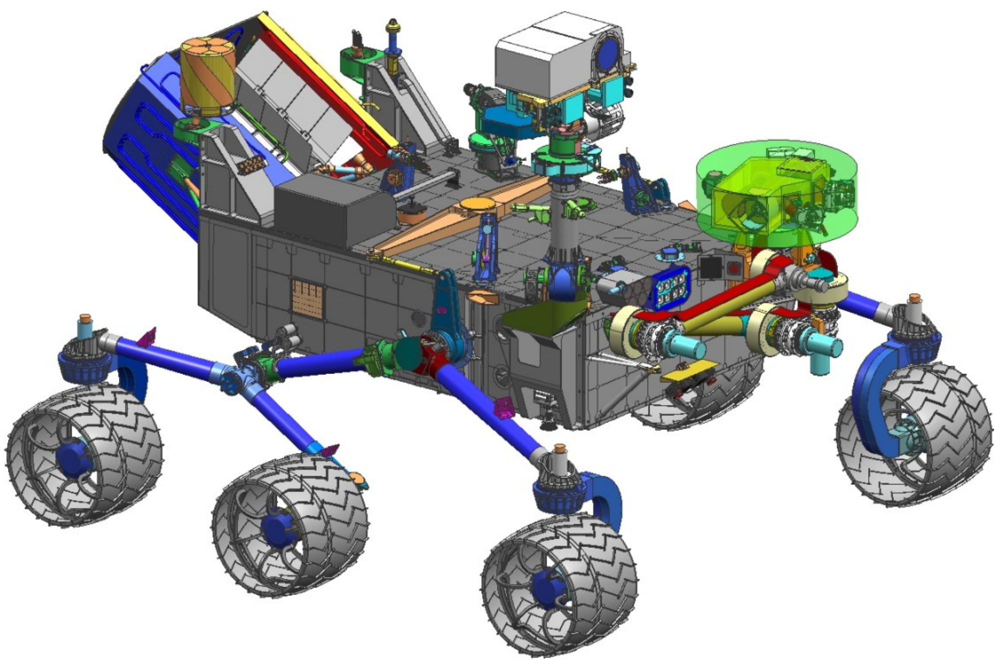


Rover Side View



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.

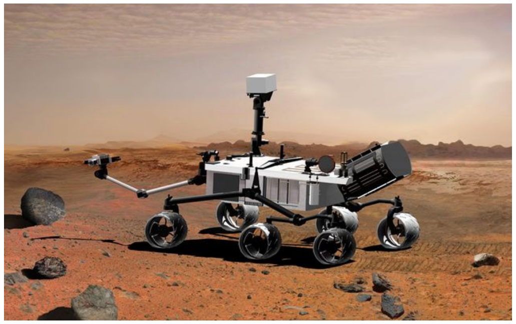


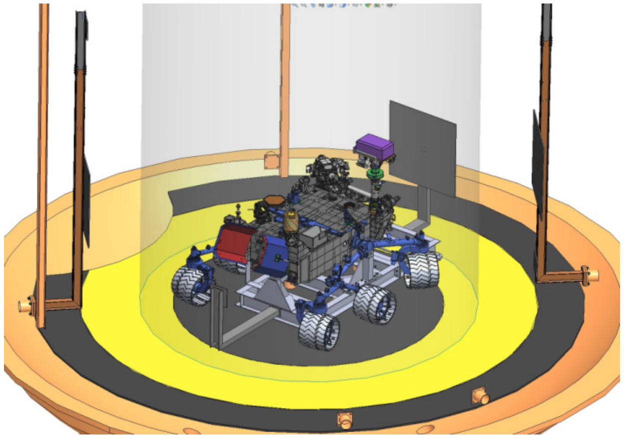
System Thermal Test Objectives Were Met

- 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 = 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) 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)

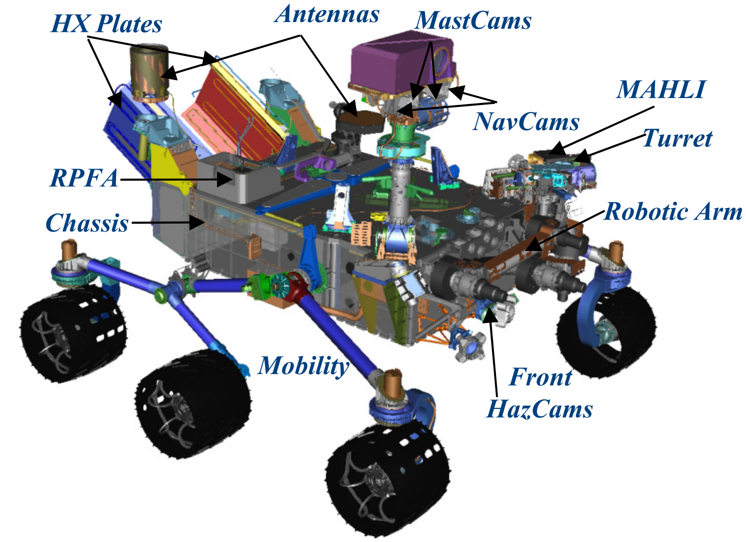
- Effect of RTG Power (Q = 1315 W to 1821 W)
  - Compare case #5 (Cold Thermal Balance at -105C) to case #11A (Hot Thermal Balance at -80C)

- 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)

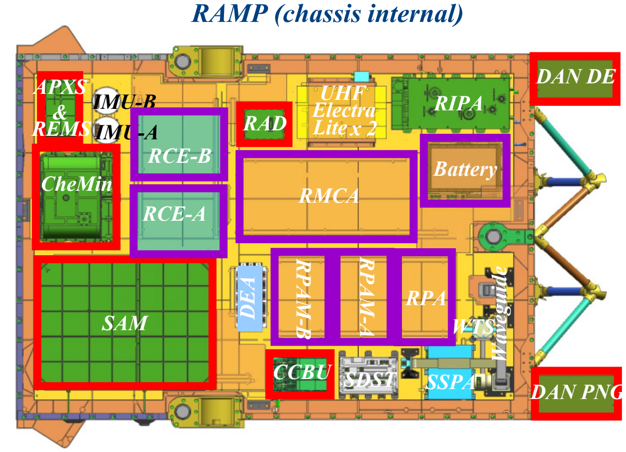
- Effect of Shroud Temp (+20C to -105C)
  - Multiple cases

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



RAMP (chassis internal)



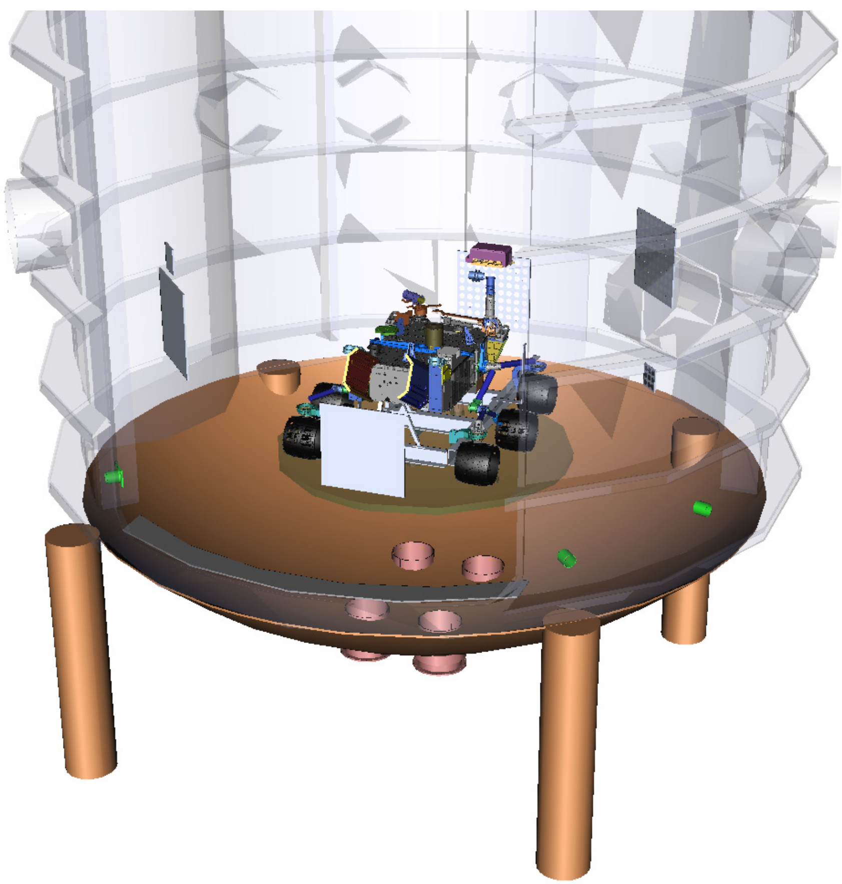
Rover Thermal Hardware

- 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

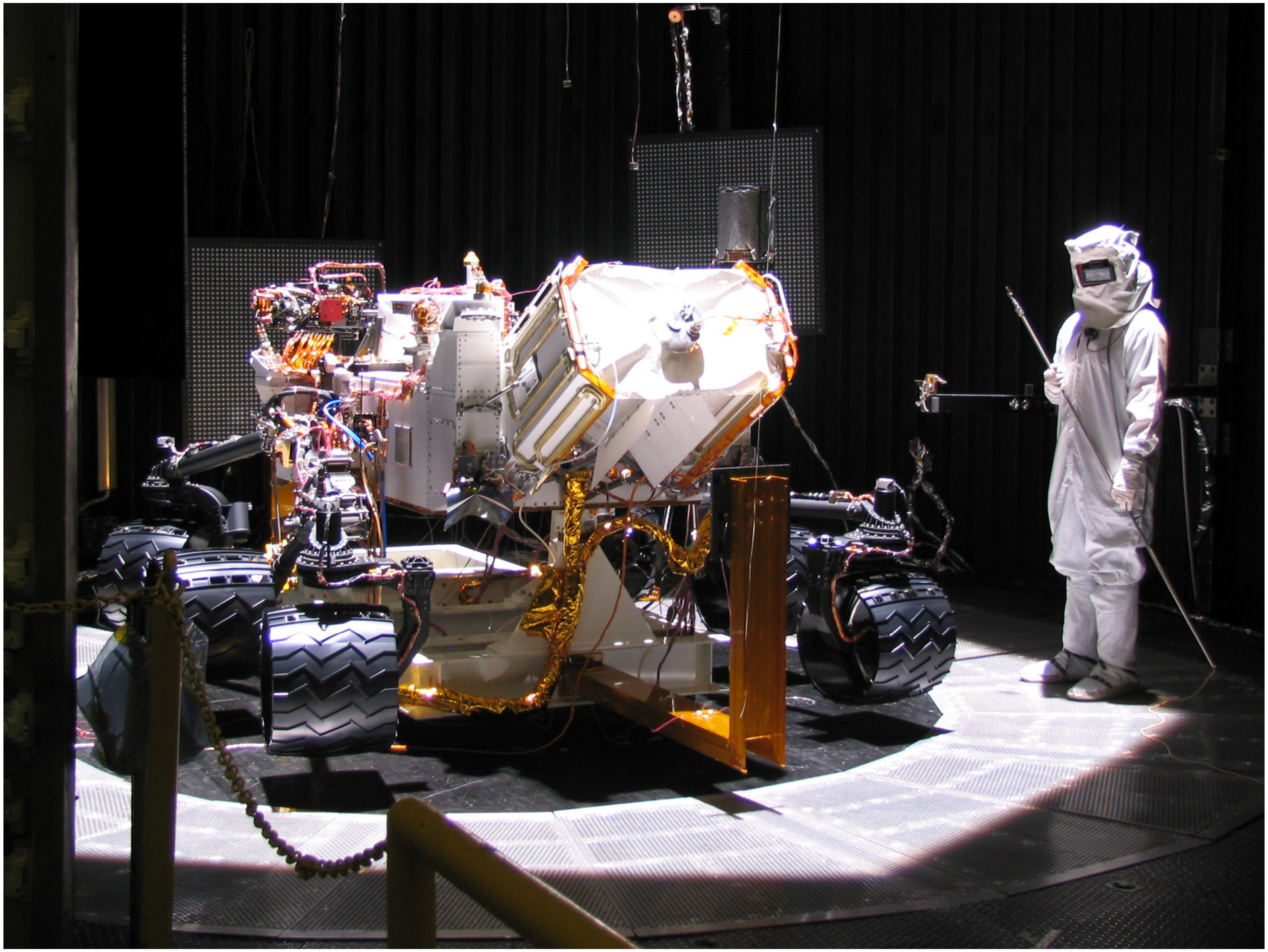
Test Setup – Rover in Chamber



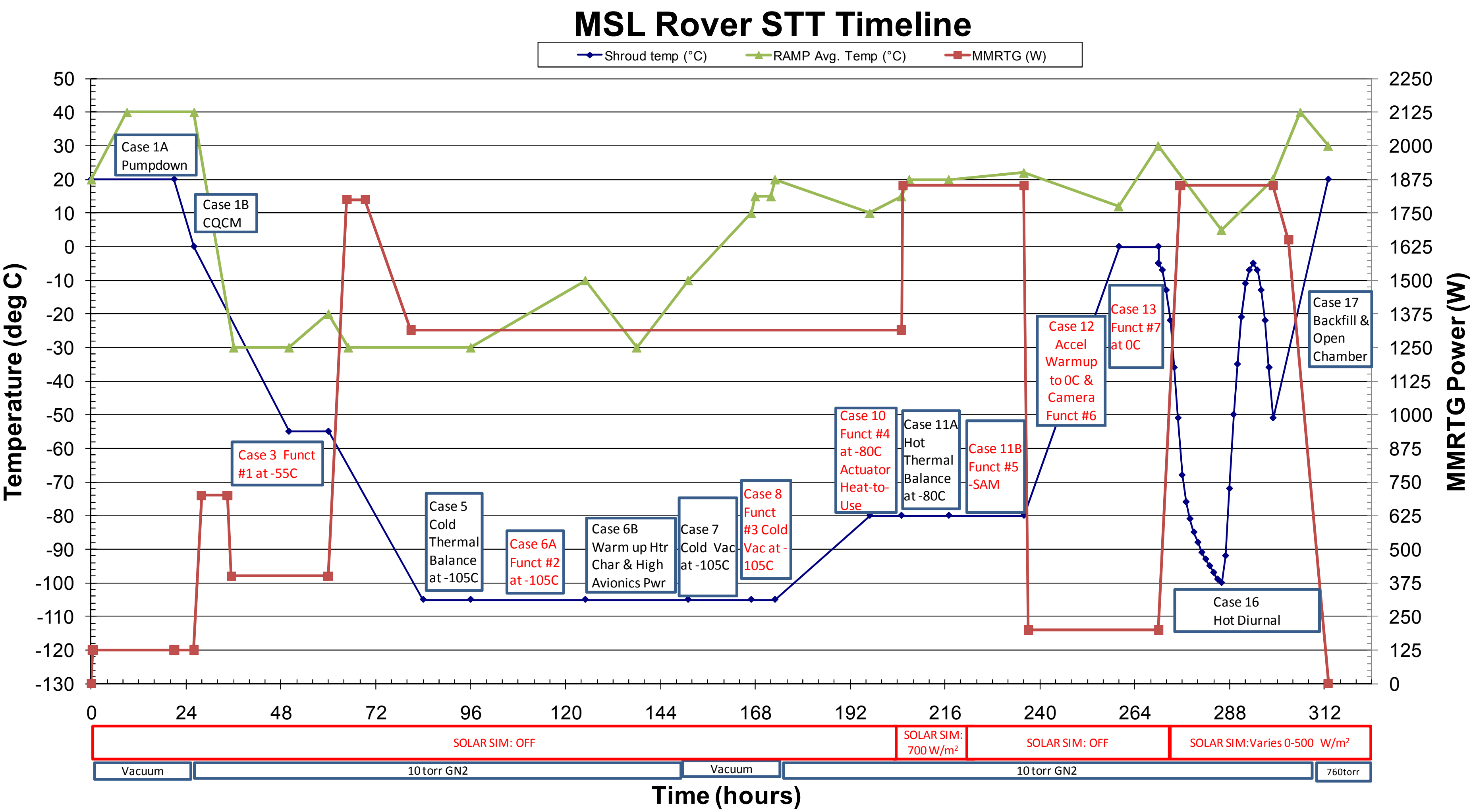
Rover Surface Configuration
Mounted on I-beam support frame 6 in. above chamber floor
Powered by Umbilical GSE Power Supply
9 Pyro firings during STT
  - *HGA, 3x HazCam Covers, RSM, Mobility Bogie Pose, Robotic Arm turret and elbow, Bit Box*
  - *Other pyros fired in B-144 & B-150 prior to chamber installation*

- *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



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)

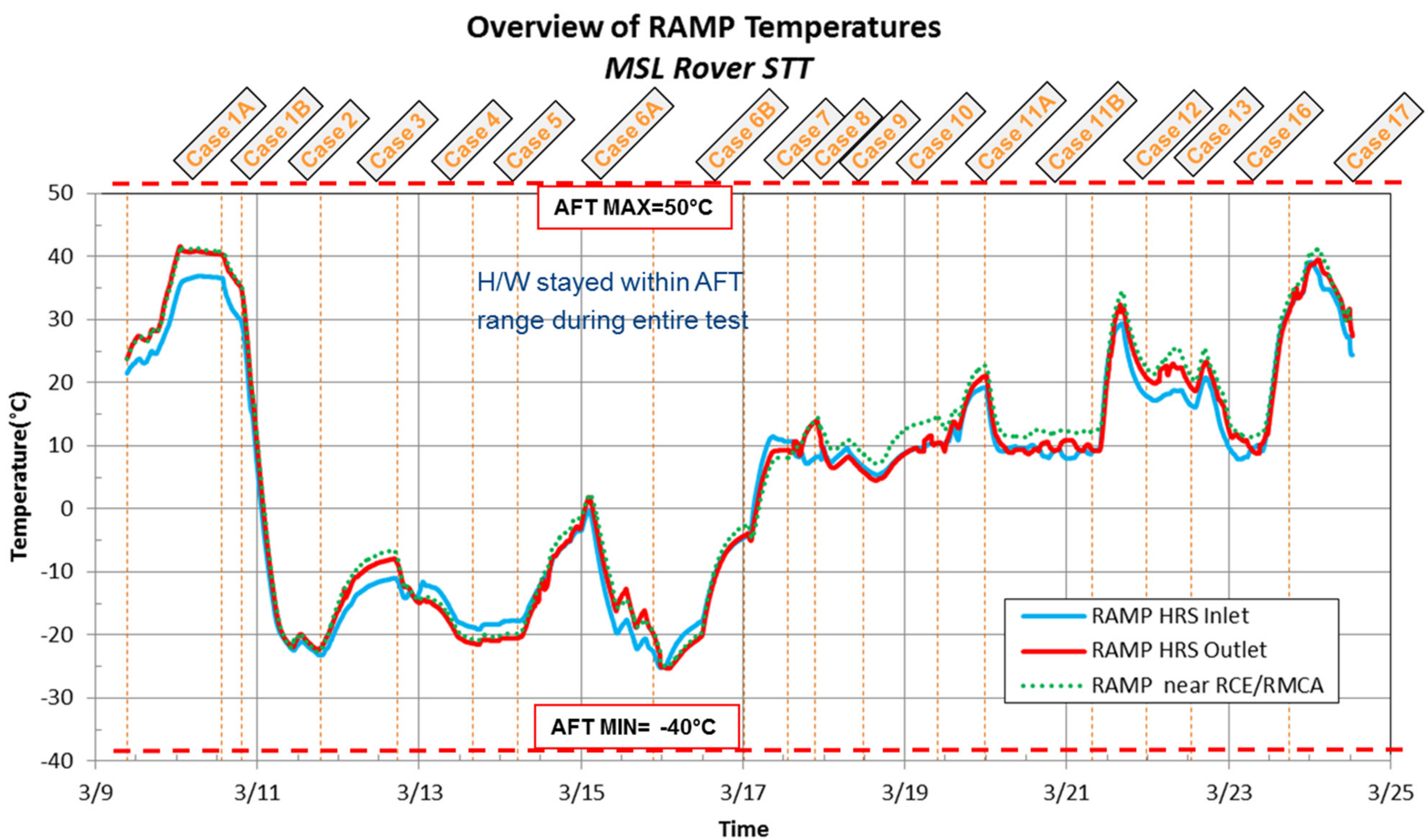
Transient Thermal Environments

- **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 temps. during STT (~ 2 C gradient in STT vs. ~7 C predicted)

Overview of RAMP Temperatures



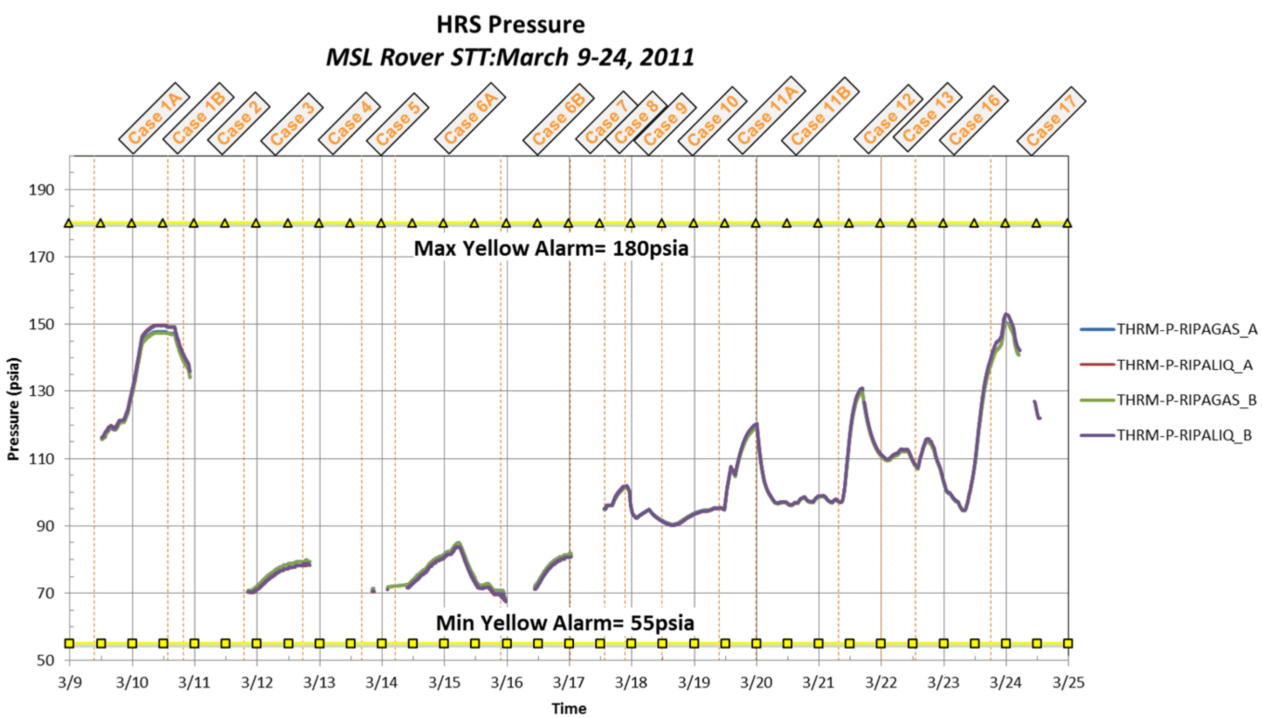
Health of RHRS during STT

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 ΔT to RAMP is 7.4°C (UHF-A)

Electronics	Electronics to RAMP ΔT(°C)	
	Case 8: Vacuum	Case 6B: GN2
CCBU	5.2	5.6*
CheMin	3.4	-1.7
DEA	2.0	2.0
RIMU-A	7.0	7.0
RIMU-B	6.4	-0.3*
RAD	1.1	0.8
RCE-A	5.8	5.9
RCE-B	6.3	0.1*
REMS	1.1	1.5
RIPA	1.4	-0.6
RMCA	4.2	2.7
RPA	2.8	1.3
RPAM-A	5.5	6.8
RPAM-B	4.7	5.9
SAM	-0.9	3.4
SDST	2.0	-0.6*
SSPA	5.1	-0.1*
UHF-A	7.4	6.8
APXS	1.1	-0.3*
UHF-B	6.2	-0.8*

***** Box was not on during Case 6B***

Rover Survival and Warm-up Heater Performance

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

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

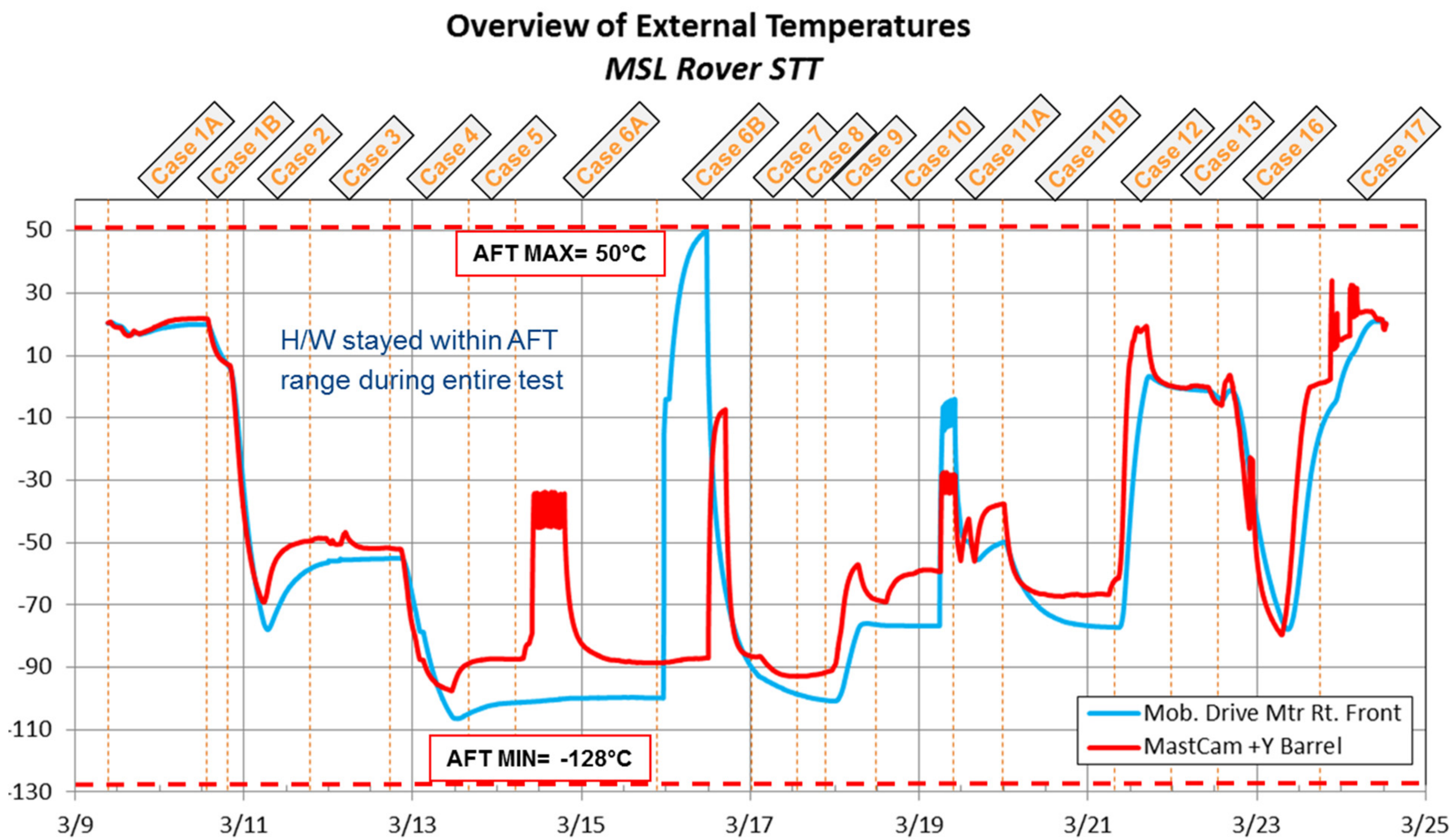
The battery can be maintained at 0°C with one warm-up heater on

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 (-105C 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



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**

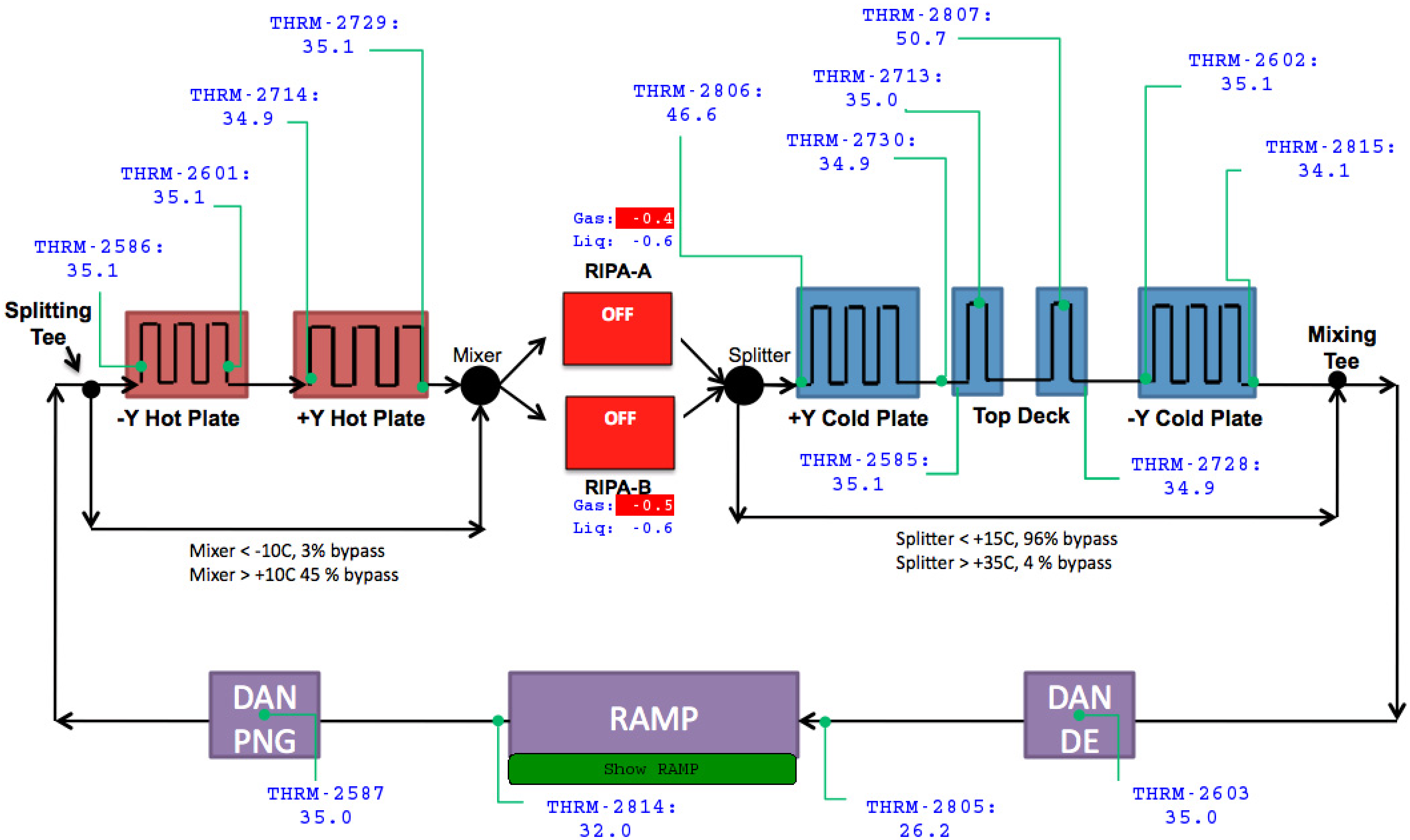
Backup

As-Run Test Timeline

MSL Rover STT Status

MSL Rover STT	Test Description	Estimated Duration (hrs)	Actual Duration (hrs)	From: m/d/11 h:mm AM	To: m/d/11 h:mm AM
	Late Start - Planned time was 8:00am	0.0	0.4	3/9/11 8:00 AM	3/9/11 8:23 AM
Test Case 1A	Pumpdown, Rover Outgas & Backup Pump Fault Protection Checkout	21.0	29.1	3/9/11 8:23 AM	3/10/11 1:30 PM
Test Case 1B	CQCM Measurement	5.0	6.0	3/10/11 1:30 PM	3/10/11 7:30 PM
Test Case 2	Accelerated Cooldown to -55C	24.0	23.3	3/10/11 7:30 PM	3/11/11 6:45 PM
Test Case 3	Functional #1: Deployment Verification at -55C	12.0	22.7	3/11/11 6:45 PM	3/12/11 5:30 PM
Test Case 4	Accelerated Cooldown to -105C Environment	24.0	23.5	3/12/11 5:30 PM	3/13/11 5:00 PM
Test Case 5	Cold Thermal Balance at -105C Survival Heater/T'stat Checkout, HGA Warmup Htr Char Test	12.0	13.1	3/13/11 5:00 PM	3/14/11 6:07 AM
Test Case 6A	Functional Test #2 Environment @ -105oC [Cold Case]	29.0	39.2	3/14/11 6:07 AM	3/15/11 9:18 PM
Test Case 6B	Warmup Heater Thermal Characterization & Cold Thermal Balance with High RAMP Avionics Power	26.0	26.7	3/15/11 9:18 PM	3/17/11 12:00 AM
Test Case 7	Cold Vacuum Test at -105C	16.0	13.0	3/17/11 12:00 AM	3/17/11 1:00 PM
Test Case 8	Functional #3 - Cold Vacuum Test at -105C	6.0	8.5	3/17/11 1:00 PM	3/17/11 9:30 PM
Test Case 9	Accelerated Warmup to -80C	24.0	15.0	3/17/11 9:30 PM	3/18/11 12:30 PM
Test Case 10	Functional Test #4: Environment @ -80C Actuator Heat-to-Use & Articulate	8.0	21.5	3/18/11 12:30 PM	3/19/11 10:00 AM
Test Case 11A	Hot Thermal Balance Test at -80C	12.0	13.5	3/19/11 10:00 AM	3/19/11 11:30 PM
Test Case 11B	Functional #5 - SAM on 20C RAMP	19.0	32.0	3/19/11 11:30 PM	3/21/11 7:30 AM
Test Case 12	Accelerated Warmup to 0C & Camera Functional #6 at -40C during Transition	24.0	16.5	3/21/11 7:30 AM	3/22/11 12:00 AM
Test Case 13	Functional Test #7: Environment @ 0oC [Hot Case]	10.0	13.0	3/22/11 12:00 AM	3/22/11 1:00 PM
Test Case 14	*deleted*	0.0	0.0	3/22/11 1:00 PM	3/22/11 1:00 PM
Test Case 15	*deleted*	0.0	0.0	3/22/11 1:00 PM	3/22/11 1:00 PM
Test Case 16	Hot Diurnal Test	29.0	29.0	3/22/11 1:00 PM	3/23/11 6:00 PM
Test Case 16B	*deleted*	0.0	0.0	3/23/11 6:00 PM	3/23/11 6:00 PM
Test Case 17	Backfill and Open Chamber	14.0	17.5	3/23/11 6:00 PM	3/24/11 11:30 AM
	Initial Estimated Total Test Duration (days):	*13.1*	15.1	*:Current Total Test Duration (days)*	
	(hours):	*315.0*	363.5	*: (hours)*	
			-48.5	*Delta in Hours (negative is behind)*	

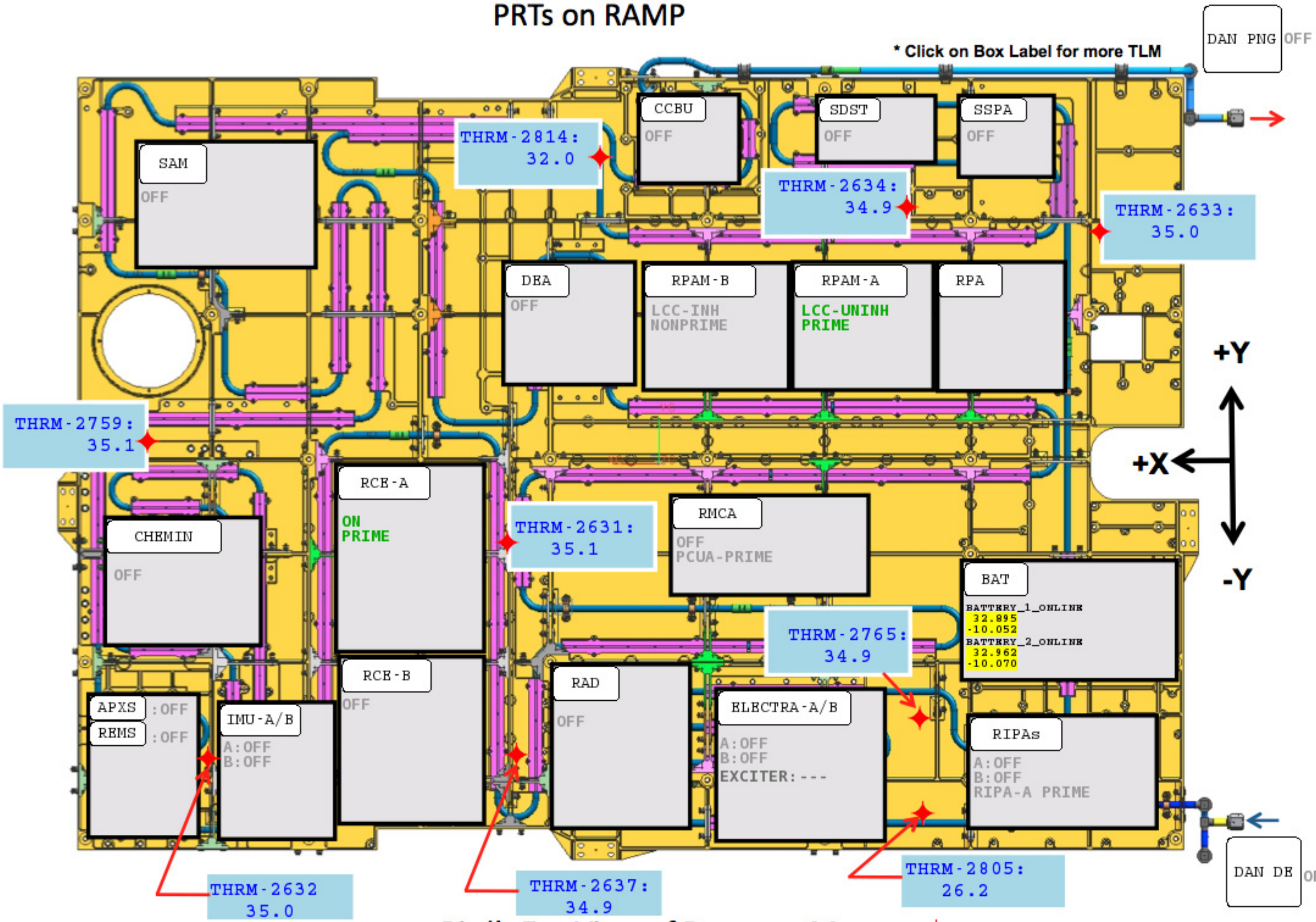
GDS Fixed Pages



RHRS Loop PRT Overview

GDS Fixed Pages

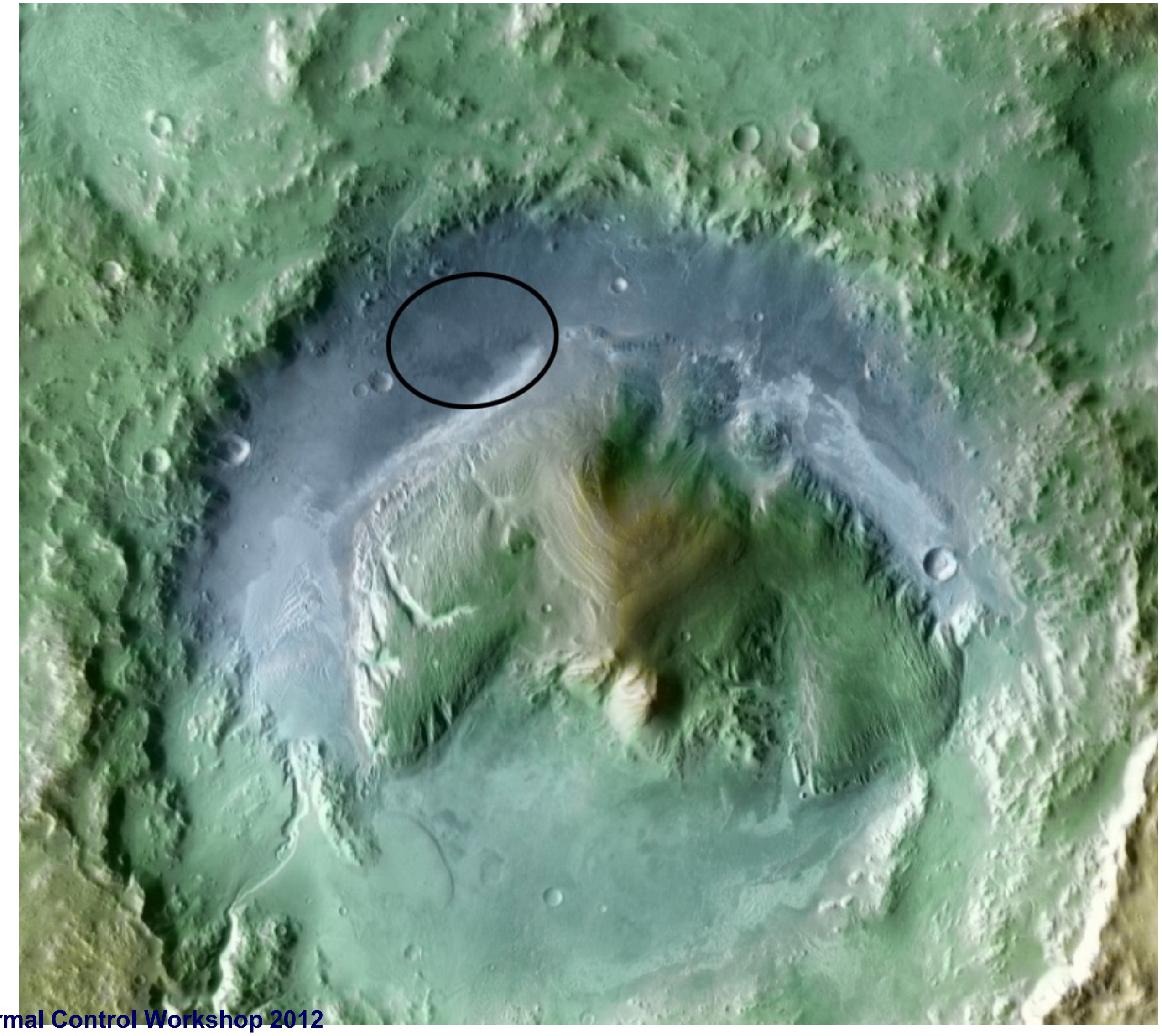
PRTs on RAMP



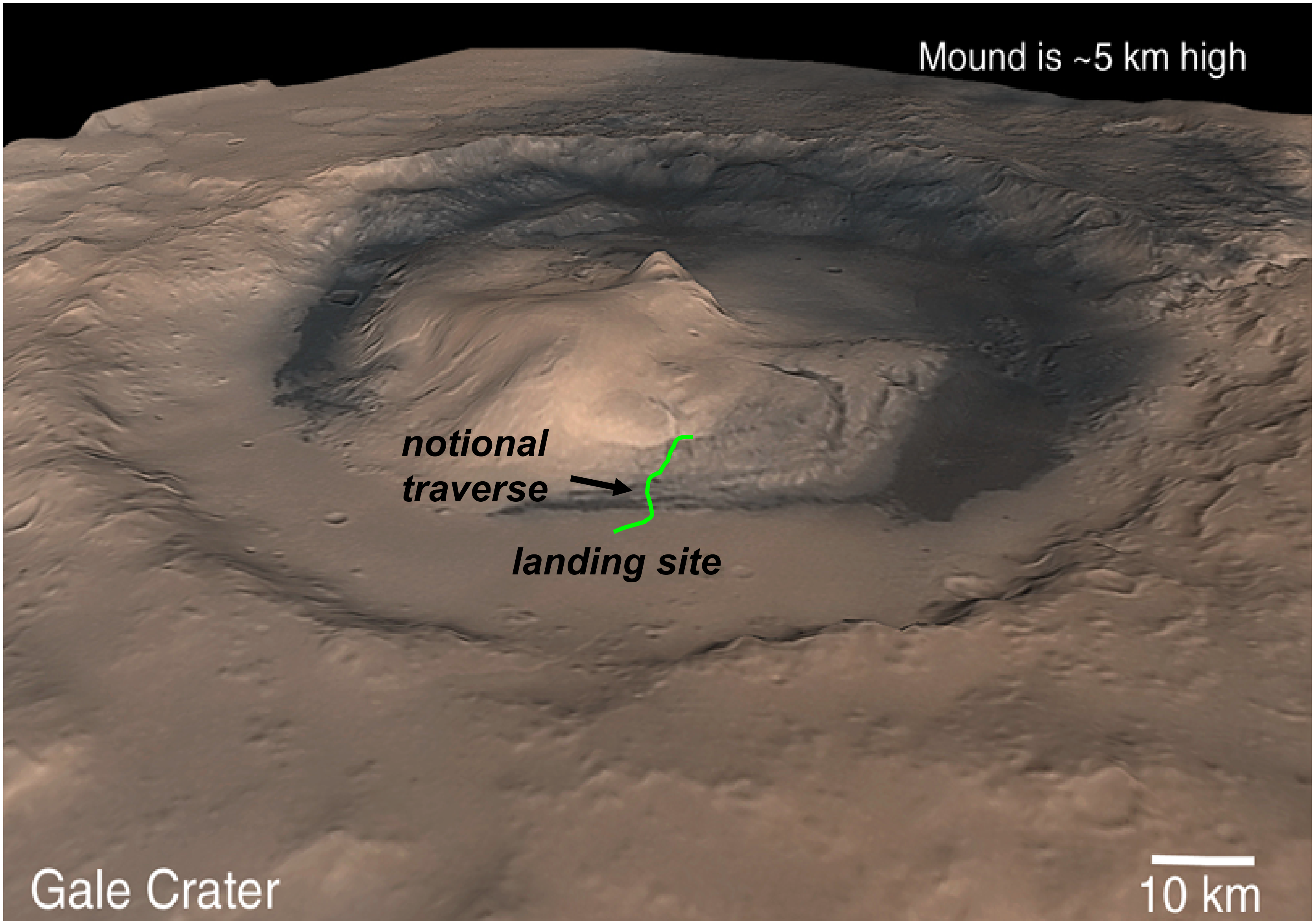
Bird's Eye View of Rover on Mars

Gale Crater

Landing Ellipse



Gale Crater


Mound is ~5 km high
notional
traverse
landing site
Gale Crater
10 km

System Test Bed Drills