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

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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
Mission Overview

Images From Mission Animation by Dan Maas
MER Cruise Stage –
Propulsion Hardware

Thruster Cluster (2)

Propulsion Lines

Propulsion Distribution Module

Hydrazine Propulsion Tank (2)

Sun Sensor & Cruise Electr.

Shunt Limiter Controller

Star Scanner

HRS Pump Assembly
MER Cruise Stage – Real Hardware

- Propulsion Distribution Module
- Hydrazine Propulsion Tank (2)
- Propulsion Lines
- Thruster Cluster (2)
• Worst-Case Hot Environment – steady state
  – Immediately after launch (1AU, sun-pointed solar array)
  – $T_{solar\ array} = +90^\circ C$

• Worst -Case Cold Environment
  – Steady State
    • At Mars, just prior to entry (1.52 AU, 46 deg off-Sun)
    • $T_{solar\ array} = 0\ deg\ C$
  – Transient (survive 70 minutes in this env’t)
    • At Mars, turn-to-entry (1.52AU, 75 deg off-Sun for MER-B)
    • $T_{solar\ array} = -65^\circ C$

• 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

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(Mars Exploration Rover)

2004 ICES
MER-A Early Cruise Flight Experience

- Overheat of Zone 1B during First Trajectory Correction Maneuver

Prop Zone 1 - Fill/Drain Zone, 1AU, 30 Degrees Off Sun, 240W CSR, 4/8 Solar Array, Catbeds On

Graph showing temperature changes over duration with various markers for different conditions.
View from Ecliptic North Pole
20 day tic marks

Earths at MER-A Arrival
1.46 AU
1.14 AU
1.52 AU
1.50 AU

Earth at MER-B Arrival
MER-A TCM-1
L+15 days
MER-B TCM-1
L+15 days
MER-A TCM-2
L+60 days
MER-B TCM-2
L+60 days

Mars at MER-B Arrival
TCM-5 at E-12 hours
MER-B TCM-4
E-10 days
MER-B TCM-3
E-60 days

Mars at MER-A Arrival
TCM-5 at E-12 hours
MER-A TCM-4
E-10 days
MER-A TCM-3
E-60 days

MER-B Trajectory
Vernal Equinox

MER-A Trajectory
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
- Tank Heater Cycling and Propellant Migration in Lines
  - Causes Irregular Heater Cycling
- 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 54°C (above max AFT limit of 50°C, but still less than qual. limit of 70°C)
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 = 67°C after 24 hours in this state
  - Higher than max AFT (50°C) but still less than max qual. (70°C)
- 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