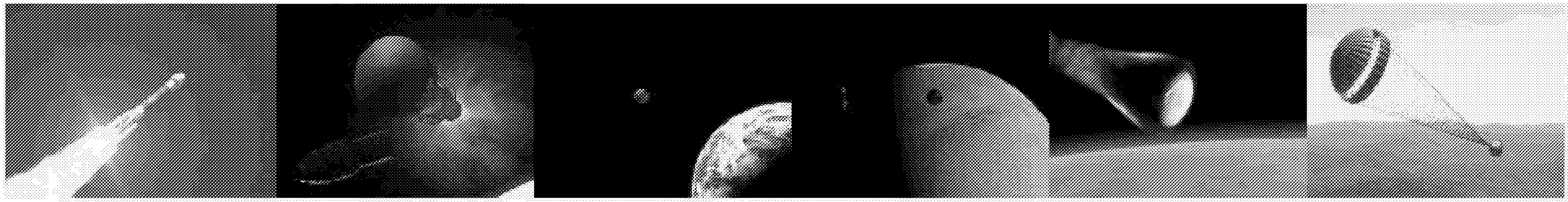


Thermal Design Overview of the Mars Exploration Rover Project

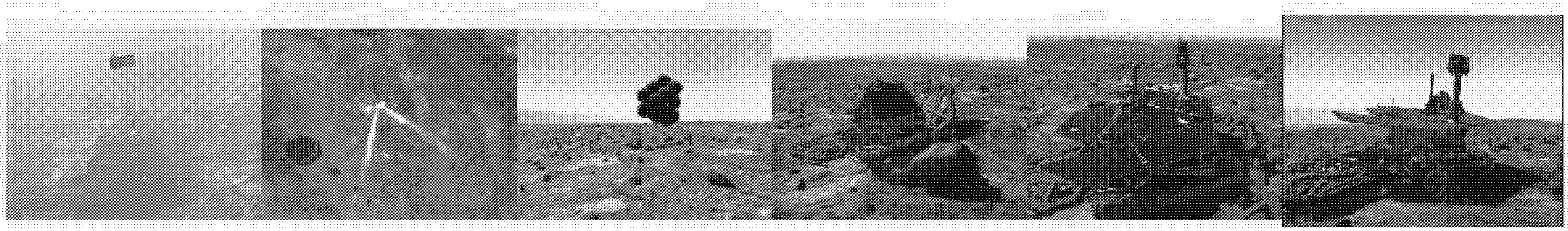
Glenn Tsuyuki

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, CA

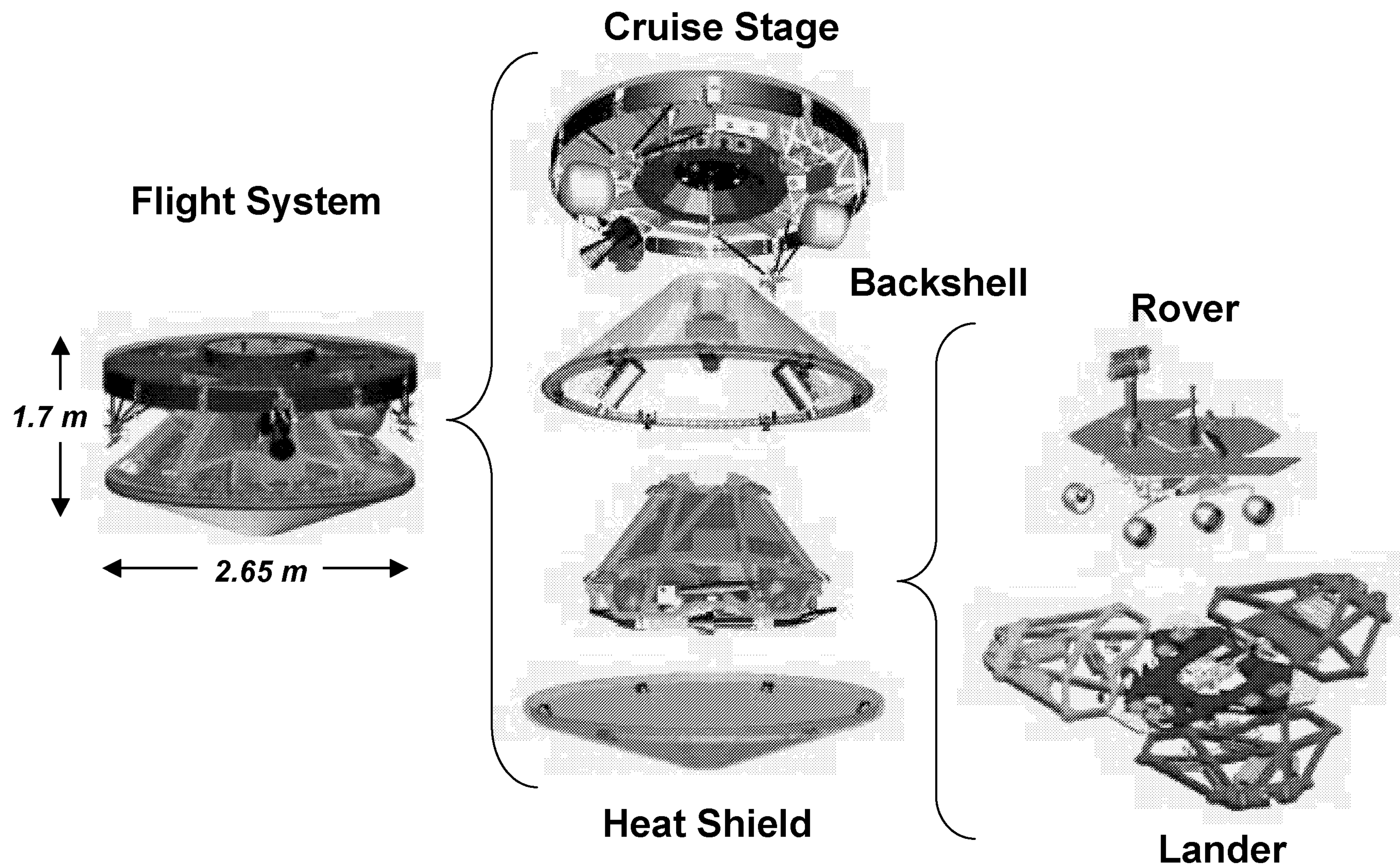
September 10, 2001



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



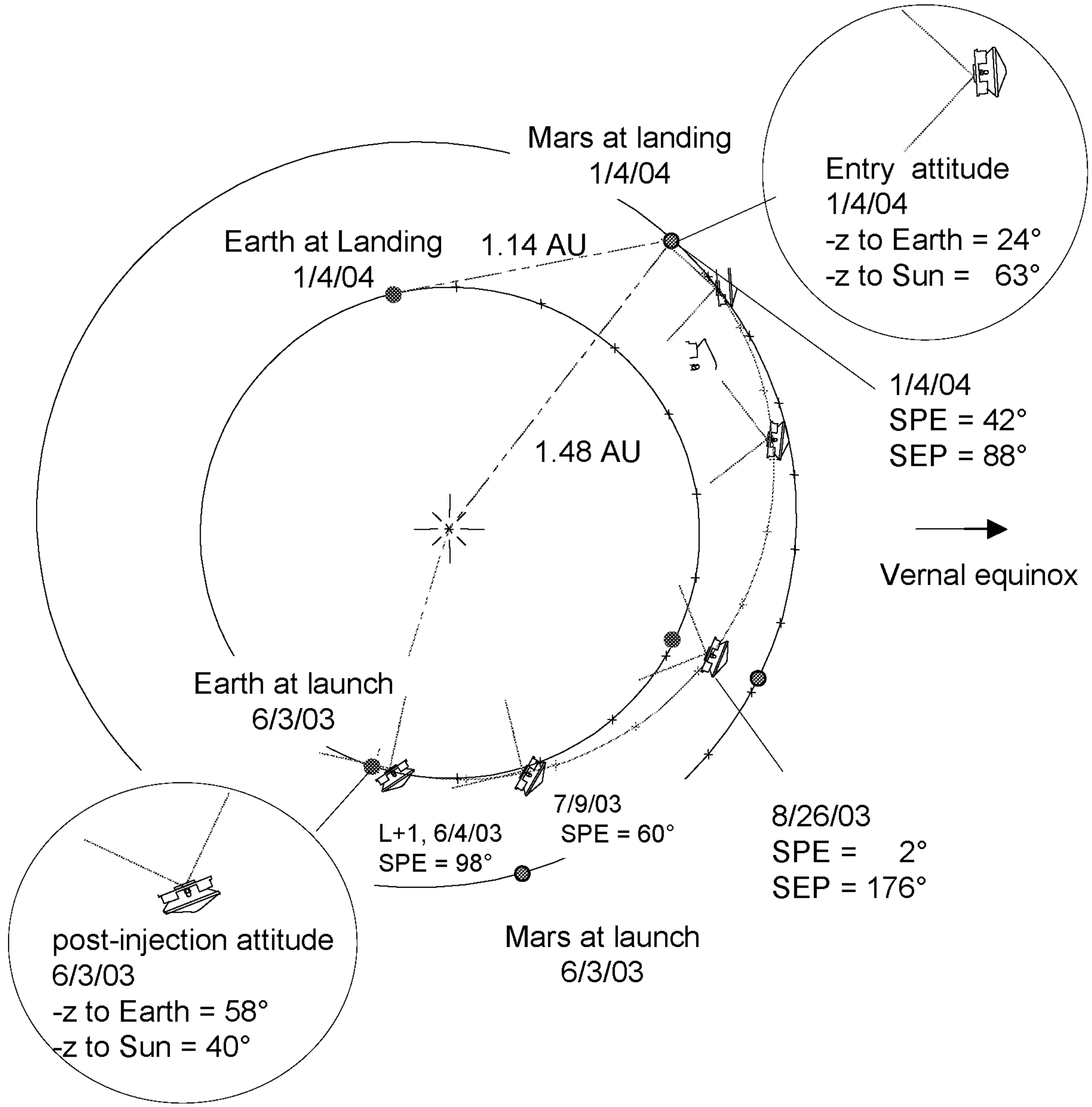
MER-A Cruise Scenario

Mars Exploration Rover

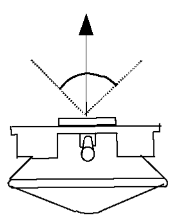
View from Ecliptic
North Pole
20 Day Tic Marks

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

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



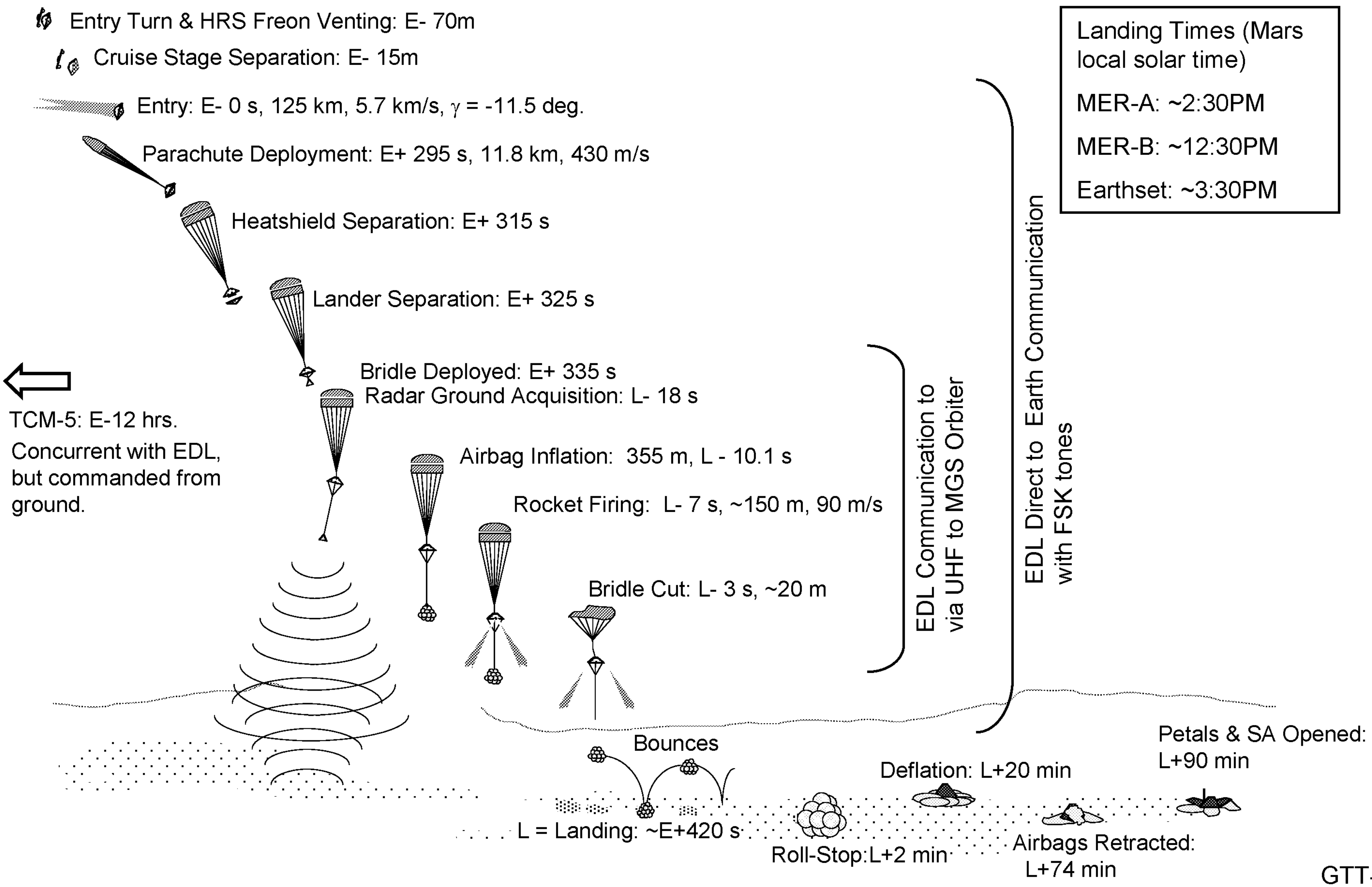
-z axis
- antenna boresight
- panel normal axis
- spin axis



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

Entry, Descent & Landing (EDL) Scenario

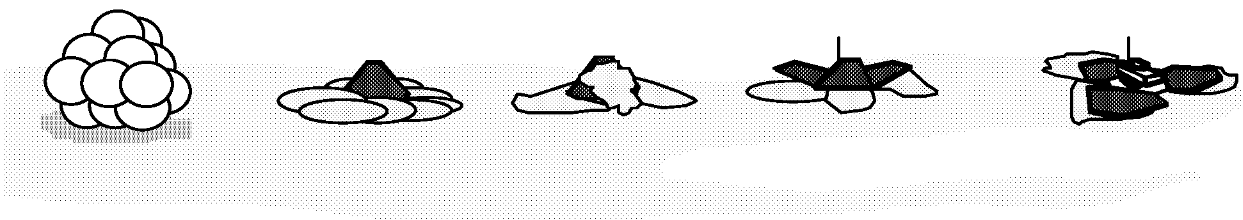
Mars Exploration Rover



Impact to Egress Scenario

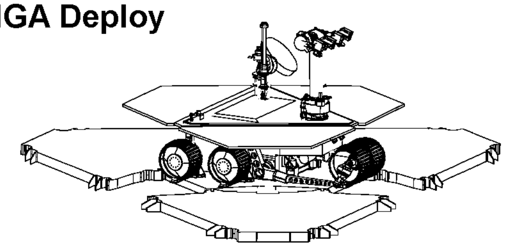
Mars Exploration Rover

Airbag Retraction / Petal Deploy / Egress Aid Deploy



Sol 1

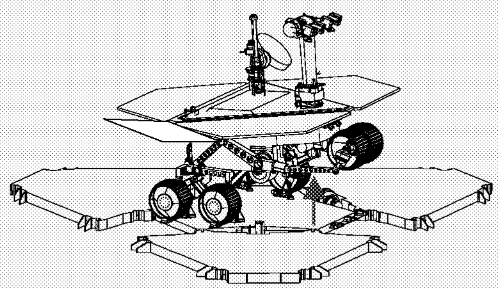
Solar Array Deploy
PMA Deploy & Imaging
HGA Deploy



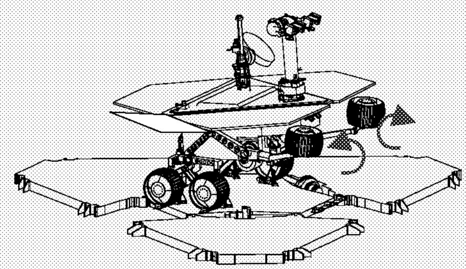
Sol 2-3

Petal / Airbag Adjustments
Pancam/Mini-TES

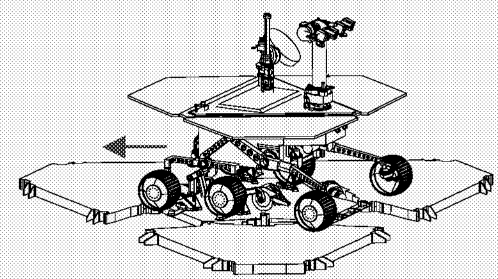
Lift Rover / Lock Rockers



Deploy Rockers

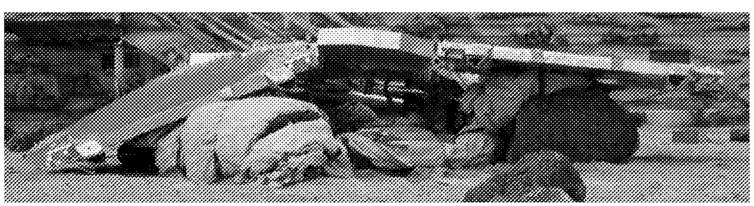


Lower Lift Mechanism & Deploy Bogies



Sol 4

Drive Petals to final Configuration

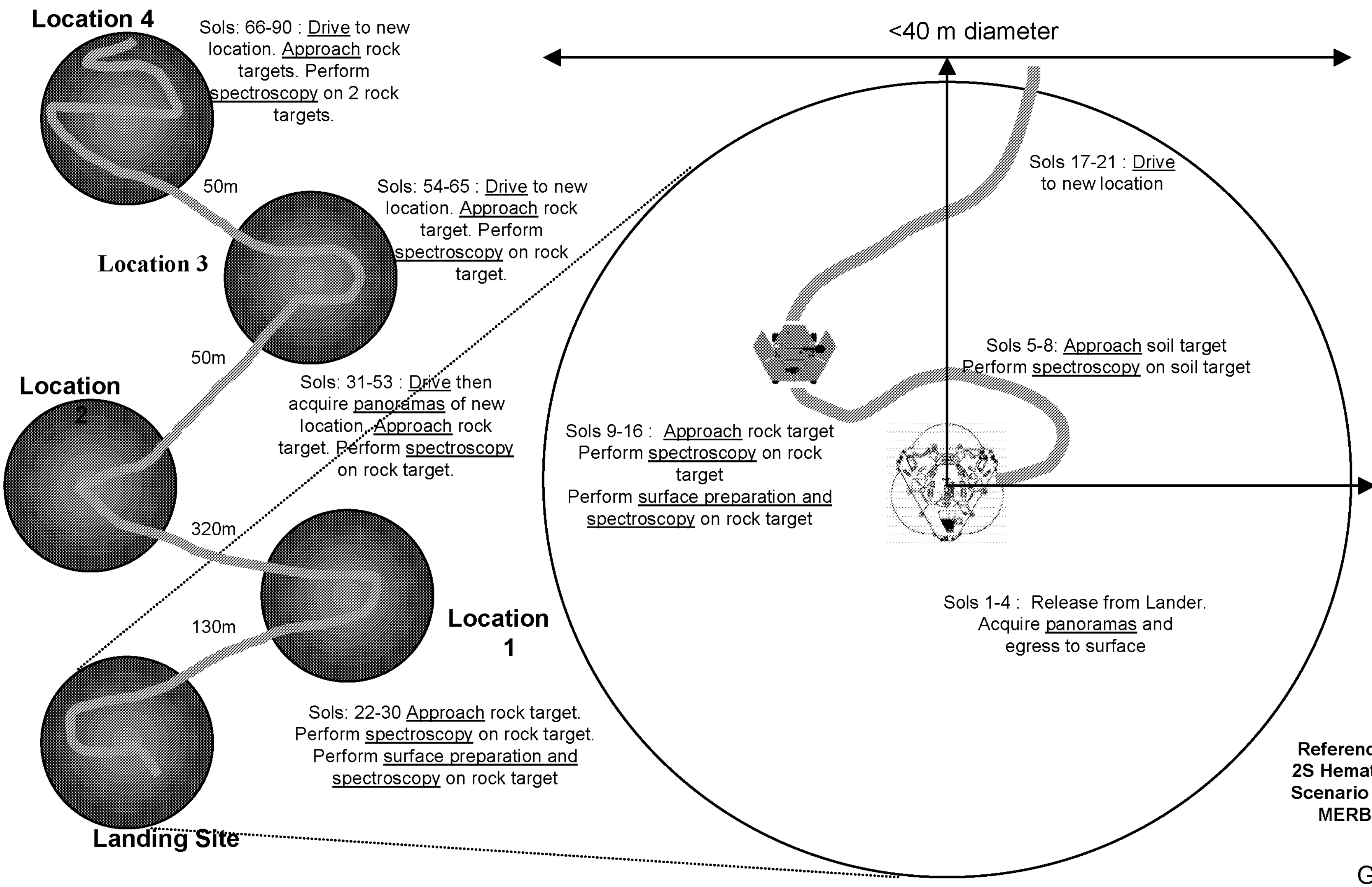


Release Middle Wheels & Fire 3rd Cable Cutter

Turn in Place

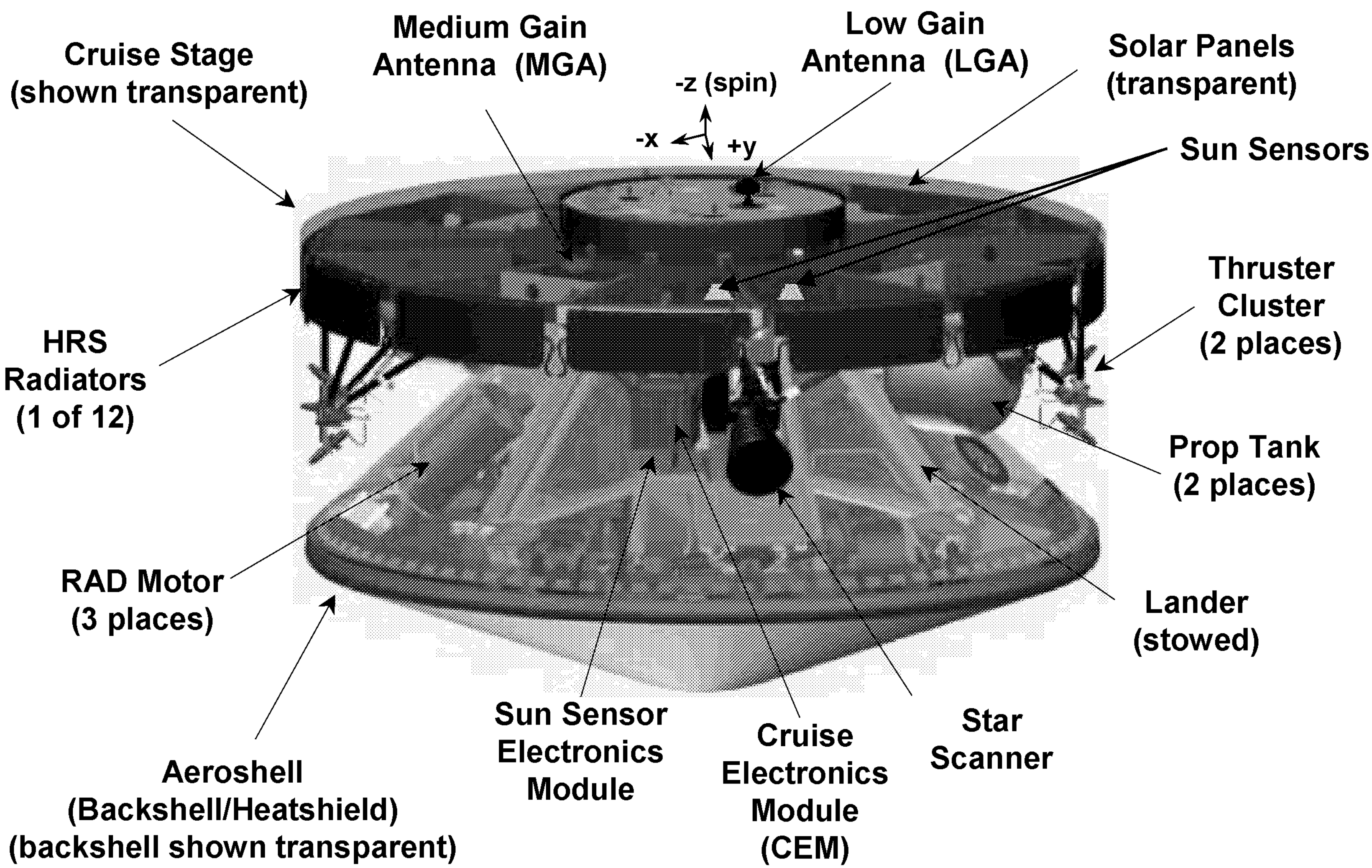
Drive Off Lander Deck

Surface Scenario



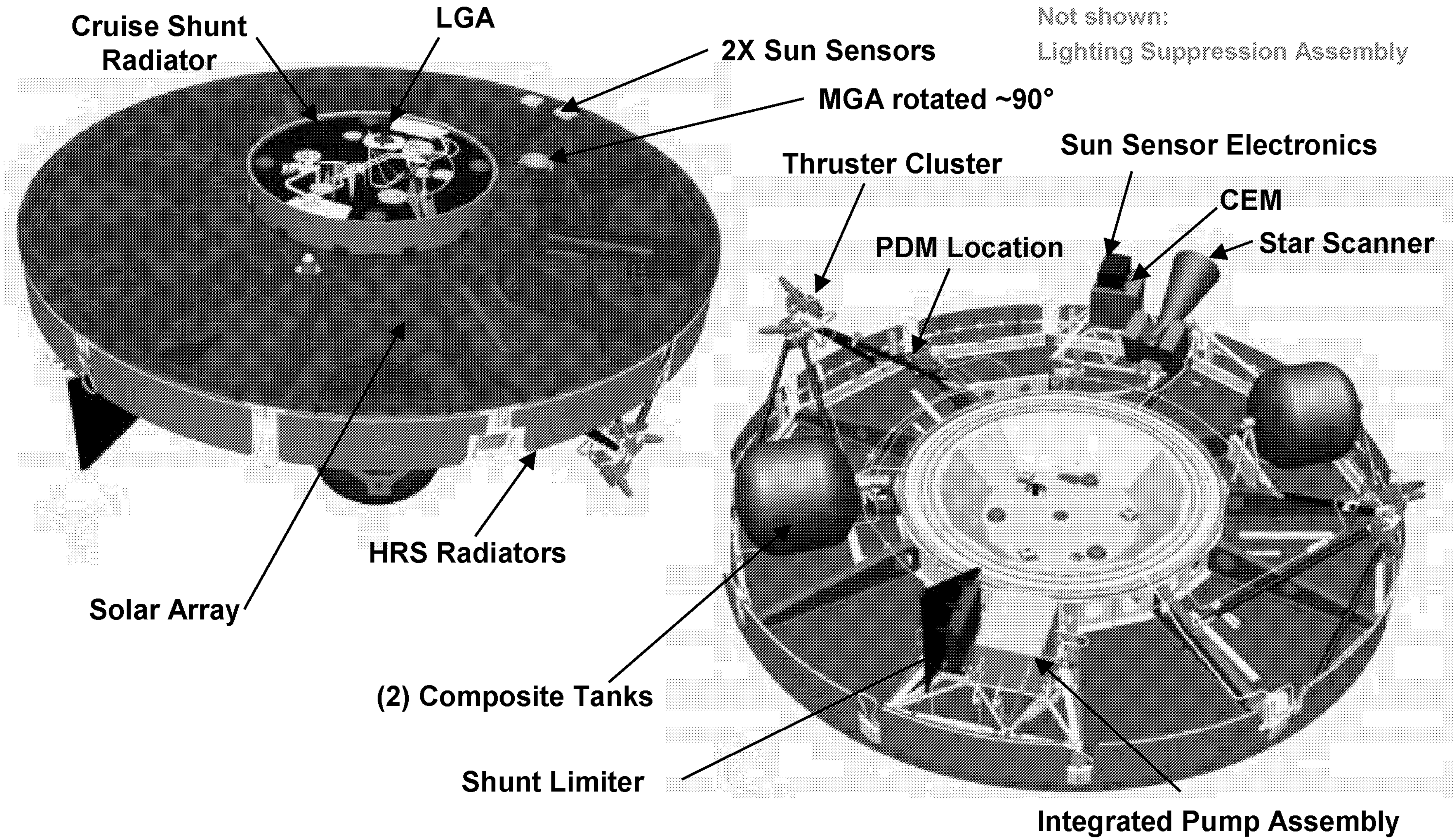
Reference: 2S Hematite Scenario for MERB

Spacecraft Cruise Configuration

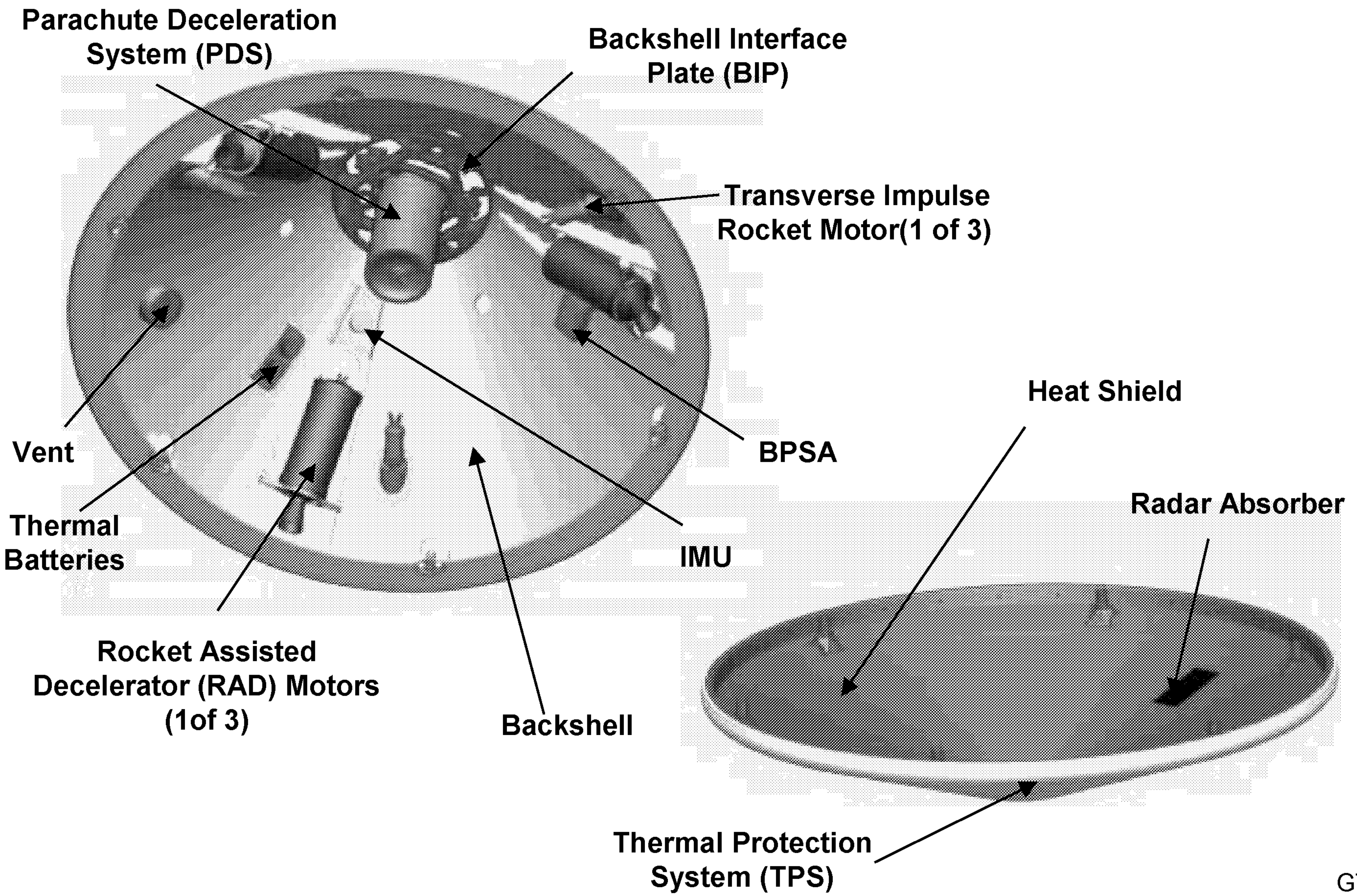


Cruise Stage Configuration

Not shown:
Lighting Suppression Assembly

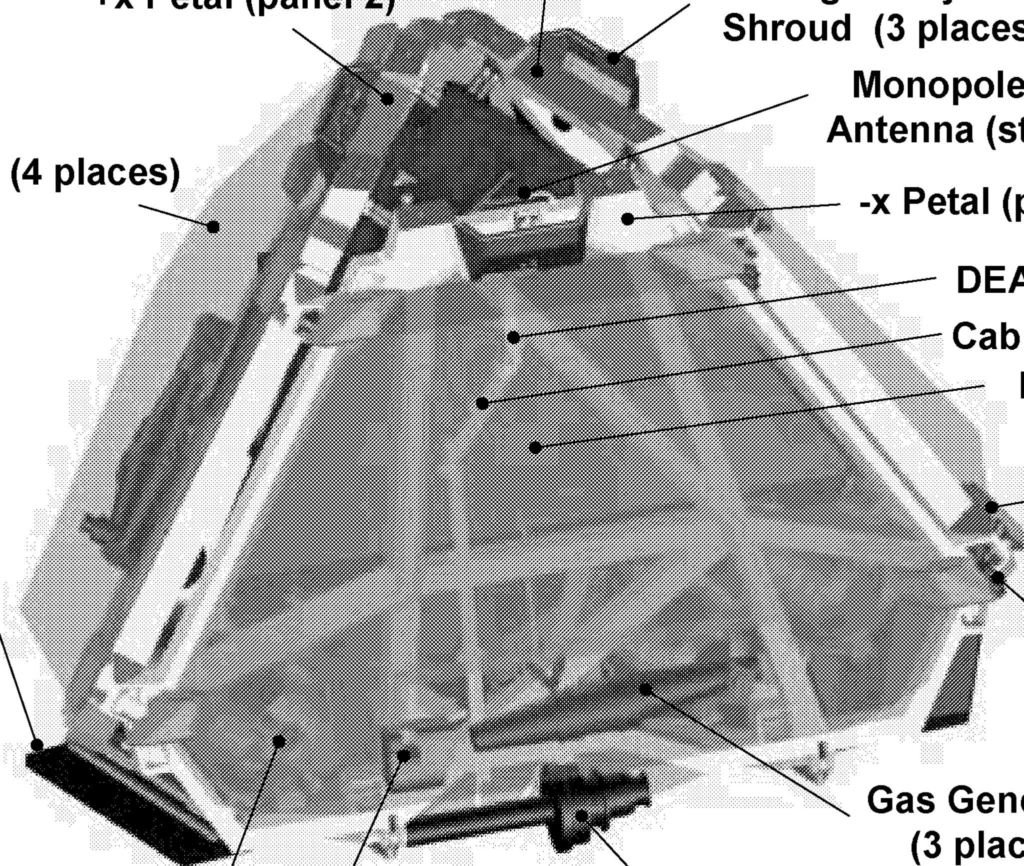


Aeroshell Configuration



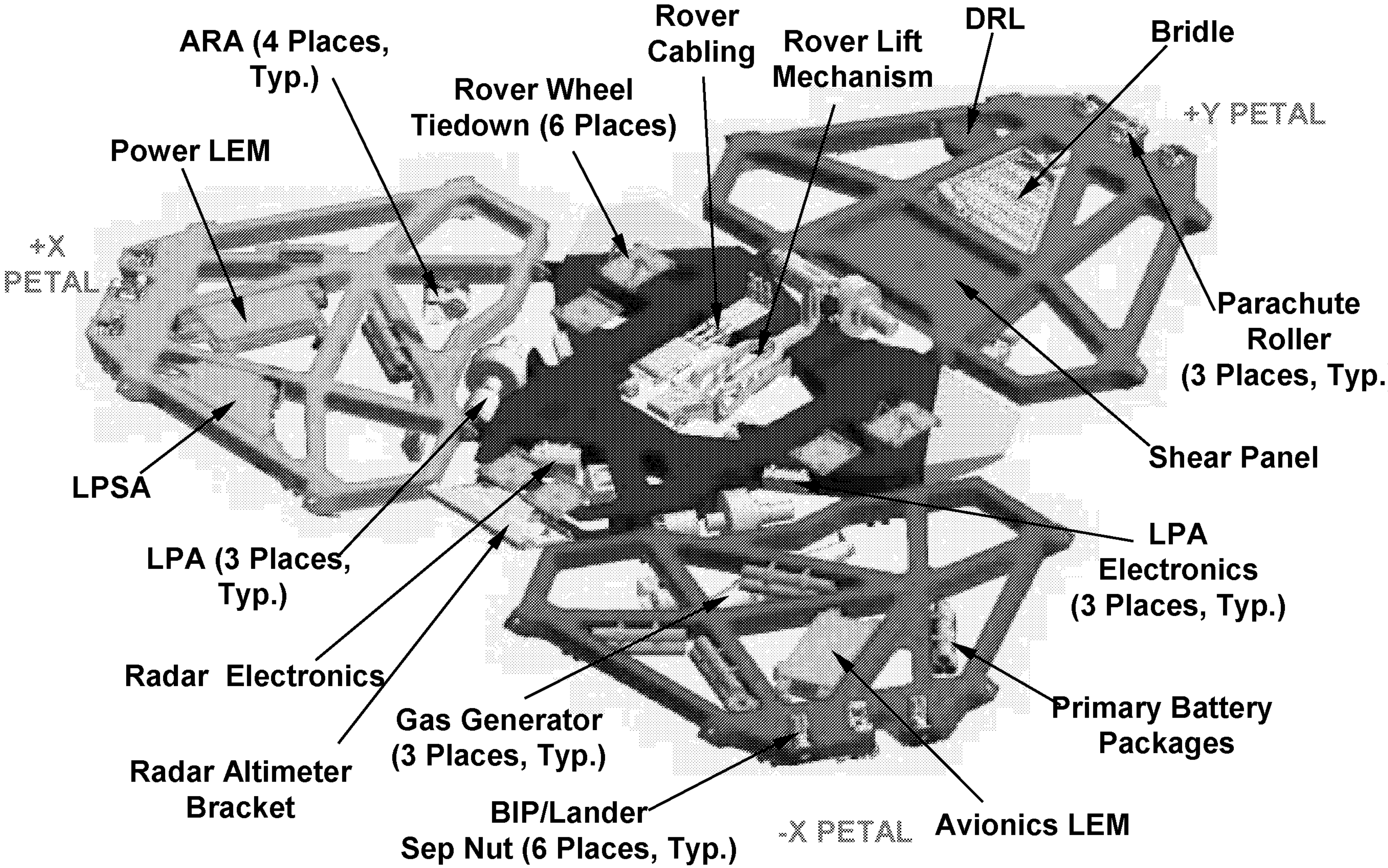
Lander Assembly - Stowed

Mars Exploration Rover

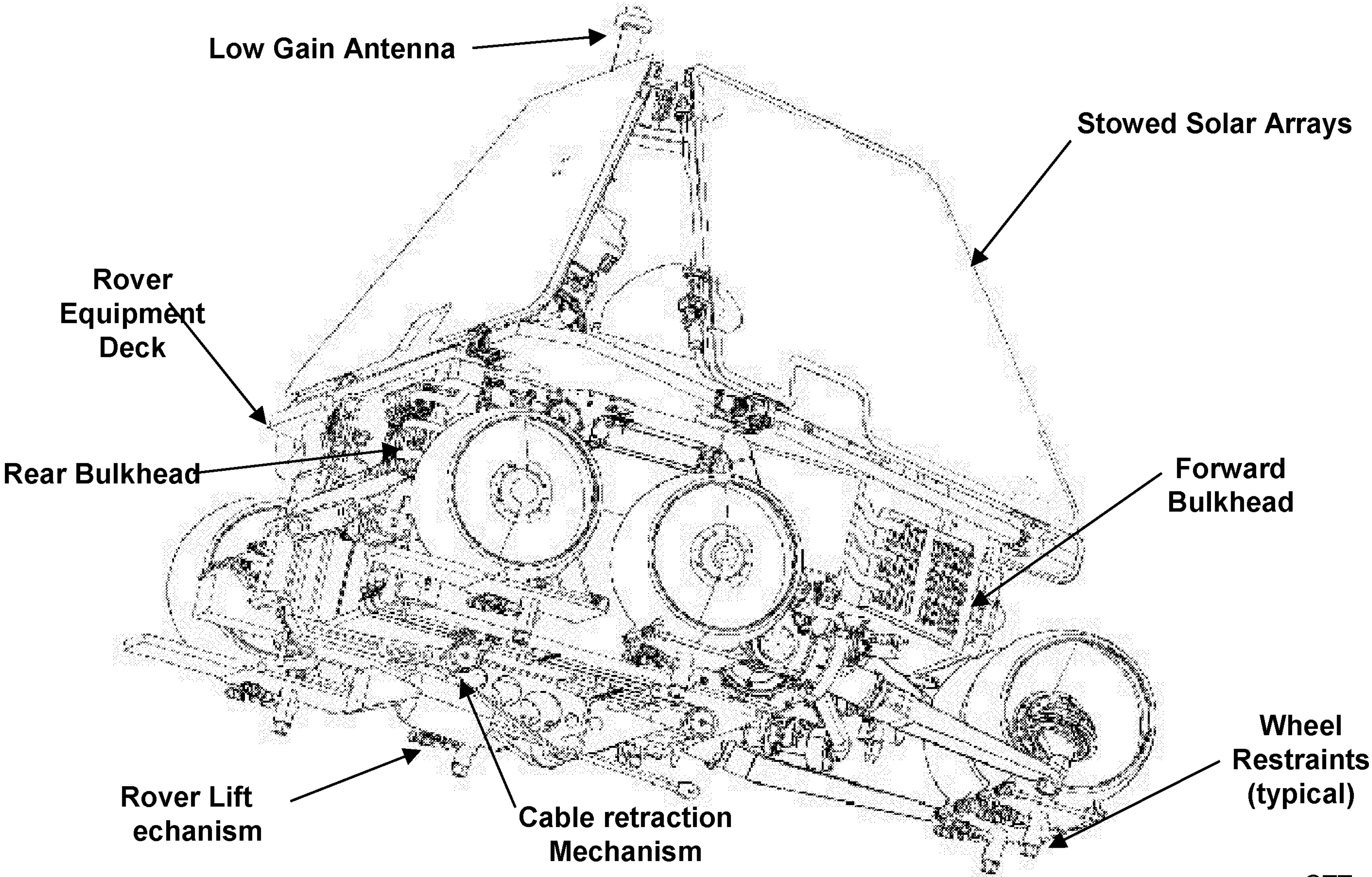


Not shown: Egress Aids

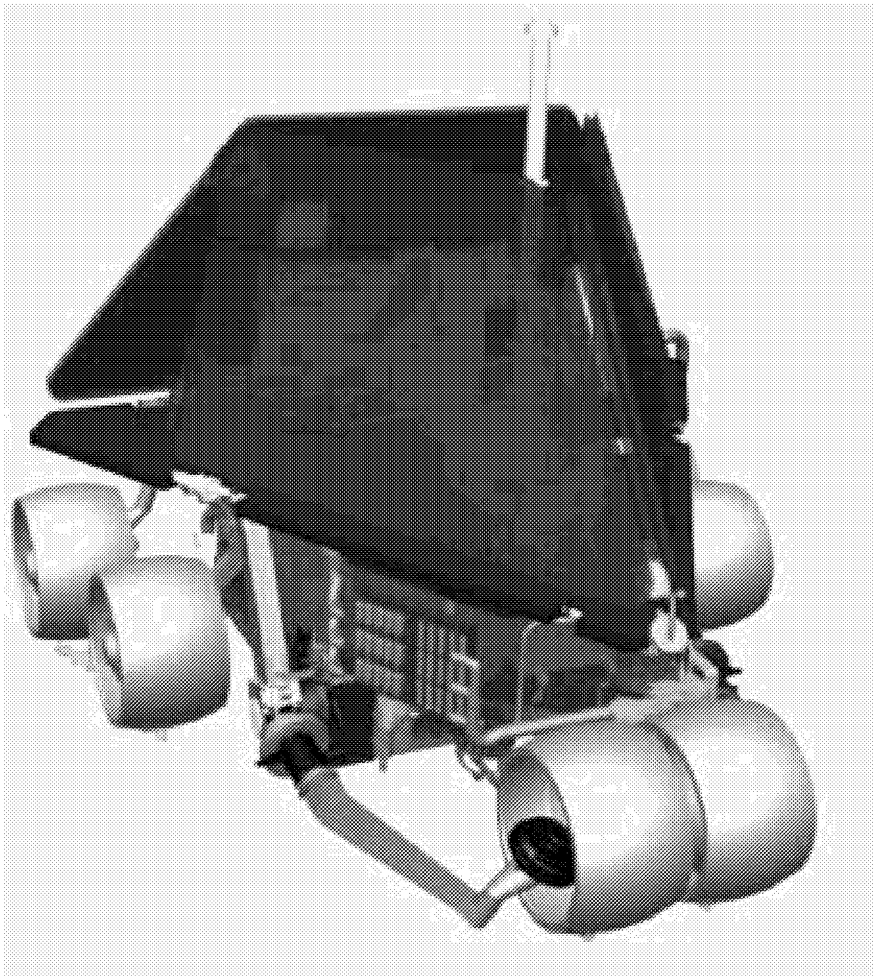
Lander Assembly - Deployed

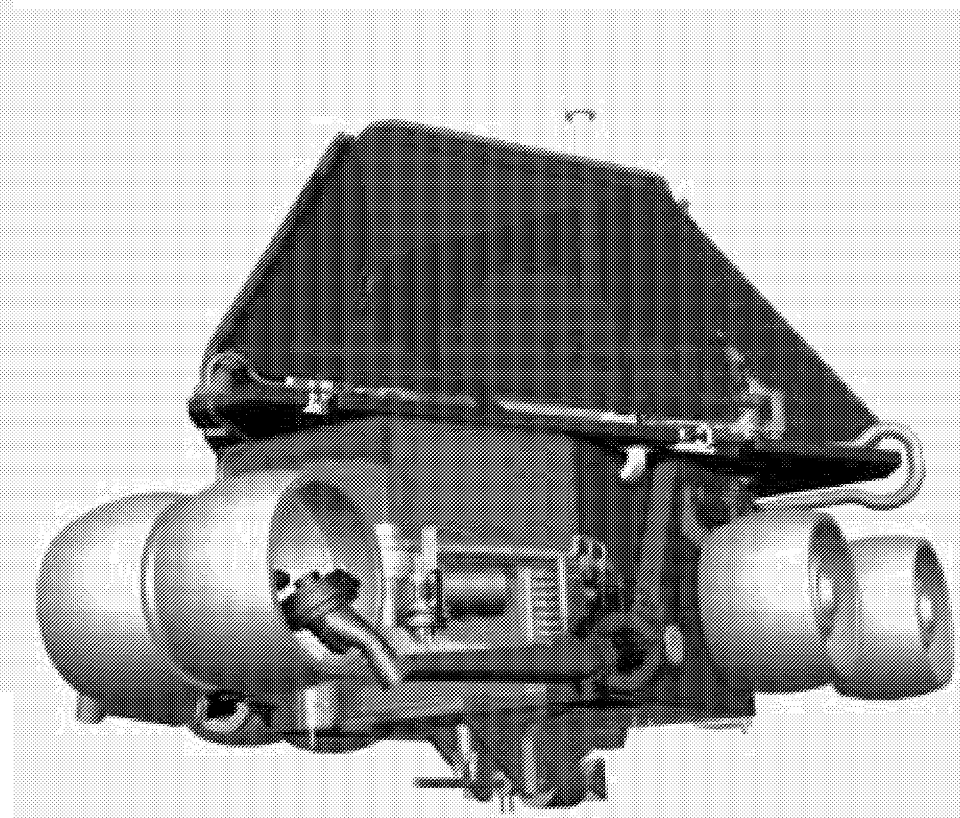


Rover - Stowed Configuration

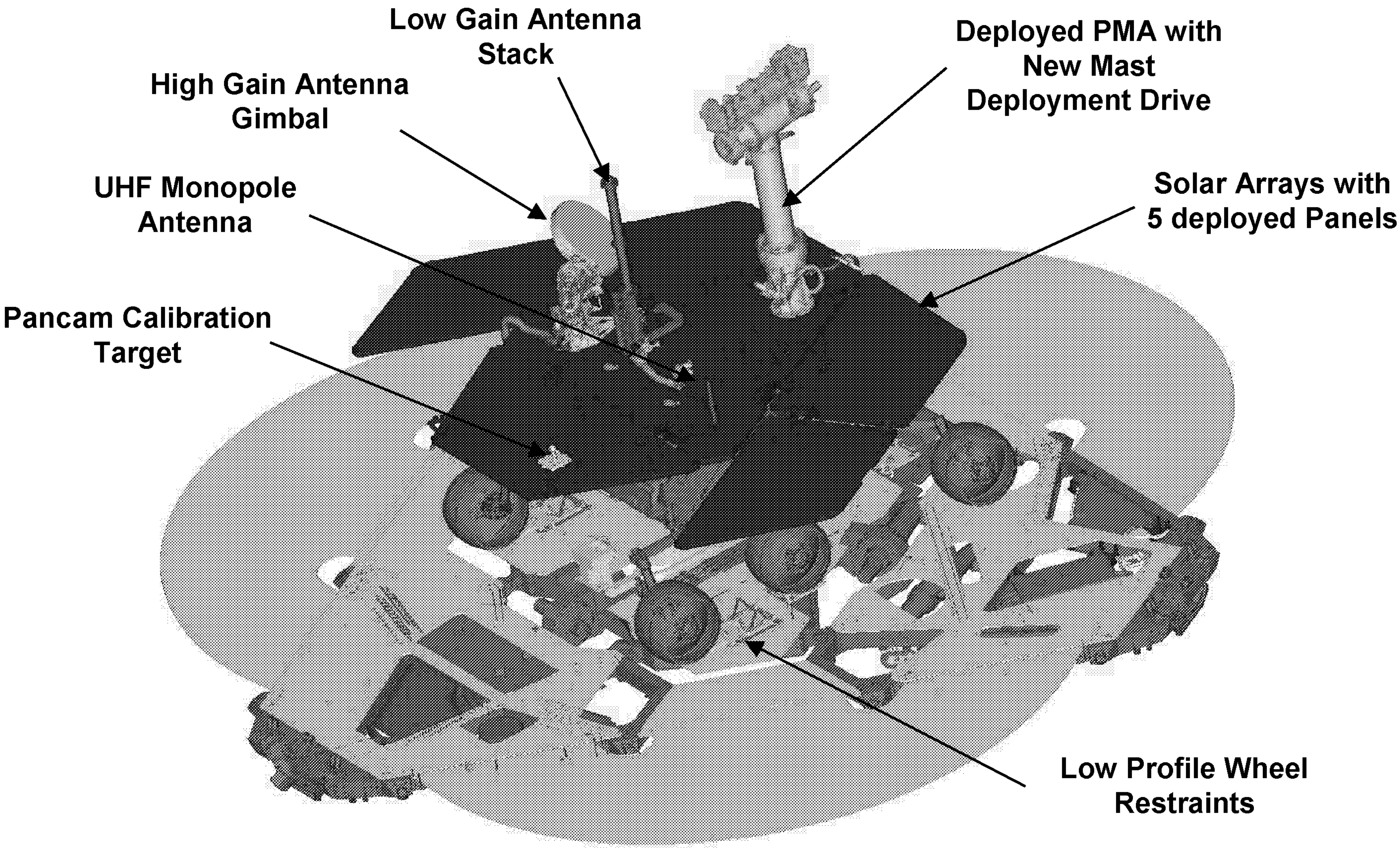


Shaded Isometric Views of the Stowed Rover

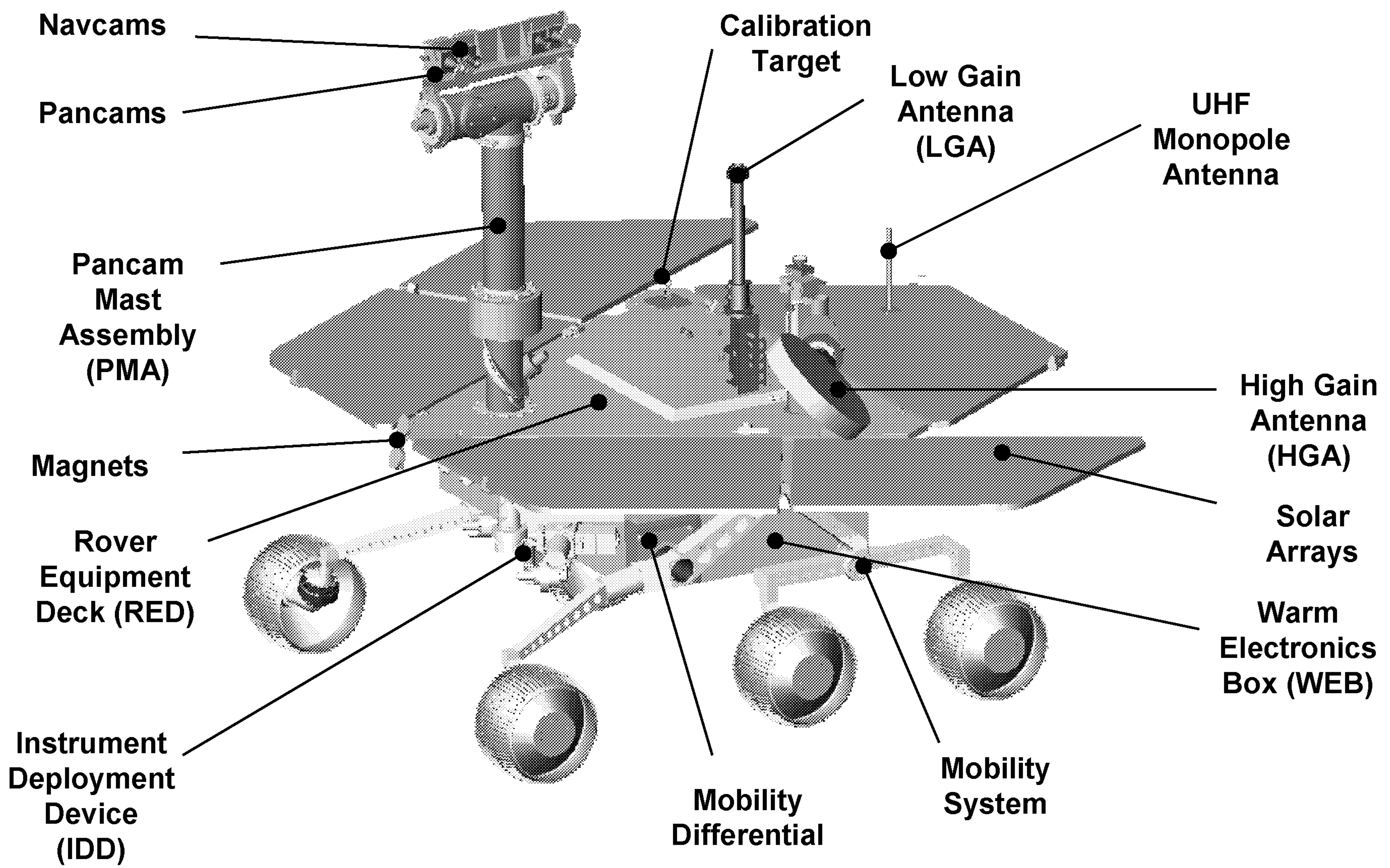




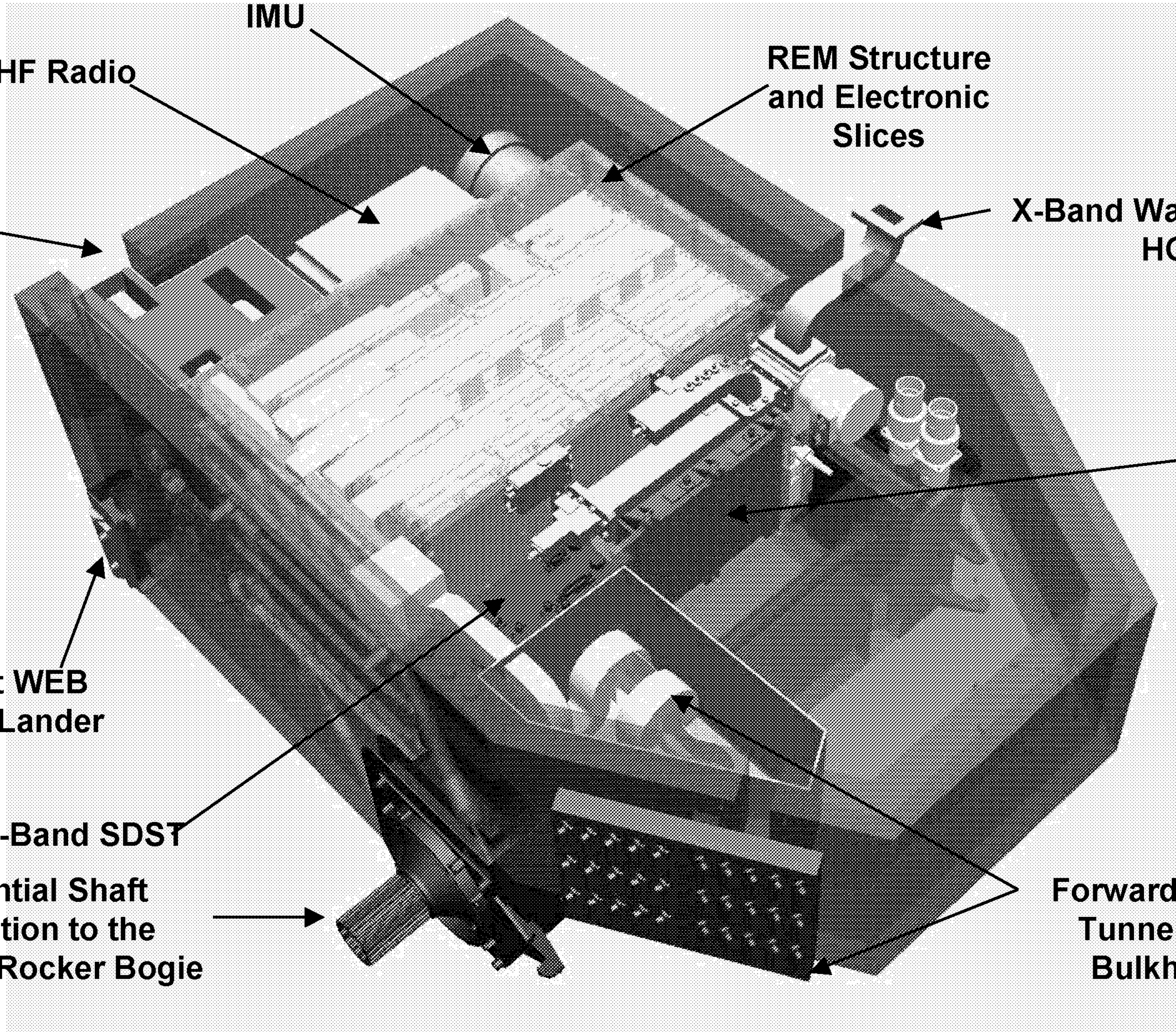
Deployed Rover on the Lander



Rover Configuration - Deployed



Isometric View of the WEB



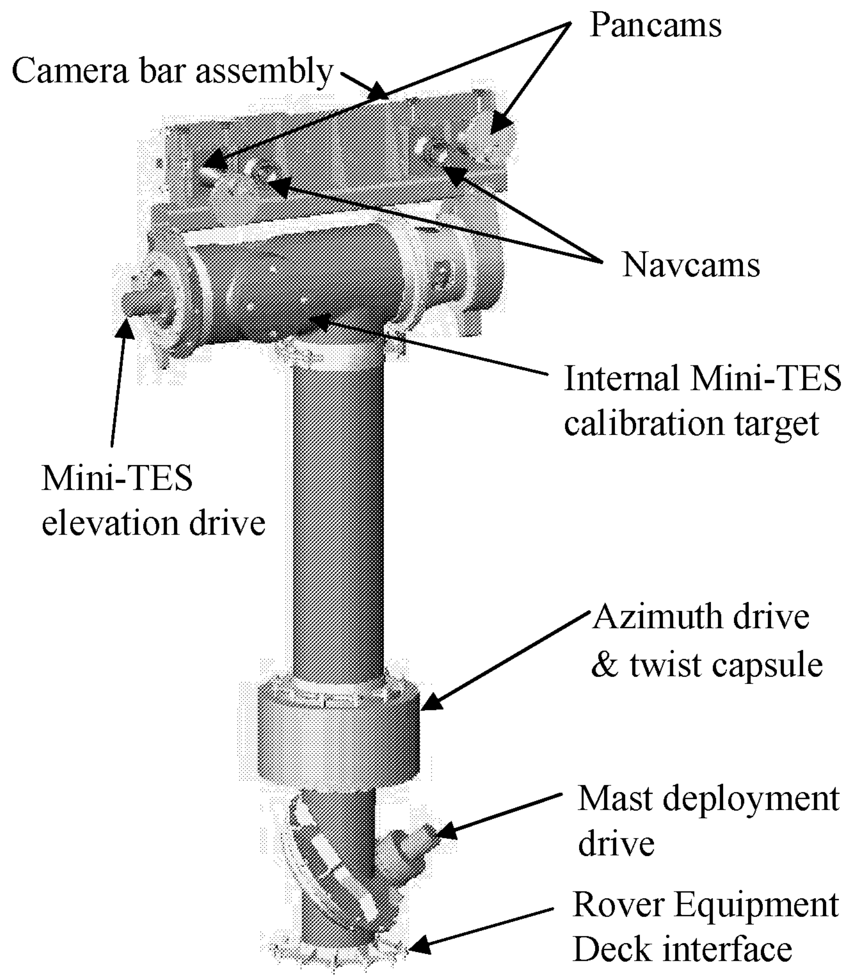
Remote Sensing Science Instruments

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"

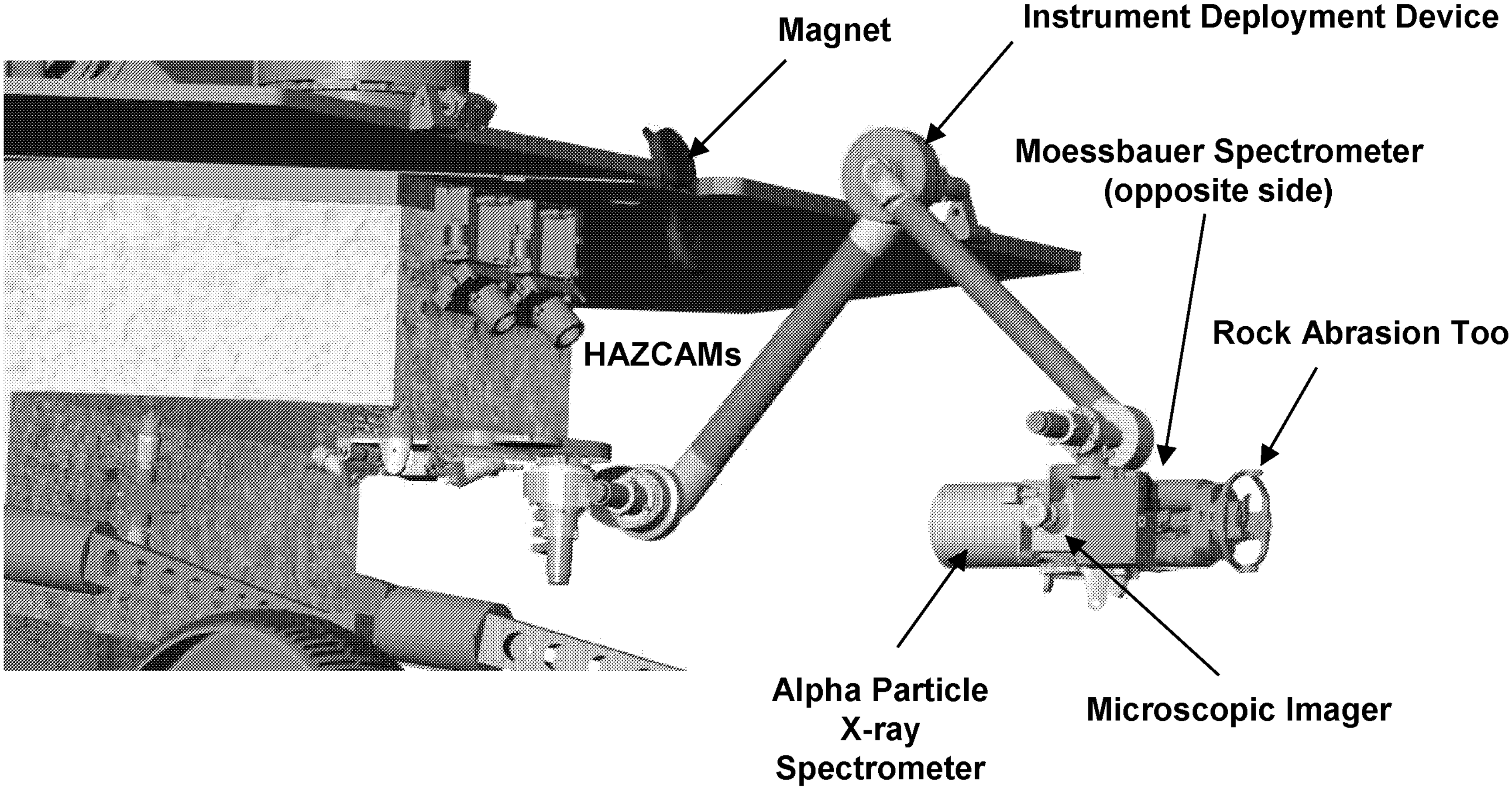


Pancam Mast Assembly (PMA)

In situ Science Instruments

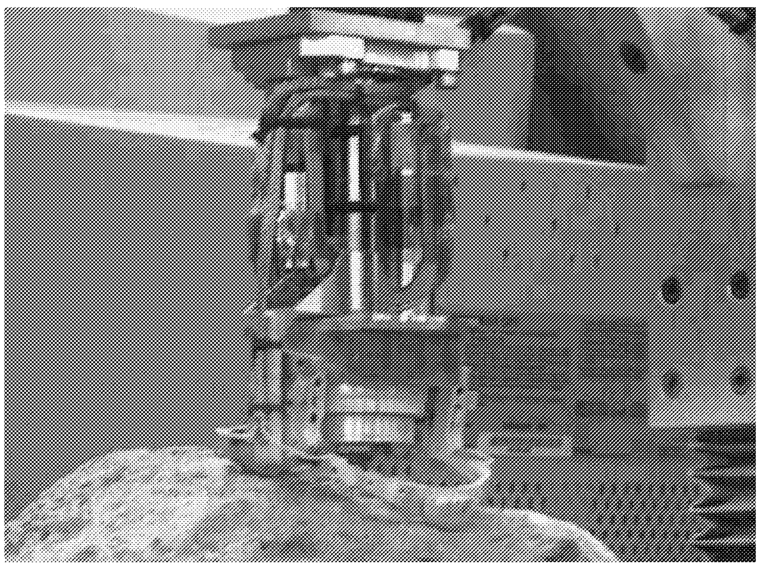
- Instrument Deployment Device (IDD) - a 5 DOF robotic arm for deployment of 3 in situ science instruments and a Rock Abrasion Tool (RAT) against rock and soil targets
  - Microscopic Imager (MI)- 1024x1024x12bit camera with 30 μm/pixel resolution with 3 mm depth of field
  - Alpha Particle X-ray Spectrometer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

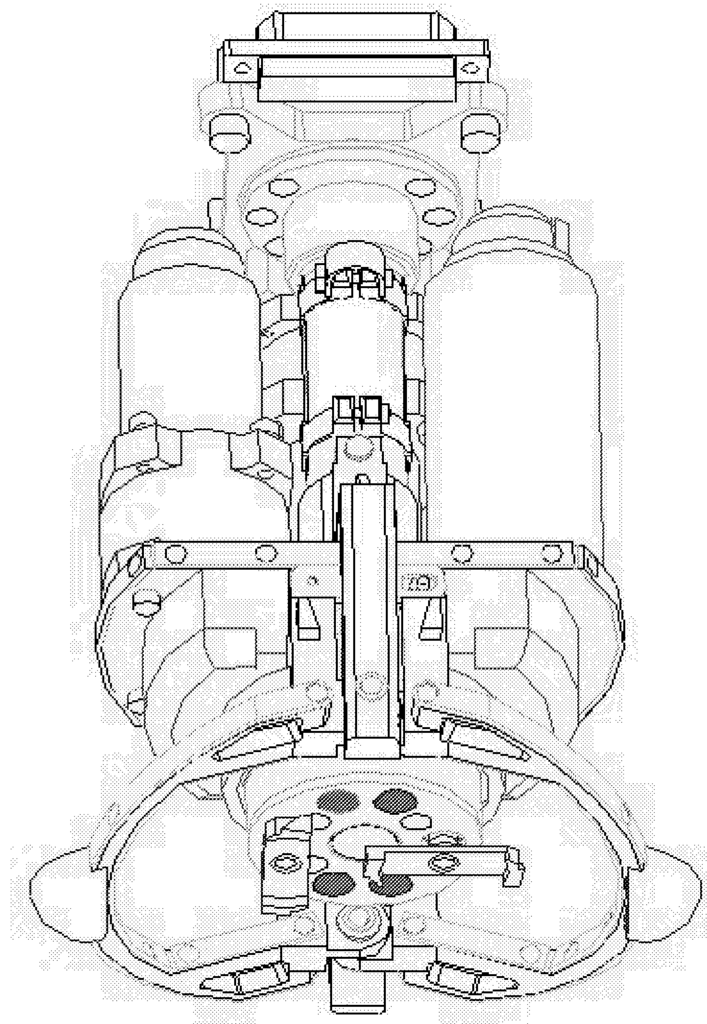
Instrument Deployment Device (IDD)



Rock Abrasion Tool

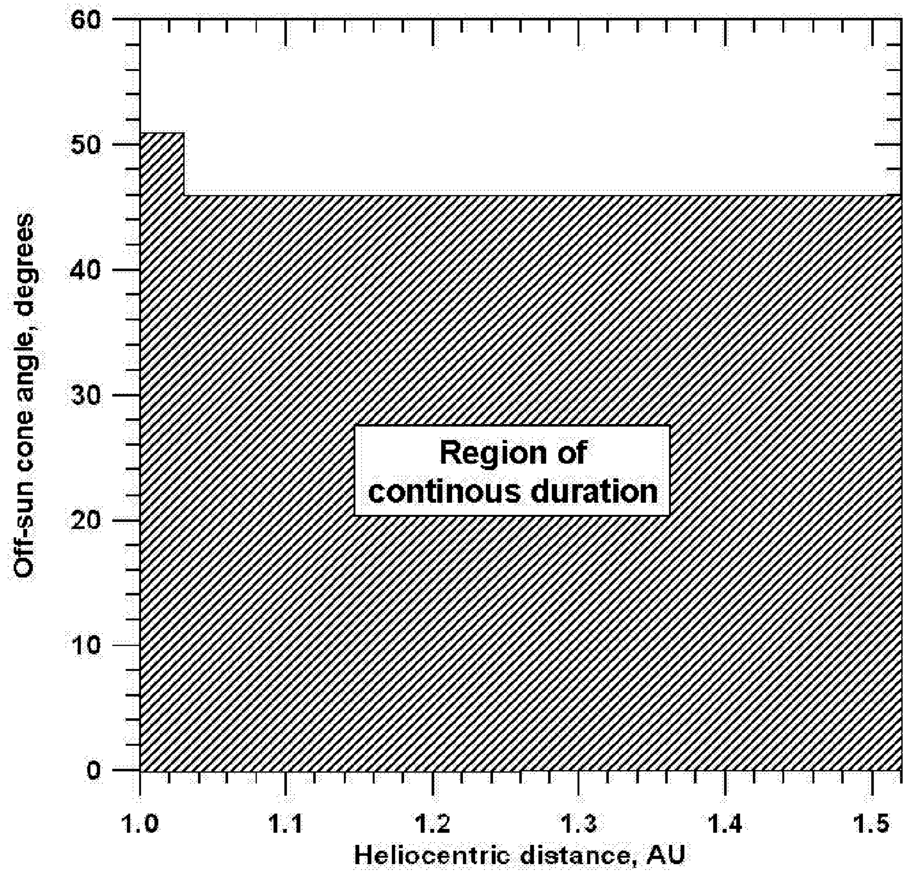
- Rock Abrasion Tool (RAT)
  - **Penetrates through dust & surface alteration that might be present on rocks, exposing materials more likely to preserve evidence of environmental conditions at the time of their formation**





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)

Mars Exploration Rover

- **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

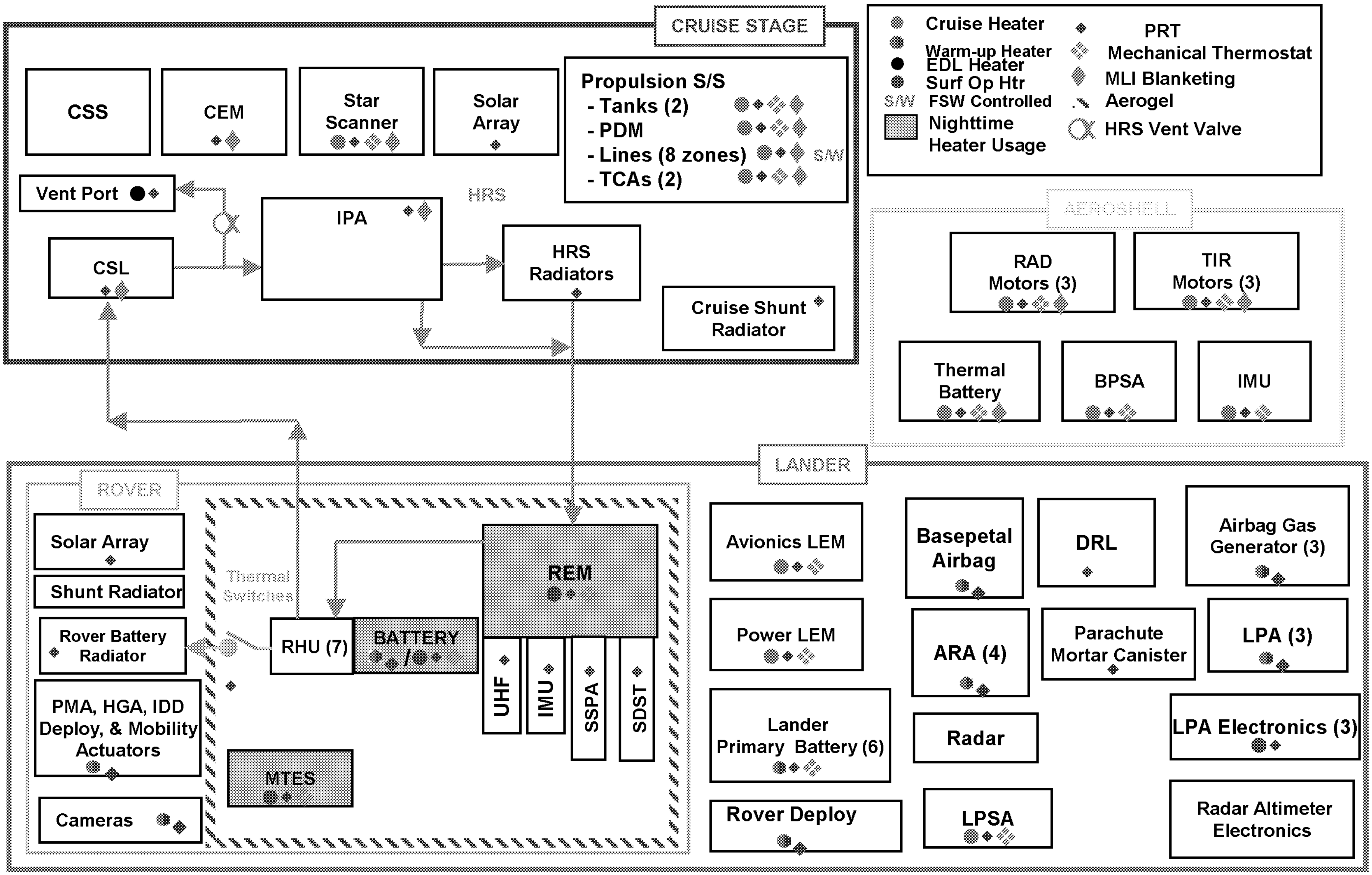
  - Capability to operate the HGA actuators at 10 am Mars local time without additional warm-up heater

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

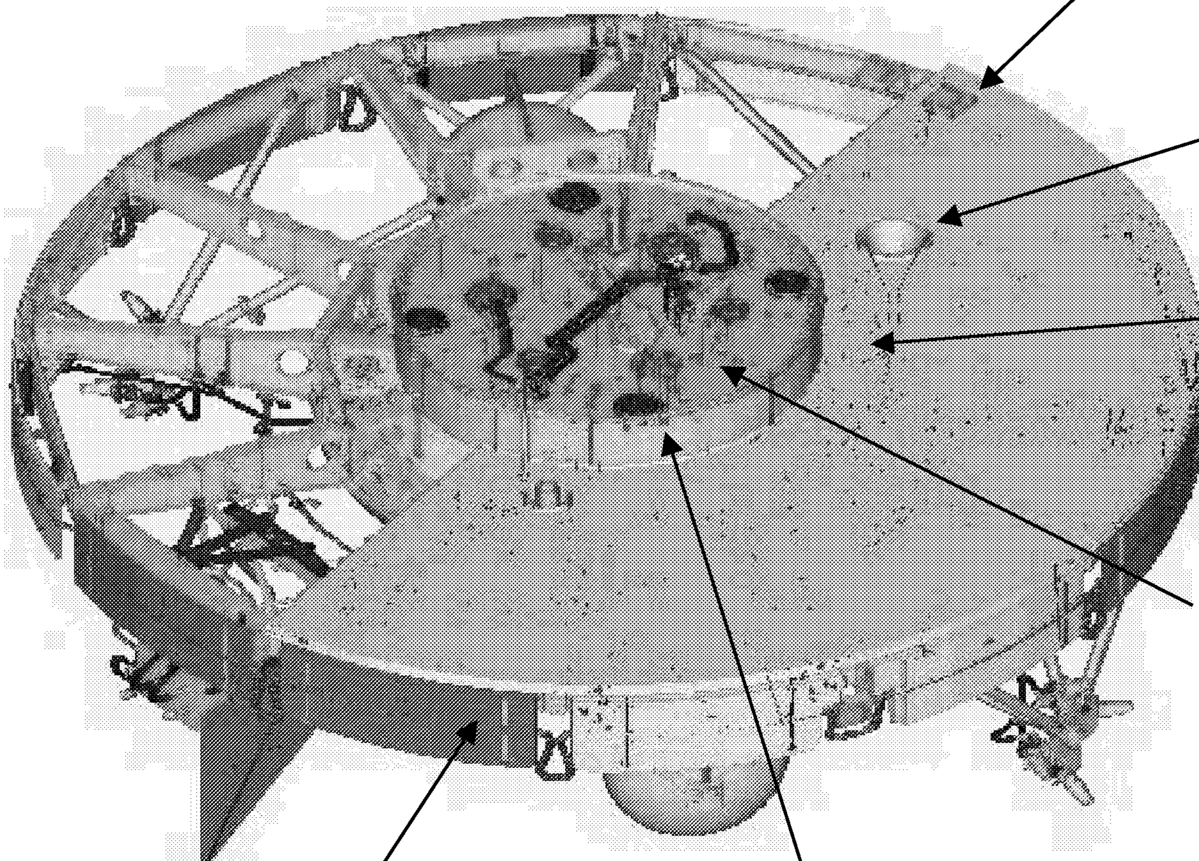
Blue text denotes changes from Project PDR

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

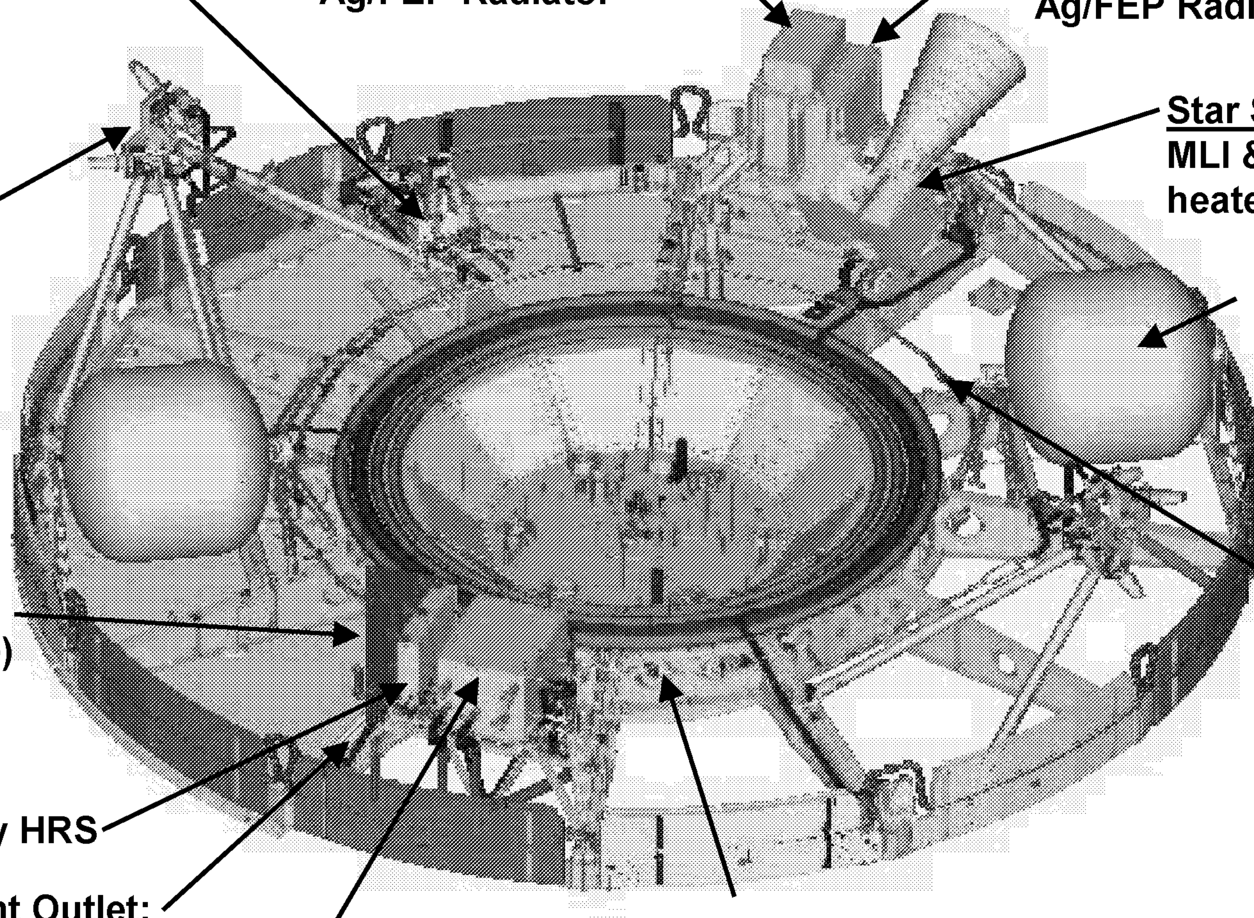
Solar Array:
Ag/FEP tape on inner ring, S13-GLO (white) paint on substrate backside

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

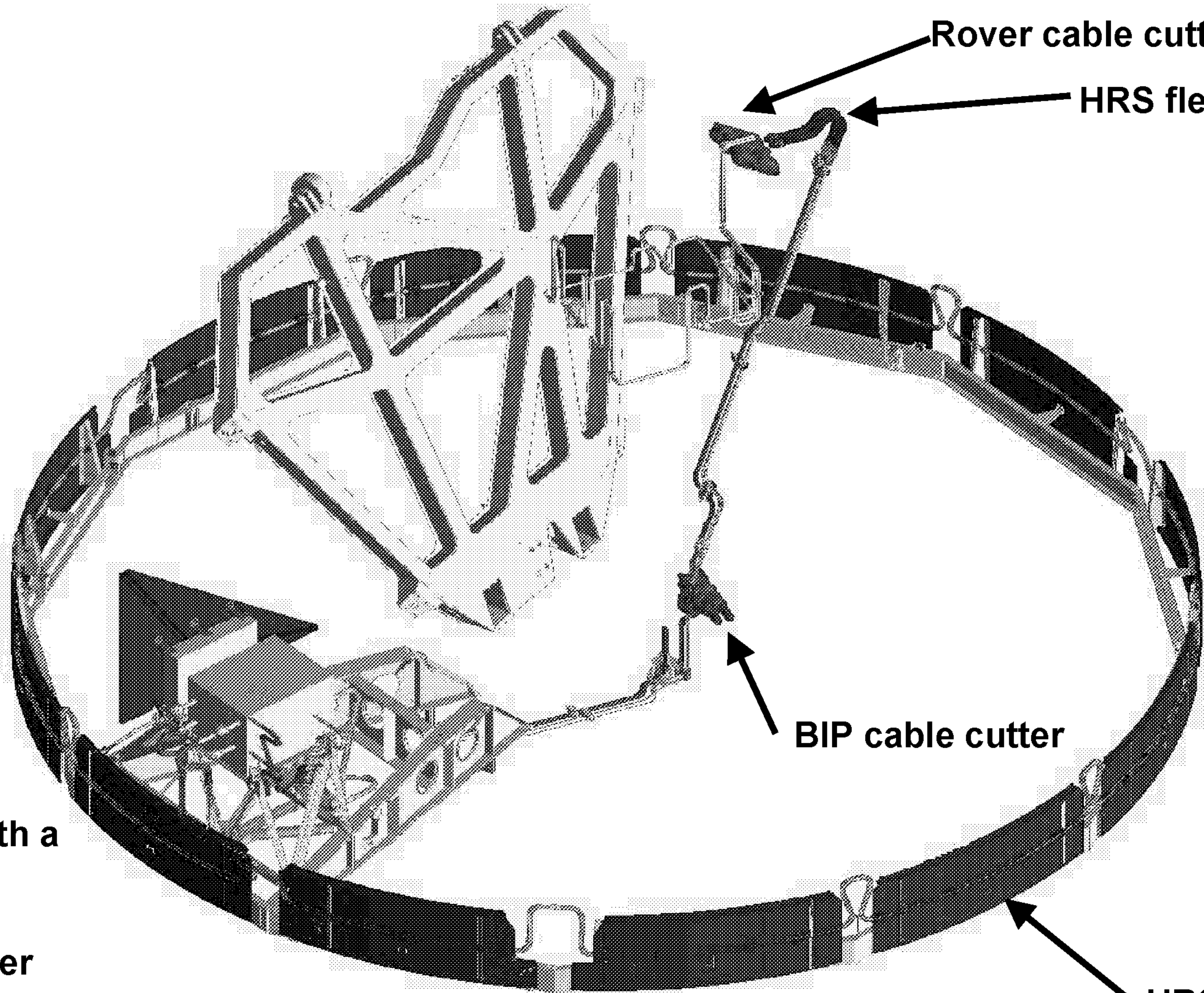
CSL: Controlled by HRS

HRS Vent Outlet: Warm-up heater

IPA: MLI & HRS

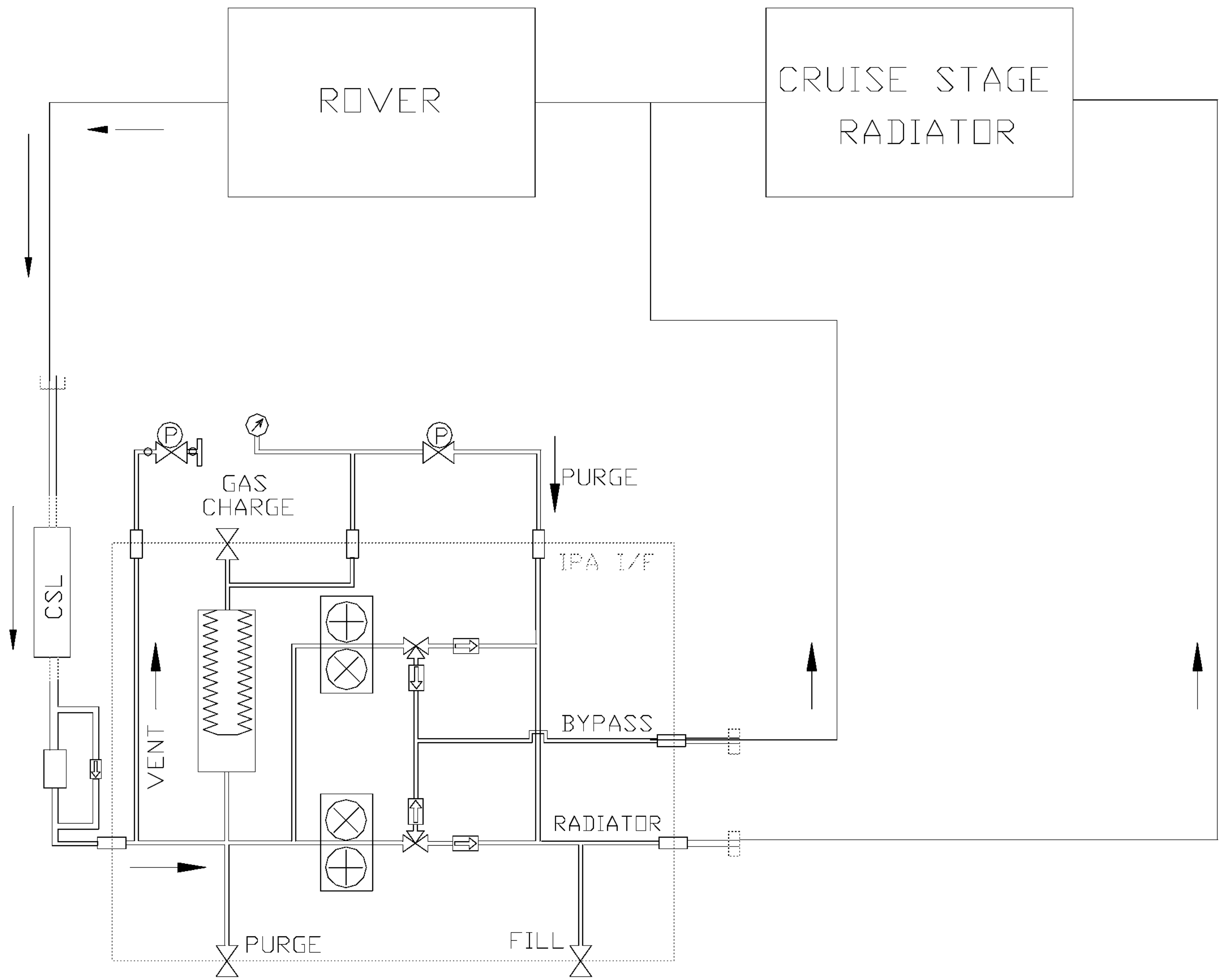
Intercostals: S13-GLO (white) white paint

HRS Overview

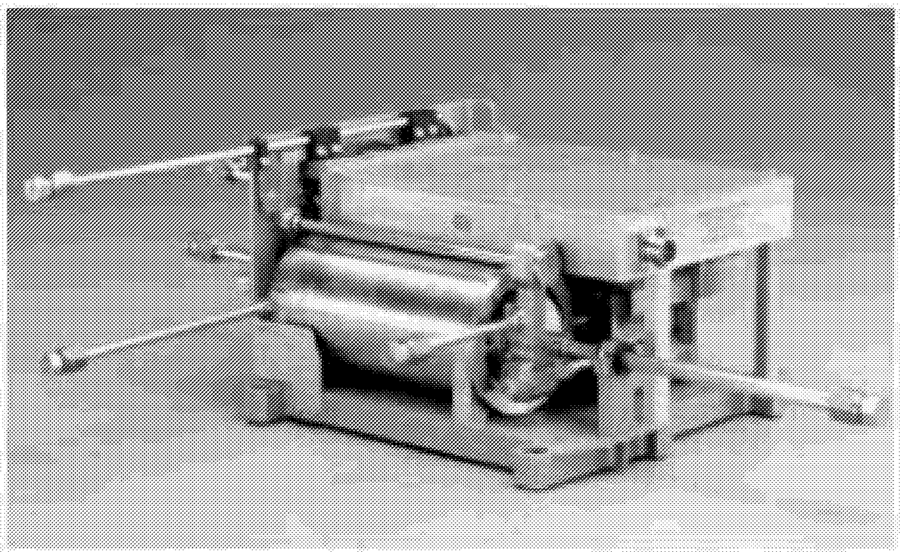


IVSR consists of:
- IVSR structure
- IPA
- 2 Pyro valves
- Filter in parallel with a relief valve
- Vent outlet
- Pressure transducer
- CSL heat exchanger
- CSL “shark fin” radiator

HRS Schematic



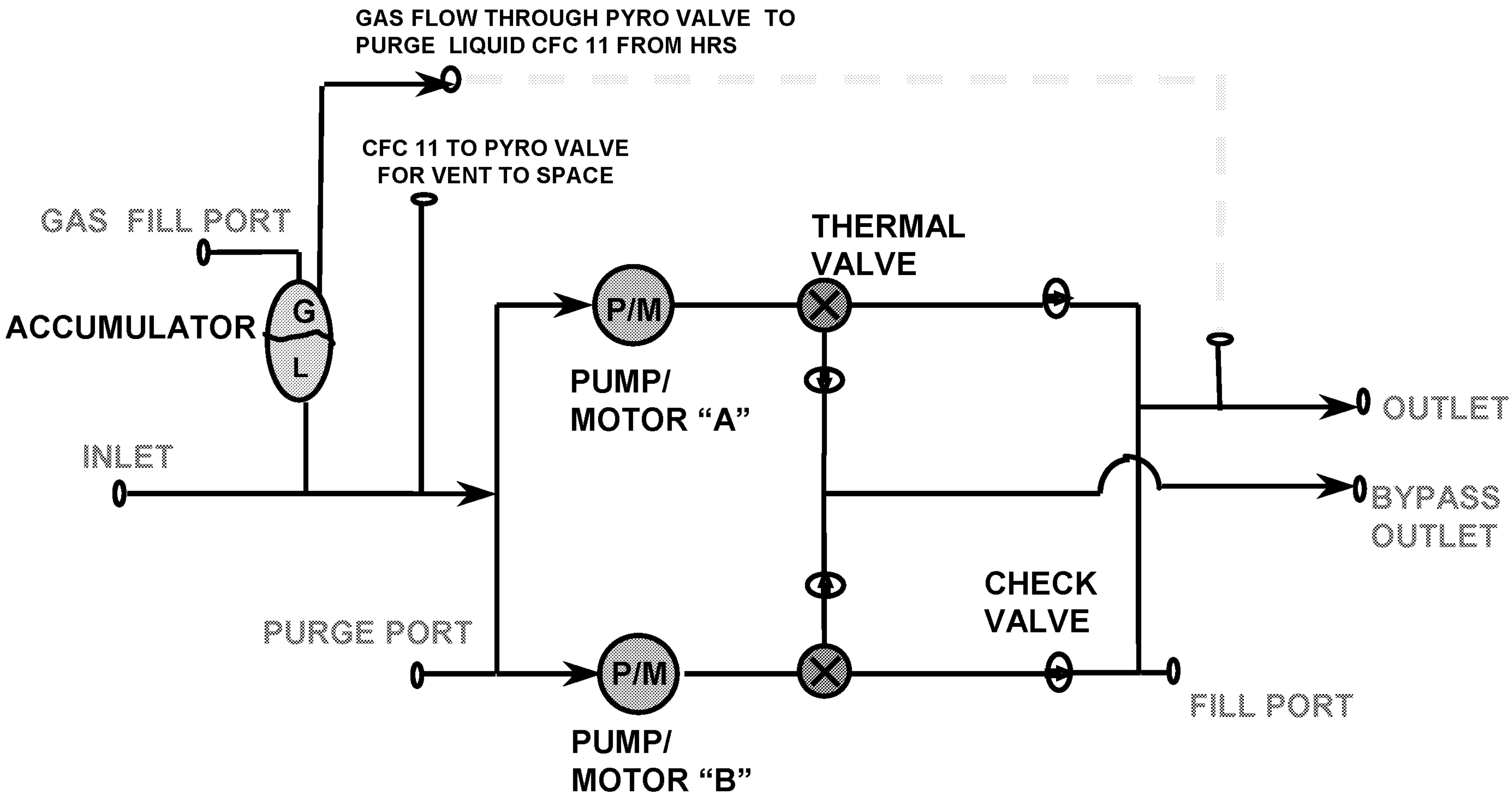
Integrated Pump Assembly



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

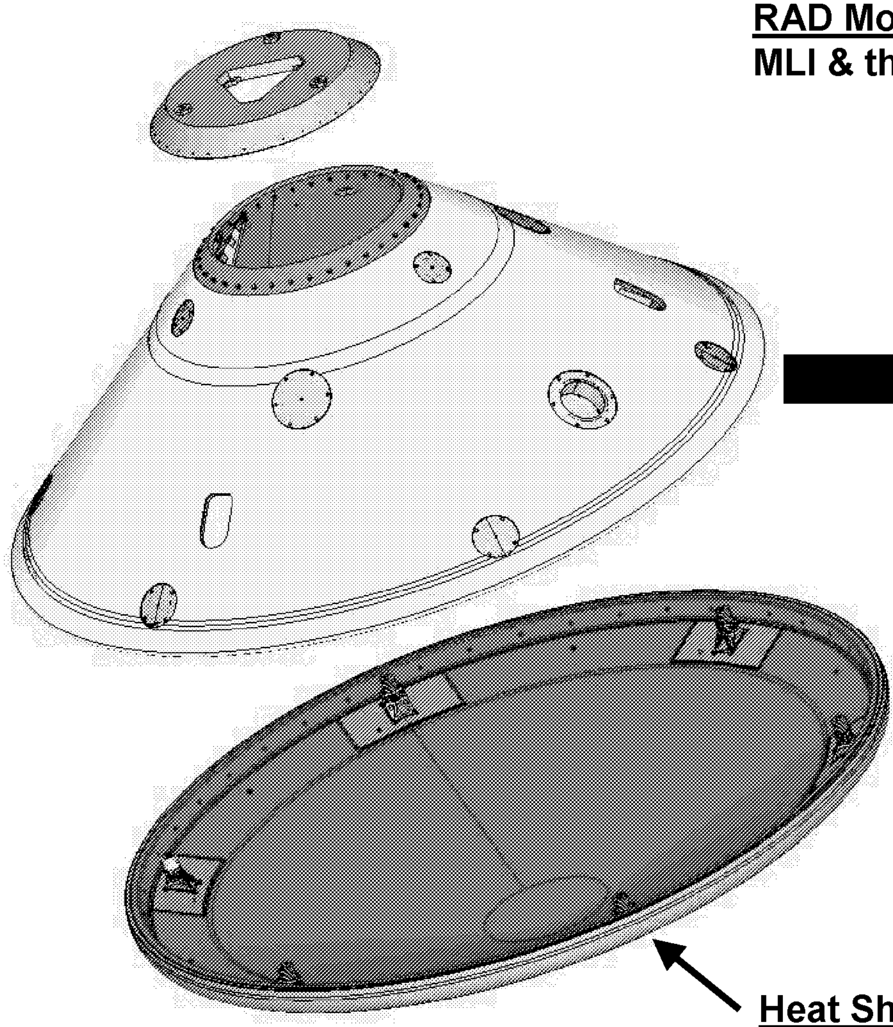
IPA Schematic

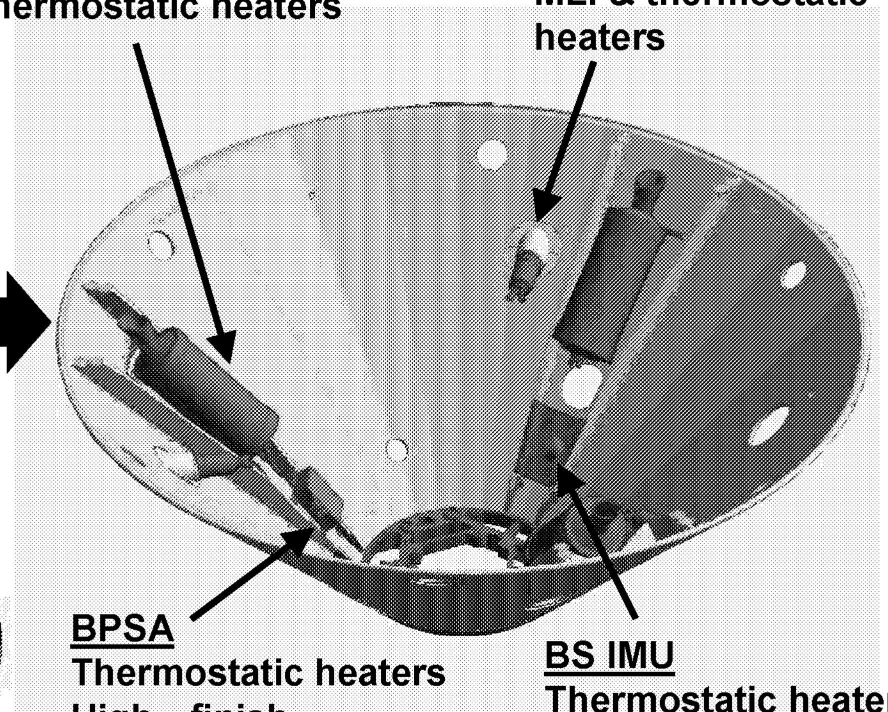
Mars Exploration Rover



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

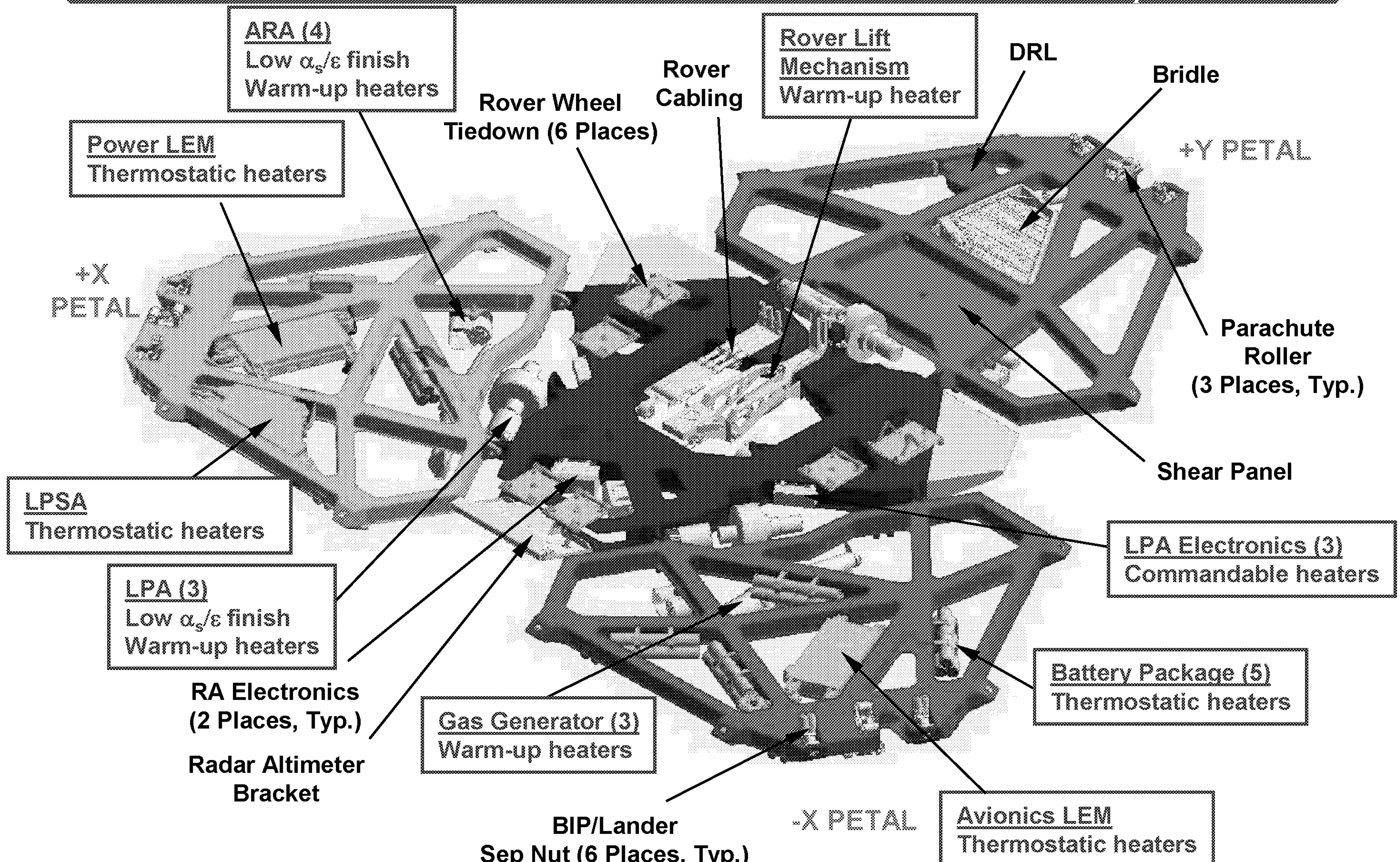
BS IMU
Thermostatic heaters
Mounting plate mass

Thermal Battery (hidden)
MLI & thermostatic heaters

Heat Shield
Interior MLI
Exterior radiation shield

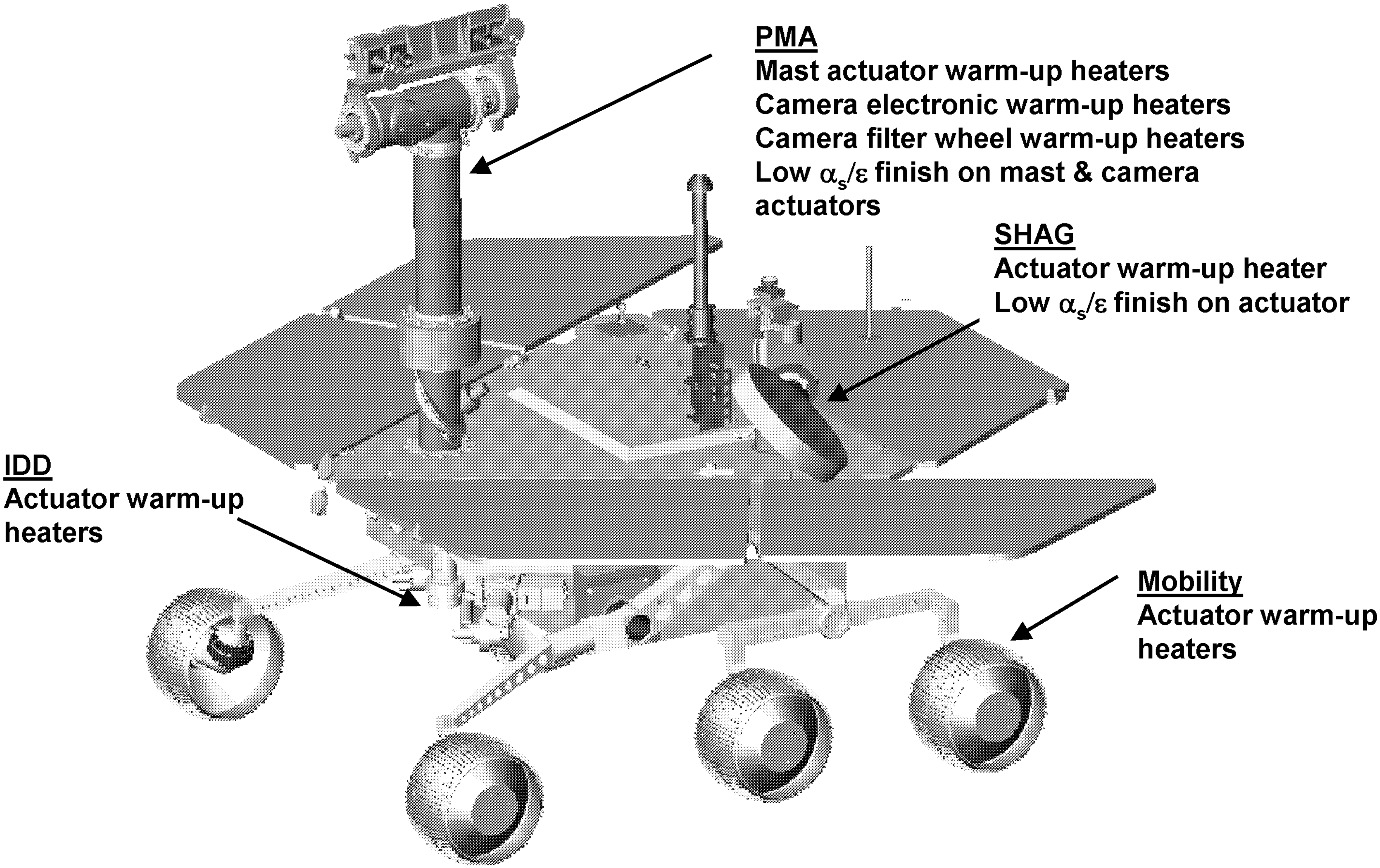
Lander Thermal Design Overview

Mars Exploration Rover



Rover Thermal Design Overview

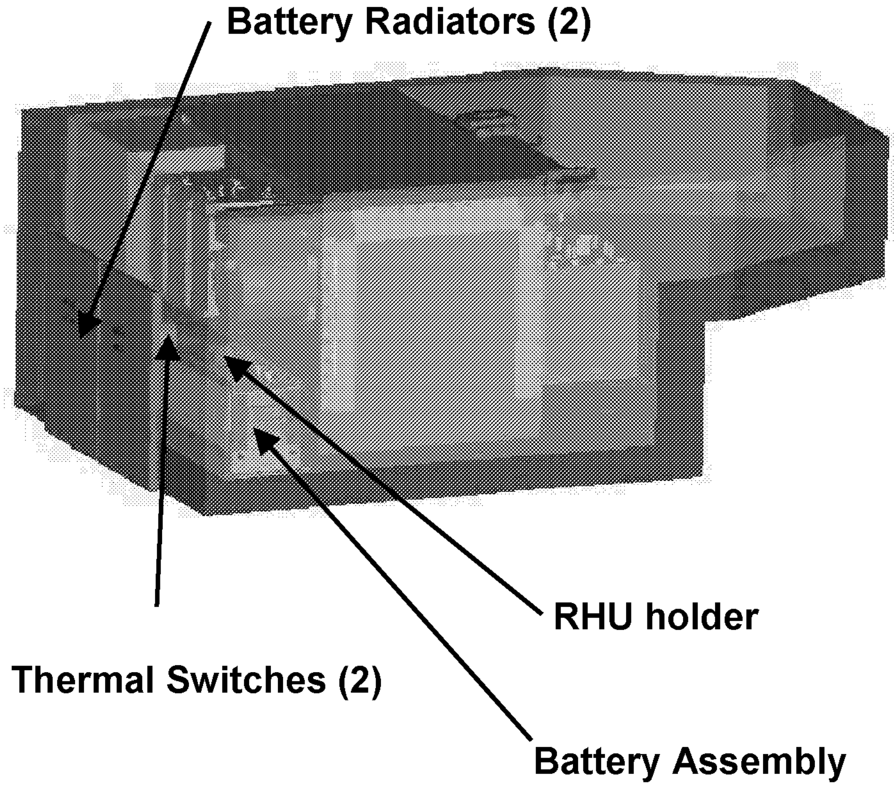
Mars Exploration Rover



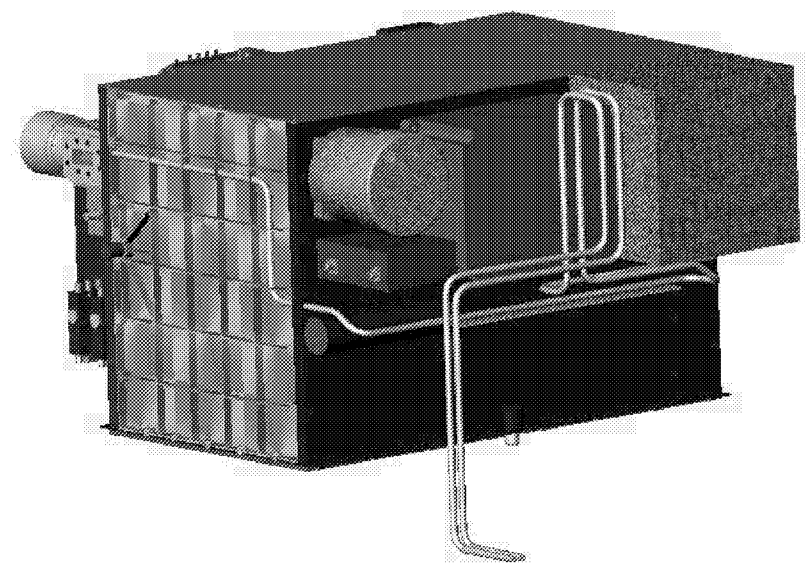
Rover Thermal Design Overview (cont'd)

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

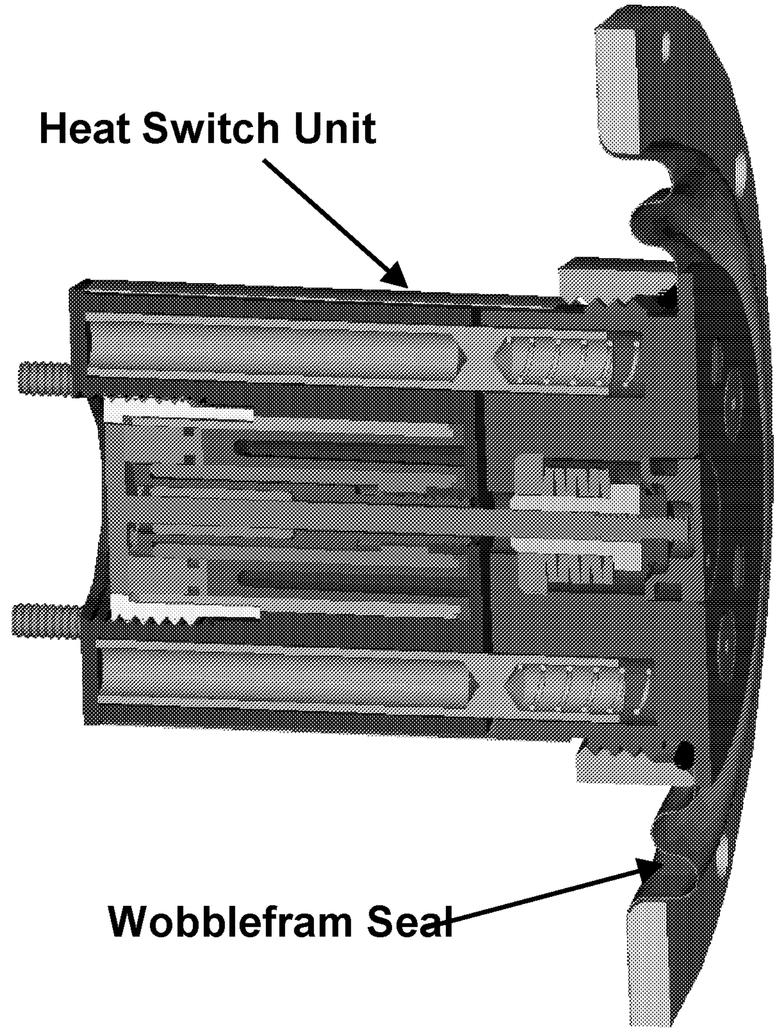


HRS tubing on REM



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

	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

	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

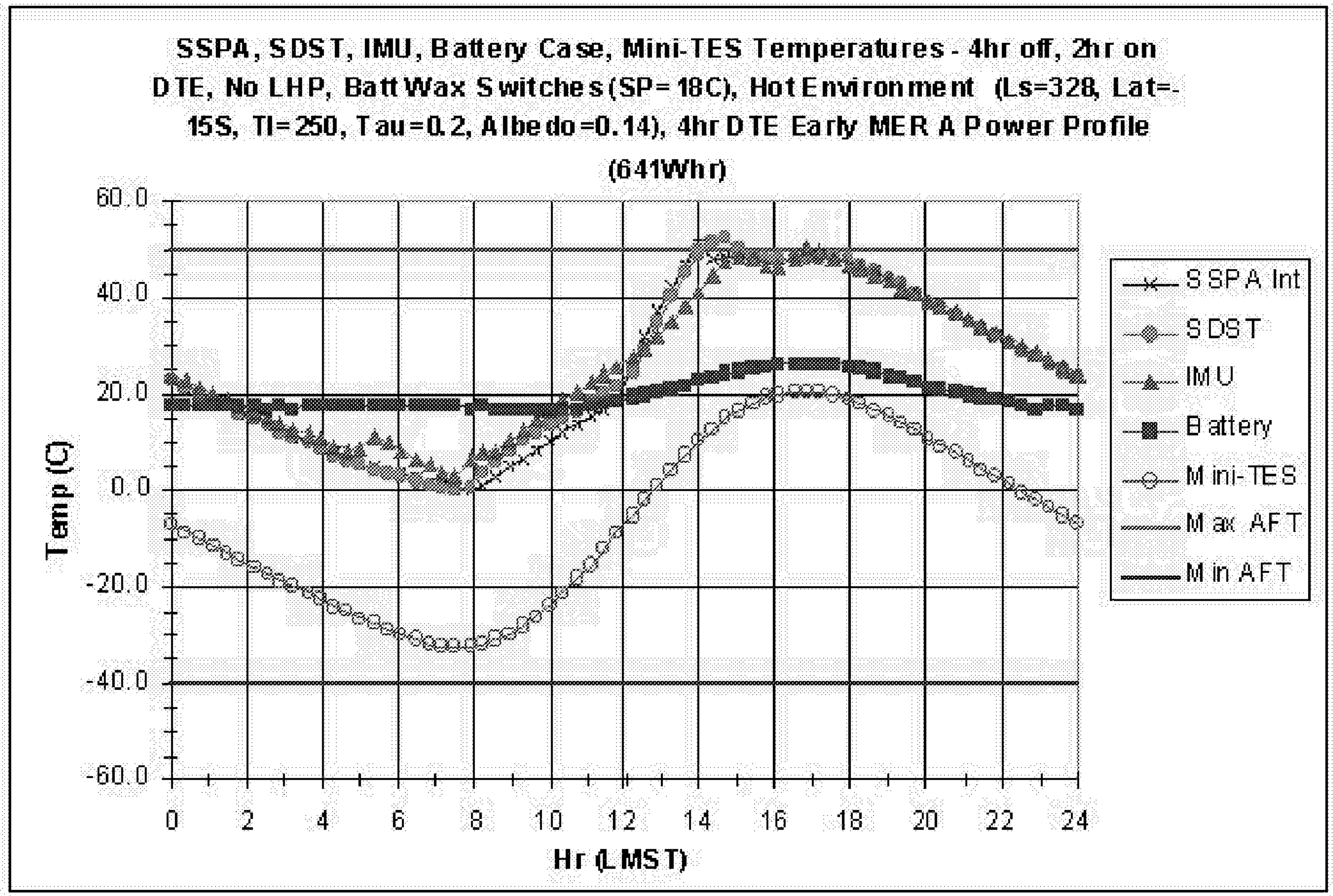
Cruise Thermal Analysis - Rover

Mars Exploration 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

Mars Exploration Rover



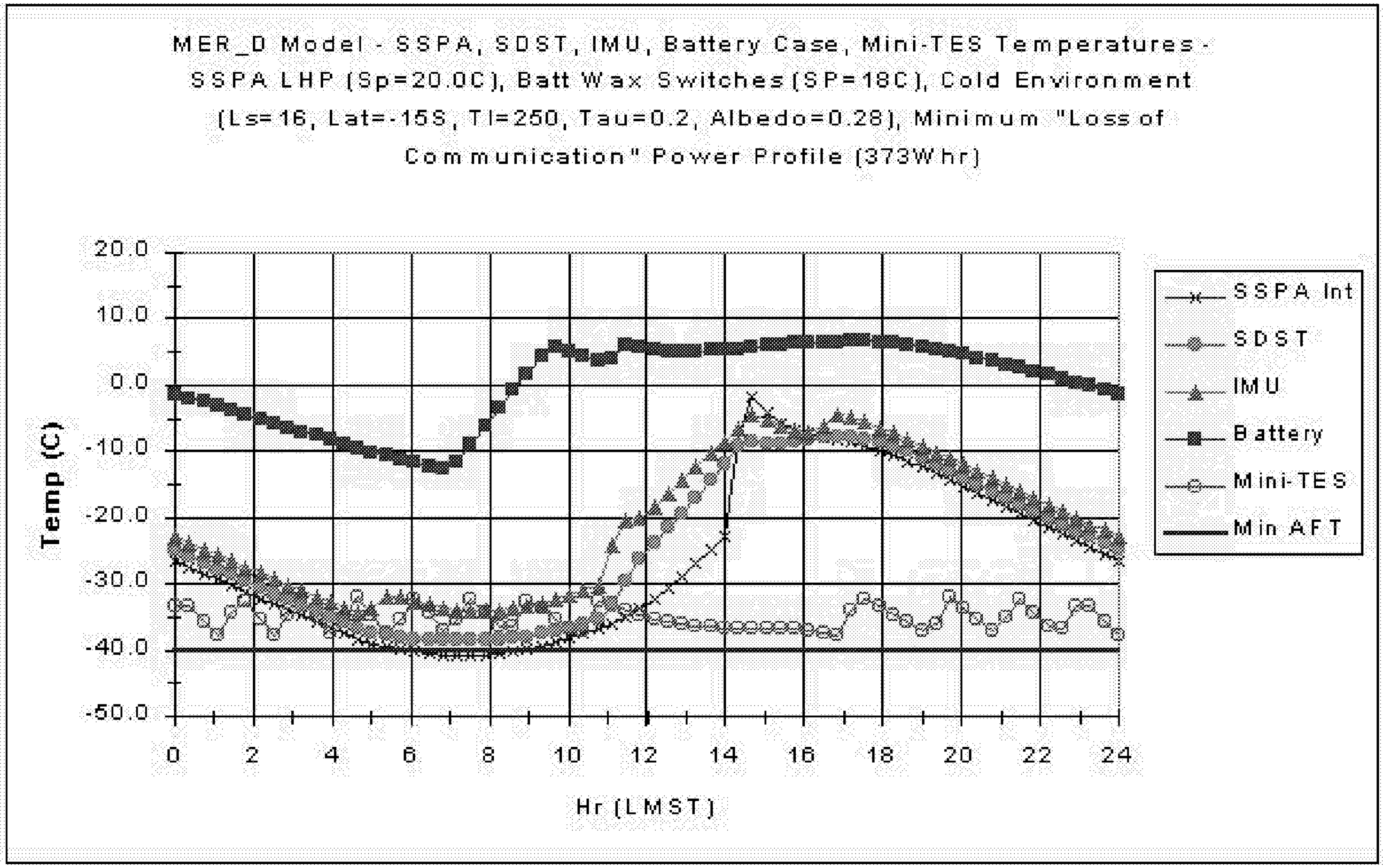
Max SSPA Interface Temp = 51°C

Max UHF Interface Temp = 52°C

Max Battery Temp = 26C

Rover Cold Surface Scenario

Mars Exploration Rover



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

Mars Exploration Rover

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.