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

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ABSTRACT

As part of the Mars Exploration Rover (MER) project, the National Aeronautics and Space Administration (NASA) launched two rovers in June and July of 2003 and successfully landed them on Mars in January of 2004. The cruise stage of each spacecraft (S/C) housed most of the hardware needed to complete the cruise from Earth to Mars, including the propulsion system. Propulsion lines brought hydrazine propellant from tanks under the cruise stage to attitude-control thrusters located on the periphery of the cruise stage. Hydrazine will freeze in the propellant lines if it reaches temperatures below 1.7°C. Thermal control of the propulsion lines was a mission critical function of the thermal subsystem; a frozen propellant line could have resulted in loss of attitude control and complete loss of the S/C.

The MER cruise stage thermal design employed a computer-controlled thermostatic heater system to keep the propellant lines within their allowable flight temperature limits (17°C to 50°C). The MER propellant line thermal design differed from previous propellant line heater designs in that the line heaters were placed only in areas of highest potential heat loss (not along the entire length of the lines) and that computer-controlled thermostats were used instead of mechanical thermostats. Computer-controlled thermostats enabled setpoint flexibility; adjustments to setpoints were made after solar thermal vacuum testing and during flight.

This paper covers the design, thermal testing and flight experiences with the computer-controlled thermostats on the propulsion line heaters. Flight experience revealed heater control behavior with propellant loaded into the system and during thruster firings that was not observable during system level testing. Explanations of flight behavior, lessons learned and suggestions for improvement of the propellant line heater design are presented in this paper.

INTRODUCTION

Two Mars Exploration Rovers designated as MER-A (Spirit) and MER-B (Opportunity), were launched in June and July of 2003 on Boeing Delta II 7925 launch vehicles from Kennedy Space Center (KSC). The cruise to Mars took seven months with both rovers landing safely on the Mars surface in January of 2004.

The MER spacecraft was designed to take a rover from the Earth to Mars (during the cruise phase) through the Mars atmosphere and onto the surface (during the entry, descent and landing phase). The rover was designed to egress from the lander and conduct science investigations of the Mars geology (during the surface phase). In order to accomplish these varied functions, the flight system (see Figure 1) consisted of: 1) a cruise stage (used only during cruise, it separated from the aeroshell prior to entry), 2) an aeroshell entry vehicle (made up of a backshell and heatshield, used in the entry, descent and landing phase), 3) a tetrahedral

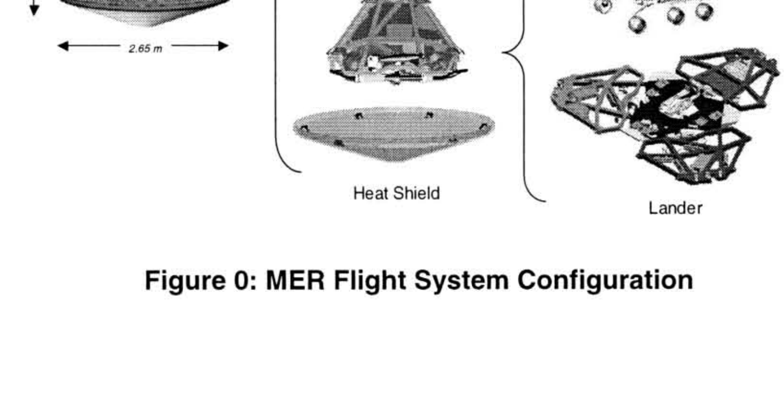

Figure 0: MER Flight System Configuration

lander structure and 4) a rover (used in the surface phase).

The cruise stage structure supported the cruise solar array on top and all of the propulsion and attitude control components needed to keep the S/C on the proper trajectory to Mars. The spacecraft was spin-stabilized at 2 RPM during the cruise to Mars. X-band communications electronics located deep inside the rover and antennas on top of the cruise stage were used to communicate with the Earth during cruise. Electronics heat dissipation inside the rover was removed by a liquid, pumped-loop cooling system known as the Heat Rejection System (HRS)[1,2,3]. The HRS consisted of a fluid pump on the cruise stage that circulated cold Freon in the rover electronics to remove internal heat dissipation. Warmed fluid flowed out of the rover to radiators on the cruise stage where the heat was rejected to the cold space environment. This HRS design was first developed for the Mars Pathfinder (MPF) spacecraft that successfully put a similar lander and smaller rover on the surface of Mars in July of 1997.[4]

The entry, descent and landing (EDL) phase of the mission is depicted in Figure 2. The EDL system was

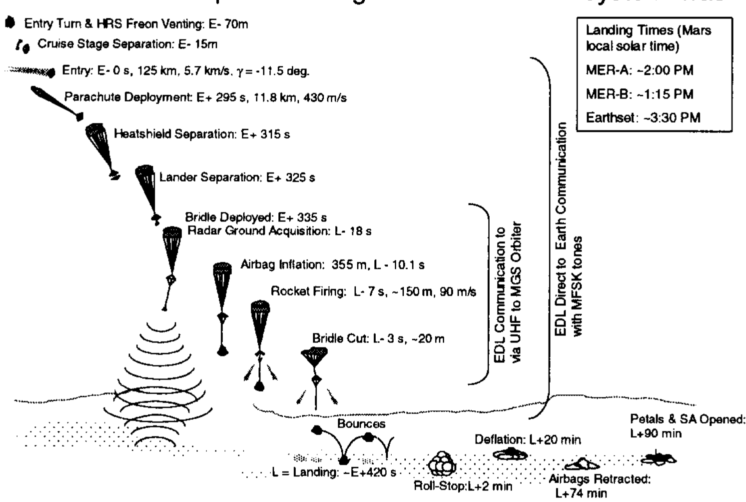

Figure 2: Entry, Descent and Landing

also based on the MPF design. Prior to entry, the cruise stage separated away from the aeroshell. The aeroshell utilized a Viking-derived heatshield with SLA-561 ablative material to protect the lander and rover from the intense aero-heating environment during entry. A modified Viking/Mars Pathfinder-derived parachute deployed at 11.8 km above the surface. Shortly thereafter, the heatshield separated from the bottom of the backshell and the lander ran down a bridle underneath the open backshell. A radar altimeter sensed the elevation of the lander above the ground. At an elevation of 355 m, airbags surrounding the lander were inflated. At approximately 150 m above the surface, solid rockets on the inside of the backshell were fired to slow the lander to zero vertical velocity. At an elevation of approximately 20 m, the bridle was cut allowing the airbag-shrouded lander to drop onto the Martian surface. The backshell solid rocket motors continued to burn after the bridle was cut in order to move the backshell down range of the lander. The lander bounced for several minutes (as many as 28 bounces) before coming to rest on the Mars surface. The airbags were deflated and retracted toward the lander petals. One and a half hours after landing the lander petals were opened and the rover solar array panels are deployed.

Additional rover deployments that occurred at the beginning of the surface mission included the Pancam Mast Assembly (PMA) camera mast structure, the High Gain Antenna (HGA) steerable communications antenna and the mobility system. After all of the deployments were completed, the rover cut its umbilical cable interface with the lander and drove away onto the Martian soil to begin its science mission.

DESCRIPTION OF THE MER PROPULSION LINE THERMAL CONTROL DESIGN

The 3-year, MER development schedule was very tight. The only way to meet the launch schedule was to borrow heavily from previous successful Mars spacecraft designs. The MER spacecraft design (for essentially all hardware except the rover) was derived almost entirely from the MPF spacecraft design.

One of the thermal lessons learned from the 1997 MPF flight experience was that an open-bus, cruise stage design (that left the propulsion lines exposed to the space environment) should be avoided, if possible.[5] Unfortunately, since the MER baseline design utilized the MPF cruise stage, thermal design engineers had to deal with an open-bus and all of its shortcomings, again. In an effort to improve on the MPF cruise stage propulsion line thermal design, the following upgrades/changes were implemented:

1) Mechanical, bimetallic thermostats were replaced by programmable computer controlled thermostats;

2) The number of distinct propulsion line heater control zones was increased from 4 to 8;

3) Line heater elements were placed only at high heat loss areas (i.e., propellant line mounting supports and cabling egresses), rather than running continuously over an entire control zone.

PROPULSION HARDWARE

The MER propulsion system (see Figure 3) consisted of 2 Titanium hydrazine tanks pressurized with helium, a series of stainless steel tubes which brought the hydrazine from the tanks to a propulsion distribution module (PDM) and another set of tubing which brought the hydrazine from the PDM out to the thrusters. Hydrazine propellant freezes at temperatures below 1.7°C. The propulsion system thermal design was driven by a hard requirement to ensure that hydrazine will not

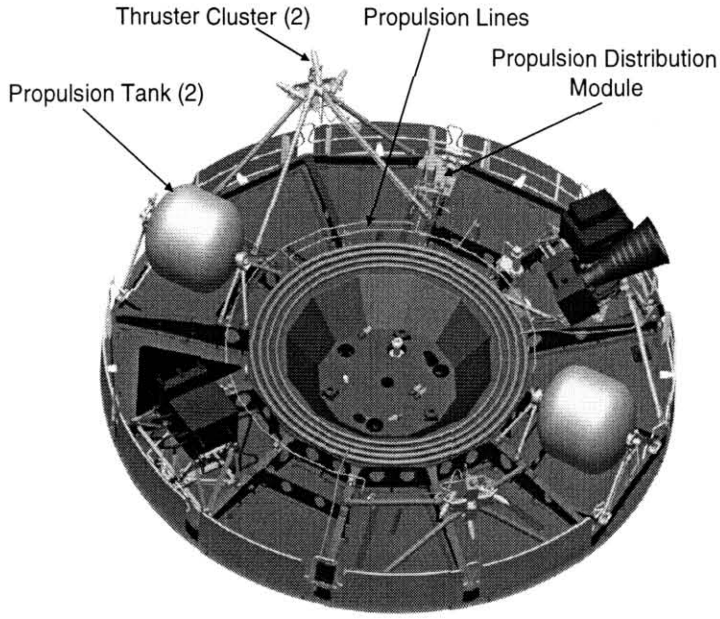

Figure 3: Propulsion Hardware on Cruise Stage

freeze anywhere in the propulsion system. Thermostatic heaters were used on the tanks, lines and thrusters.

In the MER propulsion system, two pressurized tanks stored the hydrazine propellant. The tanks were structurally supported but thermally isolated from the cruise stage with titanium struts. Multi-layer Insulation (MLI) blankets covered all exterior tank surfaces including the tank struts. The allowable flight temperature (AFT) range for the propellant tanks was 17°C to 28°C. A two-element heater controlled by series-redundant mechanical thermostats prevented overcooling. Both heater elements dissipated a minimum of 8W. The primary thermostat range was 23.2°C to 28.8°C and the secondary range was 18.2°C to 23.8°C.

Stainless steel tubes with welded fittings carried hydrazine from the tanks to the thrusters. The outer tube diameter was 6.35 mm (0.25 inches). Low thermal conductance Delrin supports and insulated P-clamps supported the lines off the cruise stage structure. High Flex II Electro-Magnetic Interference (EMI) shielding tape provided EMI protection for the cables with minimum metallic cross-sectional area and a minimized conductive heat loss. MLI blankets isolated the lines from the external environment. Heat spreaders on the lines, in the form of two layers of aluminum tape, enhanced lateral conduction and reduced temperature differences along the lines. The allowable flight temperature range for the propellant lines was 17°C to 50°C.

THERMAL HARDWARE

Custom heaters supplied power to offset the calculated heat leaks at each Delrin support. The heaters consisted of short spirals, approximately 130mm (5 inches) long, installed only at the supports. The line length between the standoffs was 381 mm (15 in) leaving 254 mm (10 in) of unheated line between the heaters. In order to provide uniform temperatures throughout each zone, the individual heaters had unique power dissipations based on the predicted local heat losses. The total propulsion line length was 8.38 m (330 in). The total power dissipation of the primary heater string was 13.5 W, resulting in an average power "density" on the lines of 1.61 W/m (0.041 W/in).

Platinum Resistance Thermometers (PRT's) mounted on aluminum blocks measured the line temperatures for telemetry and control. The PRT blocks were mounted directly to the propellant line in the heated area. An internal spiral groove in the block provided clearance for the heater. The block design allowed temperature measurements in the heated zone for more stable heater control.

PROPULSION LINE HEATER DESIGN DRIVERS

The propulsion lines experienced a worst-case hot environment immediately after launch (at 1.0 AU) with the S/C solar array pointed directly at the Sun. This heated the solar array to its maximum temperature and therefore gave the propulsion lines their warmest environment.

The steady state worst-case cold environment for the propulsion lines was at the highest off-Sun angle (46°) at Mars (1.52AU). There was an additional transient case at Mars in which the propulsion lines had to survive 70 minutes at the turn-to-entry (TTE) off-Sun angle which went as high as 75° for MER-B.

Other design considerations included: 1) the effect of switching on/off solar array sectors; switching on an array sector would drop the array temperature since some of the absorbed solar load would be converted into electrical energy, 2) the effect of power dissipation on the cruise shunt radiator located on the top of the cruise stage 3) radiative views from the lines to other S/C surfaces and to space; these views varied greatly along the lengths of the lines, 4) variations in bus voltage that will change the heat dissipations of the electrical resistance heaters and 4) heat leaks through cabling, propulsion line supports, and MLI.

PROPULSION LINE HEATER CONTROL

Eight zones of computer-controlled heaters (on-off with dead band) prevented overcooling on the propulsion lines. Each zone had primary and back-up heater circuits, both with distinct staggered control settings. In the six largest zones, the primary and backup control locations were separated to provide greater protection from hot and cold spots.

Figure 4 is a color-coded drawing showing the eight control zones with the heater and PRT locations. Heaters are denoted by colored lines and PRT's are shown as a number and a letter (Zone number followed by A for the primary heater control point or B for the secondary heater control point). Two zones (4 and 5) were

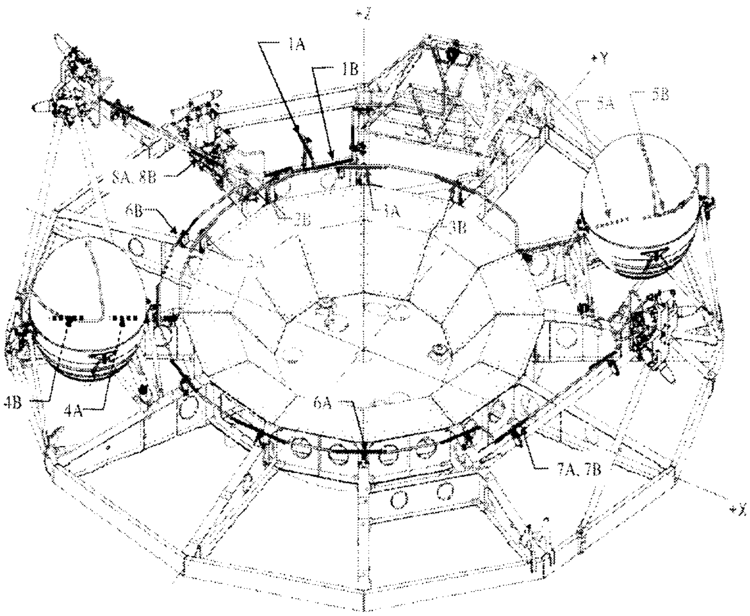

Figure 4: Propulsion Heater Control Zones

dedicated to the lines leading to the propellant tanks, two zones (2 and 3) were for the lines connecting the propellant tank legs to the common tee, three zones (6, 7 & 8) were for the lines connecting the PDM to the thruster clusters, and one zone (1) was for the line between the tee, fill valve, and PDM.

Each of the eight zones had a primary heater circuit and an identical redundant secondary heater circuit for a total of sixteen circuits. Each Kapton film heater had dual resistive traces, one trace per circuit. All heaters in a zone were connected in series. Both the primary and redundant circuits heat the entire zone at the same locations.

Flight software, with on-off control, governed the heater operation. Programmable setpoints were assigned to each heater circuit and were capable of being altered in test and flight. Primary and secondary PRTs in each zone supplied the temperature measurements used as feedback for the flight software control. The software control mimicked a mechanical thermostat. The software setpoint parameters were designated A high, A low, B high, and B low.

PRT's on the lines served double duty as heater control points and telemetry measurement points. There was no requirement to co-locate the A and B sensors. Consequently, it was possible to make sixteen measurements of the propulsion line temperatures, instead of eight, by separating the control points. The disadvantage of split control is that, under certain conditions, it can invert the primary and secondary control locations, making B primary and A secondary. Although this is not a problem for the hardware, this can be confusing from a human factors standpoint.

For most zones, the areas of highest predicted heat leak were chosen for the A control points and the areas of second highest heat leak were the B control points. Controlling at the areas of highest heat leak minimized the temperature excursions at all points in a zone. Heater powers vary, but capacitance does not. Thus, the higher-powered heaters tended to warm their locations quicker than the lower-power heaters. Overall temperature excursions are lowest when the control comes from the locations of the highest-power heaters.

The control settings were chosen with the following design rules in mind: 1) wide on-off ranges (as large as 10°C) will minimize the number of on-off cycles, 2) zone A settings should be higher than zone B settings to prevent simultaneous heater operation, 3) on-off ranges should be balanced such that the temperature margin below the B turn-on and the lower AFT is the same as the temperature margin between the upper A turn-off and the upper AFT and 4) small on-off ranges (as small as 5°C) provide more temperature margin. The initial control settings came from analytical predictions.

PROPULSION LINE THERMAL DESIGN PERFORMANCE IN SYSTEM LEVEL TESTS

The MER-A and MER-B spacecraft were tested in their cruise configurations in the 25-foot space simulator at the Jet Propulsion Laboratory (JPL).[6]

Propulsion line heater control setpoints were modified from their initial design values during testing. Two criteria dominated the choice of heater control settings: 1) there should be no simultaneous A & B string heater operation, and 2) the primary operation should be governed by the A heater. The actual control settings evolved during testing from a pre-test baseline to final post-test adjustments.

Two situations caused changes to the control settings. The first was a B temperature that was significantly colder than the A temperature. When this occurred, the propellant line minimum AFT limit could have been exceeded at the B location despite normal operation of the A heater. Accordingly, the A settings were raised to protect the B location.

The second situation was a B temperature that was significantly warmer than the A temperature. When this occurred the propellant line maximum AFT limit could have been exceeded at the B location despite normal operation of the A heater. The corrective action was to re-define the B controller as primary using the higher control settings for B and the lower control settings for A.

Table 1 shows the setpoint ranges that came out of the system level testing. These were the values set in flight software prior to launch.

Table 1: Propulsion Line Heater Control Settings

	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

FLIGHT PERFORMANCE OF THE PROPULSION LINE THERMAL DESIGN

Both flight spacecraft performed a number of maneuvers and turns during their seven-month cruise to Mars. Trajectory correction maneuvers were done to keep the spacecraft targeted on the proper Mars landing location (and time). Spacecraft turns were done during cruise to improve the angle between the spacecraft telecommunications antennas and the Earth in order to maintain high communications data rates. Flight performance of the MER propulsion line thermal control system at three distinct times during cruise is discussed in this section: 1) in the early MER-A cruise period during Trajectory Correction Maneuver #1 (TCM-A1) with thrusters firing, 2) during a quiescent period in the middle of the MER-A cruise and 3) in the late cruise period during the MER-B Turn to Entry (TTE), just prior to landing.

EARLY CRUISE – TRAJECTORY CONTROL MANEUVERS A1 AND B1

MER-A was launched on Sunday, June 10 from Cape Canaveral, Florida. The launch vehicle targeted an aimpoint biased away from Mars to prevent the third stage from entering the Martian atmosphere. Ten days after launch, the first trajectory control maneuver (TCM-A1) was performed on the spacecraft. This TCM was the largest scheduled maneuver for the entire cruise, designed to target the S/C toward its landing site on Mars. Thrusters were fired continuously during TCM-A1 for a total of 3 hours. Prior to the TCM, all propulsion line heaters had been cycling over their nominal setpoint ranges.

Twenty minutes into the TCM, the temperature telemetry in zone 1B went into red alarm, exceeding the maximum AFT limit for the propulsion lines of 50°C and continued to climb at an alarming rate (see Figure 5). Quick, on-

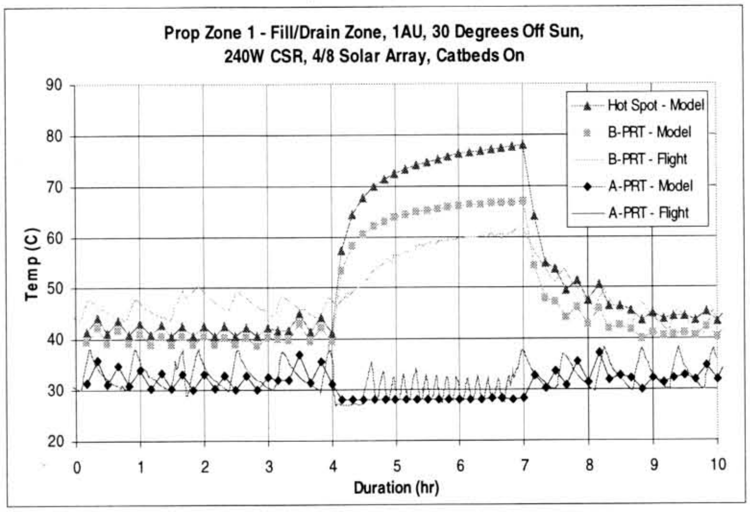

Figure 5: Propellant Line Zone 1 Temps during TCM-A1

the-spot analysis of the anomaly revealed a design flaw in the propulsion line heater layout which allowed a heater covering a stagnant (PRT B) zone of hydrazine to be controlled by a sensor (PRT A) that experienced a continuous flow of cooler hydrazine coming from the propulsion tanks during thruster firings (See Figure 6). The maximum propulsion tank control temperature was

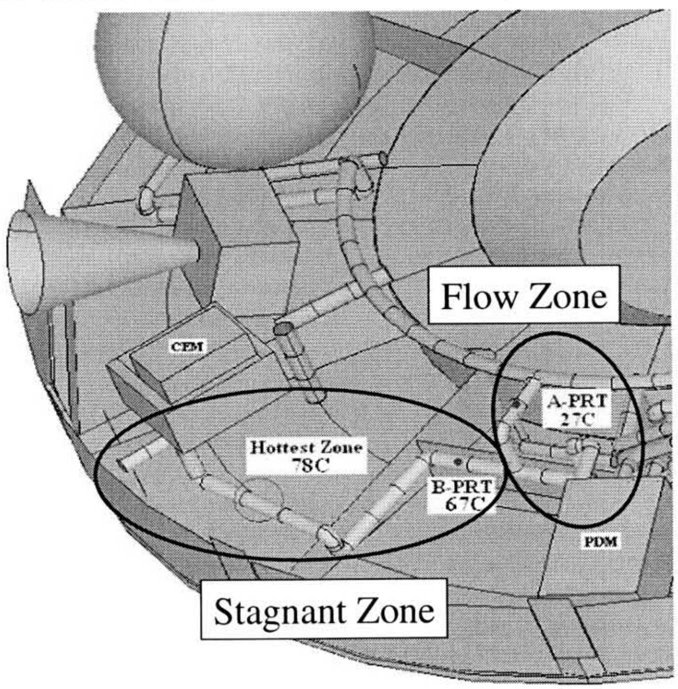

Figure 6: Locations of Zone 1 Temps during TCM-A1

28°C, while the minimum line heater control temperature was 30°C, virtually guaranteeing that the line heater would remain on continuously while fluid flowed past the control sensor. This design flaw had not been uncovered during system level testing because thrusters could not be fired during the test due to contamination concerns had the propulsion system been charged with hydrazine propellant. Simulated thruster firings were performed during the test with Argon gas to verify latch valve functional performance, but that would not be expected to uncover this deficiency nor did it.

Conservative hand calculations were done to bound the maximum expected temperature in the stagnant zone at 100°C. A quick check of the materials that would be exposed to such a high temperature revealed that there was no real concern unless the temperatures rose above 100°C. The TCM-A1 burn was allowed to continue to completion. By the end of the 3-hour burn, the sensor in the stagnant portion of the line had reached 63°C (67°C thermal model predict at the Zone 1B PRT). Later detailed analysis revealed that the hottest location on the stagnant portion of the line had reached 78°C. This predicted temperature exceeded the maximum qualification temperature for the propulsion lines (70°C). Further investigation into the materials (Teflon O-ring seals in valves, epoxy adhesives bonding down PRT's and kapton film heaters) that had potentially been exposed to this elevated temperature showed no cause for concern.

Proposals to modify setpoints in the stagnant and fluid flow sections of propellant line zone 1 prior to future MER-A TCM's were entertained, but rejected since all future thruster firings would be less than 20 minutes in duration. The decreasing solar panel temperatures for the later TCMs at larger heliocentric distances further mitigated any potential recurrence (propellant lines coupled to panel radiatively).

A strategy to make the 1B heater control during TCM-B1 was adopted in order to prevent a recurrence of this overheating problem on Opportunity. This was achieved by resetting the Zone 1A and Zone 1B control setpoints prior to Opportunity's first maneuver. Opportunity's superior propellant line MLI blanket performance created the expectation of an even higher excursion. By lowering the Zone 1A control setpoints (in the section of line that experienced flowing fluid) to a special TCM-only range of 17°C to 20°C, below the propellant tank primary setpoint range of 23°C to 29°C, we could prevent that sensor from keeping the heater on continuously during the burn. By raising the setpoint range of the sensor in the stagnant fluid zone (Zone 1B), we could create more temperature margin in both the stagnant and flowing fluid regions without running the risk of overheating. The setpoint changes described above were applied prior to TCM-B1 and the strategy worked; the stagnant portion of line zone 1 did not overheat and the flowing fluid portion of the line did not overcool. Following TCM-B1, the setpoints were returned to their nominal cruise values.

MID CRUISE

Propulsion Tank Heater Cycling Effects

The MER thermal operations team observed another propulsion line thermal control surprise shortly after launch. At particular times, propellant line temperatures upstream of the Propellant Distribution Module (PDM) began to cycle irregularly, and temperature sensors at non-controlling points were showing significant amplitude fluctuations. Figure 7 shows the location of those zones upstream of the PDM, and Figure 8 is a plot of MER-A

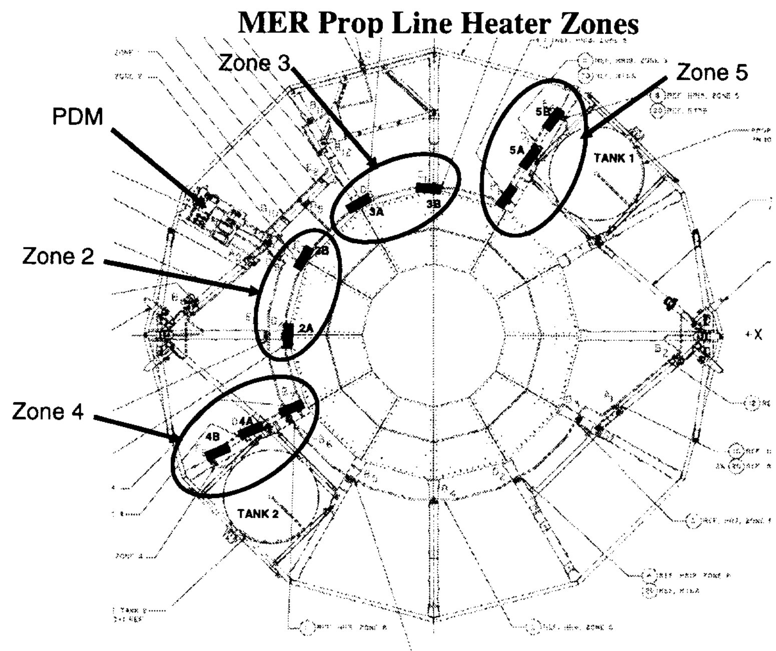

Figure 7: Propellant Line Heater Zones between Tanks

flight temperature data at these locations at a specific time during mid-cruise. These seemingly erratic temperature profiles (between 14:00 and 19:00 on DOY 243) were found to be the result of propellant migration between the two tanks. When the latch valves at the

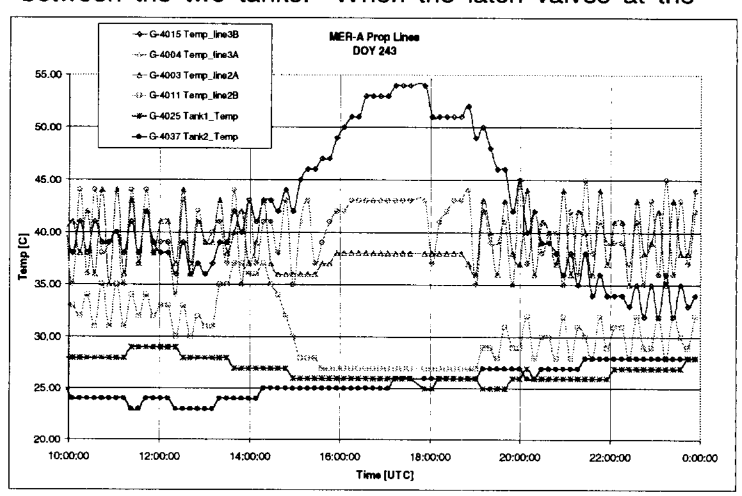

Figure 8: Prop Line Temps during Tank Fluid Migration

PDM are closed, propellant will move between tanks in an effort to equilibrate the helium filled ullage pressure. The helium pressure changes as a function of the tank temperature. This results in hydrazine moving into and out of the tanks whenever the thermostatically controlled tank temperatures are out of phase.

Temperature gradients exist throughout the propellant line system due to differences in heater power and heat leaks from stand-offs, cables losses, and MLI workmanship. Consequently, heaters may be inadvertently forced on or off due to an adjacent slug of cold or hot fluid migrating over a control point.

As shown in the plot of Figure 8, propellant migration from Tank 2 (warming up) towards Tank 1 (cooling down) resulted in propulsion line zone 2 experiencing a 5-hour time period (from 14:00 to 19:00) in which neither the A string (setpoint range = 36°C to 44°C) nor the B string (setpoint range = 22°C to 27°C) heaters were active. Warmed fluid from downstream regions flowed over these sensors at just the right temperatures to cause both heaters to turn off and stay off. No overcooling problems were seen because the flowing fluid was well above the minimum allowable flight temperature of 17°C.

Propellant migration from Tank 2 towards Tank 1 had a different effect in Zone 3. Cold fluid from Zone 2B flowed over the Zone 3A sensor causing it to keep its heater on continuously for a 3 hour time period (from 16:00 to 19:00). Warm fluid from the downstream 3A zone moved into the 3B zone where it was heated even more with a continuously on heater. The temperature of Zone 3B rose above the maximum allowable flight temperature of 50°C, and nearly reached 55°C. There was no significant cause for concern since the propellant line hardware maximum allowable qualification temperature limit was 70°C.

<u>Flight Computer Reboot</u>

During the cruise phase towards Mars, both MER spacecraft were exposed to a solar flare storm. Another spacecraft, the Mars Odyssey orbiter, also experienced effects of the solar storm and manually performed a cold reboot of its flight computer in order to clear a known bit-error memory problem. The MER spacecraft had a similar flight computer memory hardware configuration, but did not have the ability to detect any potential bit-error memory problems. Project management decided to manually command a cold reboot on both MER spacecraft as preventative measure.

The computer controlled propellant line thermostat algorithm was written such that if the flight computer were to be turned off, the last known switch state of the heaters would be maintained until the computer control could be regained. Although a nominal reboot process should only take about 20 minutes, all subsystems needed to verify survival for 24 hours with the flight computer off, for contingency planning. If a reboot were to occur when a propulsion line zone had both heaters off or both heaters on as the last known state, this clearly unacceptable switch state would be maintained until the flight computer came back on-line. Leaving all of the propellant line heaters off for the reboot was not acceptable since freezing would occur within 20 minutes. Fortunately, models showed that with a single string of heaters powered on, the propellant lines would reach a maximum temperature of 67°C after 24 hours. This maximum predicted temperature was acceptable because it did not exceed the propellant line maximum allowable qualification temperature of 70°C. Immediately prior to the reboot, all A string heaters were commanded on and all B string heaters were commanded off. When the flight computer came back on-line, the nominal cruise computer controlled setpoints came back. The cold reboot was performed in 20 minutes without incident and propellant line temperatures were never in danger of overheating during the reboot.

LATE CRUISE – TURN TO ENTRY

Certain segments of the propellant lines ran the risk of freezing during the final 70 minutes of turn to entry when the S/C off-sun angle made a step change from 37° to 75°. This dramatic change rapidly plunged solar panel temperatures by 65°C in only 20 minutes. Thermal analysis showed that radiative coupling from the propulsion lines to the nearby solar panel could cause unacceptably small margins in four MER-B propulsion line zones if the normal cruise setpoints were not adjusted. The propellant lines were in danger of freezing just prior to entry.

A propellant line rupture was possible if a slug of liquid hydrazine between two hydrazine ice slugs was continually heated. A rupture, inducing S/C forces in an unknown vector just prior to EDL, would be mission catastrophic when precise S/C attitude control and knowledge is mandatory to ensure mission success.

The MER-B TTE off-sun angle was more thermally adverse than the one for MER-A (75° versus 60°) and resulted in colder solar panel temperatures by 25°C to 30°C. This caused MER-B to have four problematic propulsion line zones, rather than the single zone on MER-A. It became clear that the propulsion line temperatures should be biased to run hotter during the last 10 days of cruise in order to be thermally safe for EDL.

In order to make accurate temperature predictions for TTE, the thermal model was first correlated to nominal cruise conditions. Analytical linear and radiative conductor values were iteratively modified to align with the propulsion line temperature variations observed in the flight telemetry. Heater duty cycles were calculated from the flight telemetry. The predicted propulsion line duty cycles and temperatures were within 5% and 4°C respectively of the flight telemetry for the DOY 364 MER-B flight data on 12/30/03.

The analytical predictions were thermally conservative since they under predicted some of the solar panel temperatures, had zero cruise shunt radiator (CSR) power during EDL, and ignored possible albedo and Mars IR warming effects of the solar panel during EDL.

The analytical thermal model was then extrapolated to future TTE conditions, which included changes in S/C attitude, S/C bus voltage, number of active solar panel segments, and heliocentric distance. New propulsion line control ranges were iteratively selected to supply acceptable 10°C propulsion line thermal margins, in alignment with JPL design standards.

The sequence integration engineers constructed and tested the software data products needed for the propulsion line control range reset recommended by the Thermal Control team. This included contingency commands in the event of problems.

The changes were implemented on January 15, 2004. The new control ranges worked successfully in three of the four propulsion line zones. Propellant migration in the fourth zone undermined the intended effect and forced further adjustments for propulsion line zone 3.

The second control range reset for propulsion line zone #3 was made on January 15, 2004. This was the last chance for the reset since the EDL software sequences controlled MER-B during the last week prior to EDL. The reset for zone 3 was successful this time, and no further propulsion line setpoint changes were made for the remaining week to EDL.

Both S/C experienced nominal EDL phases (propellant line temperatures were maintained above minimum AFT limits), culminating in two highly successful landings on Mars. As of this writing, both rovers have met all of their primary surface mission objectives and continue to operate well beyond their 90-Sol design lives.

FLIGHT EXPERIENCE LESSONS LEARNED

The following lessons were learned during the flight experience with the MER propulsion line thermal design:

1) The computer-controlled thermostat system worked extremely well. The ability to adjust thermostat setpoints during system level test and cruise to Mars was invaluable. Adjustments to setpoints allowed us to get more temperature margin in the design when we needed it, especially at the critical turn to entry, just prior to landing.

2) When designing a thermostatically controlled propulsion heater system, one needs to consider design cases for firing thrusters, when hydrazine is moving through the lines. Typically this cannot be tested in system level tests because the propellant is not loaded and thrusters cannot be fired inside the chamber. The thermostatic heaters will probably act differently when fluid is flowing through the lines, especially if the propulsion tank temperature setpoints are lower than the line temperature setpoints. Sections of line that will have stagnant fluid in them during thruster firings should have their own distinct heater control.

3) Consider the effects of migrating fluid from propulsion tanks (due to cycling of the thermostatically controlled heaters on the tanks) might have on control of the lines. Attempt to maintain tank and line temperature control values near each other to minimize the effect that migrating tank fluid might have on line thermostatic control. Minimize control deadbands to promote temperature uniformity within the propulsion system.

4) Thermostatic control zone areas and temperature feedback control points should be chosen wisely. Heater control zones should cover areas that have similar boundary conditions over all mission conditions.

5) Consider prop line thermal control with a single active heater circuit and a backup heater circuit that becomes active only in the event of a fault (rather than 2 active heaters per zone). Consider also co-location of primary and backup control sensors to simplify heater control.

6) Heater power densities should be balanced for expected heat losses at each point along the lines. Consider using a continuous heater wrap on the lines with variable heater density to put more heat where required (near line standoffs and cable egresses) and less heat in areas where it is not required (between standoffs).

7) Track temperature telemetry, correlate thermal models and extrapolate models to expected worst-case environments during flight operations to prepare for upcoming extreme events. Utilize setpoint changes to increase margins in the design, when needed.

8) Avoid open bus designs that leave propulsion lines exposed to widely varying environments. Attempt to fully enclose propulsion systems inside temperature controlled cavities that create more uniform temperature environments.

CONCLUSION

The implementation of computer-controlled thermostats for controlling temperatures on the MER propulsion lines was highly successful. The MER cruise experience emphasizes the power and flexibility of computer control.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFT: Allowable Flight Temperature
AU: Astronomical Unit
CSR: Cruise Shunt Radiator
DOY: Day of Year
EDL: Entry, Descent, & Landing
EMI: Electro-magnetic Radiation
HGA: High Gain Antenna
HRS: Heat Rejection System
IR: Infrared
JPL: Jet Propulsion Laboratory
KSC: Kennedy Space Center
MER: Mars Exploration Rover
MLI: Multi-Layer Insulation
MPF: Mars Pathfinder
NASA: National Aeronautics and Space Administration
PDM: Propulsion Distribution Module
PEM: Payload Element Manager
PMA: Pancam Mast Assembly
PRT: Platinum Resistance Thermometer
RPM: Revolution per minute
S/C: Spacecraft
TCM-A1: Trajectory Correction Maneuver #1 for MER-A
TTE: Turn to Entry