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The CHANDRA X-Ray Observatory: Thermal Design, Verification, and Early Orbit Experience

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ABSTRACT

The CHANDRA X-ray Observatory (formerly AXAF), one of NASA's "Great Observatories" was launched aboard the Shuttle in July 1999. CHANDRA comprises a grazing-incidence X-ray telescope of unprecedented focal-length, collecting area and angular resolution — better than two orders of magnitude improvement in imaging performance over any previous soft X-ray (0.1-10 keV) mission. Two focal-plane instruments, one with a 150°K passively-cooled detector, provide celestial X-ray images and spectra.

Thermal control of CHANDRA includes active systems for the telescope mirror and environment and the optical bench, and largely passive systems for the focal plane instruments. Performance testing of these thermal control systems required 1-1/2 years at increasing levels of integration, culminating in thermal-balance testing of the fully-configured observatory during the summer of 1998. This paper outlines details of thermal design tradeoffs and methods for both the Observatory and the two focal-plane instruments, the thermal verification philosophy of the Chandra program (what to test and at what level), and summarizes the results of the instrument, optical system and observatory testing.

INTRODUCTION

The Chandra X-ray Observatory is a large space-based imaging and spectroscopy mission, one of NASA's four "Great Observatories". Figure 1 illustrates the major elements of the Chandra experiment system, including the High-Resolution Mirror Assembly (HRMA), the optical bench, the Science Instrument Module containing the two focal-plane instruments, and the spacecraft service module. Chandra was launched in July 1999 into a high elliptical orbit of 10000km perigee, so that eclipses of an hour or two are the principal earth influence. An aperture shade allows pointing from the anti-sun vector to within 45° of the sun. Roll about the viewing axis is restricted so that only one side faces the sun; a cold radiator for one of the X-ray cameras is located on the opposite side. Thermal control is primarily active, with multiple heater zones on critical structure within a shroud of MLI. The exception is the SIM, passively controlled with supplemental heaters for low-temperature protection, with most external surfaces serving as thermal radiators for the high internal dissipation. The active control system is computer-driven, with all zones operating as thermostats, sampled and switched in an eight-second rotation (two seconds for some critical zones). All control parameters, especially set points and deadbands, can be changed on-orbit by a telemetered data modification.

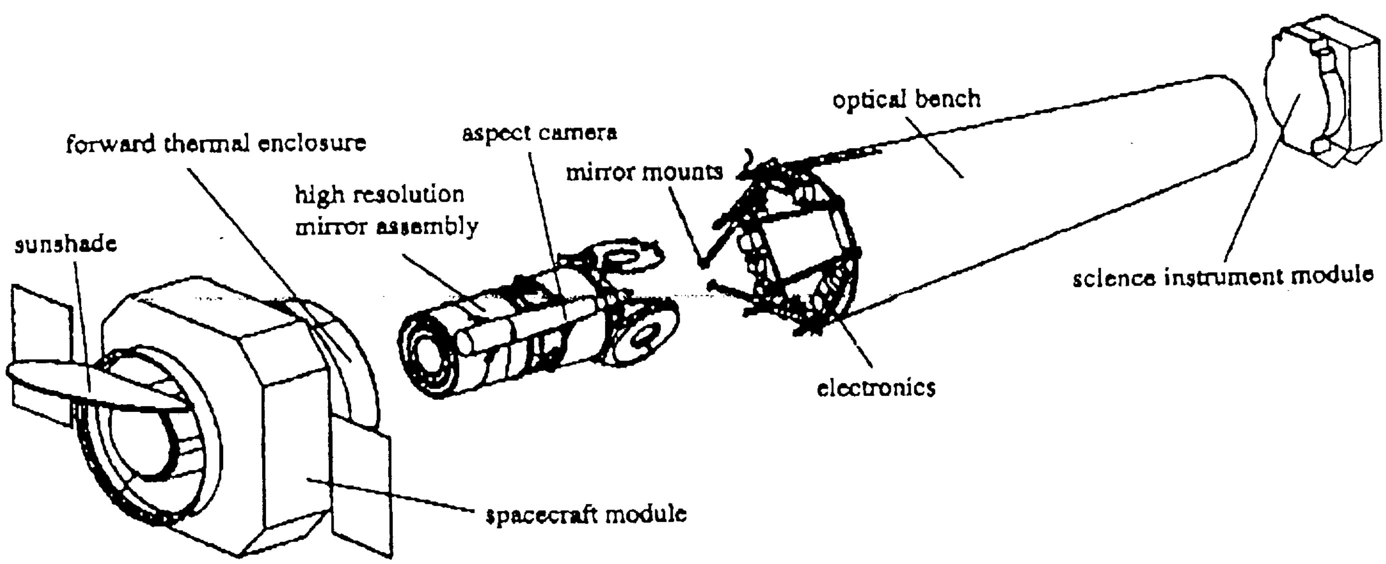

Figure 1: Elements of the Chandra X-ray Observatory

HIGH-RESOLUTION MIRROR ASSEMBLY

The mirror assembly is the most critical element of any X-ray telescope from the standpoint of thermal control. The Wolter Type I optical system, common to most high-resolution X-ray telescopes, is based on a pair of nearly-cylindrical parabolic and hyperbolic reflectors (Figure 2). Co-alignment of the two elements is critical, as is maintaining a distortion-free surface figure. To increase the collecting area, multiple mirror pairs of different diameters are commonly nested, as shown. These mirrors are nearly-cylindrical glass-ceramic shells about 1.5cm thick, and ranging in size from 0.64m to 1.22m, the largest optics of this type ever made. Thermal design is driven by the need for thermal isolation at the structural mounting interface and through the electrical harness, the necessity for radiative isolation to minimize effects of nearby surfaces and the space environment, and the need to minimize heat flow from mirror apertures while maintaining an unrestricted opening for incoming X-rays. A significant challenge in meeting these requirements is to provide a structural and thermal environment on-orbit that does not significantly degrade the imaging performance of the optics, yet allows them to survive the rigors of ground calibration and launch. Surface distortions on the order of 0.01 microns can degrade imaging, resulting in the difficult requirement of a stiff support structure that does not transmit significant forces to the optics.

The thermal design design approach was balance of the active thermal control requirements and a reasonably athermalized structural design for the HRMA. This was achieved using near-zero expansivity materials in the design where critical, balancing these with stable structural materials, since overall weight is also an issue in any space-based structure. Active control regions were provided at the structural mounts and major radiative interfaces. The large optical aperture, located very near the entrance aperture of the telescope, subjects the optics to direct exposure to space and the potential for thermal gradient distortion. This aspect of the design is a significant challenge, dealt with in the Chandra telescope, as in several previous X-ray missions, by the use of a "thermal precollimator,"[1] a configuration of "tubes" formed by aperture slots in a stacked assembly of flat, low-conduction baffle plates. These plates limit the field of view to space of the optical elements in both X-rays and thermal radiation. The two innermost baffle plates are heated so that the heat loss to space is primarily from the precollimator rather than the optical cavity. A similar structure on the aft end of the HRMA limits radiative loss to the optical bench portion of the telescope, which is maintained at a lower temperature than the HRMA itself. Finally, an intermediate cavity surrounds the outer diameter of the HRMA and is maintained at a reasonably constant temperature, limiting the effect of the changes in external environment (e.g., telescope repointing) on the optics.

Thermal control requirements were derived from an imaging error budget, combined with thermoelastic models of critical assemblies and raytrace models for imaging performance.[2] Image sensitivities to bulk temperature and thermal gradients were derived using a detailed thermoelastic model. For example, sensitivity to a thermal gradient across the HRMA diameter was found to be almost 0.7 arcsec/°C, about thirty times that to either radial or axial gradients, leading to a limit of 0.3°C for diametral gradients and less-stringent requirements for others.

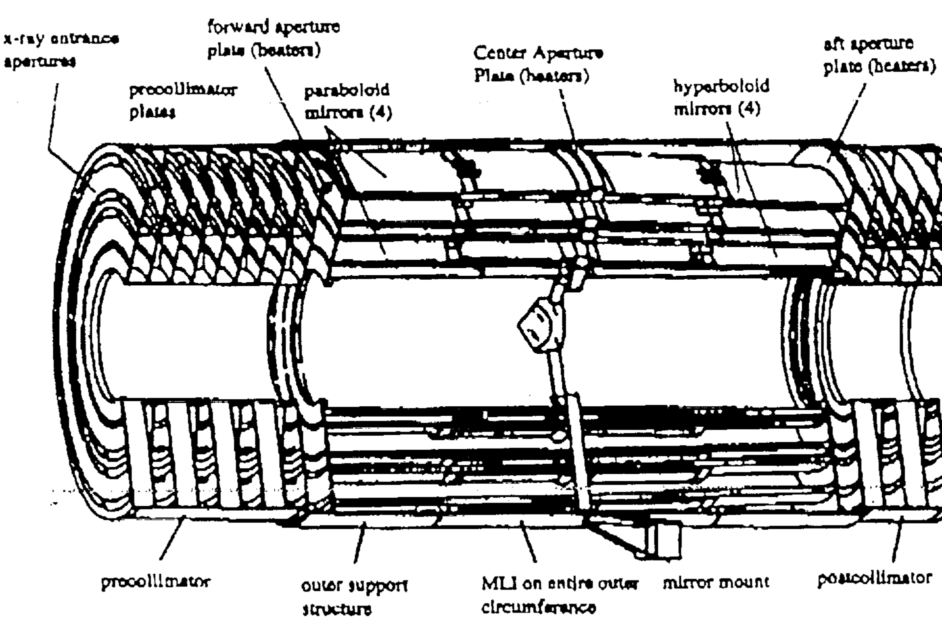

Figure 2: Chandra High Resolution Mirror Assembly

OPTICAL BENCH ASSEMBLY

The exit aperture of the HRMA and its "post-collimator" views the inside of the tubular section of the telescope, the Optical Bench Assembly (OBA). This is an MLI-covered graphite-fiber reinforced cyanate ester (GFRE) tube with a multi-zone heater system designed to maintain the structure at 10°C. The outer layer of the MLI is silver-Teflon, which for most of the mission will have a surface temperature lower than the internal design temperature even in direct sun, providing the desired cold-bias for thermal control. Reasonably tight thermal control is required for the OBA to minimize motions of the focal plane detectors relative to the telescope focus, and to present a constant thermal environment to the exit aperture of the HRMA. The external thermal environment is the principal challenge to maintaining the desired control, since mission pointing allows attitudes from direct sun on one side to sun on the aft end of the spacecraft, where the OBA is completely shaded.

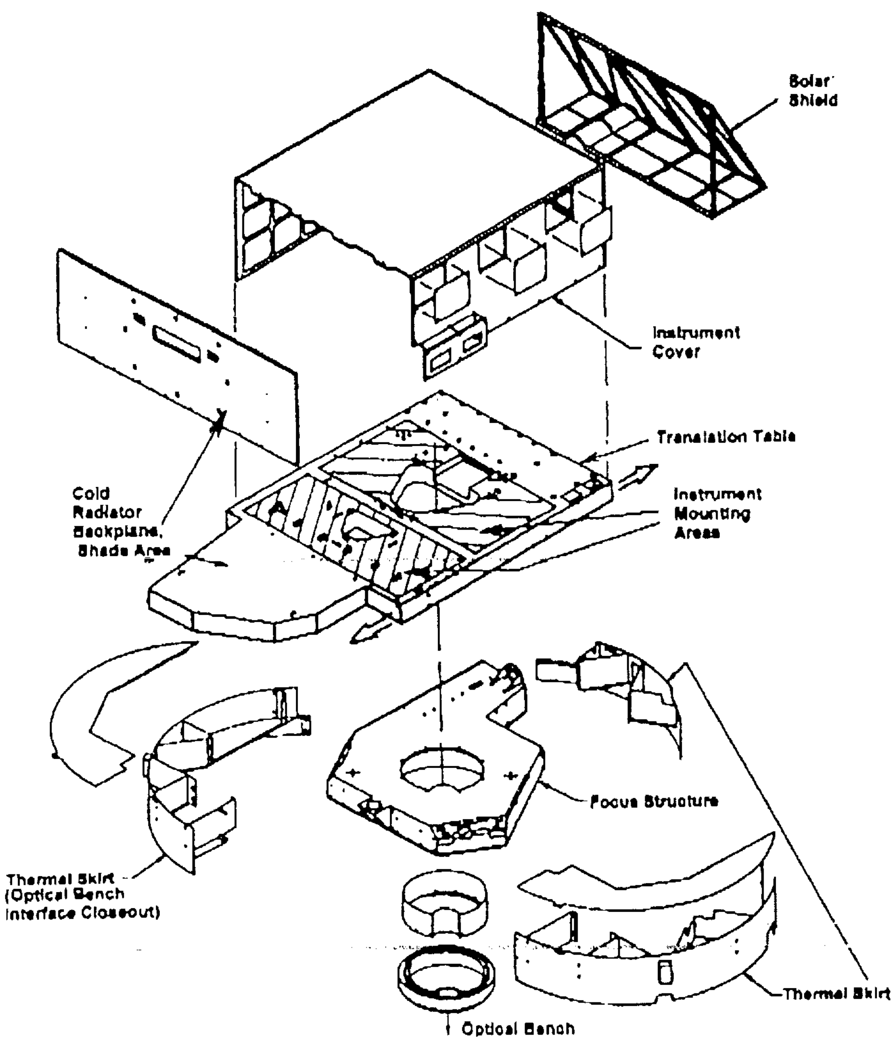

Figure 3: Chandra Science Instrument Module

THE SCIENCE INSTRUMENT MODULE

The science instrument module supports the two X-ray cameras and associated equipment, provides them mechanical and thermal protection, and translates each to the position of best focus of the HRMA, both axially and laterally. For high stiffness, minimum weight and mechanical stability, the SIM is a GFRE structure. It consists of three major assemblies (Figure 3); the focus structure, the translation table, and the instrument equipment cover. Additional equipment, primarily for thermal protection and light shielding, include the thermal skirt surrounding the focus structure, the contamination and stray light shield, and a lightweight solar shield for the primary solar facing surface.

The focus structure provides the mechanical interface of the SIM to the optical bench, and contains the two SIM mechanisms. The translation mechanism consists of support rails for the translation table, and a motor and lead screw to move the X-ray cameras laterally to select one for observation. The focus mechanism moves the entire SIM assembly axially to adjust camera position for best focus. This assembly is the most thermally sensitive of all, because the two mechanisms contain metallic rails and linkages, whose thermal expansivity is large compared to that of the graphite fiber structure. Changes in temperature or unwanted solar absorption can produce mechanical instability because of differential expansion. The structure is protected by MLI supported by a thermal skirt overlapping the end of the optical bench, and its temperature is maintained primarily by a radiation balance, supplemented by low-temperature heater protection.

The translation table is the integrating structure for the two cameras, associated electronics boxes and the CCD camera's cold radiator. Its moderate-conductance GFRE structure maintains low distortion of the mount positions even in the presence of large thermal gradients. Its exposed surfaces are protected by thermal control coatings.

Each of the two X-ray cameras consists of a central detector housing flanked in by electronics boxes on either side. The detector housings are either passive or have a small amount of active control. The cameras are thermally isolated from one another, and thermal conduction into the translation table is a minor factor. Most of the electronics dissipation is radiated to the immediately-adjacent cover, as is also the case with a supplemental electronics box. Low-temperature protection, especially for the non-operating case, is provided by a solid-state or mechanical thermostats and heaters on the most critical camera structure

The SIM cover protects the cameras from the space environment and provides thermal radiator surfaces for their control. The inside of the lateral panels is the radiative sink for the camera electronics assemblies, and the Z-93-coated outside surfaces constitute the space radiators. A sun shield protects the side most exposed to the sun, and the large back surface is a combination of white paint and OSRs for long-term stability. The shades for the cold radiator, which always faces away from the sun, are protected with MLI on the back side, and with OSRs on the sun-facing panels to prevent diffuse scattering onto the adjacent radiators. The inside panels adjacent to the cold radiator bear a specular VDA coating to improve its view to space. One concern for the completely passive design was the integrity of portions of the box away from heat sources. Because the box is filled with equipment the radiation paths are relatively short and the structure conductance is low, and there was concern about certain regions falling below qualification temperature.

The thermal environment for the SIM is relatively stable, except for different incident sun angles. In a highly elliptical orbit of 10,000km perigee, Chandra as a whole is little-affected by the earth except for occasional eclipses, and the allowed range of observing targets keeps the sun primarily on one side and the back of the SIM. However, the cold radiator is affected by facing the earth in certain seasons. Occasional roll maneuvers that expose one radiator to the sun are of short duration. The carefully-designed passive thermal balance has kept both cameras at the low end of their allowed temperature range for the first mission year, and there is considerable margin for temperature increase as the external coatings degrade slowly.

VERIFICATION

Verification of the many items of equipment and elements of thermal design for Chandra was dictated and constrained by numerous factors:

- perceived need to verify formally each supplier product before acceptance for upward integration
- large size of many of the components, which would require large and expensive test facilities
- extremely stringent contamination control restrictions on the HRMA, and therefore on other elements
- allowable deviation of temperature or heat flow
- criticality of the thermal element to mission success
- use of active or passive thermal control
- incompatibility of hot/cold cases for some equipment with others that were more restrictive
- difficulty of simulating thermal interface conditions

HRMA optical performance was the most mission-critical element, followed by the SIM and X-ray cameras, the optical bench, the shell surrounding the HRMA, and the spacecraft equipment module. Unfortunately, the HRMA was also the most constrained by small allowable temperature deviation and contamination control. The mirrors could not be cleaned, even of dust, after assembly. Science performance was calibrated with open apertures only once, in a clean NASA X-ray test facility, but this could not be combined with a full space-environment simulation test for the front aperture because of size, complexity, and schedule constraints. The precollimator was the most important element in HRMA thermal control, and verification focused on an extremely detailed thermal model of the precollimator, confirmed by an early test of a full-size engineering model.[1] The calibration test confirmed the structural mount and exit aperture heat flows, but the HRMA would never be exposed to a complete thermal test environment. The contamination covers remained closed even in the spacecraft thermal test. The first full confirmation of thermal performance occurred after launch, when the door covering the aperture was opened.

The spacecraft equipment module is thermally the least critical of the five. It is actively controlled with supplemental heaters for low-temperature protection. It is also contains much of the spacecraft mission equipment and provides local radiator area for concentrated heat sources. Verification of thermal design was accomplished by an analytical model, and confirmed in the final payload test. All internal equipment had been individually tested at the component level over the predicted temperature range plus hot and cold margins.

The optical bench assembly is primarily critical in precisely positioning the instruments with respect to the HRMA. Active thermal control and low expansivity both contribute to position stability, and partial failure of the thermal control system would have affected only observing time. Its thermal design was therefore verified analytically, and control power margins were confirmed during the payload test.

The SIM assembly was the most complex of the five in its thermal verification. With the exception of a few thermostat zones to maintain temperatures above cold limits, its control is completely passive. Different external surfaces are exposed to the sun over 135 degrees of pointing maneuvers, and simulating these external sun environments, while maintaining a simulated deep-space sink for the CCD X-ray camera's cold radiator and light shade, was a test challenge. The two X-ray cameras and associated equipment have allowable operating ranges of about ±20°C, but the most likely mission conditions were known to be biased to the low end of the range. The cameras are primarily radiation-coupled to the inside of the cover, and one required trimming of its radiating surface to bias it correctly within the operating range.

SIM thermal verification included both extensive thermal modeling and testing. The two cameras and associated equipment were supported by detailed thermal models, reduced versions of which were incorporated in the overall SIM thermal model. In an iterative process, the cameras were provided with boundary conditions for detailed temperature predictions and thermal design adjustment as needed. Updated results were fed back to the SIM design and model, and updated boundary conditions prepared. An engineering model of the cryogenic portion of the CCD camera was tested, and the thermal design and model modified accordingly. Because camera temperature control was the responsibility of the SIM, detailed thermal balance tests were not performed. However, the two camera thermal-vacuum tests were conducted with simulated SIM boundary conditions, and the high-resolution camera was tested again during the HRMA X-ray calibration, providing information to adjust both the thermal models and the radiating surface area.

Verification of the SIM with dummy cameras before its acceptance for further integration was originally planned, but schedule pressures dictated that the first test of the integrated assembly be performed with flight cameras. Two thermal-vacuum and thermal-balance tests were completed with the integrated SIM assembly. The final SIM thermal test was accomplished after payload integration in the final payload thermal-balance test, although over a restricted temperature range.

HRMA MODELING AND PRECOLLIMATOR TEST

A thermal analytical model of the AXAF HRMA in its flight configuration was created in NASTRAN. This model was generated with the structural model in mind to facilitate later "mapping" of temperatures from the thermal to the structural model. Because the structural model is used for optical performance predictions, and thermal load cases are among the most important of the imposed environments, the NASTRAN finite element temperature solutions could be transferred directly into mechanical distortion calculations and optical performance predictions. To represent properly the specular radiative networks (which dominate the mirror assembly and pre- and postcollimators), an independent 3000-surface radiation model was developed using NEVADA. These two models were integrated by combining the radiation and conduction matrices in the NASTRAN data file, which solved the combined matrix using finite element methods.

A rigorous thermal precollimator test was performed to obtain an accurate power balance to validate the Chandra HRMA thermal model, and to verify the ability to control the precollimator and forward HRMA structure to the required set points. The precollimator and forward portion of the HRMA structure were identical to the flight structures with the exception of the baffle plate aperture sizes. All MLI blankets required for the thermal test were manufactured using flight-like procedures and materials throughout. Test results showed this to be an important parameter in test/model correlation. All aspects of the HRMA thermal environment were simulated, including the forward thermal enclosure, the optical bench assembly aft of the HRMA, and other portions of the HRMA. A cryogenic shroud simulated deep space.

A separate test analysis model was constructed from a subsection of the flight HRMA thermal analysis model, modified to incorporate the as-tested precollimator aperture sizes and the actual test configuration, including all boundary conditions. After verifying and modifying this test analysis model, the flight thermal model was corrected to predict flight temperatures and heater power requirements. The calorimetric test yielded power and temperature measurements for a range of set points about the nominal.

Results showed that the measured test power values were always less than those predicted through analysis. This verified that the thermal models gave conservative power predictions. Post-test model checks showed MLI effective emittance to be an important correlation parameter. Effective emittance for the test MLI was found to be 0.003, in contrast to the 0.02 used in earlier models; 0.005 was used for subsequent models. Finally, the AXAF precollimator was shown to reduce the overall HRMA aperture-face heat loss from 138 watt to 47 watt, roughly a factor of three. These results guided revision of the thermal model used for flight predictions, which became the main thermal system verification tool for the remainder of the program.

After HRMA assembly and alignment, its X-ray focusing performance was tested in a 600-meter X-Ray Calibration Facility. The thermal-vacuum test environment for the HRMA mounts, outer cylinder, and aft heater zones was flight-like at 10C. However, no simulated space environment was used for the aperture end; forward heater zone power correlations were made through extrapolation. All zones met requirements and displayed satisfactory control, confirming the aft flight collimator design (and precollimator, by similarity).

SIM THERMAL TEST PROGRAM

The SIM was tested as a fully-integrated flight structure in a combined thermal-vacuum and thermal-balance test program. The space environment was simulated by cryogenic test chamber walls, with solar fluxes simulated by infrared panels for two surfaces of the cover. A separate cryogenic sink was provided for the cold radiator. The optical bench thermal interface to the focus structure was simulated by a constant-temperature plate. Accurate simulation was more difficult than usual because of the requirement for translating the instrument compartment during the functional portion of the test. This required additional fixtures and clearances between the flight hardware and ground support equipment.

This SIM-level test was the primary verification for the passive thermal control system for the module. Only at this test level would it be possible to produce the hot and cold design cases and the transition to the cold power-off case that could not be simulated after integration with the complete payload. This test also provided the primary verification for thermal control of the two X-ray cameras, because their operating environment was determined by SIM conditions.

The test program was quite successful in verifying the thermal control system. A few external temperatures were beyond acceptable limits, and portions of the MLI needed adjustment. The Z-93 thermal control coating did not allow secure fastening of test-only sensors to the radiator surfaces, making verification measurements for radiator performance quite difficult. However, the test results not only showed acceptable operating conditions for both science instruments, but also allowed adequate verification of the detailed SIM thermal model.

The final SIM thermal verification was accomplished during the fully integrated payload thermal test. There was no solar simulation — heater panels simulated the predicted on-orbit incident fluxes. Boundary conditions were less stringent than the SIM-only test, but two difficulties were encountered during its course. A critical experiment door failed to open under vacuum conditions, and some of the SIM low-temperature heaters were observed to be inoperative.

Inspection following the test showed that the faulty heaters had failed because of overtemperature. Concerned over differential expansion between the heaters and GFRE substrate had led to mounting them with a compliant urethane material about 0.5 mm in thickness rather than conventional bonding directly to the SIM surface. The additional thermal impedance of the compliant layer had not been accounted for and, combined with the unexpected capability to operate both primary and redundant circuits simultaneously, produced unacceptably high power densities and temperatures in a few heaters. Replacement heaters were bonded in a conventional manner. Repairs for the failed heaters were verified later in a separate test.

INTEGRATED OBSERVATORY TEST

The Observatory thermal test was the first test of the thermal interfaces of the payload's major elements, and of the integrated suite of components, especially in the critical vicinity of the HRMA. For the telescope thermal control hardware, it was the first thermal balance test. All payload flight hardware was present except for the solar arrays, and the HRMA contamination covers were closed for protection, as previously noted, so that heat loss through the apertures was not flight-like. Environmental loads for the sun-facing surfaces were simulated by heater panels, as noted earlier.

Hot, cold and survival-case conditions were tested, verifying the capability of the thermal control system to perform its functions properly with demonstrated margin. The primary focus was on power margins in the control system since most of the Observatory was actively controlled. Thermal balance information also supported an update of the comprehensive thermal model, allowing corrected flight predictions for the final mission.

Results for the systems that had been tested previously showed no surprises, demonstrating that the additional equipment present in the flight system had negligible effect on thermal control. Power levels for the HRMA were about 20% lower than predicted for test conditions, still within the region of positive control. Science instrument temperatures were nominal at the low end of the acceptable range, allowing plenty of margin for increases as coatings degrade during the mission.

The optical bench assembly showed the largest deviation from predictions. Dominated by the performance of the MLI, it had been modeled conservatively, and cold-case test power levels were less than half what had been predicted. Post-test model correlation derived an effective emittance of 0.0045 for the large conical blanket segments, where particular attention had been directed to maintaining plenty of internal spacing even when the outer layers shrank under cold mission conditions. Only in the rather complex section near the SIM interface was ε^* shown to be as high as 0.12.

Model correlation required some additional detail in the enclosure surrounding the HRMA, and an update of thermal mass values to include assembly hardware and electrical harness. With local detail in MLI performance variation, the correlated model corresponded well to test data. Flight predictions with the correlated model showed total thermal control power to be well within mission capability for all phases.

Some of the most interesting results came from the computer-driven active control system, and both advantages and disadvantages were observed. On the positive side, set points and deadbands were identified for adjustment to improve performance, control authority and power balance between control zones. This would not have been possible for the fully-integrated flight payload had the parameters been determined by hardware. But logic errors were observed that occasionally left heaters switched on in an uncontrolled manner when switching between modes in a system unrelated to thermal control. Had this not been seen in test where operation was closely watched, serious mission consequences could have resulted in periods when the observatory is out of contact with a ground station.

HRMA mount heater zone deadband was reduced from 0.1°C to 0.08°C to reduce heater overshoot in these regions. To reduce heater overshoot within the optical bench, all deadbands were reduced from 0.6°C to ±0.3°C. Also, the setpoints of two bench heater zones were raised from 10°C to 11°C to achieve a better power balance among several zones in that region – a neighboring zone was running at a relatively high duty cycle before this change was made. Finally, it was determined that the OBA aft bulkhead zones were capable of maintaining a 10°C setpoint, although the thermal model had shown that these zones could only maintain a temperature of 8°C prior to testing. As a result of the test, the setpoint for these zones was raised to the preferred 10°C and no control problems were found at this temperature.

ON-ORBIT EXPERIENCE

Within the first weeks of operation of the Chandra Observatory, it was noted that for certain angles of the Observatory relative to the sun vector, heating was occurring in the area of the attachment of the SIM to the OBA. For the first days of the on-orbit checkout, the sun was directly perpendicular to the axis of the telescope. The unusual heating was first noted during a maneuver where the sun fell on the forward end of the spacecraft (66 degrees from the optical axis). With this forward pitch angle, the three flexures that mount the SIM to the OBA began to warm up markedly. These flexures are evenly spaced around the axis of the telescope with one located directly on the sun side. In two reasonably long pointings of 66 and 55 degrees, the two flexures on the shaded side warmed up 5-6 degrees C, while the sun-side flexure warmed between 12 and 15 degrees.

During observatory thermal-vacuum test setup, an examination of the SIM/OBA interface revealed a substantial annular gap in the MLI insulation between the

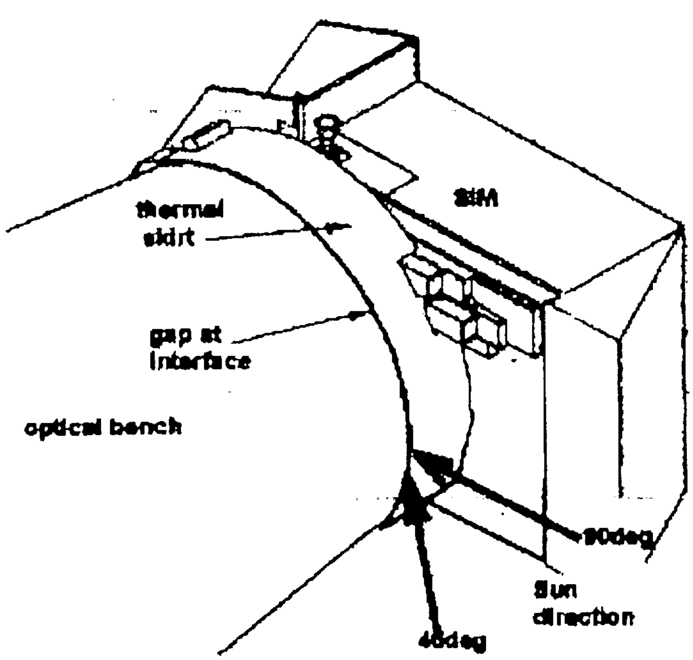

Figure 4: Gap at SIM/OBA Interface

OBA and the overhanging extension of the SIM module called the Thermal Skirt (Figure 4). A mechanical gap here is necessary to accommodate the focus motion of the telescope, although the gap was quite large (1-1.25cm). The OBA MLI, with its silver-Teflon outer layer, extends inside the annulus, and provides a near doubling of the effective area of the opening due to its low solar absorptance and moderate specularity. We estimated that more than 50 Watts of power are absorbed through this gap, while only about 9 Watts are radiated. This results in a net increase in power to this area of the SIM that is substantial relative to the applied heater power in the same region. Other possibilities, such as reflected sun from the +X face of the SIM, were considered but dismissed as unlikely to produce such large changes. A test was run at the minimum pitch (45 degrees) to establish the maximum equilibrium temperature, which was 25C for the sun-side flexure.

The pre-launch setpoint temperature for the flexures was at 10C. Since the equilibrium temperature for the sun-side flexure would exceed this value for most pitch angles less than 90 degrees, tests were run to evaluate the feasibility of setting the control point to a higher value to maintain control margin at all pitch angles. In the initial test, the control point was set to 25C, since the feedback thermistor's maximum readout temperature was limited to 25C due to on-board software. During this test it was noted that although the flexures were being maintained at temperature, the motion of the SIM, as measured by the aspect system, was relatively rapid and "noisy." This was traced to the cycling of the flexure heaters and the fact that, with slightly different but similar duty cycles, at certain times the motions produced by thermal expansion of the flexures during heating reinforced and produced relatively rapid motions. This was compared to the uncontrolled periods, where the total of the SIM was much greater but manifested as a slow drift, a simpler motion easily corrected in post-facto image processing. This has been adopted as the operational scheme.

ACIS FOCAL PLANE/RADIATOR TEMPERATURE

The ACIS is a CCD-based X-ray detector with 13 CCD devices in two arrays forming the heart of the detector assembly. To maintain the low background noise levels required for this instrument and prevent unnecessary radiation damage, the detector is coupled to a cold radiator located on the anti-sun side of the SIM. This radiator, connected directly to the focal plane devices, typically runs at -128C, allowing the CCDs to achieve an operating temperature of -120C.

The only significant deviation from the expected performance of Chandra Observatory as a whole has been an unanticipated level of radiation damage to the ACIS detector. This damage has been checked by procedural changes for Chandra's passages through the magnetosphere near orbit perigee, but to minimize the effect of this damage on the imaging performance, the focal plane is now being controlled at the lowest possible setpoint temperature. This has stressed the radiator capabilities, particularly during the period near orbit perigee. During these perigee passes, the spacecraft is oriented with the radiator pointed away from the sun, and the pitch set to minimize gravity gradient and consequent momentum effects. Under these constraints, the radiator begins to point directly toward the earth during certain seasons, and earth IR causes a significant rise in the radiator (and focal plane) temperature. Figure 5 shows the radiator temperature for the first nine months of the mission. It can be seen that spikes in the radiator temperature occur every orbit (a 2.5-day period for this highly-elliptical orbit of 140,000km apogee). These spikes were large in the early days of the mission, decreasing to a minimum around day 150, when the orbital major axis is sunward so that the radiator points away from the earth near perigee. The setpoint was lowered around day 190 to allow the focal plane to run at minimum temperature.

The focal plane temperature rise has not yet impacted observing time because observations are conducted only above 65000km.. But as the radiator performance degrades over mission life, it is expected that the recovery to temperature control will extend beyond the non-observing periods. It would be beneficial from the thermal perspective to point the radiators as far away from earth as possible during these periods; the impact on spacecraft operations will be investigated.

CONCLUSIONS

The complexity of a space mission as sophisticated as Chandra, with contributions from many institutions and corporations, rendered the textbook step-by-step process of thermal design and verification impossible. We have detailed many of the compromises that were needed: early development tests that ultimately constituted verification of a design element; integrating and testing together items that would usually be tested

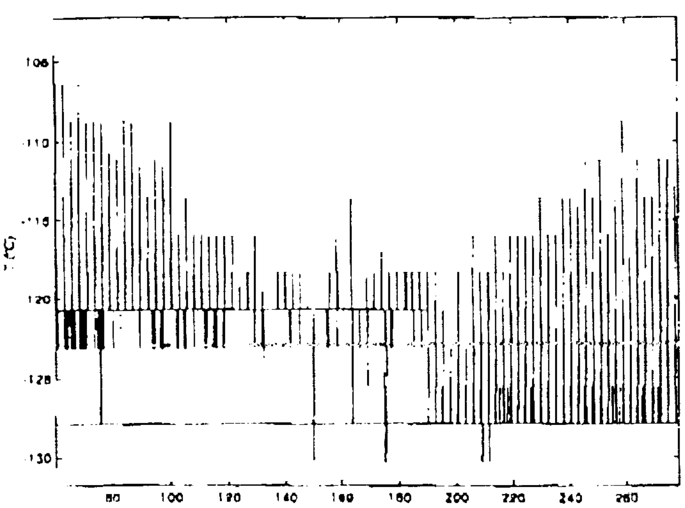

Figure 5: ACIS Cold Radiator Temperature (270 days)

separately. But no critical element or piece of equipment went unverified, and we continually focused on erring on the side of limiting mission risk.

We were fortunate to have two companies and a NASA center that had worked together two decades earlier on the progenitor of Chandra, the Einstein Observatory. The personnel of the science and engineering team at the Center for Astrophysics had designed key elements of that mission; its heritage was incorporated in the most critical thermal design areas, particularly the HRMA. And we credit much of the successful perform-ance of the MLI system to lessons learned by that team on the unrelated but contemporaneous SWAS mission. [3]

In specific technical areas there were few surprises. We note the SIM heater failures as an example of a legiti-mate concern – differential expansion of heater and low-expansivity substrate – leading to an apparent design solution adopted without adequate testing. Computer control of active thermal control loops is seen more often in recent mission designs, but the software/hardware implementation seems to be reinvented with each, and thus fails to incorporate the heritage of established technology in the same way that thermo-mechanical and electronic control elements do.

Performance of the Chandra thermal control system post-launch has been nearly flawless. Only one anomaly, related to behavior of a thermal closeout between major system modules when sunlit at some orientations, has produced some minor operational restrictions. We have seen seasonal effects of the perigee passes on the cold radiator for the CCD camera, but do not have a full year of data to evaluate them at this writing.

ACKNOWLEDGEMENTS

The authors would like to thank Keith Havey of Eastman Kodak Company for his contributions to the success of the design and verification of the Chandra Observatory thermal control systems.

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