The MSX Thermal Design

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This article presents the thermal design, analysis, and testing of the Midcourse Space Experiment (MSX) satellite. The MSX spacecraft is planned for a 4-year life with a 5-year goal. Its thermal design is driven by its main sensor, the cryogen-cooled Spatial Infrared Imaging Telescope III, which requires a dewar shell temperature below 250 K. Other MSX science instruments are described as well. Thermal models developed to predict spacecraft and instrument temperatures for the range of expected orbital attitudes are explored. The MSX thermal control scheme to maintain and monitor acceptable temperature levels is examined. Results of spacecraft-level thermal testing performed at Goddard Space Flight Center are reported.

INTRODUCTION

The Midcourse Space Experiment (MSX) satellite is scheduled for launch aboard a Delta II rocket. The primary MSX instrument is the cryogen-cooled Spatial Infrared Imaging Telescope III (SPIRIT III). MSX is to fly in an 898-km circular orbit with a 99.2° inclination. It has a 4-year required lifetime with a 5-year goal and a 15-month minimal cryostat life. SPIRIT III has stringent thermal requirements that significantly affect the design of MSX. This article describes the spacecraft requirements, the resulting thermal design, and the thermal testing done on the satellite.

SPACECRAFT REQUIREMENTS

Given the spacecraft orbit, the following primary (1–4) and secondary (5–7) requirements for the thermal subsystem design must be met (see Ref. 1 for additional details):

1. The spacecraft design must support two operational modes: parked, a waiting mode maintained in normal attitude with no science instrument operation; and track, full science instrument operation maintained in virtually any attitude for up to 37 min.
2. All instruments and subsystems must be maintained within specified operating temperature limits.
3. A 4-year spacecraft life with a 5-year goal and a 15-month SPIRIT III sensor life must be provided.
4. The SPIRIT III sensor dewar shell must be maintained at less than the 250 K (−23°C) specification temperature (225 K goal).
5. The spacecraft design must accommodate about 20 min of full spacecraft and instrument operation per orbit (transient or episodic design).
6. The spacecraft thermal design must recover from any operational event within 24 h. Full recovery includes

restabilization of all spacecraft temperatures and heater currents.

7. A thermally stable platform for mounting additional sensors co-aligned to SPIRIT III must be provided. Mechanical distortion due to thermal gradients must be controlled to less than 0.03°.

SPACECRAFT OVERVIEW

The MSX spacecraft has three main parts: the instrument section at the top, the truss section in the middle, and the electronics section at the bottom. These sections are thermally isolated from one another. Figure 1 shows the overall spacecraft configuration. The instrument section is the platform on which most of the science sensors are mounted. These sensors include the UVISI (ultraviolet and visible imagers and spectrographic imagers) and SBV (space-based visible imagers), the optical bench, the beacon receiver antenna, and the reference object ejectors. The truss section provides a stable mounting structure for the instrument section as well as the mounting point for the SPIRIT III cryostat and telescope. The electronics section houses the spacecraft and instrument support electronics and the solar array panels.

ORBITAL DEFINITION AND SPACECRAFT ATTITUDE

Two very important factors affecting the MSX thermal design are its orbit and attitude. The lifetime and performance requirements of the primary instrument necessitate strict control of direct sunlight on the spacecraft.

MSX is to operate in a high-altitude, circular, polar orbit with a precession rate of less than 0.04° per day. Over the 5-year mission goal, the Sun line/orbit plane angle will increase from 45° through 120°; significantly, that angle is never less than about 45°. This orbit allows the spacecraft to fly in a roughly Earth-oriented attitude while keeping direct sunlight out of the instrument apertures. Controlling the spacecraft's attitude relative to the Sun is one requirement that shapes the whole mission.

The MSX spacecraft and its coordinate axes are shown in Fig. 2. The *x* axis is parallel to the line of sight of the instruments. The *z* axes form a line parallel to the drive axes for the solar array. The *y* axis completes a right-handed coordinate system. In this system, the spacecraft flies with the $-x$ axis pointed to Earth and the $+x$ axis pointed to space.

Preferably, both from a thermal and power standpoint, the Sun will remain in the *xy* plane, constrained between ±90° from the $-y$ axis. This orientation allows the solar panels to develop full power and provides a stable, cold environment for the SPIRIT III cryostat.

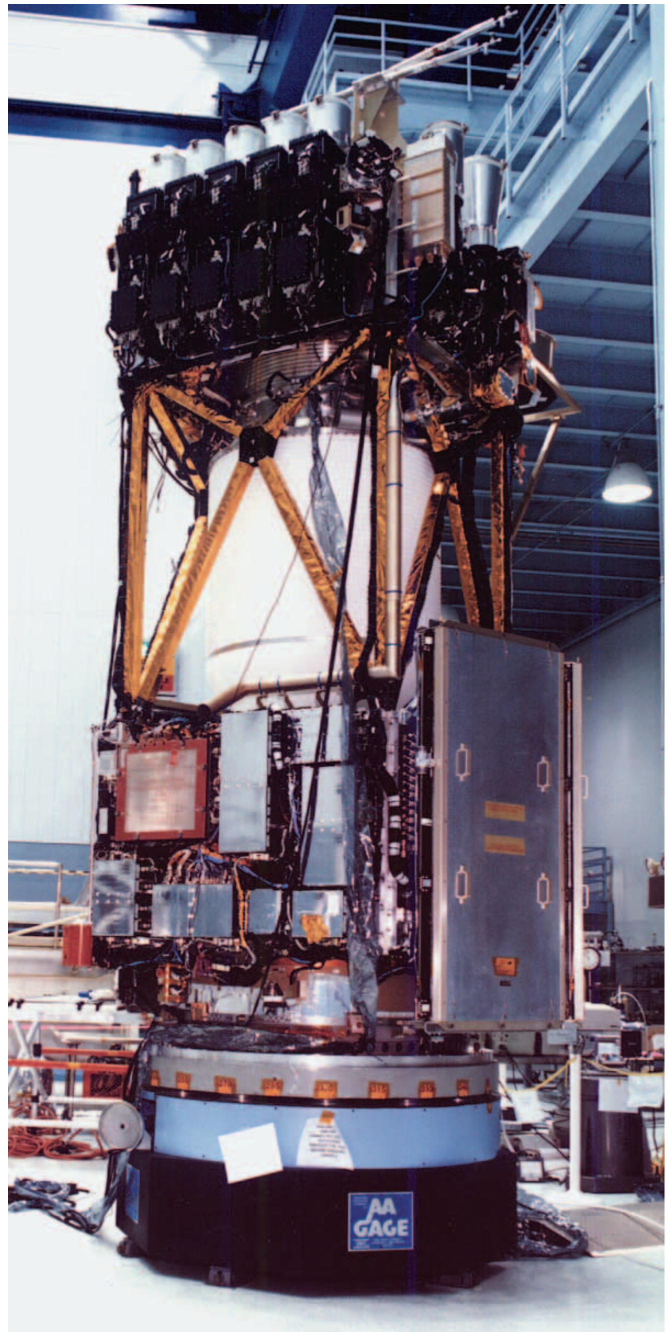


Figure 1. The overall configuration of the Midcourse Space Experiment (MSX) spacecraft with the instrument section at the top, the truss section in the middle, and the electronics section at the bottom.

Normally, in an Earth-orientated orbit, one spacecraft axis points nadir and one is fixed along the velocity vector. During one orbit, the Sun sweeps out a cone equal to the angle between the Sun line and the orbit normal. As the orbit precesses, the cone varies from 0° in a dawn–dusk orbit to 90° in a noon–midnight orbit. Maintaining stable environments for the SPIRIT III cryostat and spacecraft radiators requires that the range of solar angles be minimized. MSX satisfies this need

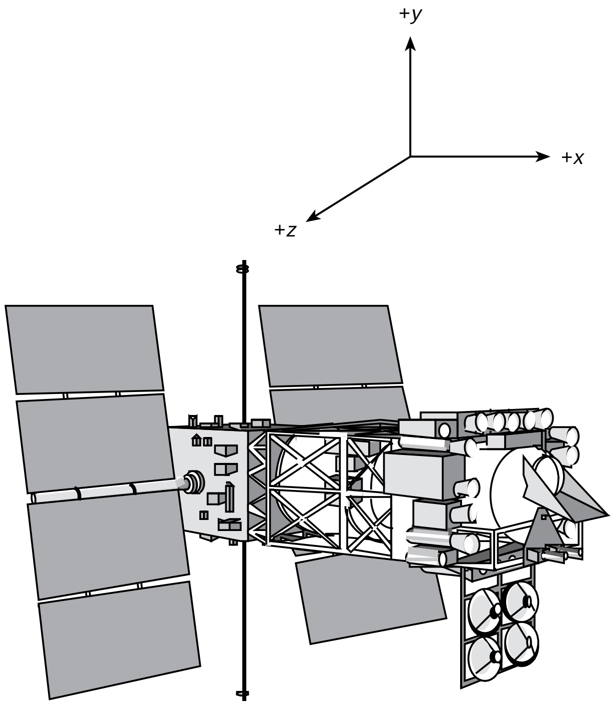


Figure 2. The MSX satellite and coordinate axes. The spacecraft flies with the $-x$ axis pointed toward Earth.

by controlling the orbit precession and by using active roll-steering. The Sun line/orbit angle is constrained between 0° and about 53° based on the orbit precession. During the orbit, the $-x$ spacecraft axis points nadir while the satellite is roll-steered using onboard reaction wheels to maintain the Sun in the *xy* plane. These orbital controls and attitude maneuvers keep the Sun line on the spacecraft in the *xy* plane, restricted between ±53° from the $-y$ axis.

SPACECRAFT DESCRIPTION

Instrument Section

The instrument section is a four-sided box structure that provides mounting locations for most of the spacecraft sensors. The entire section is blanketed. It contains the SBV instrument telescope, the UVISI instruments, and the contamination experiments. The section is cut away in the middle to allow for the SPIRIT III telescope.

The SPIRIT III cryostat temperature requirement as well as the instrument co-alignment and stability requirements drive the thermal design of the instrument section. On the basis of SPIRIT III life considerations, the vacuum shell temperature must be maintained below −25°C. To minimize heat input to the cryostat, the entire instrument section must be maintained at as low a temperature as practical for the other instruments.

Instrument co-alignment is the determining factor for the design of the instrument section decks. As the mounting structures for the sensors, the decks must maintain structural stability over the range of operating temperatures. This requirement resulted in the use of heat pipes in the instrument section panels to provide heat spreading and minimize thermal gradients across and between the four panels. The design goal is to keep temperature gradients to less than 10°C across the instrument section.

The heat pipes also provide thermal distortion control of the alignment-sensitive optical instruments mounted to the decks. The UVISI sensors have local gradient requirements across the mounting surface between 2.5 and 10°C. The heat pipes embedded in each of the four panels remove heat from the instrument mounting feet, dump it into the heat pipe system, and transfer the heat to two external radiators (Fig. 3) where it is radiated to space. The two radiators are mounted on each of the instrument section's *z* sides.

Figure 4 shows instrument section temperatures from a thermal balance test and illustrates heat spreading between the instrument section panels during simulated on-orbit conditions.

Truss Section

An open truss structure connects the instrument section to the electronics section. Because pointing accuracy must be maintained within 0.03°, the truss is made from graphite epoxy. This material effectively thermally isolates the instrument section (operating at about −25°C) from the electronics section (operating between −19 and +56°C). It is a low-expansion, low-conductivity composite that minimizes thermally induced distortions.

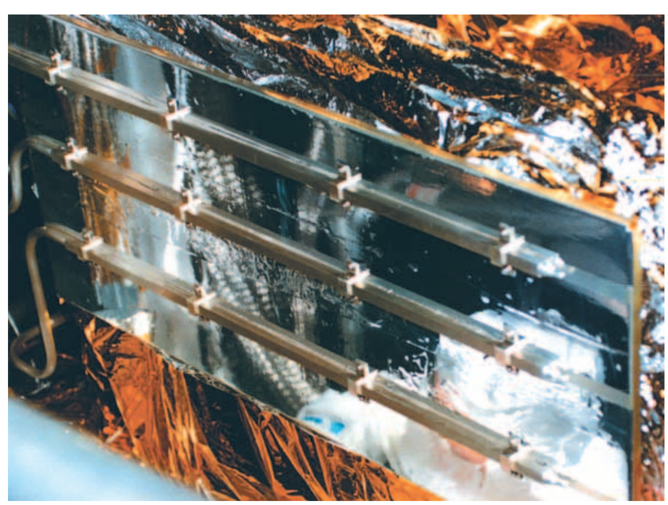


Figure 3. The $+z$ side instrument section heat pipe radiator, one of two that reject instrument heat.

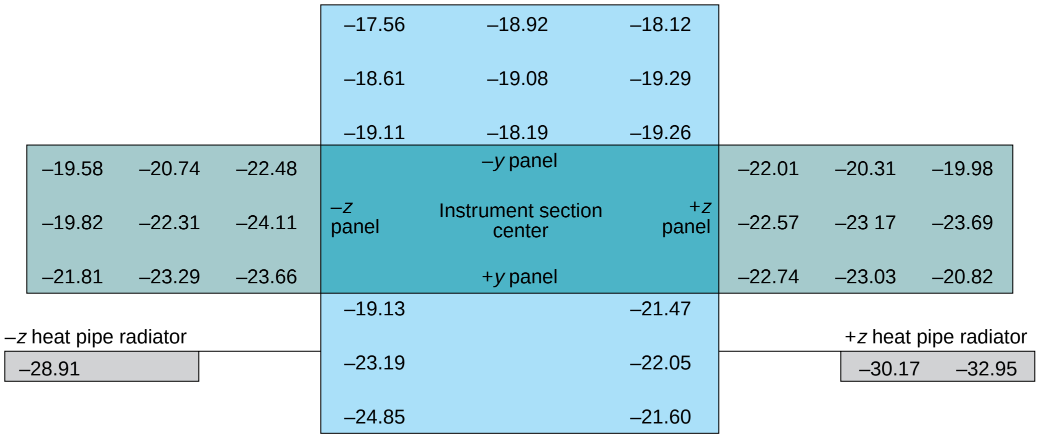


Figure 4. A typical temperature distribution (in °C) across the instrument section during thermal balance testing. These results show the successful operation of the heat pipes in spreading the heat loads and keeping temperature gradients within required levels.

The truss also provides the mounting points for the SPIRIT III sensor. The mounting flange on each truss face is located where the diagonal truss members cross. Each truss member is blanketed to further help reduce thermal gradients. Three sides of the truss are blanketed: the $+z$, $-y$, and $-z$ faces. The remaining side ($+y$) is left open to provide a view to space for the SPIRIT III cryostat.

Electronics Section

The electronics section is a 142.24 × 142.24 × 116.84 cm box located directly beneath the instrument section and truss structure. Its walls are made of aluminum honeycomb panels. The electronics section houses all the spacecraft housekeeping equipment, batteries, solar arrays, and instrument support electronics. Placement of the instrument support electronics here minimizes thermal dissipation in the instrument section and allows the instruments to run at as cold a temperature as possible. The overall operating temperature range for the electronics section is −19 to +56°C. The battery and tape recorders have tighter temperature constraints.

Because of packaging and size constraints early in the program, most of the components are mounted to the outside of the electronics section panels. The reaction wheels, torque rods, and tape recorders are all mounted internally. The tape recorders are heat sunk to the $+z$ and $-z$ panels and reject heat through an external radiator surface on the z panels. The remaining electronics boxes are mounted externally, including the solar array drives and deployment mechanisms. The boxes are tied thermally to the structure with Cho-seal thermal gaskets.

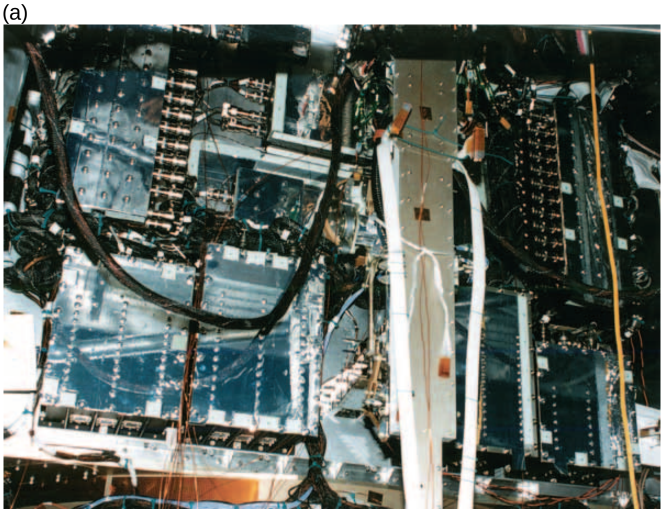
Mounting the boxes externally to the electronics section panels complicates the thermal design by restricting the available radiator area. The outside faces of the individual components must be used as spacecraft radiators. As a design goal, each box had to provide enough radiator area to dissipate its own internally generated heat. In practice, radiator area was allocated on the basis of available component surface area and blanketing constraints. The blanketing of boxes of different heights was a challenge. Figure 5 shows the $+z$ side of the electronics section with and without thermal blankets.

The boxes mounted on the outside of the electronics section present a unique thermal configuration; the heaters are all mounted directly to the inner panel surface, whereas the radiators are at the tops of the externally mounted boxes. Figure 6 shows the heater and thermostat layout for the inside of the electronics section panels. This picture was taken looking at the inside of the $+y$ panel with the $-z$ panel removed.

The radiator area also had to be based on the orbital environment. The $-y$ side of the electronics section is completely blanketed since it faces the Sun. Two radiators for equipment mounted on the $-y$ electronics section panel face the $+z$ and $-z$ sides. Most of the SPIRIT III electronics are mounted on the $+z$ side of the electronics section. These boxes have individual radiators. The $+z$ side also has radiator area for the internally mounted tape recorder; the remaining area is blanketed. The $+y$ electronics section panel houses the SBV instrument electronics as well as other housekeeping boxes. The SBV electronics have their own radiator (optical solar reflectors) and are isolated from the panel. The other boxes on this side have individual box radiators, and the remaining area is blanketed.

The battery assembly is thermally isolated and is mounted to the $-x$ panel within the launch vehicle adapter ring. The top of the battery is a radiator surface. Its thermostatically controlled heaters maintain minimum temperatures. In the parked mode, the bat-

(a)



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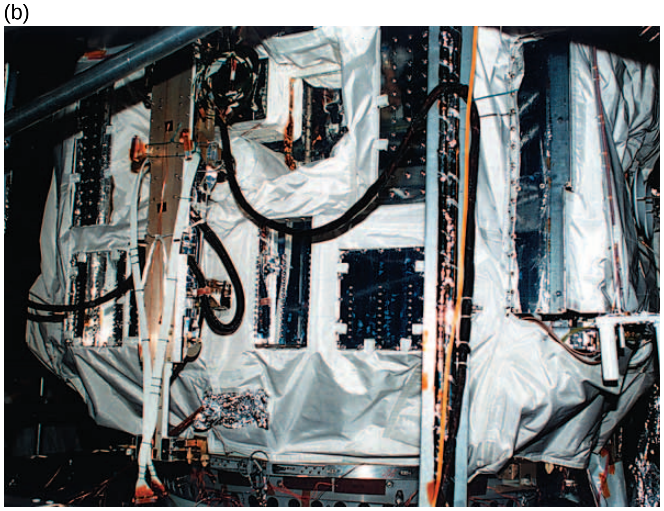

Figure 5. The $+z$ electronics section panel before (a) and after (b) thermal blanket installation.

Figure 6. Heater and thermostat layout for the electronics section, looking at the inside of the $+y$ panel.

tery faces down toward Earth. Environmental input from Earth, combined with the internal dissipation, provides the heat necessary to maintain the battery's temperature. Heaters are incorporated into the design to allow for colder spacecraft attitudes.

Subsystems

A beacon receiver antenna is mounted to the $-y$ instrument section panel. It comprises four parabolic dish antennas and the flat deck to which they are mounted. Each dish is used to locate incoming radio signals. To perform this task the four antennas are tilted slightly with respect to each other. This misalignment causes a differentiation in the incoming signal that allows the signal's direction to be determined.

Because the signal differences are small, thermal gradients in the antennas and bench must be minimized. In particular, it is the differences between the antennas that produce uncorrectable errors. The antenna design stresses symmetry between the antenna dishes. Each is covered with a cylindrical chimney and cover, which reduce the environmental differences between the antennas. The dishes are arranged symmetrically on the mounting deck. Semirigid cable lengths are laid out in equal lengths between the four dishes. Thermal distortion in the antenna deck is minimized through the use of a highly stable graphite epoxy honeycomb structure. The beacon bench is completely blanketed except for the top of the four antennas.

An optical bench mounted to the $-y$ instrument section provides a stable mounting platform for the primary attitude control sensors. The bench supports two gyros, one star camera, and an autocollimator. The placement of the bench is driven by the need to have the science instruments on the $+z$, $-z$, and $+y$ panels. Being on the sunny side of the spacecraft poses thermal problems in finding satisfactory radiator areas for both the internal dissipation and the thermal control heaters.

The bench structure is that of a "bent" graphite epoxy honeycomb. The bench is mounted to the instrument section panels by three kinematic joints. There are two small radiators on both of the z sides. One radiator is used by each of the two gyros. The other two are used together by the higher-powered star camera. The remainder of the area is blanketed except for two small apertures used by the autocollimator. The bench is isolated from the instrument section with G10 (fiberglass) washers and a small blanket under the mounting feet.

Because strict limits are placed on the thermal distortion, the temperature control system for the bench is critical. As the control region is smaller than what could be obtained from a mechanical thermostat, an electrical control system was planned. An on/off electronic thermostat with a narrow dead band was chosen over a proportional system because of system complexities and the electromagnetic interference problems associated with a pulse-width–modulated device. The final system uses remote temperature sensing to control seven separate heater channels from one box. Two units are used to make the system fully redundant.

SCIENCE INSTRUMENT DESCRIPTIONS

SPIRIT III

The primary instrument on MSX is the SPIRIT III, a solid-hydrogen–cooled telescope. The top protrudes through the center of the instrument section (Fig. 7). An aperture shade shields the telescope from the Sun and Earth. This shade is blanketed on the Sun side and has a highly reflective gold surface on the side that faces the telescope aperture. The bottom portion of the instrument is a cryogenic dewar, which extends down through the truss section to the top of the electronics section.

The SPIRIT III instrument presents three thermal problems that involve system lifetime and sensor data quality. The first and only essential requirement is that the spacecraft provide an average vacuum shell temperature below 250 K. The second problem involves defining the heat flow into the instrument aperture. This issue also affects system life. The last problem concerns the operating temperature of the instrument baffle; as the baffle temperature rises, the noise level to the sensor increases.

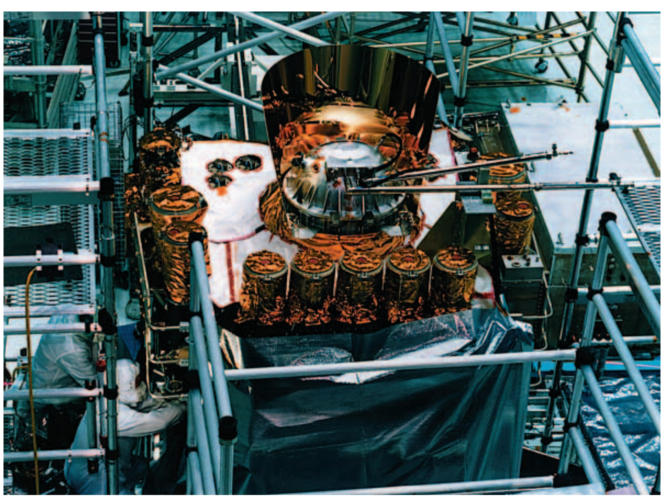

Figure 7. The SPIRIT III telescope sticks through the top of the MSX instrument section. The aperture shade protects it from the Sun.

Cryogen life is a function of heat leakage into the cryostat, which occurs primarily in one of three ways: (1) electrical power from the telescope is dissipated in the focal plane area, which is directly coupled to the frozen hydrogen; (2) heat is input through the aperture during normal operations; and (3) parasitic heat works its way in through the many layers of insulation.

Background heat leakage into the cryogen must be defined in order to predict the instrument's life. The parasitic heat input is perhaps the easiest to define. As a result of the large thermal resistance between the outer shell and the internal cryogen, local temperature gradients are not important. Parasitic heat leakage is defined in terms of an average vacuum shell temperature, which is kept below the 250 K requirement by using the open side of the truss ($+y$) as a radiator. The dewar shell is painted with a high-emissivity, low-absorptivity coating to maximize heat rejection to space. Cryogen sensitivity to shell temperature was analyzed by the Lockheed Martin Corporation and was found to be about 1 month per 10°C change, indicating that sensitivity to temperature is a major factor in the prediction of the instrument's lifetime.

Another factor that is more difficult to define is the aperture heat input. This heat is not directly coupled to the cryogen since the aperture baffle temperature is controlled through secondary cooling. These baffle structures are tied to the vaporized (but still very cold) hydrogen. The heat load is small while the satellite is in the parked mode but can become quite large (>100 W) during some maneuvers. The small background level and the potentially large but uncertain operational levels must be combined into a life average. This combination has been performed on the MSX program by limiting the operational duty cycle. The SPIRIT III cryogen life prediction assumes a 90% parked mode attitude, a 5% celestial viewing mode ($+x$ away from Earth), and a 5% Earth-limb viewing mode.

In addition to affecting cryogen life, the baffle temperature more importantly figures into the sensor's data quality. As the baffle temperature increases, the baffle adds to the noise level of the instrument. At some point the observed data are swamped by the baffle input. The defined upper limit for the baffle temperature is 70 K. Although this limit is soft rather than hard, it still indicates a strong need to maintain a very cold baffle temperature. Baffle cooling is a very slow process. Depending on the background heat input, cooldown could take days after a stressful incident. Complicating this already murky picture is the impact on baffle temperature from the SPIRIT III instrument aperture shade. Near-perfect optical properties are assumed for this shade (emissivity = 0.03, specularity = 90%). Degradation of these properties increases the background flux level and decreases the heat flow to space.

SBV

The SBV instrument is divided into two sections: the telescope units mounted to the instrument section and the electronics units mounted to the electronics section. Both units are thermally isolated from their respective mounting panels and incorporate dedicated optical solar reflector radiators and heater control systems.

The telescope units are mounted to the $-z$ instrument section panel. The local radiator faces along the $-z$ axis. The telescope sunshade design incorporates a reclosable door, which has an opening mechanism located on the $-y$ side of the SBV instrument and is thermally controlled using the Sun's input to that surface. The electronics support assembly is mounted to a honeycomb panel suspended by a truss support structure off the $+y$ electronics section panel.

UVISI

The UVISI comprises three electronics boxes mounted to the electronics section and nine imaging telescopes mounted to the instrument section. The latter include two ultraviolet imagers mounted to the $+z$ instrument section panel, two visible imagers mounted to the $-z$ panel, and five spectrographic imagers mounted to the $+y$ panel. Originally it was assumed that as these were low-power imagers, they could radiate their own dissipated heat using localized radiators mounted on the sensors. As the design progressed it became clear that the requirement to minimize thermal distortion in the imagers would preclude this option. The need to remove the dissipated heat but maintain control of thermally induced distortion led to the heat pipe concept presently in use.

Three heat pipes (see discussion on Instrument Section) remove the local heat inputs and minimize thermal gradients in the structure. They are bonded to the external face of the honeycomb panels. The pipes in the panels are level to allow ground testing but are arranged to pass near as many of the instruments' mounting feet as possible. Where feasible, the mounting foot insert and pipe cradle are machined in the same piece.

The UVISI sunshades are thermally isolated from the telescope housings to reduce the net heat flow. In the parked mode, the sunshades will come within 45° of the Sun each orbit. As the orbit precesses, the solar impingement angle will decrease. The early mission orbit will produce a varying, but small, positive average heat input to the system. Later orbits will produce a more stable, but larger, heat loss.

Covers controlled by a one-shot opening mechanism protect each UVISI sunshade. The covers are opened after orbit is achieved. A special set of protective heaters was needed to maintain the opening mechanism within its operating temperature range. A small heater was therefore mounted near the door mechanism on each sunshade. The proper operation of these heaters was verified by a separate thermal vacuum test of the sunshades.

The electronics boxes needed to support the UVISI instrument are mounted to the $+y$ electronics section panel. These boxes, which are treated as spacecraft support electronics, are supported by the panel-mounted heater system. They incorporate radiator surfaces on their external faces and are internally designed to conduct heat to the external faces.

Contamination Experiment

To measure contamination, a number of sensors are used to monitor particle type and density around the instrument section. The sensors include a pressure sensor, a mass spectrometer, four temperature-controlled quartz crystal microbalances, and two lasers. As the sensors are low-powered and most efficient when powered continuously, their operation does not itself present a thermal problem. Rather, it is the type of measurement that makes the situation potentially difficult. To get the necessary data, the spacecraft must be put in some attitude other than parked mode for extended periods of time. The impact of these other maneuvers on the thermal and power systems is a function of orbit position, Sun angle, satellite attitude, and instrument operations before and after the maneuver. These variables are difficult to define in terms of a duration that can be analyzed; therefore, it is difficult to decide whether a proposed operation fits within the constraints of the spacecraft resources.

THERMAL MODELING

Thermal modeling and analysis of MSX were performed using the TRASYS (Thermal Radiation Analyzer System) and SINDA (Systems Improved Numerical Differencing Analyzer) thermal analyzer programs. The former is a geometric modeler that computes the environmental heat loads and thermal radiation couplings for spacecraft surfaces in a given orbit. The resulting environmental fluxes and couplings from TRASYS are input into a corresponding SINDA model, and the SINDA model is then run to give temperature predictions. Separate, detailed thermal models exist for the instrument and electronics sections, as well as for some subsystems (beacon receiver, optical bench, etc.). The models are biased for hot and cold temperature extremes. Surface property values and environmental parameters corresponding to the end of the mission are used in the analysis. The models were used for test and flight temperature predictions.

Spacecraft modeling of the SPIRIT III sensor is restricted to the calculation of the vacuum shell temperature. All internal thermal modeling for this sensor is done by the Utah State University Space Dynamics Laboratory. The boundary conditions assume a vacuum shell temperature and an aperture heat load. The thermal insulation in the cryostat is large enough to allow the vacuum shell to be modeled as an adiabatic surface. Calculation of the aperture heat load was done by General Research Corporation (GRC) under contract to APL. GRC developed an algorithm that takes specific orbits and attitude maneuvers and calculates the heat input to the SPIRIT III aperture. The algorithm includes direct and reflected energy inputs from the Sun, Earth, and Moon. Also included is direct radiation from the aperture shade.

Several aspects of the thermal modeling effort on MSX separate it from typical spacecraft analyses. The primary atypical characteristic of the spacecraft is its ability to change attitudes, but more importantly, neither a typical attitude nor even a range of attitudes is required.

To maximize available resources, operational limits are generally confined to two categories. The first involves repeated orbital operation. A 20% duty cycle was taken as a design goal. This duty cycle doubles the design operation of the SPIRIT III sensor and generally allows unconstrained mission planning. A further clarification of this limit involves the battery depth of discharge. Operations that require the depth of discharge to exceed 40% should not be regularly scheduled. Other factors contributing to this duty cycle limitation are battery temperature, tape recorder temperature, and baffle temperature.

The second category involves high-priority one-at-a-time operations. These scenarios are essentially the same as a target mode. The spacecraft goes into a preparation mode that lasts several orbits. Then the event takes place, followed by several recuperative orbits. A longer operation can be planned this way, but the overall duty cycle is reduced because event duration and recovery time do not scale linearly (a 20-min operation once per orbit is not analogous to a 40-min operation every other orbit). An upper bound for this type of operation is given by the target mode timeline of about 40 min.

An issue related to the variable mission profile is power dissipation. The MSX parked mode is low-powered. An operation can result in an increase to that power of over 1000 W. The size and location of the power increase depend on the type of mission selected. The thermal design provides some flexibility through the heater system. As power is dissipated in a particular subsystem, less power is required by the heaters. The heaters and radiator area are designed so that, at the full 20% operation, the heaters draw virtually no power.

For analytical purposes, an operational attitude had to be defined during data-taking events. Two such attitudes were chosen—the parked mode and the Sun-fixed mode. During operation in the parked mode, the power dissipations were changed to reflect the operational values, but the attitude remained unchanged. This resulted in a benign hot or cold case. All predictions were expected to maintain the required margin. During repeated operation in the Sun-fixed mode, the same side of the spacecraft would always be turned toward the Sun. This attitude produced worst-case hot and cold predictions. Such predictions may not have the full margin typically required for a design case. For most components the temperatures of the worst-case prediction were still well within limits. The only exceptions were the tape recorder, battery, and optical bench temperatures. The temperature predictions for those items did not exceed their design limits, and it should be noted that the Sun-fixed mode was not a design case. The analysis was used to define the system's operating boundaries, which will be reevaluated on the basis of flight data once they become available.

THERMAL HARDWARE

Heat Pipes

Two different types of heat pipes are used on the MSX spacecraft, both fabricated by Dynatherm, Inc. The pipes embedded in the instrument section honeycomb panels are of a square 1/2-in. trapezoidal axially grooved (TAG) design, as are the pipes mounted to the external radiator. The pipes connecting the $+z$ and $-z$ panels to the radiators above them are of a 3/8-in. TAG design with an integral "H" web.

Temperature Sensors

The spacecraft is instrumented with two different types of temperature sensors: PT103s and AD590s. The PT103s can read colder temperatures than the AD590s, and are therefore used anywhere that temperatures are predicted to reach below −55°C. The temperature sensors are bonded to the spacecraft with delta bond. The performance of each temperature sensor was verified during the spacecraft thermal vacuum test by comparing results to test thermocouples.

Heaters and Thermostats

Kapton film-type heaters manufactured by Tayco are mounted to both the instrument and electronics section panels. Five different thermostat set points are used. Operational heaters maintain minimum operating temperatures, and survival heaters maintain minimum survival temperatures.

Thermal Blankets

All of the spacecraft's external surfaces are insulated with thermal blankets except for the radiator area. The blankets typically comprise 18 internal layers of aluminized Mylar alternating with mesh, an outer layer of aluminized Kapton, and an inner layer of sail cloth. The instrument section blankets have an additional outer layer of indium tin oxide–coated aluminized Teflon, which provides an electrically conductive outer surface while minimizing contamination. The electronics section and truss blankets have an additional outer layer of beta cloth, which has a 10.16 × 15.24 cm graphite grid woven into the fabric that limits the size of the area that can build up charge. The blankets are attached to the spacecraft with Velcro. The instrument section blankets are closed out with tape, and the electronics section blankets are laced to close any gaps. All blankets are grounded to the spacecraft as they are installed and are designed to allow access on the launch pad for battery air-conditioning, electrical connectors, and SPIRIT III cryo lines.

THERMAL TESTING

Thermal-vacuum/thermal balance testing of MSX occurred between 25 July and 22 August 1994 at Goddard Space Flight Center. The 4-week test consisted of two hot and two cold thermal balance points, a hot and cold functional test, and a hot and cold survival test.

Testing took place in the large thermal-vacuum chamber (#290). The spacecraft was placed on a mounting fixture and was in a flight configuration with all instruments installed. Temperature control of the spacecraft during the thermal-vacuum test was maintained with a set of heater shrouds. The shrouds formed an irregular octagon that completely surrounded the spacecraft. Figure 8 shows the assembled heater shroud before it was put into the test chamber. The heater shroud was used to provide equivalent sinks, and the chamber cold wall was set to liquid nitrogen. Over 400 test thermocouples were installed to monitor temperatures. Details of the test setup and hardware can be found in Refs. 2 and 3. The thermal conditions (total testing hours, number of thermal cycles, and temperature levels) were derived from the requirements listed in Ref. 4. The purpose of the test was to simulate flight environments and ensure proper functionality of the spacecraft and all its components.

During the test, while MSX was in the chamber, SPIRIT III was filled with argon and helium. This was the first time cryo-servicing operations were done during thermal-vacuum testing. Test heaters were installed on the SPIRIT III lines to keep the O-rings from freezing, and ultimately leaking, during filling operations. The temperatures and heater powers were monitored during filling operations, and acceptable levels were maintained. The chamber's residual gas analyzer detected only small amounts of helium during each fill, and argon was detected during only one fill.

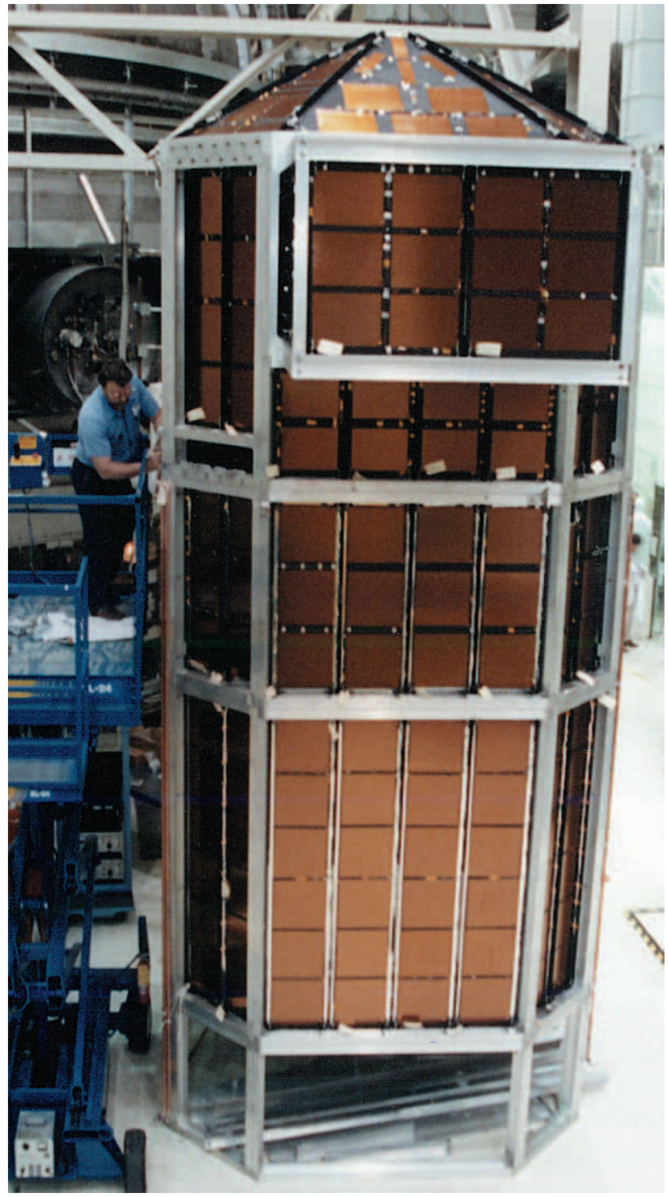

Figure 8. The heater shroud shown here surrounds the MSX spacecraft for thermal-vacuum testing. It is located between the spacecraft and the chamber wall and provides temperatures to simulate orbital environments.

CONCLUSIONS

The spacecraft requirements, both primary and secondary, shaped the final design of MSX. All requirements were met, and all aspects of the spacecraft (in addition to thermal) were thoroughly tested and operated normally.

The overall results of the thermal test were excellent. Repeated system-level performance was demonstrated at the extremes of the qualification test temperatures. The heat pipes of the instrument section operated better than predicted. There was good spreading of heat across the panels, and the maximum allowable gradient in the instrument section of 10°C was not exceeded. All spacecraft flight heaters, thermostats, and temperature sensors operated nominally. No temperature limits were exceeded, and the test temperatures correlated with the thermal analysis models to within 5°C.

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ACKNOWLEDGMENT: The MSX mission is sponsored by the Ballistic Missile Defense Organization. This work was supported under contract N00039-94-C-0001.

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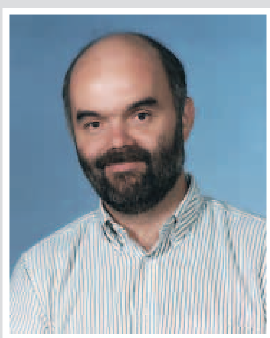

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