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CONSIDERATIONS ASSOCIATED WITH THE DESIGN OF THE THERMAL SUBSYSTEM OF THE ORBITING ASTRONOMICAL OBSERVATORY

STANFORD OLLENDORF
MICHAEL J. COYLE, JR.

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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Michael J. Coyle, Jr.

Thermophysics Branch,
Spacecraft Technology Division, NASA

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ABSTRACT

A detailed review is presented of the measures taken to improve, modify, and test the thermal subsystem of the Orbiting Astronomical Observatory (OAO A-2) subsequent to the first spacecraft. Three-month flight results and plans for future spacecraft are included.

A discussion is presented which outlines the thermal modifications to the OAO A-2 spacecraft, first, from the hardware viewpoint with addition of louvers and heaters, and second, with regard to the analytical methods used. Attention is given to the adaptation of louvers to an internally mounted heat sink as opposed to those previously flown, i.e., Mariner, which were externally mounted on the spacecraft.

Results of a research program investigating the stability of Alzak, a commercial product with a low α/ϵ coating, in the space environment, is discussed. The resulting data were used to qualify control this material for high reliability and long life.

The programs and studies developed for analyzing the thermal design of the OAO are presented. Included are: (1) a flux study, with blockage, to define the environment, (2) an active control tradeoff study to define the use of louvers versus heaters, and (3) a comprehensive 350-node model of the spacecraft and Experiment Optical package. The computer program for the flux study included, for the first time, a blockage routine which handled solar, albedo, and earth fluxes. With regard to the experiments, the models developed were the first to predict to within 5°C, critical areas of the optical packages.

Six-month flight data illustrating the actual versus predicted temperatures in the spacecraft and experiment are presented. An examination of pre-flight thermal constraints is made. Their ultimate relaxation as a result of the flexibility found to exist in the spacecraft under abnormal conditions in orbit is discussed. A comparison is made of in-flight degradation of the Alzak to that measused in ground testing and previously flown on the ATS-3 reflectometer experiment.

Future improvements in follow-on spacecraft is discussed with regard to use of low flux, low Δ T heat pipes to reduce gradients; limiting equipment and experiment temperature variations to increase reliability; and improving thermal control coatings.

Important conclusions to be drawn from this paper are: (1) the increase in flexibility acquired in the thermal subsystem of the OAO due to the addition of active control, (2) flight verification of analysis, and (3) future improvements including the use of heat pipes and low α/ϵ stable thermal coatings. These factors have not been discussed in previous publications.[4]

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INTRODUCTION

The Orbiting Astronomical Observatory (OAO) was placed in a 500-nautical mile circular orbit on December 7, 1968 to collect scientific data concerning the ultraviolet spectra of stars heretofore unobservable with ground-based instruments. A total of eleven telescopes, each with different sensitivities, have made more than 2500 observations of discrete objects and the crab nebulae.

The primary objective of the thermal subsystem was to provide temperature control for the experiments and spacecraft electronic components. In the discussion that follows, information will be provided that will show how this objective was achieved.

DESCRIPTION OF SPACECRAFT

As shown in Figure 1, the satellite is an octahedron, 80 inches across the flats and 118 inches long. Solar paddles extend perpendicularly from sides C and G at an angle of 33° to the central axis. A cylindrical hole the full length of the spacecraft and 48 inches in diameter accommodates the primary telescope system. Sunshades are provided at the optical openings to prevent sun impingement inside the telescope cavity when it is oriented to a star.

Internally, aluminum trusses and shelves are integrally connected to the 48-inch diameter structural tube and form 48 truncated bays, as seen in Figure 2. These bays house the electronic equipment which is mounted to hinged honeycomb panels. The panels swing outboard to permit access to the equipment and wiring while installed in the spacecraft. Ten mil, polished, anodized aluminum skins (Alzak)* cover the equipment and are used for both a thermal protection to incident radiation and heat radiator. The skins are thermally isolated from the structure by means of nylon insulators. The overall normal spacecraft load that must be managed by the thermal subsystem is 425 watts.

During slewing maneuvers, the satellite can revolve about any of its three axes. When positioned to a star, it is roll-oriented such that the earth-sun line

*Alzak is a commercial product of the Aluminum Company of America.

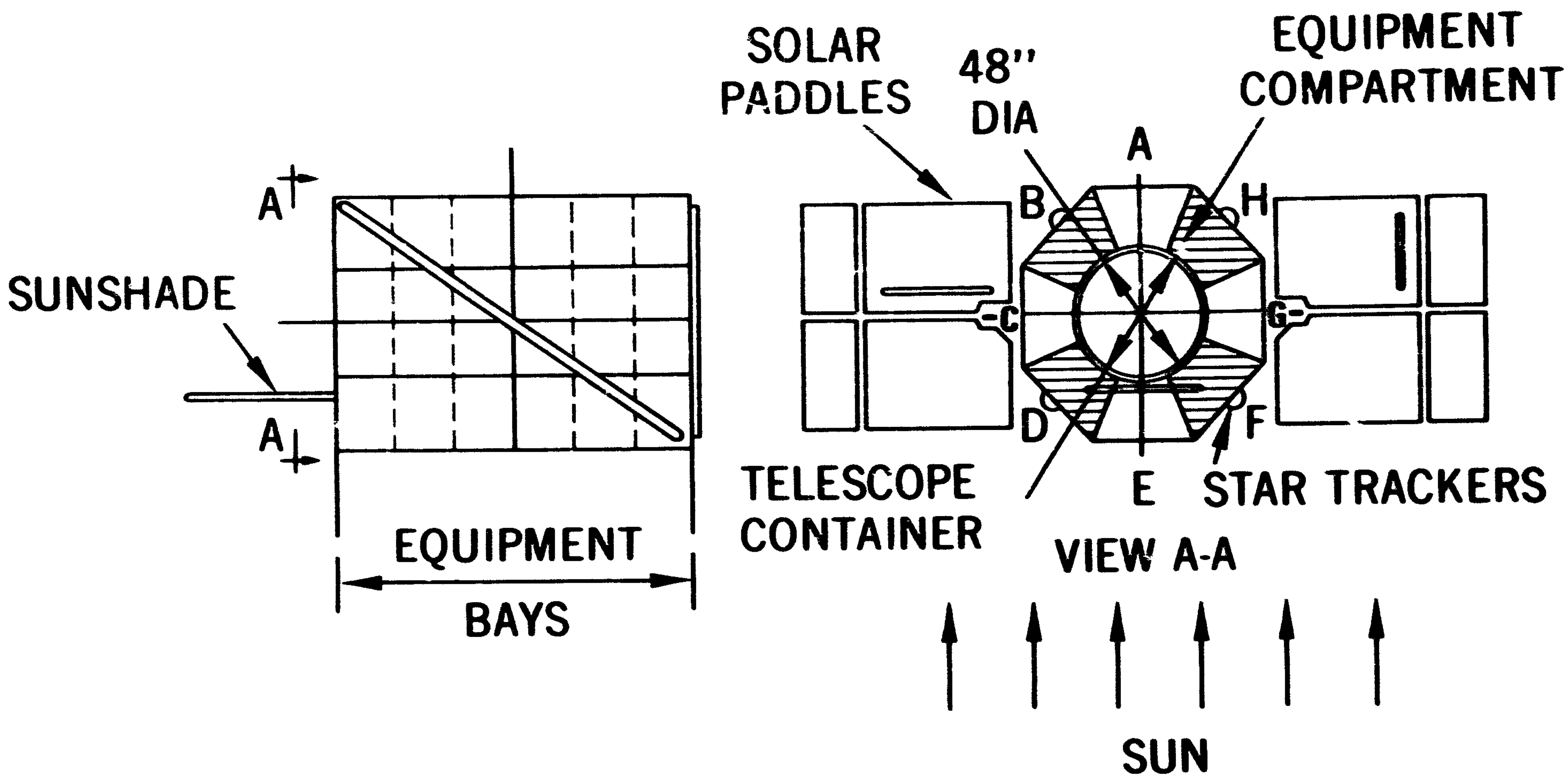

Figure 1. Orbiting Astronomical Observatory

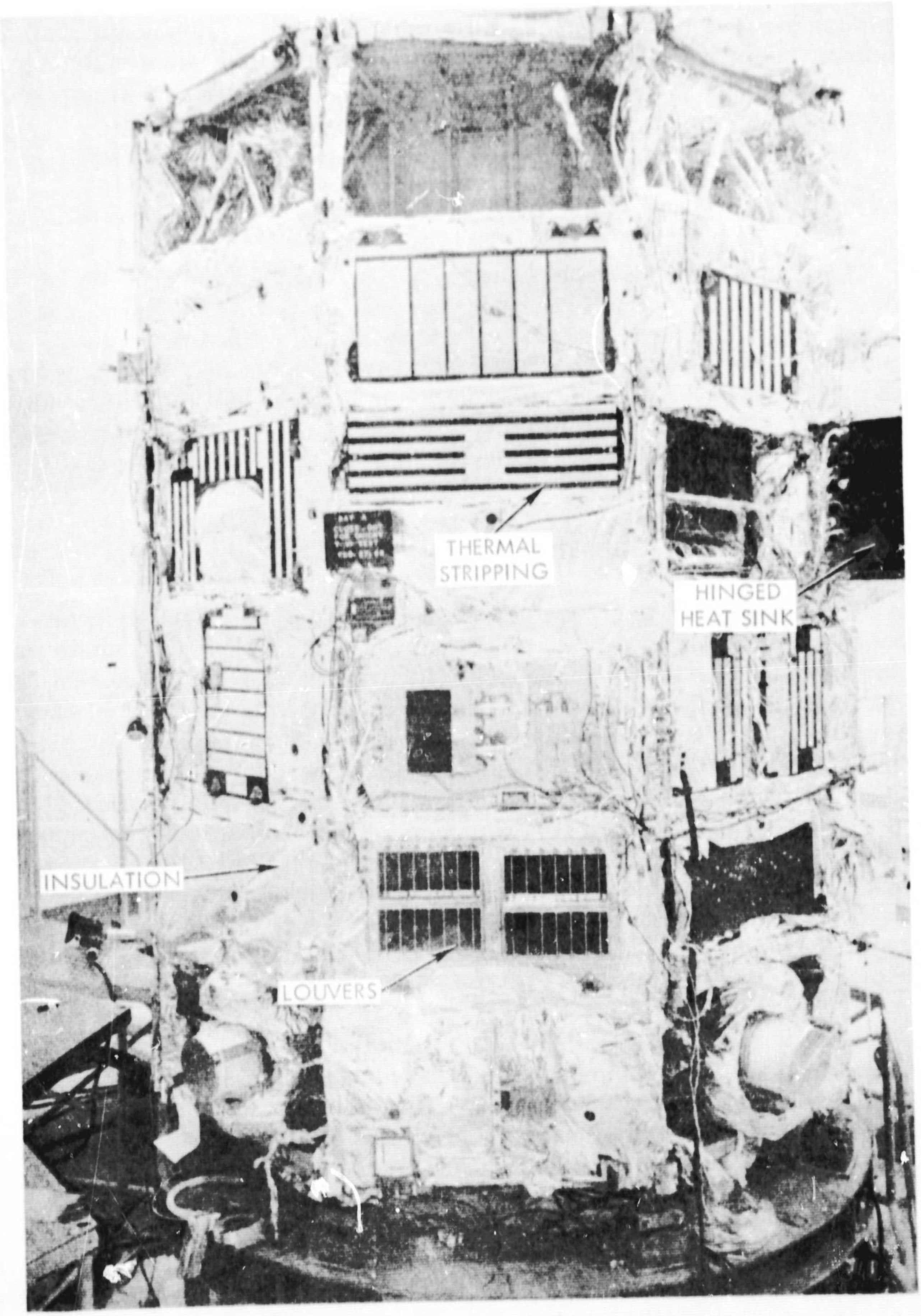

Figure 2. OAO Thermal Configuration

is always parallel to the C and G skins (see Figure 1). This position allows maximum solar paddle output and provides the OAO with a set of stable temperature skins that are used as radiators to cool the spacecraft structure and equipment.

DESCRIPTION OF THE EXPERIMENT

The Wisconsin Experiment Package (WEP), the primary experiment, consists of four 8-inch stellar telescopes, two scanning spectrometers, and a 12-inch nebular telescope all housed in the forward half of the central tube. The Smithsonian Astronomical Observatory (SAO) consists of four 12-inch telescopes with a Uvicon camera in each. It is housed in the rear half of the central tube. The overall power dissipated in the experiments is 8 watts in the optics and 22 watts in the bay electronics.

THERMAL CONTROL SUBSYSTEM

The thermal control of most electronic equipment is primarily achieved by a passive design approach. Each box is designed to conduct and radiate its heat to the heat sink surface which mounts to the honeycomb panel. The heat is then conducted through the honeycomb panel which radiates to the external skin. Figure 2 shows the overall thermal configuration of the OAO without skins installed. A heat balance is then made between the bay and the external environment (see Figure 3). The radiative coupling between heat sink and skin is adjusted to the temperature requirements of the equipment. The anodized skin coating with a nominal α/ϵ of 0.20 minimizes the effect of solar radiation and allows for the maximum heat rejection capability. In general, the objective of the thermal subsystem is to maintain the equipment in the range of 0° to 130°F. Components such as the battery and tape recorder are held to tighter limits in the range of 40° to 85°F.

Heaters, actively controlled by thermostats, are employed where minimum temperatures cannot be maintained by passive means. Louvers (see Figure 4) with bimetallic actuators are employed where a heater power saving can be realized or tight temperature control must be maintained. These louvers are in intimate thermal contact with the heat sink and adjust the radiative coupling to the skin as a function of heat sink temperature.

The spacecraft structure temperature is maintained by calculating a heat balance between equipment energy leaked to it through insulation via the equipment bays and that which is radiated via the "C" and "G" cooling skins and the apertures of the experiments.

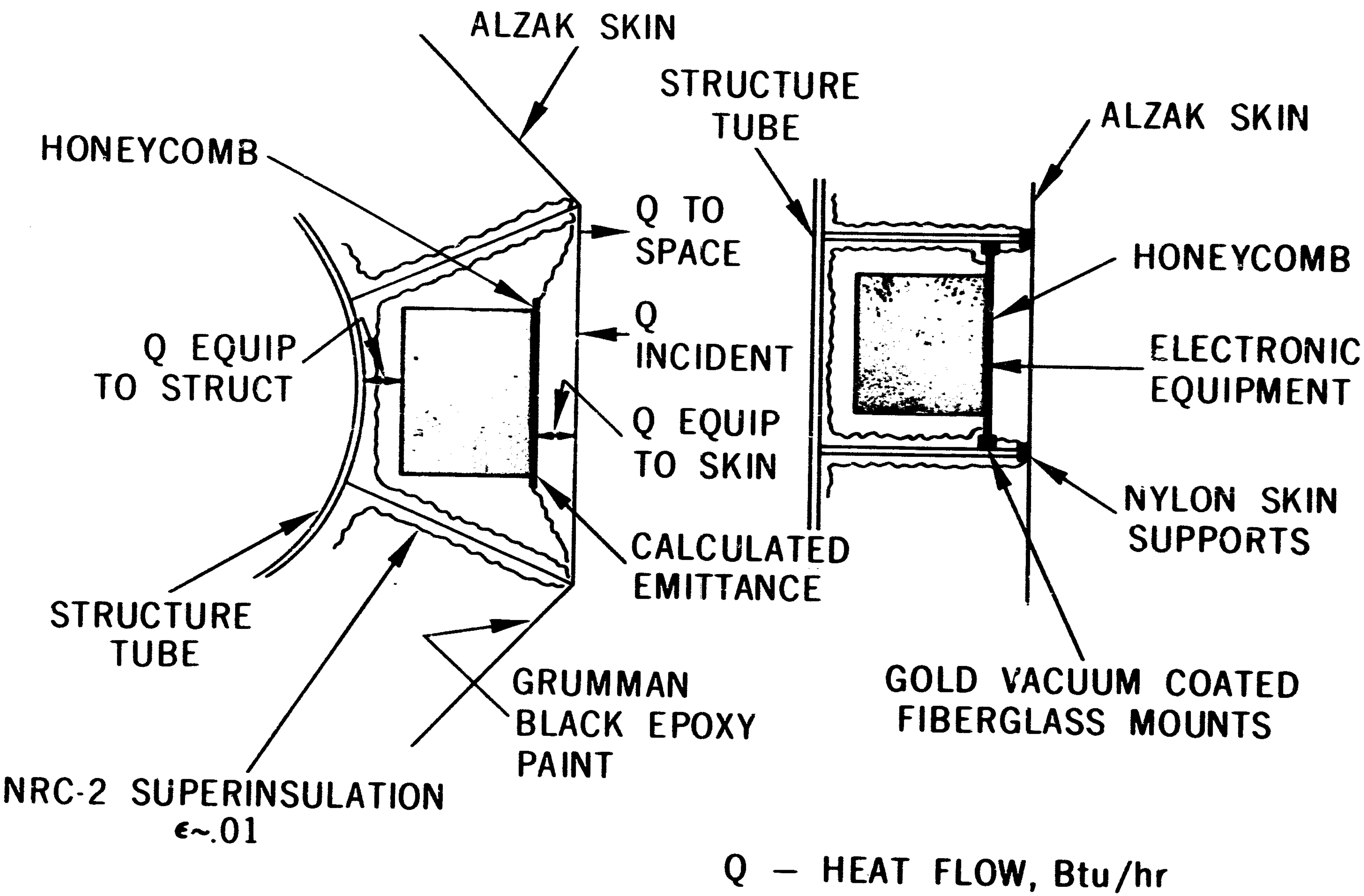

Figure 3. Typical Equipment Bay

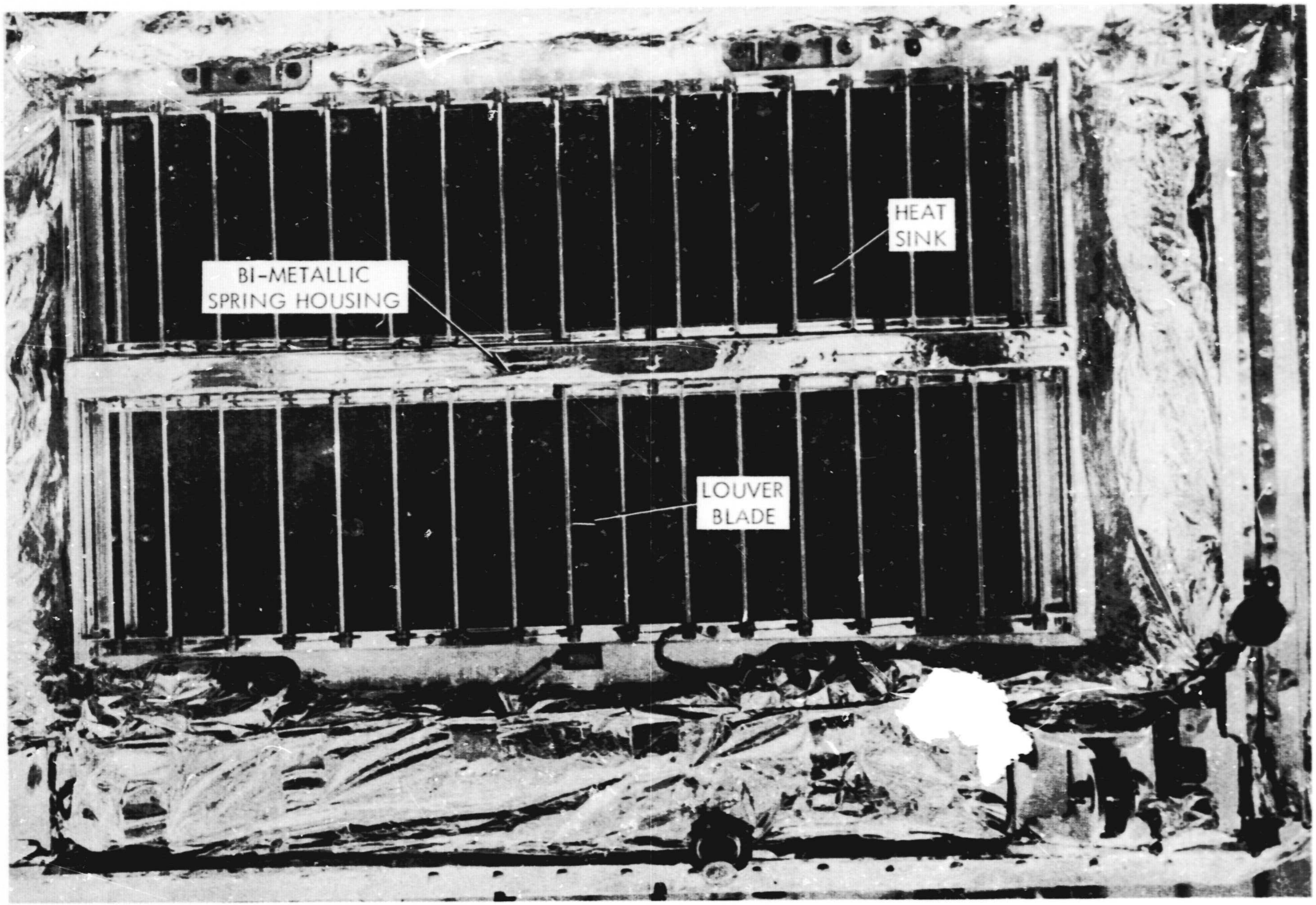

Figure 4. Louver Installation

To minimize the energy lost through the experiment aperture, each experiment was designed to reduce this heat leak by a different method. The Wisconsin Experiment Package (WEP) couples itself to the spacecraft central tube by radiation and decouples itself from space by insulation blankets on the space side of the telescope as shown in Figure 5. The WEP therefore runs within a few degrees of the structure temperature. As structural gradients would be reflected into the experiment, they had to be minimized. The Smithsonian Astronomical Observatory (SAO) decoupled each telescope from the spacecraft structure and each other by insulation blankets as shown in Figure 6. The SAO telescope temperature was highly dependent on the effective space temperature.

The Uvicon tubes were the only temperature sensitive equipment in the SAO telescopes and their temperature was strongly dependent upon internal heat dissipation.

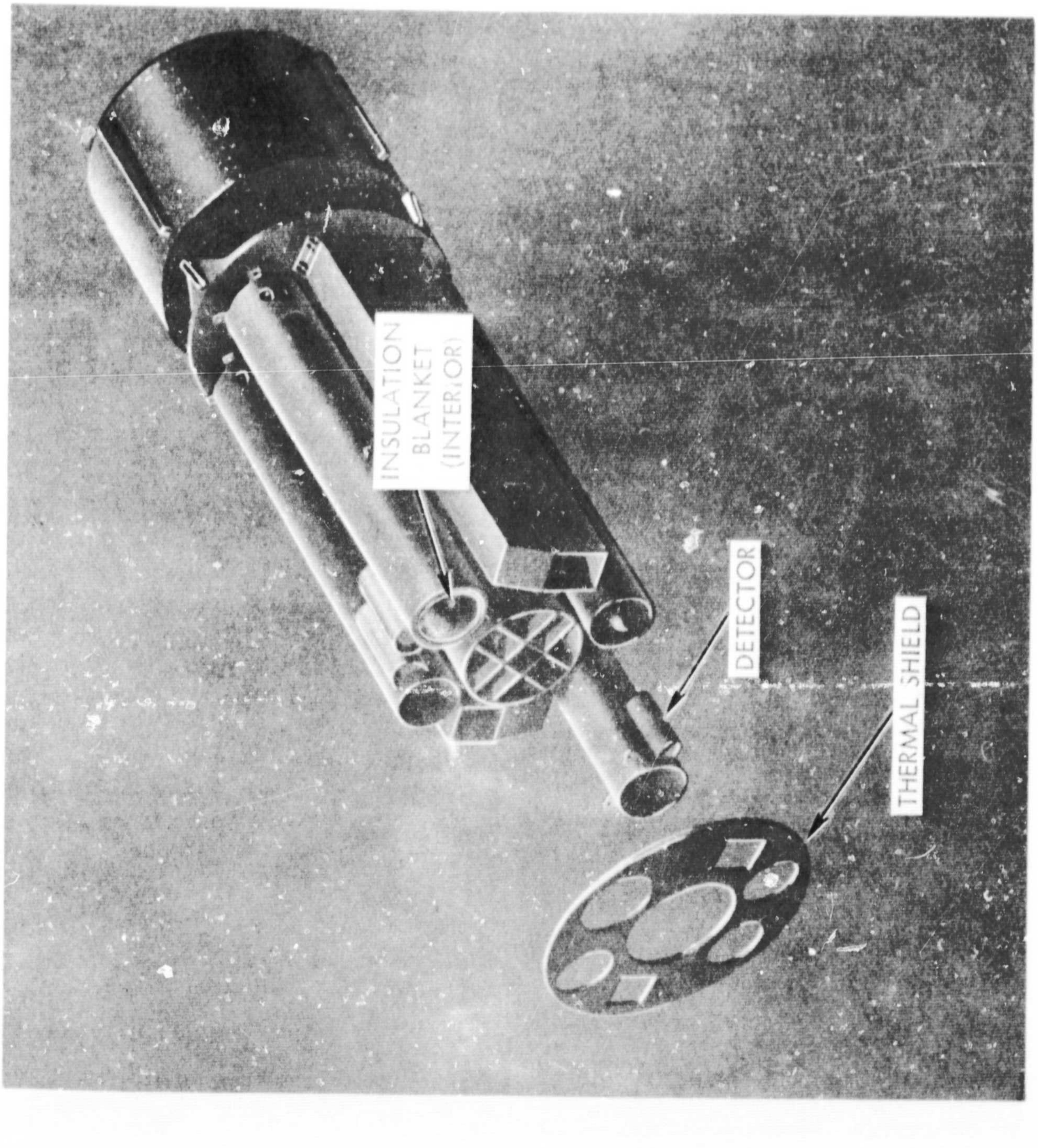

Figure 5. University of Wisconsin Experiment

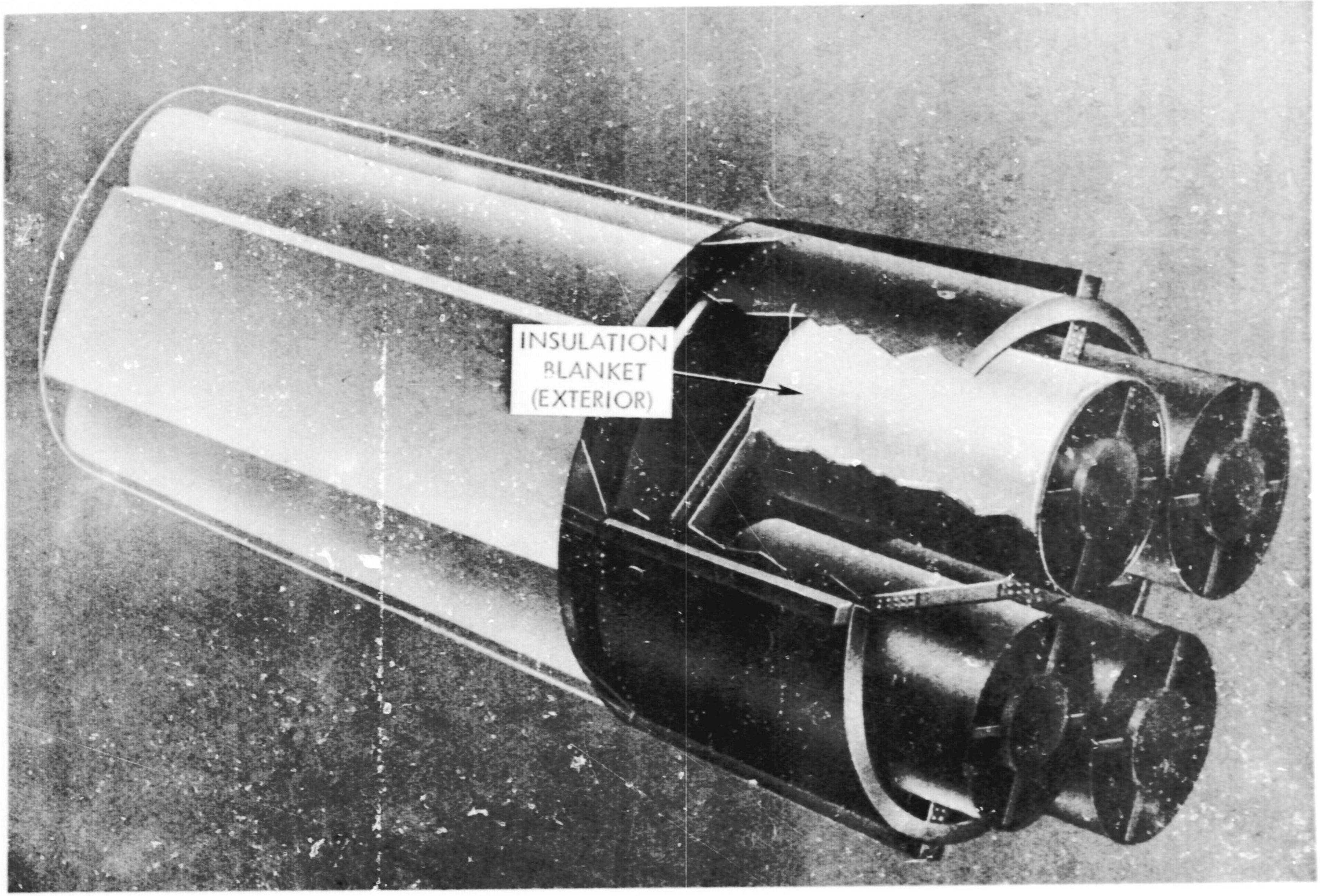

Figure 6. SAO Experiment Package

CONSIDERATIONS ASSOCIATED WITH THE THERMAL DESIGN AND ANALYSIS

Hardware Modifications to Thermal Subsystem

Subsequent to the OAO-I flight, it was found that deficiencies existed in certain areas of the spacecraft to cope with all contingencies in power dissipation and incident flux. A comprehensive study was initiated which examined each equipment bay for placement of louvers. A typical result is shown in Figure 7 where a power saving of 8 watts could be realized. A smaller dynamic range of temperature swing is also achieved over various power and flux conditions. This adds to the overall reliability of the electronics. Cost and weight also entered into the tradeoff study. The results showed that four equipment bays could gain significantly from the use of louvers; they were A5, B5, C4, and E1.

Flux Study

Prior flux calculations used orbital average blockage factors of appendages on spacecraft surfaces when calculating earth and albedo fluxes. It became apparent that a modification should be written into the computer program which calculated blocked fluxes based on an instantaneous value. This modification was written (ref. 1) and coupled to an orbital flux program. After integrating this routine, a comprehensive study was instituted which examined all spacecraft surfaces for their worst case environmental fluxes. In addition, it was found that such parameters as uncertainties in coating properties, seasonal variations in albedo and uncertainties in earth temperature and solar intensity should be accounted for. A statistical tolerance of these parameters was chosen for the design.

Comprehensive Nodal Analysis

A 350-node model of the observatory was developed which enjoined the individual bays, the structure, the experiments and appendages into one analytical model. This model permitted a close examination of the observatory under a variety of operating modes and helped establish a realistic mission profile. Previous approaches to the thermal analysis took a "boundary condition" approach to the various components of the observatory. This tendency overdesigned the equipment bays as well as experiments and would have resulted in prohibitive constraints on spacecraft operations. The comprehensive analysis also permitted a more detailed examination of structure temperatures and gradients.

Coating Degradation Investigation

A closer look at the anodized process (Alzak), on whose ultraviolet stability the thermal design heavily depends, revealed the susceptibility of this coating

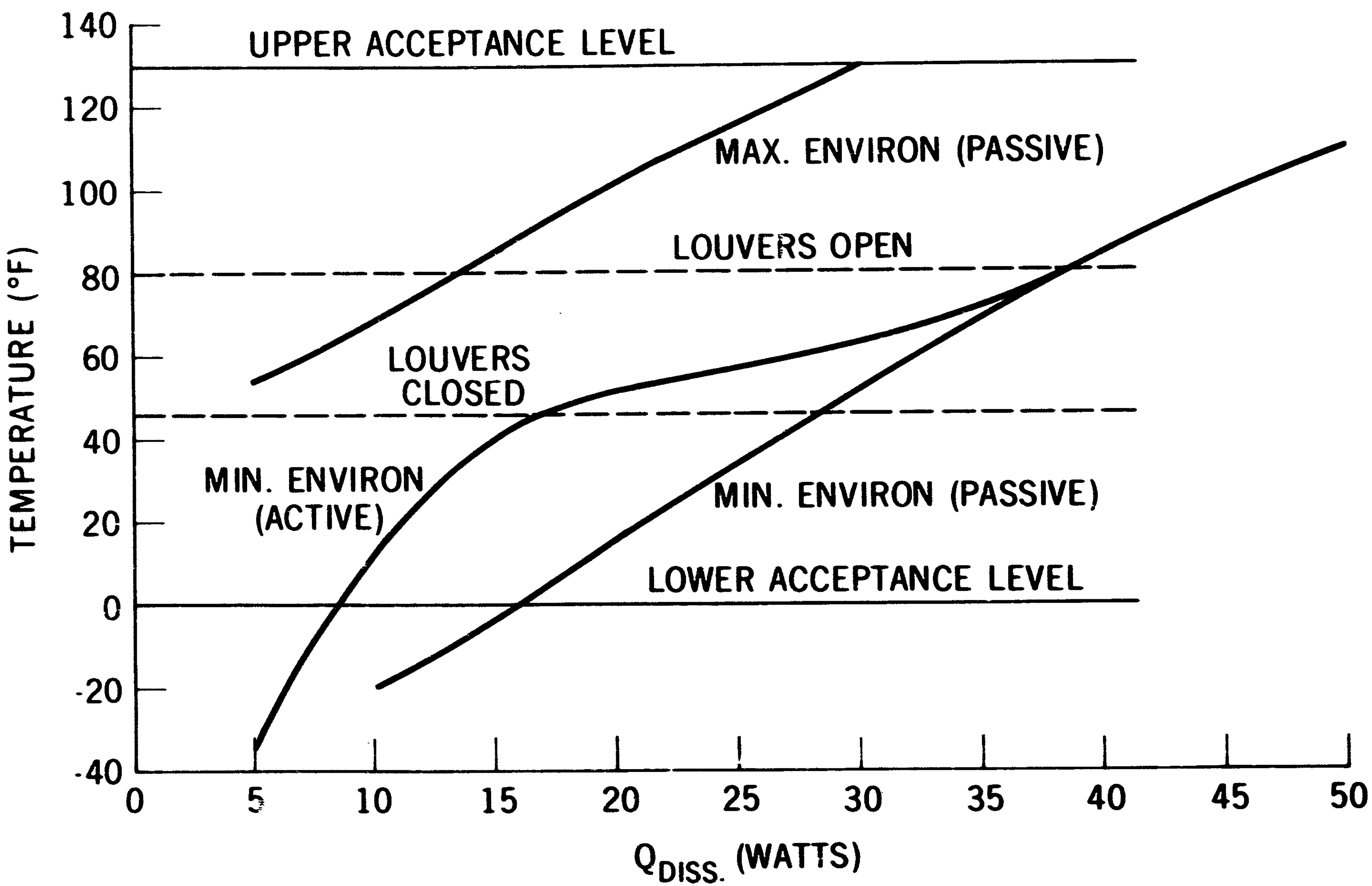

Figure 7. Variation of Heat Sink Temperature with Changes in Power

to such parameters as temperature, anodize thickness, and impurities. A research program was begun to investigate these parameters. The results of this program showed that (a) damage increased with coating thickness, (b) damage increased upon exposure to the shorter wavelengths of the ultraviolet, (c) damage increased disproportionally with temperatures above 125° F, and (d) no correlation could be made to damage as a function of the type of impurities, i.e., iron oxide, sulphur, etc. Included in this program was a sample flown on the ATS-3 satellite and reported in Reference 2. Figure 8 shows the comparisons of Alzak degradation on the OAO with that on ATS-3. The close correlation to the shielded sample (shielded from the effects of charged particle damage) indicates that damage was a result of ultraviolet exposure.

Test Considerations

The thermal testing was essentially accomplished in several stages. Each piece of electronic equipment was thermal vacuum tested at the manufacturers by exposing the subassemblies to their expected extreme ranges of temperature and monitoring their performance. This insured maximum reliability before spacecraft integration.

Two major tests were performed to verify the thermal subsystem. The first one was a full-scale thermal model in which spacecraft components were represented by geometrically equivalent boxes powered internally using electrical resistors. The WEP was a prototype experiment while the SAO had three prototype telescopes without electronics and one thermal model telescope. The use of this inert model permitted the spacecraft to be exercised through a variety of conditions in order to verify the thermal design and to establish a test philosophy for final observatory testing. A fundamental question that had to be answered was whether or not to use solar simulation. The advantages of the solar simulation test would be (a) exposure of the observatory to its true environment, with the exception of earth infrared and albedo, and (b) operation of the spacecraft under solar array power. From the thermal viewpoint, it would have been advantageous to study such phenomena as energy entrapment at corners, reflections from appendages, solar absorptance variations in skins, and infrared interchange from the solar arrays. Tests were performed which compared solar simulation to equivalent heat inputs using skins provided with strip heaters to simulate absorbed energy. It was found that the variation of solar intensity, as high as ±20% in some areas, infrared background from the solar simulator, and spacecraft mounting fixture blockage severely compromised the results. The overall size of the observatory made each of these variables more pronounced. The decision was then made to test the observatory using heater skins.

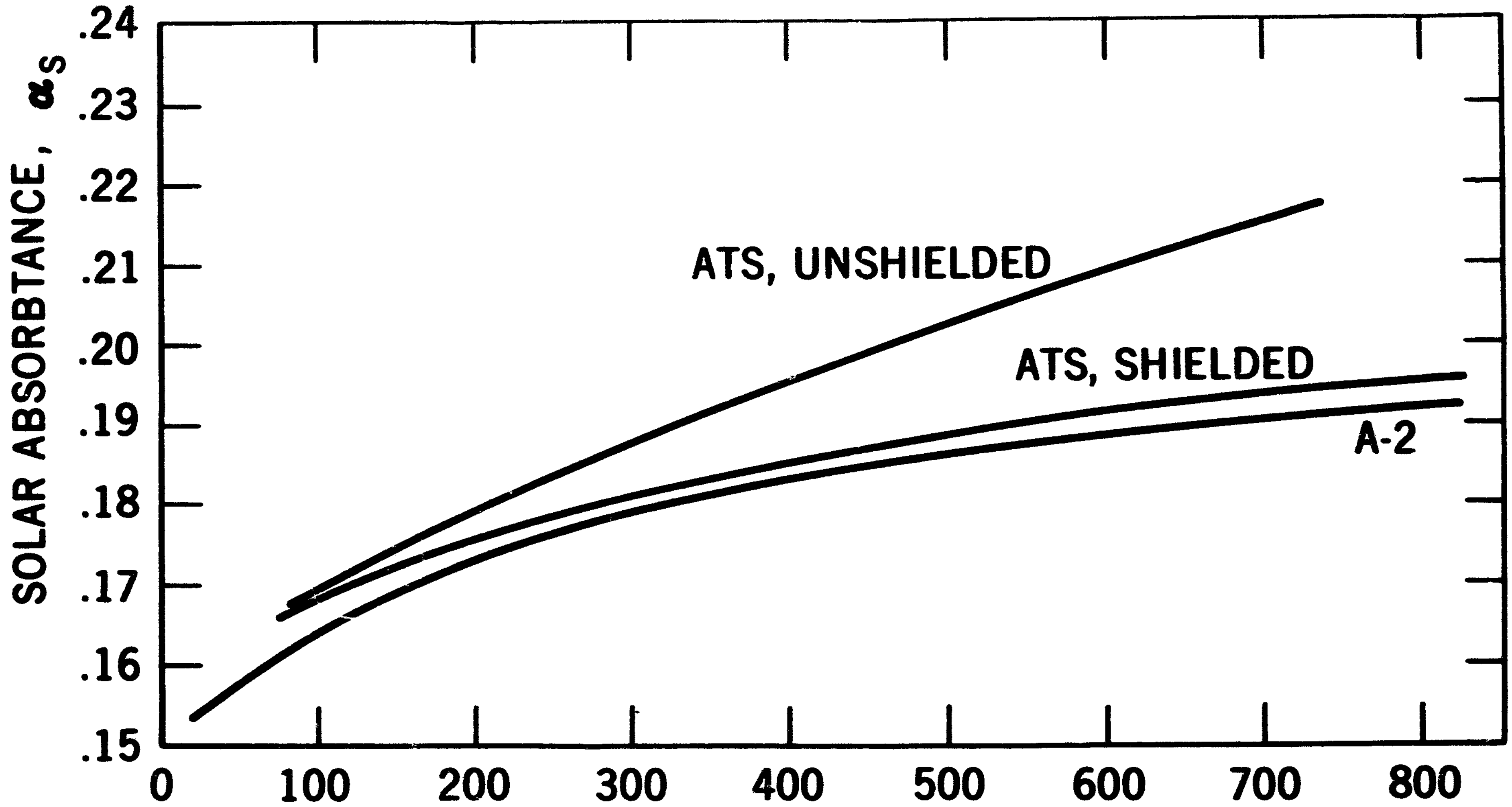

Figure 8. Alzak Degradation Comparison

In the area of the experiments, two main points were of concern: (1) to simulate the proper input aperture flux, and (2) maintain contamination control over the optics. The aperture fluxes that had to be simulated were direct earth and albedo inputs and indirect infrared flux from the sunshade. To adequately simulate these inputs, which in some cases were directional in nature, would have involved sophisticated and costly techniques. It was decided to cover the experiments with a temperature controlled panel which would apply an equivalent black body radiation to the experiments. Calculations showed that the configuration of the experiments was not sensitive to the directional quality of the inputs and therefore their testing would not be compromised. What was effected was the resultant forward and aft circumferential gradients in the structure. The test results were 10°F less than flight data, due to the lack of hardware, i.e., sunshade hinges, actuator motors, etc. and their resultant heat leaks.

To avoid particulate contamination of the optics, very careful procedures had to be followed which allowed the temperature control panel to be maintained at least 20°F cooler than the optics. This allowed any contaminants to be condensed at the panel as opposed to the optics. This technique proved quite successful. After the test, a noticeable amount of contamination was found on this panel outside the experiments while sample mirrors, imbedded in the optics were free of contaminants. A more complete description of the OAO test results may be found in Reference 3.

Prior to the flight acceptance test, the question arose as to the philosophy of the test. Two approaches were examined: (1) to exercise all subsystems power, thermal, experiments, etc. to their worst case conditions in order to prove flight readiness, or (2) restrict the test to compatible conditions where no subsystem would be asked to perform outside normal operational bounds. As an example, if the thermal subsystem would be exposed to its coldest orientation coupled with the minimum equipment heat loads, the resultant heater power would have caused a power negative condition and battery rundown. The second method of testing was adopted and thus permitted the most realistic data to be accrued.

Flight Data

The Orbiting Astronomical Observatory was successfully launched on December 7, 1968 and after a short period of initial stabilization was placed in a "sunbathing mode" with paddles normal to the earth-sun line. The electronic equipment came to thermal stability within the first 14 orbits with experiments and structure exhibiting a larger time constant. As soon as the observatory checkout phase was completed, the spacecraft was slewed to various pointing angles for scientific observations. There have been no serious thermal subsystem anomolies in almost eight months of spacecraft operation.

Electronic Equipment

Figure 9 illustrates the thermal behavior of the electronic equipment. It is interesting to note that the equipment where louvers are employed, i.e., A5, B5, C4, E1, exhibit a far less excursion than those bays which are passively controlled.

The majority of the dynamic range in Figure 9 came as a result of the spacecraft's experiencing a "flip" or a maneuver which placed bays on the dark side, in sunlight. The effects of degradation of the Alzak was superimposed on this excursion. Some equipment temperatures such as those in Bays F5 and G3, the gyros and command processor, exceeded the expected range. In the case of the gyro this excursion was found to occur at the heat sink during transient sunlight to dark conditions. However, the proportional heater within the gyro held the internal temperature constant throughout the transient. The command processor exceeded its predicted value due to variations in its duty cycle and hence its power dissipation.

Structure

The structure gradients are illustrated in Figure 12. Their magnitude at the forward and aft ends were higher than expected due to heat losses through hinge points of the sun shades. The degree of these gradients did not result in any apparent distortions to either the star trackers or experiments. Thus, their fields of view were not constrained. The structure mean temperature was within 4°F of expected values and varied over a 25°F range depending upon pointing angle and percent sun time (see Figure 10).

Experiments

The critical portions of the experiment packages, that is, the detectors in the case of the WEP package and Uvicon cameras in the SAO experiment, were within 10°F of expected levels. Figure 11 illustrates the excursions of both these instruments. It can be seen that the WEP experiment exhibits less of an excursion, being tied more closely to structure temperature, than the SAO cameras which are influenced by the changing aperture temperature. This swing in aperture temperature is mainly caused by the solar illumination of the black sun shade. As a consequence of this decoupling from the spacecraft structure, the filaments of the cameras must be kept on even during periods when SAO is not observing, in order to keep the cameras warm. The fact that camera life is directly proportional to the time these filaments are on has caused some degradation in their performance.

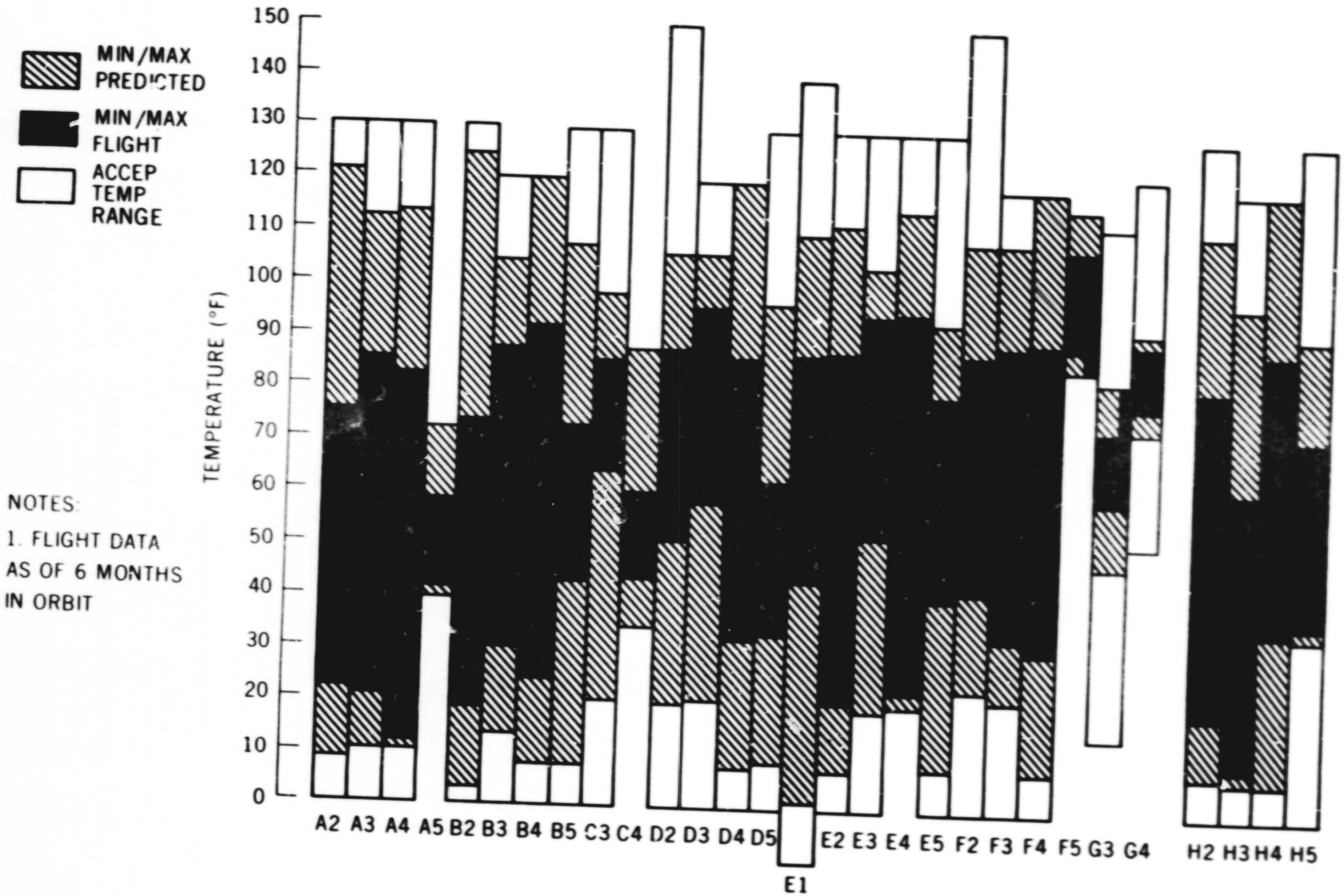

Figure 9. Equipment Temperatures

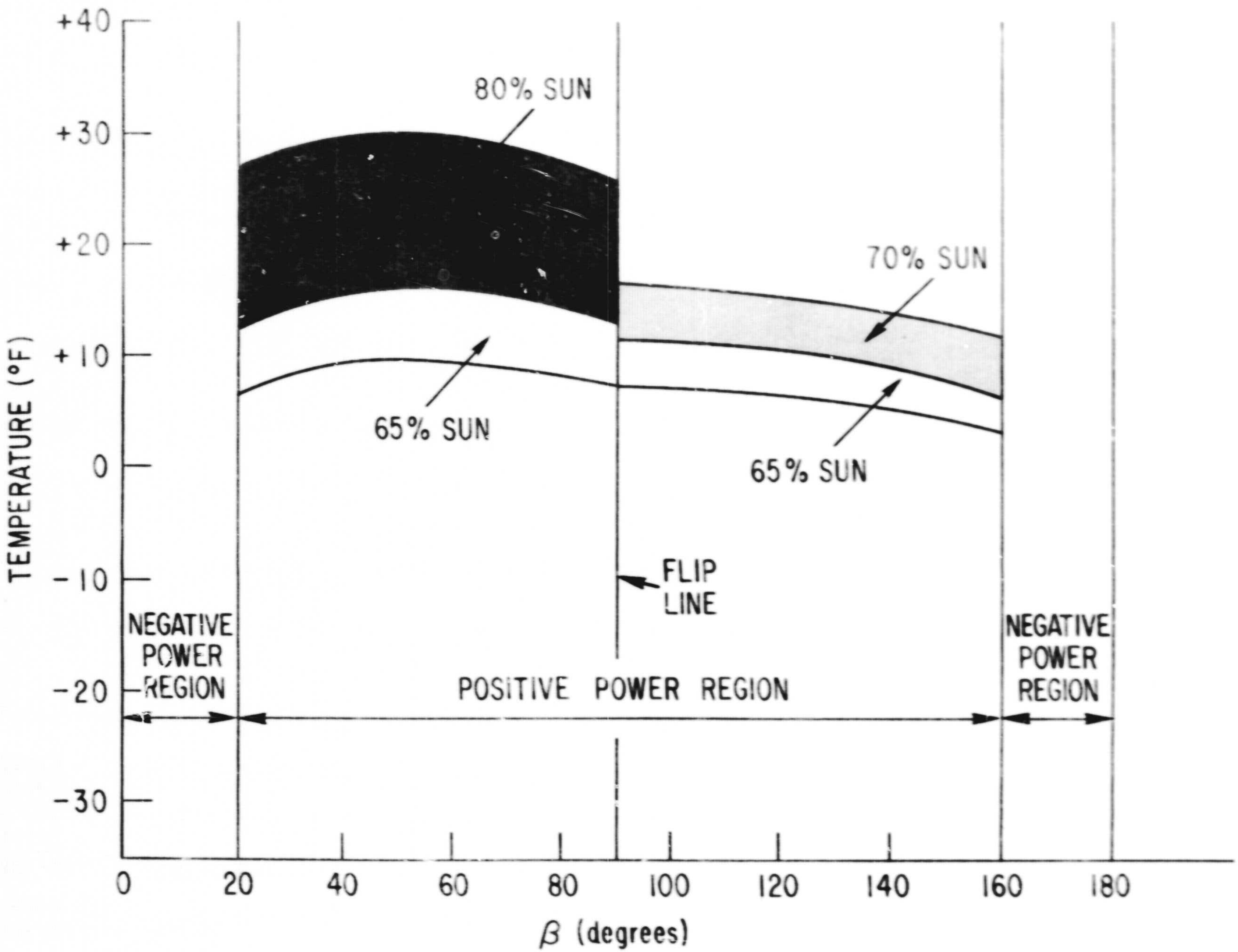

Figure 10. Average Structure Temperature OAO-A-2

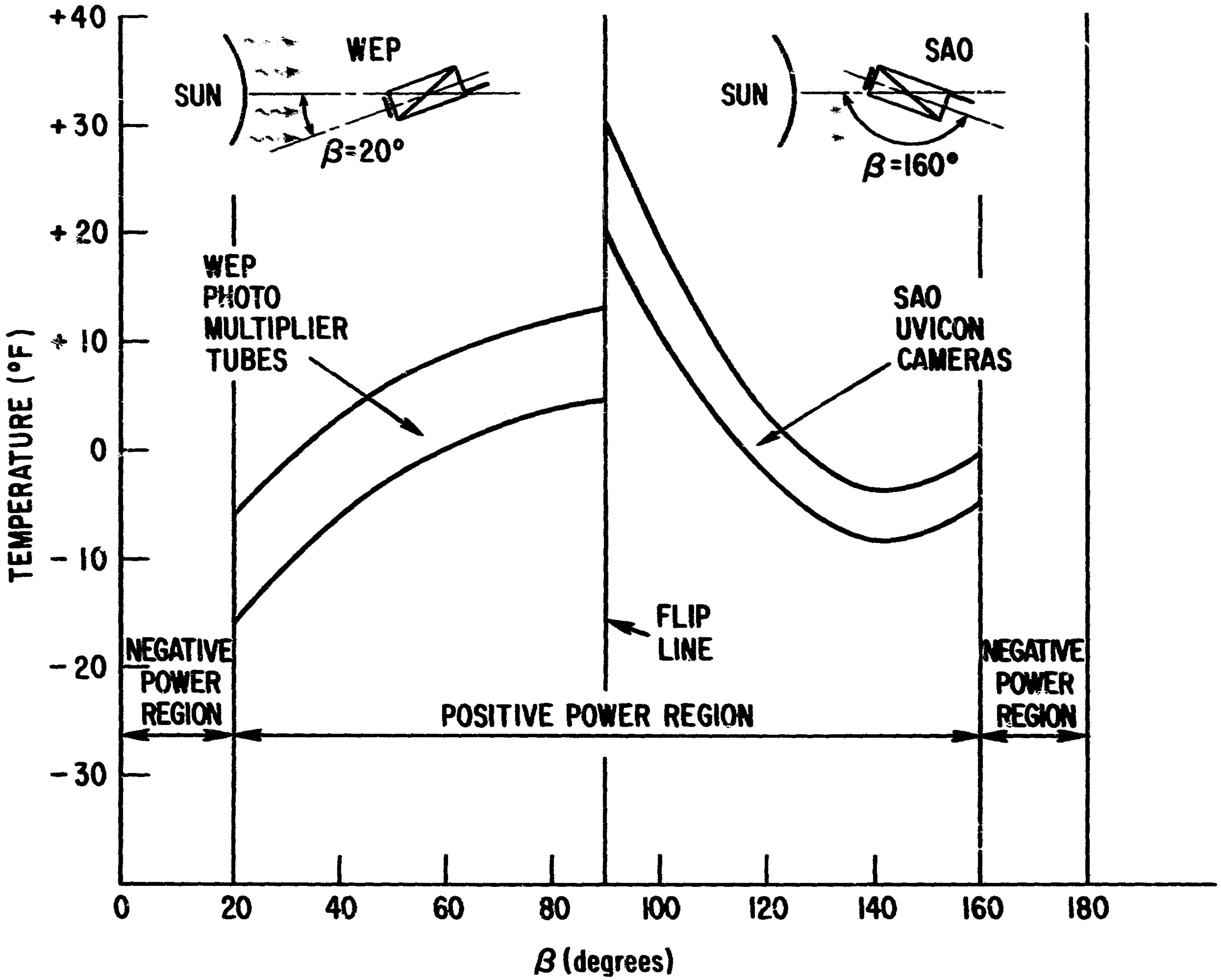

Figure 11. Experiment Temperatures OAO-A-2

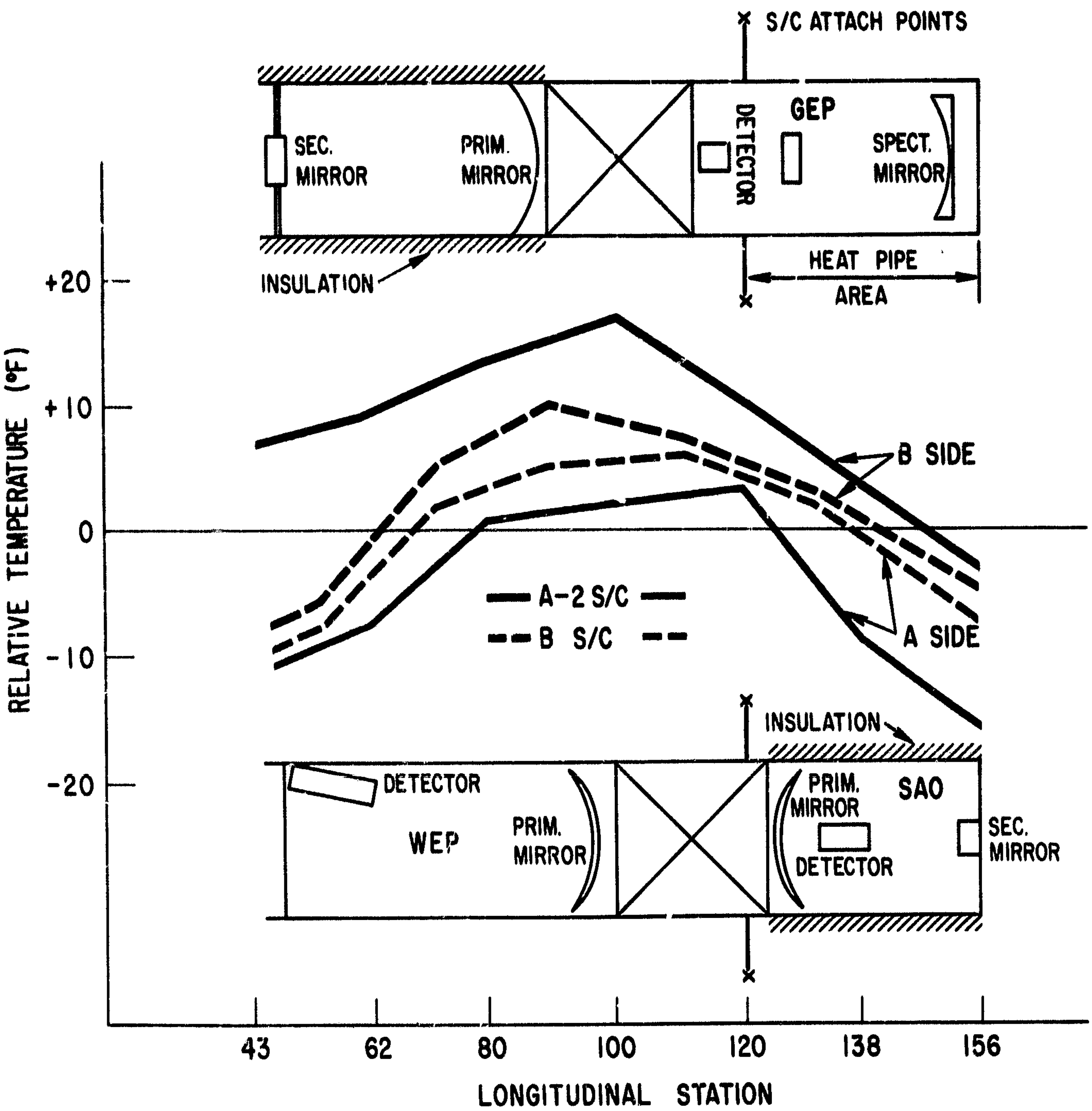

Figure 12. Temperature of Central Tube Relative to Average Structure Temperature

FUTURE OBSERVATORY DESIGNS

OAO III and IV

Subsequent OAO flights, such as OAO-III (to be launched in June of 1970), will employ three circumferential heat pipes around the structural tube supporting the Goddard Experiment Package. This experiment has much finer pointing requirements than the OAO-II experiments and would be more susceptible to distortion from thermal gradients. These pipes are of a low ΔT design and will hold circumferential gradients to a few degrees. Figure 12 illustrates the relative gain these pipes will offer the next spacecraft.

A new innovation of the heat pipe, presently under study, will be flown on OAO-IV as an experiment. It is called a Variable Conductance Heat Pipe. It is specifically designed to maintain an electronic package over an extremely narrow temperature range, possibly 1-2° F. Figure 13 illustrates the scheme of the heat pipe. An inert gas, held at evaporator temperature is the control media which adjusts the exposed conductance area to a radiation plate. As the temperature of the working fluid increases, its vapor pressure increases forcing gas back into the reservoir and exposing more area. This, in turn, adjusts the temperature at the source. It is hoped that power variation of 3:1 and external flux changes of a factor of two can be accommodated by this device.

Advanced OAO

As the requirements for finer pointing and light gathering capabilities increase, newer approaches to the thermal design must be made. Large telescopes (see Figure 14) with diffraction limited performance must be designed for long life to encompass a variety of missions. Using the technology as it evolves from the present OAO series and learning from the limitations of its design one can set forth a series of guidelines to follow. As shown in Figure 14, extensive use of heat pipes is made to (a) provide an isothermal cavity for the optics, (b) an isothermal reference structure for mounting critically aligned components, (c) control temperature sensitive instruments, and (d) isothermalize electronic equipment heat sinks. With the knowledge of life-limiting coating degradation, the design will point all heat rejection areas away from the sun. A sun baffle will be provided to minimize excursions in aperture temperature and reduce scattered light.

It is hoped that with this evolutionary concept in mind, a National Observatory, with a myriad of instruments on board can be flown to provide an even better view of our galaxy and beyond.

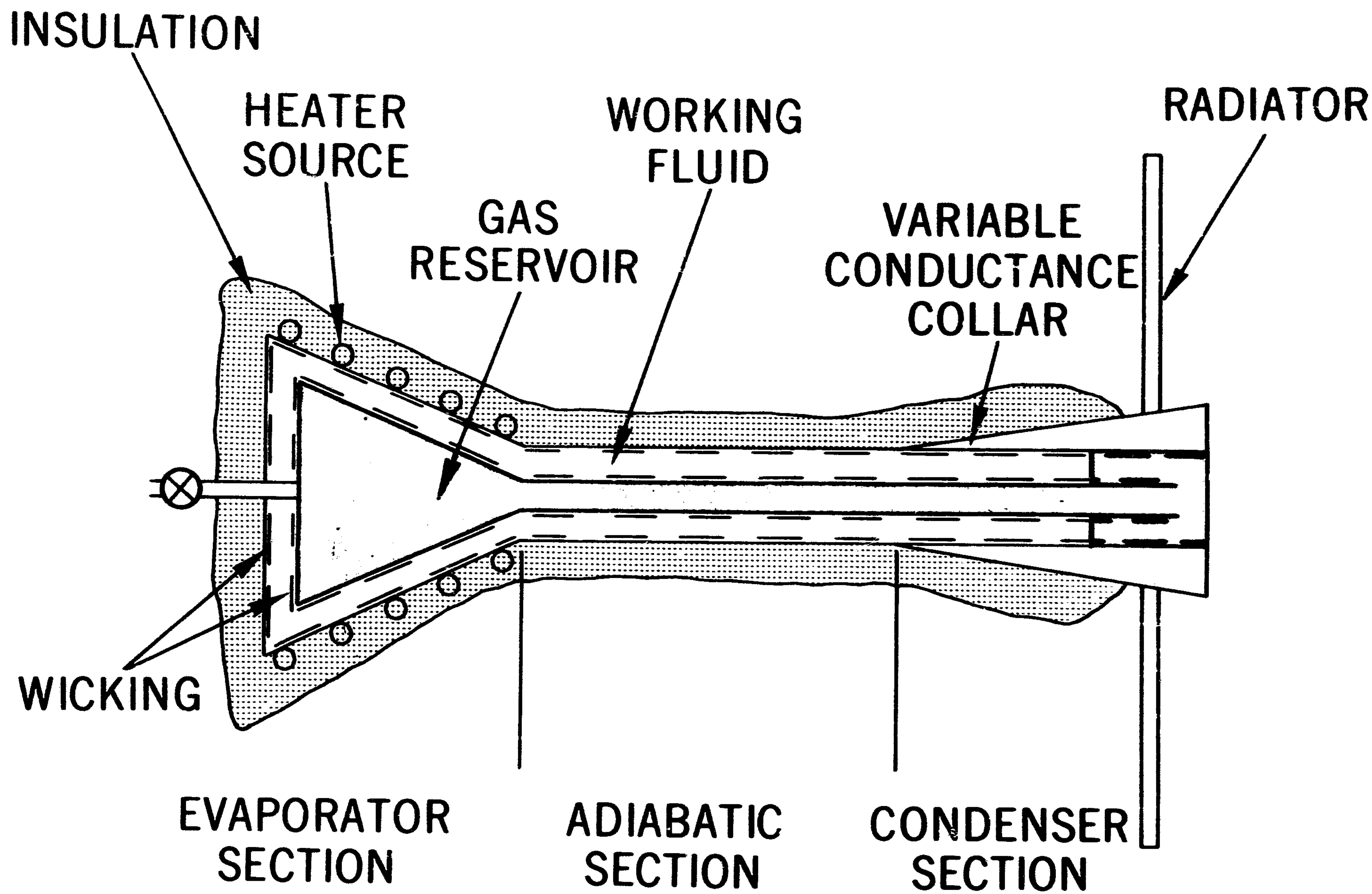

Figure 13. Schematic Diagram of Variable Conductance Heat Pipe

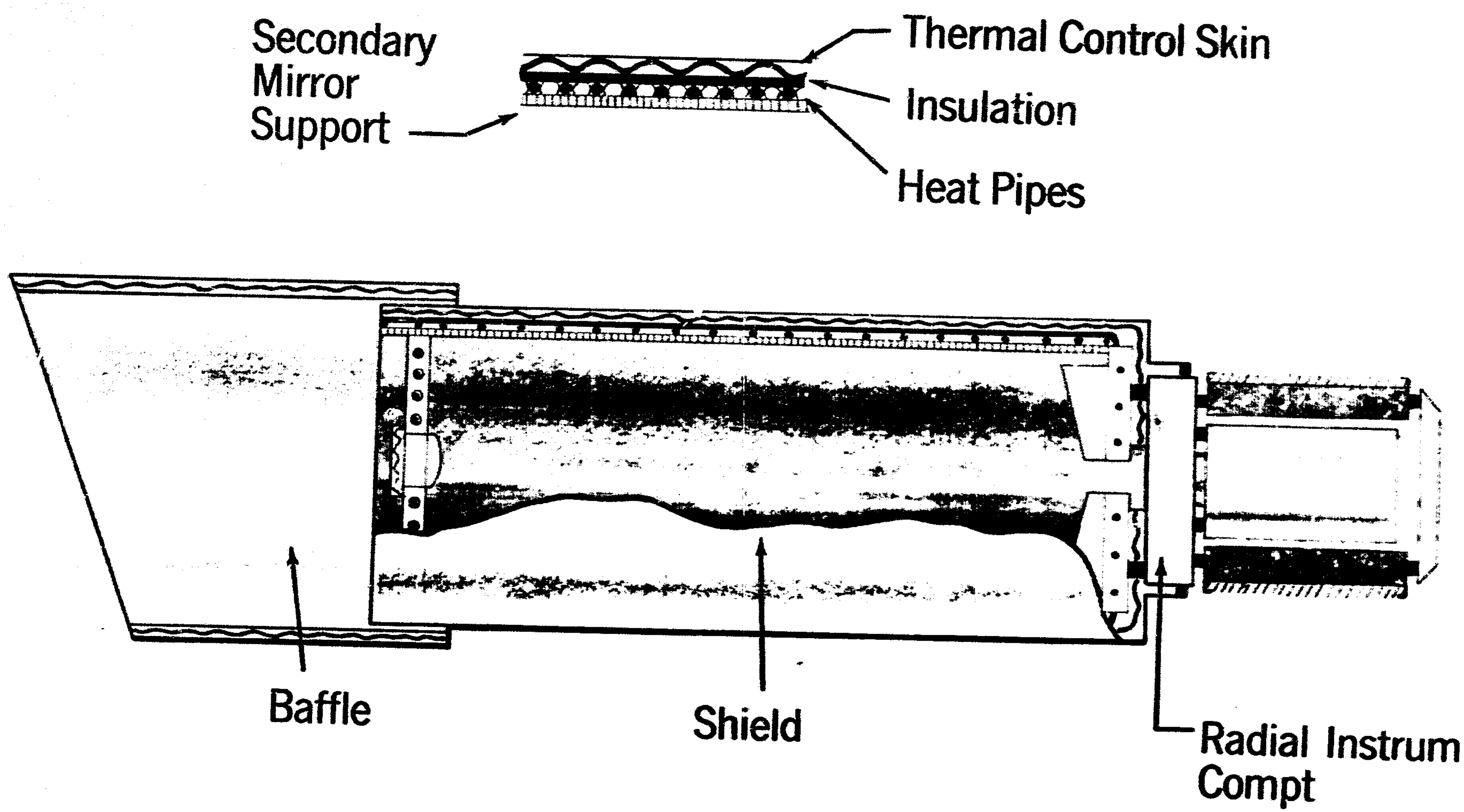

Figure 14. Observatory Thermal Control

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