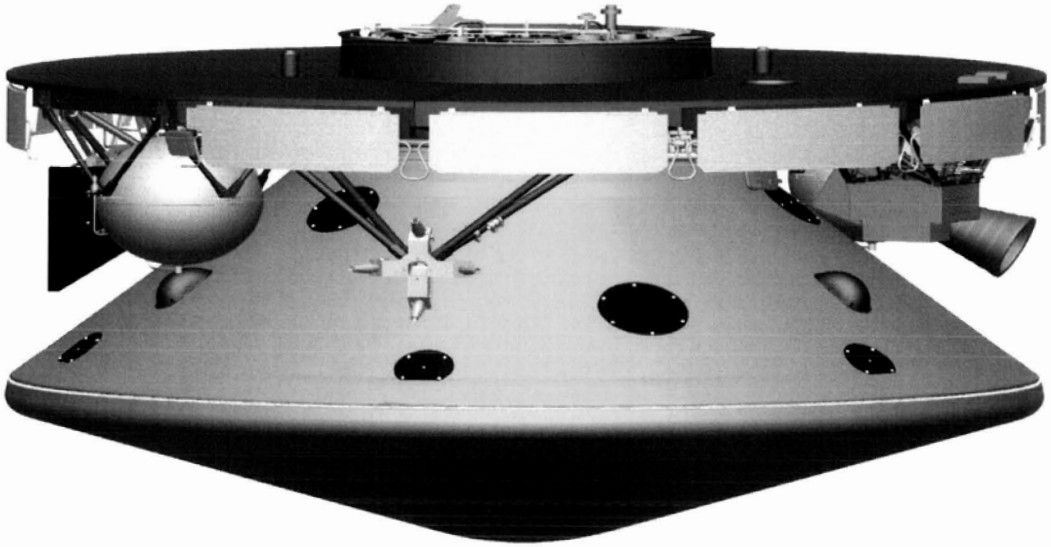
Thermal Design and Flight Experience of the Mars Exploration Rover Spacecraft Computer-Controlled, Propulsion Line Heaters



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Jet Propulsion Laboratory/California Institute of Technology
2004 ICES Conference – July 21, 2004

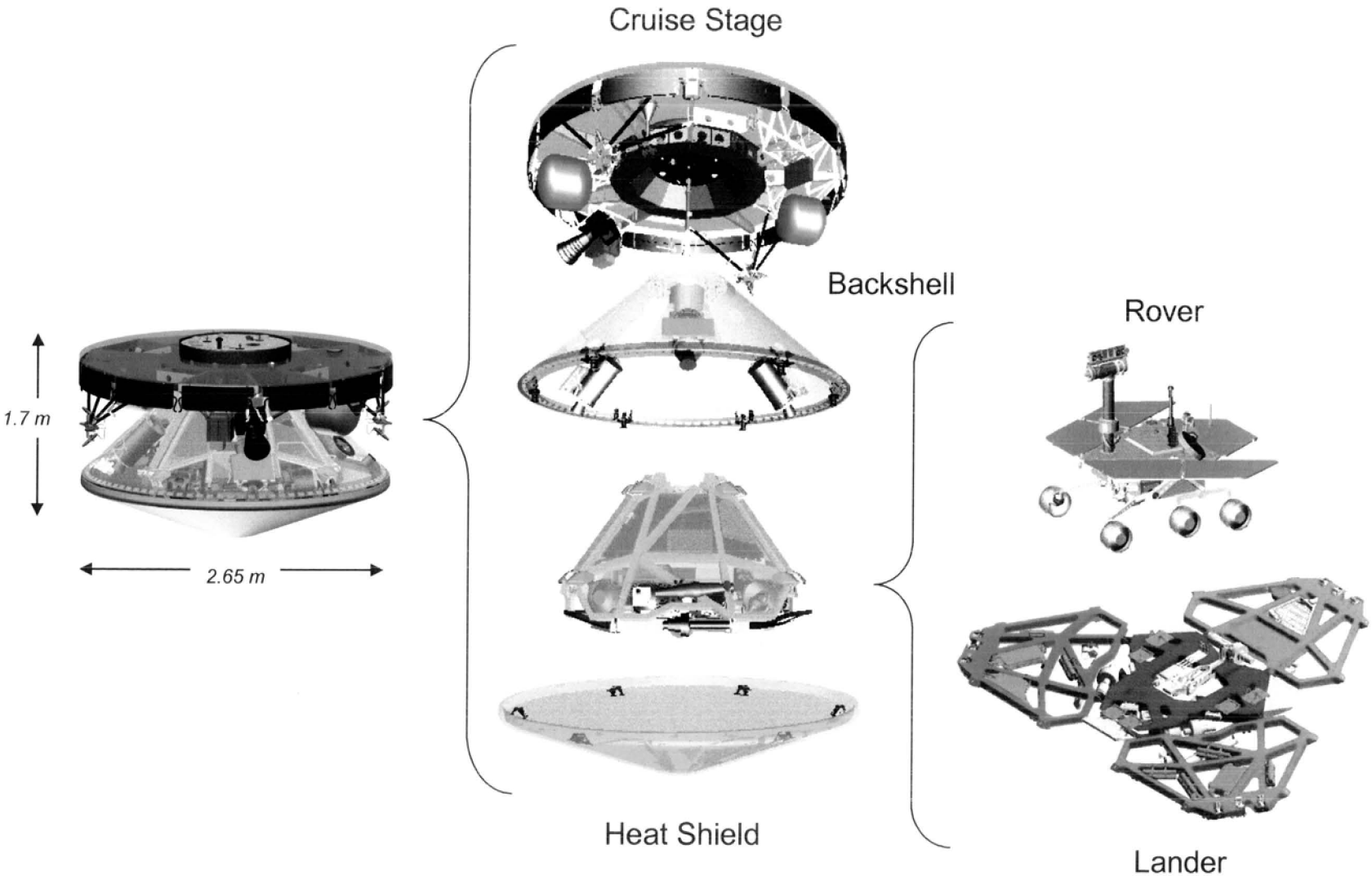
MER Project Description

- The Mars Exploration Rover (MER) project landed two identical roving science vehicles on Mars in Jan. 2004; they continue to perform geological science data collection well beyond their surface design lifetime of 90 sols (today is Sol 195A & Sol 175B).

- The missions launched in June & July of 2003 on separate Delta II class vehicles

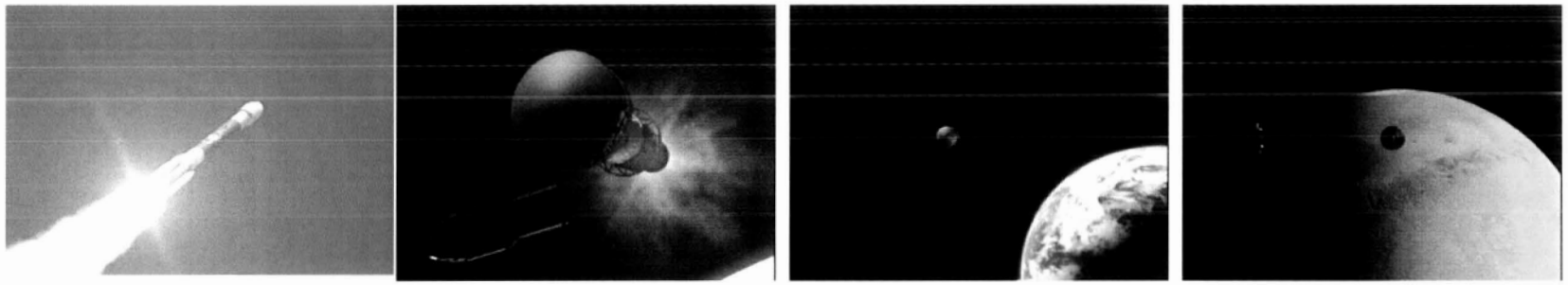
- Each Flight System consisted of:
  - A cruise stage and entry, descent and landing system (EDL) with inheritance from the Mars Pathfinder (MPF) development
  - A rover based upon the Athena Rover developments undertaken for the Mars '01 and Mars Sample Return projects (MER-A >3.5 km traverse and increasing)
  - Athena Science Package, 5 science instruments to conduct remote and in-situ observations

MER Spacecraft Configuration

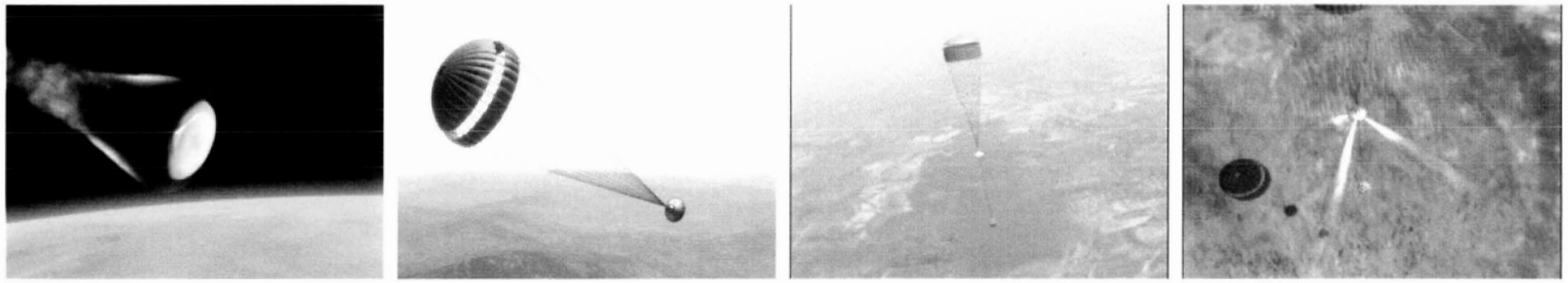


Mission Overview

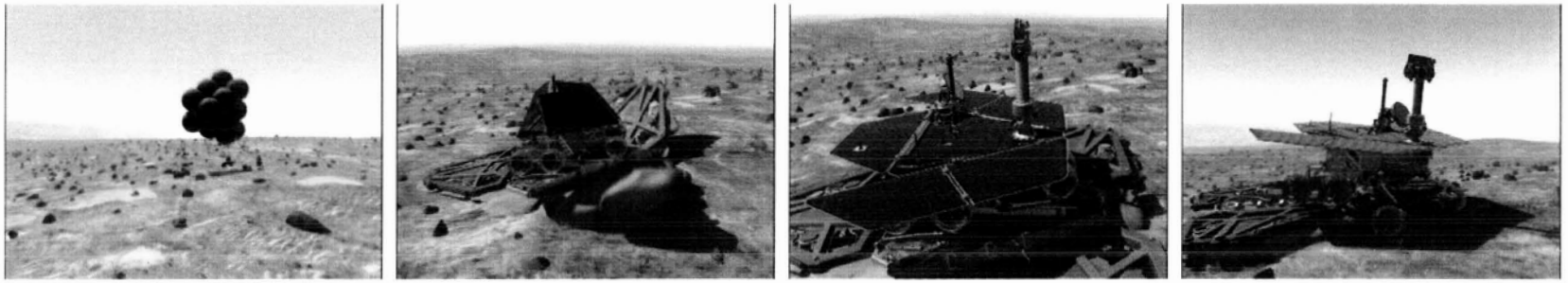
Launch/Cruise



EDL

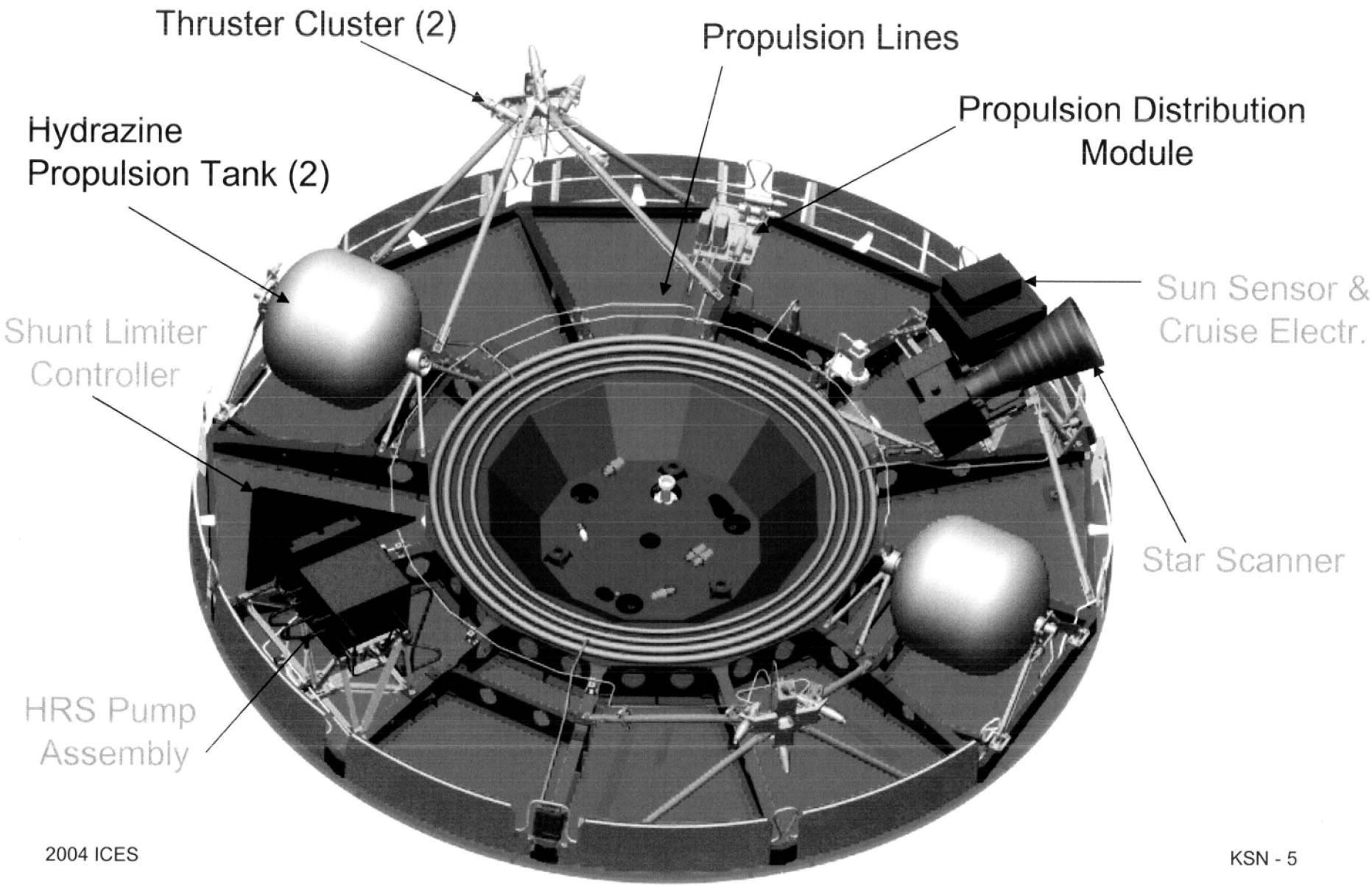


Surface



Images From Mission Animation by Dan Maas

MER Cruise Stage – Propulsion Hardware



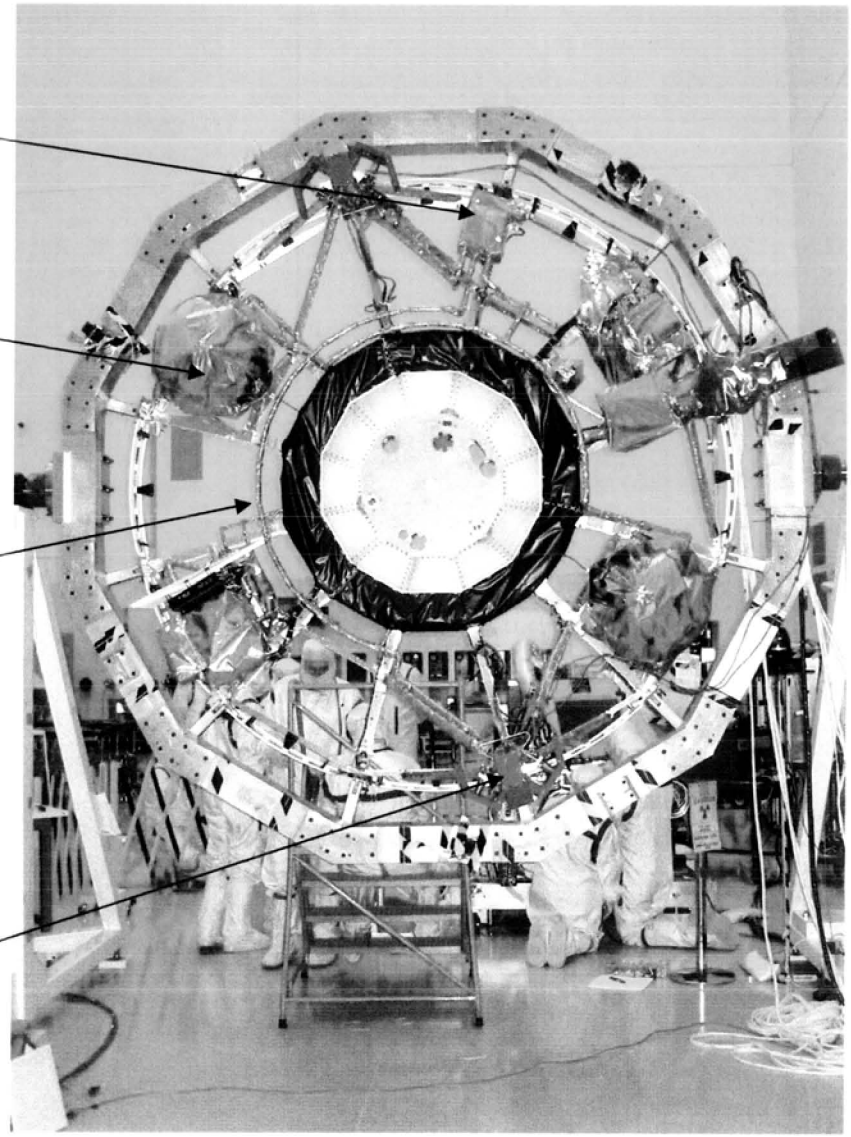
MER Cruise Stage – Real Hardware

Propulsion Distribution Module

Hydrazine Propulsion Tank (2)

Propulsion Lines

Thruster Cluster (2)



MER Propulsion Lines – Thermal Design Drivers

- Worst-Case Hot Environment – steady state
  - Immediately after launch (1AU, sun-pointed solar array)
  - T solar array = +90C

- Worst -Case Cold Environment
  - Steady State
    - At Mars, just prior to entry (1.52 AU, 46 deg off-Sun)
    - Tsolar array = 0 deg C
  - Transient (survive 70 minutes in this env't)
    - At Mars, turn-to-entry (1.52AU, 75 deg off-Sun for MER-B)
    - Tsolar array = -65C
- Hydrazine freeze point = 1.7C (prop line AFT limits 17C to 50C)
- Heat leaks thru cabling, standoffs & MLI
- Varying radiative views to space & S/C hardware
- Bus voltage variation – (heater dissipation variation)
- Switching of solar array sectors
- Variation in Power dissipation on shunt radiator

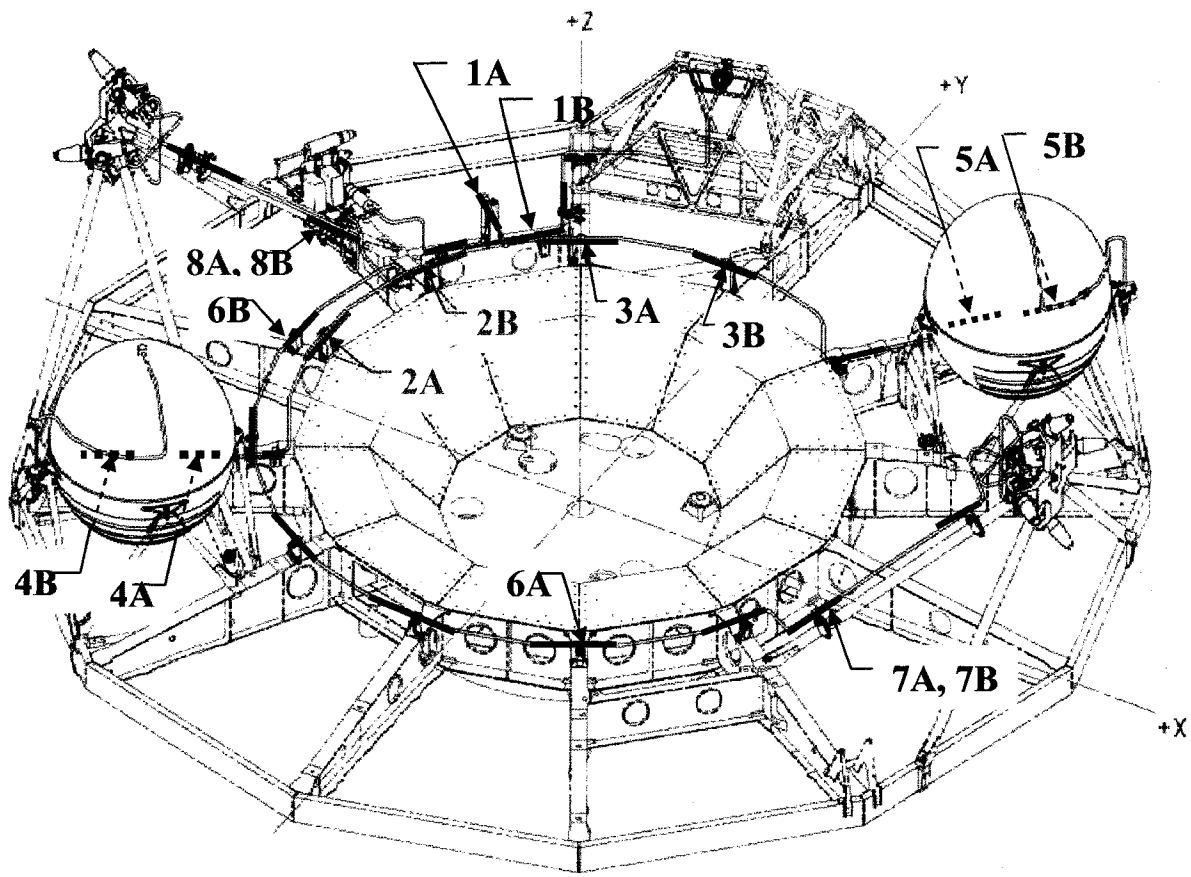
Propulsion Line Thermal Design Features

- Eight Control Zones
- Primary – A
- Backup – B

- Heater segments only in high heat loss areas

- Programmable setpoints for on-off control
- 16 PRT's for control & telemetry

- Total line length = 8.38m (330")
- Total power per string = 13.5W



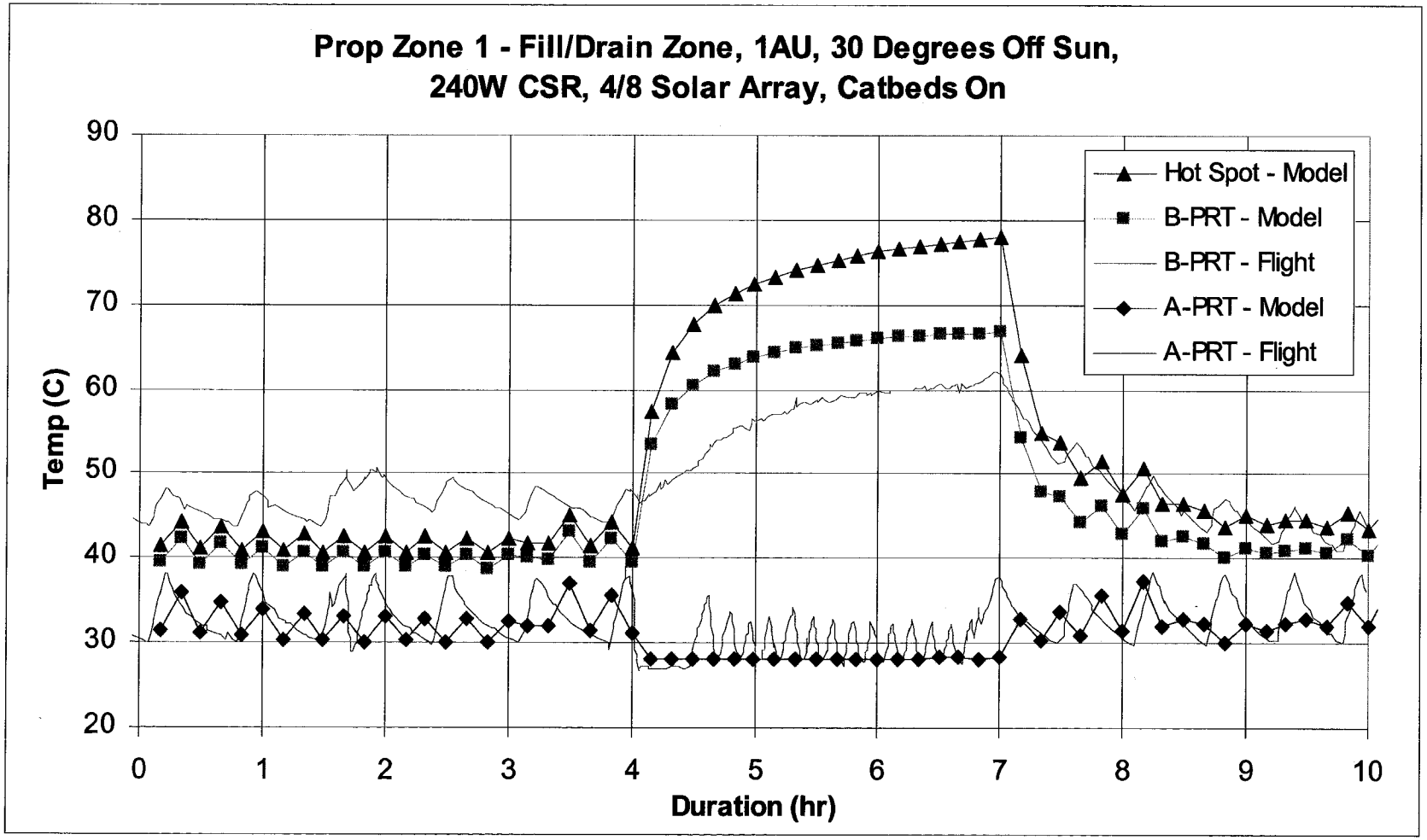
Prop Line Control Setpoints Prior to Launch

- Wide ranges to minimize number of cycles (up to 10C)
- Staggered settings – allow A string to control
  - prevent simultaneous operation
- Balance setpoints inside AFT range (17C to 50C)
- Setpoints chosen based on System Thermal Test behavior

	MER-A			MER-B	
Zone	Low	High		Low	High
1A	30	37		28	34
2A	36	44		36	46
3A	36	44		37	43
4A	36	44		23	30
5A	36	44		34	43
6A	37	44		33	40
7A	31	40		31	40
8A	31	41		31	41
1B	38	44		31	41
2B	22	27		22	27
3B	24	30		24	30
4B	23	30		36	44
5B	23	31		23	31
6B	22	29		26	33
7B	26	35		26	35
8B	26	35		26	35

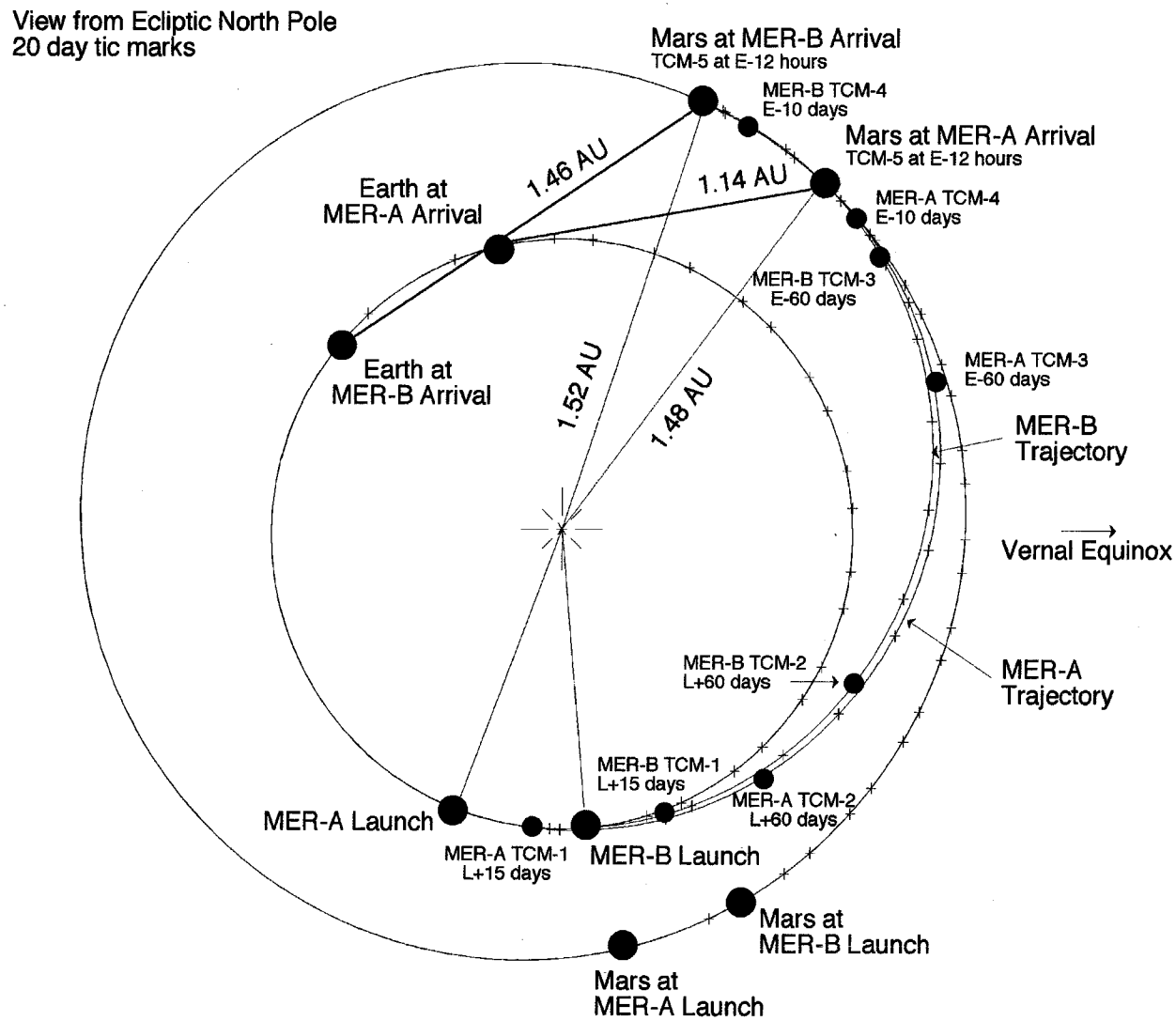
MER-A Early Cruise Flight Experience

– Overheat of Zone 1B during First Trajectory Correction Maneuver



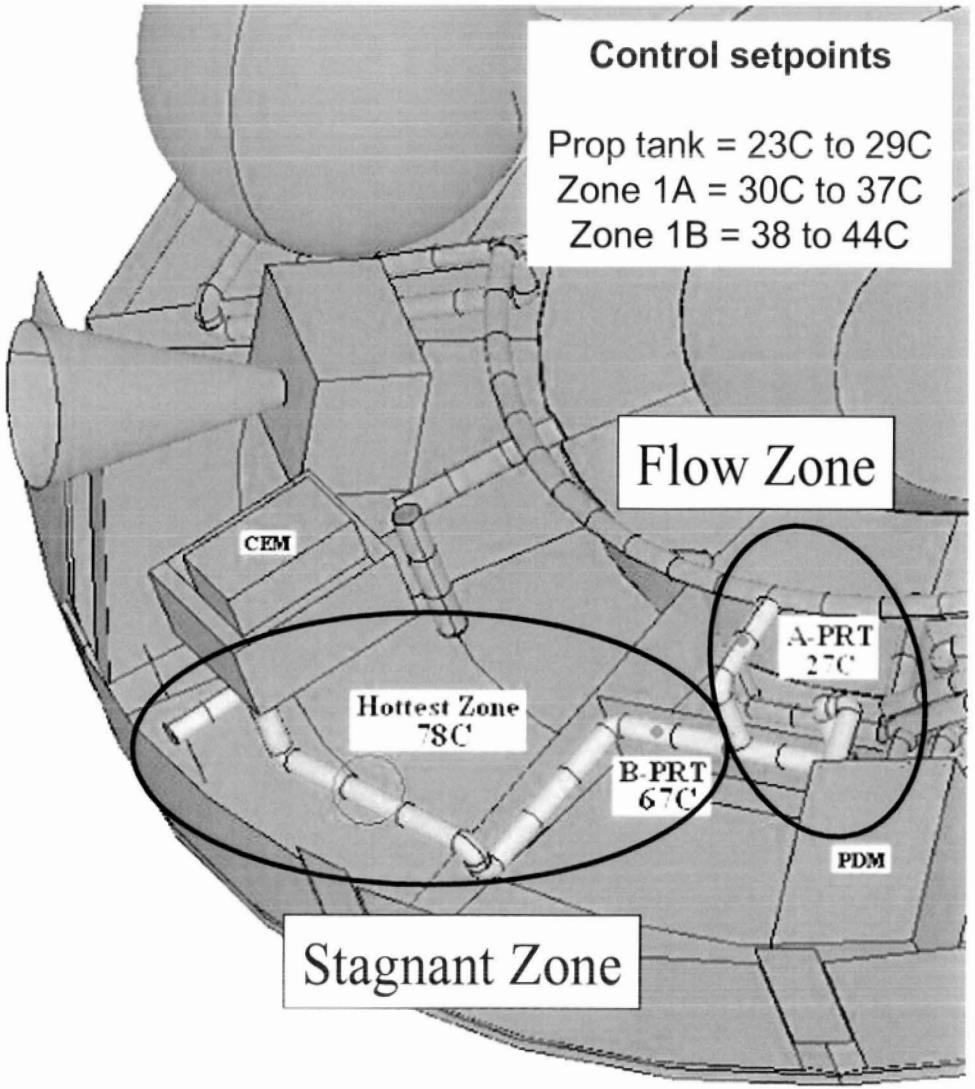
MER A & B Flight Trajectories

Mars Exploration Rover



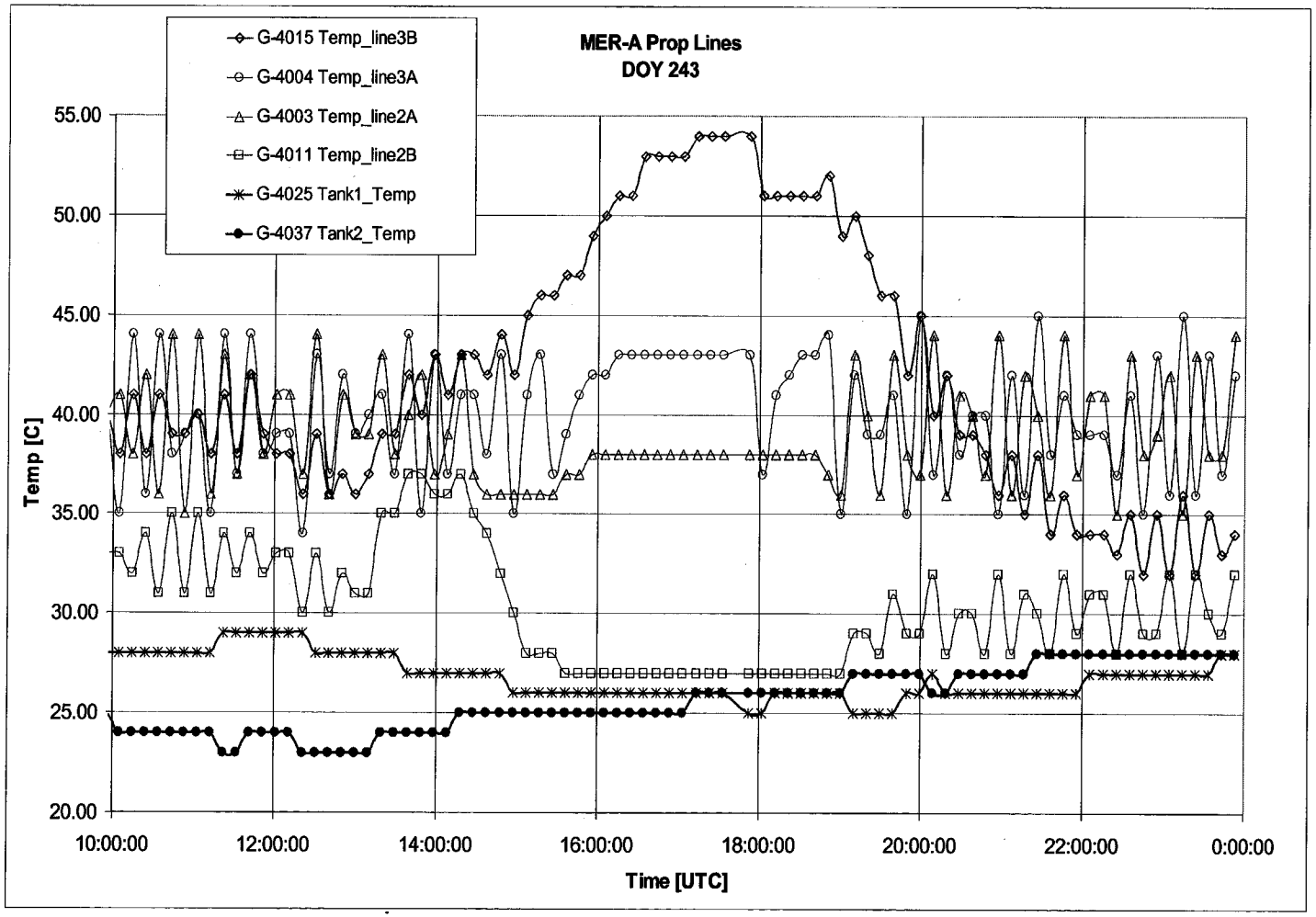
MER-A Early Cruise Flight Experience

- Overheat Occurred in Fill & Drain Region (Zone 1B) which had no propellant flow during 3-hour thruster firing
- Problem prevented during MER-B TCM-1 by changing 1A setpoints (to 17C to 20C) less than tank setpoints (23C to 29C)
- All subsequent TCM's were less than 20 minutes in duration



MER-A Mid Cruise Flight Experience

- **Tank Heater Cycling and Propellant Migration in Lines**
  - **Causes Irregular Heater Cycling**

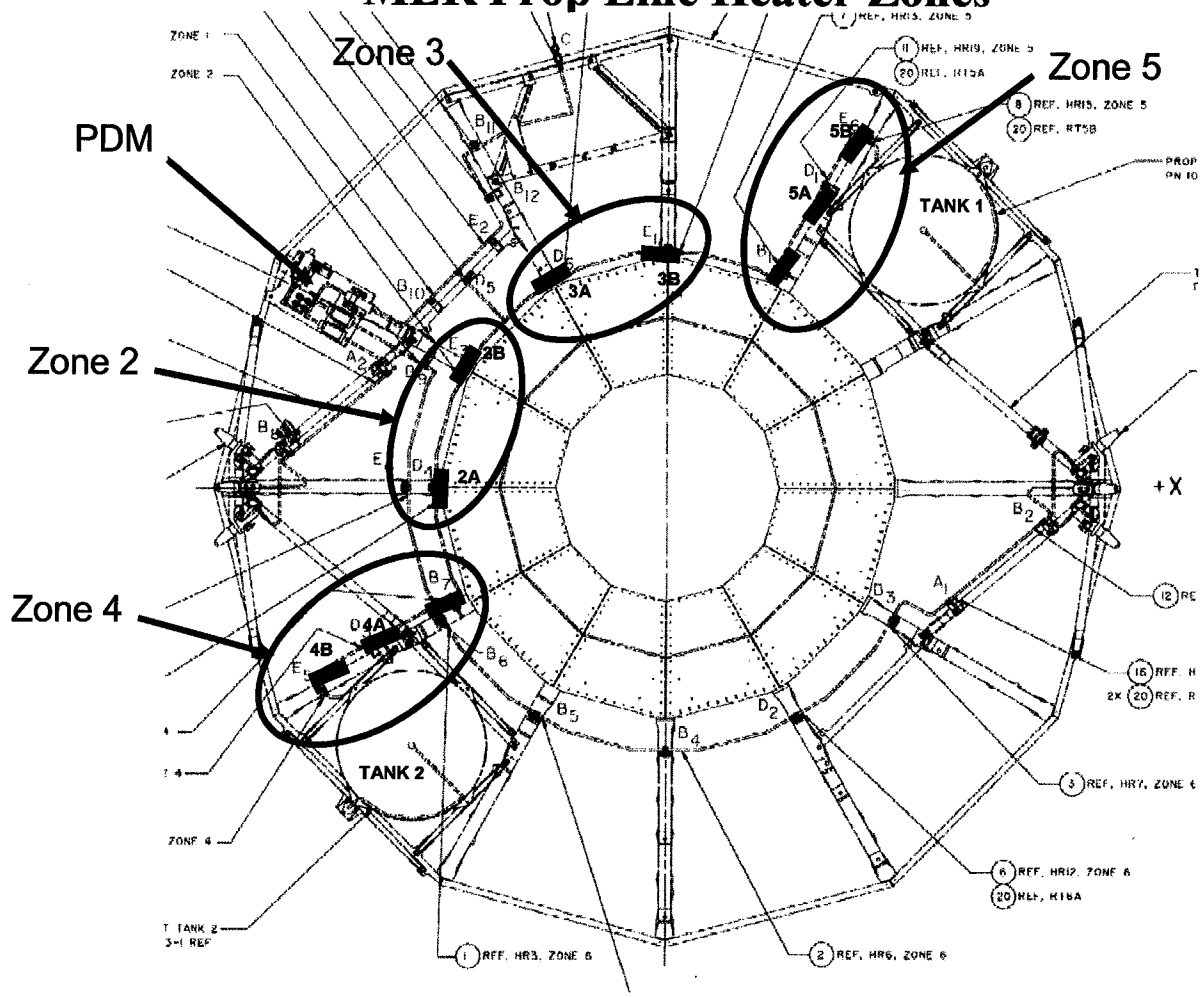


MER-A Mid Cruise Flight Experience

Mars Exploration Rover

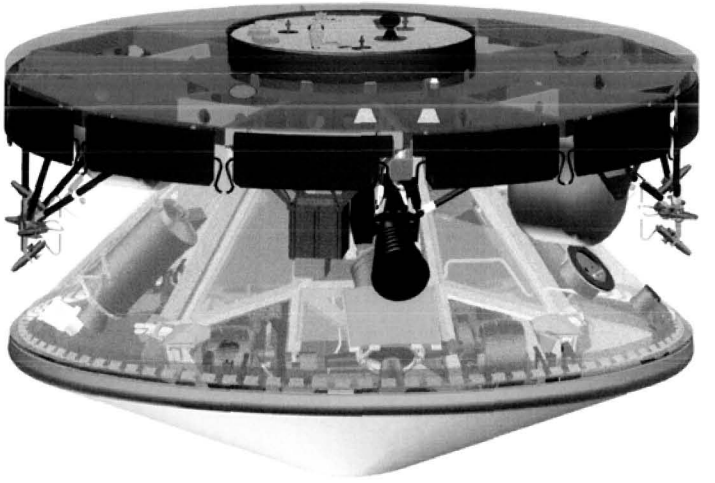
- **Propellant Migration from Tank 2 (warming up) to Tank 1 (cooling down)**
- **Cold fluid from Zone 2B flows into Zone 3A causing the Zone 3 heater to remain on constantly for 3 hour period**
- **Sensor for zone 3B reaches 54C (above max AFT limit of 50C, but still less than qual. limit of 70C)**

MER Prop Line Heater Zones



MER A & B Mid-Cruise Flight Experience

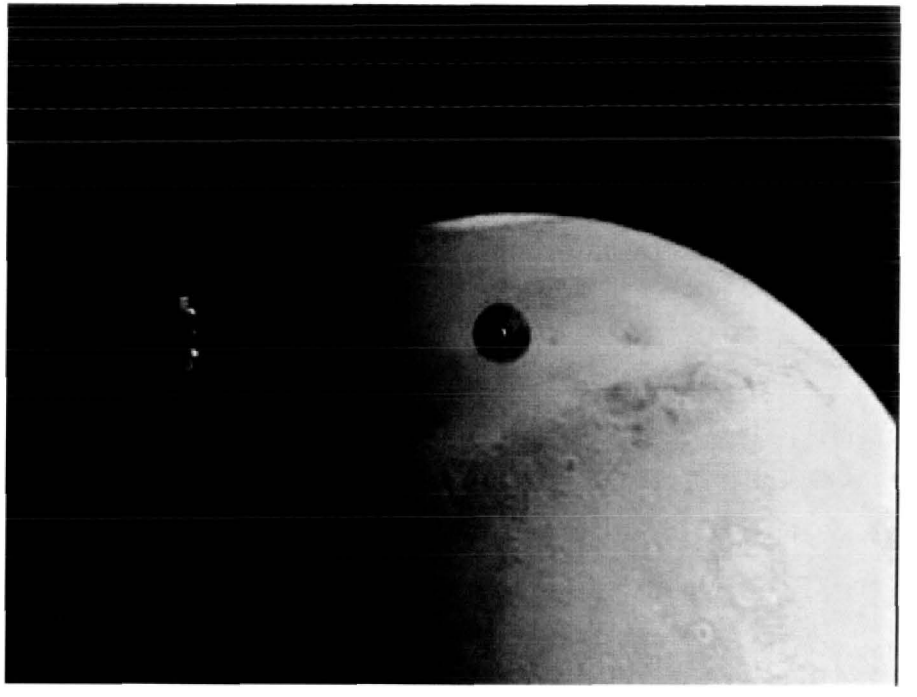
- Flight Computer Cold Reboot
  - Deemed necessary to clear bit error memory problem on flight computer after solar storm
  - Flight computer holds prop line heater switch states in last known condition during reboot
    - Not desirable if last known condition is A&B OFF or A&B ON



  - Reboot process designed to take 20 minutes but must be able to survive an anomaly for 24 hours
  - Decision to command A string ON, B string OFF prior to reboot
    - Max predicted temp = 67C after 24 hours in this state
    - Higher than max AFT (50C) but still less than max qual. (70C)
  - Cold Reboot performed in 20 minutes without incident
    - Lines never in danger of overheating
    - Nominal setpoints controlled immediately after reboot

MER-B Late Cruise Flight Experience

- Turn to Entry – 70 minutes prior to cruise stage separation
- Off-Sun angle increases from 37 deg to 75 deg
  - Solar array drops in temp from 0C to -65C in 20 minutes
- If propline setpoints were left unchanged 4 segments of the propulsion lines were in danger of freezing

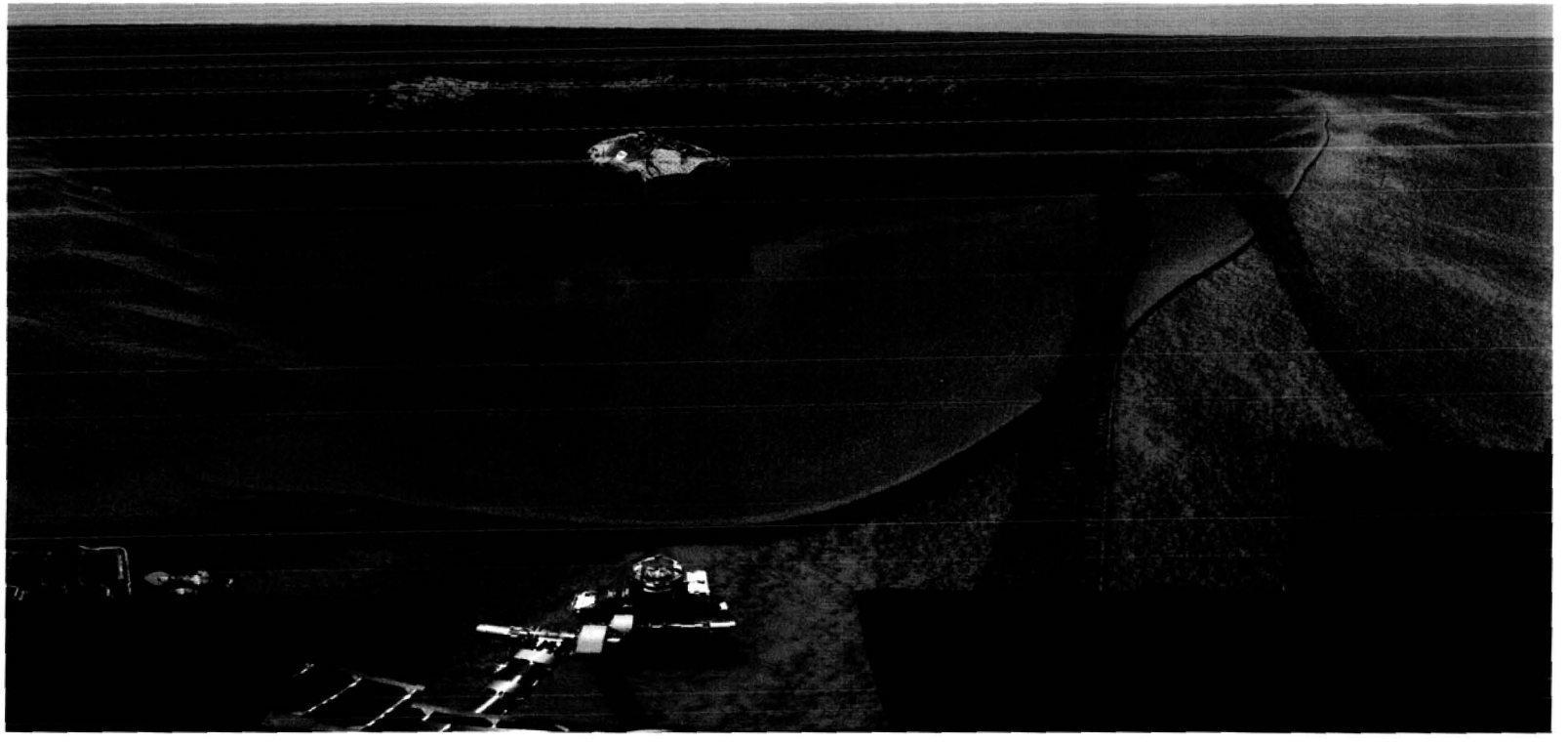


- A ruptured propline would have resulted in unknown thrust vector at rupture point and loss of mission
- Adjustments to setpoints increased temperature margins to 10C or greater in conservative models
- RESULT: EDL successful

Lessons Learned/Conclusions

- When doing prop line heater design/layout consider:
  - Design cases for firing thrusters
    - Stagnant sections of line should have individual heater control
  - Effects of fluid migration between tanks
    - Keep tank & line control temps in same region
    - Minimize control deadbands to promote temp uniformity
  - Locations of control zones
    - Lines in a zone should have similar BC's over entire mission
  - Simplified control
    - Single heater circuit with co-located primary & backup sensors
    - Activate backup heater string only in case of fault condition
  - Continuous wrap heaters with higher density wrap near higher heat loss areas (standoffs & cable egress)
- Track telemetry & correlate models during flight
  - Extrapolate models predicts to worst-case conditions
  - If necessary, adjust setpoints to work heaters harder; inc. temp margin
- Avoid Open bus designs
  - Enclose propulsion hardware in temp controlled cavities, if possible

Conclusion



MER-B, (Opportunity) leaves Eagle Crater in Meridiani Planum, Sol 60B, March 25, 2004

- **Computer Controlled T'stats worked very well**
  - **Setpoint adjustability was one key to successful Entry, Descent & Landing**