Thermal Design Overview of the Mars Exploration Rover Project

Glenn Tsuyuki

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, CA

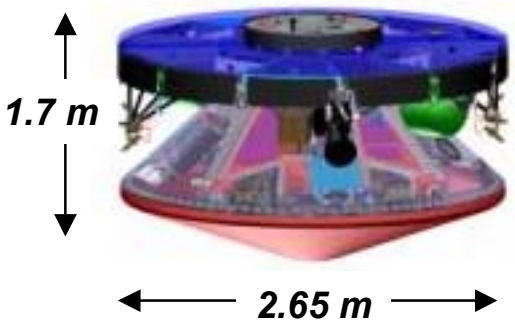
September 10, 2001

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

Flight System

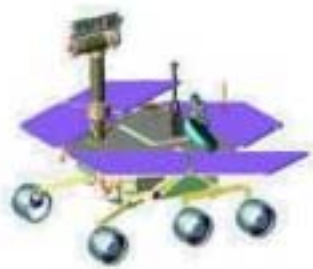


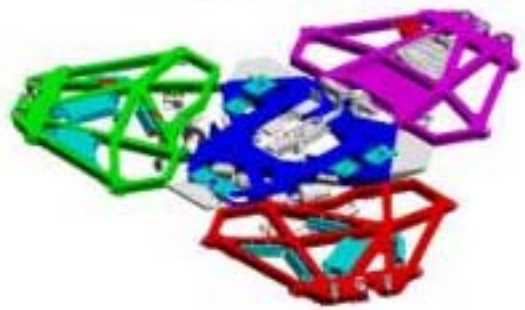
Cruise Stage

Backshell

Heat Shield

Rover





Lander

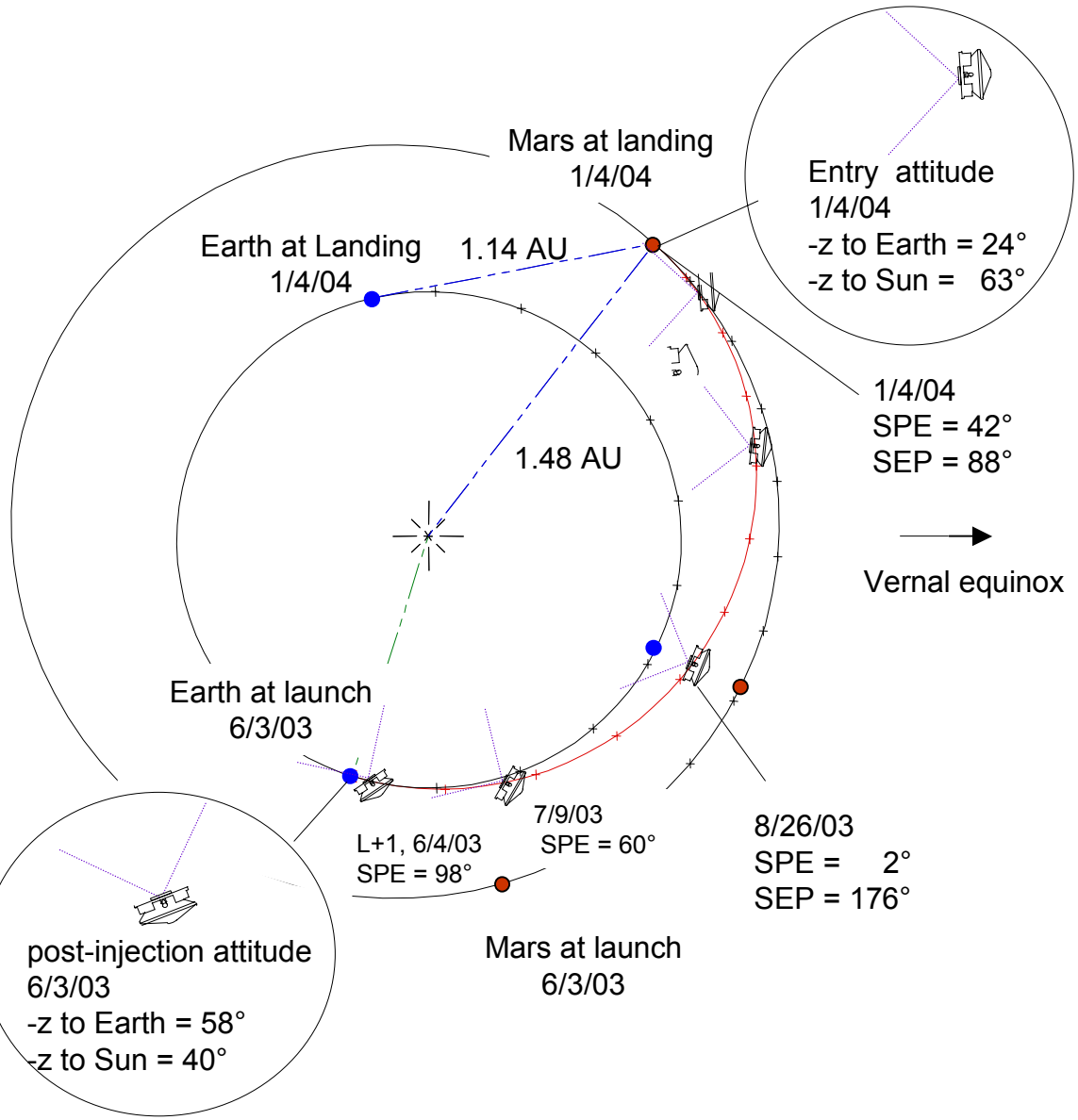
MER-A Cruise Scenario

Mars Exploration Rover

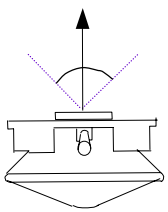
View from Ecliptic North Pole
20 Day Tic Marks

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

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



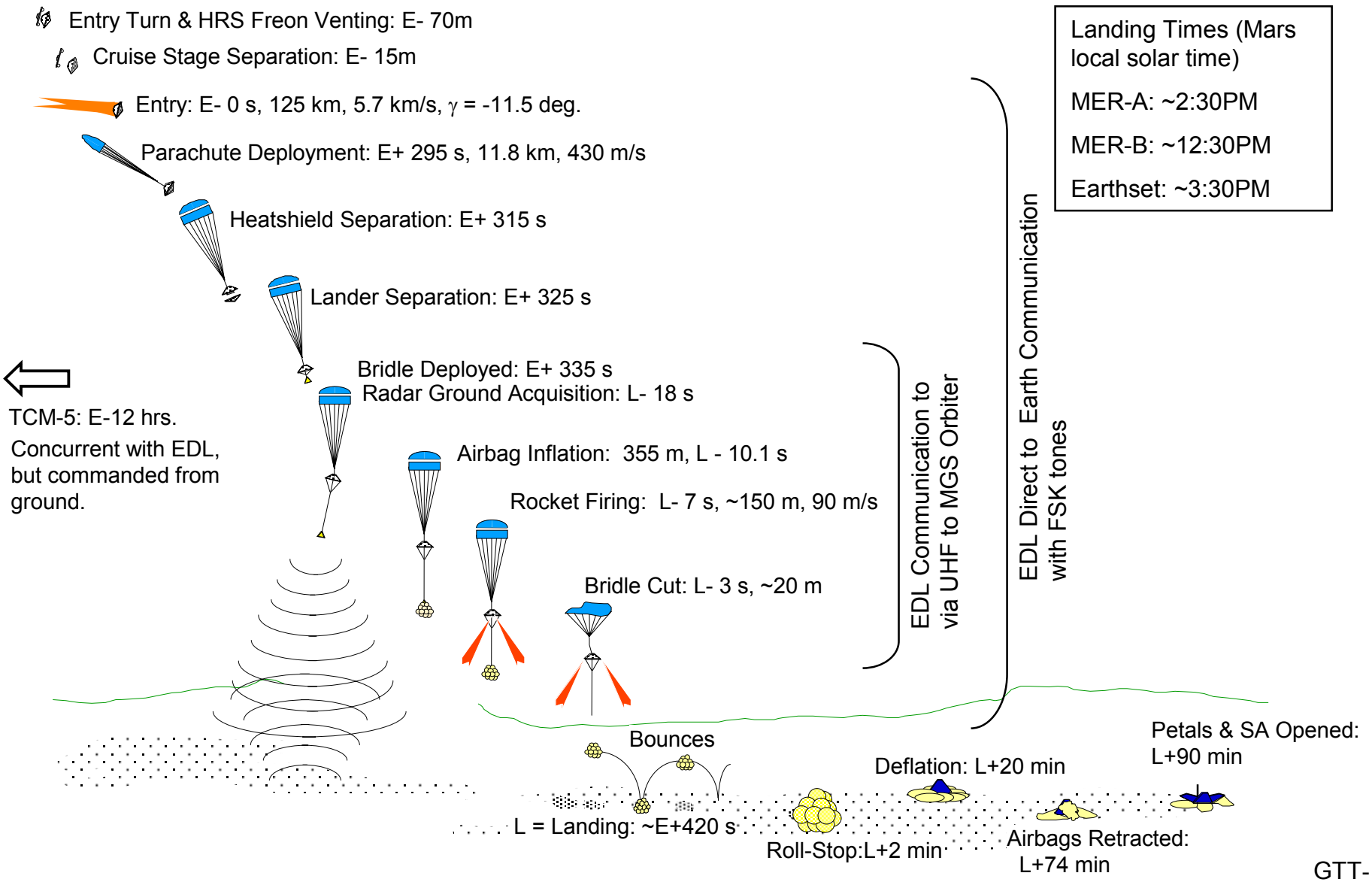
-z axis
- antenna boresight
- panel normal axis
- spin axis



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

Entry, Descent & Landing (EDL) Scenario

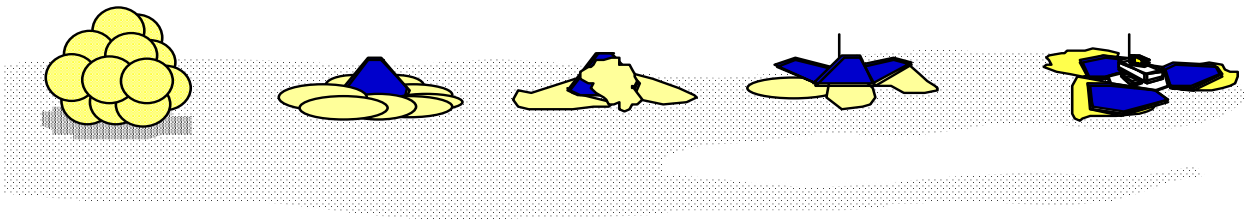
Mars Exploration Rover



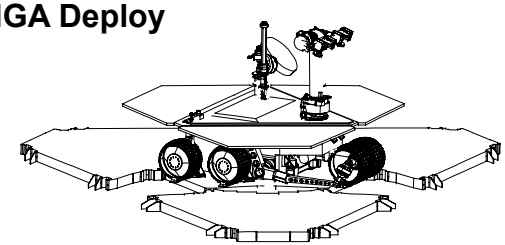
Impact to Egress Scenario

Sol 1

Airbag Retraction / Petal Deploy / Egress Aid Deploy



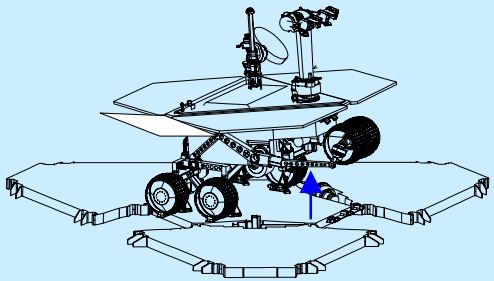
Solar Array Deploy
PMA Deploy & Imaging
HGA Deploy



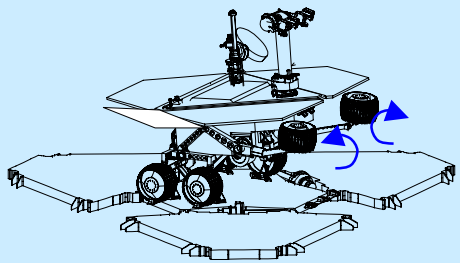
Sol 2-3

Petal / Airbag Adjustments
Pancam/Mini-TES

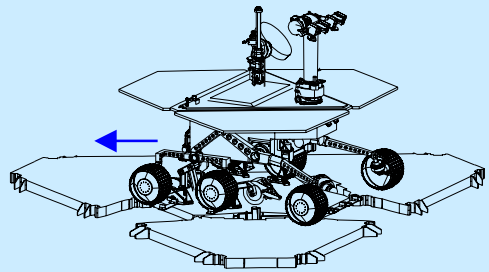
Lift Rover / Lock Rockers



Deploy Rockers



Lower Lift Mechanism & Deploy Bogies



Sol 4

Drive Petals to final Configuration

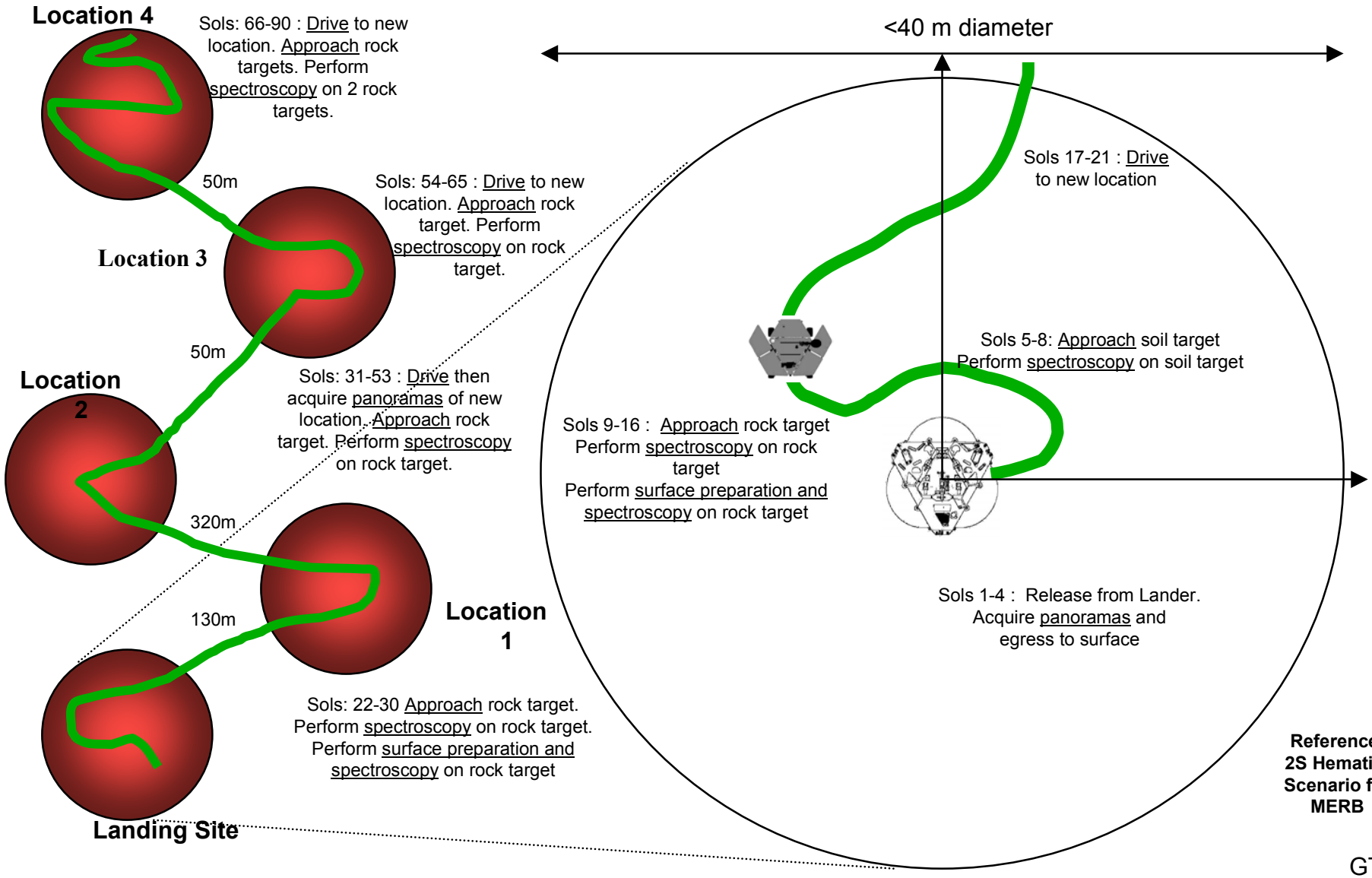
Release Middle Wheels & Fire 3rd Cable Cutter

Turn in Place

Drive Off Lander Deck

Surface Scenario

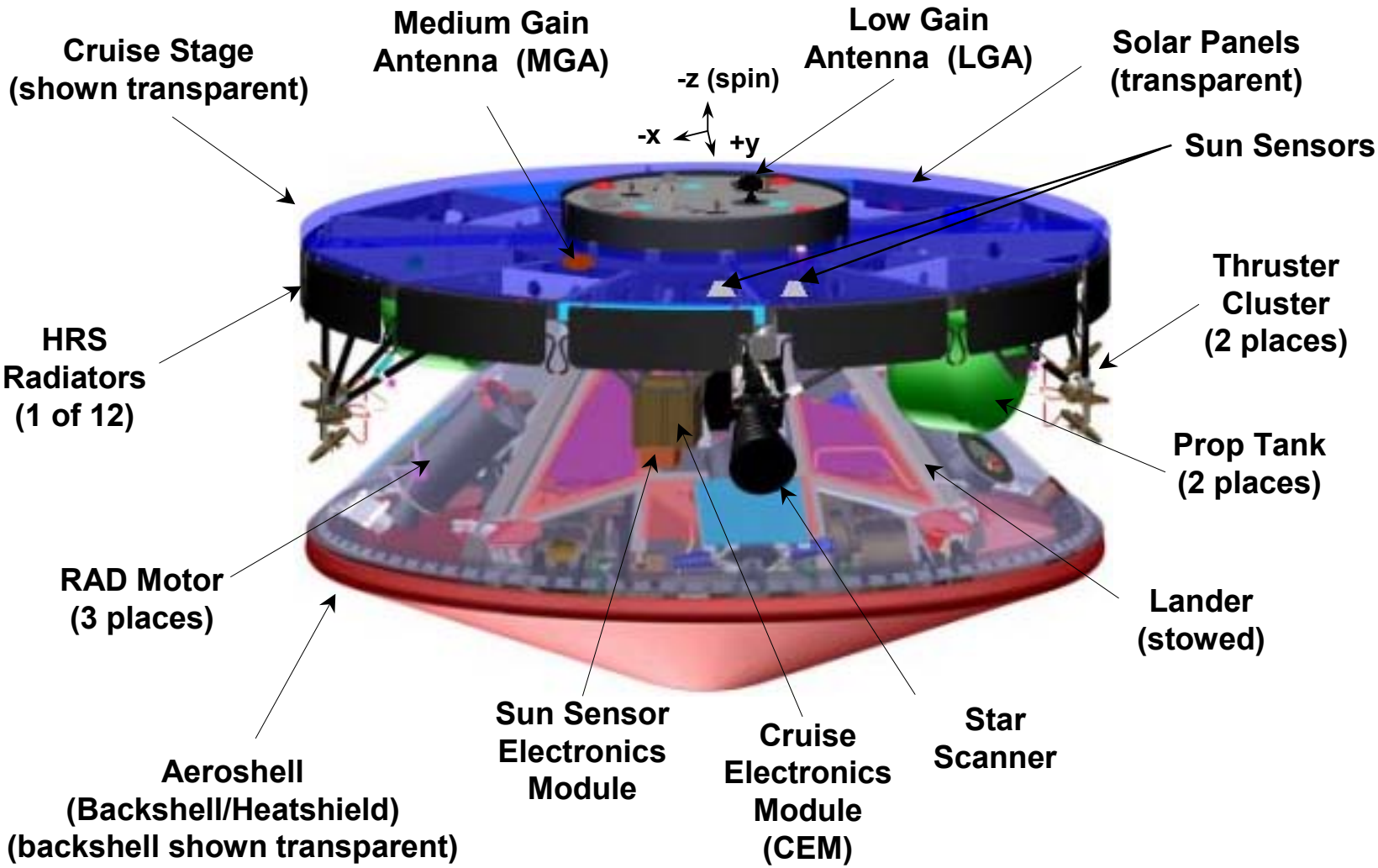
Mars Exploration Rover



Reference: 2S Hematite Scenario for MERB

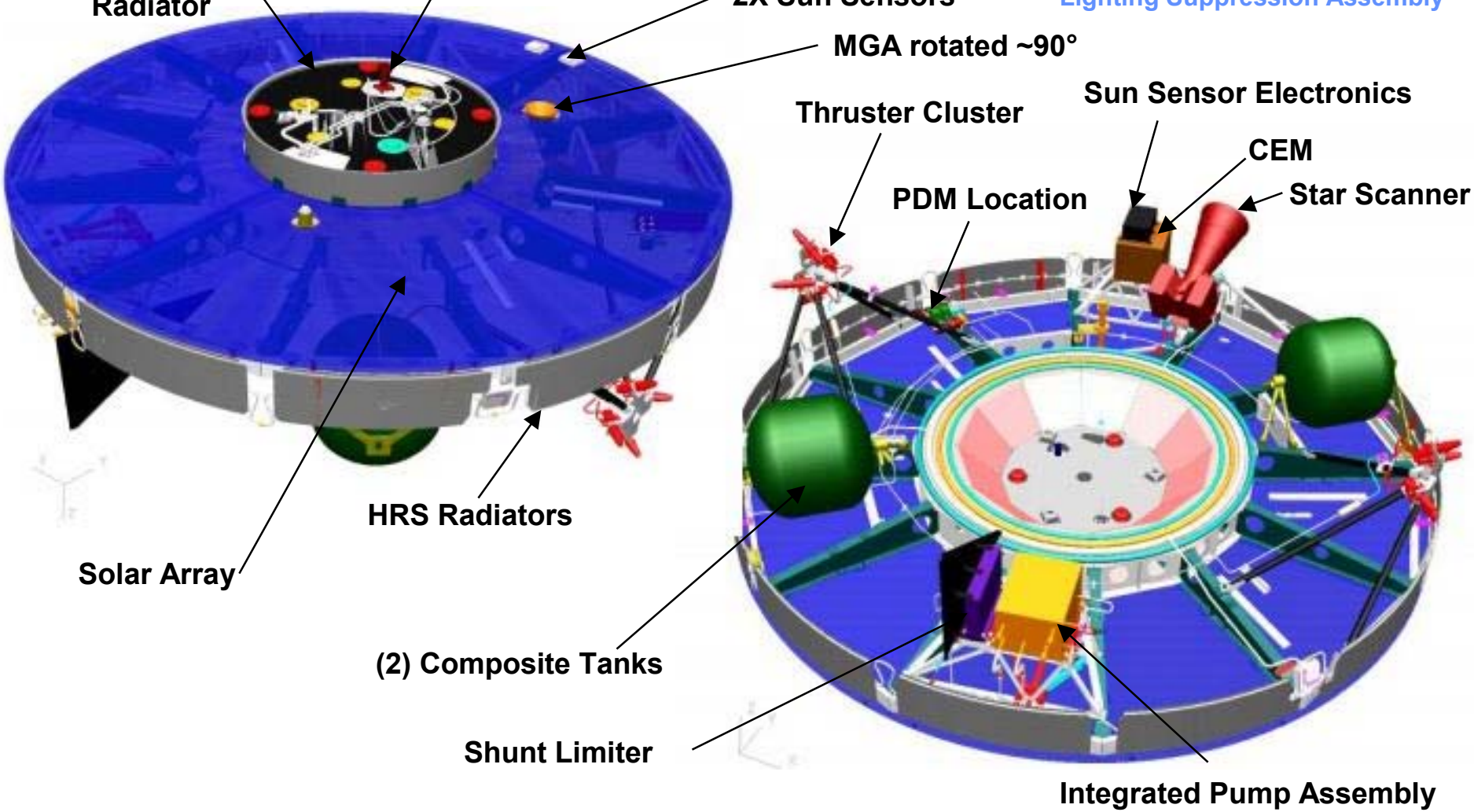
Spacecraft Cruise Configuration

Mars Exploration Rover

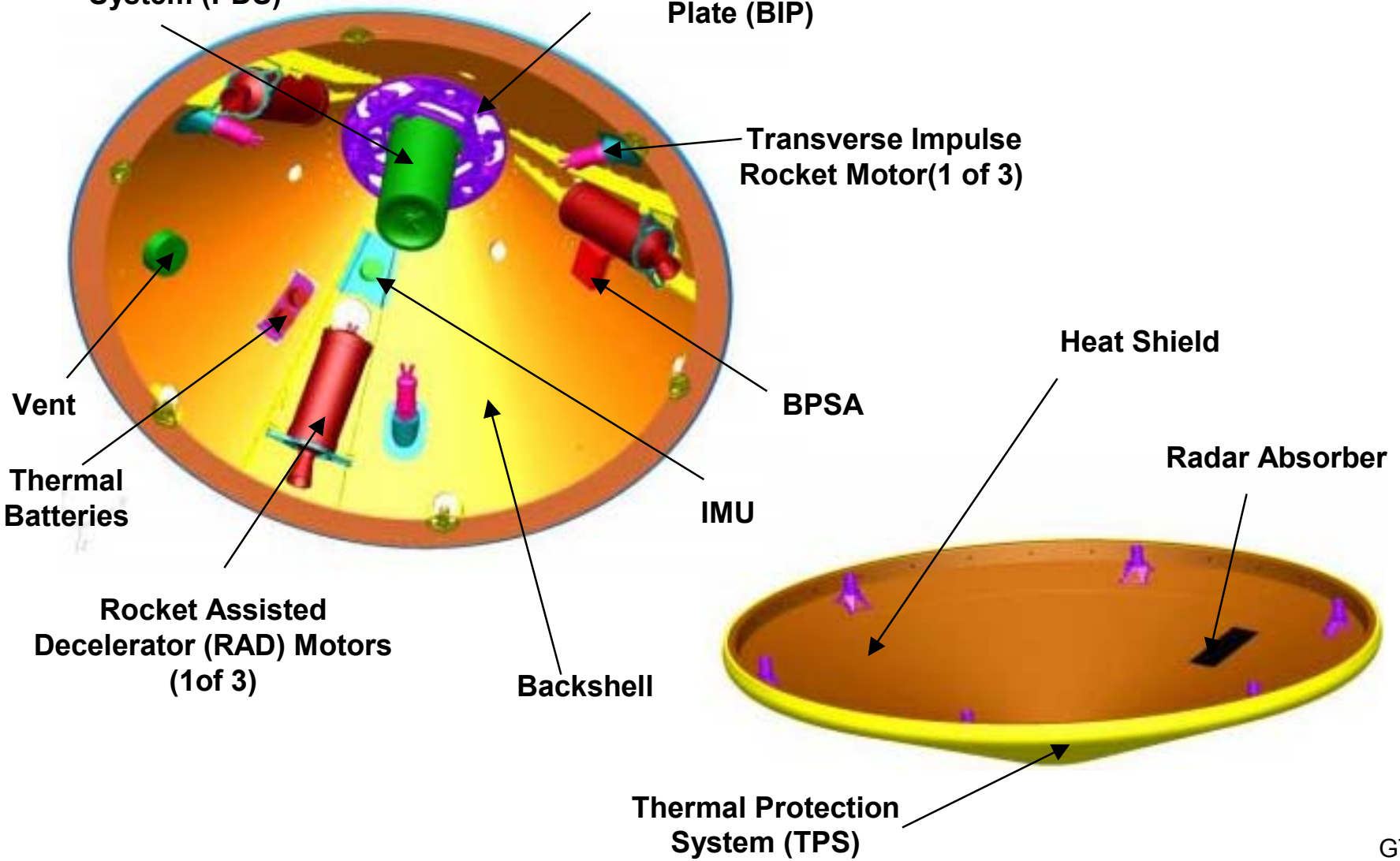


Cruise Stage Configuration

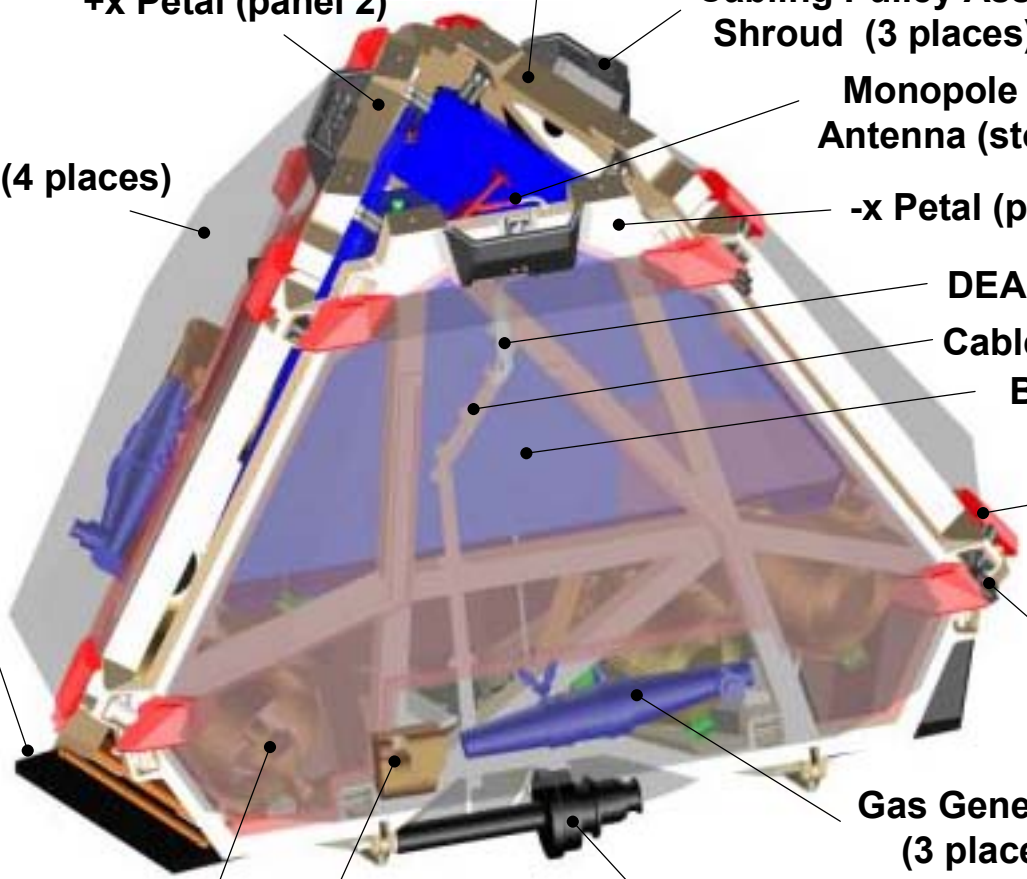
Mars Exploration Rover



Aeroshell Configuration

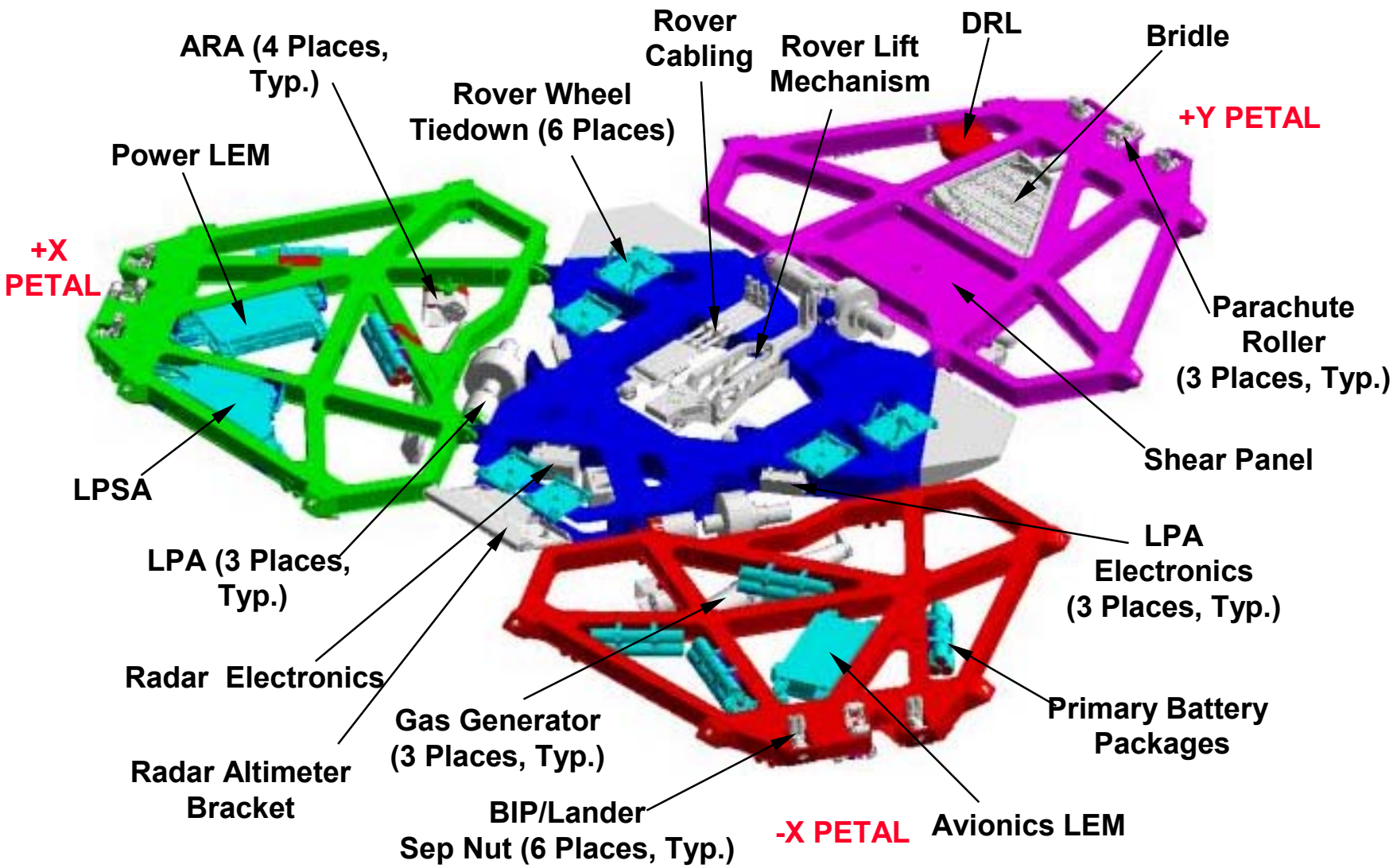


Lander Assembly - Stowed

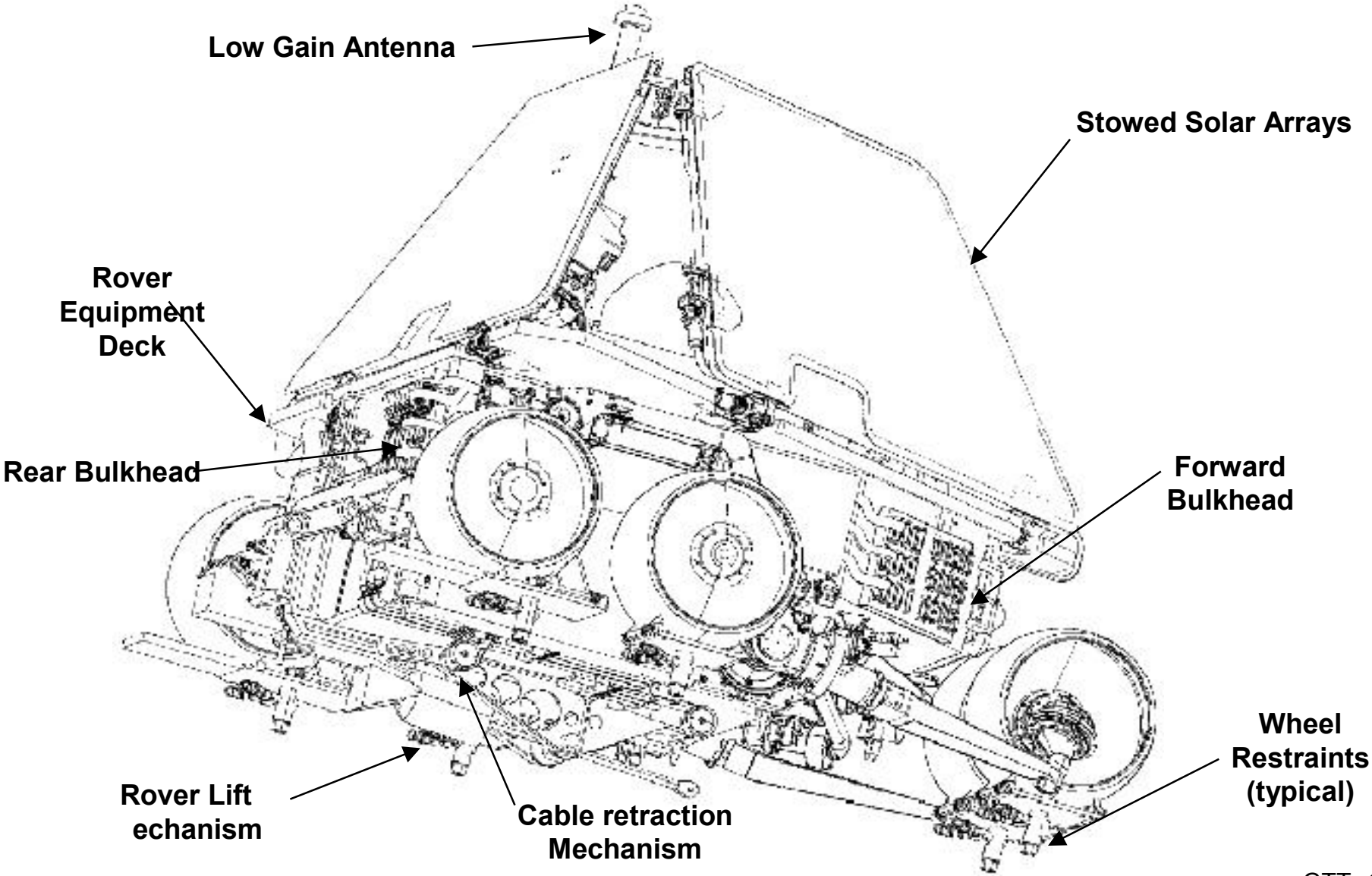


Not shown: Egress Aids

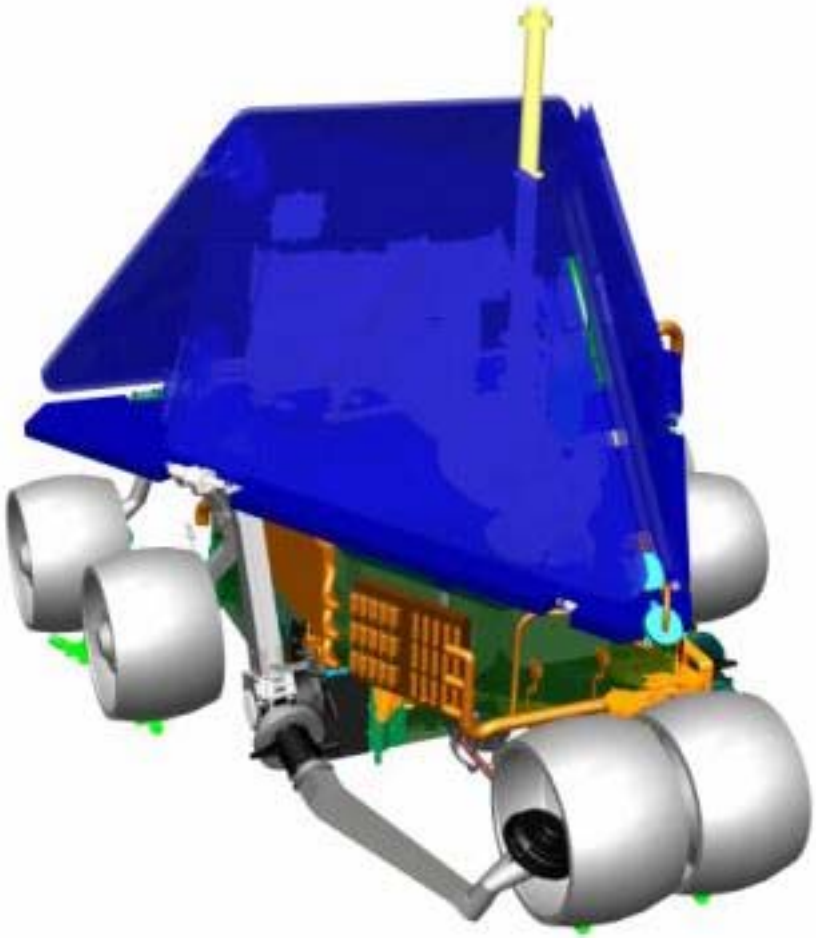
Lander Assembly - Deployed

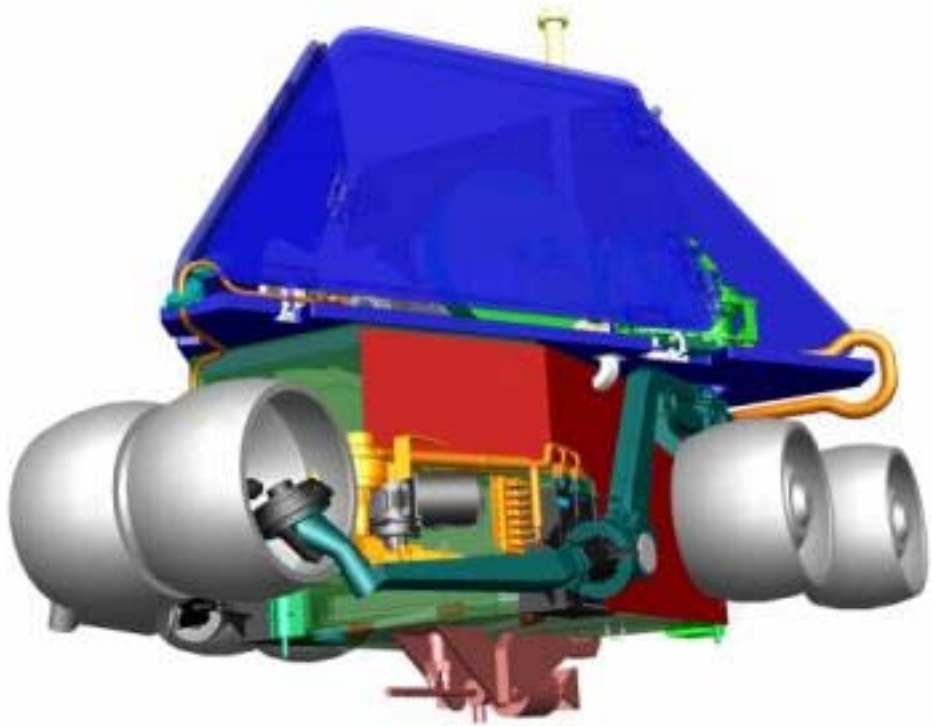


Rover - Stowed Configuration



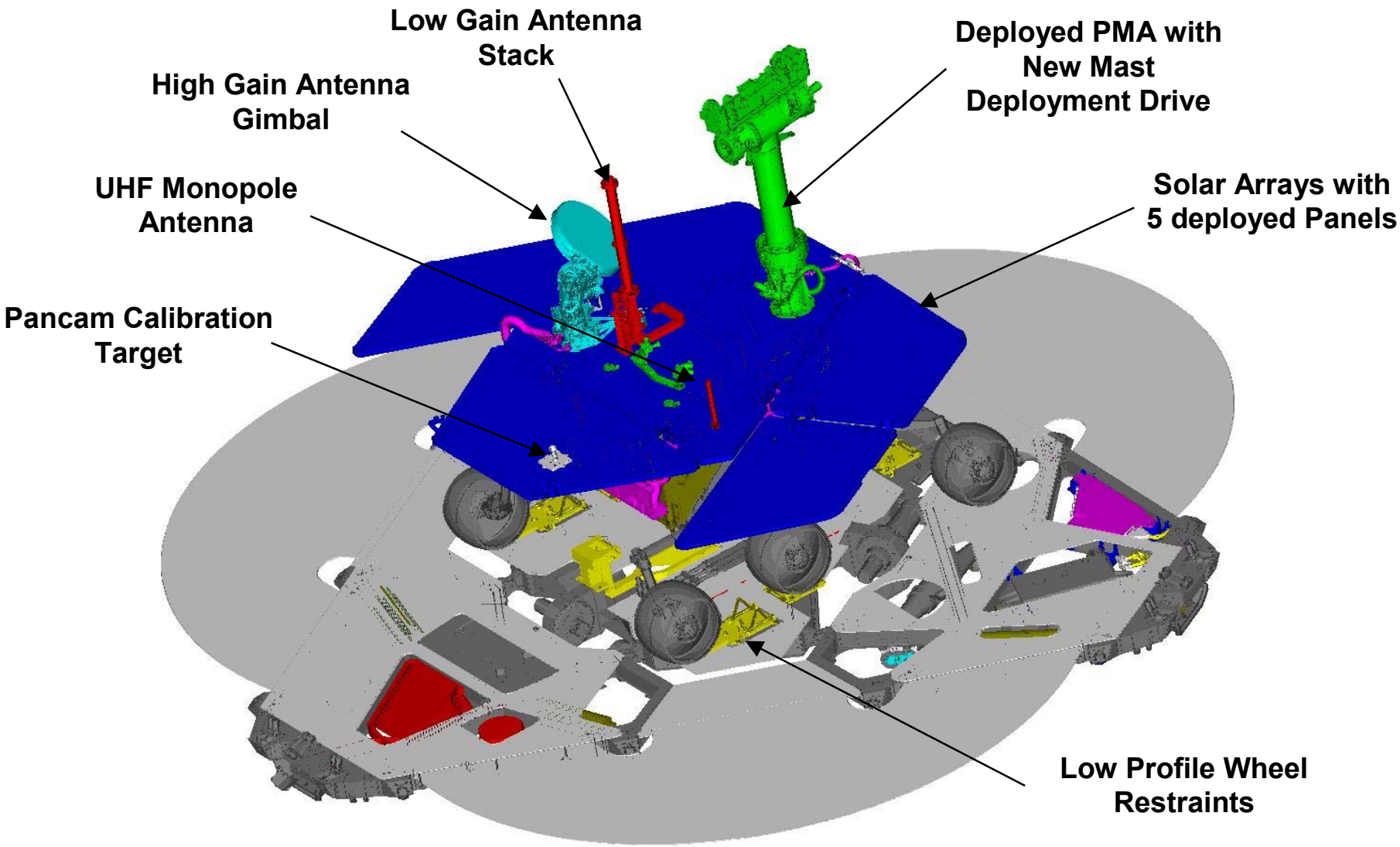
Shaded Isometric Views of the Stowed Rover



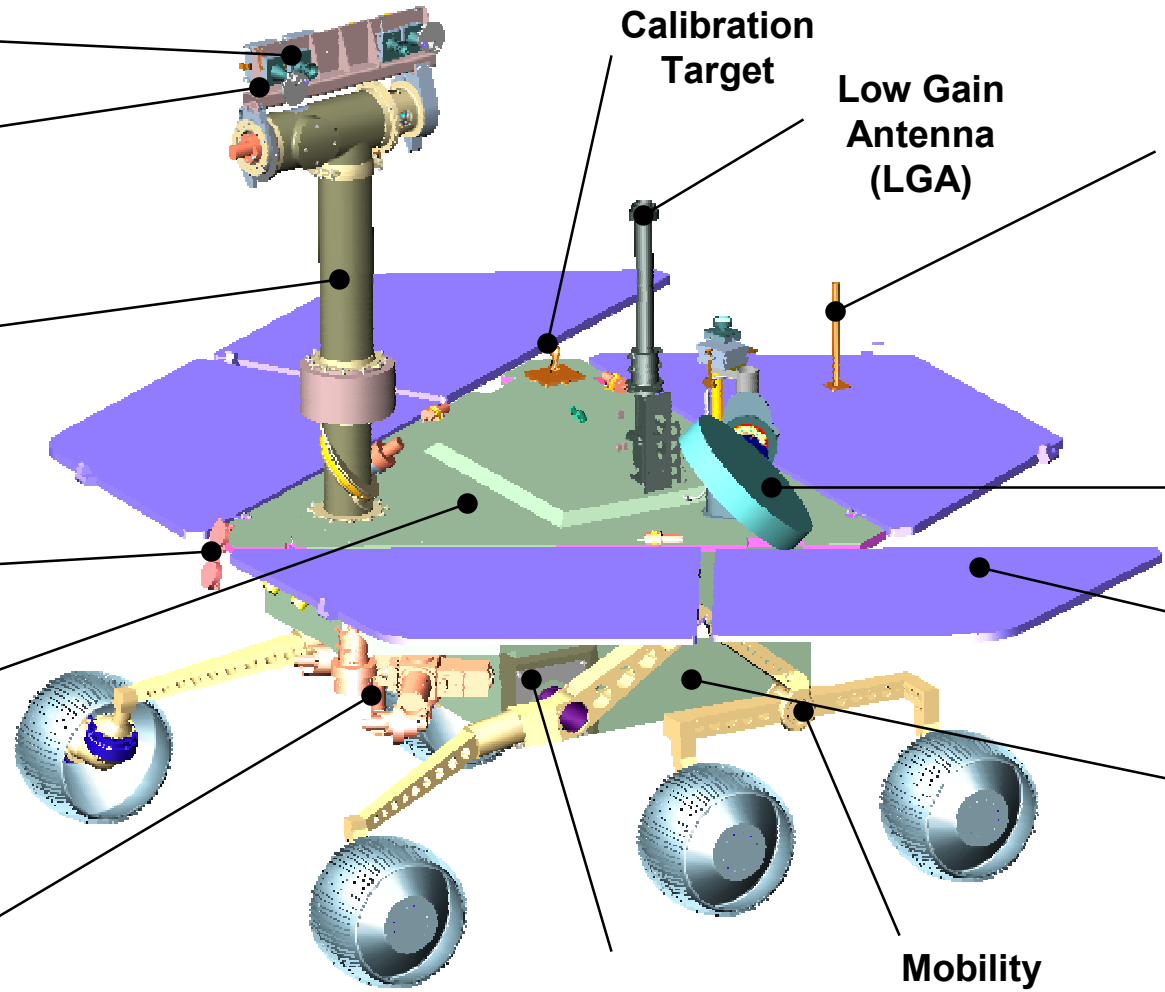


Deployed Rover on the Lander

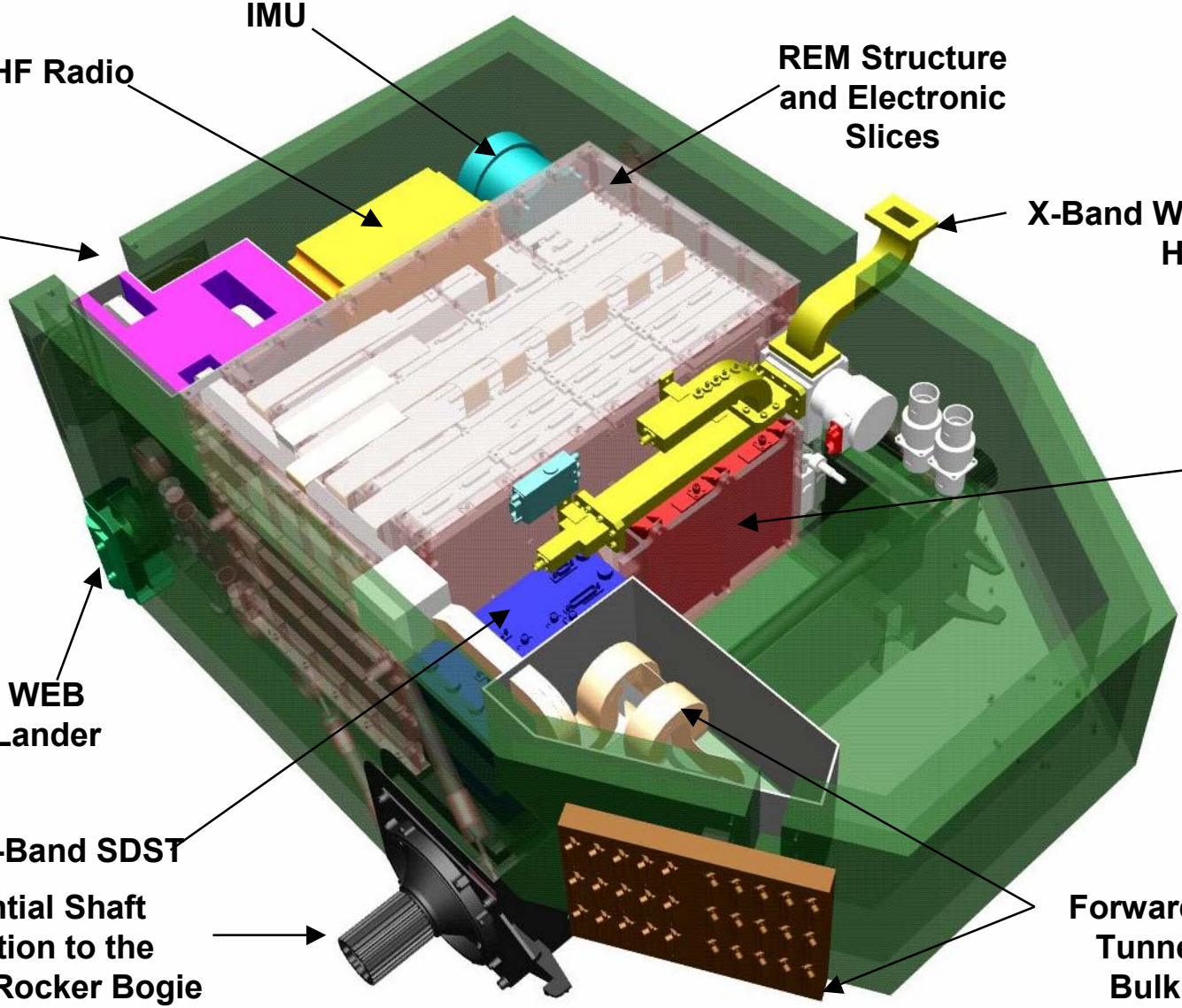
Mars Exploration Rover



Rover Configuration - Deployed



Isometric View of the WEB



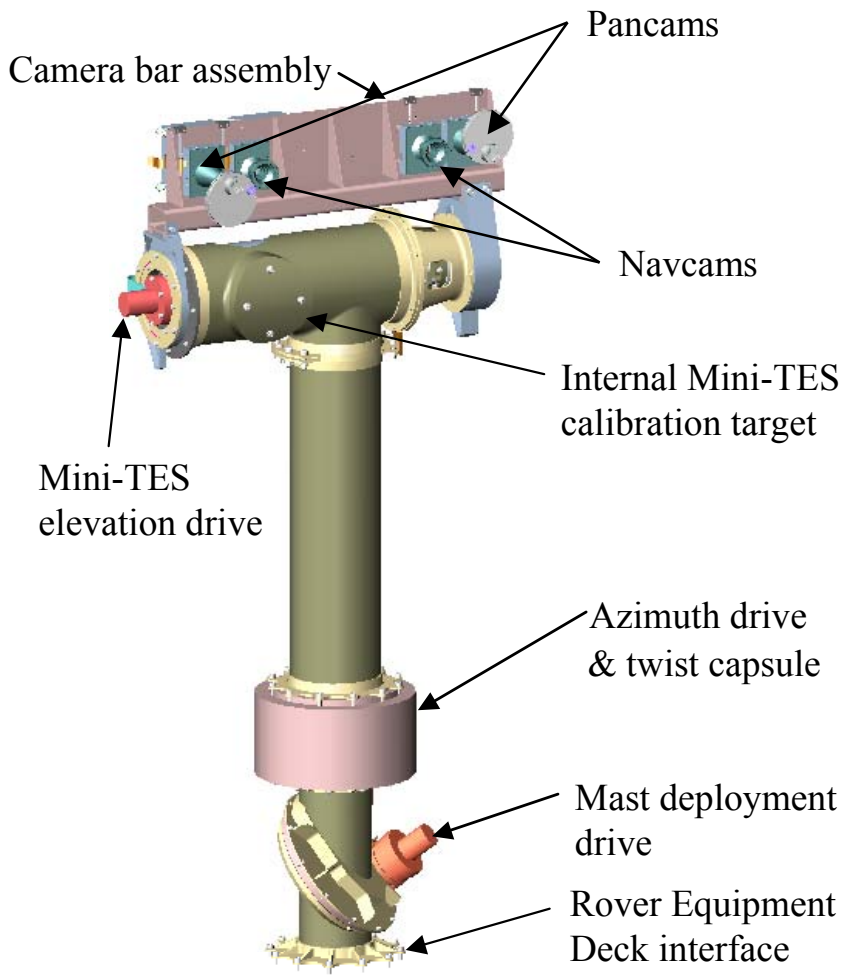
Remote Sensing Science Instruments

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"**

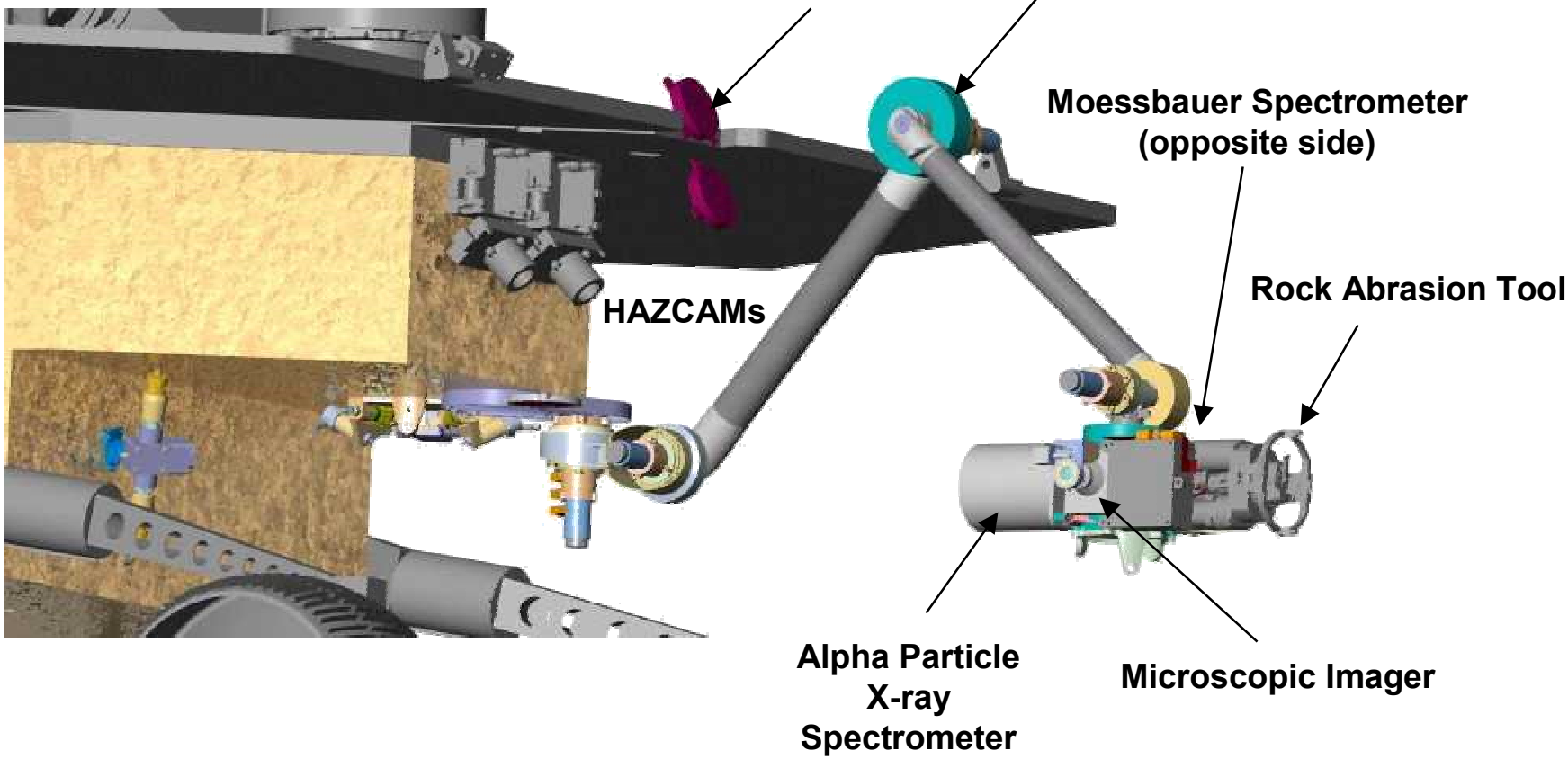


Pancam Mast Assembly (PMA)

In situ Science Instruments

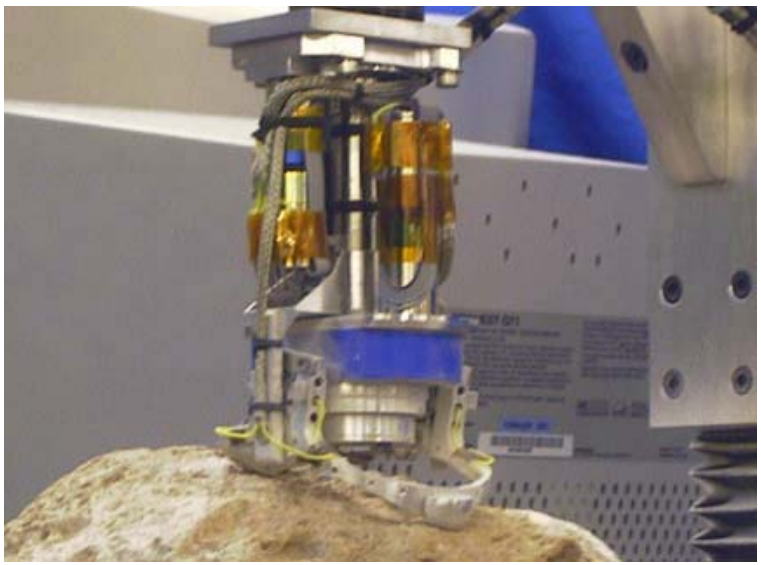
- Instrument Deployment Device (IDD) - a 5 DOF robotic arm for deployment of 3 in situ science instruments and a Rock Abrasion Tool (RAT) against rock and soil targets
  - Microscopic Imager (MI)- 1024x1024x12bit camera with 30 μm/pixel resolution with 3 mm depth of field
  - Alpha Particle X-ray Spectrometer (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

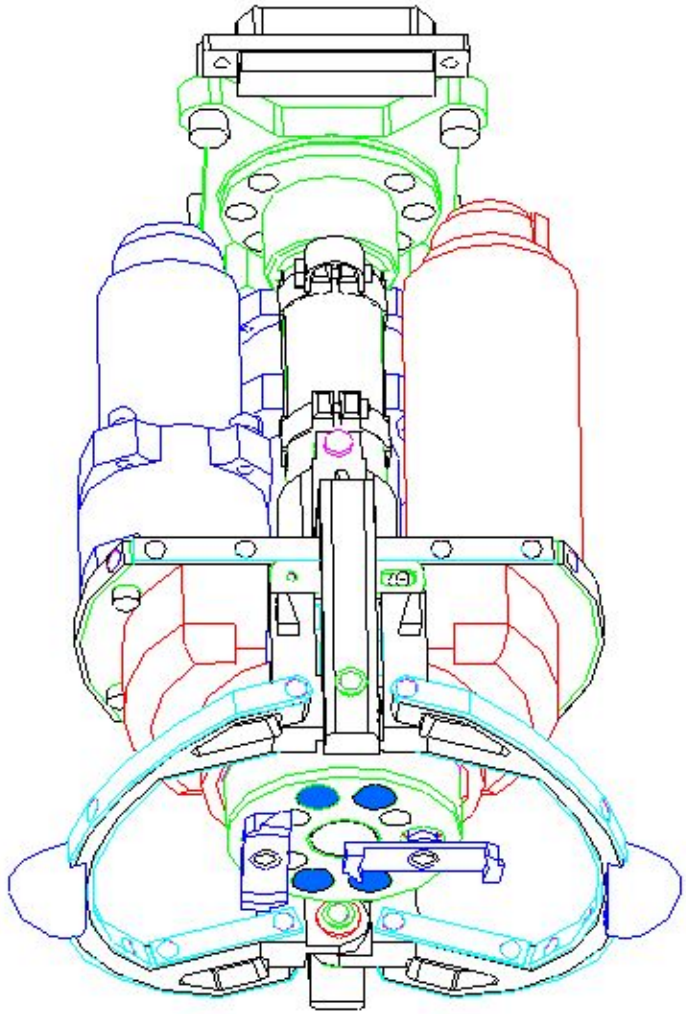
Instrument Deployment Device (IDD)



Rock Abrasion Tool

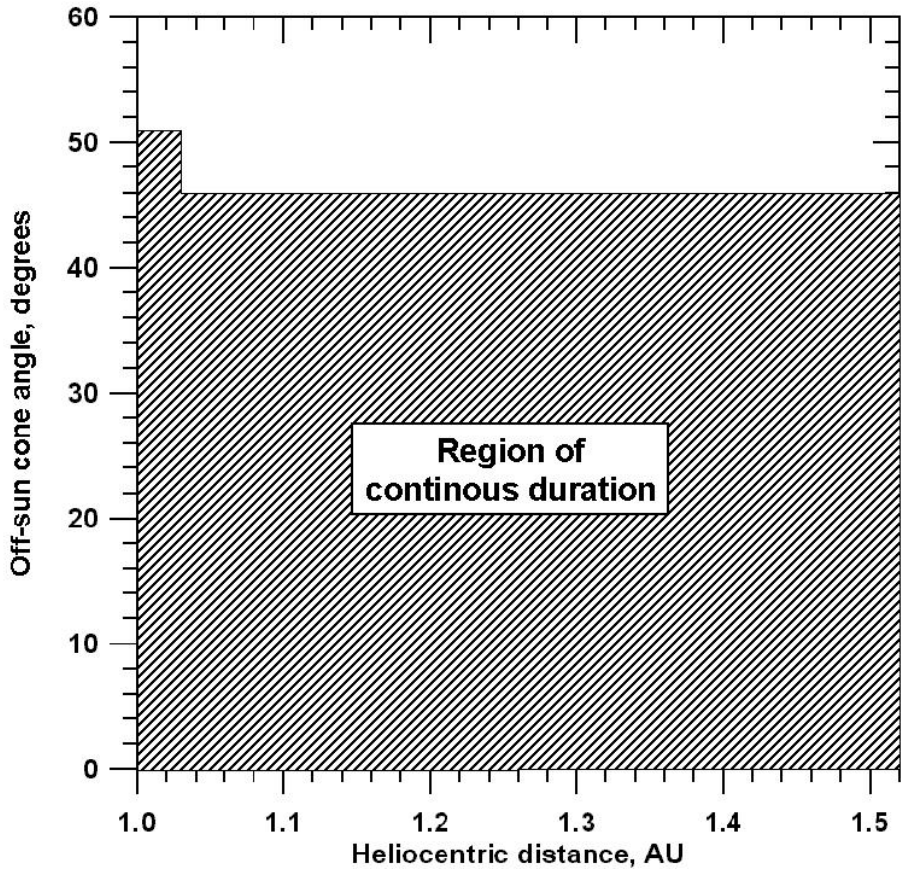
- **Rock Abrasion Tool (RAT)**
  - **Penetrates through dust & surface alteration that might be present on rocks, exposing materials more likely to preserve evidence of environmental conditions at the time of their formation**





Thermal Environment

- **Off-sun during cruise requirements:**
  - **Continuous: 0° to 51° off-sun cone angle**
    - **Launch to Launch + 21 days: up to 51°**
    - **Launch + 22 day to Mars turn-to-Entry: 0° to 46°**
  - **Transient off-sun cone angles & durations**
    - **TCM1: 90° for up to 110 minutes at 1.02 AU**
    - **Mars turn-to-Entry: 83° for up to 70 minutes**



Thermal Environment (cont'd)

- **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/m^2**
  - **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**
    - Tighest 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**

Key Driving Level 3 Requirements (cont'd)

- **Surface communication requirements:**
  - **2 hours of continuous DTE operation per Sol and up to 3 total hours per Sol**

DOORS ID	*Requirement*	*Status*
888	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	Comply by design & analysis

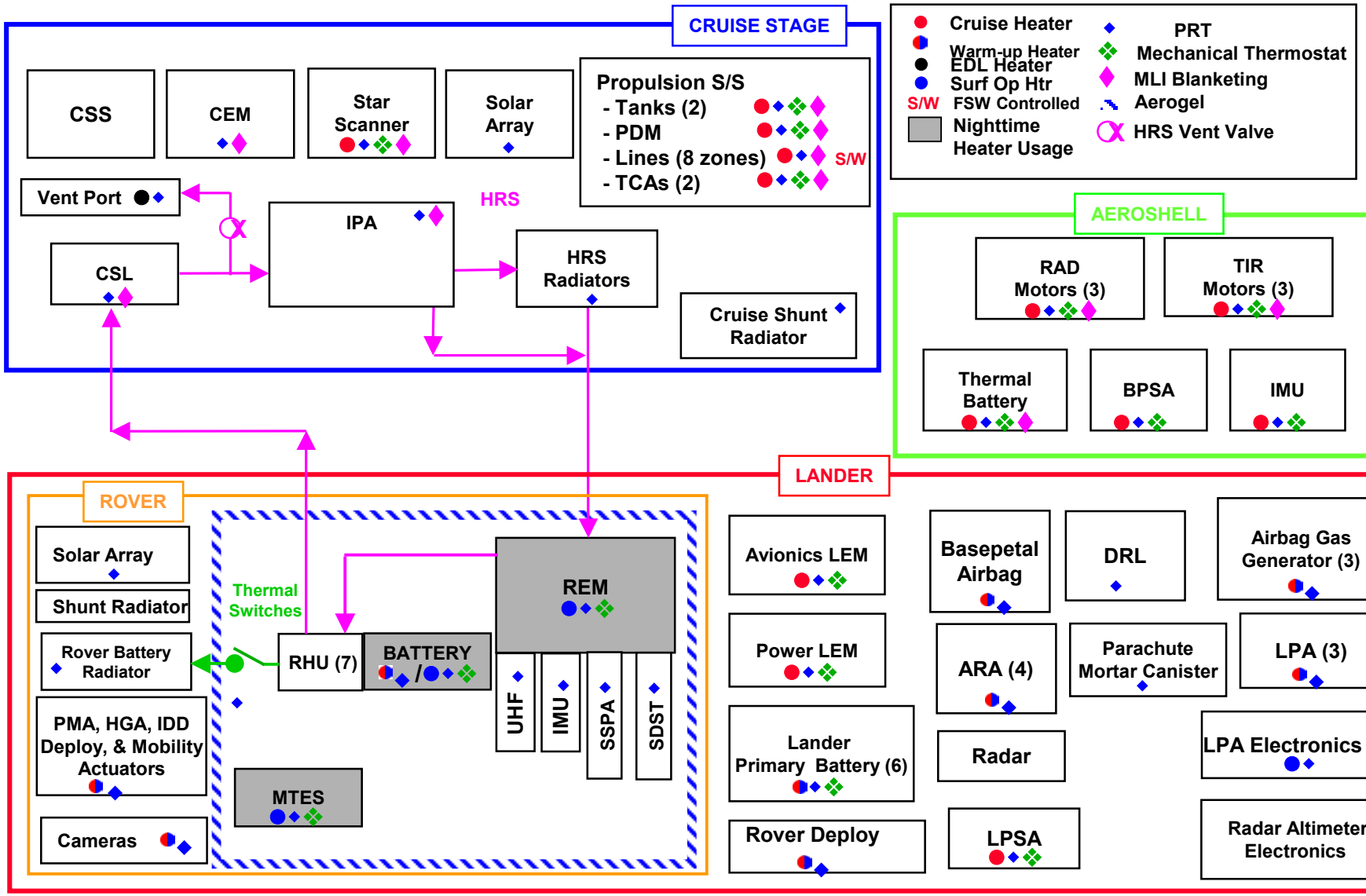
  - **Capability to operate the HGA actuators at 10 am Mars local time without additional warm-up heater**

DOORS ID	*Requirement*	*Status*
607	The Flight System shall be capable of operating the HGA actuators at 10 am Mars local time without additional warmup.	Comply by design & analysis

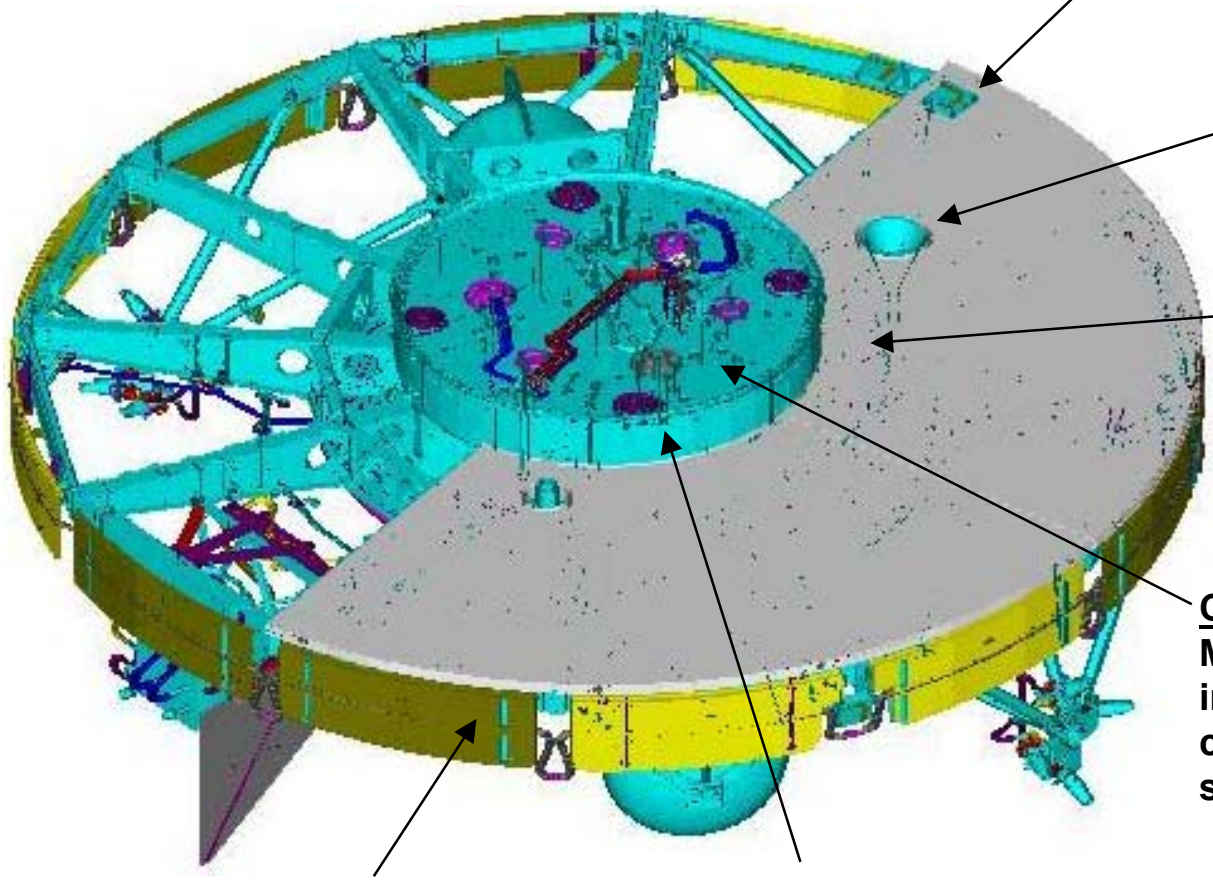
Blue text denotes changes from Project PDR

System Thermal Block Diagram

Mars Exploration Rover



Cruise Stage Thermal Design Overview



Sun Sensors:
Ag/FEP tape on top

MGA:
S13-GLO (white) paint on back

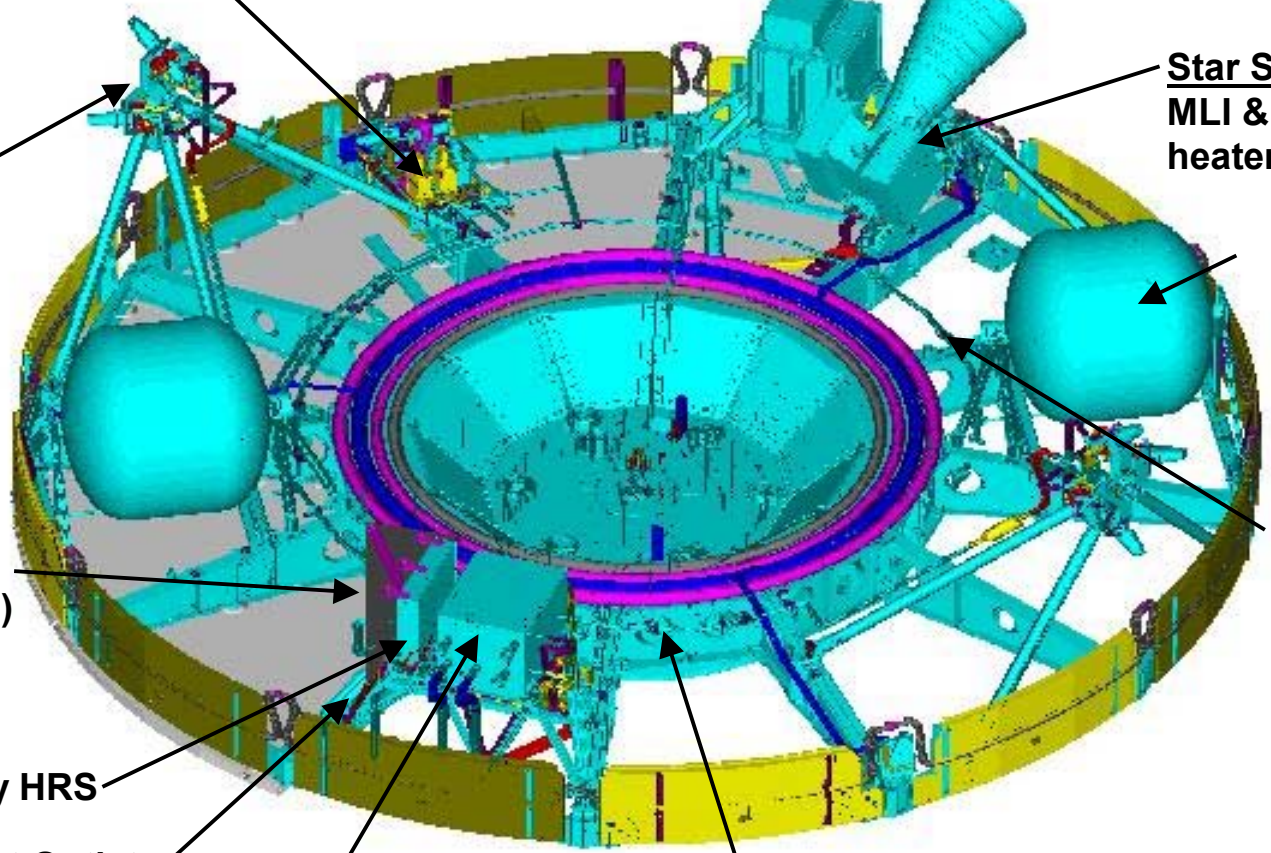
Solar Array:
Ag/FEP tape on inner ring, S13-GLO (white) paint on substrate backside

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

Cruise Stage Thermal Design Overview (cont'd)



PDM: MLI & thermostatic heaters

Sun Sensor Elect.: MLI & Outward Ag/FEP Radiator

CEM: MLI & Outward Ag/FEP Radiator

Star Scanner: MLI & thermostatic heater

TCAs: MLI & thermostatic heaters

Propellant Tanks: MLI & thermostatic heaters

Propellant Lines: MLI, aluminum cladding, thermostatic FSW heater control for 8 zones

CSL Radiator: S13-GLO (white) paint

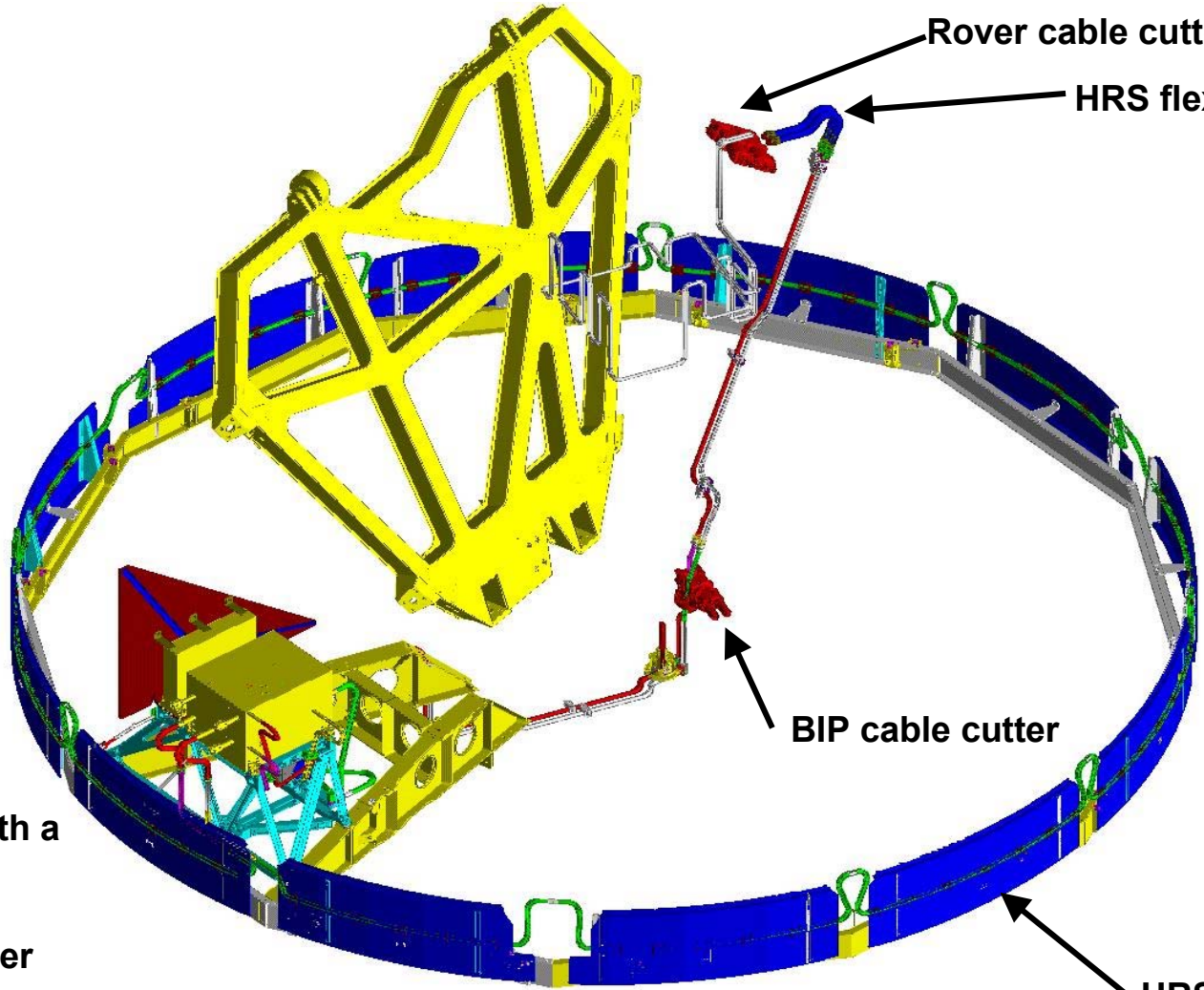
CSL: Controlled by HRS

HRS Vent Outlet: Warm-up heater

IPA: MLI & HRS

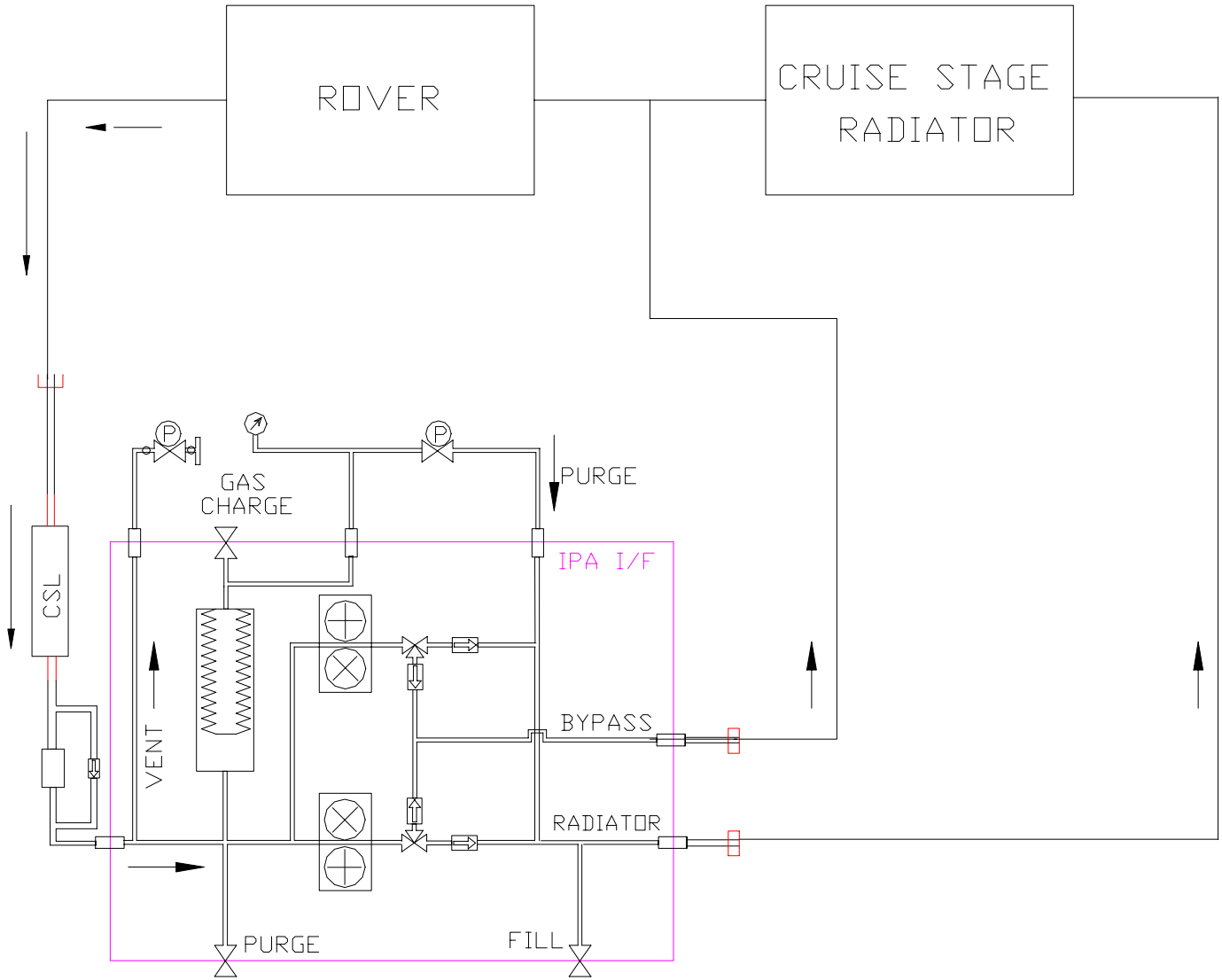
Intercostals: S13-GLO (white) white paint

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

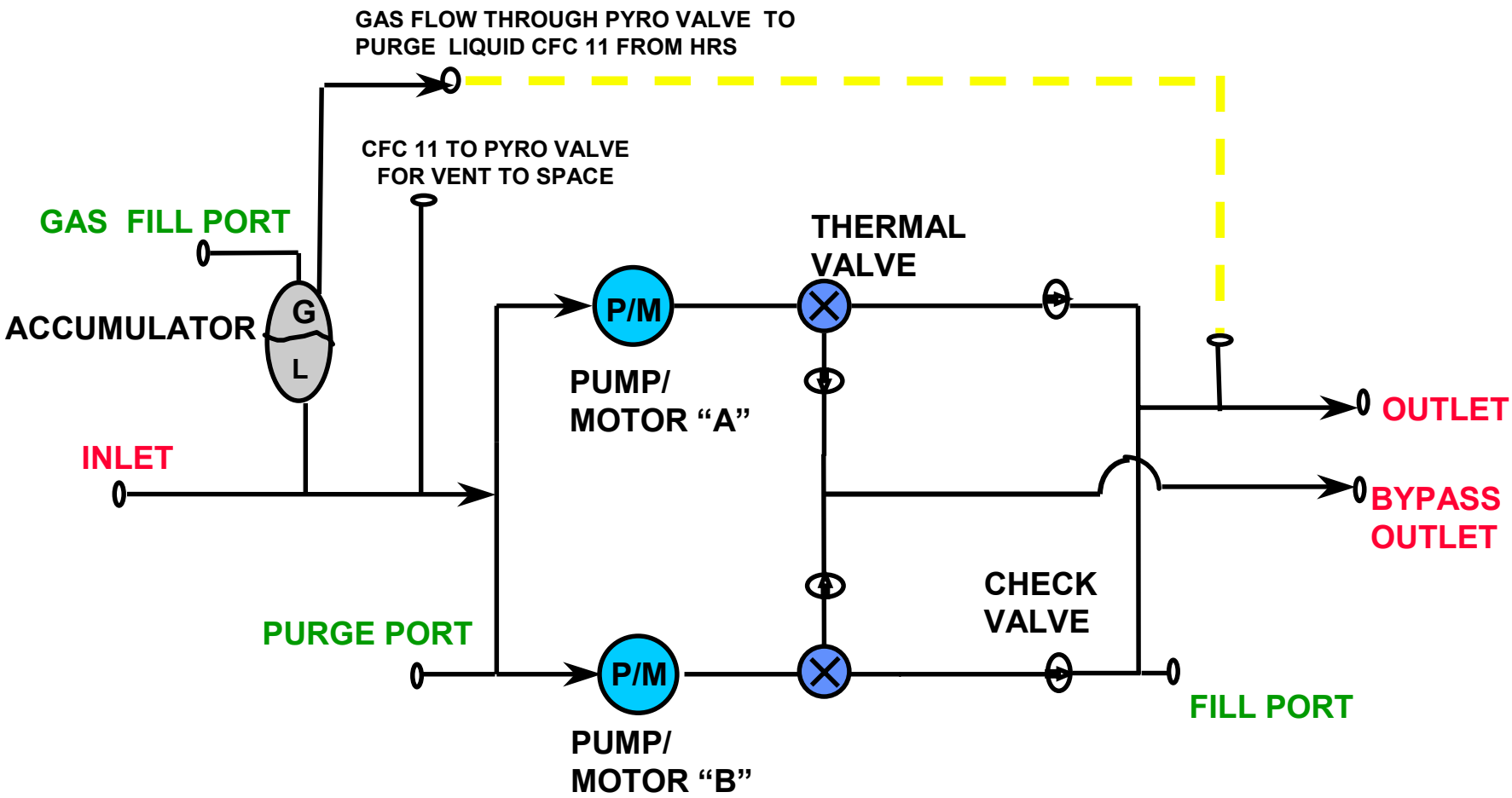
HRS Schematic



Integrated Pump Assembly

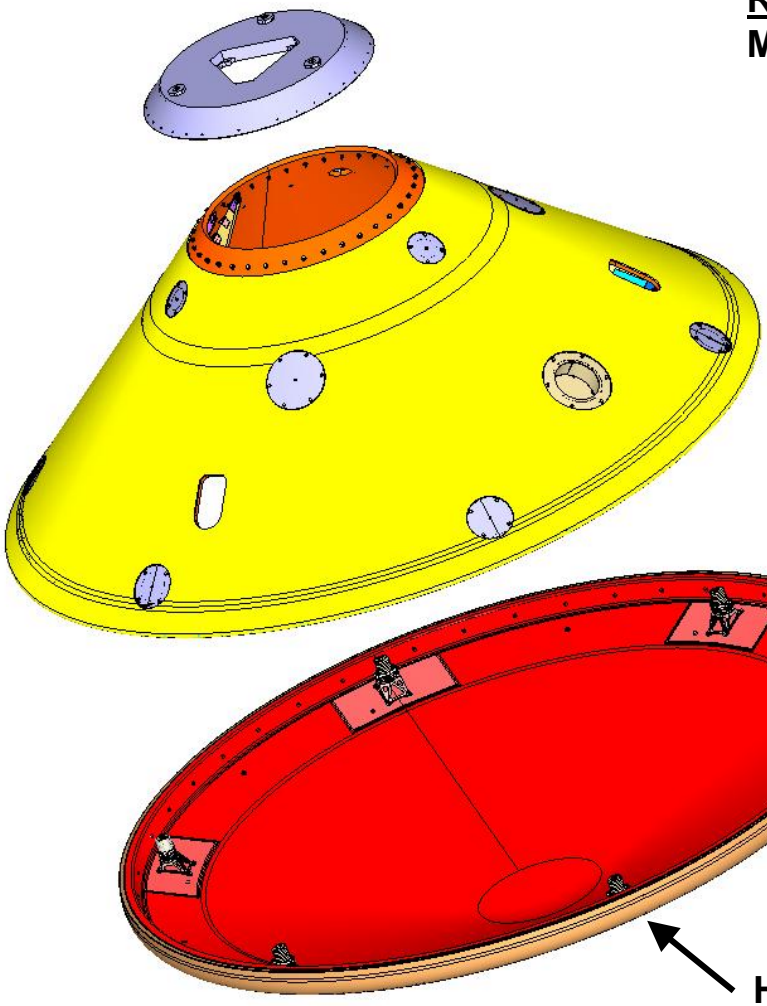
- **Mars Pathfinder IPA shown**
- **MER adopted a Mars Pathfinder build-to-print approach for the IPA**

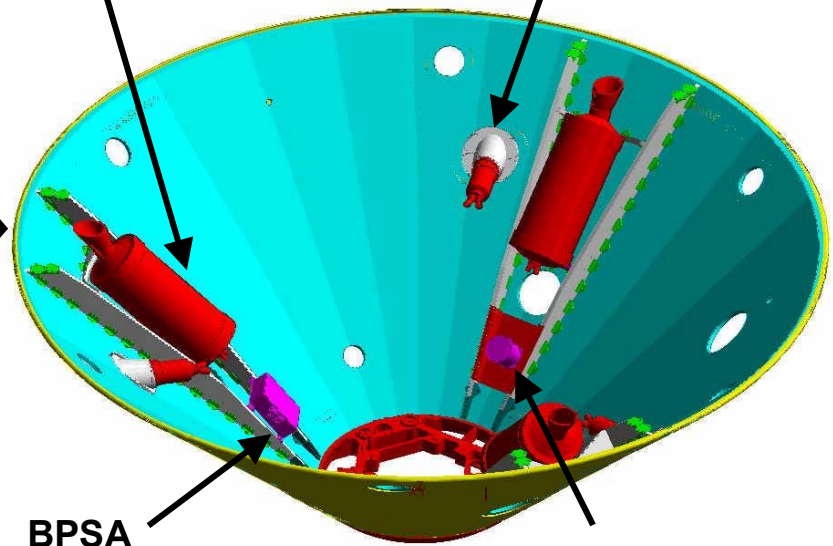
IPA Schematic



Aeroshell Thermal Design Overview

Mars Exploration Rover





RAD Motors (3)
MLI & thermostatic heaters

TIRS Motors (3)
MLI & thermostatic heaters

BPSA
Thermostatic heaters
High ε finish

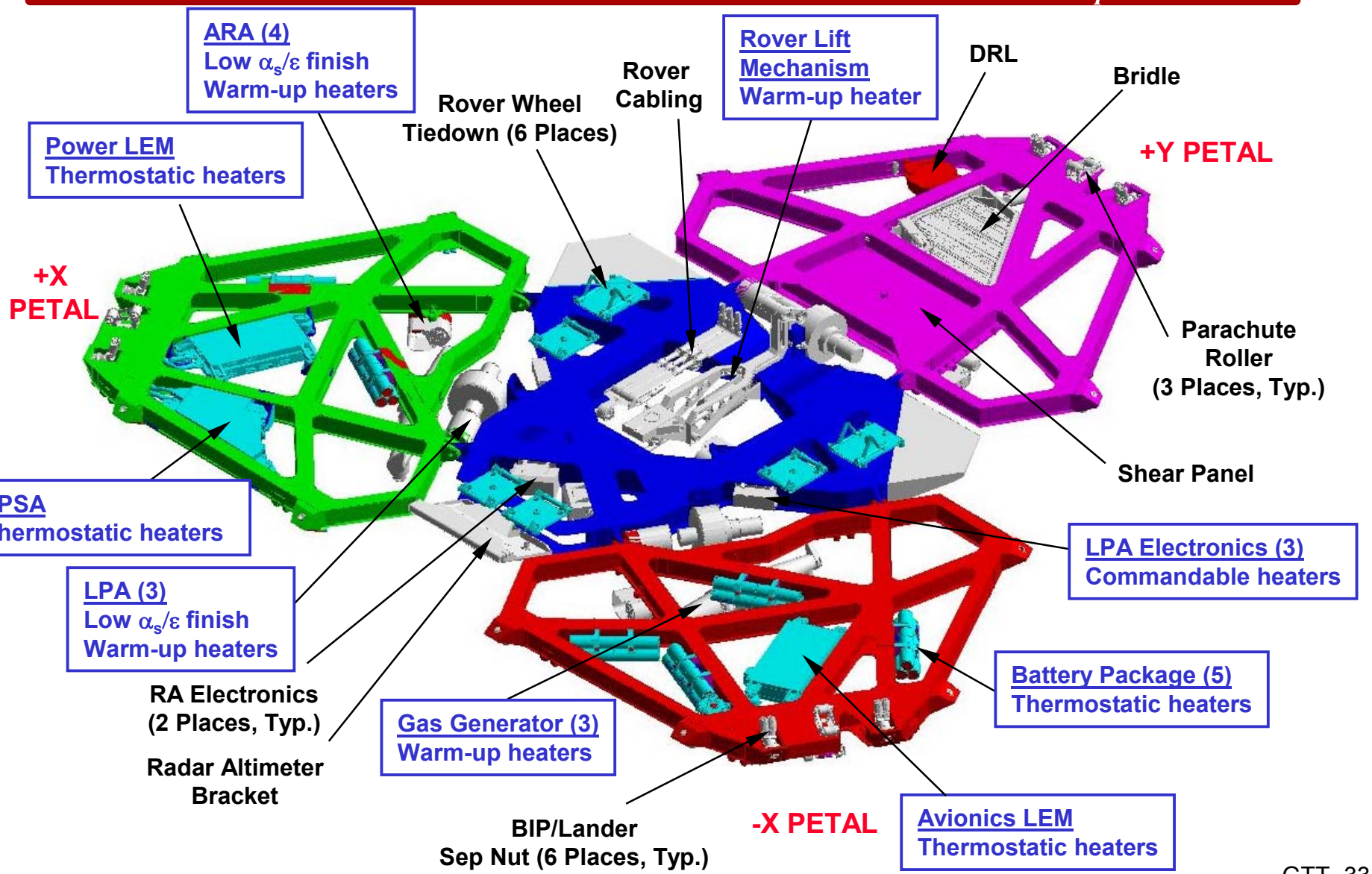
BS IMU
Thermostatic heaters
Mounting plate mass

Thermal Battery (hidden)
MLI & thermostatic heaters

Heat Shield
Interior MLI
Exterior radiation shield

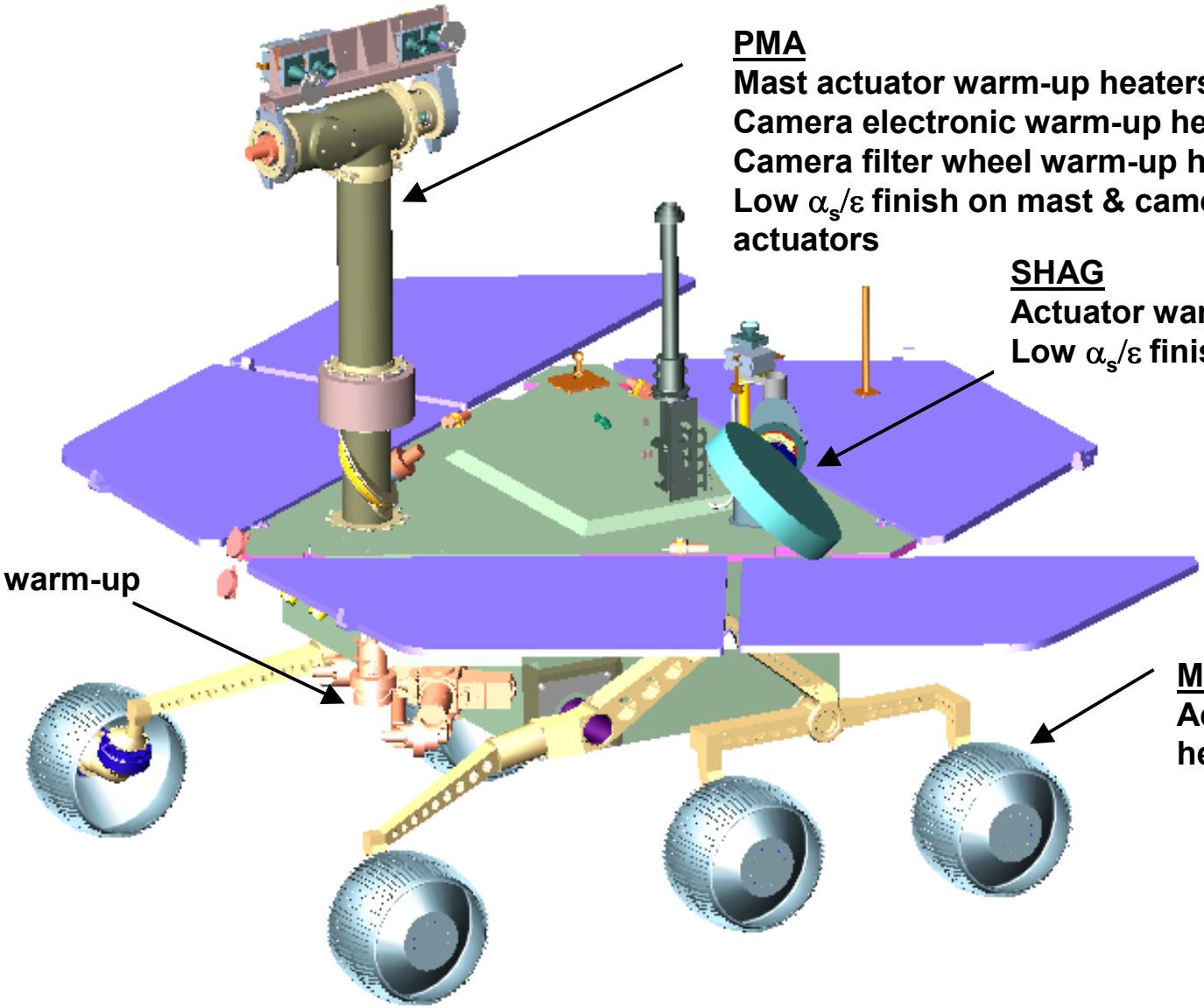
Lander Thermal Design Overview

Mars Exploration Rover



Rover Thermal Design Overview

Mars Exploration Rover



PMA
Mast actuator warm-up heaters
Camera electronic warm-up heaters
Camera filter wheel warm-up heaters
Low α_s/ε finish on mast & camera actuators

SHAG
Actuator warm-up heater
Low α_s/ε finish on actuator

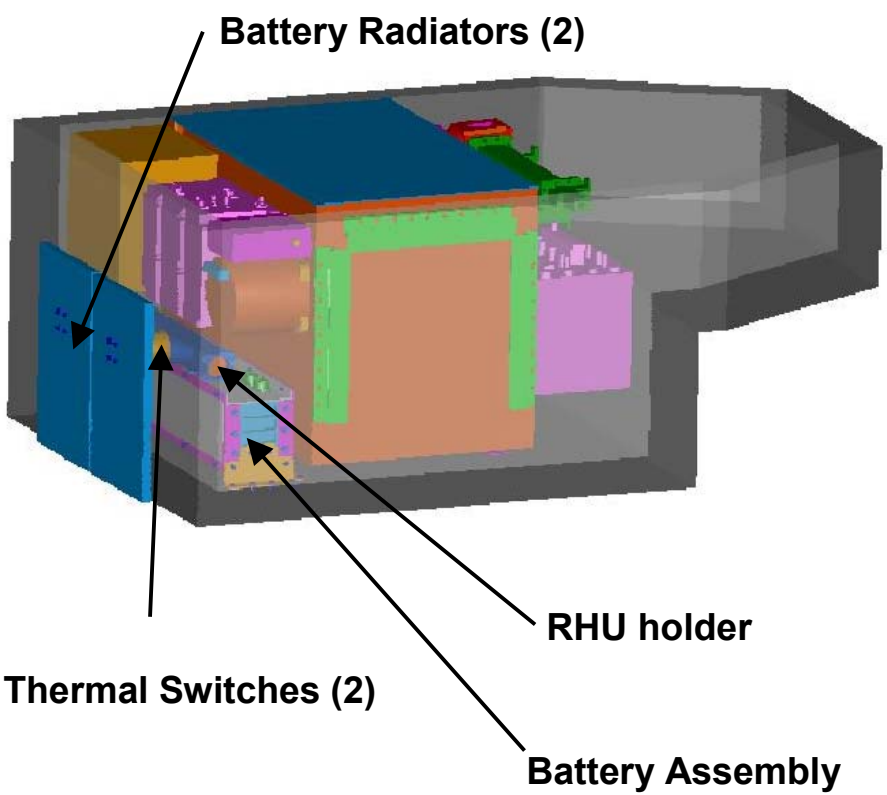
IDD
Actuator warm-up heaters

Mobility
Actuator warm-up heaters

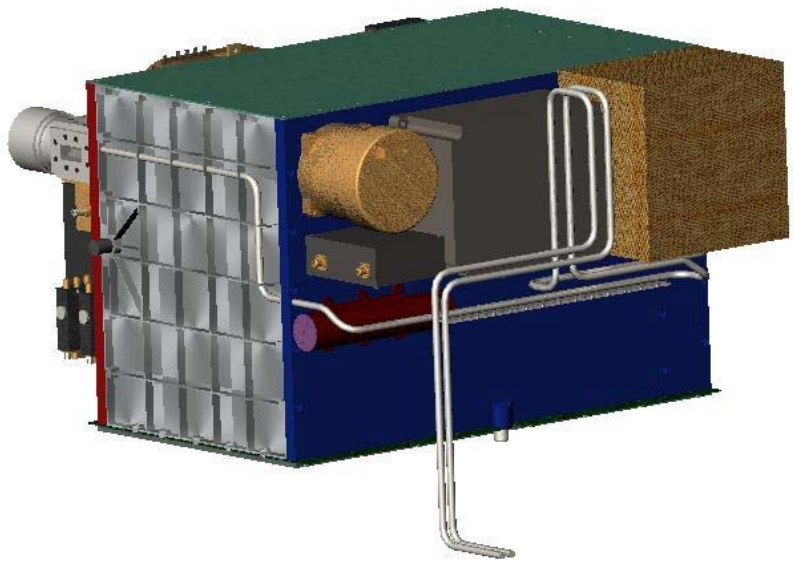
Rover Thermal Design Overview (cont'd)

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

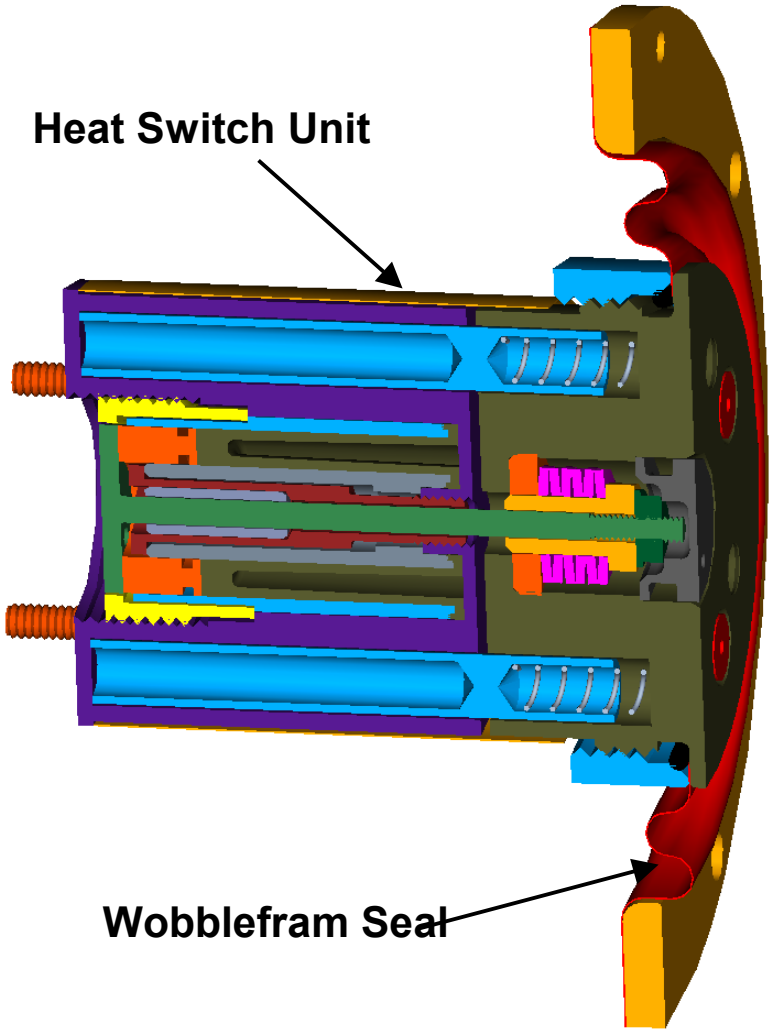


HRS tubing on REM



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

Mars Exploration Rover

	TEMPERATURE (°C)											
	ALLOWABLE FLIGHT				PREDICTED FLIGHT				Margin			
	OP		NOP		OP		NOP		OP		NOP	
	min	max	min	max	min	max	min	max	min	max	min	max
CRUISE STAGE												
Cruise Solar Array average	-50	90	-70	110	-17	71	n/a	n/a	33	18	n/a	n/a
Cruise Shunt Limiter Assembly	-25	40	n/a	50	-12	2	n/a	n/a	12	38	n/a	n/a
Propellant Tanks (includes gas service valves)	15	30	15	30	23	23	n/a	n/a	8	6	n/a	n/a
Tanks during ground operations	n/a	n/a	n/a	40			n/a	n/a			n/a	n/a
Thruster Valve, 1 lbf	20	110	20	50	24	24	n/a	n/a	4	26	n/a	n/a
PDM	15	50	15	50	23	23	n/a	n/a	8	26	n/a	n/a
service valve outside PDM make it a unit	n/a	n/a	n/a	n/a			n/a	n/a			n/a	n/a
filter	n/a	n/a	n/a	n/a			n/a	n/a			n/a	n/a
latch valve	n/a	n/a	n/a	n/a			n/a	n/a			n/a	n/a
pressure transducer	n/a	n/a	n/a	n/a			n/a	n/a			n/a	n/a
CEM Assembly	-40	50	-40	50	3	22	n/a	n/a	43	27	n/a	n/a
Star Scanner head & electronics	-14	**50**	n/a	n/a	0	27	n/a	n/a	14	23	n/a	n/a
Sun Sensor electronics	-30	50	n/a	n/a	3	22	n/a	n/a	32	28	n/a	n/a
Sun Sensor Heads (2 on -Z, 3 on X/Y)	-25	85	n/a	n/a	-3/-22	28/67	n/a	n/a	22/3	53/18	n/a	n/a
5/8" Ti Bolt, Bushing & Sep. Spring	-60	60	-60	60	-20	51	n/a	n/a	40	8	n/a	n/a
IPA	-20	40	-20	40	-3	6	n/a	n/a	16	34	n/a	n/a
IPA electronics	-20	50	-20	50	-3	6	n/a	n/a	16	44	n/a	n/a
Pyro valve-HRS purge	-30	66	-30	66	-3	6	n/a	n/a	26	60	n/a	n/a
HRS radiator	-90	n/a	n/a	n/a	-40/-65	-7/-16	n/a	n/a	50/24	n/a	n/a	n/a
Cruise Shunt Radiator	-40	100	-40	100	-14	67	n/a	n/a	25	33	n/a	n/a
LVA	n/a	n/a	n/a	n/a	-20	51	n/a	n/a	n/a	n/a	n/a	n/a

Cruise Thermal Analysis - Aeroshell

Mars Exploration Rover

	TEMPERATURE (°C)											
	ALLOWABLE FLIGHT				PREDICTED FLIGHT				Margin			
	OP		NOP		OP		NOP		OP		NOP	
	min	max	min	max	min	max	min	max	min	max	min	max
AEROSHELL												
BIP:					n/a	n/a	-34	9	n/a	n/a	n/a	n/a
5/8" Cable Cutter (BIP)	-100	30	-100	60	n/a	n/a	-34	9	n/a	n/a	65	50
1" Cable Cutter in (BIP)	-100	30	-100	60	n/a	n/a	-34	9	n/a	n/a	65	50
5/8" Pyro Sep Nut, Cruise Stage Sep. (BIP)	-100	30	-100	60	n/a	n/a	-34	9	n/a	n/a	65	50
Parachute Canister & Mortar	-45	45	-45	45	n/a	n/a	-35	9	n/a	n/a	10	36
Backshell:												
BS Thermal Batteries	-40	35	-40	35	n/a	n/a	-29	6	n/a	n/a	11	29
Backshell Pyro Switch Assembly (BPSA)	-40	50	-40	50	n/a	n/a	-29	0	n/a	n/a	11	50
IMU-Litton LN 200S (Rover & Backshell)	-39	51	-47	65	n/a	n/a	-29	-1	n/a	n/a	18	66
3/8" Pyro Sep Nut, B/S side	-120	30	-120	60	n/a	n/a	-94	3	n/a	n/a	26	56
3/8" Ti Bolt & Sep Mech. (LMA Supplied)	-120	30	-120	60	n/a	n/a	-94	3	n/a	n/a	26	56
RAD Rockets	-40	-20	-40	40	n/a	n/a	-24	2	n/a	n/a	16	38
TIRS Motors	-40	-20	-40	40	n/a	n/a	-24	5	n/a	n/a	16	35
Backshell-outer surface (TPS)	-150	n/a	-150	n/a	n/a	n/a	-36/-97	-6/10	n/a	n/a	114/53	n/a
Backshell-Bond line	-100	150	-100	150	n/a	n/a	-35/-95	-4/7	n/a	n/a	64/5	154/143
Heatshield:												
Heatshield-outer surface (SLA561)	-150	n/a	-150	n/a	n/a	n/a	-81	-7	n/a	n/a	69	n/a
Heatshield-Bond line	-150	250	-150	250	n/a	n/a	-81	-6	n/a	n/a	69	256

Cruise Thermal Analysis - Lander

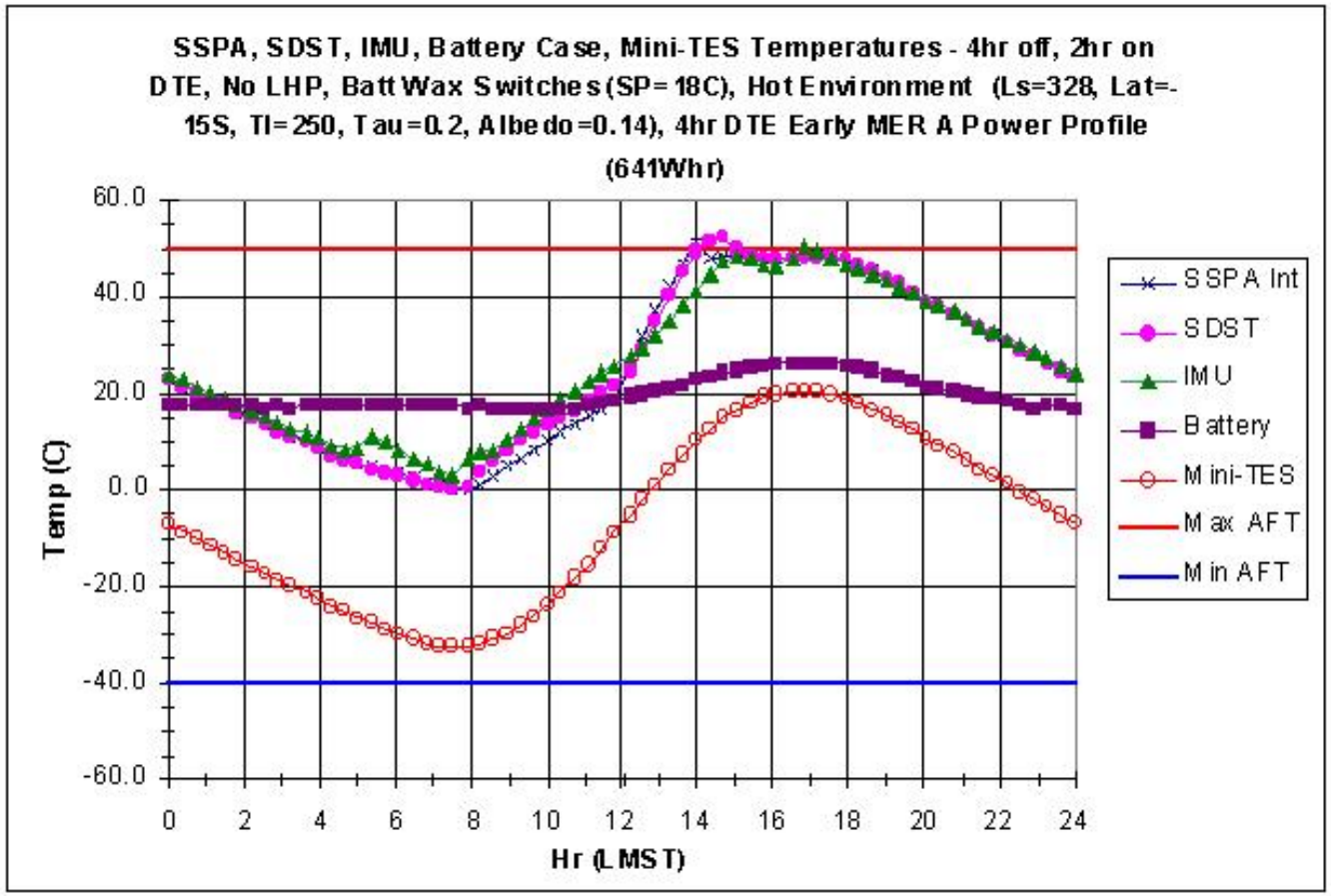
Mars Exploration Rover

	TEMPERATURE (°C)											
	ALLOWABLE FLIGHT				PREDICTED FLIGHT				Margin			
	OP		NOP		OP		NOP		OP		NOP	
	min	max	min	max	min	max	min	max	min	max	min	max
LANDER												
Descent antenna	-110	45	-110	45	n/a/	n/a	-38	4	n/a/	n/a	72	41
Radar Altimeter X-mit Antennas	-85	45	-85	45	n/a/	n/a	-38	4	n/a/	n/a	47	41
Radar Altimeter Rec Antennas	-85	45	-85	45	n/a/	n/a	-38	4	n/a/	n/a	47	41
Radar Altimeter electronics	-40	40	-40	40	n/a/	n/a	-38	4	n/a/	n/a	2	36
Coax tansfer switch (CxS4)	-35	50	-35	50	n/a/	n/a	-39	4	n/a/	n/a	-4	45
Lander Primary Battery (LiSO2)												
Cruise (non-op)	n/a	n/a	-40	10	n/a/	n/a	-38	5	n/a/	n/a	2	5
Lander Pyro Switch Assembly (LPSA)	-50	50	-50	50	n/a/	n/a	-38	5	n/a/	n/a	12	45
Power-LEM Assembly	-40	50	-50	50	n/a/	n/a	-37	4	n/a/	n/a	13	46
Avionics-LEM Assembly	-40	50	-50	50	n/a/	n/a	-38	5	n/a/	n/a	12	45
3/8" Release Nuts	-120	30	-120	60	n/a/	n/a	-35	9	n/a/	n/a	85	51
5/8"Lander Cable Cutter	-105	30	-105	60	n/a/	n/a	-35	9	n/a/	n/a	70	51
1" Cable Cutter w/HRS on Base Petal	-105	30	-105	60	n/a/	n/a	-38	4	n/a/	n/a	67	56
Lander Petal Actuator (+Y, +X, -X)	-45	15	-105	40	n/a/	n/a	-39	4	n/a/	n/a	66	36
Airbag Retraction Actuator (+Y, +X, -X, basepetal	-45	15	-105	40	n/a/	n/a	-38	5	n/a/	n/a	67	35
Rover Deploy (lift) Actuator Assembly	-45	15	-105	40	n/a/	n/a	-38	4	n/a/	n/a	67	36
Airbag material, cruise	n/a	n/a	-85	80	n/a/	n/a	-58	5	n/a/	n/a	27	75
Gas Generator (+Y, +X, -X)	-40	0	-50	50	n/a/	n/a	-39	-1	n/a/	n/a	11	51
Bridle cutter assy (B/S)	-120	30	-120	60	n/a/	n/a	-38	5	n/a/	n/a	82	55
Bridle Descent Rate Limiter	-55	30	-55	40	n/a/	n/a	-38	5	n/a/	n/a	17	35
Bridle Assy	-60	30	-60	40	n/a/	n/a	-38	5	n/a/	n/a	22	35
Lander Structure	-55	40	-55	40	n/a/	n/a	-39	9	n/a/	n/a	16	31

Cruise Thermal Analysis - Rover

	ALLOWABLE FLIGHT				PREDICTED FLIGHT				Margin			
	OP		NOP		OP		NOP		OP		NOP	
	min	max	min	max	min	max	min	max	min	max	min	max
ROVER												
SSPA	-25	50	-40	50	0	7	-9	-3	25	43	31	53
SDST	-25	50	-40	50	na	na	-3	3	na	na	37	47
UHF Transceiver	-40	55	-40	55	na	na	-4	3	na	na	36	52
Rover Solar Array (3J)	-125	90	-125	90	na	na	-37	5	na	na	88	85
Li-Ion Battery												
Cruise	-20	10	n/a	n/a	na	na	-8	-1	na	na	na	na
REM Assembly	-40	50	-40	50	-4	3	n/a	n/a	25	43	n/a	n/a
Web Structure												
WEB Bumper Limit Switches	-105	50	-105	50	na	na	-31	5	na	na	74	45
Solar Array Bumper Limit Switches	-105	50	-105	50	na	na	-31	5	na	na	74	45
RHU	-100	300	n/a	n/a	-31.0	5.0	n/a	n/a	25	43	n/a	n/a
SCIENCE												
Mini TES	-40	35	-40	45	na	na	-19	4	na	na	21	41
IMU-Litton LN 200S (Rover & Backshell)	-39	51	-47	65	na	na	11	17	na	na	58	48

Rover 2 Hour of Continuous DTE

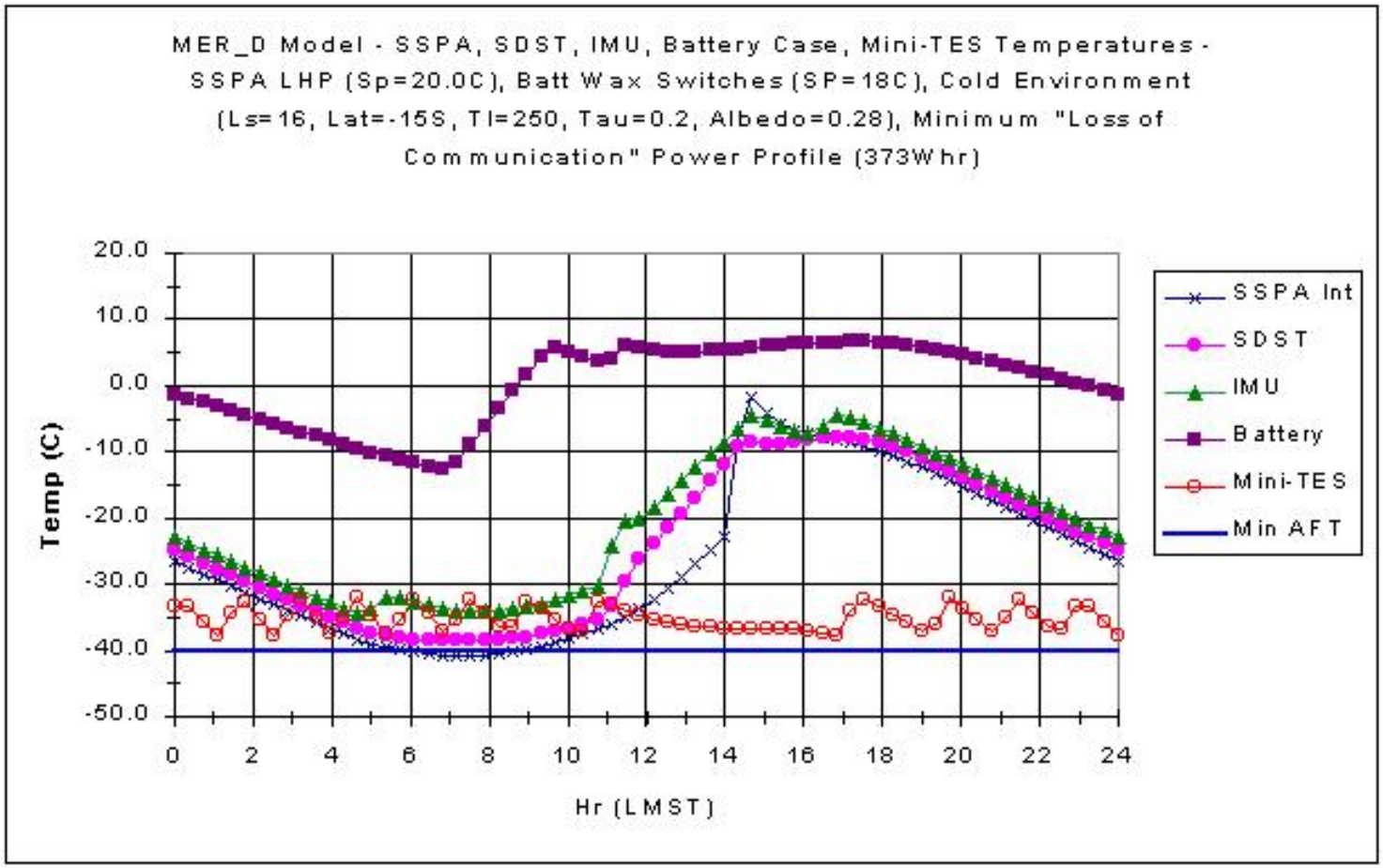


Max SSPA Interface Temp = 51°C

Max UHF Interface Temp = 52°C

Max Battery Temp = 26C

Rover Cold Surface Scenario



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**

Subsystem 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**

Issues & Concerns:
CEDL Design & Analysis

Issue/Concern	Resolution Plan
Difficult to quantify uncertain parameters for BS IMU thermal analysis. Absolute worst-case results only permit 60 minutes of operation	Review analysis & 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.

Issues & Concerns:
Thermal Testing

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