Ae 105b Aerospace Engineering

Thermal Design is a System Engineering Activity

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April 8, 2009

Outline

- Thermal Design Development
- Mission Description & Flight System Configuration
  - MER-1 H/W designated for MER-A mission (1st launch)
  - MER-2 H/W designated for MER-B mission (2nd launch)
- System Thermal Design Description
- System Engineering Lessons Learned
  - Cruise Stage
    - Propulsion Fill Valve
    - Digital Sun Sensors
  - Lander
    - Backshell Inertial Reference Unit
  - Rover
    - Actuator Warm-Up Heaters
- Conclusions

Thermal Design Development (1/2)

- Two primary elements for the thermal design definition

Temperature Requirements

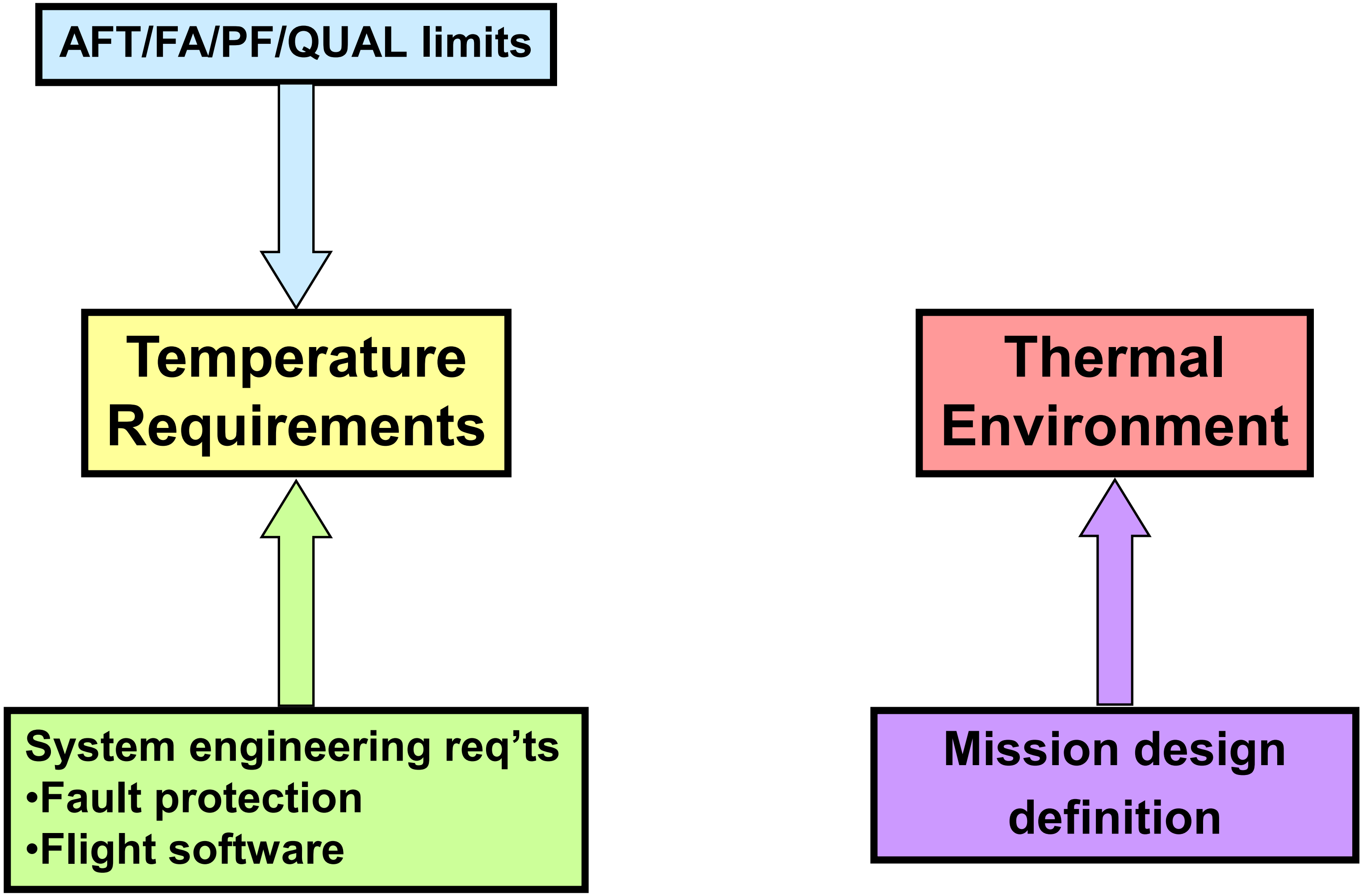
- What can the hardware tolerate?
  - Allowable Flight
  - Flight Acceptance
  - Protoflight/Qualification

Thermal Environment

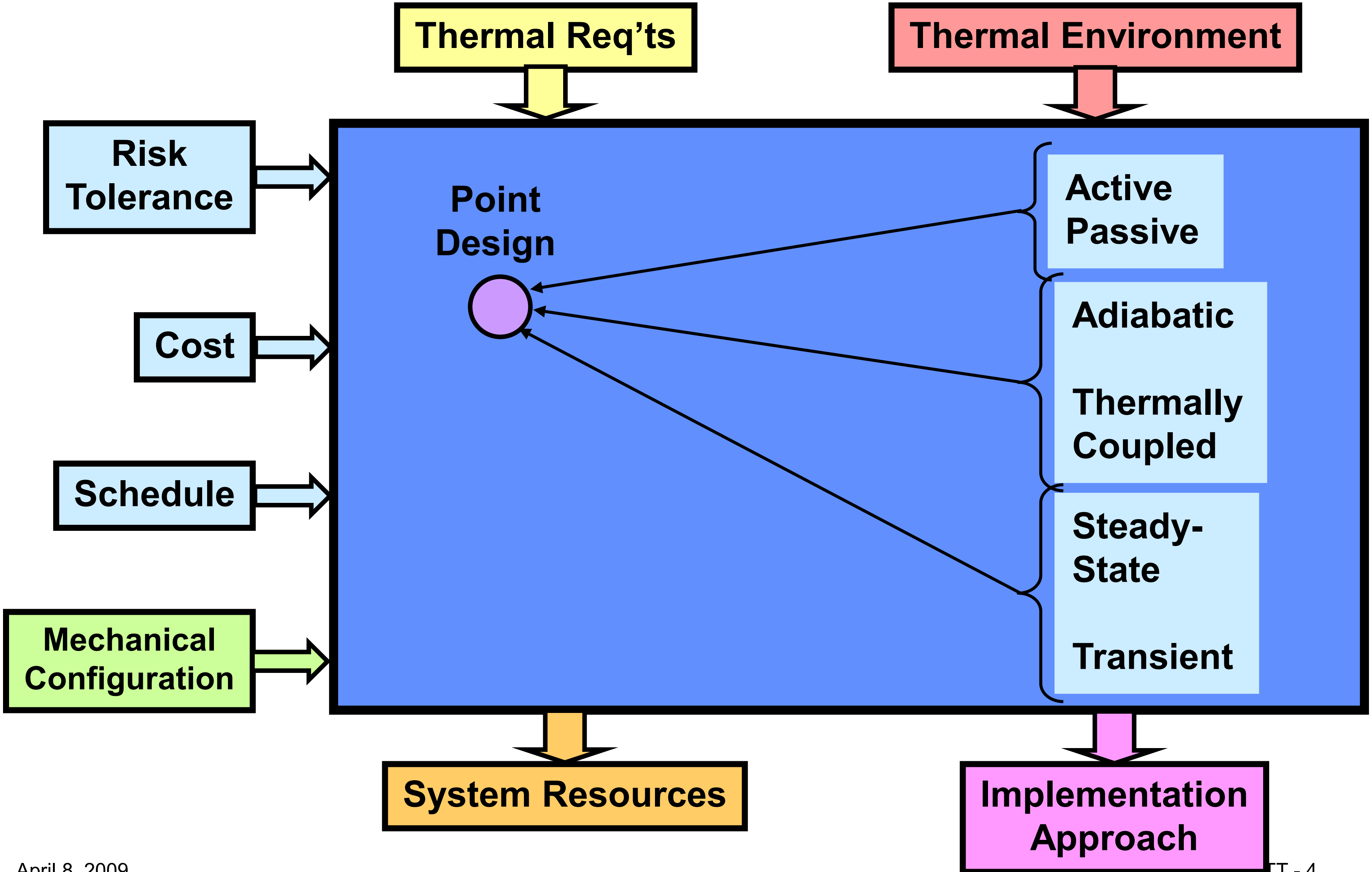
- What will the hardware be exposed to?

Thermal Design Development (2/2)

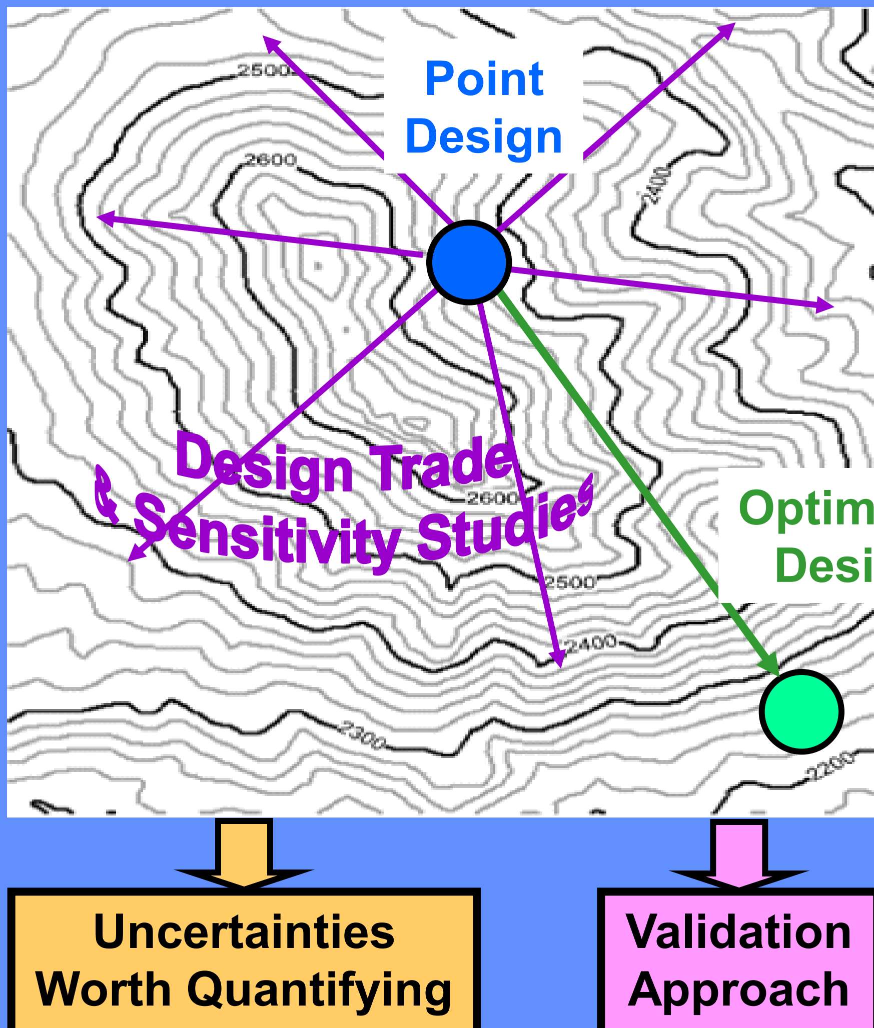
- **How are these elements formulated?**



Thermal Design Space



Thermal Design Evolution



Tenuous Design: Sensitive to Uncertainties

Robust Design: Insensitive to Uncertainties

Increasing Your Success Probability

Remove Uncertainties From Design | **Create Design Margin** | **Test-As-You Fly Validation Approach**

TIER 1

- Modify Design
- Perform Worst-Case Analysis
- Conduct Full-System Test in Representative Environment

TIER 2

- Characterize Uncertainties Thru Test → Reassess Design With Test Data
- Avoid Dependence On Specific Performance of Uncertainties
- Extensive Development Testing + Analyses

TIER 3

- Avoid Low Thermal Balance Situations
- Limited Assembly Testing + Analyses

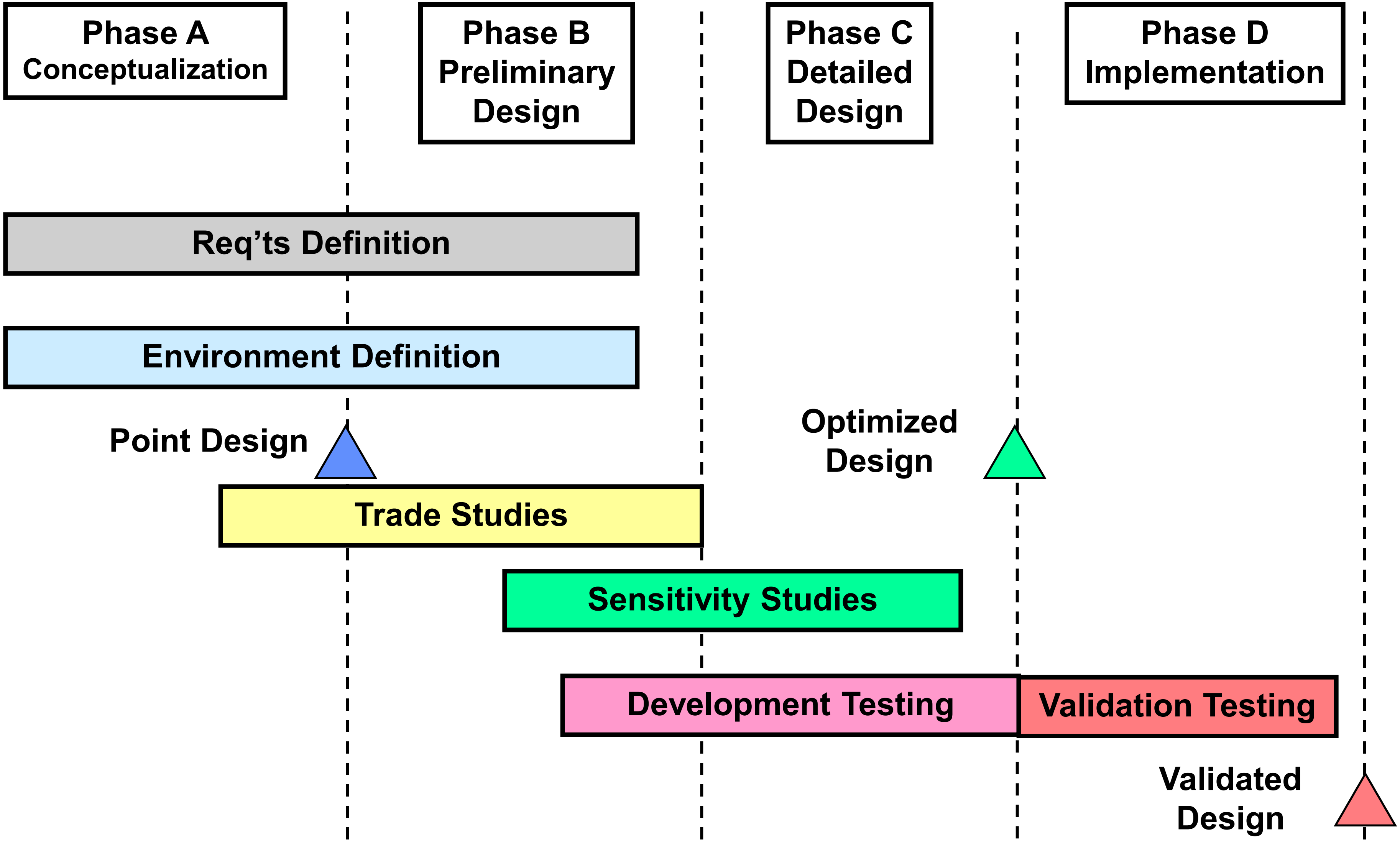
A Good Test is Worth 1000 Analyses

- **The operative word is "good"**
  - **A good test is one that singly focuses to meet your primary objectives & accommodates the needs of secondary objectives including functionality**
  - **Primary objectives are synthesized by asking yourself why are you conducting a test?**
  - **Generally, an empirical test is performed to improve your knowledge of some hardware of design aspect**
  - **A poorly conceived test is practically worthless**

Three General Testing Categories

DEVELOPMENTAL TESTING	ASSEMBLY PROTOFLIGHT/ QUALIFICATION OR FLIGHT ACCEPTANCE	SYSTEM- OR ASSEMBLY-LEVEL THERMAL BALANCE
• To characterize parameters that are difficult to quantify analytically • To characterize design performance/behavior	• To demonstrate in-specification hardware performance beyond allowable flight temperature range • To uncover design or workmanship defects	• To validate a thermal design • Empirical validation is the goal • To demonstrate functionality at expected temperatures
• Thermal environment is known • Temperature is a dependent parameter	• Temperature is an independent parameter; specified *a priori* along with dwell times, ramp rate, & number of cycles	• Thermal environment is known • Temperature is a dependent parameter

Thermal Design Development Cycle



MER Project Description

- The Mars Exploration Rover (MER) is a mission to land two identical roving science vehicles on Mars and perform geological science data collection with a surface science operations lifetime of at least 90 sols.
- The missions were launched in June & July 2003 on separate Delta II class vehicles, landed on Mars in Jan 2004, deploy the rovers and conduct surface operations.
  - MER - A was the first launched (June 2003); first arriving flight system (January 4, 2004)
  - MER - B was the second launched (July 2003); second arriving flight system (January 25, 2004)
- Each Flight System consists of:
  - A cruise stage and entry, descent and landing system (EDL) with inheritance from the Mars Pathfinder (MPF) development
  - A rover based upon the Athena Rover developments undertaken for the Mars '01 and Mars Sample Return projects (600 m traverse capability)
  - Athena Science Package, 5 science instruments to conduct remote and in-situ observations

Spirit Launch
June 10, 2003
17:58:47 UTC

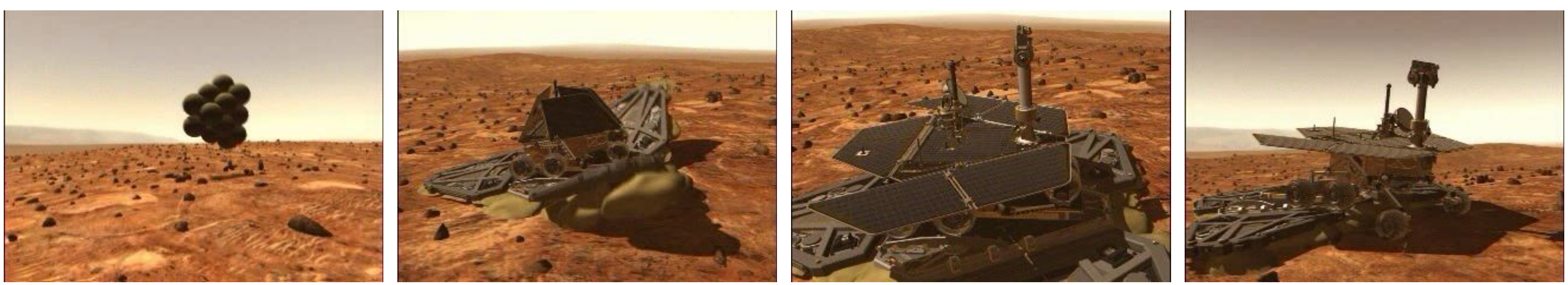
Opportunity Launch
July 8, 2003
3:18:15 UTC

Mission Overview

Launch/Cruise

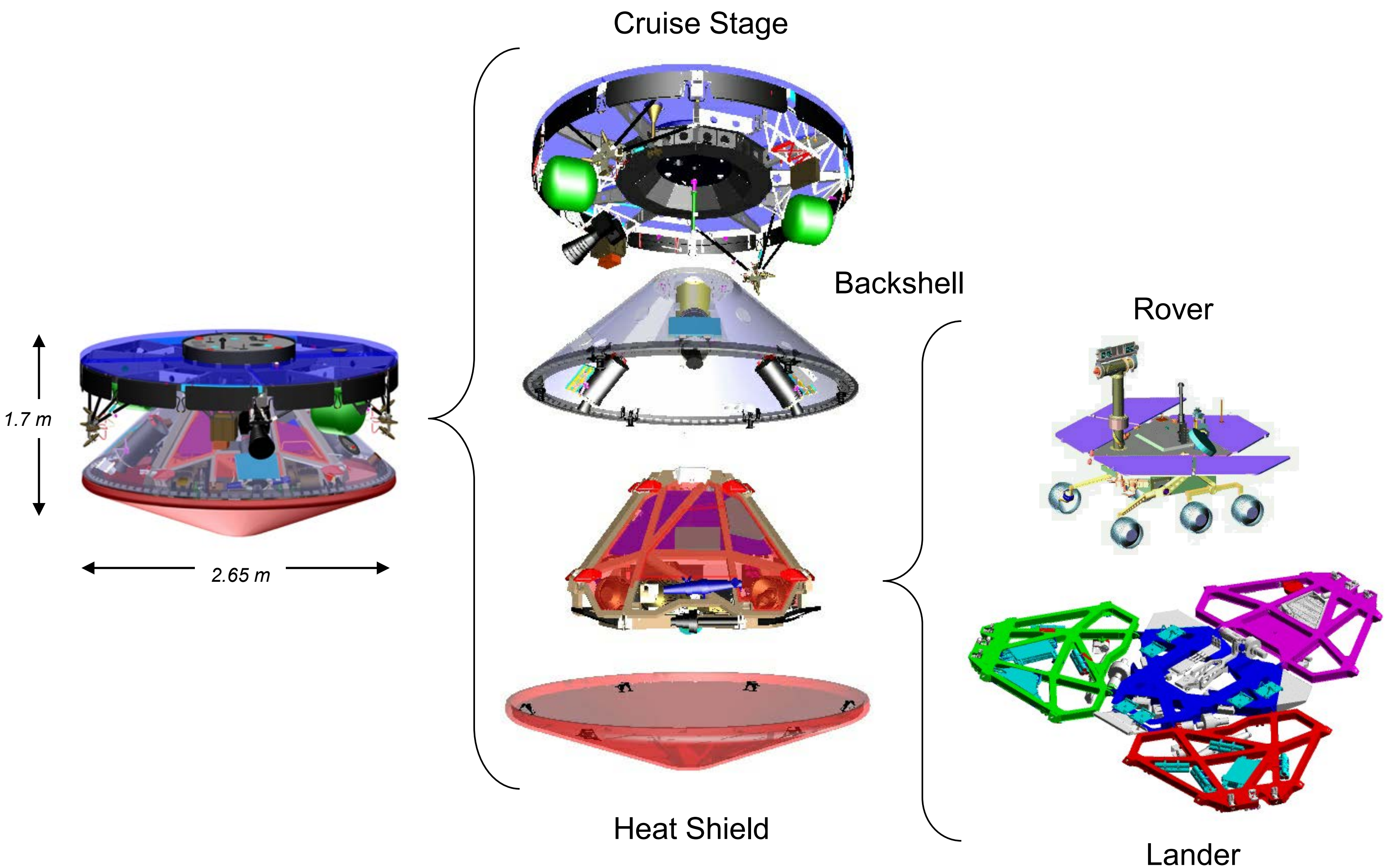
EDL

Surface

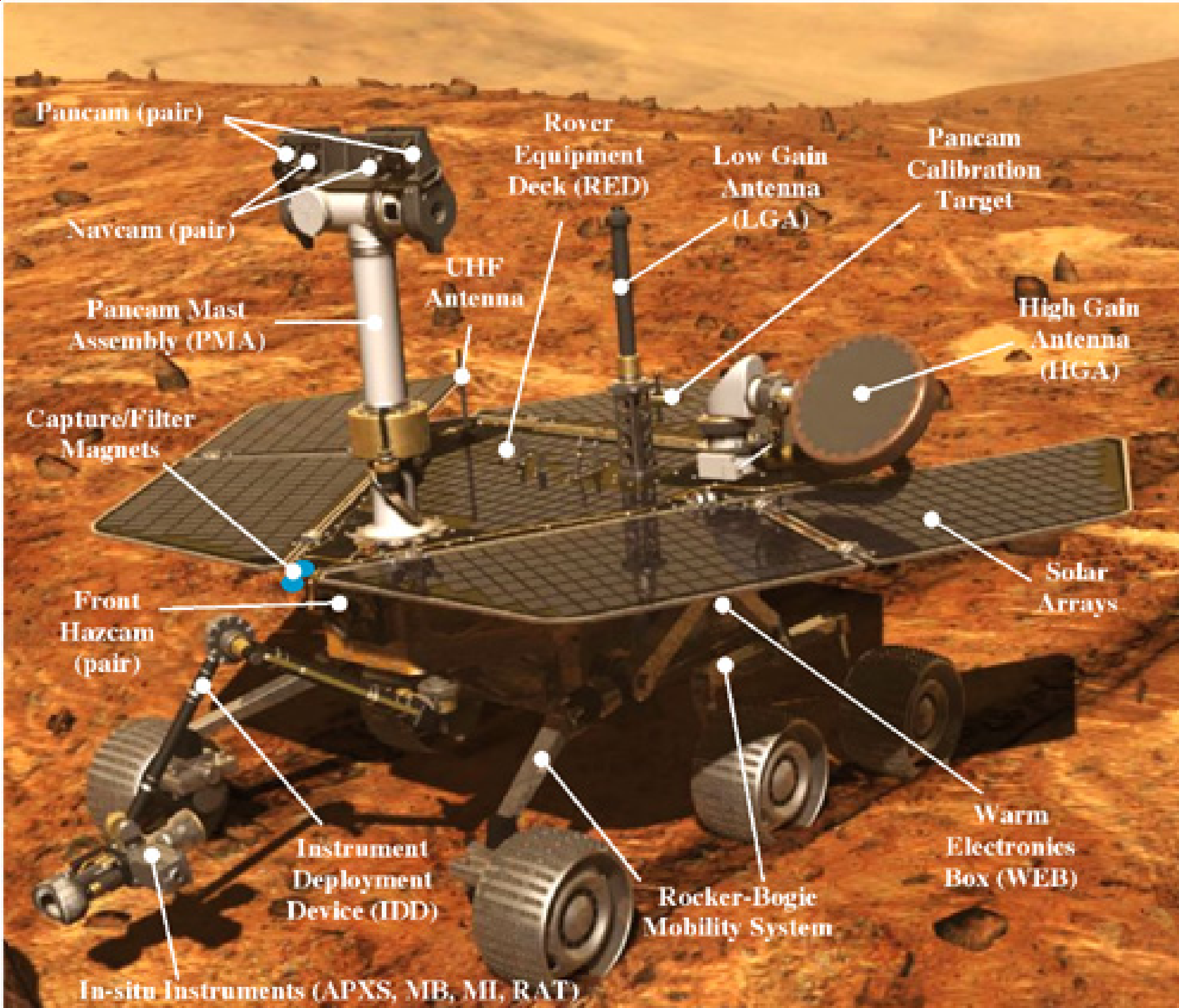


Images From Mission Animation by Dan Maas

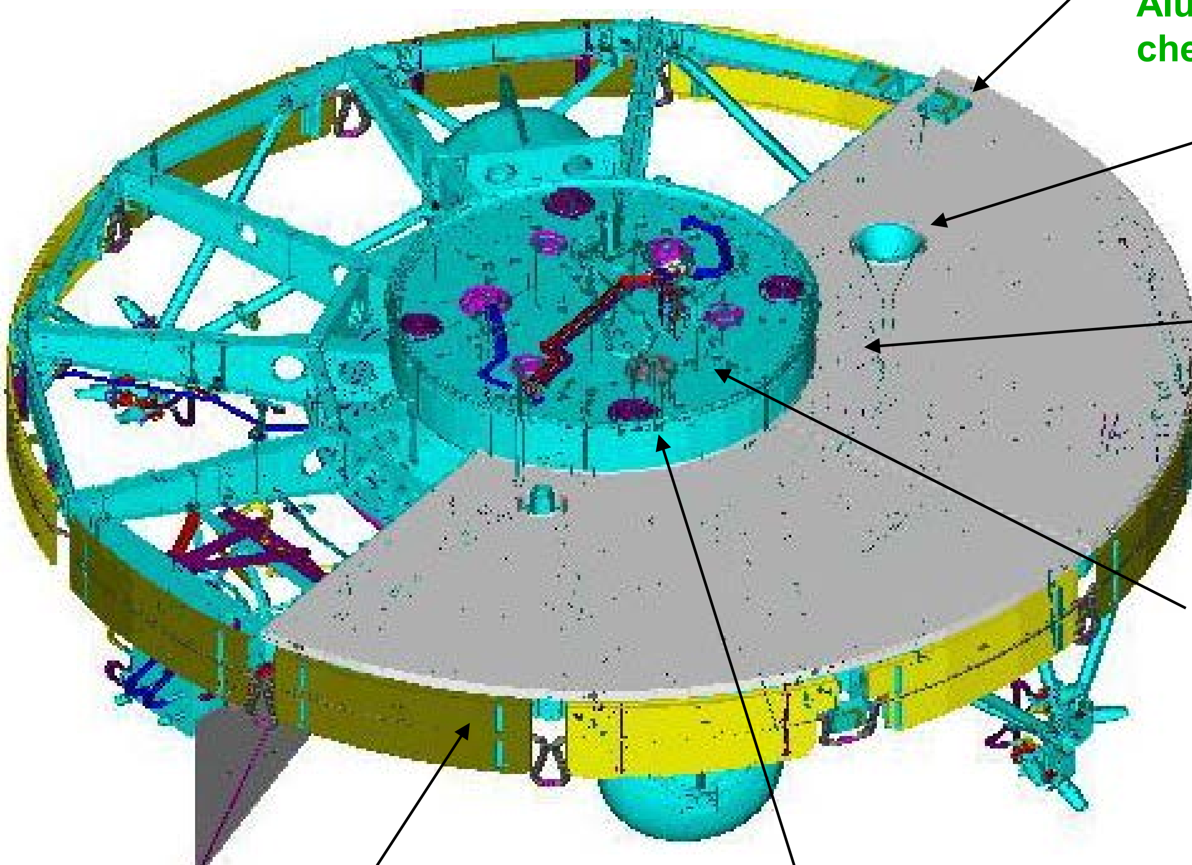
MER Spacecraft Configuration



Rover Configuration



Cruise Stage Thermal Design Overview (1/2)



Sun Sensors:

Aluminum with chem-film finish

MGA:
S13-GLO (white) paint on back

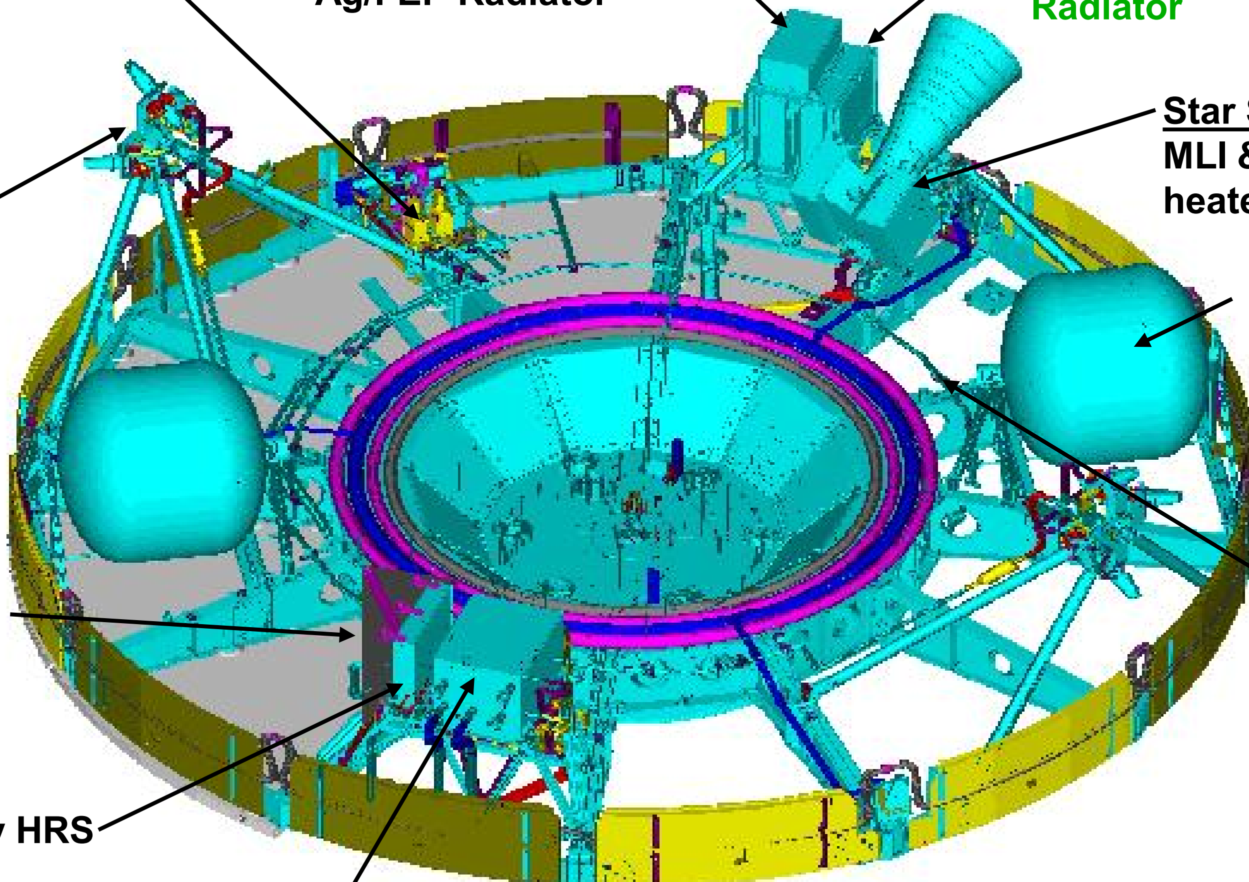
Solar Array: Ag/FEP tape on inner ring, White paint on substrate backside

Cruise Shunt Radiator: White paint including sep. spring covers, anodized L/V spring pads

HRS Radiators: White paint on both sides

LVA: White paint on lateral side

Cruise Stage Thermal Design Overview (2/2)



<u>PDM</u>: MLI & thermostatic heaters

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

<u>CEM</u>: MLI & Outward Ag/FEP Radiator

<u>Star Scanner</u>: MLI & thermostatic heater

<u>TCAs</u>: MLI & thermostatic heaters

<u>Propellant Tanks</u>: MLI & thermostatic heaters

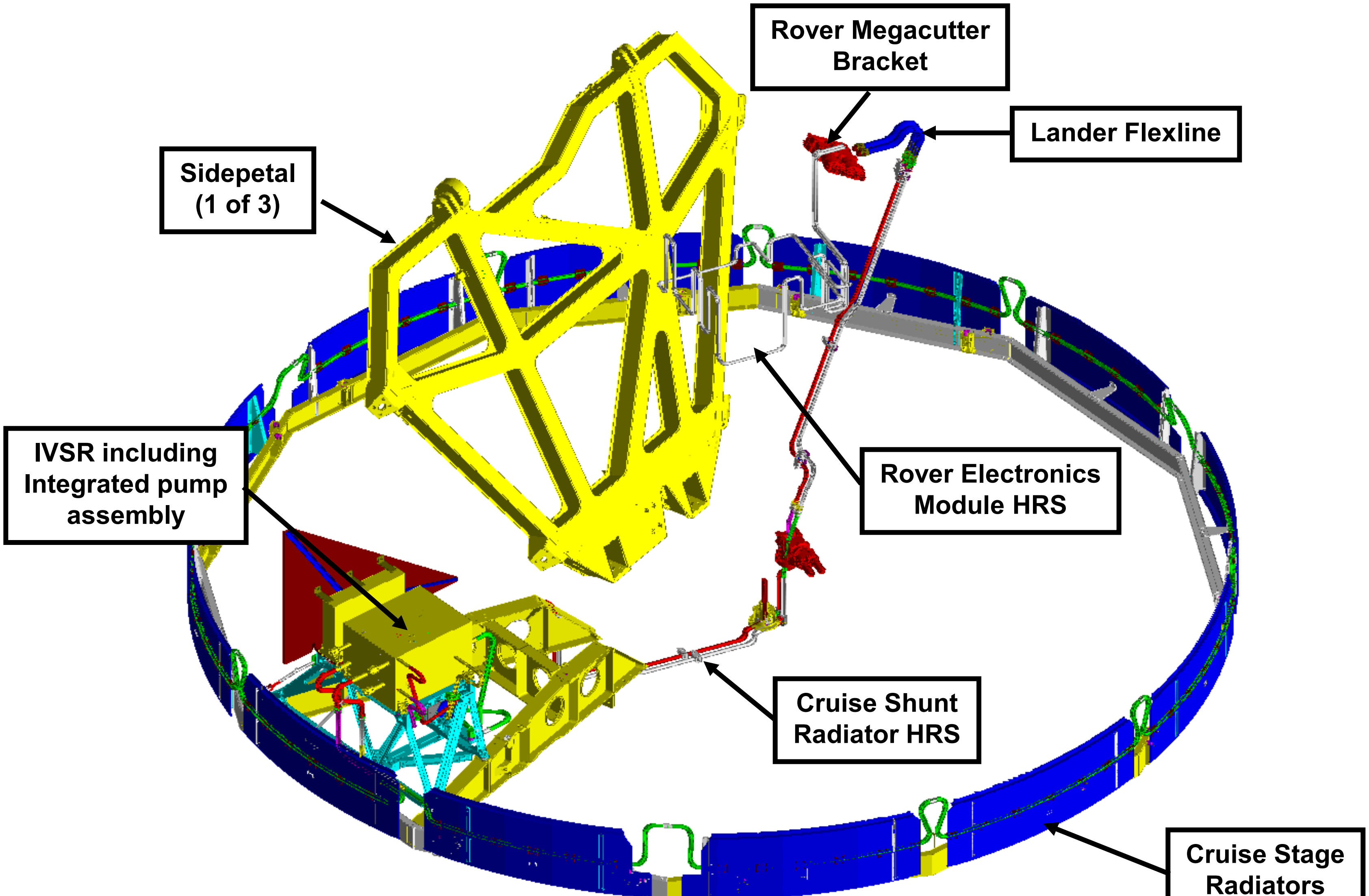
<u>Propellant Lines</u>: MLI, aluminum cladding, thermostatic FSW heater control for 8 zones

<u>CSL Radiator</u>: White paint

<u>CSL:</u> Controlled by HRS

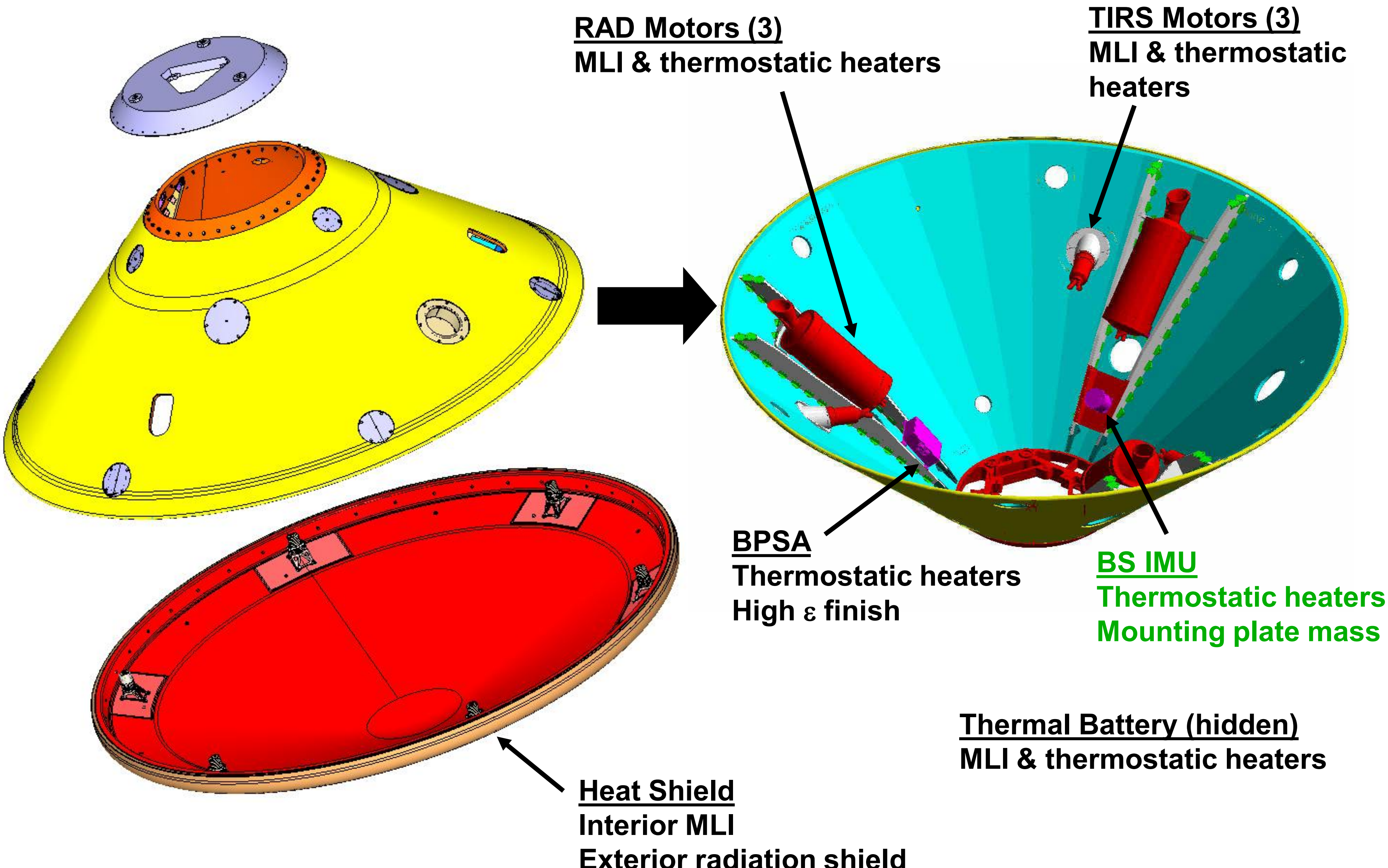
<u>IPA</u>: MLI & HRS

Heat Rejection System Overview

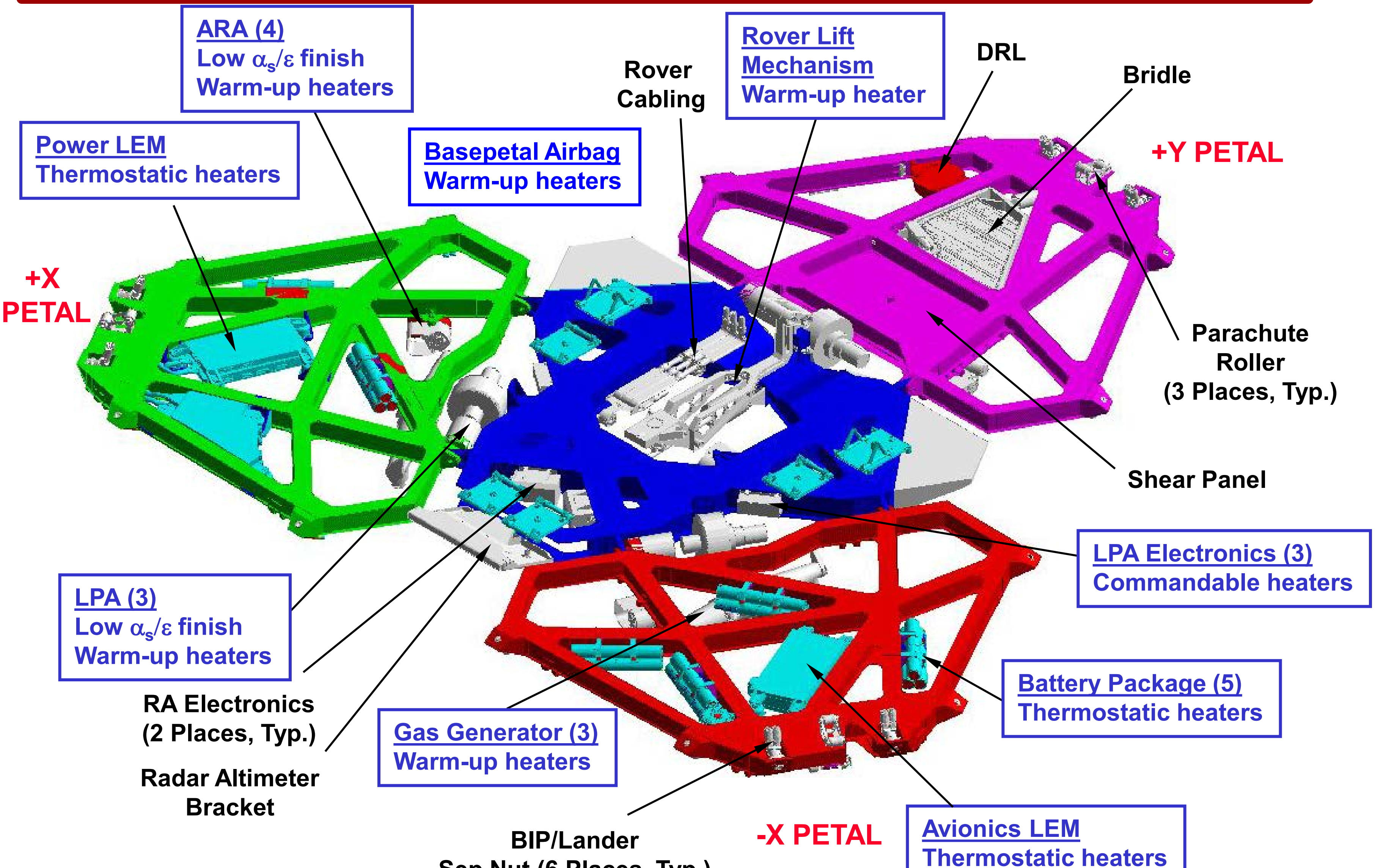


Aeroshell Thermal Design Overview

Ae105B

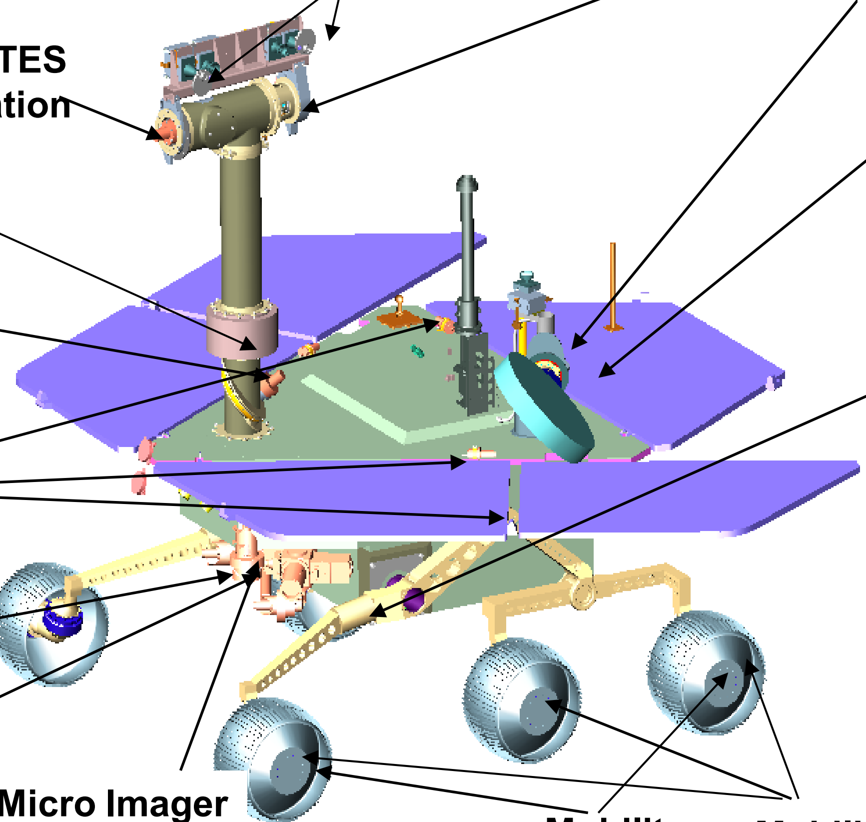


Lander Thermal Design Overview



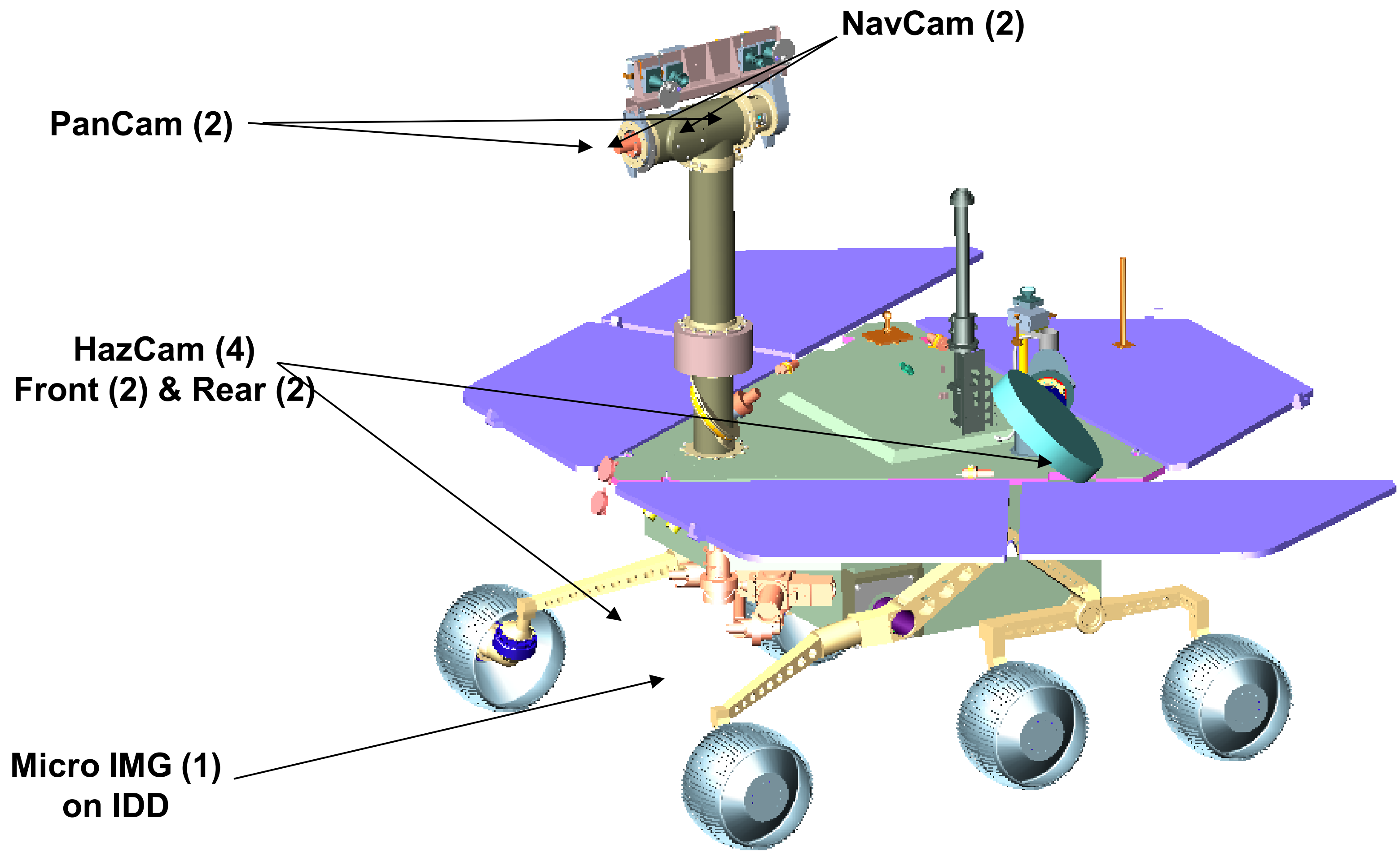
Rover External Thermal Design (1/3)

- **<u>34 Actuators</u> on Outside of Rover**

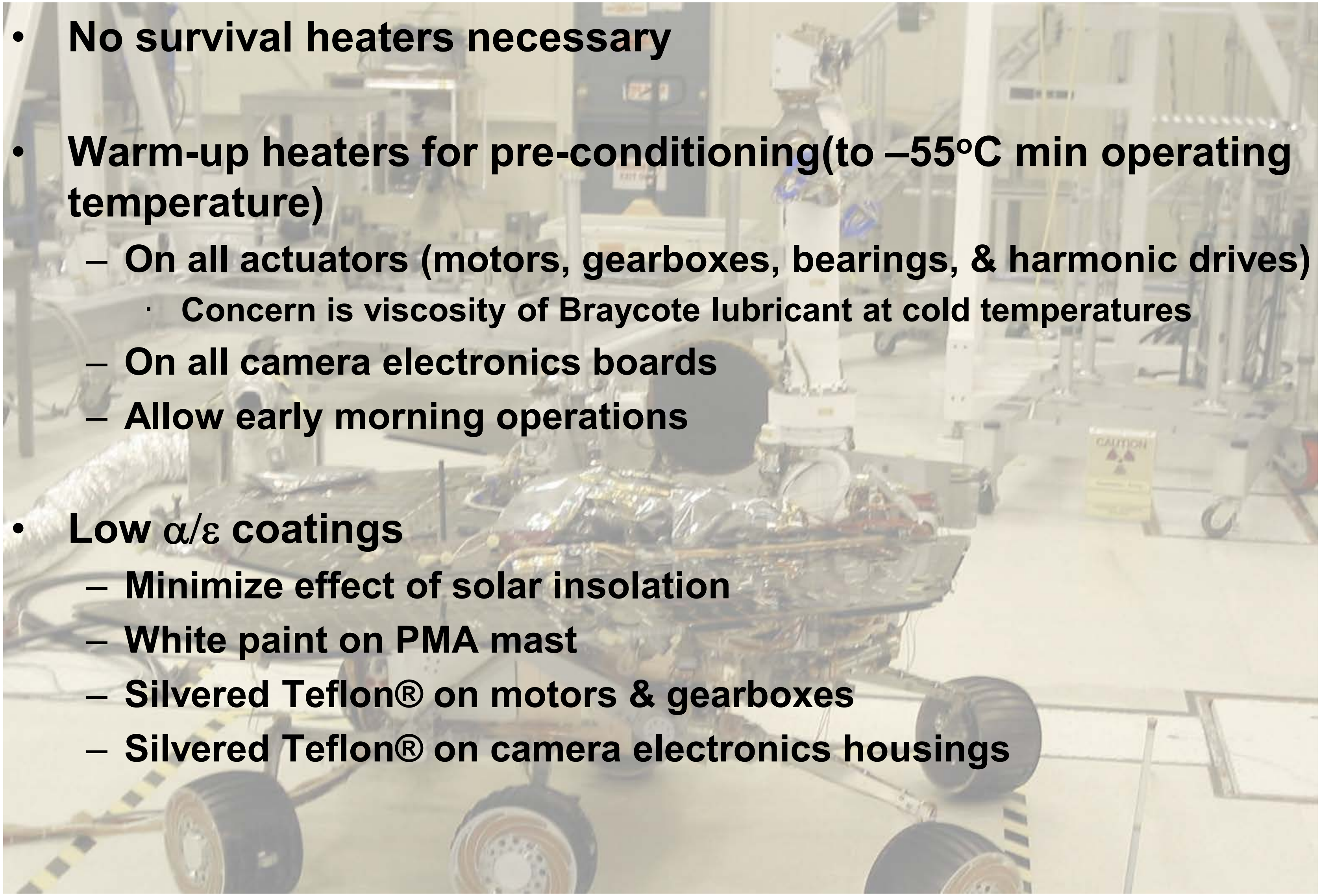


Rover External Thermal Design (2/3)

- **<u>9 Cameras</u> on Outside of Rover**



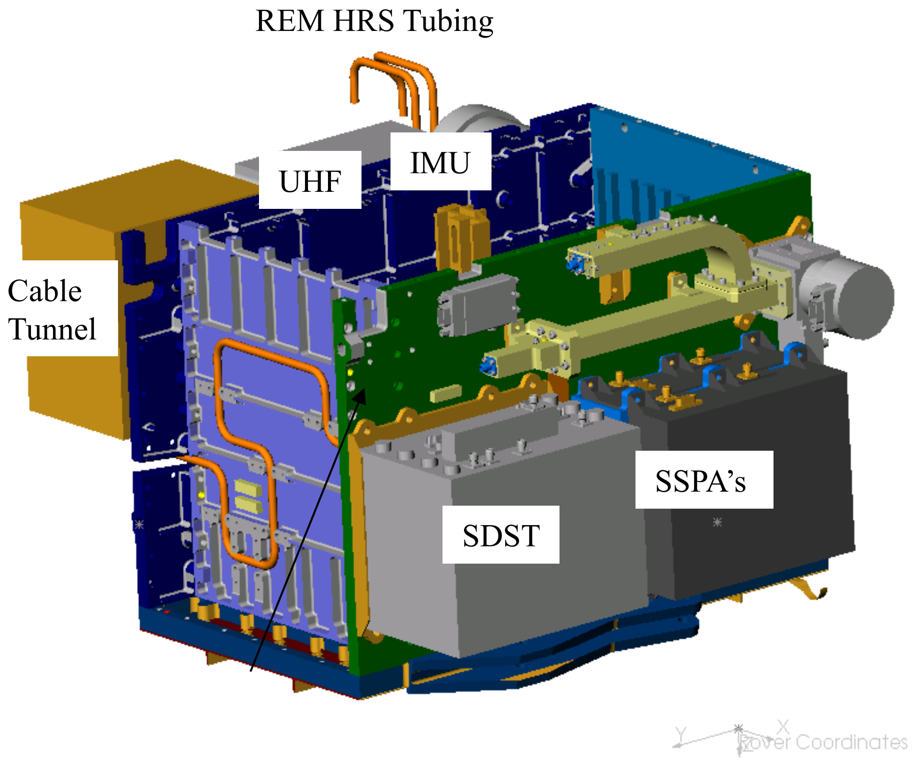
Rover External Thermal Design (3/3)



- **No survival heaters necessary**
- **Warm-up heaters for pre-conditioning(to –55°C min operating temperature)**
  - **On all actuators (motors, gearboxes, bearings, & harmonic drives)**
    - **Concern is viscosity of Braycote lubricant at cold temperatures**
  - **On all camera electronics boards**
  - **Allow early morning operations**
- **Low α/ε coatings**
  - **Minimize effect of solar insolation**
  - **White paint on PMA mast**
  - **Silvered Teflon® on motors & gearboxes**
  - **Silvered Teflon® on camera electronics housings**

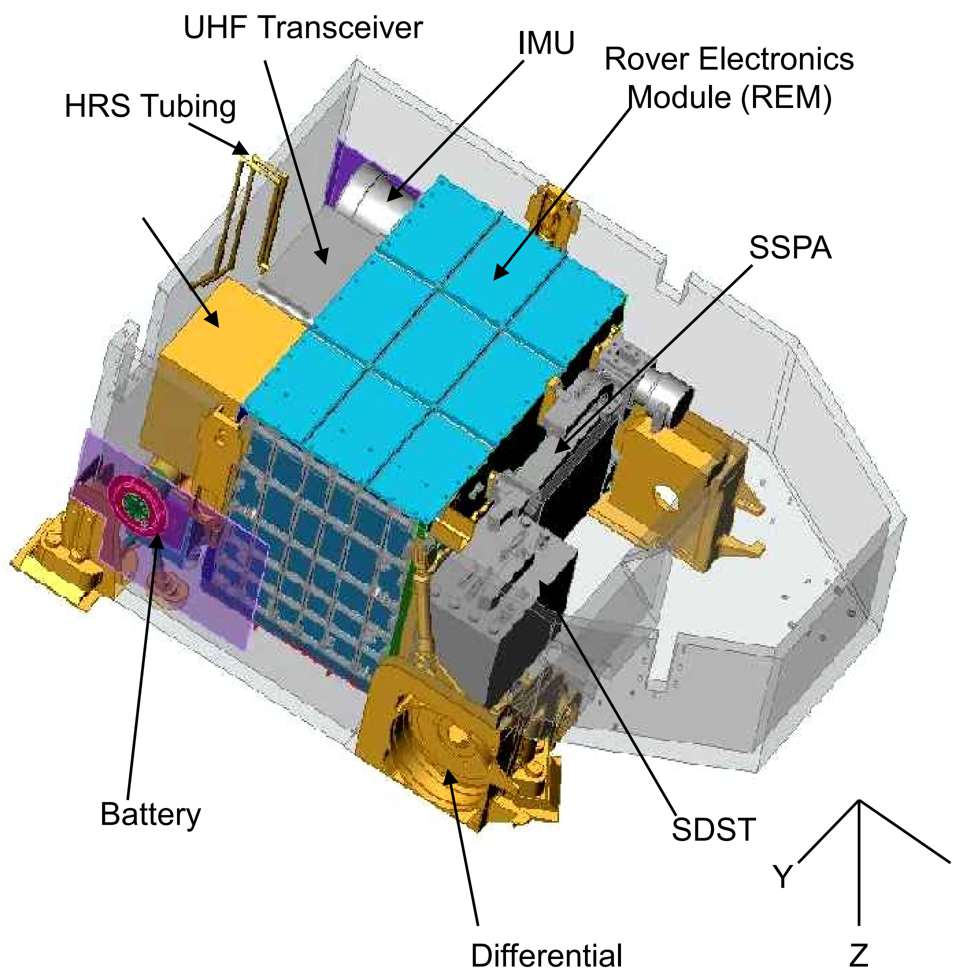
Rover Internal Thermal Design (1/2)

- **Maximize thermal time constant (τ = Resistance * Capacitance)**
  - **Minimize ΔT's driven by internal dissipation profiles & ΔT driven by external diurnal environment**
  - **Maximize thermal capacitance**
    - **Concentrate thermal mass in WEB (36kg) by coupling together**
    - **Allow power sharing**

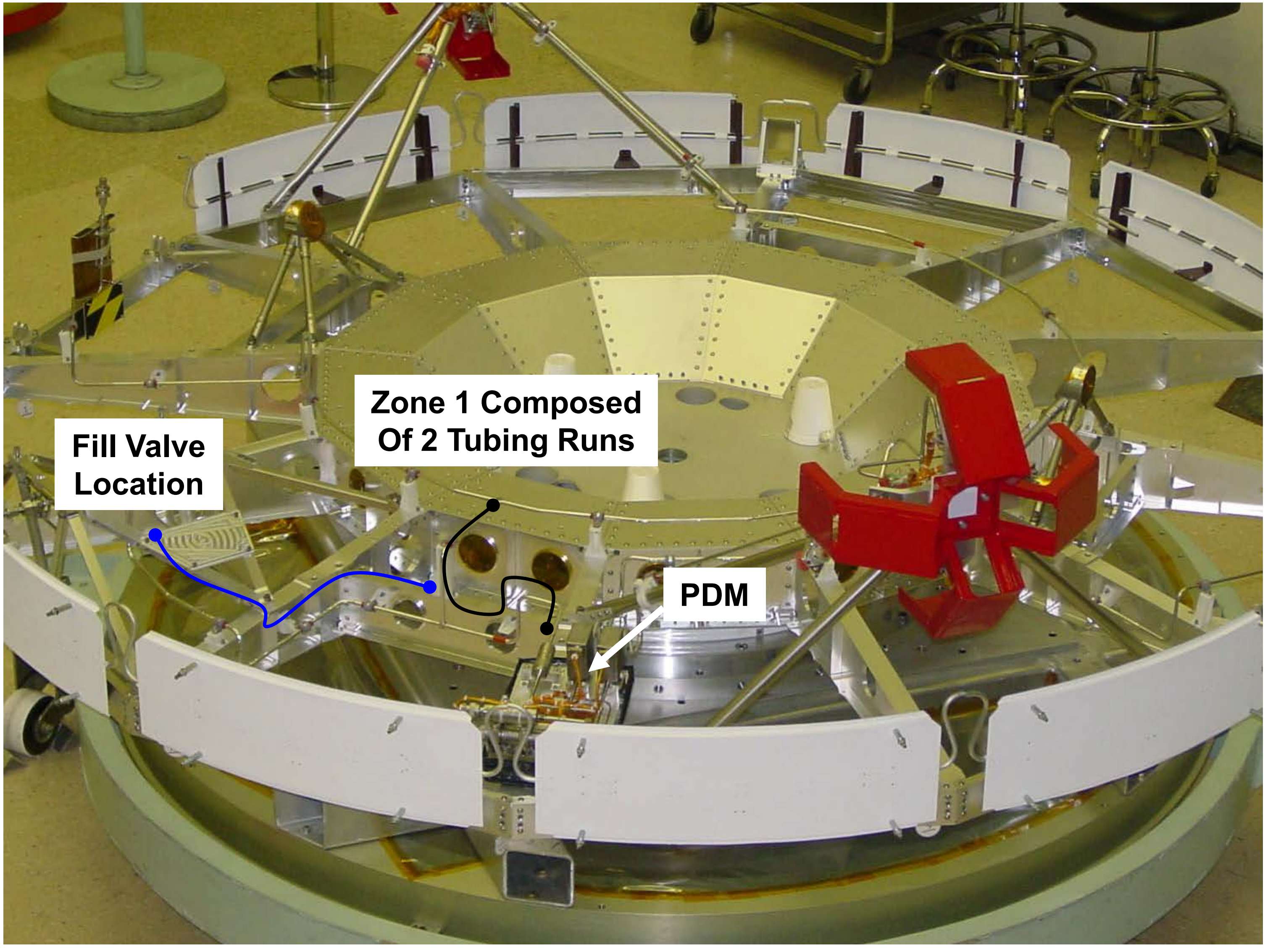


Rover Internal Thermal Design (2/2)

- **Maximize WEB thermal resistance to environment**
  - Carbon-opacified aerogel insulation (k=0.012 W/m*K)
  - Low emissivity gold internal & external surfaces
  - Flex cables with lower copper cross-section
  - Cable tunnels for flex & coax
  - Battery thermal switches open when battery is cold
  - Stainless steel section of HRS tubing at egress
  - Low conductivity boron-epoxy tubes support H/W



Propulsion Fill Valve Lesson (1/3)



Propulsion Fill Valve Lesson (2/3)

- **During the MER-B system thermal balance test, the propulsion fill valve as part of the propellant line Zone 1 ran 4^{o}C <u>BELOW</u> minimum allowable flight temperature limit of 17^{o}C for the worst cold case**

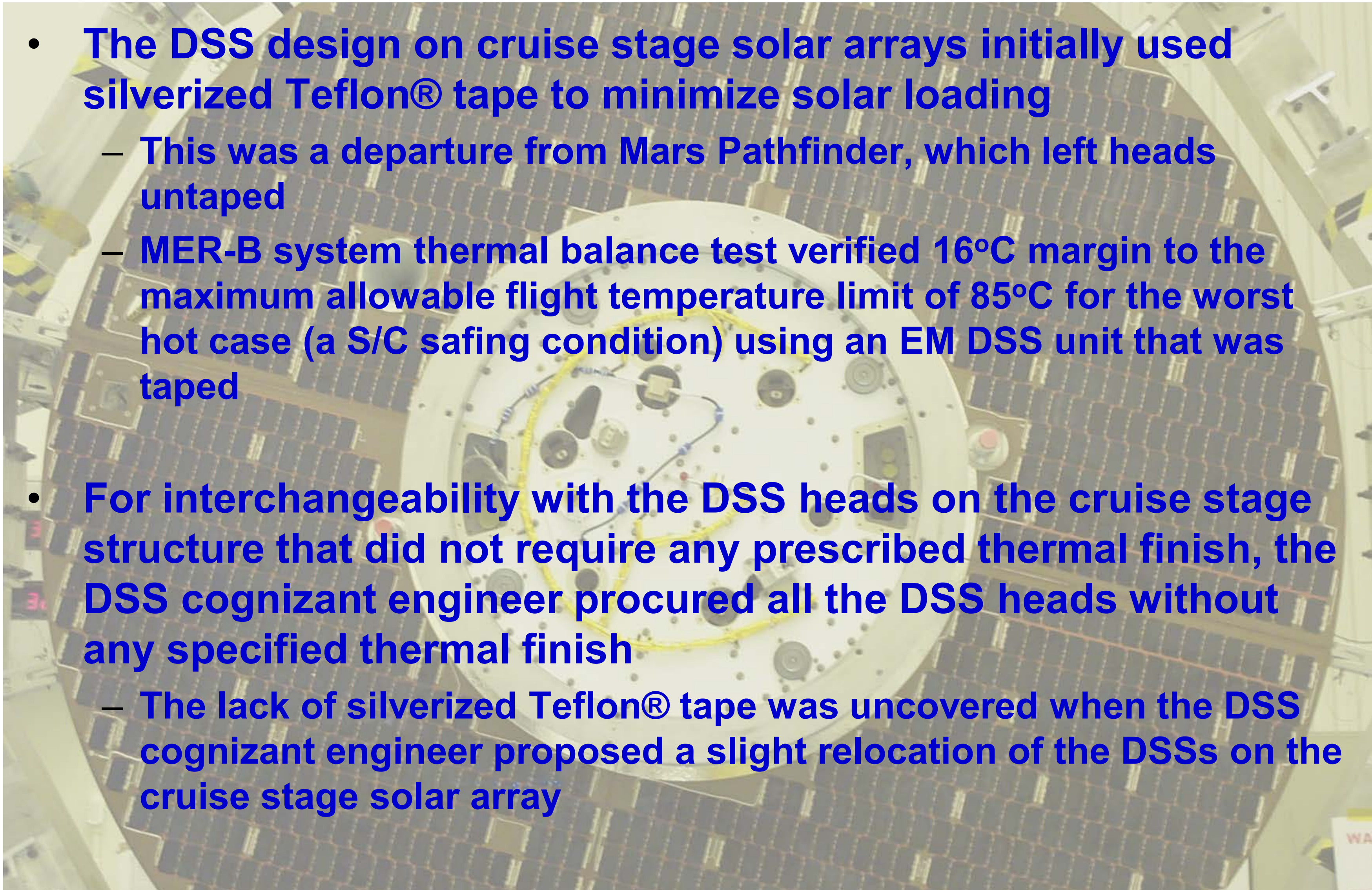
- **Post-test analysis for the flight condition indicated that the worst cold case fill valve temperature would be 5^{o}C, *<u>only 3^{o}C above hydrazine freezing point</u>***

- **Fill valve dominated by conductive coupling to CEM, which is has a minimum allowable flight temperature limit of –35^{o}C**

Propulsion Fill Valve Lesson (3/3)

- **Design modifcations involved warm-biasing CEM by reducing radiator area & improving local blanketing around fill valve**
  - **Worst case cold fill valve temperature increased to 11^{o}C**
  - **Further warm biasing of CEM would jeopardize worst hot case & capability to perform first trajectory correction maneuver (TCM) within 15 hours (CEM expected to violate maximum allowable flight temperature limit of 50^{o}C by 3^{o}C during this duration with current design modifications**
- **Project decided to waive worst case cold fill valve temperature violation as well as CEM maximum allowable flight temperature limit during first TCM**
  - **First TCM actually completed within 8 hours**
- **Lesson: Avoid even the most subtle of coupling between two distinct thermal "zones," late fixes will be constrained**

Digital Sun Sensor (DSS) Lesson (1/3)

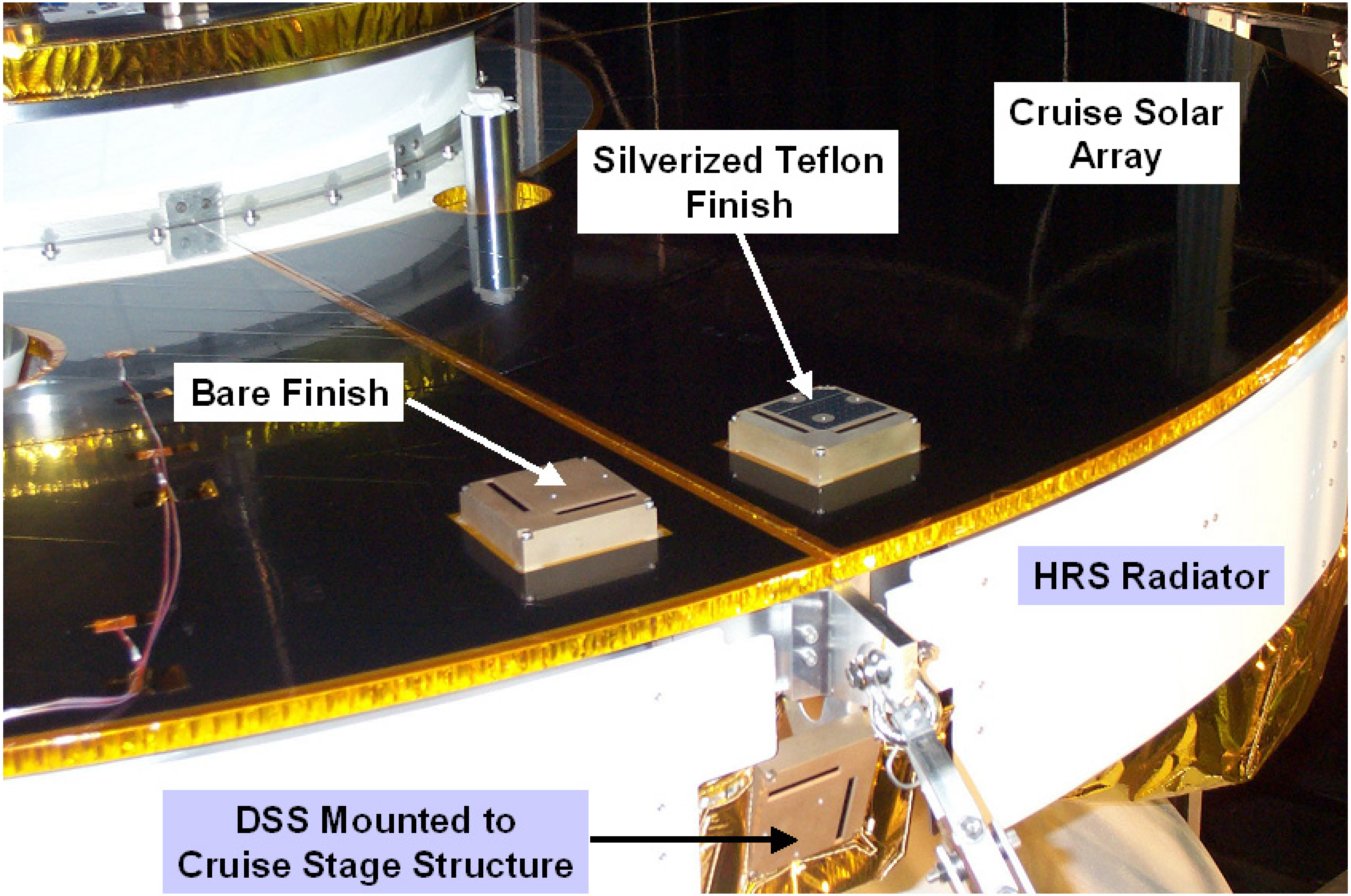


- **The DSS design on cruise stage solar arrays initially used silverized Teflon® tape to minimize solar loading**
  - **This was a departure from Mars Pathfinder, which left heads untaped**
  - **MER-B system thermal balance test verified 16°C margin to the maximum allowable flight temperature limit of 85°C for the worst hot case (a S/C safing condition) using an EM DSS unit that was taped**
- **For interchangeability with the DSS heads on the cruise stage structure that did not require any prescribed thermal finish, the DSS cognizant engineer procured all the DSS heads without any specified thermal finish**
  - **The lack of silverized Teflon® tape was uncovered when the DSS cognizant engineer proposed a slight relocation of the DSSs on the cruise stage solar array**

Digital Sun Sensor (DSS) Lesson (2/3)

- **Application of silverized Teflon® had profound technical & programmatic risks with only a month before the MER-A system thermal balance test**
- **Extrapolation of previous test data suggested only a 7^{o}C rise in DSS worst hot case temperature when silverized Teflon® removed**
- **The lead thermal test engineer suggested that both –Z DSS head configurations (one bare finish and one taped with silverized Teflon) be installed for the MER-A test**
- **MER-A results indicated that the bare and taped DSS worst hot temperatures were 83 & 65^{o}C, respectively**
  - **Bare finish selected since worst hot case is a fault condition**
- **Lessons: 1) Follow thermal design implementation through hardware delivery, 2) understand impact of departing from a heritage design, & 3) minimize use of non-flight H/W in system thermal balance testing**

Digital Sun Sensor (DSS) Lesson (3/3)



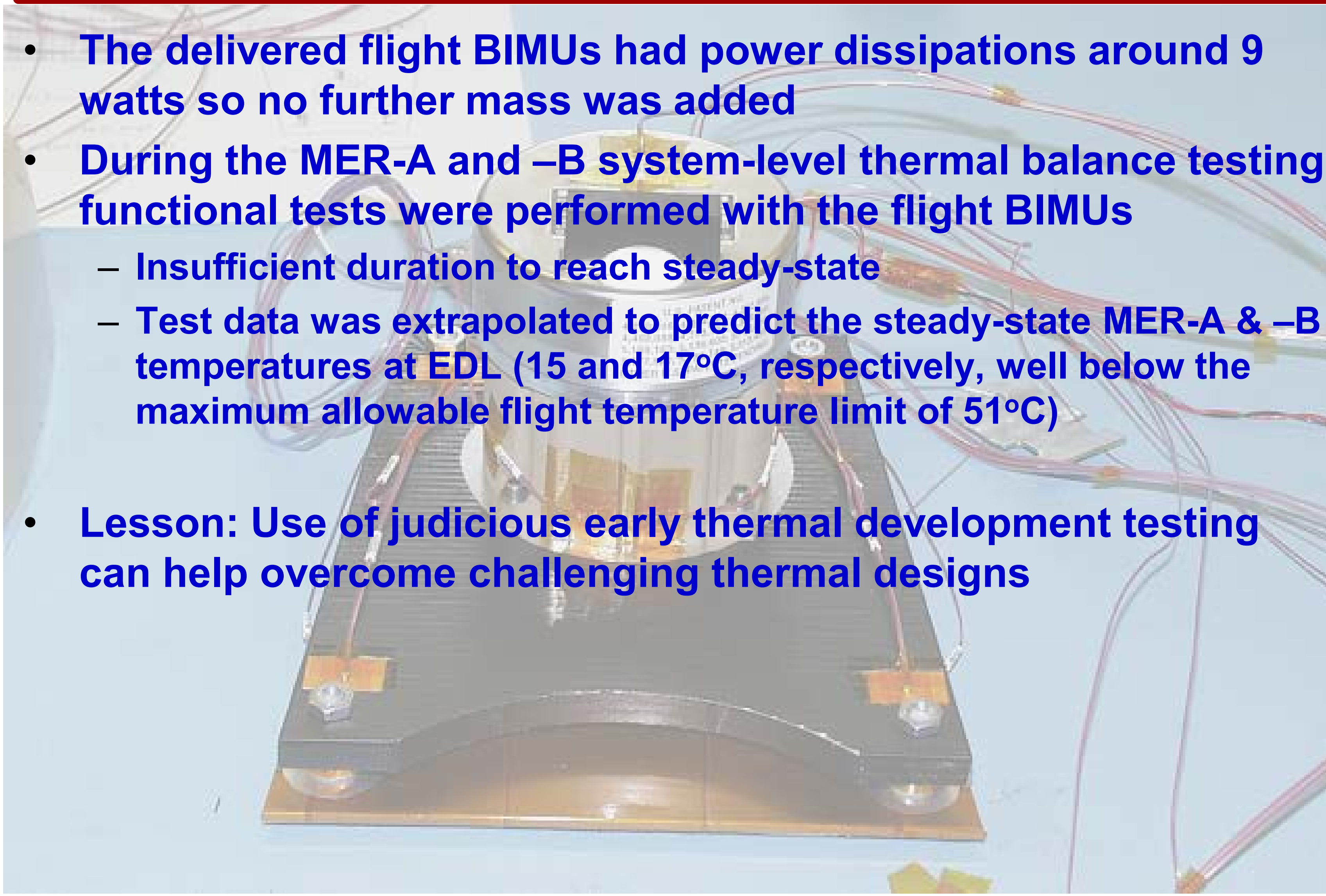
Backshell Inertial Measurement Unit (BIMU) Lesson (1/3)

- **During the EDL, the BIMU provided updated entry vehicle attitude knowledge**
  - **3 to 4 hours of operation required**
  - **During cruise, thermostatic heaters maintained BIMU at –29^{o}C**
  - **BIMU operational allowable flight limits: -39 to 51^{o}C**
- **Mechanical accommodation resulted in a challenging thermal design situation**
  - **Shock isolation mounting significantly attenuates conductive path to backshell**
  - **Lack of an adequate radiative heat path**
- **BIMU operating thermal design relies on absorbing its internal power dissipation into its thermal capacitance**
  - **Initial analysis indicated 1.5 hours of operation with only the existing BIMU mass**
  - **Most feasible design option involved adding mass to the BIMU mounting structure**

Backshell Inertial Measurement Unit (BIMU) Lesson (2/3)

- **A thermal development test was conducted in November 2001 to characterize EDL performance**
  - **BIMU power dissipation varied between 8 & 14 watts; test article dissipated 9 watts**
  - **Under the EDL conditions, the BIMU temperature achieved a steady-state of 20°C, well below the maximum allowable flight temperature limit of 51°C**
  - **For the 14-watt case (BIMU power dissipation plus 5 watts from a test heater), BIMU temperature rose from –20 to 51°C in about 3 hours**
  - **A case considering 12-watt power dissipation resulted in a steady-state temperature of 63°C**
- **The flight design would not add any mass to the BIMU bracket**
  - **Operational time would be limited to less than 2 hours at this time**
  - **When the BIMU flight units were delivered &power dissipation determined, a final decision regarding adding mass to the BIMU bracket would be made**

Backshell Inertial Measurement Unit (BIMU) Lesson (3/3)



- **The delivered flight BIMUs had power dissipations around 9 watts so no further mass was added**
- **During the MER-A and –B system-level thermal balance testing, functional tests were performed with the flight BIMUs**
  - **Insufficient duration to reach steady-state**
  - **Test data was extrapolated to predict the steady-state MER-A & –B temperatures at EDL (15 and 17°C, respectively, well below the maximum allowable flight temperature limit of 51°C)**
- **Lesson: Use of judicious early thermal development testing can help overcome challenging thermal designs**

Rover Actuator Warm-up Heater Lesson (1/3)

- **Warm-up heaters for external elements on the Rover were initially designed to only meet the 1-hour conditioning requirements**
  - **The planned hardware implementation lacked single point failure tolerance**
  - **An operational scenario was identified where a warm-up heater could be left on during the daytime**
    - **Actuators must be maintained within dry heat sterilization temperature (110°C)**
    - **Camera electronics must be maintained with hot protoflight test level (85°C)**
    - **Analysis indicated that that the PMA, HGA, rocker deployment, & IDD actuators would exceed 110°C & the Navcam and Pancam electronics would exceed 85°C when the bus voltage was at a maximum of 33 V**
- **First course of action involved re-sizing heaters using a nominal bus voltage (28V) rather than minimum bus voltage (24V)**
  - **The rocker deployment actuator & the Navcam & Pancam electronics no longer overheated at a maximum bus voltage of 33 V**
  - **However, the PMA, HGA, and IDD actuators still overheated**

Rover Actuator Warm-up Heater Lesson (2/3)

- The problematic actuators were all associated with the warm-up heater enabling nighttime or early morning operation
- Bi-metallic thermostats were proposed to “cut-off” a stuck-on heater
  - Thermostats located on Rover exterior
  - Thermostats would sense diurnal atmospheric temperature
  - An open & close set-point temperature of –30°C was selected
- Thermal analysis using this set-point demonstrated that the Pancam and HGA actuators would be protected from overheating
  - IDD had a small window of vulnerability (5:00 to 7:00 LST)
  - Eliminating IDD overheating threat with this approach was impractical
- High-reliability space-qualified thermostats typically require 3 to 6 months lead time for a new build
  - A more expedient approach would be to canvas thermostat vendors for their residual stock
  - This approach proved successful when 30 previously flight-qualified thermostats were located with a set-point of –40°C & procured in about 2 months
  - The lower set-point than the specified –30°C was acceptable since it did not significantly change the cut-off or return to operation times

Rover Actuator Warm-up Heater Lesson (3/3)

- **5 warm-up heaters circuits throughout the PMA, HGA, & IDD were cabled through the Rover heater thermostat assembly**
  - **The chassis of the Rover heater thermostat assembly was fabricated from carbon-fiber composite so there was no thermal expansion mismatch with its mounting location on the Rover WEB**
  - **Exterior painted white to reduce solar loading impact**

- **When MER-B (Opportunity) landed on Mars on January 25, 2004, an anomalous nighttime current draw was detected**
  - **A stuck-on IDD warm-up heater was suspected**
  - **This suspicion was corroborated with circumstantial telemetry**
  - **The Rover heater thermostat protected the IDD heaters from overheating**
  - **More importantly, it conserved about 180 W-hrs of Rover battery energy per Sol**

- **Lesson: A fault scenario was permitted to drive the thermal hardware implementation, however, the protective measure proved invaluable**

Conclusions

- Despite the most proactive planning & preparation, thermal design challenges arise throughout the entire design & implementation life cycle
- Programmatic factors such as budget & schedule tend to further complicate the situation
- The resolution of these challenges requires a systems engineering perspective since thermal design usually crosses over several subsystem boundaries
- Both Rovers have safely landed on the Martian surface
  - Thermal design performance has met all functional requirements