MAP Propulsion System Thermal Design

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Abstract. The propulsion system of the Microwave Anisotropy Probe (MAP) had stringent requirements that made the thermal design unique. To meet instrument stability requirements the system had to be designed to keep temperatures of all components within acceptable limits without heater cycling. Although the spacecraft remains at a fixed 22° sun angle at L2, the variations in solar constant, property degradation, and bus voltage range all significantly affect the temperature. Large portions of the fuel lines are external to the structure and all components are mounted to non-conductive composite structure. These two facts made the sensitivity to the MLI effective emissivity and bus temperature very high. Approximately two years prior to launch the propulsion system was redesigned to meet MAP requirements. The new design utilized hardware that was already installed in order to meet schedule constraints. The spacecraft design and the thermal requirements were changed to compensate for inadequacies of the existing hardware. The propulsion system consists of fuel lines, fill and drain lines/valve, eight thrusters, a HXCM, and a propulsion tank. A voltage regulator was added to keep critical components within limits. Software was developed to control the operational heaters. Trim resistors were put in series with each operational heater circuits and the tank survival heater. A highly sophisticated test program, which included "real time" model correlation, was developed to determine trim resistors sizes. These trim resistors were installed during a chamber break and verified during thermal balance testing.

INTRODUCTION

The Microwave Anisotropy Probe (MAP) measures the cosmic microwave background from the L2 Sun-Earth Lagrange point. The MAP spacecraft has a unique open structure (Figure 1) that was originally developed to minimize spacecraft mass. The main structural components are the upper deck, hex hub, and lower deck. These components were made of non-conductive M46J composite. At L2, the sun impinges on the bottom of the lower deck at an angle of 22°. There are blankets on back of and in between the solar arrays that act as a sun shield. An aluminum payload adapter fitting (PAF) is attached to the lower deck. Figure 2 shows the layout of the propulsion lines, tank, and thrusters. The lower deck, which is always in direct sunlight, is relatively warm (303-323 K). The external bottom deck fuel lines are protected from the sun by MLI blankets. Most of the electronics are mounted outside the hex hub. The propulsion tank, Hex Component Module (HXCM), and fuel lines are internal to the hub. A single vertical fuel line is mounted to the exterior of the hex hub. This region of the spacecraft has a moderate temperature (293-308 K) that is controlled by individual box radiators. The top deck is the coldest region of the spacecraft. The instrument is isolated from the top deck by a Gamma alumina cylinder (GAC).

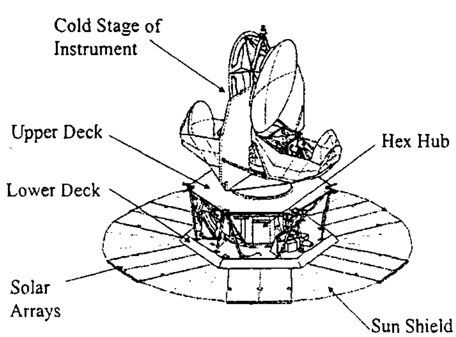

FIGURE 1. MAP Spacecraft.

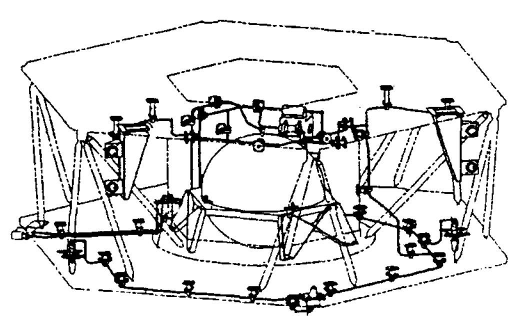

FIGURE 2. MAP Propulsion System.

To make measurements with high accuracy all temperatures on the spacecraft and instrument must remain extremely stable. Typical spacecraft propulsion systems utilize oversized heaters with mechanical thermostats to regulate temperatures. For MAP the operational heaters had to be either fully on or fully off, with no duty cycling. Trim resistors were added in series with all the propulsion operational heaters. By changing the resistor values, the dissipations in the operational heaters propulsion components could be adjusted to keep temperatures within specifications (Table 1). Factors that affect temperatures include variations in thermal properties, solar constant, blanket effective emissivities (ε^*), power dissipation, electronics radiator sizing, and bus voltage. The thermal system is designed for a bus voltage range of 28-35 V with the ability to survive for two hours at 24 V. Originally the no-cycling bus voltage range was 31-35 V, but this was modified after thermal vacuum testing to 30.5-33.5 V.

TABLE 1. Thermal Requirements for the Propulsion System.

Component	Operational Limits (K)	Survival Limits (K)
Fuel lines	283 to 328	278 to 333
Thruster Valves 3-8	283 to 318	278 to 398
Thruster Valves 1-2	283 to 328	278 to 398
HXCM	283 to 313	278 to 323
Fill and Drain Valve	283 to 313	278 to 323
Tank	283 to 313	278 to 328

THERMAL DESIGN

The MAP propulsion system has thirty-four operational heater circuits. Each circuit had the capability to add a trim resistor in series with a heater element to adjust the power dissipation of the circuit. Kapton-film heaters that were used on the lines were dual elements of equal resistance values. One element was used for the operational heaters, the other one for the survival heaters. With the exception of the propulsion tank circuit, the survival heaters were not trimmed.

The observatory-level thermal vacuum test results were used to size the trim resistors. Resistors were installed during the chamber break and verified during thermal balance testing. The resistor values could not be selected prior to testing because the temperatures have a very high dependence on the spacecraft blanket ε^*, bus voltage, and electronics box temperatures. Thermal vacuum testing was needed to better define these parameters.

Analysis showed that for some propulsion system components a single resistance value could not keep temperatures within specification for the design spacecraft bus voltage range. A voltage regulator box, called the VRAIL, was added to the spacecraft less than two years prior to launch. The VRAIL maintains a constant voltage of 29.6 V for bus voltages greater than or equal to 31.6 V. For less than 31.6 V the voltage delivered to the VRAIL circuits is two volts less than the bus voltage. The voltage on the top deck lines, thruster valves 3-8, and the top thruster bracket heaters was regulated.

There was a limited amount of heater services available; therefore it was crucial to put circuits that have approximately the same temperature on the same service. During the redesign, circuits were distributed onto eight services. Four services were used for fuel lines; the top deck lines, the lines internal to the hexagonal hub of the spacecraft structure, the vertical line external to the hex hub, and the bottom deck lines and fill-and-drain lines (Table 2). The HXCM heater was included in the internal hex hub service. The circuits in each service were selected based on the environment that they would be exposed to. The sun always impinges on the bottom deck of the spacecraft and the top deck receives no environmental input. The remaining three heater services were assigned to thruster valves. Operational heaters on the four top deck thruster valves and associated mounting brackets were grouped into one service. The bottom deck thruster valve heaters were divided into two services, one for the sun facing thrusters and one for the space-viewing thrusters. The remaining service was dedicated to the propulsion tank operational heaters.

TABLE 2. MAP Operational and Survival Heater Services.

Switch #	Description	# of Ckts	Comments
MAC C&DH #10	Op Heaters – Bottom Deck Lines, Fill &Drain Lines	9	
MAC C&DH #6	Op Heaters – Thrusters 1 and 2	2	
MAC C&DH #9	Op Heaters – Vertical Line	1	
MAC C&DH #3	Op Heaters – Internal Fuel Lines and HXCM	9	
MAC C&DH #2	Op Heaters – Propulsion Tank	1	
MAC C&DH #5	Op Heaters – Thruster Brackets 1&2, Thrusters 5-8	6	Voltage Regulated
MAC C&DH #7	Op Heaters – Top Fuel Lines	4	Voltage Regulated
MAC C&DH #8	Op Heaters – Thrusters 3 &4	2	Voltage Regulated
PSE #5	Survival Heaters – Bottom Deck, Fill &Drain Lines, Vertical Line, Thruster Bracket 2, Top Fuel Lines	14	
PSE # 3	Survival Heaters – Internal Fuel Lines, HXCM, and tank	10	Tank circuit trimmed
PSE #4	Survival Heaters – Thrusters 1-8, Thruster bracket 1	9	

To meet the "no cycling" requirement autonomous software determines whether the operational heater services are on or off. The software reads the temperatures of designated thermistors. The minimum and maximum temperature of the thermistor group is then compared to the software "thermostat" set points. If either value is outside the specified temperature range the heater service is autonomously commanded on or off. The software thermostats can be modified in flight to any set point values or to read any group of thermistors.

During maneuvers sun hits the top deck and hex hub. Over-temperature mechanical thermostats were installed to provide an additional safety feature to the software thermostats. These thermostats turn-off the operational heaters for the vertical line or top deck lines if needed.

There was an equivalent survival heater with dual mechanical thermostats for each operational heater circuit. The fill and drain valve did not have an operational heater but did have a 301Ω Dale resistor on it to provide survival heater power. The survival heater for the propulsion tank was trimmed because gradients in the tank would be unacceptability high with full power. Survival heaters are on three commandable switches as shown in table 2.

Propulsion Lines

The fuel lines' thermal design is as follows. The lines were made of stainless steel tubing with an inner diameter of 0.194" and an outer diameter of 0.25". They were isolated from the spacecraft structure using Ultem stand-offs with a measured conductivity of 0.003-0.007 W/K. The line tubing was covered with 1100 series, 0.0028" thick, aluminum tape. Two 1.7" long strips were applied to get a minimum cross-sectional area of 0.00952 in^2. Next a spiral-wrap Kapton film heater was applied. Two 2.5" long strips of aluminum tape were applied over the heater to produce a minimum cross-sectional area of 0.014 in^2. A 50% overlap of taping was done to ensure continuous coverage. The purpose of the aluminum tape was to minimize gradients in the lines. This configuration was already implemented in the hardware prior to the redesign and could not be altered. The top deck lines, which are exposed to a cold environment external to the bus, would have benefited from additional tape or some doublers. The entire assembly was covered in multi-layer insulation (MLI) cable wrap. The basic cable wrap consisted of six layers of ¼ mil double-sided Vapor Deposited Aluminum (VDA-2) Mylar separated by Dacron mesh. The aluminum side of Mylar faced outwards. The Dacron mesh could not survive the high temperatures associated with thruster firing. An analysis was conducted to determine the worst-case temperature of the lines. Six layers of Kapton separated by Nomex scrim was used any location predicted to be over 353 K during firing.

External fuel lines were surrounded by MLI that did not contact the lines. The "doghouse" blankets have 18 layers of ¼ mil VDA-2 Mylar alternating with Dacron mesh netting. An additional three layers of ¼ mil VDA-2 crinkled Kapton were added to bottom deck MLI to ensure that the blankets were survive the high temperatures associated with the third stage kick motor's burn. There are 2 mil Kapton inner and outer handling layers. The outer layer was coated with Indium Tin Oxide (ITO) to meet surface charging requirements.

Survival heater mechanical thermostats were placed approximately in the center of the vertical line and bottom deck lines' heater circuits (figures 3 & 4). However for hex hub fuel lines the thermostats were improperly positioned at the end of heater circuits (figure 5). The top deck line thermostat placement is shown in figure 3. The thermostats were installed, taped, and blanketed prior to the thermal redesign and could not be moved without severe schedule delays. Gradients caused by conduction deficiency and poor thermostat placement produced minimally acceptable temperatures during the survival case in thermal balance.

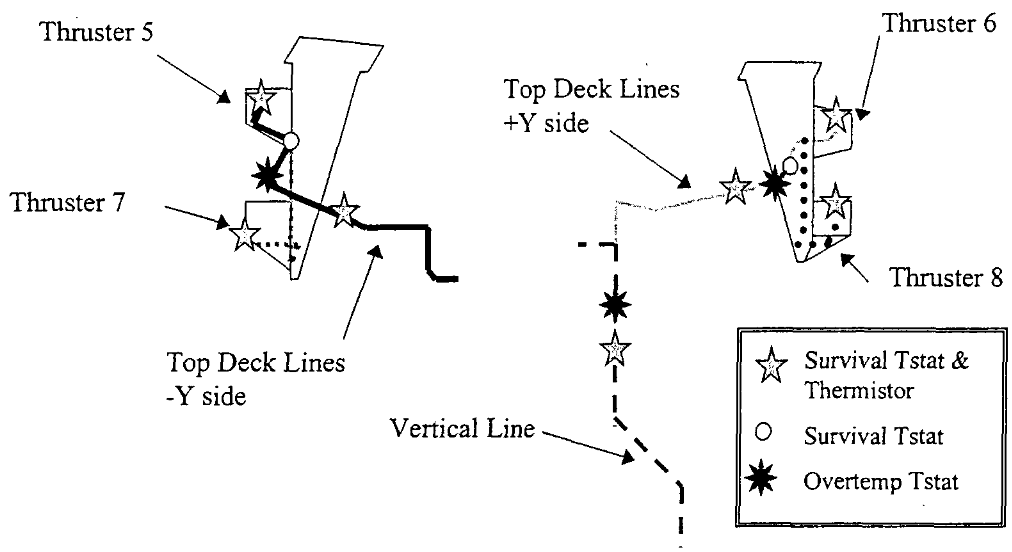

FIGURE 3. Top Deck Lines, Vertical Lines, and Top Deck Valves.

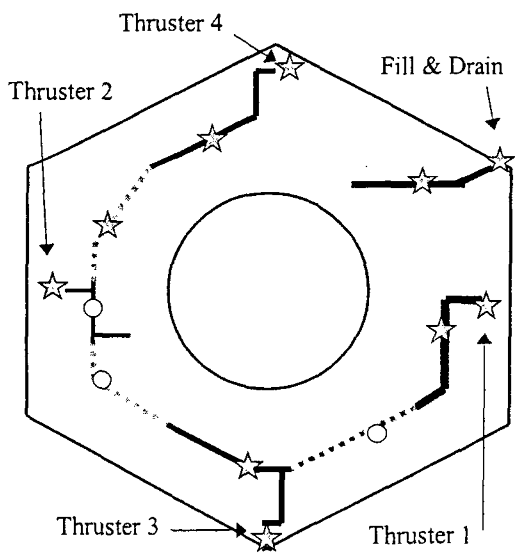

FIGURE 4. Bottom Deck Lines and Valves.

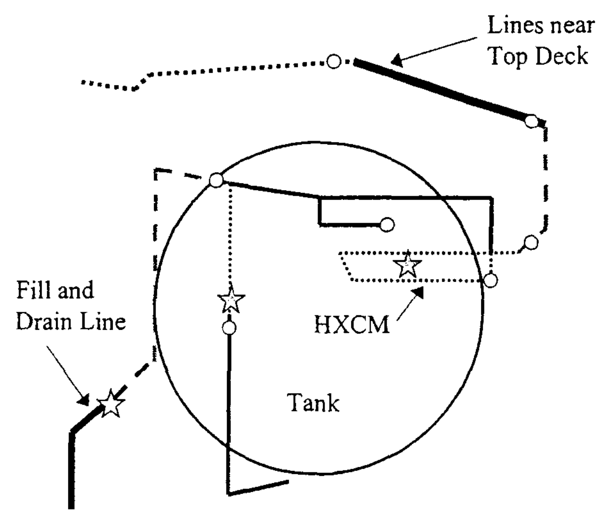

FIGURE 5. Hex Hub Lines and HXCM.

Hex Component Model

The Hex Component Model, HXCM, consists of a pressure transducer, filter, lines, and latch valve. This assembly is mounted to the interior of the hex hub in bay 2 through 0.062" thick fiberglass washers. An instrument electronics box is mounted to the exterior of the hex hub in this location. When the instrument is turned off, the box interface cools to 263 K. This was not accounted for in the original design. To compensate an additional heater and internal blanketing was added to the HXCM.

Propellant Tank

The MAP propulsion tank is essentially a 22.4" diameter sphere with 0.031" thick titanium walls. The tank is isolated from the structure with G10 washers. A flexible diaphragm separates the Hydrazine from the Nitrogen gas pressurant. There are two 1"x5" operational heaters on the fuel side of the tank and two on the gas side. The survival heaters are identical in configuration to the operational heaters but are spaced 90° from them.

The original propulsion tank model consisted of only one node, during the redesign effort a detailed 62-node model of the tank was created. This analysis showed that without aluminum tape on the tank, the "hot spots" caused by the heater dissipation could be as high as 468 K. However the tank was already fully integrated onto the spacecraft and blanketed over. The significant amount of disassembly time required to improve heater coverage and enhance conduction was preclusive. Instead trim resistors were added to both the operational and survival heater circuits. This reduced the power dissipation in the circuits thereby minimizing the gradients. The original tank blanket consisted of 6 layers of aluminized Mylar/Dacron mesh with Kapton-out handling layers. This blanket was contoured to fit around the tank and had multiple seams. To minimize the heater power required a blanket with a low effective emittance was needed. Therefore an additional twelve-layer aluminum-side out blanket was added. This blanket had minimal seaming and was loosely fitted over the existing blankets.

Thruster Valves

The thruster valves experience very different thermal environments. The four valves mounted to the warm bottom deck require no heater power to maintain them within specification. The sun facing thrusters on the bottom deck are approximately 15 Kelvin warmer in-flight then the space-viewing thrusters due to the solar input. The upper thrusters are mounted to two heated brackets that hang from the top deck. These four thrusters require a small amount of heater power to keep them within limits. All valves are isolated from the structure with fiberglass to minimize heater power.

Catbed heaters are commanded on to heat the reactors prior to firing. The catbed heaters were sized for a 24-35 volt bus voltage and a fixed interface temperature of 313 K in the hot case and 193 K in the cold case. However during the redesign it was analytically determined that the bottom thrusters' interface temperature could be over 425 K. The non-conductive composite structure that the thrusters were mounted to could not effectively conduct the additional eight watts of power in each catbed heater. The predicted thruster valve temperature for this condition was 50 Kelvin above survival limits. At this point the thrusters were already installed on the spacecraft and aligned. Changing the catbed heater size would mean buying and integrating new thrusters. Instead copper tape was added to the bottom deck near the thrusters in order to spread the heat out. The outer layer of the blankets on the sun-facing side of the bottom deck was changed from Kapton to silver Teflon in these regions. The design changes kept the interface temperature below 353 K. A unique opportunity presented itself when the sun-facing thrusters had to be realigned. The thickness of these valves' isolator was reduced from 0.125" to 0.100". Because of this change the temperatures of the sun-facing and space-viewing valves are approximately the same during catbed operation. Under worst-case conditions, the top deck thruster valves were within limits without any design changes. The mounting brackets' remain relatively cool since their operational heaters turns off when the valves reach 318 K.

Thermal Models

Propulsion line thermal models were generated from mechanical drawing files using FEMAP (Finite Element Modeling and Post-Processing) and translated into SINDA (Systems Improved Numerical Differencing Analyzer) using TCON™. Nodes were created on thermostat locations and generated approximately every two inches on each circuit. The surrounding MLI "doghouses" were generated using the same method and translated into TSS (Thermal Synthesizer System) format for inclusion into the spacecraft system level geometric model. Using this highly graphical method new propulsion models were quickly generated to perform analysis for the thermal redesign.

The thermal models had to be correlated in less than a week during thermal vacuum testing. To accomplish this complex Fortran code logic was developed within SINDA. This logic allowed all of the test and flight cases to be analyzed from a single deck. The logic also calculated the heater, trim resistor, and VRAIL power dissipations as a function of bus voltage, trim resistor values, and heater switch configuration.

Testing

The observatory-level test program for MAP was extremely ambitious. The thermal balance test could not be done until trim resistors were installed. However, the trim resistors for the heaters could not sized without knowing the spacecraft radiator sizes and blanket performance. The thermal vacuum testing, with no trim resistors installed, was done first. The thirty-five trimmed circuits were wired to an external rack to manually vary the trim resistance values. Four "Mini-balance" points were conducted at the beginning of thermal vacuum. The data was used to perform a real-time correlation of the thermal model. The selected trim resistors were installed on various brackets and qualified during the rest of the thermal vacuum test.

The survival heaters were tested during thermal vacuum. The thrusters' survival heater thermostats (283/293 K set points) did not activate even when the valve temperature reached 279 K. The thermostats were positioned on aluminum blocks on the fuel lines approximately one inch away from the valves. The system's thermal time constants were such that the thermostats would not be cold enough to activate before the valves exceeded survival limits. During chamber break new survival thermostats were installed directly on the bottom deck thruster valves. The top deck valves were inaccessible since they are mounted inside of brackets. The schedule did not allow for the level of disassembly needed to replace valve survival thermostats. Instead of heating the thrusters with the valve heaters it was decided to keep the brackets warm during the survival case. New bracket survival heater thermostats were installed during chamber break. The set points were changed from 246/251 K to 303/308 K. The modification was done within the limited schedule and the additional survival heater power was acceptable.

Testing showed that the fill and drain valve survival heater was marginally acceptable under worst-case conditions. During the chamber break a new resistor was installed to increase the available heater power. The thermal balance test confirmed that all design changes were performing as expected during worst-case hot, cold, and survival conditions. All new survival heater thermostats and heaters were tested.

SUMMARY

The propulsion system of the MAP spacecraft had to be thermally redesigned utilizing the hardware that was already installed. The heater and trim resistor system was completed redone less than two years prior to launch. Although not optimum, the current thermal system balanced technical considerations with schedule and cost in order to produce an acceptable design. Thermal vacuum testing showed problems with the placement of some thermostats. The modifications done during chamber break were proven to be effective during thermal balance. On June 30th, 2001 MAP launched. Maneuvers produced temperatures as expected. All propulsion system temperatures are within specifications.

ACKNOWLEDGMENTS

I would to acknowledge the MAP team for their support, dedication, and hard work in accomplishing the propulsion system thermal redesign. To design, implement, and test the new thermal system in only two years was truly a team effort. This involved dozens of people from the electrical, mechanical, thermal, blanketing, propulsion, software, system, and project teams. The help and support of each person allowed this mission to be highly successful.

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