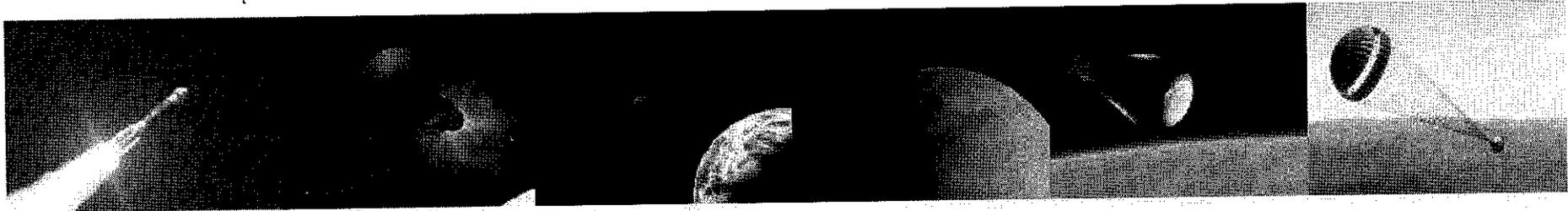




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Mars Exploration Rover



Thermal Design Overview of the Mars Exploration Rover Project

Glenn Tsuyuki

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, CA

September 10, 2001





Agenda



Mars Exploration Rover

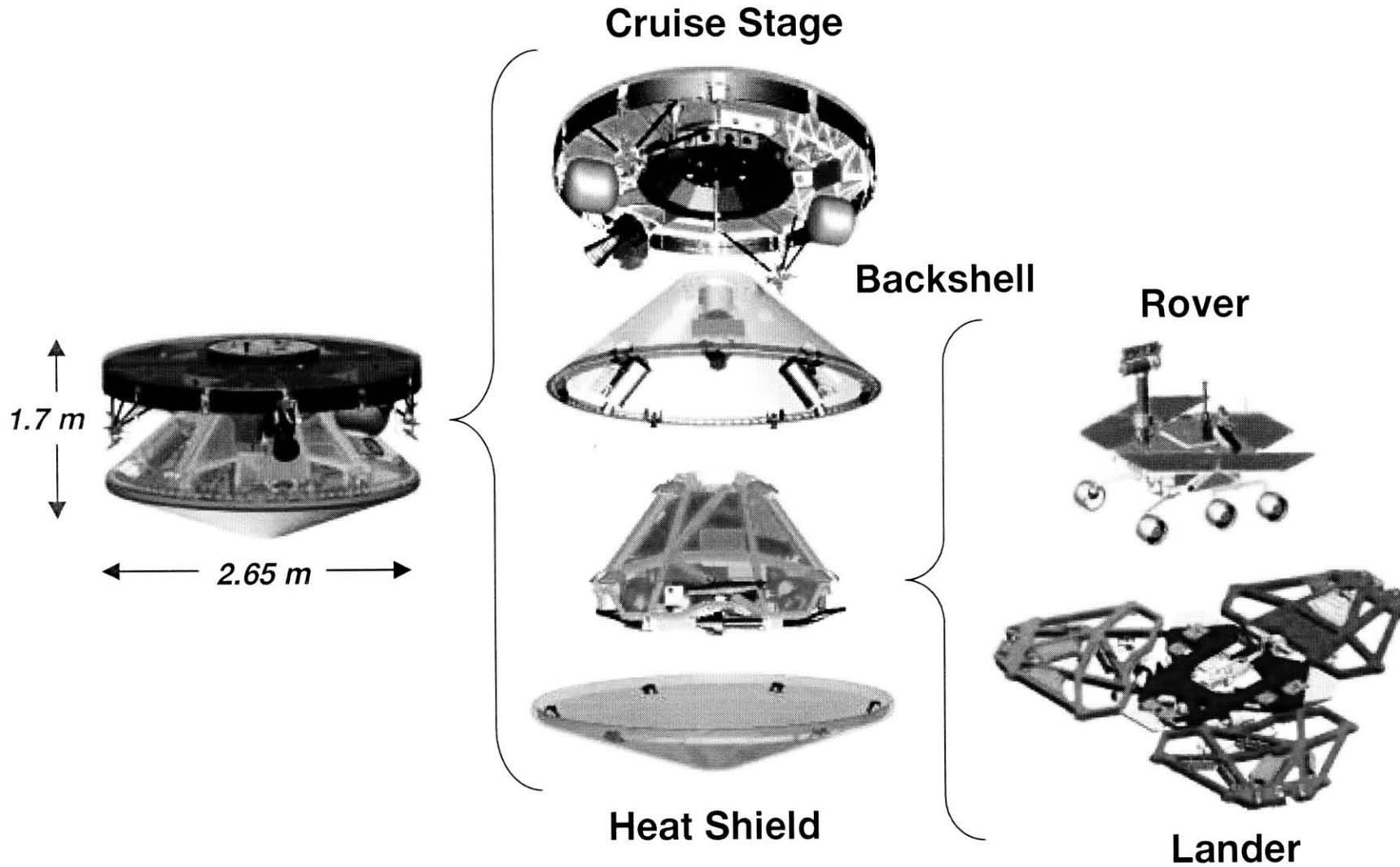
- **Mission Overview**
- **Thermal Environments**
- **Driving Thermal Requirements**
- **Thermal Design Approach**
- **Thermal Control Block Diagram**
- **Thermal Design Description**
- **Thermal Analysis Results Summary**
- **Testing Plans**
- **Issues & Concerns**



Spacecraft Configuration



Mars Exploration Rover





MER-A Cruise Scenario



Mars Exploration Rover

View from Ecliptic North Pole
20 Day Tic Marks

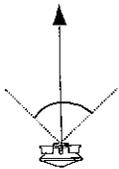
MER-A

Launch Date = 5/30/03
Arrival Date = 1/4/04

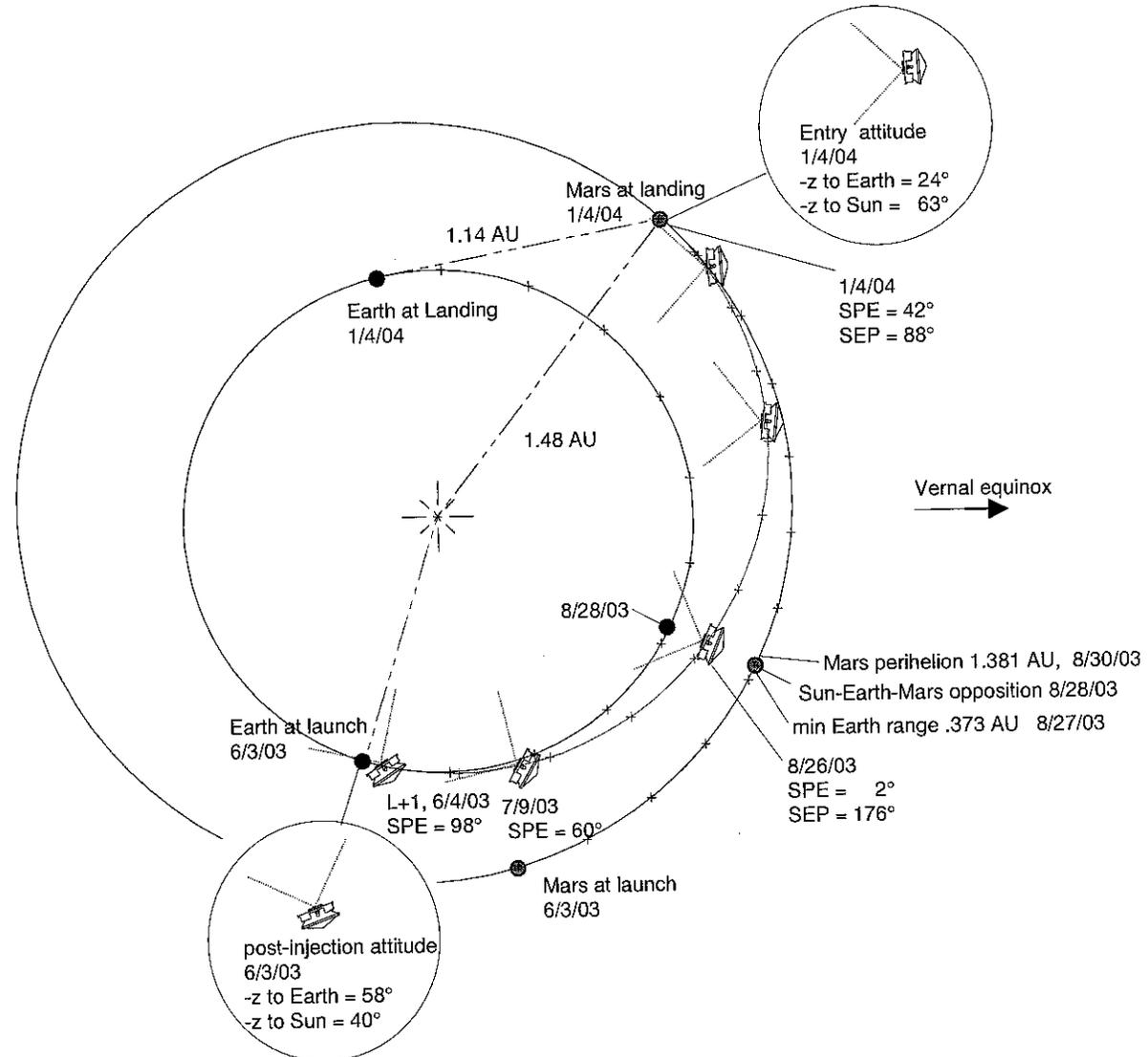
MER-B

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

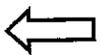


Mars Exploration Rover

- Entry Turn & HRS Freon Venting: E- 70m
- Cruise Stage Separation: E- 15m
- Entry: E- 0 s, 125 km, 5.7 km/s, $\gamma = -11.5$ deg.
- Parachute Deployment: E+ 295 s, 11.8 km, 430 m/s

Landing Times (Mars local solar time)	
MER-A:	~2:30PM
MER-B:	~12:30PM
Earthset:	~3:30PM

- Heatshield Separation: E+ 315 s
- Lander Separation: E+ 325 s



TCM-5: E-12 hrs.
Concurrent with EDL,
but commanded from
ground.

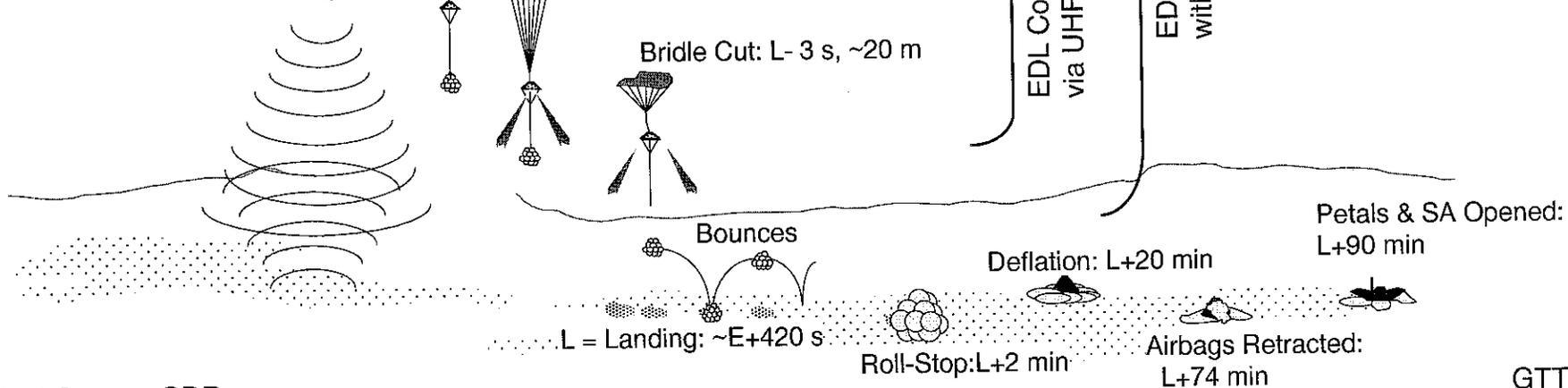
- Bridle Deployed: E+ 335 s
- Radar Ground Acquisition: L- 18 s

- Airbag Inflation: 355 m, L - 10.1 s
- Rocket Firing: L- 7 s, ~150 m, 90 m/s

Bridle Cut: L- 3 s, ~20 m

EDL Communication to
via UHF to MGS Orbiter

EDL Direct to Earth Communication
with FSK tones





Impact to Egress Scenario

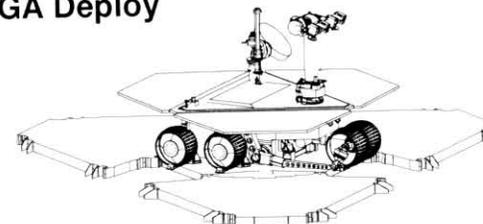


Mars Exploration Rover

Airbag Retraction / Petal
Deploy / Egress Aid Deploy

Sol 1

Solar Array Deploy
PMA Deploy & Imaging
HGA Deploy



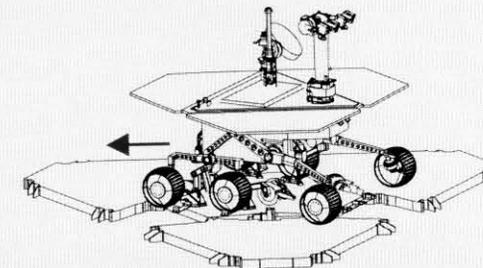
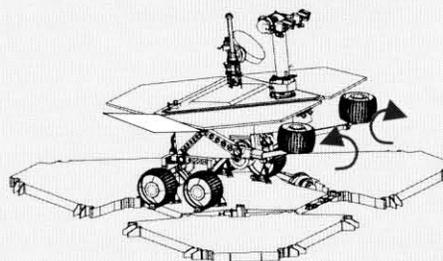
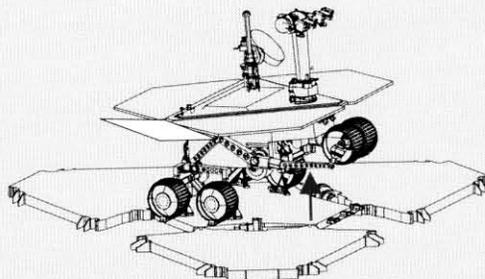
Sol 2-3

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



August 1 & 2, 2001



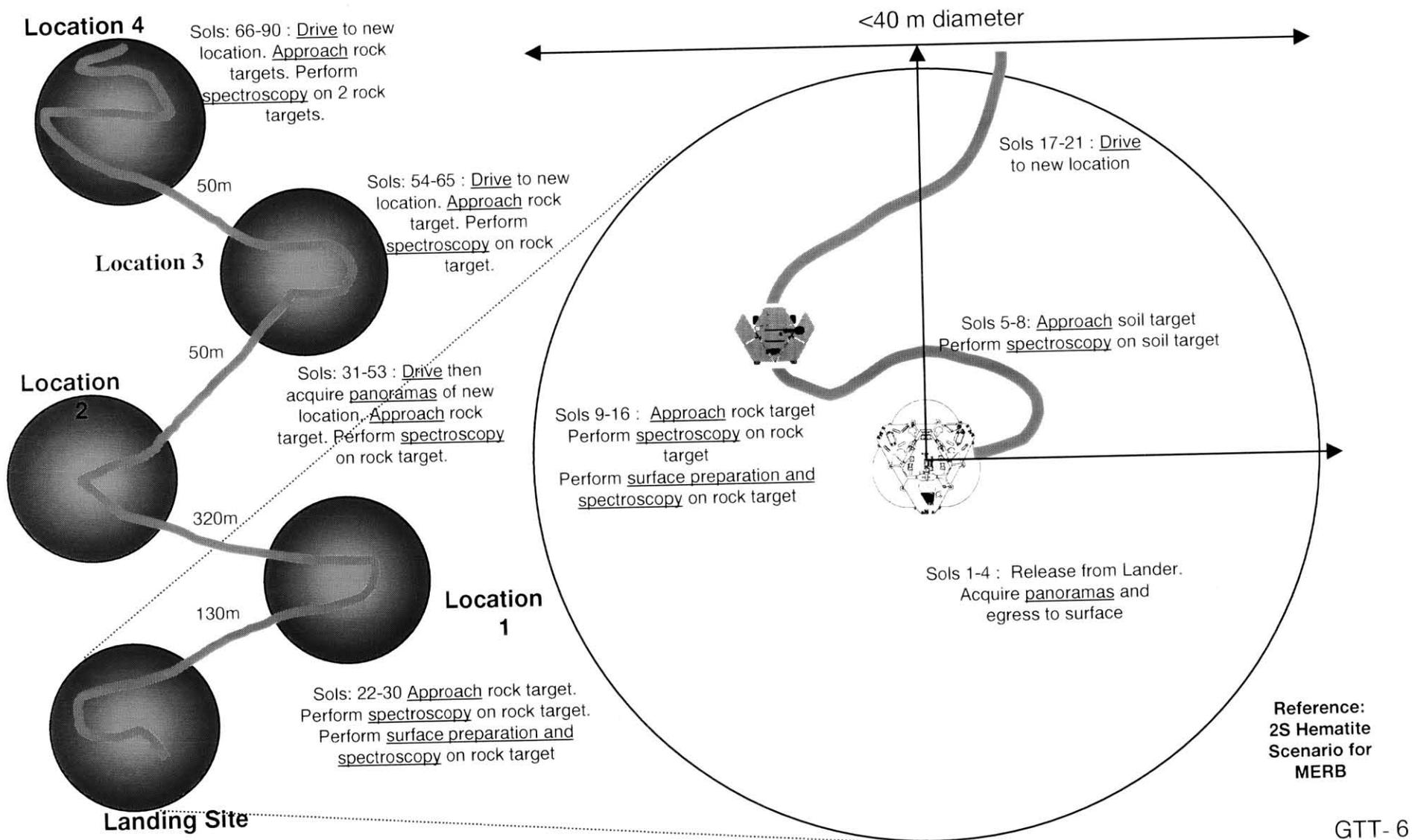
GTT- 5



Surface Scenario



Mars Exploration Rover

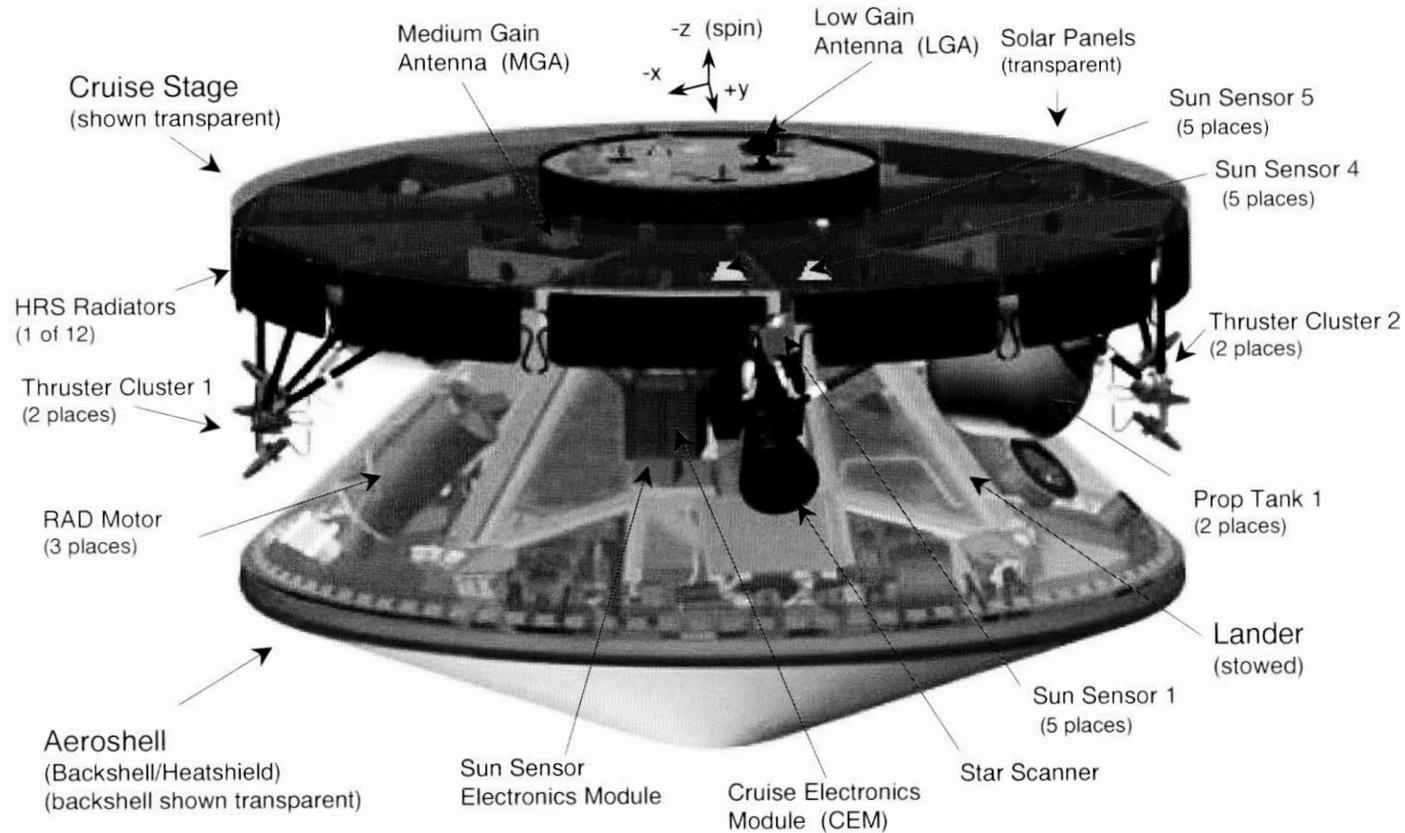




Spacecraft Cruise Configuration



Mars Exploration Rover

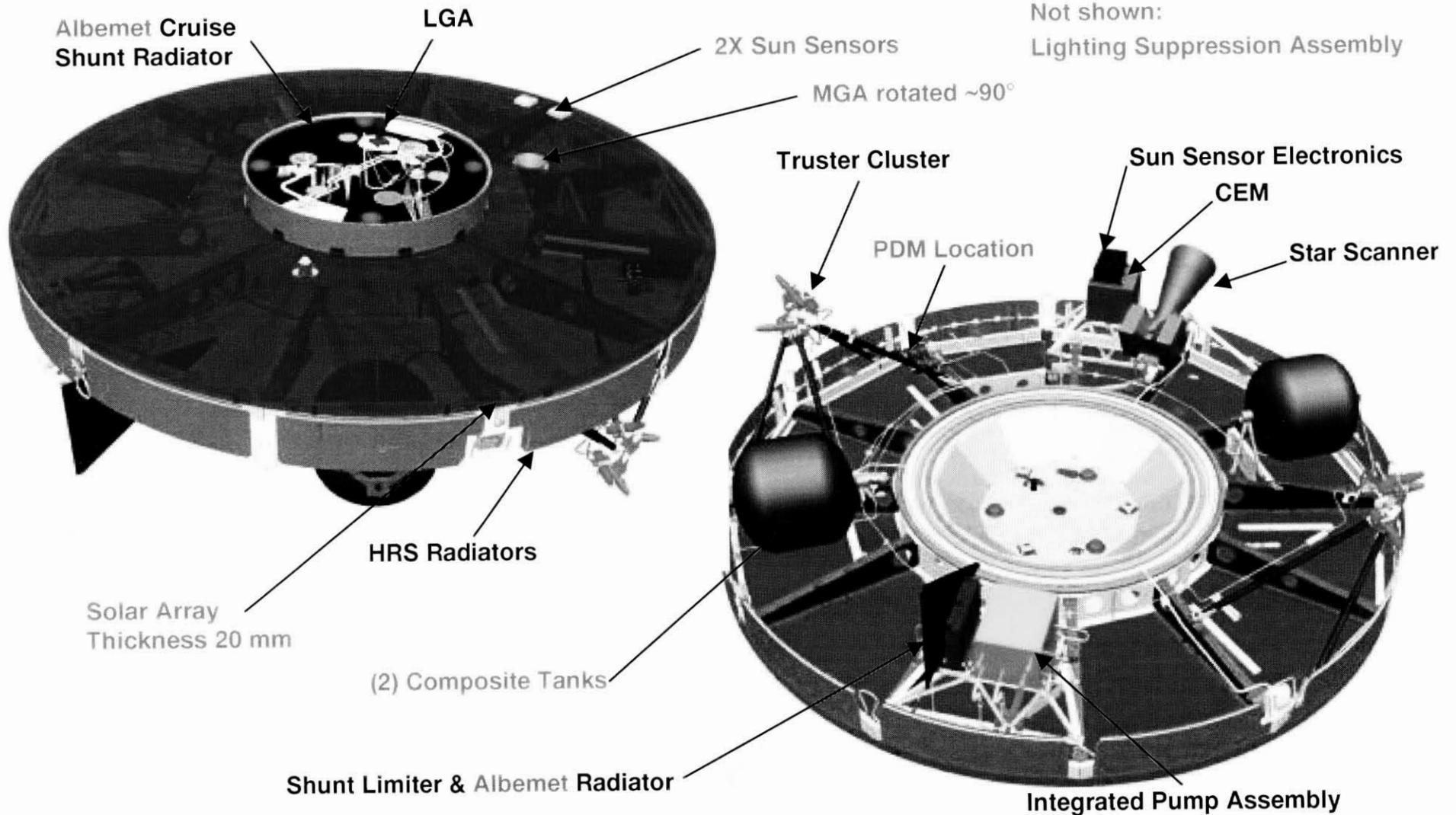




Cruise Stage Configuration



Mars Exploration Rover

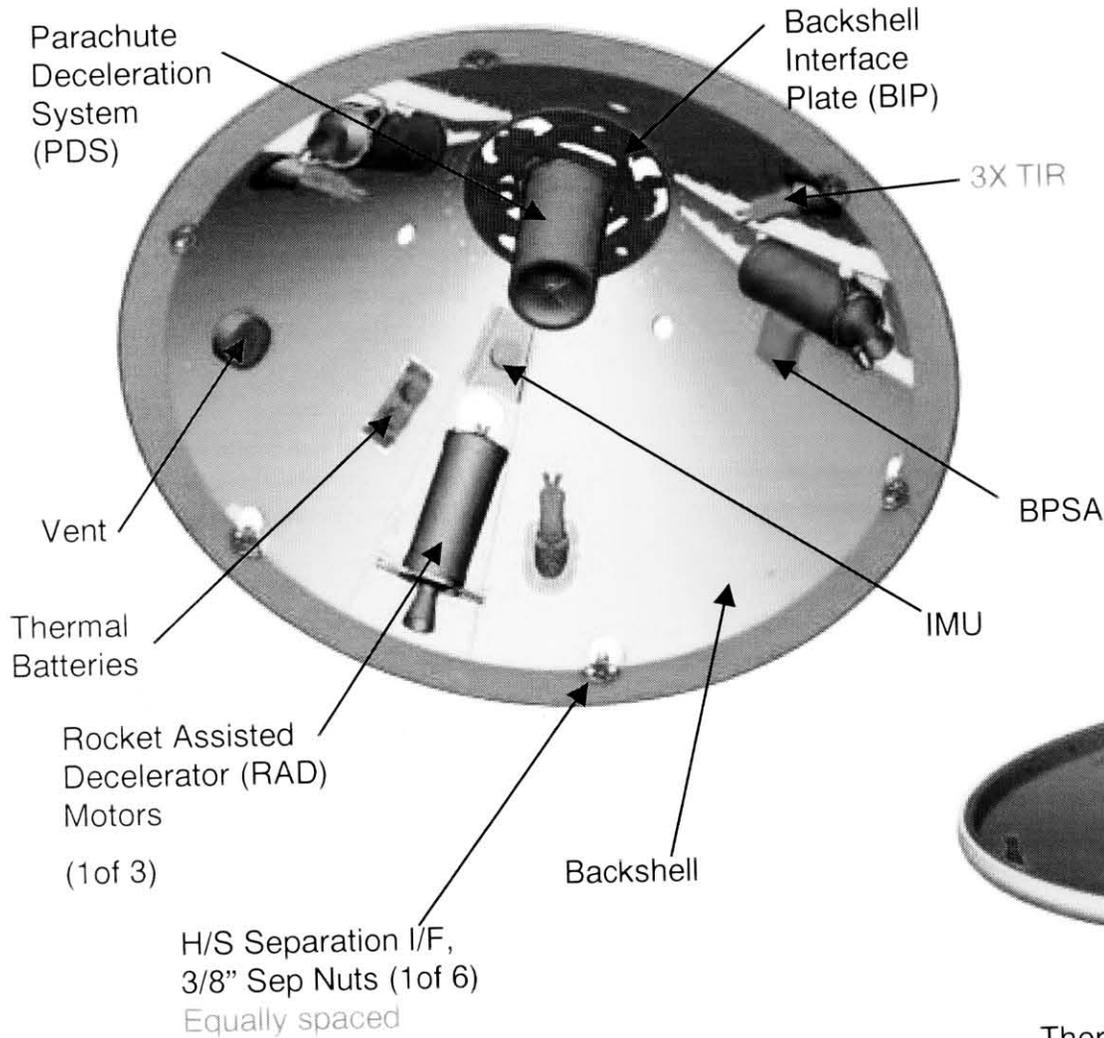




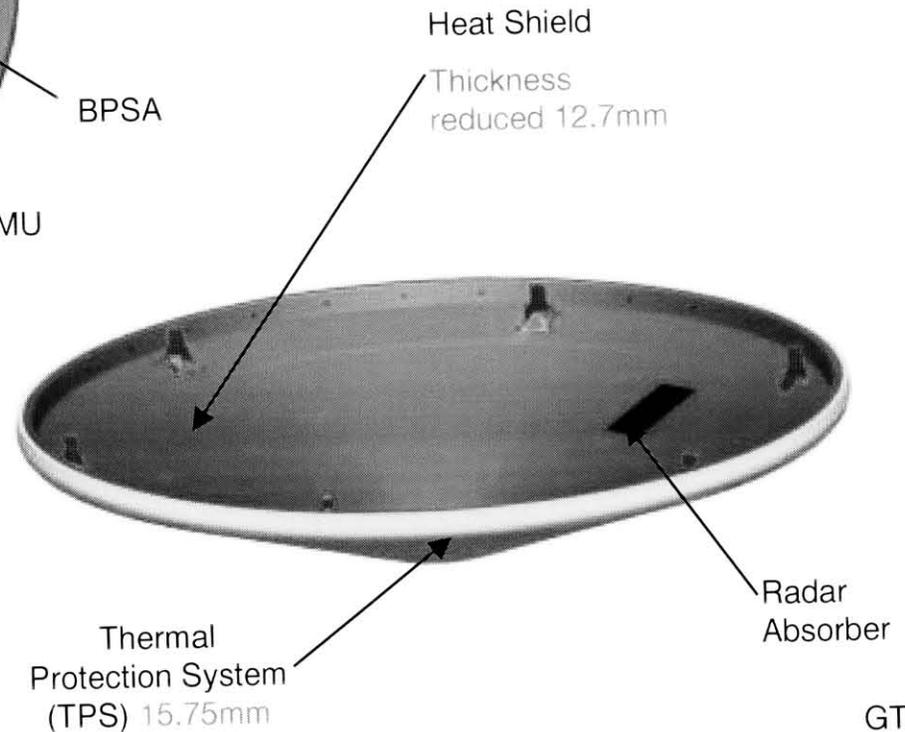
Aeroshell Configuration



Mars Exploration Rover



Note: Significant changes since PDR shown in green



Flight System CDR
August 1 & 2, 2001

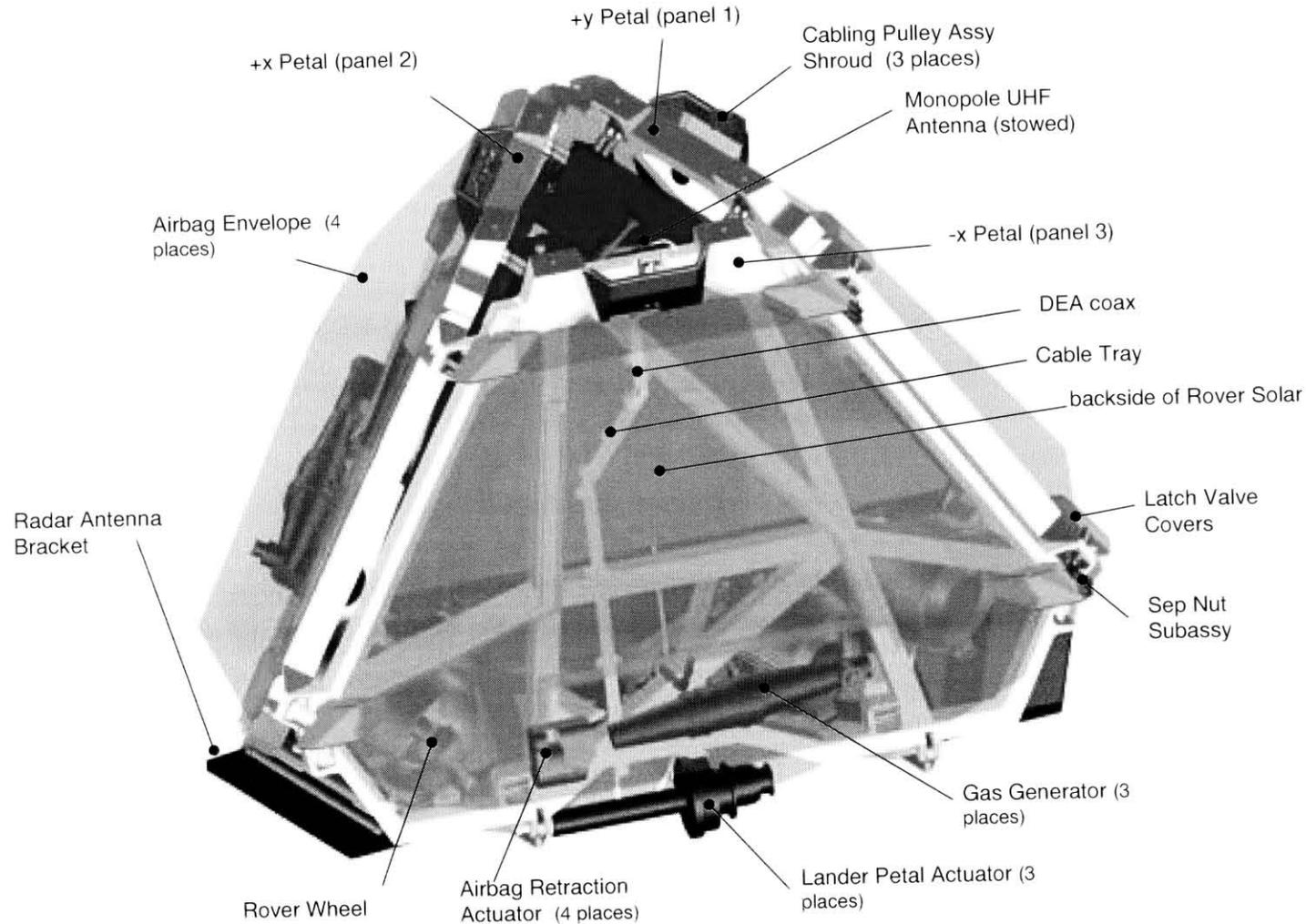
GTT-9



Lander Assembly - Stowed



Mars Exploration Rover

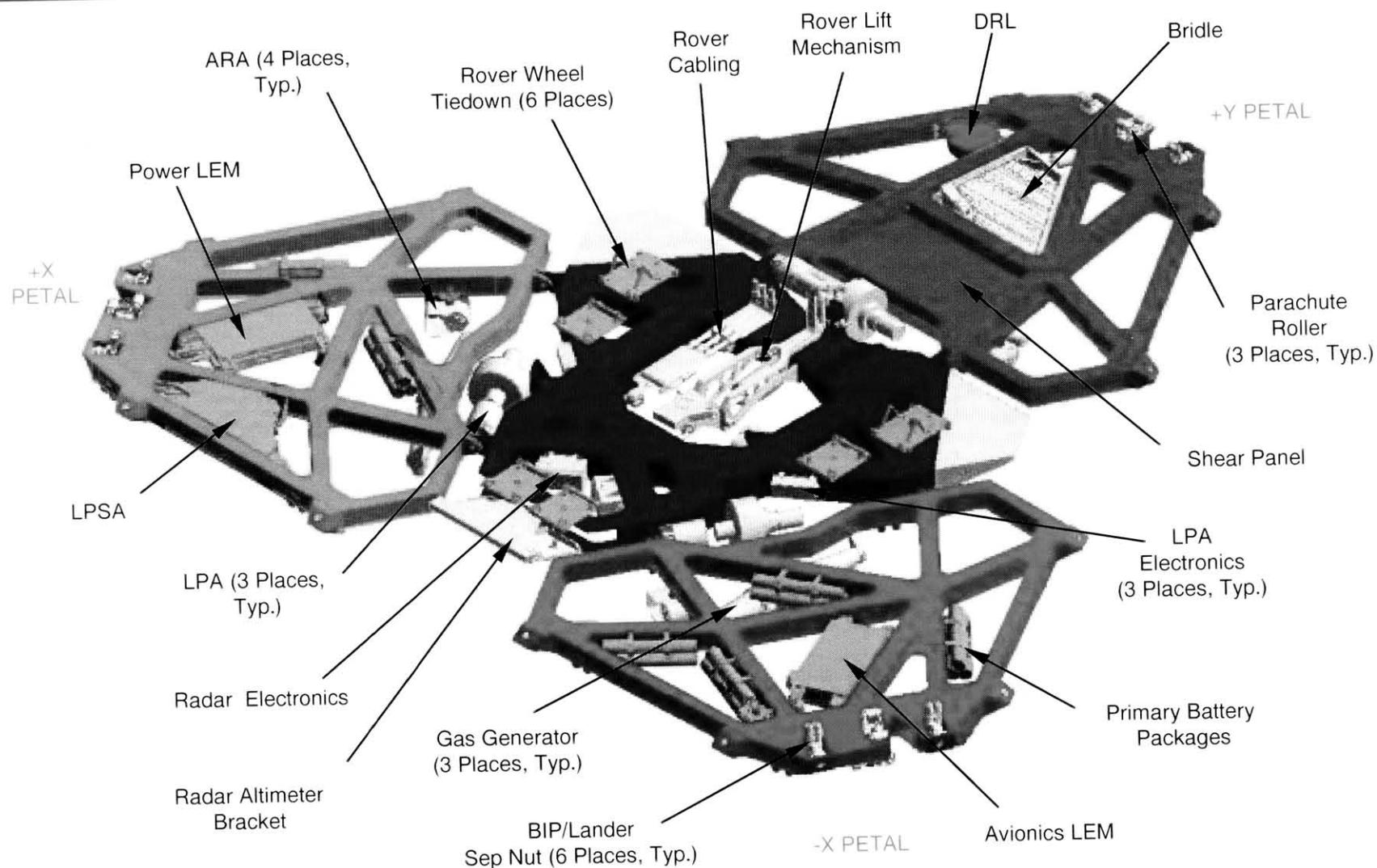




Lander Assembly - Deployed



Mars Exploration Rover

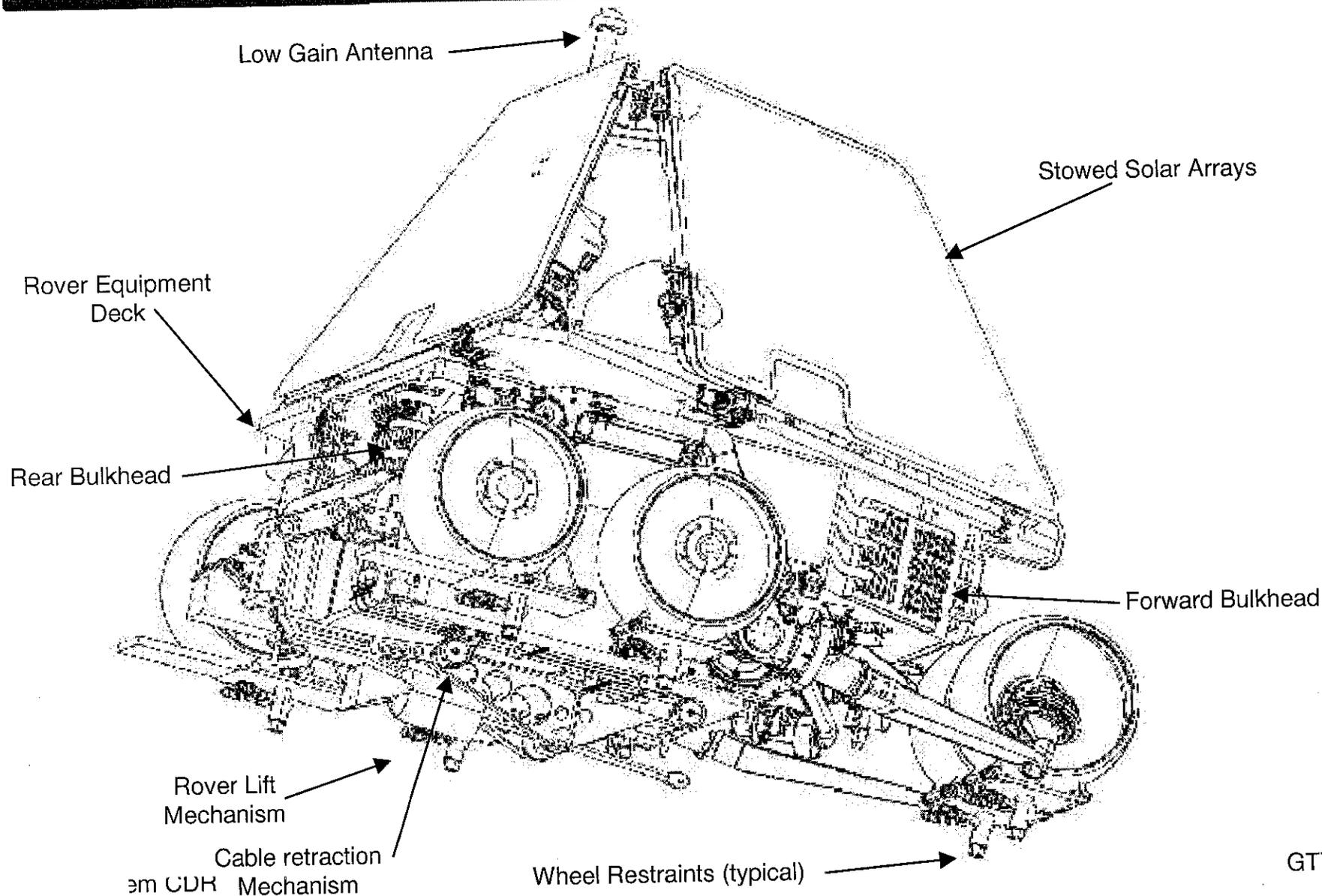




Rover - Stowed Configuration

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Mars Exploration Rover



em CDH
AUGUST 1 & 2, 2001

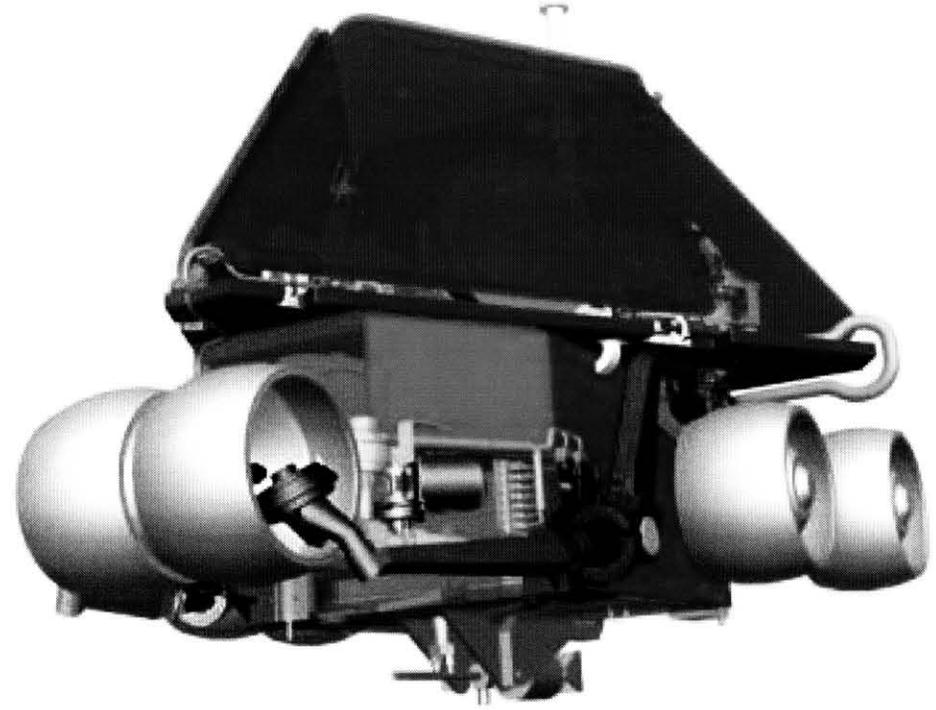
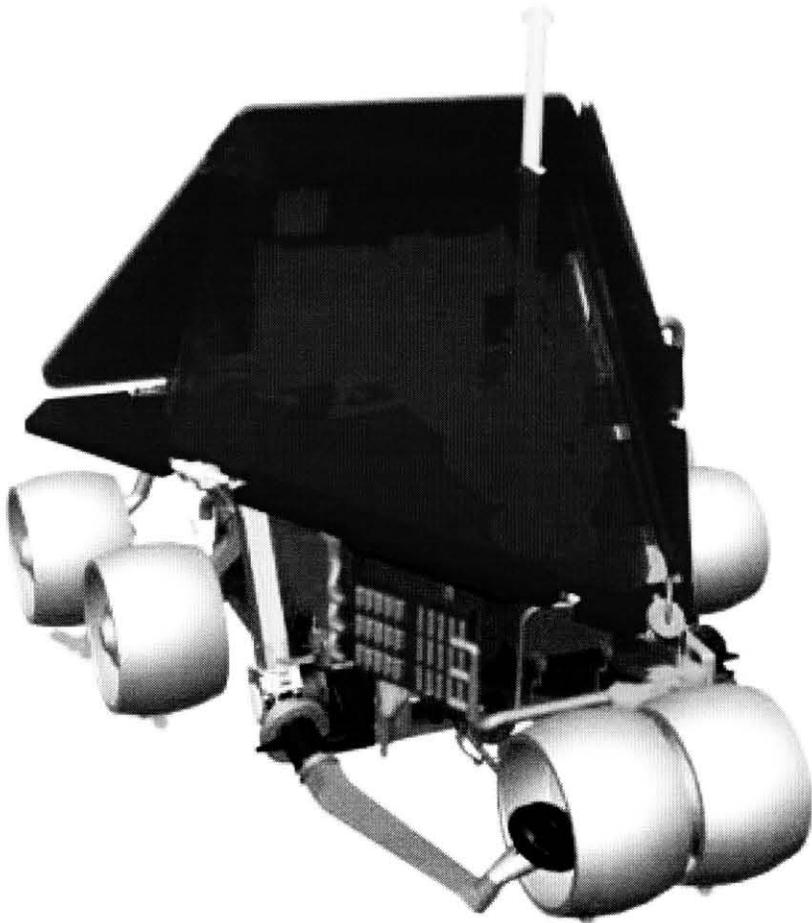
GTT- 12



Shaded Isometric Views of the Stowed Rover

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Mars Exploration Rover

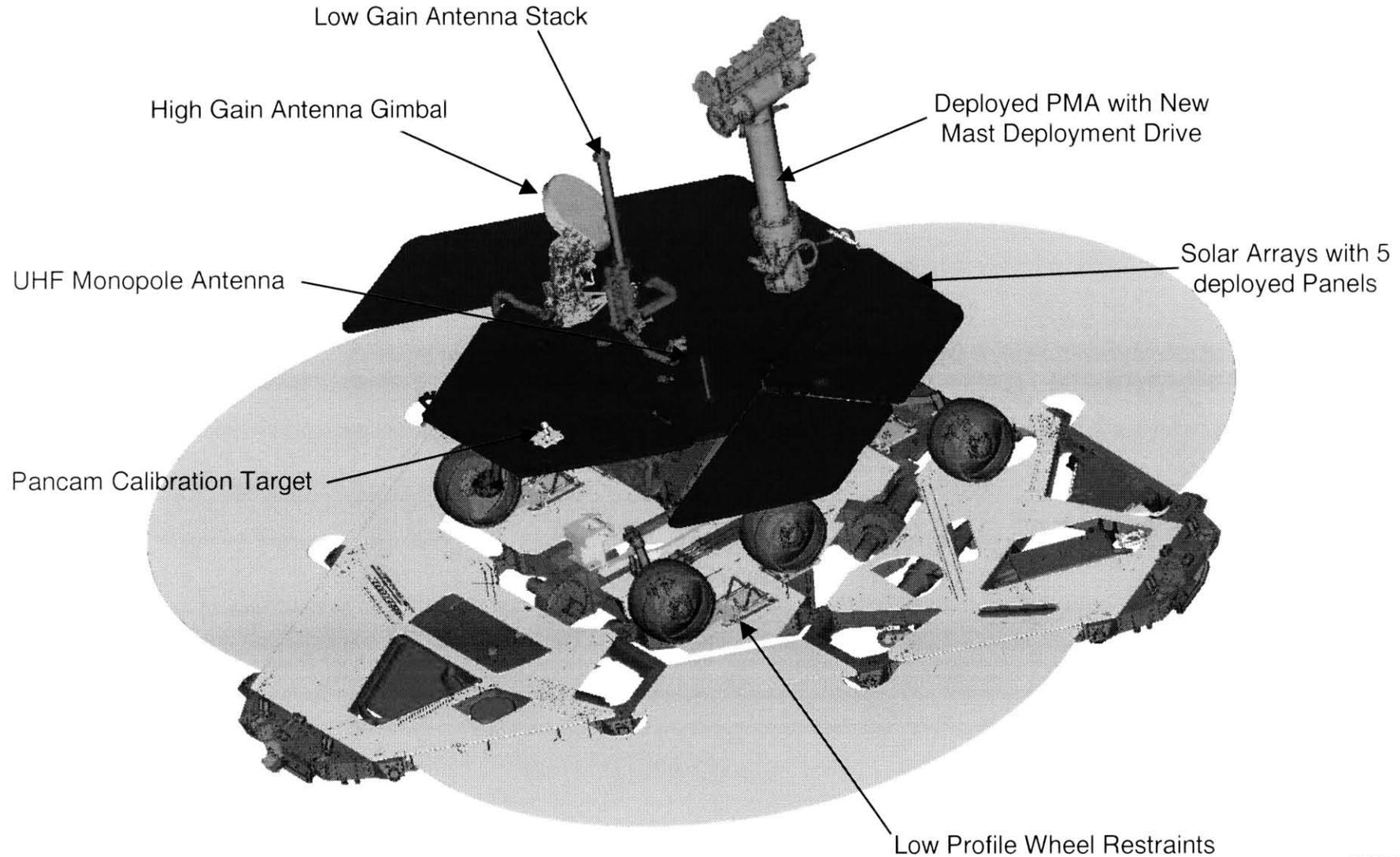




Deployed Rover on the Lander



Mars Exploration Rover

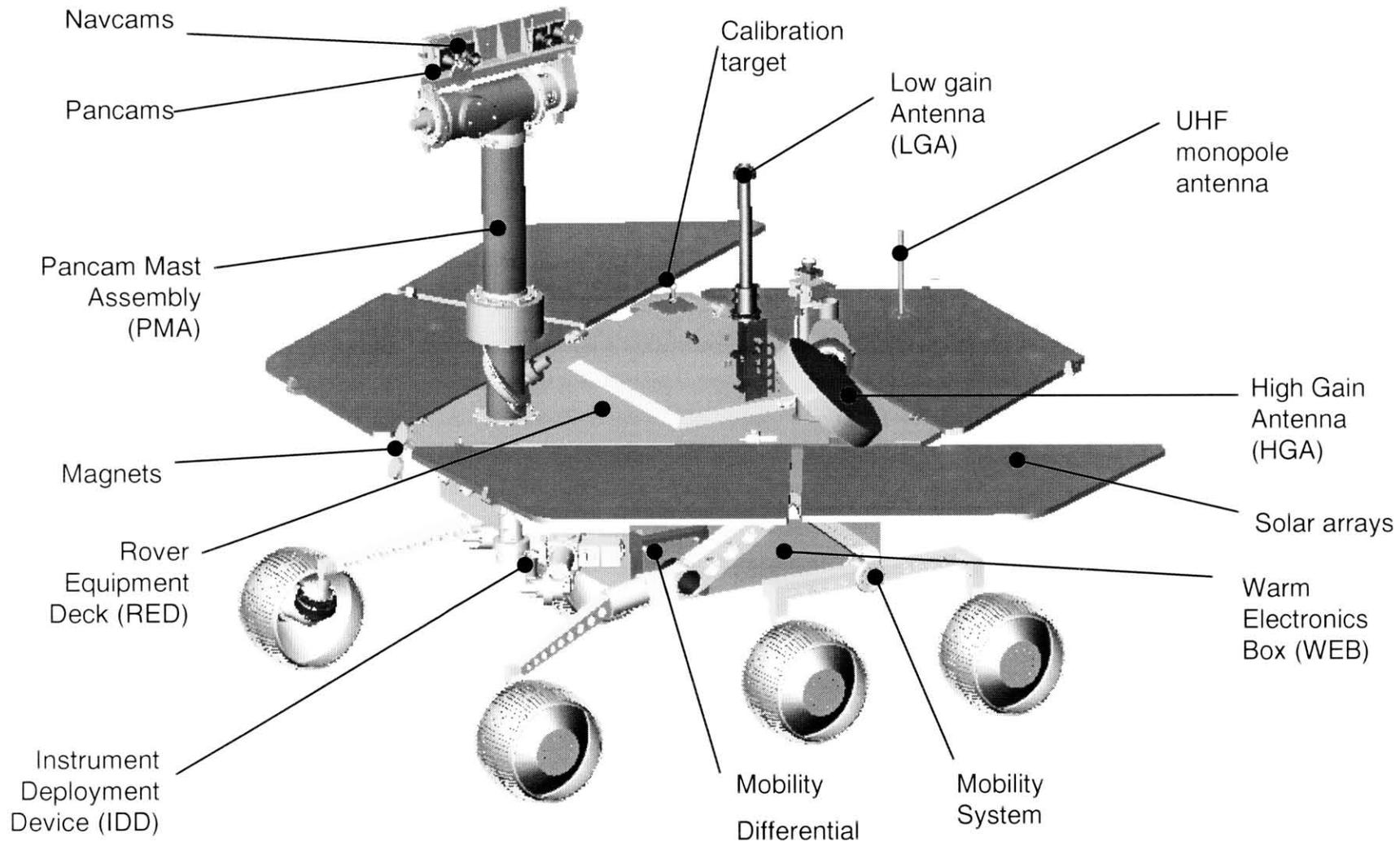




Rover Configuration - Deployed



Mars Exploration Rover

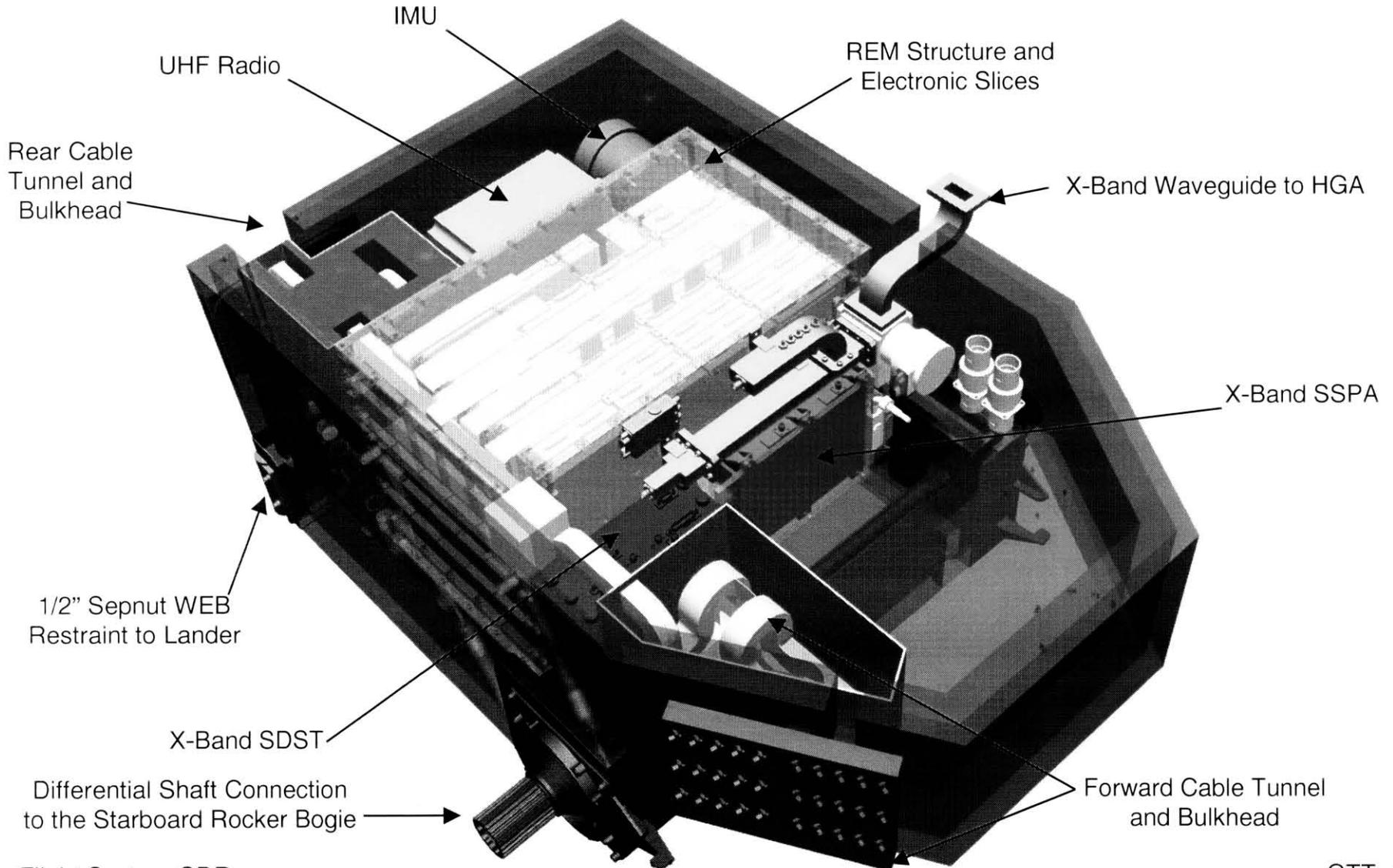




Isometric View of the WEB



Mars Exploration Rover



Flight System CDR
August 1 & 2, 2001

GTT- 16

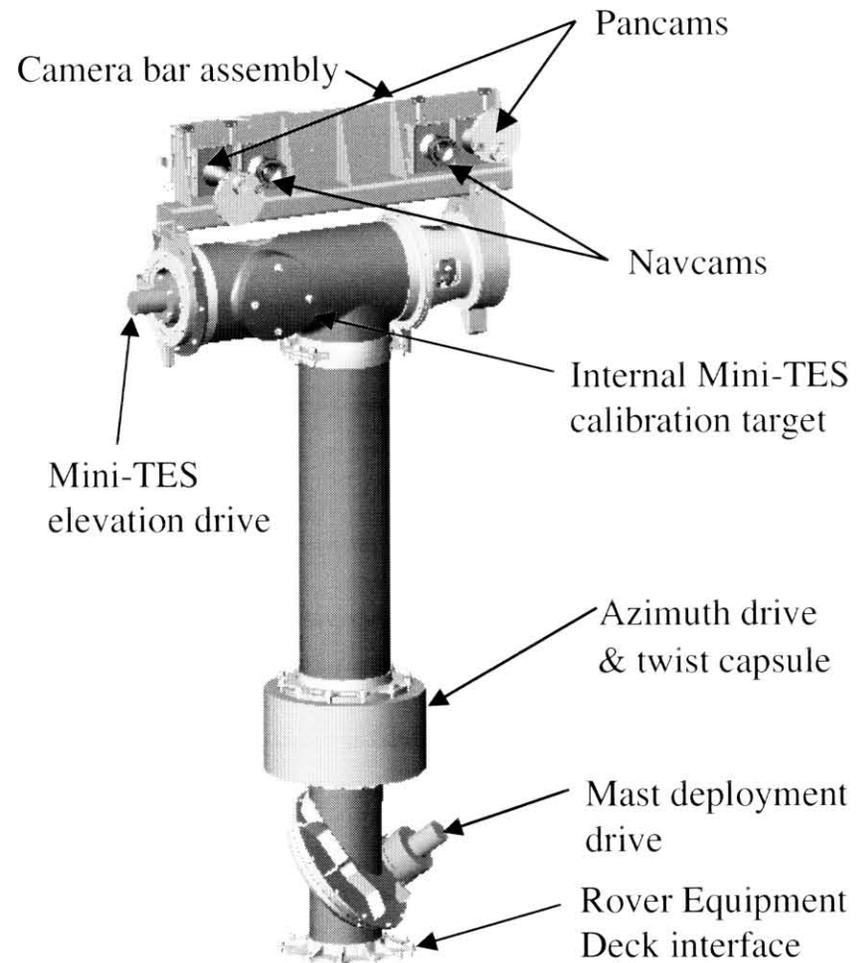


Pancams - Mast mounted stereo panoramic cameras with color filters on pan/tilt gimbal

- 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

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Mars Exploration Rover

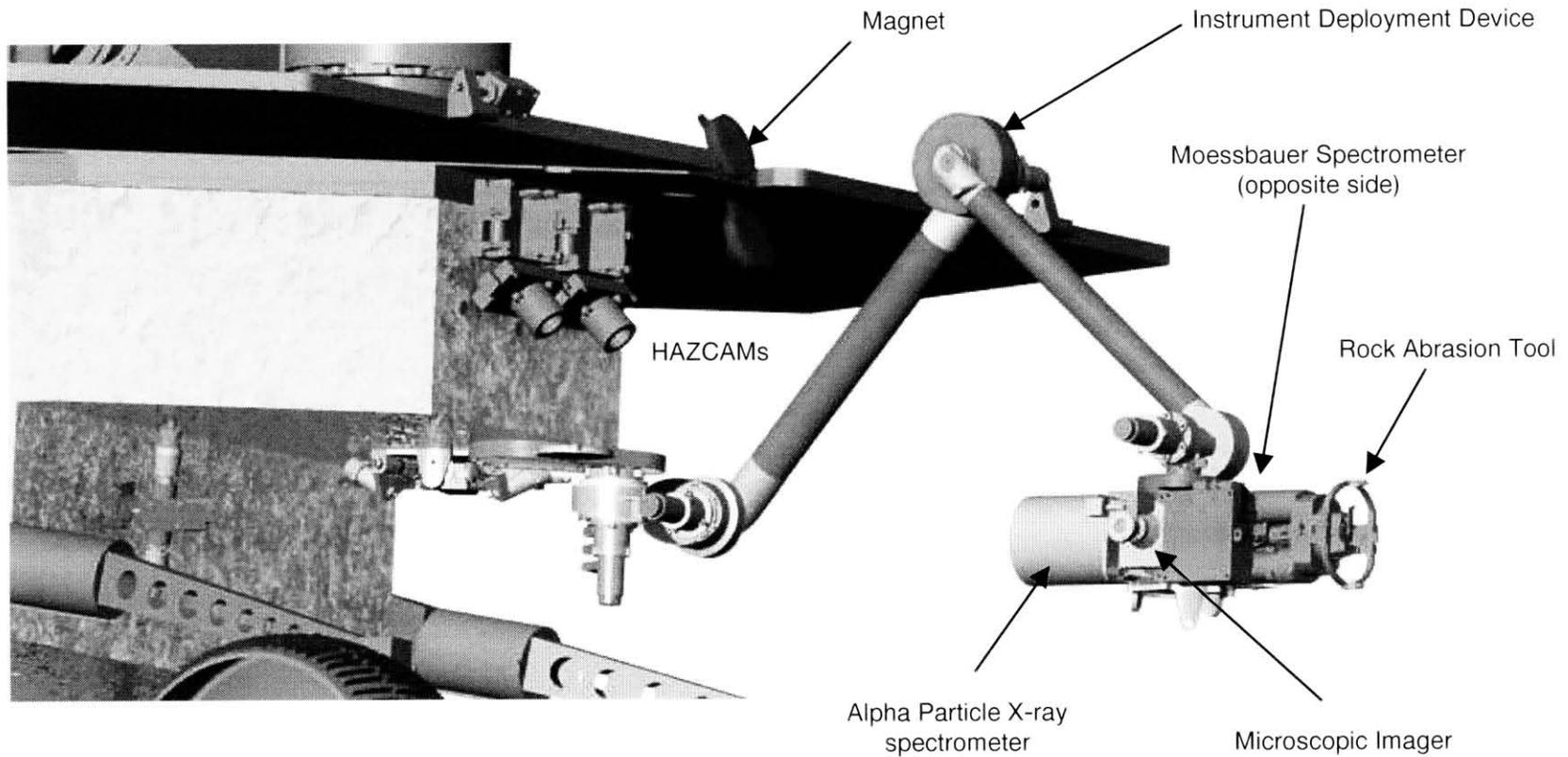
- Instrument Deployment Device (IDD) - a 5 DOF robotic arm for deployment of 3 in situ science instruments and a Rock Abrasion Tool (RAT) against rock and soil targets
 - Microscopic Imager (MI)- 1024x1024x12bit camera with 30 μm /pixel resolution with 3 mm depth of field
 - Alpha Particle X-ray Spectrometer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

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Mars Exploration Rover



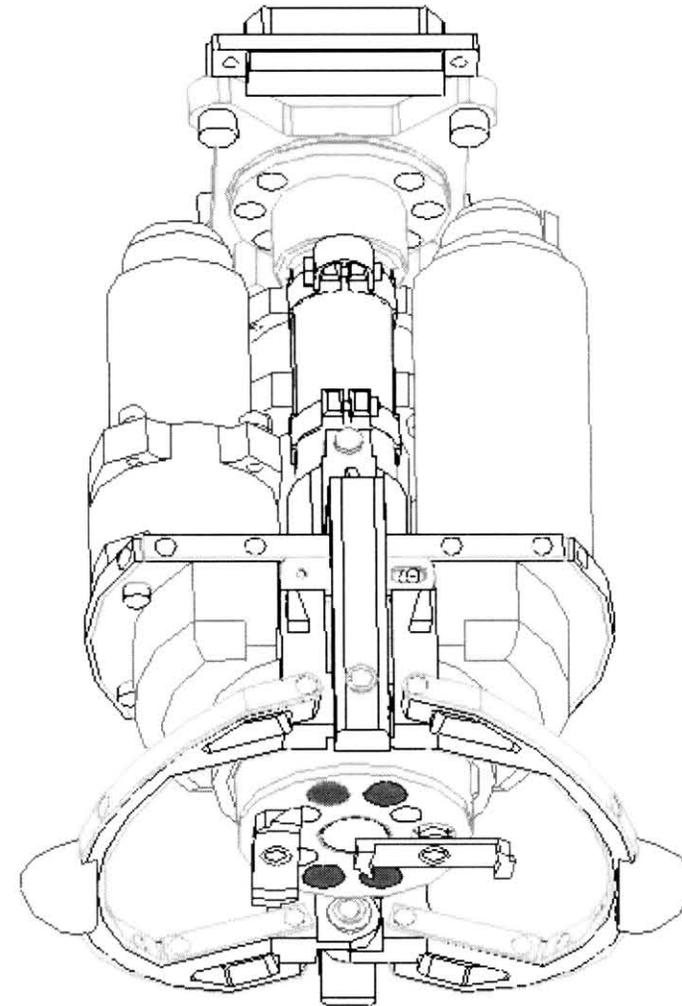
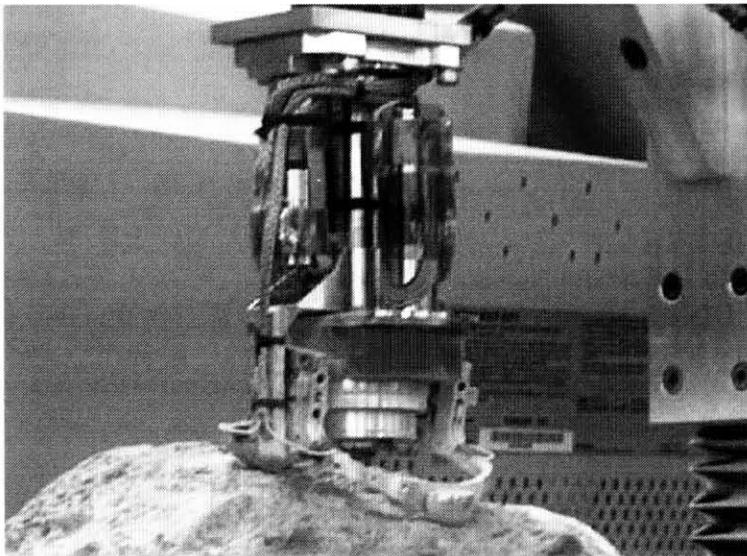


Rock Abrasion Tool



Mars Exploration Rover

- **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



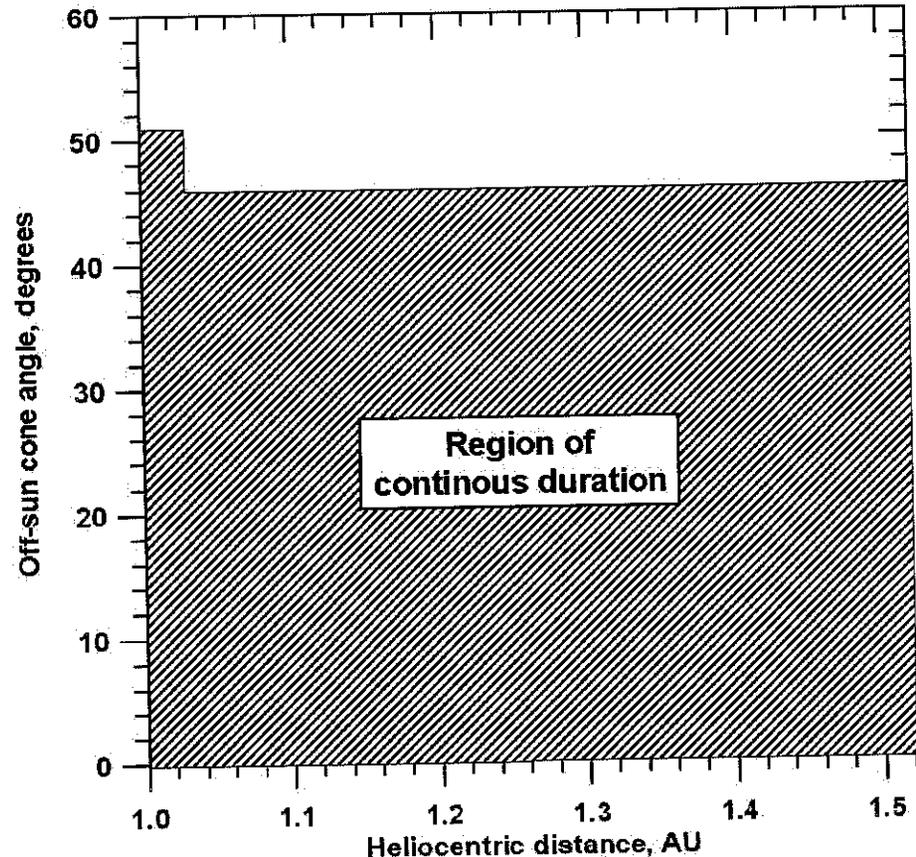


Thermal Environment



Mars Exploration Rover

- **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)

JPL

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/m²
 - 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



Mars Exploration Rover

- **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)



Mars Exploration Rover

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

<i>DOORS ID</i>	<i>Requirement</i>	<i>Status</i>
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**

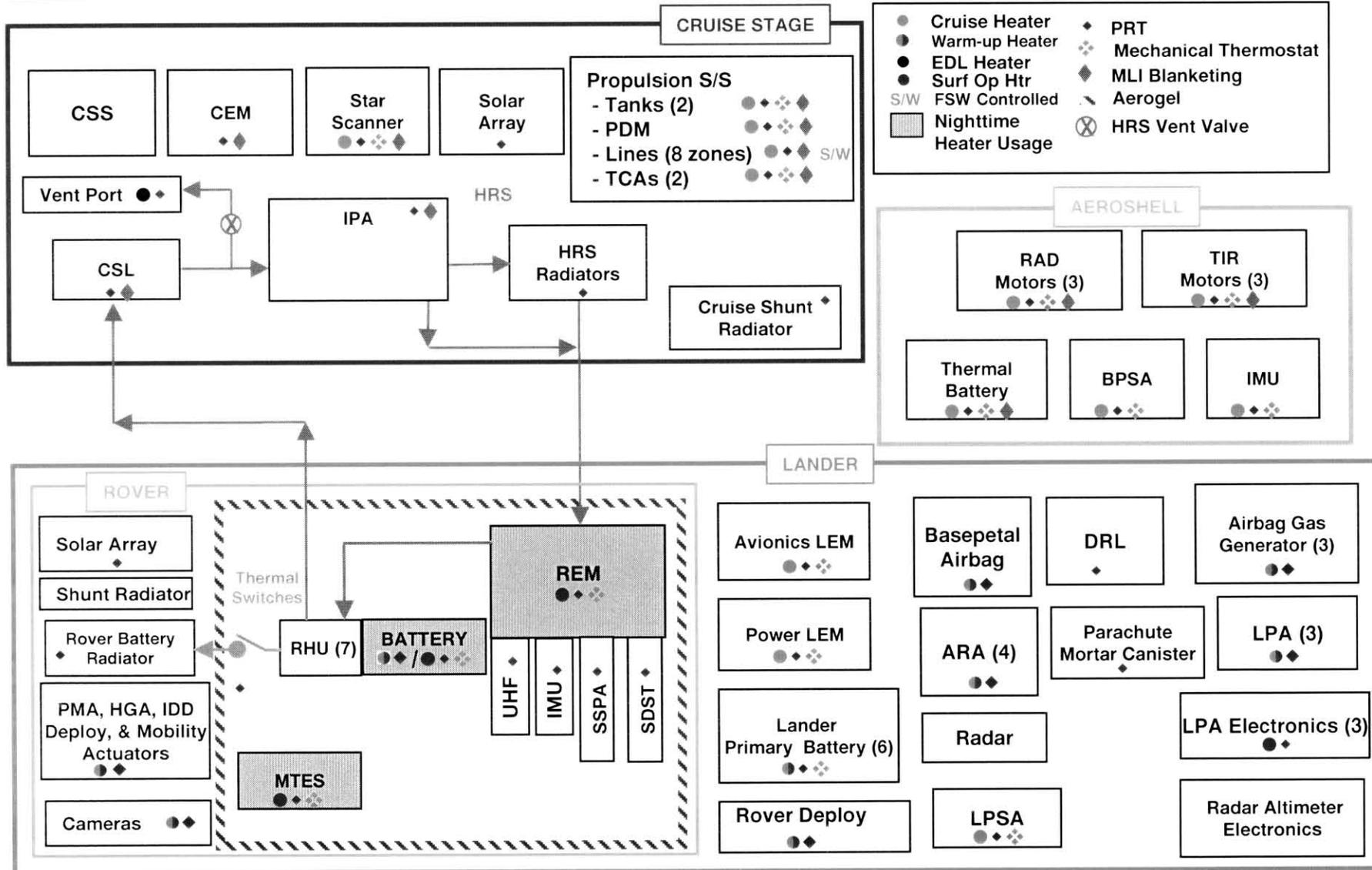
<i>DOORS ID</i>	<i>Requirement</i>	<i>Status</i>
607	The Flight System shall be capable of operating the HGA actuators at 10 am Mars local time without additional warmup.	Comply by design & analysis



System Thermal Block Diagram



Mars Exploration Rover

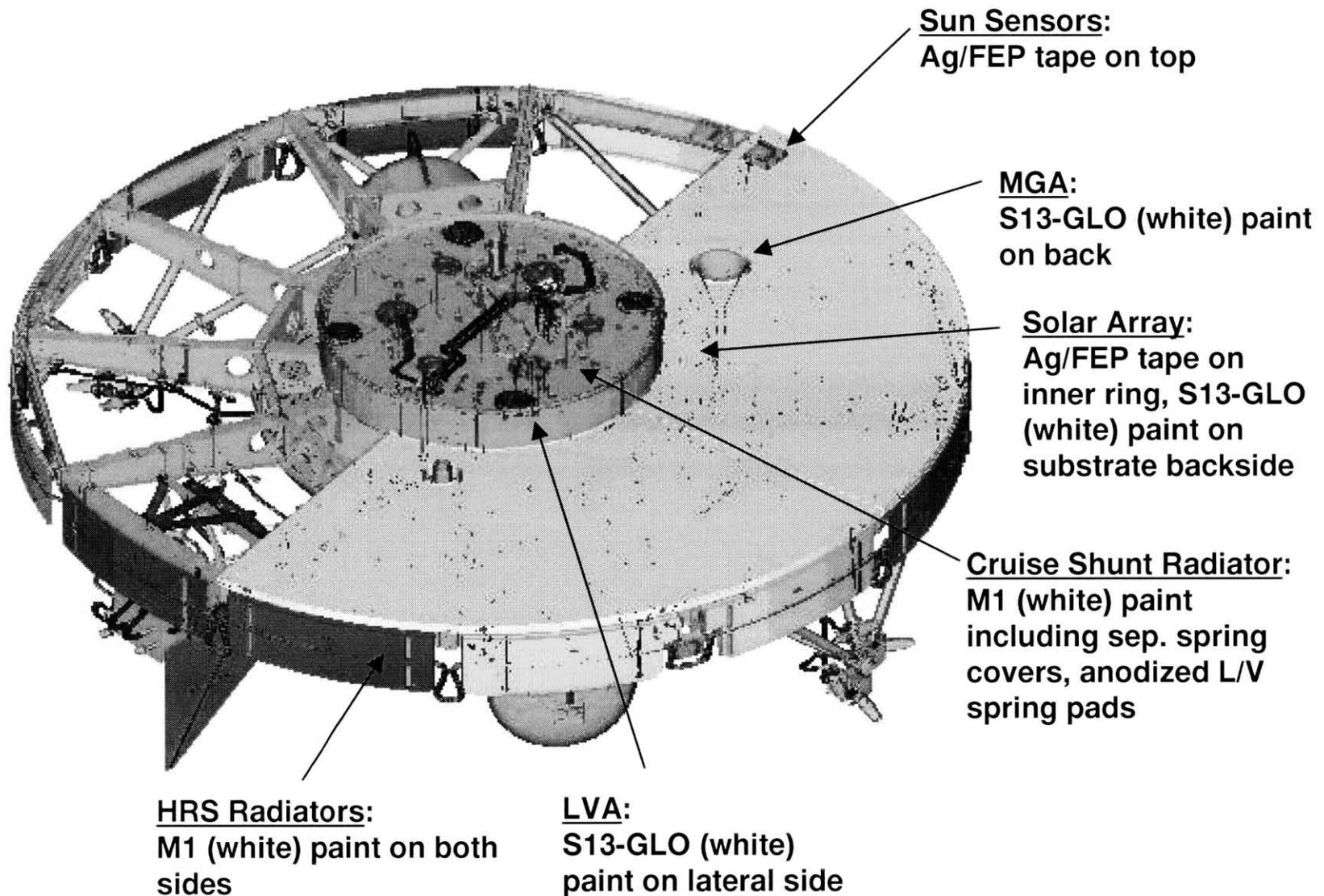




Cruise Stage Thermal Design Overview



Mars Exploration Rover

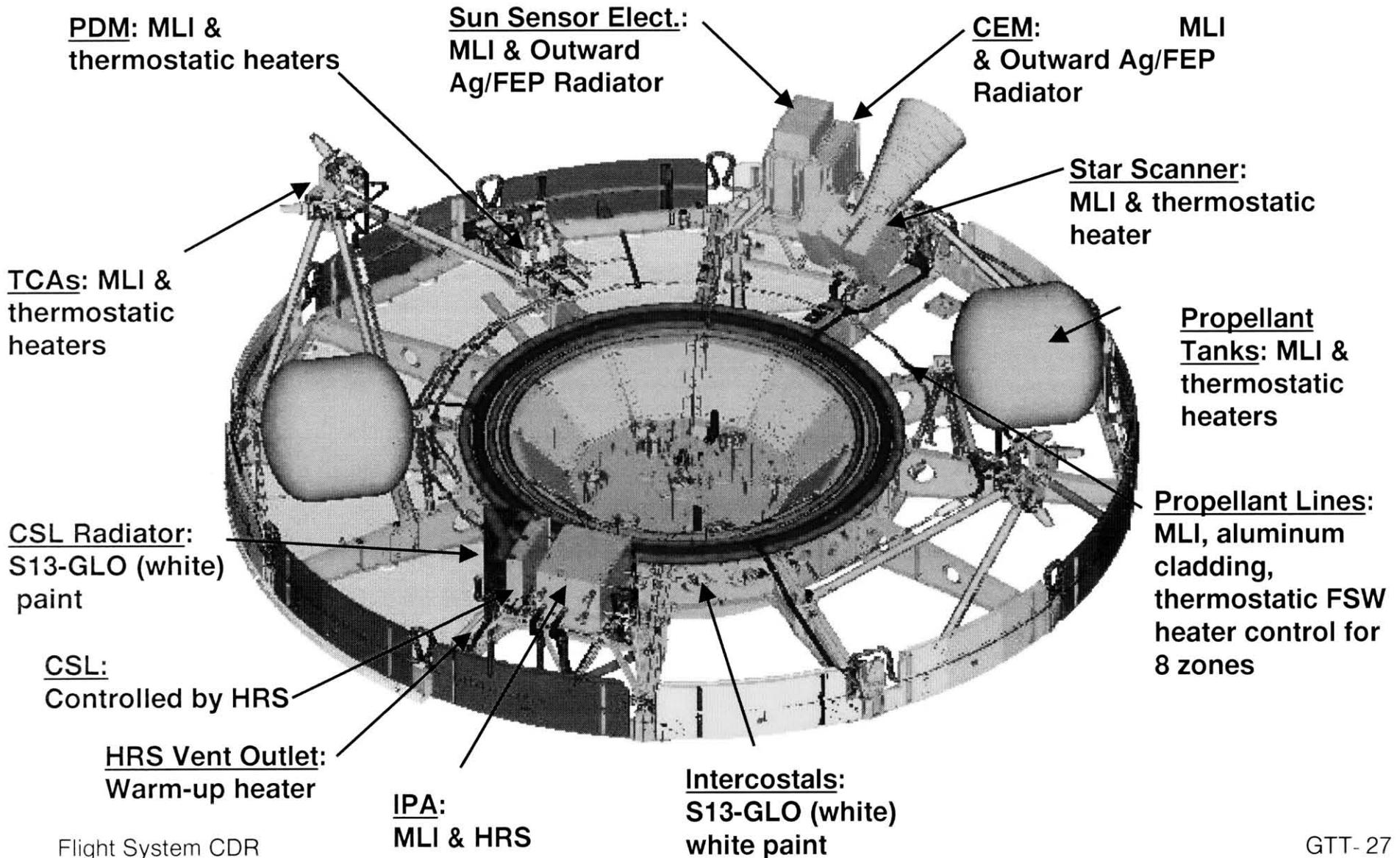




Cruise Stage Thermal Design Overview (cont'd)



Mars Exploration Rover

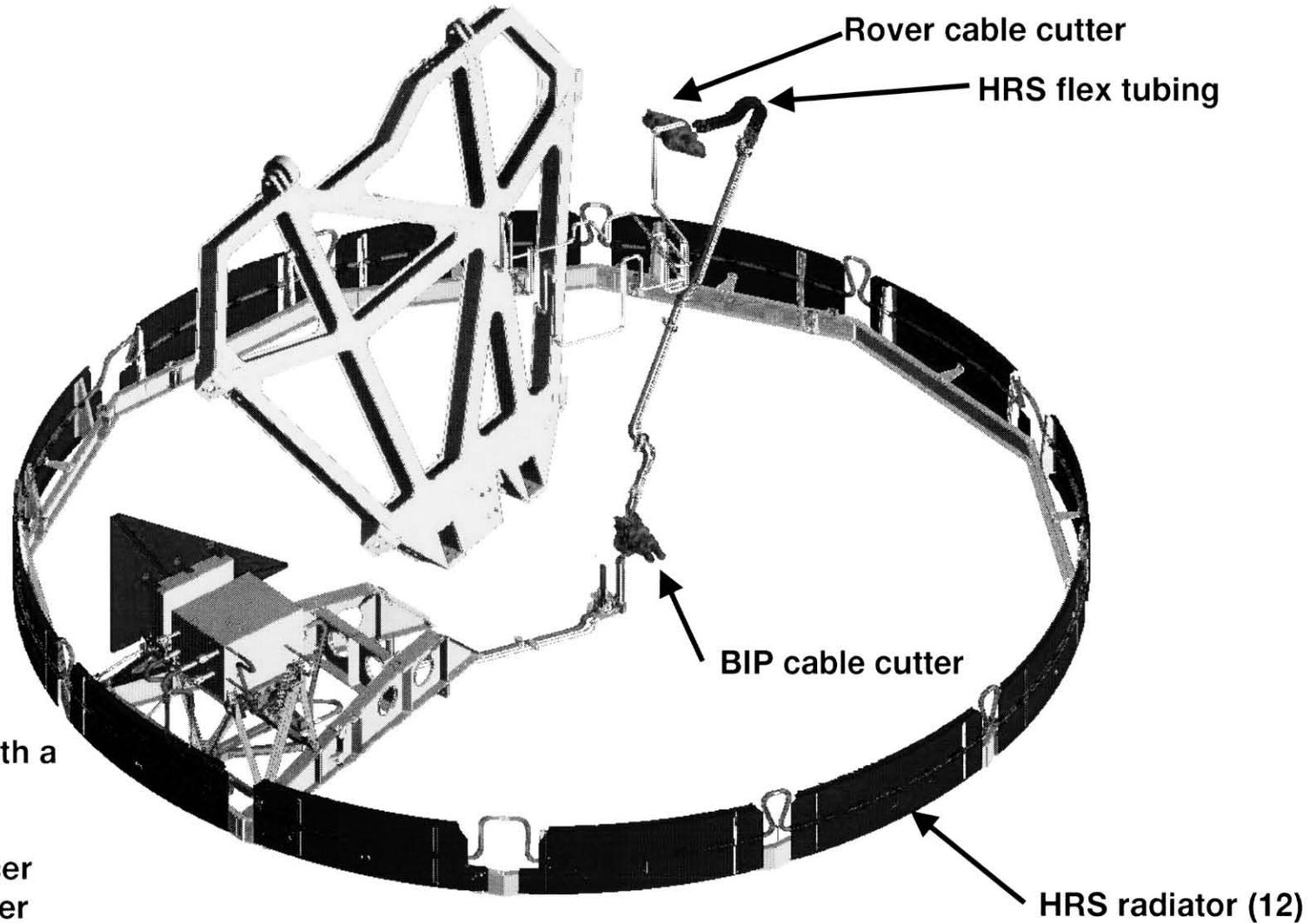




HRS Overview



Mars Exploration Rover



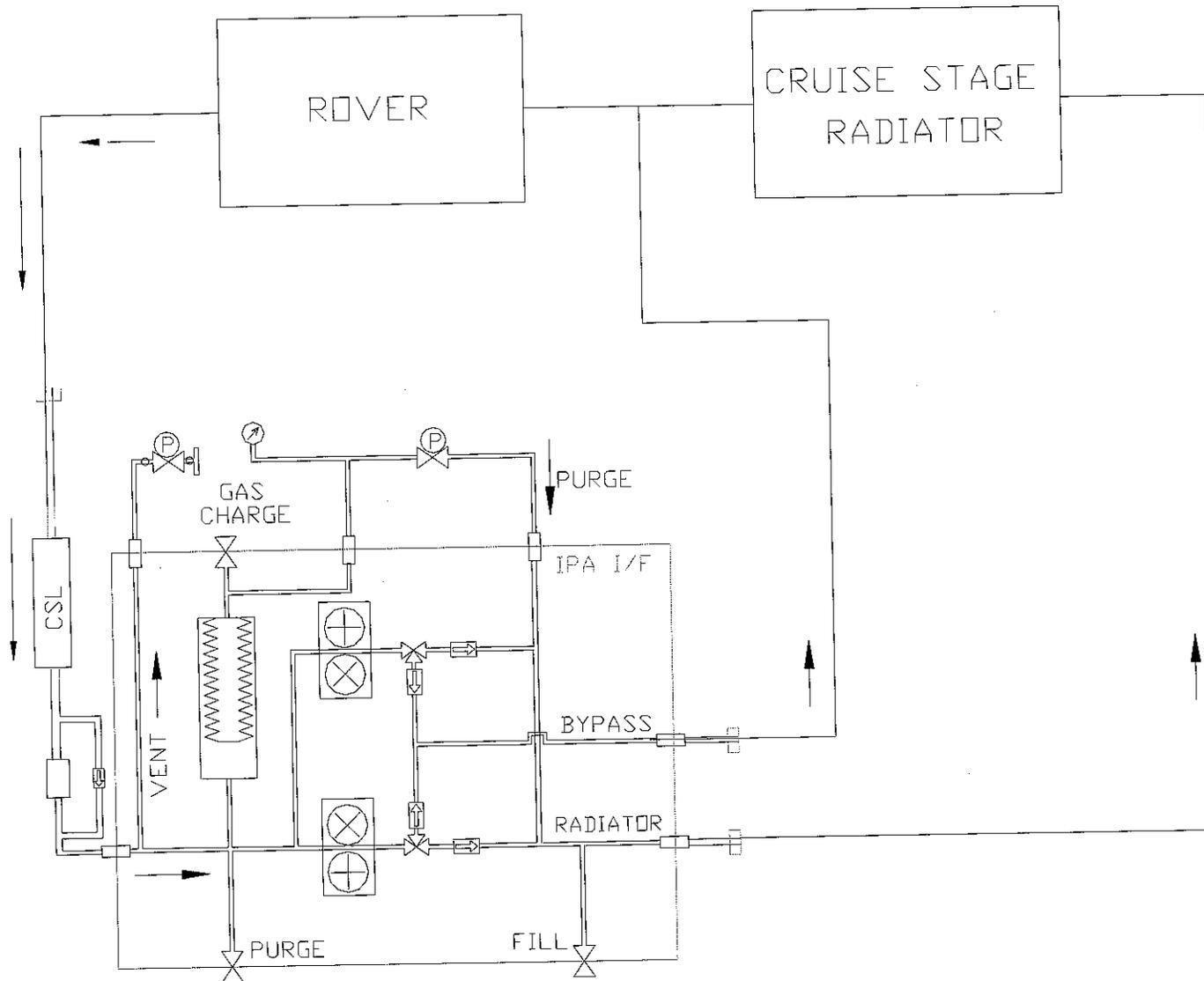
IVSR consists of:
IVSR structure
IPA
2 Pyro valves
Filter in parallel with a relief valve
Vent outlet
Pressure transducer
CSL heat exchanger
CSL "shark fin" radiator



HRS Schematic



Mars Exploration Rover

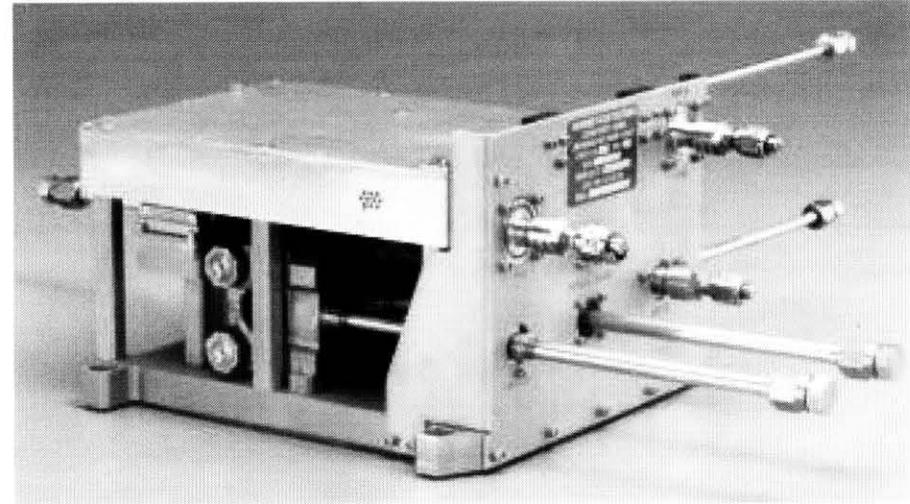
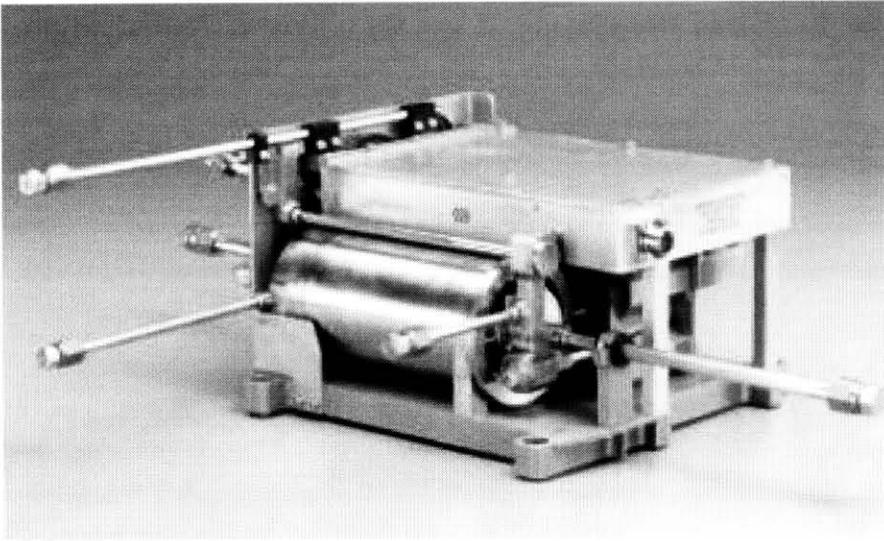




Integrated Pump Assembly



Mars Exploration Rover



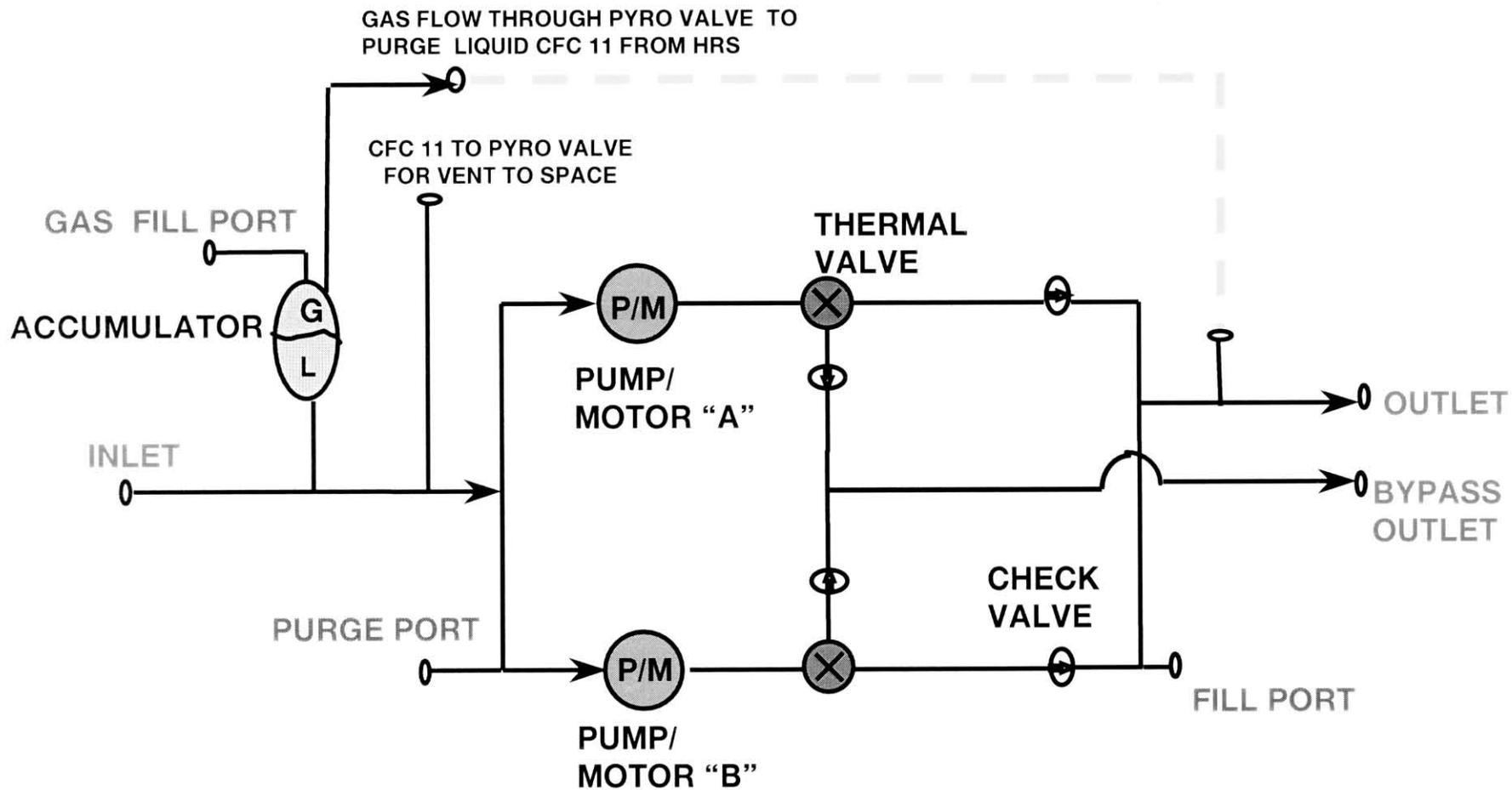
- Mars Pathfinder IPA shown
- MER adopted a Mars Pathfinder build-to-print approach for the IPA



IPA Schematic



Mars Exploration Rover

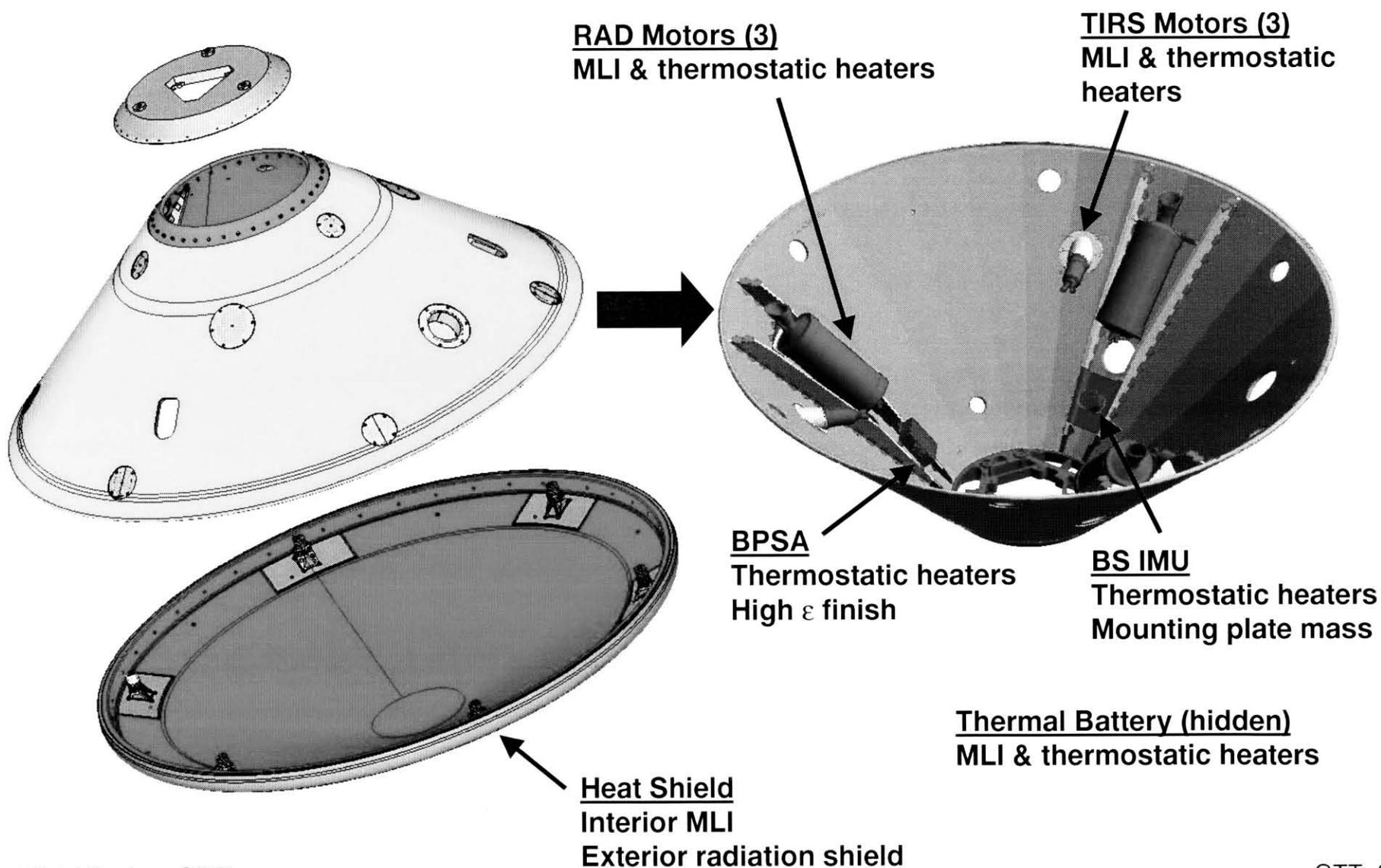




Aeroshell Thermal Design Overview



Mars Exploration Rover

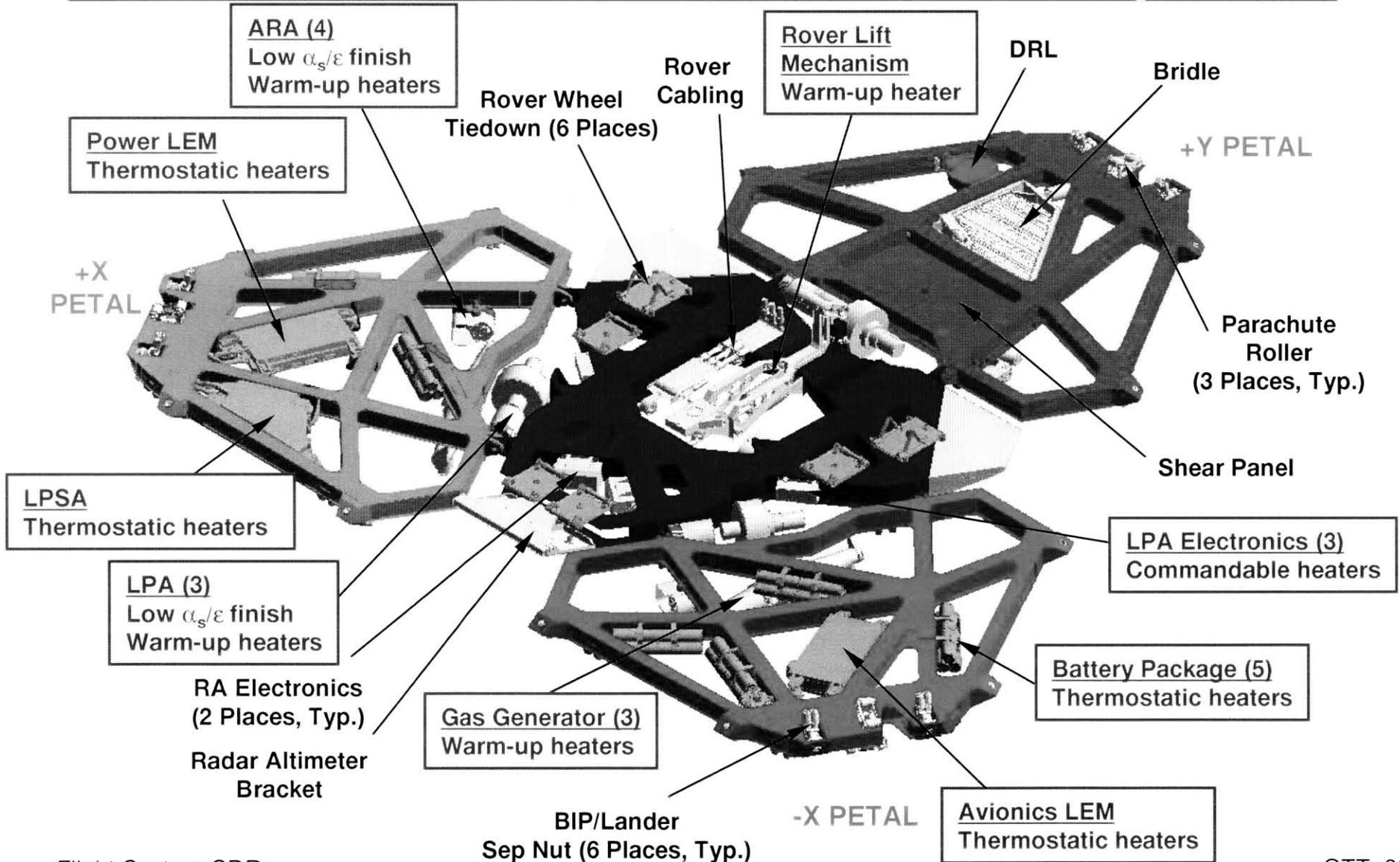




Lander Thermal Design Overview



Mars Exploration Rover

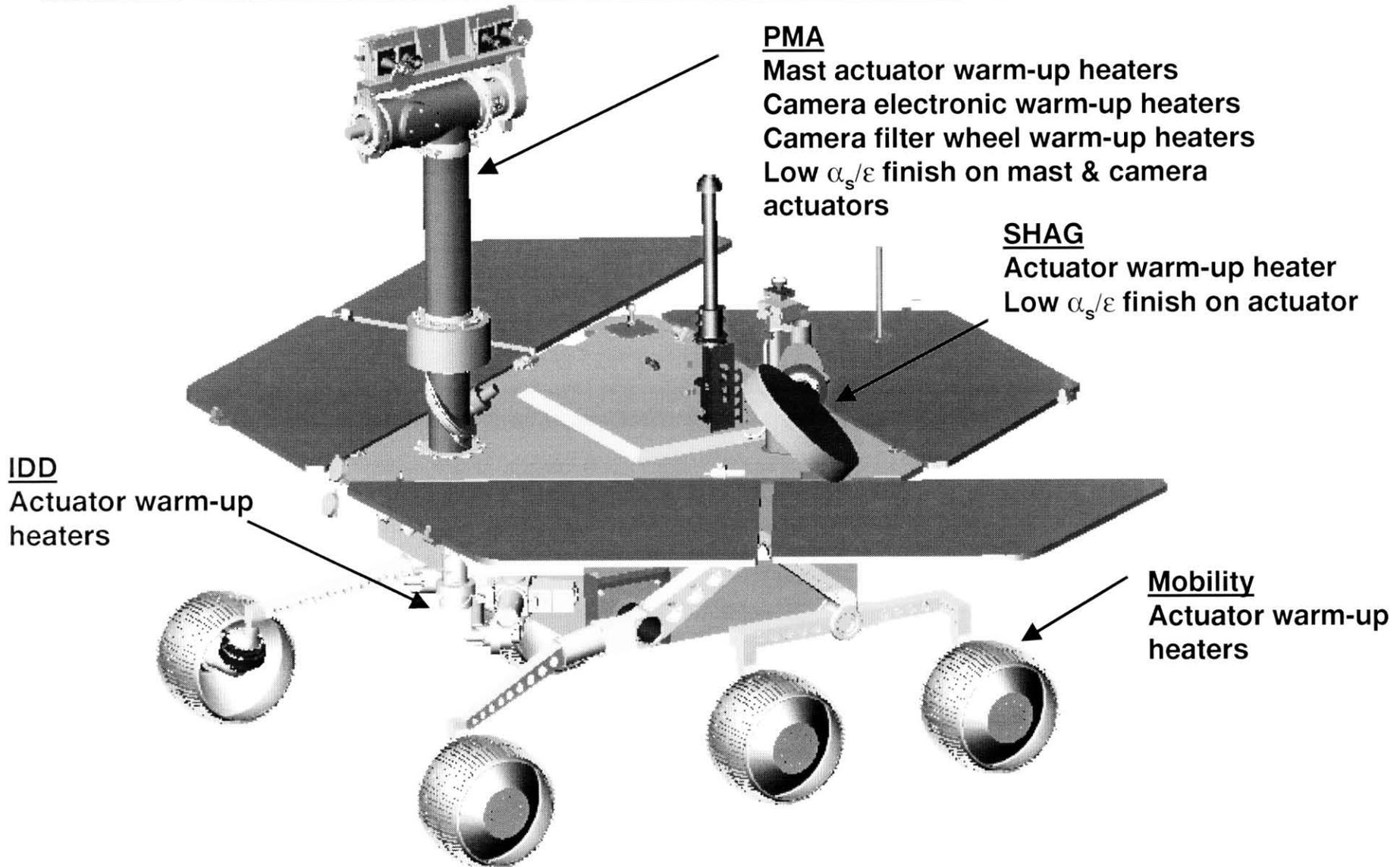




Rover Thermal Design Overview



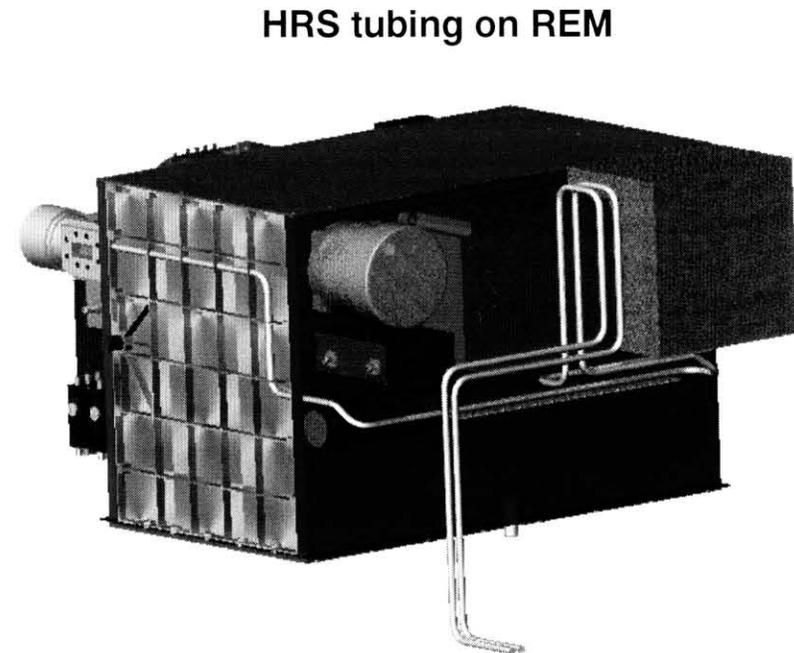
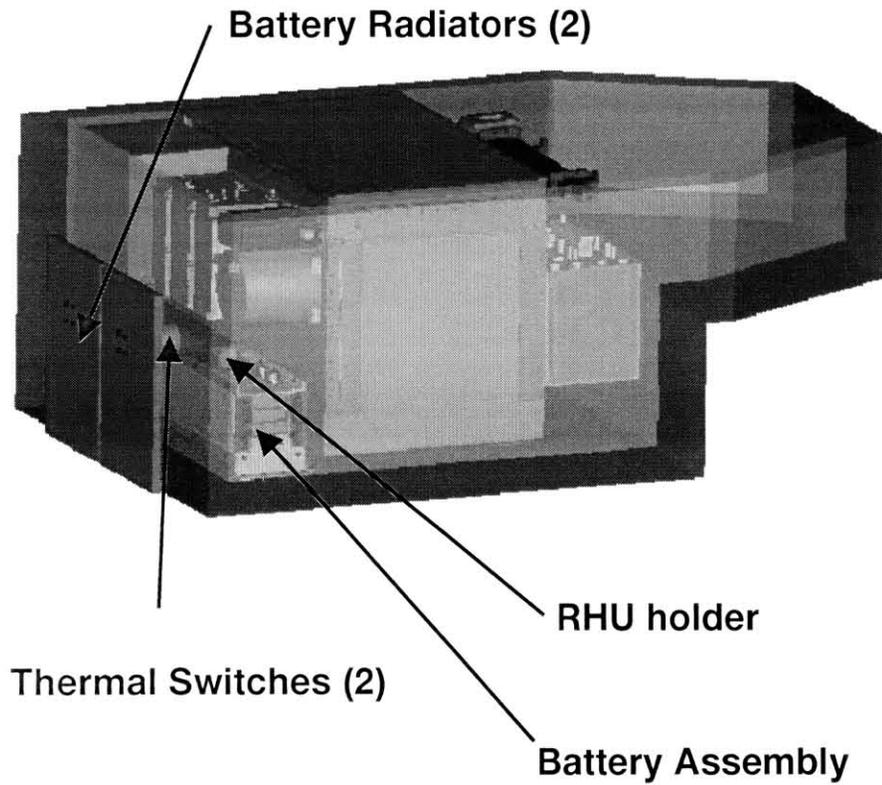
Mars Exploration Rover





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



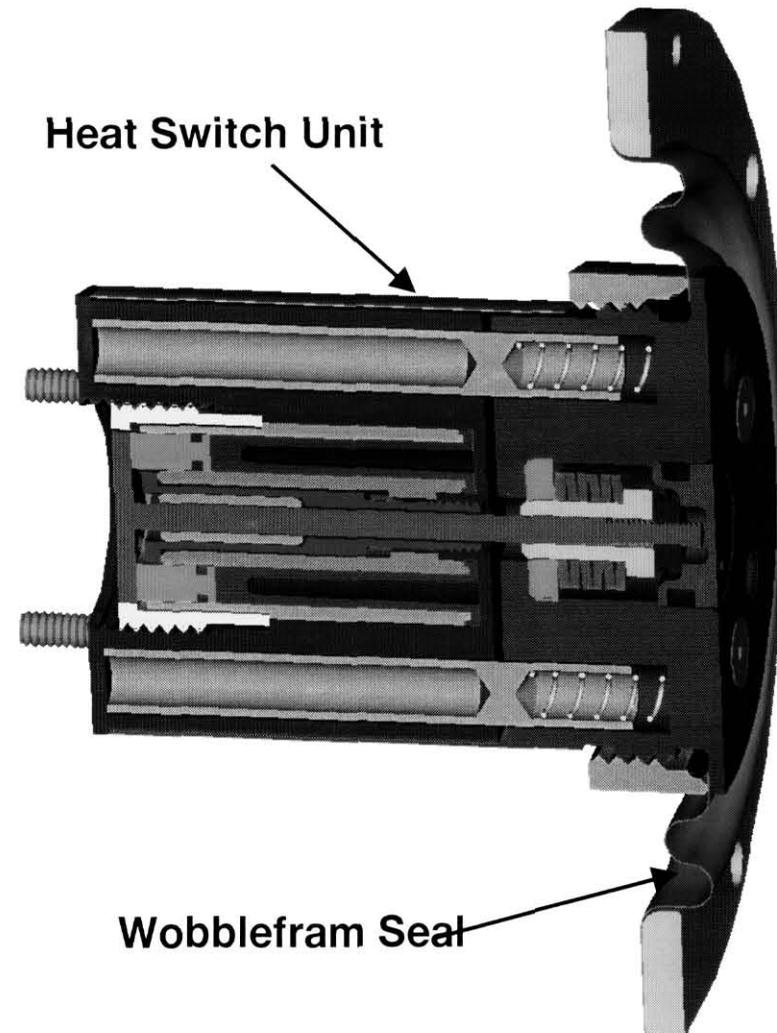


Thermal Switch

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Mars Exploration Rover

- 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 - 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												
<i>BIP:</i>					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
<i>Backshell:</i>												
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
<i>Heats hield:</i>												
Heats hield-outer surface (SLA561)	-150	n/a	-150	n/a	n/a	n/a	-81	-7	n/a	n/a	69	n/a
Heats hield-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 transfer switch (CxS4)	-35	50	-35	50	n/a	n/a	-39	4	n/a	n/a	-4	45
Lander Primary Battery (LiSO ₂)												
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

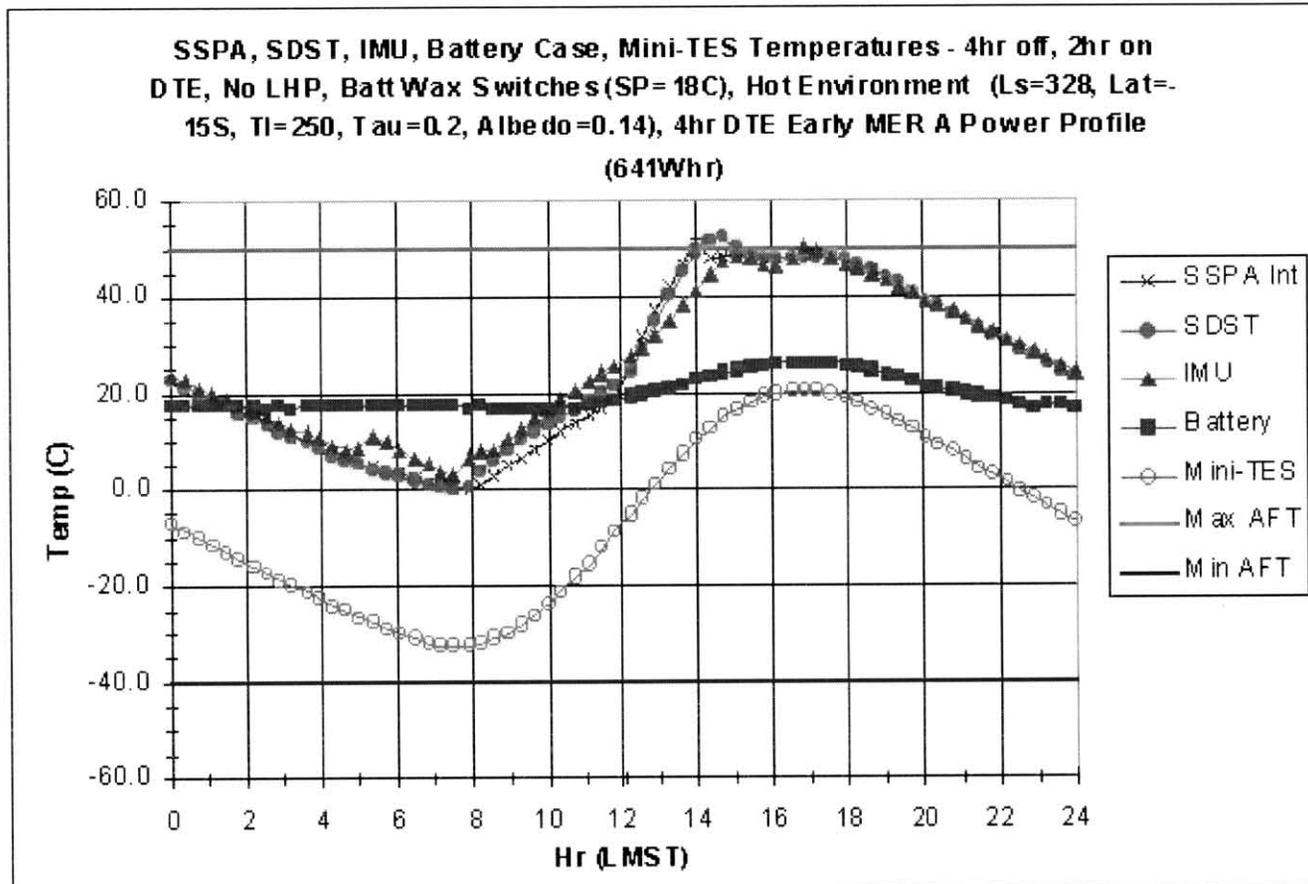
	ALLOWABLE FLIGHT				PREDICTED FLIGHT				Margin			
	OP		NOP		OP		NOP		OP		NOP	
	min	max	min	max	min	max	min	max	min	max	min	max
ROVER												
SSPA	-25	50	-40	50	0	7	-9	-3	25	43	31	53
SDST	-25	50	-40	50	na	na	-3	3	na	na	37	47
UHF Transceiver	-40	55	-40	55	na	na	-4	3	na	na	36	52
Rover Solar Array (3J)	-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

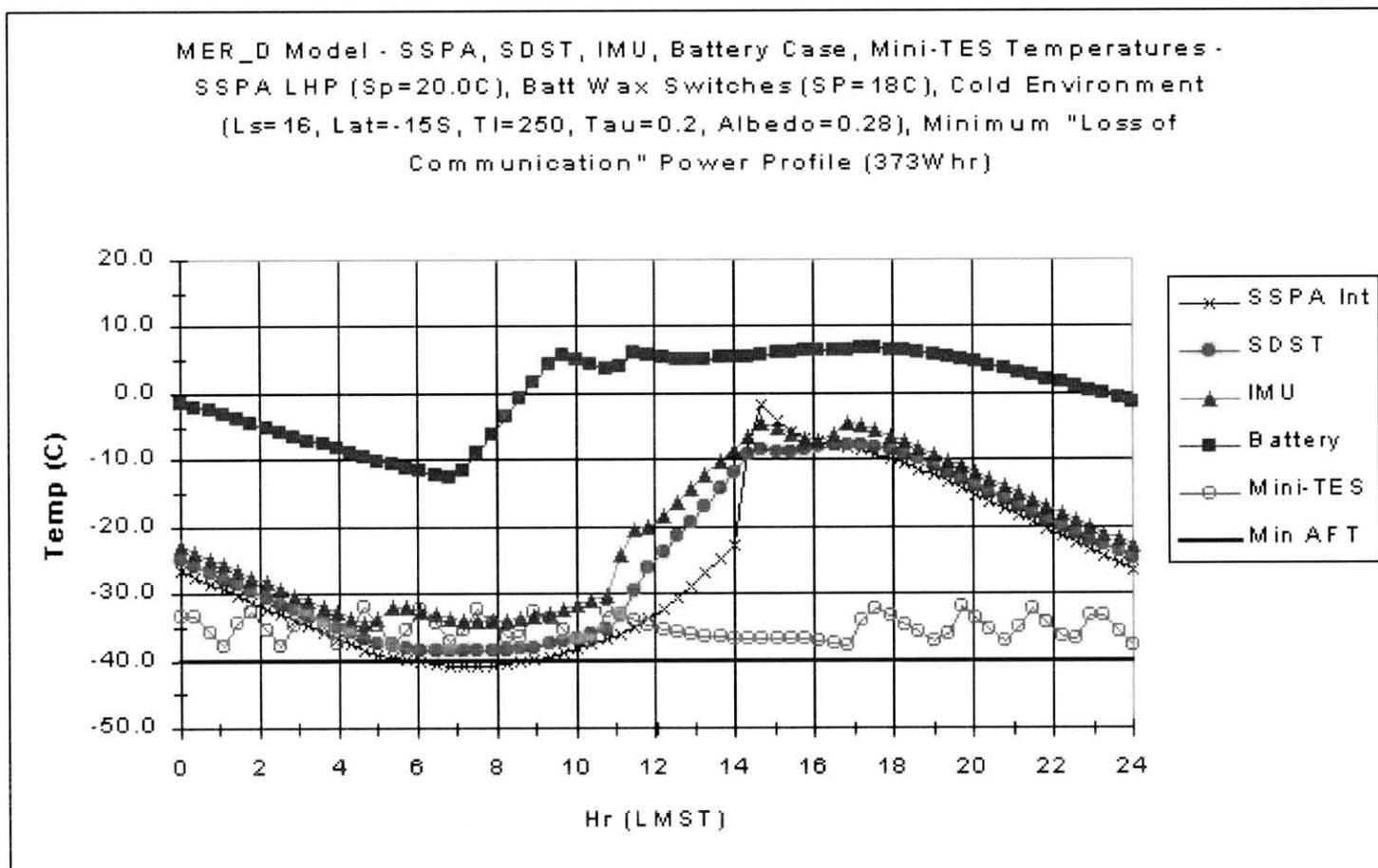
Max Battery Temp = 26C



Rover Cold Surface Scenario



Mars Exploration Rover





Subsystem Test Plans



Mars Exploration Rover

- **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)



Mars Exploration Rover

- **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
<p>Difficult to quantify uncertain parameters for BS IMU thermal analysis. Absolute worst-case results only permit 60 minutes of operation</p>	<p>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.</p>



Issues & Concerns: Thermal Testing

JPL

Mars Exploration Rover

Issue/Concern	Resolution Plan
<p>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</p>	<p>Work with ATLO to inject sufficient margin between both Rover tests.</p>
<p>Separate flight lander test not part of ATLO thermal test baseline</p>	<p>Currently carried as a reserve request. Consider a descoped test where: Lander is tested in a smaller chamber OR only critical elements are tested.</p>