Cryogenic and Thermal Design for the Space Infrared Telescope Facility (SIRTF)

J.H. Lee* and W.F. Brooks*
NASA Ames Research Center, Moffett Field, California

The preliminary cryogenic and thermal design for the Space Infrared Telescope Facility (SIRTF) is discussed. The design lifetime of the cryogenic cooling system is two years with 50% margin. The temperature of critical telescope components can be maintained to allow natural background limited astronomical observations from 2 to 100 μm. A proposed design of the aperture shade for telescope thermal protection is analyzed. A mathematical thermal model is used to study the cryogenic system sensitivity.

Nomenclature

$\dot{m}$ = helium mass flow rate
$\dot{Q}_{AP}$ = aperture heat load
$\dot{Q}_{para}$ = parasitic heat load
Q_{total} = total heat load reaching the helium tank
SM = secondary mirror
T_{FB} = forward baffle temperature
T_{IVCS} = inner vapor cooled shield temperature
T_{SM} = secondary mirror temperature

Introduction

THE Space Infrared Telescope Facility (SIRTF) is a 1-m-class cryogenically cooled infrared telescope planned for development by NASA with a planned launch date of 1995. SIRTF was formerly studied as a Shuttle sortie mission using the spacelab instrument pointing system (IPS) for series of 14-day missions.[1] The recent success of the Infrared Astronomical Satellite (IRAS) mission, which catalogued the entire sky at wavelengths from 10 to 120 μm and demonstrated the long-term storage of superfluid helium in space, has resulted in a redefinition of SIRTF to a long-duration mission.[2] The current baseline is a minimum initial lifetime of one year in orbit with extended mission capability through on-orbit servicing of the cryogenic system.

This paper discusses the details of an all superfluid helium design for a 700 km Sun synchronous polar orbit which is one of the mission options under consideration. Other options include a low inclination 28 deg orbit and a space station attached mission in a similar orbit. The free-flyer cryogenic system sensitivity and transient response which are quite different from the previous sortie studies and IRAS mission are explored.

Background

The heart of the SIRTF system is an f/24 Ritchey-Chretien telescope with a clear aperture of 0.85 m. A 1-m-long multiple instrument chamber (MIC) houses the infrared focal plane instruments and a visible fine guidance sensor (FGS) as shown in Fig. 1. The telescope also includes a stray radiation baffle system which increases the telescope overall length to 5 m. The SIRTF system performance requirements are given in Table 1. To achieve the required background limited performance, the optics and baffles must be kept extremely cold. The derived requirements, boundary temperatures and fixed heat loads of the cryogenic and thermal subsystems are also given in Table 1.

The aperture cover is a motor-operated gate-valve capable of sealing the telescope in space to prevent contamination during servicing. It is possible to make this cover function as a vacuum seal on the ground. Because of the large structural loads on such a flat plate design and the problems with cooling it to helium temperatures, a deployable cover using either solid hydrogen or helium as a coolant will be used during ground test and launch.

The spacecraft is not shown in Fig. 1 and could be either an end mounted module or a wrap-around type design which uses the telescope outer shell as part of the spacecraft support structure.[3] The telescope and spacecraft thermal systems take advantage of the Sun synchronous orbit to reduce the parasitic heat load to the cryogen.

Thermal Protection

A cryogenic space telescope presents a difficult Dewar design problem since it requires long life, but the telescope aperture represents a large break in the Dewar insulation system. The aperture shade shown in Fig. 1 is a key element in reducing aperture heat loads. It is a conical design with a three-stage passive radiator system which maintains the inner surface of the shade at 100 K. The shade is truncated with the high side facing the Sun which allows the telescope to be tilted 30 deg toward the Sun without any solar radiation striking the inner surface of the shade. The horizon depression at the orbital altitude of 700 km is 22 deg. The small lip on the low side of the shade allows the telescope to be tilted 30 deg toward the Earth without direct Earth radiation striking the aperture shade radiators or telescope barrel baffles. Since no direct or scattered solar radiation or direct Earth radiation enters the telescope aperture, the aperture load is due to the diffusely scattered radiation when the inner surface of the shade is illuminated by the Earth, and to thermally self-emitted radiation from the shade inner surface.

The aperture shade was modeled using Monte Carlo ray trace and view factor programs to calculated diffuse and specular radiation couplings. The design and properties assumed are shown in Fig. 2. Because the orientation of the telescope line of sight with respect to the Sun and Earth depends on the specific scientific observations, a nominal viewing scenario was constructed (see Fig. 3).

The thermal results of this telscope operational sequence are shown in Fig. 4. The resulting orbit average 85 mW aperture heat load and the heat load variation are both important parameters in the telescope dewar model. They impact the barrel heat exchanger design and the overall size of the cryogenic system.

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*Research Scientist. Member AIAA.

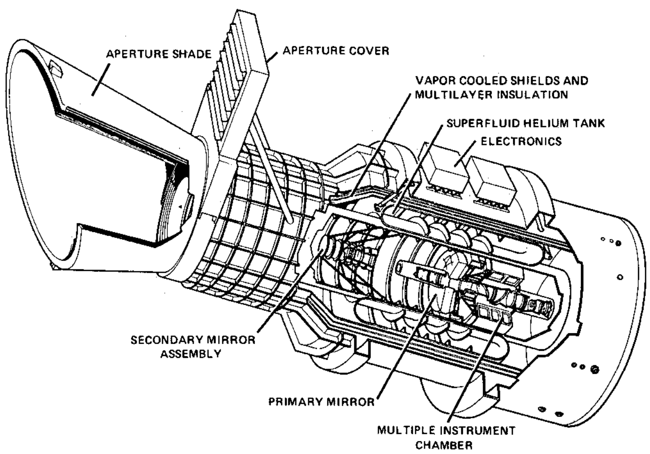

Fig. 1 Major elements of the SIRTF system.

Table 1 Telescope requirements and constraints

Spectral range	1.8-700 μm
Natural background limited	2-100 μm
Diffraction limit	5 μm (2 μm goal)
Lifetime	1 year (2 year goal)
Primary and secondary mirror	$T<7$ K
Allowable gradient @ 7 K	$\dot{T}<2$ μK/s
Aft Baffles	$T<7$ K
Allowable Gradient @ 7 K	$\dot{T}<1.5$ μK/s
Forward Baffles	T<12 K
Helium	T=1.85 K
Instrument Power @ 2 K	50 mW
Instrument power @ 7 K	100 mW
Fine guidance sensor power @ 2 K	10 mW
Secondary chopper power @2 K	35 mW

The orbital heat load and thermal analyzer program known as the Simplified Shuttle Payload Thermal Analyzer (SSPTA)[4] was also used to calculate the outer shell temperature. For the nominal orbit using the observational sequence described above, the average temperature was 210 K with orbital variations of 5 K. The shadowing of the shell by the solar panels was not modeled and the outer shell temperature is higher than the 200 K measured during the IRAS flight mission. Later analysis in this paper will show that the current SIRTF design is not very sensitive to outer shell temperature. Because of this, the model was not modified to include the solar panels. An outer shell temperature of 210 K was used as a boundary condition for the cryogenic model of the Dewar and telescope.

Cryogen Choice

Because of the stringent requirements on the optics temperature, the options for cooling the system are limited. Supercritical helium, which was used in the previous sortie design, must be used in conjunction with a Joule-Thompson expander or auxilliary superfluid helium tanks to meet the requirements for instrument cooling at 2 K. In addition, supercritical helium has little margin to meet the less than 7 K optics requirement. Because it is a single state cryogen, there is no cooling due to phase change and the cryogen is constantly warming which is a severe disadvantage for a long duration mission.

Mechanical coolers could be used but they are susceptible to microphonics owing to mechanical imbalance. The infrared detectors planned for use on SIRTF are extremely sensitive to such disturbances. In addition, mechanical coolers used to cool typical SIRTF heat loads at 4 K require 0.5 to 1.5 kW which would double the solar panel area, thus increasing the demands on the spacecraft pointing and electronic subsystems. Finally, no mechanical cooler has yet demonstrated 2-5 years of continuous operation. It has been projected that the technology for a spacecraft-borne mechanical cooler with a specific power requirement of 10 kW/W at 4 K will be mature in the early 1990s. The targeted lifetime will be five years with a 90% service life reliability.[5]

A hybrid cooling system which utilizes superfluid helium and a higher heat capacity cryogen is a valid option, especially in the lower inclination orbits where the aperture heat load could be as much as four times higher.[6] For the polar orbit the added complexity of a dual cryogen is not necessary.

Telescope Dewar

An all-superfluid-helium system was modeled. The telescope Dewar utilized the enthalpy of the helium boiloff gas to provide additional cooling for the instruments at 7 K as well as the aperture heat load. The system consists of a 4000-liter aluminum toroidal tank which serves as the main support for the telescope. The ends of the toroidal tank are attached to the outer shell by twelve support struts. These Passive Orbital Disconnect Struts (PODS)[7] have two different thermal paths. When the gravity load is released, the thermal conductance of the system can decrease by as much as a factor of eight. The PODS support three shields which are cooled by the helium boiloff gas. The shields are separated by multilayer insulation (MLI) consisting of double aluminized Mylar (DAM) with silk net spacers.

The barrel baffle is separated into forward and aft sections. The forward baffle terminates at the secondary mirror support and is separated from the aft baffle by a fiberglass thermal isolator ring. The aft baffle is also the optical bench for the primary and secondary mirrors. The entire telescope assembly is supported on a helium tank bulkhead ring which also forms the primary thermal path to the helium tank.

The multiple instrument chamber mounts onto the opposite side of the same bulkhead ring. The rear cover of the main shell and vapor cooled shields (VCS) are removable to allow installation and servicing of the instruments. The VCS heat exchangers are located on the cylindrical sections of the VCS to avoid having to make and break connections during MIC servicing.

The cryogen tank uses a sintered porous plug which utilizes the thermomechanical "fountain pressure" in superfluid helium to contain the fluid but allows the vapor to escape.[8] Both internal (cold) and external control valves are required on the fill and vent lines to control the fluid during ground and space operations.

The Model

A lumped node transient model was developed which allowed system sensitivities to be explored. A number of steady state and transient runs were performed to predict lifetime and to determine the performance of the optical system and instruments.

The Ames Research Center Cryogenic/Thermal Analyzer (ACAP) was used to exercise the lumped parameter thermal model. The ACAP used the relaxation (residuals) technique for steady state solution, and forward difference formula (Euler's method) for transient solution. Euler's method is accurate to the first order which depends on the size of the time step chosen. This method is also conditionally stable; however, ACAP calculates the size of the time step required to meet the stability criterion.

The model used in this analysis is shown in Fig. 5, and Table 1 gives the heat loads used in the model.

The MLI was modeled using equations developed from calorimeter tests and degraded to represent actual layup on a complicated shape and penetration losses due to wires, helium lines and the tank supports.[9]

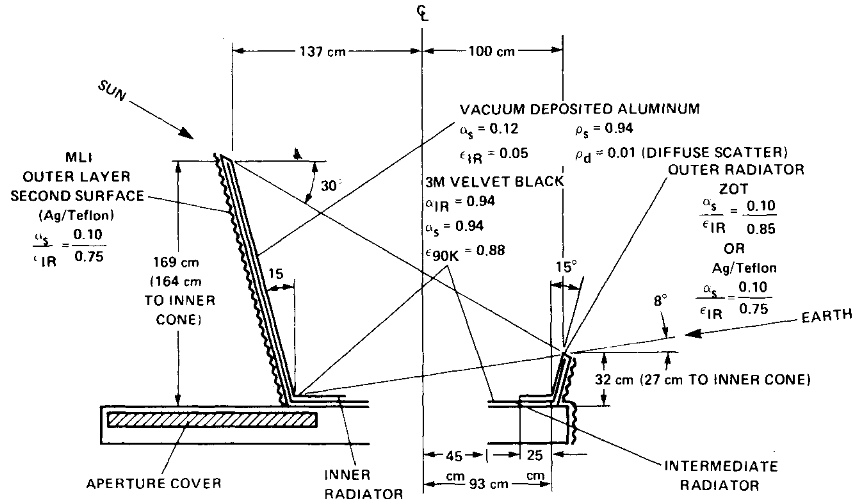

Fig. 2 Aperture shade design of polar orbit.

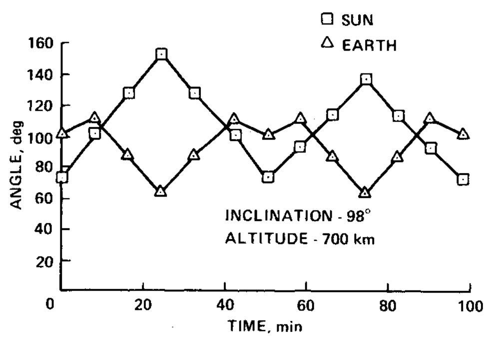

Fig. 3 Sun and Earth angle to SIRTF line of sight.

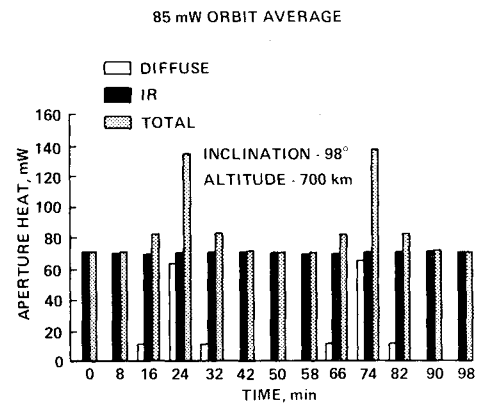

Fig. 4 Orbitral aperture heat load profile.

The focal plane instruments and housekeeping wires were heat sunk at each of the vapor cooled shields. Manganin (400) and coaxial (800) wires were assumed to start at the outer shell and terminate at the cryogen tank. The vent line was used to vapor cool the shields. Heat transfer from the shield to the gas was modeled using either laminar or fully developed turbulent flow equations as determined by the Reynolds number of the helium flow. The transition region was assumed to be laminar which is conservative since it results in lower heat exchange film coefficients. The helium fill line was connected to the inner vapor cooled shield.

Conductances of the bolted joints used for mounting the telescope and instruments were characteristic of those measured during the IRAS program.[10]

The model assumed negligible pressure drop in each heat exchanger section of the vent line. No additional pressure drop due to flow meters was modeled since low impedance ultrasonic techniques are available.[11] The tubing at each heat exchanger section was assumed to be well attached to the shield. No gas conduction effects were modeled for the MLI since pressures of 10^{-7} Torr are easily achievable in orbit. The superfluid helium tank and outer shell were assumed to be isothermal, and treated as boundary nodes fixed at 1.85 and 210 K, respectively.

Vapor Cooling

A key design issue involves the use of vapor cooling. The most straight-forward design approach would couple the aperture and instrument heat loads directly to the tank. However, this approach results in the largest boiloff rate ana the shortest lifetime for a fixed tank size. In this type of design, the enthalpy of the helium gas would be used to cool the shields only.

Alternately, some of the telescope heat loads can be intercepted using the enthalpy of the boiloff gas. The primary sources of low temperature heat which are candidates for vapor cooling are the 100 mW instrument heat load at approximately 7 K, 35 mW secondary mirror actuator dissipation at 7 K, and the 85 mW aperture heat load at 12 K.

The implementation of vapor cooling in the SIRTF design is particularly difficult because of the variability of these heat loads. The IRAS focal plane instrument was turned on and left on at a constant electrical power dissipation. The nature of the all sky survey IRAS performed also resulted in a relatively constant aperture heat load. SIRTF will use the secondary mirror actuator over a wide variety of dissipations from 0 to 50 mW, and the instruments will be cycled between standby and observation modes so that the total instrument heat dissipation may vary from 30 to 100 mW. Because SIRTF will be performing long integrations on single targets, the aperture heat loads may vary from 70 to 135 mW during a single observation as shown in Fig 4.

Optics Cooling

The result of these tank heat load variations is a continual variation of the helium flow. In the model, therefore, the mirrors and aft barrel baffle were not vapor cooled. The optics assembly was conductively coupled directly to the helium tank. The secondary mirror actuator power of 35 mW is, therefore, dissipated at the 2 K helium tank. Vapor cooling of the secondary mirror to intercept the heat would also significantly complicate the telescope construction since the helium vent line tube would have to penetrate the baffles and attach to the secondary mirror support assembly.

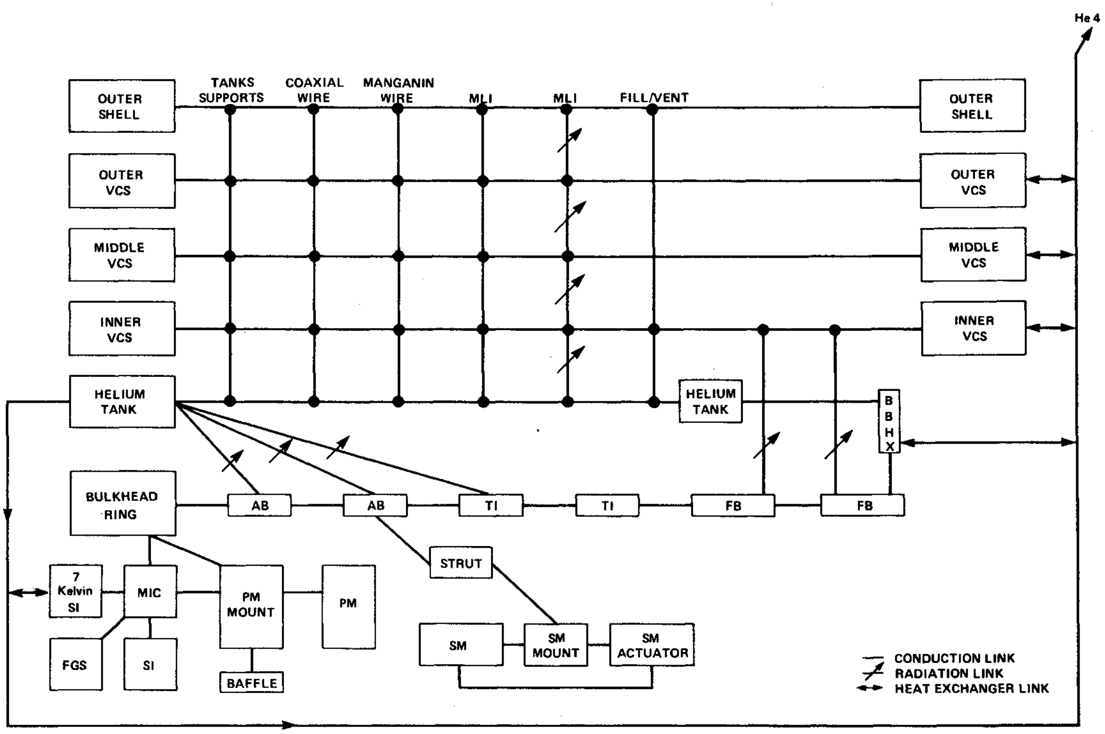

Fig. 5 Telescope and Dewar cryogenic model.

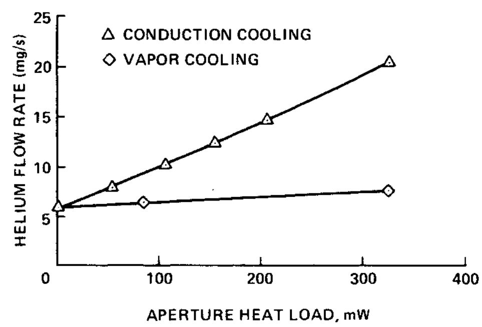

Fig. 6 Effect of aperture heat load on lifetime—barrel baffle cooling design comparison.

Instrument Vapor Cooling

Some of the instruments baselined for SIRTF have mechanisms and detectors which do not require the 2 K superfluid helium temperatures. Because additional cooling is available in the boiloff gas, an instrument heat station at a nominal 7 K was implemented in the model.

The cooling capacity and temperature of this sink are dependent on the variations in the helium boiloff rate. To utilize the vapor cooling, the instruments are thermally coupled to a vent line heat exchanger. These higher temperature components of each instrument must be extremely well isolated from the tank and the 2 K section of the instruments to prevent the heat from reaching the helium tank. In the model, thermal isolation of 0.6 mW/K was used between the 7 K and 2 K instrument nodes. This resulted in 2% of the 7 K instrument power feeding back into the helium tank. Since the instrument heat paths from the 7 K to 2 K heat stations are parallel, a thermal conductance of only 0.2 mW/K would be allowed for each of the three focal plane instruments. This level of thermal isolation may be difficult to achieve while satisfying the instrument requirements for optical alignment and structural integrity.

Barrel Baffle Cooling

Since the forward baffle receives all of the aperture heat load and can be allowed to reach temperatures in the 12 K range, vapor cooling can be used effectively. However, because the aft baffle must remain at the lower optics temperature, some isolation must be introduced between the two elements.

The baseline design for the SIRTF system utilizes a fiberglass section in the barrel baffle to ensure that the secondary and primary mirrors are isolated from the temperature fluctuations of the forebaffle caused by the aperture load. Two cases were run using the model: all-vapor and all-conduction cooling of the forward baffle.

The all-conduction cooling case was modeled by coupling all the aperture load directly into the tank. This could be required if stray light analysis indicates that the forward baffle must operate at temperatures close to the mirrors (7 K). The system lifetime is decreased because the aperture heat is intercepted using only the latent heat of evaporation of the helium. The upper curve in Fig. 6 illustrates the behavior of the system under a large range of aperture heat loads when such a design is used. A background power of 95 mW was also applied to the tank due to the power dissipated at 2 K by the science instruments, FGS and secondary mirror actuator.

Using the all conductive cooling of the barrel baffle, the flowrate at the nominal 85 mW orbit average aperture load is equivalent to a lifetime of two years. This meets the one-year requirement and satisfies the design goal of two years, but with no margin.

For the baseline design, the aperture load is intercepted using all vapor cooling. The lower curve in Fig. 6 demonstrates the sensitivity of cryogen consumption to a range of aperture heat loads. The gradual increase in flow indicates that although the aperture heat is being intercepted, primarily by vapor cooling, some of the heat load reaches the tank through the barrel baffle. In addition, heat added to the helium gas results in a slightly higher inner vapor cooled shield temperature which increases the conduction and radiation parasitics from the support system and the MLI. As in the previous case, 95 mW was applied directly to the tank.

Specifically, the flow rate for the vapor cooling case increases about 1 mg/s which is the equivalent of 25 mW increase in tank load for a 240 mW increase in aperture load from 85 to 325 mW. Therefore, only about 10% of the aperture heat is sneaking back to the helium tank. This is in contrast to the conduction case in Fig 6 which shows a substantial increase in flow as aperture load is increased.

Table 2 illustrates the detailed difference in performance between vapor and conduction cooling of the barrel baffle. For the vapor cooling case, the forebaffle temperature is higher but still below the 12 K requirement. The helium tank parasitic heat load is a higher fraction of the total tank heat load but the helium flow rate is 30% lower than the direct conduction case. Almost all of the aperture load has been intercepted by the helium vapor with only 3% going directly to the tank. A helium lifetime of two years with 50% margin can be achieved using the vapor cooling method.

As the system design progresses, the temperature requirements will be better defined. It may be necessary to introduce conduction cooling to lower the forward baffle temperature, but the model indicates that the current optics temperature requirements can be met using all-vapor cooling.

Tank Support Sensitivity

To determine the importance of the tank support system to the design, the model was run with both a tensioned fiberglass support strap system similar to the IRAS design and an orbital disconnect system which is now under development (PODS). The in-flight area to length ratio for the tensioned straps is seven times larger than for the PODS. The support components in both cases were sized for stiffness and buckling considerations.[12] Table 3 shows a comparison of the results from the model for the two systems. The model assumed a 210 K outer shell and vapor cooling of the forward baffle. The tensioned fiberglass support straps double the flow rate and result in a Dewar in which over half of the total tank heat leak is due to structural and MLI parasitics. The resulting flow rate with the tensioned straps allows SIRTF to reach the design requirement of one year lifetime with 40% margin.

Thermal Isolator Sensitivity

All the analysis has been based on a model which utilizes a fiberglass isolator section to separate the forward baffle from the aft baffle. Table 4 compares the telescope performance with and without such an isolator. The principal difference is the temperature of the secondary mirror and this is directly related to the percentage of the aperture heat load that flows through the aft baffle to the helium tank instead of being vapor cooled. This difference is dramatic with only 7% with the isolator, as opposed to 46% with a continuous aluminum baffle. The secondary mirror temperature at 9 K is above the allowable temperature for the telescope optics and will be much more susceptible to temperature fluctuations caused by the varying aperture load. This clearly illustrates the importance of the separated baffles for the higher aperture heat load missions such as SIRTF. IRAS did not use such an approach but the aperture heat load on IRAS were a factor of eight times smaller than for the SIRTF polar orbit mission; IRAS also had no secondary mirror actuator, but a calibrator dissipated less than 1 mW intermittently at the IRAS secondary mirror.

Outer Shell Sensitivity

Helium lifetime as a function of outer shell temperature was modeled for both the PODS and tensioned straps and is shown in Fig. 7. Both designs are less sensitive than the IRAS Dewar because of the increased flowrate which intercepts a much higher fraction of the system parasitic heat load. The use of the PODS support system decreases this sensitivity at the lower outer shell temperatures although not dramatically.

Transient Response

For the tansient analysis, the temperature variations caused by the aperture and the instrument heat loads were examined. The results were derived from the same model as shown in Fig. 5.

Table 2 Comparison of barrel baffle cooling designs

Fore baffle cooling $\dot{Q}_{AP}$ = 85 mW	T_{FB}, K	T_{IVCS}, K	Q_{AP} to tank	Q_{para}/Q_{total}	$\dot{m}$, mg/s
Vapor	11	19	3%	.20	6.4
Conduction	8	10	9 5 %	.03	9.4

Table 3 Comparison of tank support designs

Tank support	T_{IVCS}, K	T_{FB}, K	LIFE (4000 liters), years	$\dot{Q}_{para}/\dot{Q}_{total}$	$\dot{m}$, mg/s
Orbit disconnect	19	11	2.9	.20	6.4
Tensioned strap	27	10	1.4	.64	13.7

Table 4 Comparison of barrel baffle construction concepts

Barrel baffle design	T FB, K	T SM, K	T IVCS, K	$\dot{Q}_{AP}$ into tank via BB	$\dot{m}$, mg/s
Fiber glass isolator	11	7	19	7%	6.4
All aluminum baffle	8	9	14	46%	7.4

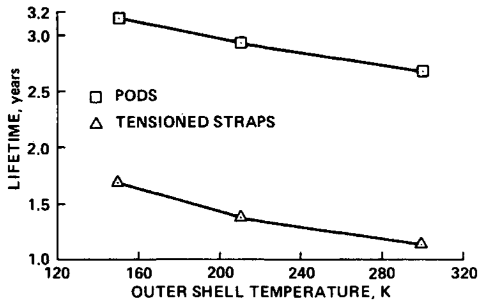

Fig. 7 Effect of outer shell temperature on lifetime—tank support design comparison.

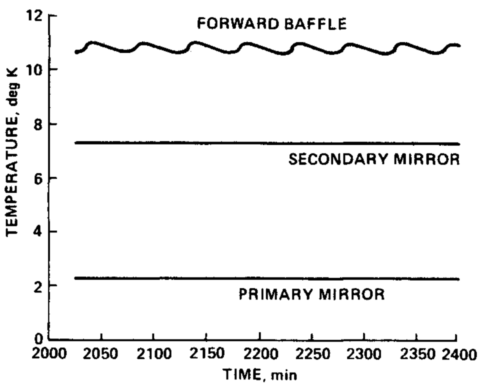

Fig. 8 Optics response to aperture heat load.

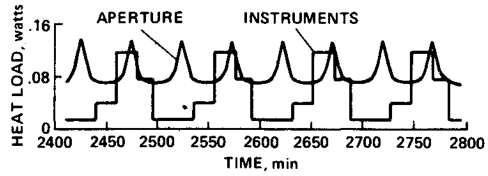

Fig. 9 Instrument and aperture heat load.

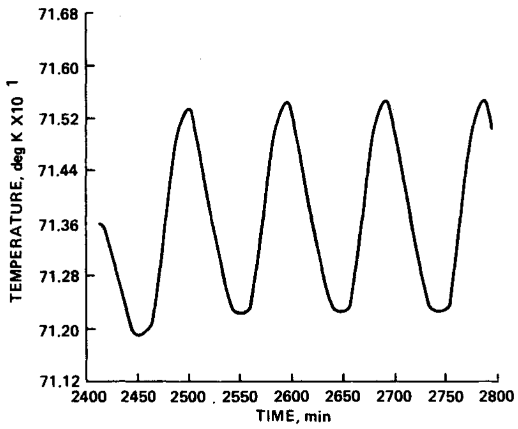

Fig. 10 Secondary mirror response to instrument heat load.

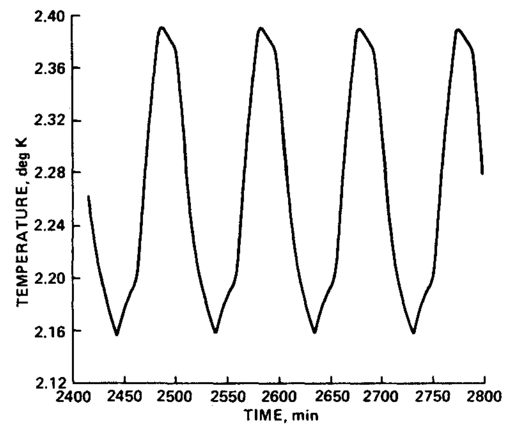

Fig. 11 Primary mirror response to instrument heat load.

Figure 8 illustrates the response over several orbits of the secondary mirror, primary mirror and forward baffle to the nominal aperture heat load given in Fig. 4. Although the resolution of the plot is not fine enough, the model indicated that temporal variations in temperature in the principal optical components are well under the requirement. The primary mirror is changing at the rate of 30 nK/s; the secondary mirror is changing at a rate of 1 μK/s. The forward barrel baffle temperature fluctuates but is within the 12 K requirement.

A potential transient situation involves measurements which require the secondary mirror actuator to be turned off. When the 35 mW steady state power dissipation is removed, the secondary mirror undergoes a large temperature change with the mirror temperature gradients at the 1 mK/s level for the first 20 minutes, the new equilibrium temperature is 3.5 K. The initial gradients are a problem if the instrument is trying to observe at the lowest background. Several solutions are possible including a compensating heater system which maintains constant dissipation at the mirror or utilizing this relaxation time to perform measurements that are not at the limiting sensitivity of the telescope.

Transient runs were made assuming the aperture and instrument power dissipation profiles shown in Fig. 9. This profile is based on the strawman complement of instruments and was used in previous studies.[13]

Figures 10 and 11 show the optics temperature fluctuations during several orbits. The primary mirror fluctuates at the 100 μK/s level and the secondary at the 10 μK/s level. The primary and secondary mirror temperature fluctuation is large enough to affect the required natural background limits and to warrant consideration of some form of active or passive compensation. Direct strapping of the instrument and optics to the helium tank instead of routing through the same bulkhead ring would help damp out temperature variations. Another solution would be active feedback control of the optics mounting plate using high accuracy thermometers and heaters.

Conclusion

Utilizing the lift capability of the Space Shuttle, it is possible to design a superfluid helium Dewar and thermal control system to maintain a 1 m telescope on orbit for two years with 50% margin. The design assumes a Sun synchronous polar orbit at 700 km. The Dewar utilizes an orbital disconnect system for the tank supports and vapor cooling of the barrel baffle. Certain operations, however, such as an abrupt change in focal plane instrument power dissipation or powering off the secondary mirror chopper, can cause temporal variations in the primary and secondary mirror temperatures. For the worst cases, these variations prohibit observations at the limiting sensitivities of the instrument for periods of up to 20 minutes; however, these conditions are expected in frequently. The transient analysis of the design indicates that the superfluid helium tank with no active feedback meets the temperature requirements for the nominal orbital aperture heat load and quiescent instrument and chopper conditions.

Acknowledgments

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