Gravity Probe B Cryogenic Payload

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Abstract

This paper gives a detailed account of the Gravity Probe B cryogenic payload comprised of a unique Dewar and Probe. The design, fabrication, assembly, ground and on-orbit performance will be discussed, culminating in a 17 month 9 day on-orbit helium lifetime.

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I. Introduction

For its measurement of two gyroscope precession effects of Einstein's theory of gravity, general relativity, the NASA Gravity Probe B mission required a Dewar and cryogenic Probe operating at 1.8 K with on-orbit lifetime of 16 months. This paper covers the design, construction, and flight operations of the hardware, the features that distinguish this from all prior flight Dewars, and the ground-based program to develop it. Its core was a Science Instrument Assembly (SIA), comprising four electrically suspended gyroscopes and star-tracking telescope in a Quartz Block Structure (QBS) 0.92 m long. Essential were the constraints on cleanliness, stability, ultra-high vacuum, ultra-low magnetic field, etc. detailed in Section II. The helium hold-time on orbit was 17 months 9 days. Uniquely, the boil-off gas from the Dewar was used as thrust authority for the spacecraft Attitude/Translational Control (ATC) system.

Gravity Probe B rested on two technologies, space and cryogenics. Space brought an enormous reduction in gyro drift through not having to suspend the gyroscopes against gravity, enhanced by making the satellite 'drag-free'. It also neatly separated the two relativity terms in polar orbit, eliminated atmospheric 'seeing' in the guide star measurement, and increased the geodetic effect by 12.4 over a ground-based test at the Equator. Cryogenics, no less vital, deserves more extended discussion. Central was a new kind of gyroscope readout based on superconductivity applicable to the ideally round, uniform gyro rotor required in the experiment.

A spinning superconductor develops a tiny magnetic moment, the London moment, aligned with its instantaneous spin axis. The gyroscopes were 38 mm diameter, niobium-coated fused quartz spheres spinning at 60-80 Hz. Readout was via a 4-turn circuit on each gyro housing tied to a Superconducting QUantum Interference Device (SQUID) magnetometer capable of resolving 1 milliarcsecond (4.8×10^{-9} rad) change in spin direction in ~ 10 hours. Two critical magnetic constraints, met by a combination of shielding technique (Section II), were low trapped flux in the gyro rotors and 240 dB attenuation of varying external fields.

The vehicle rolled with 77.5 s period about the line to IM Pegasi. The conjunction of cryogenics, space, and roll gave the instrument extraordinary stability. Operation at 2 K eliminated thermal distortion; zero-g eliminated sag; roll averaged certain gyro torques, symmetrized the telescope output, and optimized $1/f$ noise in the SQUID readout.

The payload was the joint product of two institutions, Stanford University and Lockheed Martin, with review and technical contributions by NASA Marshall Center. The process was intensely interactive, Stanford building the SIA and Lockheed the Dewar and Probe, with final assembly and testing on campus at Stanford utilizing two unique facilities, a 16 ft high horizontal flow Class 10 clean room for SIA/Probe assembly and a dedicated Class 10,000 high bay laboratory for Dewar/Probe operations, with numerous items of specialized Ground Support Equipment (GSE), not least a giant helium airlock for inserting the warm Probe into the cold Dewar. Success hinged on close day-to-day collaboration at all levels with an orderly management/systems engineering process to ensure requirements were met. Central was the application of incremental prototyping through successive development of three Probes: A, B, and C.

The following sections cover design and requirements, Dewar/Probe development, the thermal model, and ground-based and on-orbit operational performance. We conclude with a comparison of the Gravity Probe B Dewar with other flight cryostats.

II. Cryogenic Payload Design and Requirements

Overview.

Paper I in this volume, J.P. Turneaure, et al. [Title], offers a comprehensive account of the mission and its results. Papers L, M, and N cover the Science Instrument Assembly and the engineering requirements on it. Here we describe the cryogenic payload, emphasizing design requirements of three distinct kinds:

1) <u>Science</u>: the specific operating temperature, cryogenic lifetime, telescope aperture, gyro configuration, acceleration levels, satellite roll rate, pressure, magnetic field levels, etc. required to allow the instrument to reach its on-orbit performance goal;
2) <u>Assembly</u>: crucial as against all earlier flight Dewars was *isolation*; the SIA had to be enclosed in a separate sealed probe, which in turn had to be capable of repeated insertion and removal from the cold Dewar during ground-based testing;
3) <u>Launch</u>: a payload/spacecraft design of mass, size, mechanical robustness, etc. capable of accommodation in the proposed Delta II launch vehicle.

Looking deeper, the science requirements were of two kinds: *ultimate* such as gyro readout performance, acceleration levels, cryogenic lifetime, and so on defining the experiment's measurement accuracy; and *setup* such as guide star acquisition, flux-flushing, and on-orbit spin up of the gyroscopes required to make the mission happen.

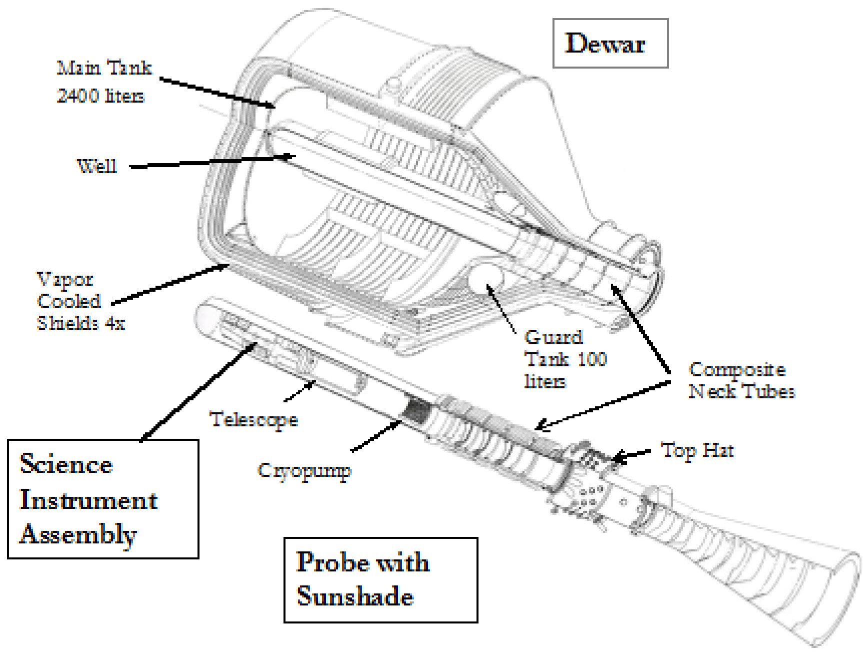


FIGURE 1. Payload components shown include the SIA (built by Stanford University), the cryogenic Probe with sunshade, and the Dewar (all built by Lockheed Martin).

Figure 1 shows sectioned views of the Dewar/Probe/SIA payload. Dimensions were: *Dewar* – length 3.0 m (9.9 ft), diameter 2.2 m (7.2 ft), dry mass 810 kg, superfluid He capacity (95% full) 2139 ℓ; *Probe* – overall length including sunshade 5.7 m (18 ft), length to end of 'top hat' containing pumping lines and feedthroughs 2.8 m (9.2 ft), outer diameter 0.25 m (10 in); *SIA* – length 0.92 m (3 ft), principal diameter 0.17 m (6.7 in). Three features of the Dewar explained in Section III were: 1) Passive Orbital Disconnect Struts (PODS) to combine rigid support of the He tank during launch with low heat leak on orbit; 2) four, rather than the customary three, vapor-cooled shields in the primary vacuum space for a 6% gain in hold-time; 3) a 100 ℓ toroidal guard tank filled with normal He at 4.2 K during certain ground operations, eliminating superfluid He transfer to the main tank during the critical period at the launch pad.

Intersecting Design Issues

Critical to the integrated Dewar/Probe/SIA design were: 1) cryogenic lifetime; 2) fixed pointing; 3) spacecraft roll; 4) gyro spin-up; 5) ultra-low magnetic field technology; 6) ultra-high vacuum operation; 7) rotor charge control. What follows is an overview of issues and requirements, preparatory to the more detailed accounts in Sections III, IV, & V.

Cryogenic Lifetime

Science required the Gravity Probe B spacecraft to have fixed pointing in inertial space, truly a formidable task with a solar heat load ~ 10 kW on the Dewar and an allowed input into the He of 150 mW. Where the Spitzer spacecraft could cool its shell to 50 K by pointing away from the Sun, ours could not. The answer had two parts, well-known but taking great rigor of design: 1) covering the spacecraft with second-surface mirrors to reflect sunlight but radiate in the infrared, thereby lowering the skin temperature; 2) using the cold He boiloff gas to intercept incoming heat. The latent heat $\mathcal{L}$ of He at 2 K is 21 J/g; the specific heat of the gas 5.2 J/g/K. To raise one gram of gas from 2 K to 273 K takes 67 $\mathcal{L}$, a huge gain in available refrigeration. The method is to circulate gas through one or more vapor-cooled shields in the vacuum space between the main He tank and the outer shell. Table 1 details an early investigation for one, two, and three optimally located shields in a specific model, G being the gain in hold-time over a Dewar with no shields. The same model, applied to the scaling of lifetime τ with skin temperature T_s, made $\tau \propto T_s^{-1.33}$, as compared with the T^{-4} dependence for radiative transfer with no vapor cooling.

Table 1: Gain in Dewar hold-time through vapor-cooled shields

# of Shields	Gain Factor	Temperatures in K		
n	G	T_1	T_2	T_3
One	11.1	62.5		
Two	19.9	41	128	
Three	25.5	25.5	87.5	185

The actual Dewar/Probe was far more intricate, with four radiation windows in the Probe neck linked to four vapor-cooled shields in the main Dewar vacuum space. Mechanical details are in Sections III and IV; thermal design including shield temperatures in Section V. The G at T_s 261 K was ??; the fourth shield increased the hold-time by 6%, i.e. about 1 month.

Fixed Pointing, Solar Radiation and the Earth's Albedo

Other consequences of fixed pointing were: 1) occultation of IM Pegasi each half-orbit, exposing the SIA to the Earth's albedo; 2) the changing direction of the Sun through the year with the gyro right ascension line meeting the Earth-Sun line on March 11. The conical sunshade of Figure 4 attenuated sunlight at closest approach by ~ 10^{14}, sufficient to allow one of the mission's neatest cross-checks, a measure of the gravitational deflection of light by the Sun, using the gyroscopes as references for the telescope. Included also was a shutter to be closed each half-orbit against albedo. On-orbit, the actual shutter generated excessive vibration shocks and had to be left open. SIA temperature swings up to 40 mK were observed (Section VII, Figure 7.X), but found to have no significant effect on data analysis.

Spacecraft roll, SIA layout, and Dewar 'bubble wrap'

For a succession of reasons, the vehicle was rolled about the line to IM Pegasi at a rate balancing two constraints: ATC stability and SQUID $1/f$ noise. Reducing $1/f$ noise made for a high rate, ideally at or above the $1/f$ breakpoint of the SQUID (~ 0.1 Hz). ATC factors, principally thrust authority and bandwidth, limited the rate to ~ 0.013 Hz (77.5 s roll period).

The conjunction of roll, Earth gradient accelerations and a need to keep the mean cross-track acceleration on the system < 10^{-11} g, severely constrained the SIA layout. The four gyroscopes had to be mounted in line with continuous 10^{-7} g suspension to counter the gradient terms. The centrifugal acceleration from roll then required all four to be set in both planes to within 50 μm (0.002 in) of the telescope boresight. To stay within the ATC control authority, a mass-trim mechanism was added to the vehicle, adjusted twice during the mission.

During Initial On-orbit Checkout (IOC), the roll-rate was raised slightly (to 0.015 Hz) for 4.2 days to symmetrize the He distribution in the Dewar, thereby improving ATC stability by reducing unbalanced attraction on the proof mass. For more on this ‘bubble wrap’ process, see Section VII.

Probe Diameter, Telescope Aperture, SIA Mounting, & Gyro Spin-up
The Probe diameter faced requirements of all three kinds: science, assembly, and launch. From science came first the 0.14 m telescope aperture set by the brightness of candidate guide stars, leading to a QBS diameter of 0.17 m. With that, one might look to a 0.18 m Probe, which also met various gyro shielding requirements. Launch and spin-up ruled otherwise. Crucial for launch was the robust SIA mounting (Section IV) with four extended ears held compressively within a fixed ring structure, but the decider was gyro spin up. Spin meant applying a torque, then switching it off by 13 orders of magnitude, which meant in turn differential pumping with gas at moderate pressure (~ 3 torr) run through a channel in one half of the gyro housing, while maintaining ~ 10^{-4} torr elsewhere. The final Probe diameter was 0.25 m (10 in).

Probe length, Dewar hold-time, & Ultra-low field shielding
Probe length engaged two issues, hold-time and magnetic shielding. Referring to Figure 1, the 0.25 m diameter section within the Dewar itself included necktube and cryogenic sections whose length needed to be in right balance. Long hold-time meant a large Dewar, and since the launch constraint was weight not size, made rigorous weight-saving techniques essential. Shielding had two aims, low field and the 240 dB attenuation of varying external fields. Accurate gyro readout meant a trapped flux in each rotor ~ 1% of the London moment, calling for slow deliberate cooldown in a uniform ~ 10^{-7} gauss field. ‘Lead-bag expansion’ was the key. The quantity conserved in a cold superconductor is magnetic flux (= field × area). Cooling a folded bag and then expanding it lowers the field; done four times, this yielded a 0.25 m (10in) diameter 10^{-7} gauss bag held in the Dewar well. Reaching 240 dB field attenuation took a combination of three factors: the lead bag, accurately-centered transverse superconducting shields around each gyroscope, and a cryoperm magnetic shield surrounding the Dewar well, together with one element internal to the gyroscope, the self-shielding through its own superconductivity. Reviewing overall design, it is fair to say without the 327 kg weight-saving actions described in Section III both requirements, hold-time and shielding, would have been hard to meet.

Ultra-high vacuum via ‘low-temperature bakeout’
‘Bakeout’, i.e. heating a UHV system to drive off adsorbed gases, is well-known: here, it took a unique form, *low-temperature bakeout*, raising the SIA temperature from 2 K to 6 K to restore high vacuum after spin. At 2 K, all gases except He^3 and He^4 are frozen out. Spin-up injected large quantities of He^4 gas. The final requirement, set by differential damping torques, was an exponential spin-down time τ_s > 2000 years (< 10^{-9} torr pressure). During the spin-up process, each gyroscope slowed by ~ 15% in the hour of the next spin. With all complete and the Probe exhausted to space, the spindown times ranged from 40 to 50 years. After ‘bakeout’, they were

7,000 to 25,900 years depending on the gyroscope. Evidence presented in Section VII is that the actual pressure reached ~ 10^{-14} torr, which would if that were the only source of damping have given $\tau_s \sim 2 \times 10^8$ years. Crucial to UHV success was the large cryopump described in Section IV.

Rotor charge control

Two factors, gyro suspension voltages and image torques from out-of-roundness, set a bound of 3×10^7 electrons on the allowed electric charge on any rotor. Each gyroscope had an elegant UV discharge system (Paper L); a study based on the ESA __ __ model emphasized the need for heavy attenuation of cosmic rays up to 100 MeV. The Dewar well was a 0.26 m diameter tube with XX mm wall thickness over most of its length. For the 0.5 m long region around the gyro portion of the QBS, the wall thickness was increased to ZZ mm. On-orbit discharge, requiring a few hours, was performed twice during the mission.

Summary with Table

Table 2 summarizes the principal mission requirements for the cryogenic payload, to be compared against actual on-orbit values in Table z of Section IX. The many interwoven design features of the Dewar and Probe are in Sections III & IV.

Table 2: Cryogenic Payload Requirements

Parameter	***Dewar, Probe***	***Requirement***
Lifetime	Dewar	16.0 months
Maximum helium temperature	Dewar	1.9 K
Ground hold	Dewar	90 day
Temperature stability	Dewar	< 30 mK
DC magnetic field	Dewar & Probe	< 1e-6 gauss
AC magnetic field attenuation	Dewar & Probe	2e-12
Gas flow conductance	Probe	xx
Probe science pressure	Probe	< 1e-12 t
Clear Aperture	Probe	14 cm
Radiation attenuation	Probe	> 40 dB
Proton shield	Probe	> 20 g/cm^3
Off axis light attenuation	Probe	> 220 dB (?)
Cross-track acceleration	Dewar & Probe	< 1e-11 g
Helium slosh control	Dewar	Baffles
Maximum mass	Dewar & Probe	xx

Meeting these top level requirements hinged on a series of more detailed ones, some found analytically and others empirically through incremental prototyping as described in Section VI.

III. Dewar Development

The helium flight Dewar, shown in Fig 3.1, is 3.0 m high, 2.2 m in diameter and weighs 810 kg dry. It was designed to meet all science instrument (SIA) requirements described previously while maximizing lifetime and minimizing weight (to stay within the launch vehicle capabilities).

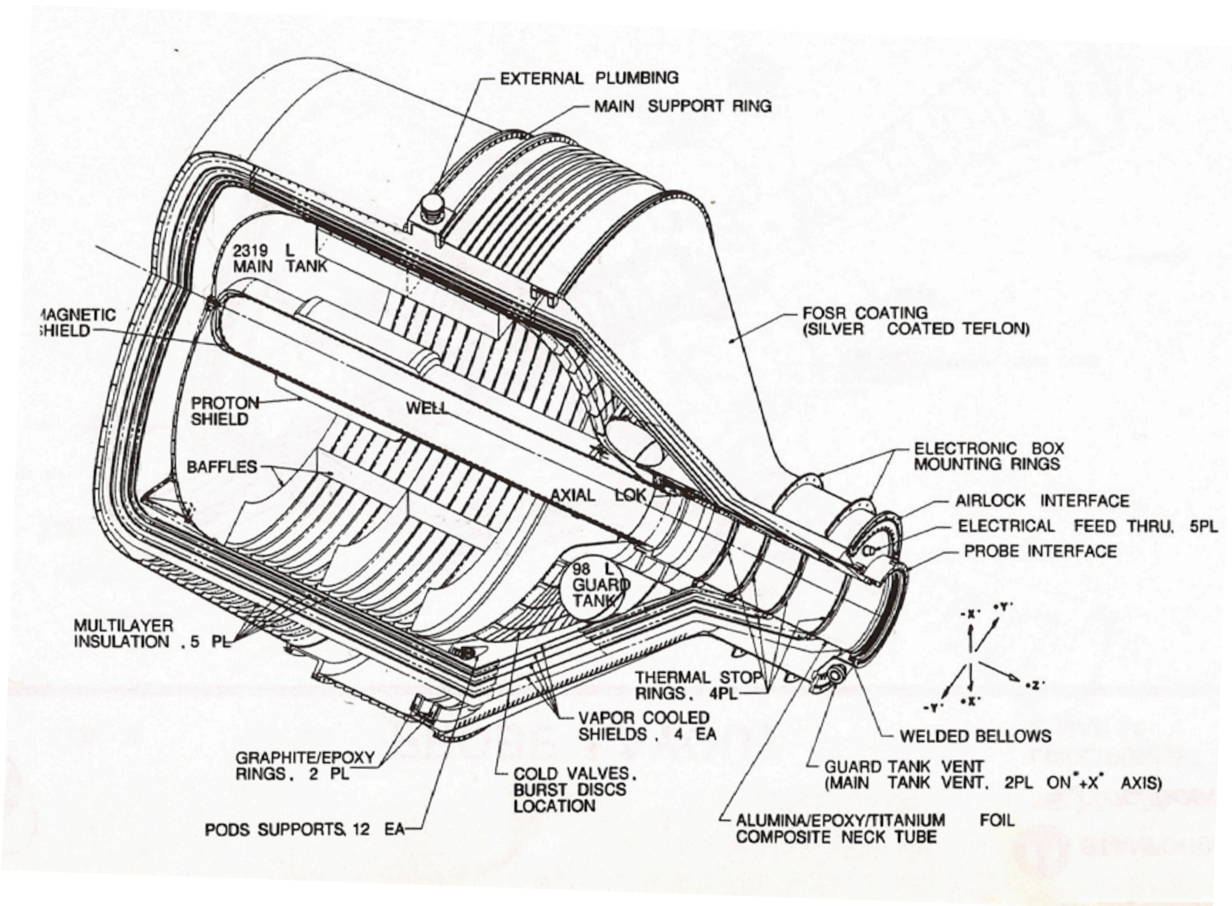


Figure 3.1 Flight Dewar Layout

The flight Dewar (1) maintains the SIA at 1.8 K for more than 16.0 months, (2) provides a magnetic field for the SIA of $<10^{-7}$ gauss using a Cryoperm shield and an expanded superconducting lead bag, (3) provides aluminum proton shielding for the SIA, (4) provides vent gas to 16 thrusters for spacecraft control, (5) provides two stable star tracker platform mounts off of graphite epoxy rings, (6) is capable of being operated in the vertical or horizontal attitude during ground tests, (7) has sufficient hold time for ground operations without losing any helium from the main tank, (8) dampens helium slosh motions, (9) measures the vent rate and amount of helium left in the main tank at any given time in orbit, (10) has multiple temperature sensors, heaters, liquid-level sensors, and accelerometers, and (11) can transfer normal or superfluid helium from the main tank to the Dewar well.

Description of the Dewar design is broken into 7 sections (1) vessels, (2) plumbing, (3) instrumentation, (4) unique thermal/mechanical features, (5) weight reduction, (6) leak check and proof pressure test results and (7) magnetic considerations.

Vessels
There are three vessels that makeup the Dewar: (1) the main tank/well (2) the guard tank and (3) the vacuum shell. Figure 3.2 shows the main tank, necktube, guard tank and forward passive orbital disconnect struts (PODS) attached to two graphite/epoxy rings.

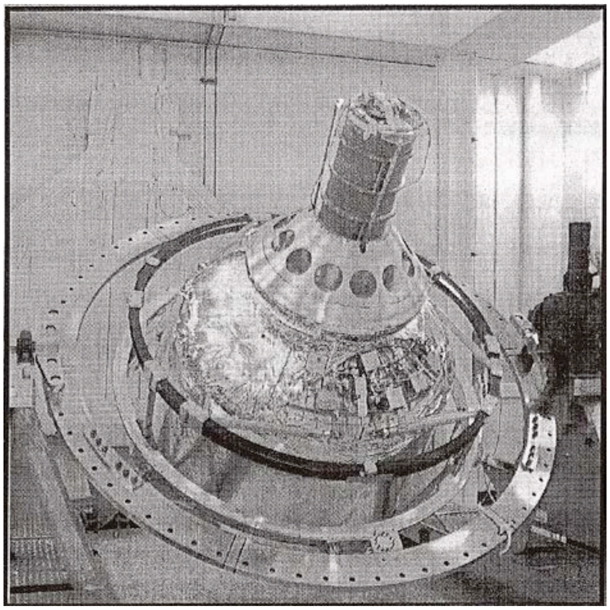


Figure 3.2 Main Tank, Cold Plumbing, Guard Tank, Composite Necktube, PODS V Supports and Graphite Ring

Main Tank and Well

The main tank contains 2328 1 of SFHe weighing 337 kg with a vapor ullage of 5%. It is constructed from 2219 aluminum and is optimized for internal and external pressure requirements in order to minimize mass. This alloy has excellent mechanical properties and excellent weldability. This optimized design makes extensive use of ring-stiffened and waffle structures. Features internal to the tank include: baffles for slosh control, fill and vent plumbing, liquid level sensors, heat pulse meter components, and temperature instrumentation.

To expand the lead bags and insert the probe at helium temperature, the main tank must provide a separate volume called the well. This volume must be accessible from the ambient environment and capable of being filled with liquid helium and then evacuated.

The well is divided into two sections: (1) the metallic section is part of the main tank and (2) the alumina composite necktube. The metallic section is constructed from 6063 aluminum, which has a relatively high thermal conductivity at liquid helium temperatures in order to maintain the lead bag temperature below the transition temperature of 7.2 K. Vacuum isolation is accomplished with a unique titanium foil liner on the composite necktube that prevents permeation of helium into the insulation vacuum. The composite necktube also provides thermal isolation since it must seal at the main tank well (1.8 K) and at the vacuum shell (ambient).

Control of Fluid Center of Mass

Knowledge and control of the liquid helium in the tank was important to determine effects of the helium motion on the space vehicle control authority and the science gyroscopes. The vehicle rolled about the telescope bore sight such that the fluid is subjected to centrifugal forces shaping the fluid and ullage. While the vehicle circles the earth, varying gravity gradients effect the location of the fluid thus changing the location of the fluid center of mass (COM) relative to the instrument proof mass and gyroscopes.

Analyses were performed to determine the change in the center of mass as the vehicle orbits the earth. It was determined that no baffling with minimal operational constraints was sufficient to achieve the fluid control and limit the motion while the vehicle was rotating. A set of baffles was installed in the tank primarily to help dampen any slosh motion during orbit insertion and to assist in rotating the fluid as the vehicle is spun up. In order to have the fluid COM on the axis of the tank, it is required to have the fluid in an axisymmetric profile. Rotating the fluid sufficiently results in centrifugal accelerations large enough to force the fluid into an axisymmetric configuration. The roll rate is maintained sufficiently long to get fluid and the tank rotating as a solid body. It was important to maintain the torus above its lower stability limit (the minimal rotation speed at which it is stable). If the rotation is too slow, the torus breaks up.

The analyses were performed using several techniques: closed-form solutions of the liquid-vapor interface, a computational fluid dynamics code called FLOW3D developed by Flow Science, Inc, a version of FLOW3D with the two-fluid model of superfluid helium by G. Ross, an interactive program for the study of surfaces shaped by surface tension and other energies called Surface Evolver by K. Brakke, and 1-G scale model tests with a storable fluid conducted by Prof. S. Collicott.

The results from Surface Evolver shown in Figure X1 agree fairly well with the other analysis techniques. Results show that axisymmetric profile is achieved with a roll rate of 0.5 rpm at the initial high fill level and stable at 0.1 rpm for residuals of 92% or less. Data taken at the maximum 0.9 rpm during the mission provided evidence of achieving the axisymmetric profile.

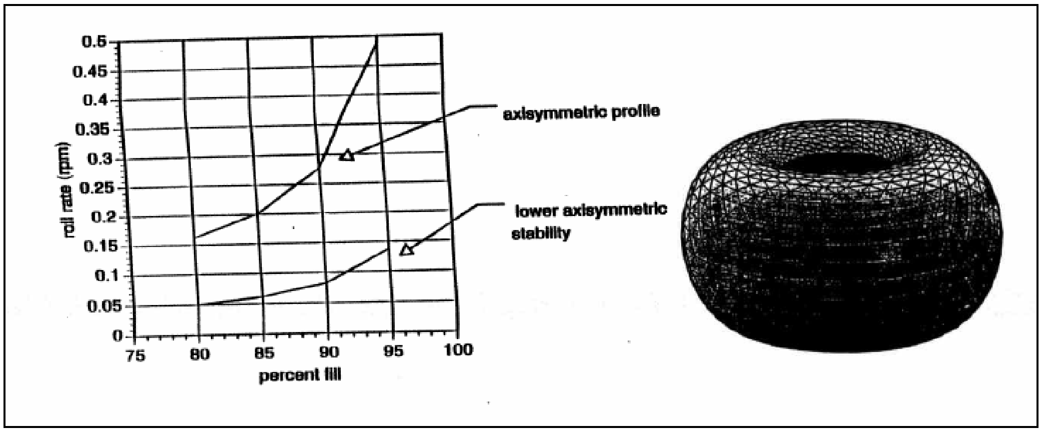


Figure X1: Roll rate to achieve an axisymmetric toroidal profile and the minimum stability profile from Surface Evolver.

Further calculations were performed to determine the axial displacement of the COM. These displacements result from the movement of the ullage due to the effects of the orbital gravity gradient. Figure X2 shows the steady state profile of different ullages at 0.1 rpm computed using the 3D model. The model was used to determine the roll rate required to flatten the liquid/vapor interface sufficiently such that the ullage stretches the length of the tank. At the time of the analysis, the baseline roll rate during science was 0.1 rpm. The actual roll rate turned out to be 0.77 rpm.

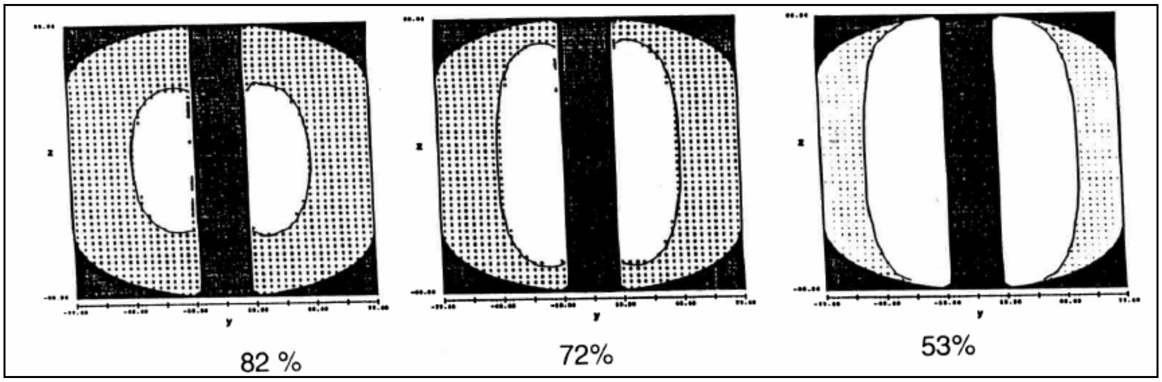


Figure X2: Ullage stretches the tank as the fluid depletes. At 0.1 rpm, the end domes of the tank restrain the ullage with the tank 53% full

When the ullage is not in contact with both end domes of the tank, any disturbances or effects of the orbital gravity gradient can push the ullage into different axial positions causing the fluid COM to shift. The maximum axial drift of the ullage was calculated along with the shift in COM of the fluid. The maximum possible drift in the COM is approximately +/- 6.7 cm, which occurs when the tank is approximately 80% full at 0.1 rpm.

A model of the orbital gravity gradients was incorporated into the FLOW3D code and a number of cases at various fill fractions and roll rates were analyzed to determine their effect on the COM of the fluid. Based on these results, it was determined that the forces due to the gravity gradient (on the order of 2x10-7 G) were not sufficient to be of concern.

The baffle system was designed to dampen the fluid and assist in setting the fluid in rotation during the spin-up of the spacecraft vehicle. The baffle design shown in figure 4 was designed such that it would not interfere with an ullage that had not stretched the entire length of the tank at 0.1 rpm.

The damping characteristics were assessed by subjecting the tank to an impulse disturbance of 0.01G for 10 ms in the lateral or axial direction and predicting the displacement of the fluid and the resultant forces on the tank. Results were also used for the attitude control system model of the spacecraft.

In analyzing the fluid behavior, questions arose as whether one should treat the liquid as a single classical fluid or two fluids as suggested by the two-fluid model for superfluid helium. It was determined that the fluid in the tank is above it’s critical velocity and that there is interaction between the superfluid and the normal fluid through vortex lines such that the He II can be treated as a single fluid.

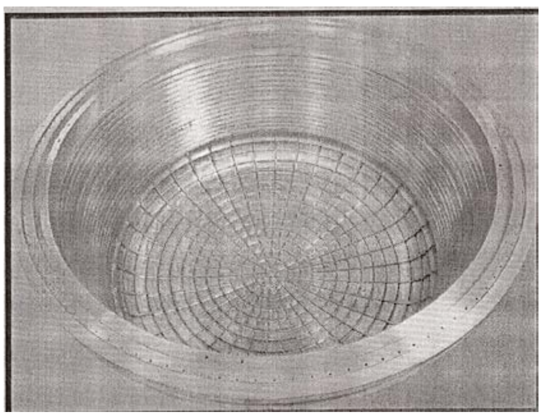
Guard Tank

The guard tank contains up to 99 l of helium at 4.2 K. It is constructed from 2219 aluminum and is mounted off the well composite necktube. The innermost vapor cooled shield, in turn, is attached to the guard tank, greatly reducing the parasitic heat leak to the main tank.

Consequently, the main tank can be kept non-vented for up to three months greatly simplifying launch pad operations. Filling the guard tank with NBP helium every seven days during ground testing and every three days on the launch pad (to be conservative) is a relatively simple operation. Consequently, all of the helium from the main tank is available for use on orbit, as opposed to a system that pumps on the sub-atmospheric main tank right up until shortly before launch. Also, the orbit lifetime is extended due to cooling of the vapor cooled shields (below their equilibrium temperatures) as the guard tank empties in orbit. Another benefit was found. After the lead bags were expanded, the main tank was kept cold on the ground for 7 years. As the helium level dropped in the main tank, keeping the guard tank filled insured the top of the lead bag never exceeded 7.2 K.

Vacuum Shell

The vacuum shell shown in Figure 3.3 is constructed from 2219 aluminum in three parts: (1) the aft dome/cylinder, (2) the support ring, and (3) the forward cylinder/cone section. A vacuum tight seal between the sections is made with the world's largest Helicoflex seals (Figure 3.4).



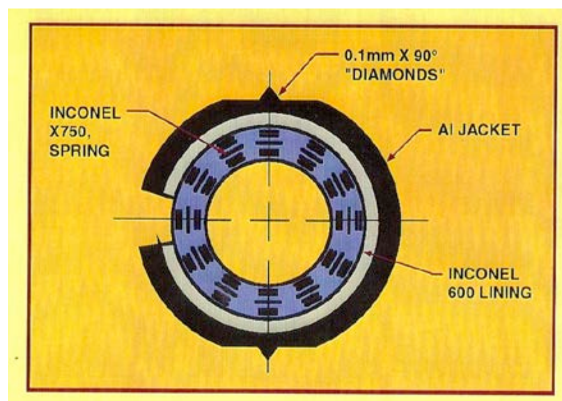


Figure 3.3 Aft Vacuum Shell

Figure 3.4 Delta Helicoflex Seals

The shell provides vacuum isolation from the ambient environment during ground operations and during launch. Like the main tank, the vacuum shell is highly optimized for both internal and external pressure requirements in order to minimize Dewar mass.

Plumbing

The plumbing is divided into four categories: the plumbing used to fill the three liquid helium vessels, plumbing associated with normal venting of the vessels, that which is used to vent the vessels in the case of a loss of the guard vacuum, and finally the plumbing associated with maintaining the guard vacuum space. The plumbing schematic is shown in Figure 3.5.

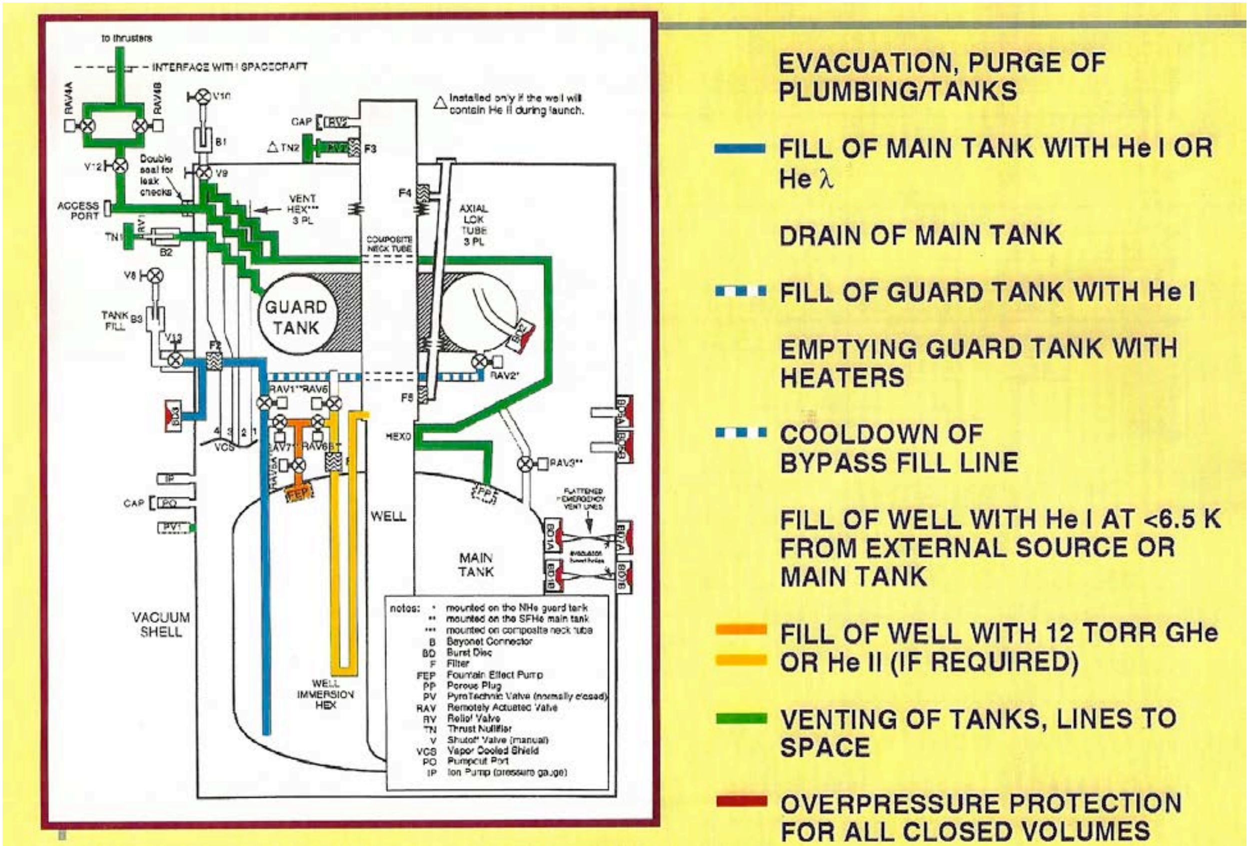


Figure 3.5 Dewar Plumbing

Filling

Filling of the three vessels from an external supply Dewar is performed by a single bayonet/manual valve port. Due to the sensitivity of magnetic contamination, all the incoming liquid helium passes through a filter internal to the vacuum shell. This single fill line accesses each of the three vessels through the Remotely Actuated Valves (RAV) 1, 2 and 5. Mission Research Corporation of Logan, Utah developed these leak tight valves.

In addition to being able to be filled by an external supply, the plumbing is designed such that the guard tank and well vessels can be filled with normal boiling point helium with a total of seven RAVs internal to the vacuum shell. In practice, an internal transfer from the main tank always did the well fills. All liquid helium transferred into the well passed through a second cold internal filter.

Venting

The main tank is vented through a bypass valve (RAV-3) on the ground and through the porous plug in space with the vent line vapor cooling at five locations. The first location is at the forward part of the tank (Sta 200) which is also the coldest mechanical and thermal attachment point to the science probe. Subsequent cooling is at each of the four neck tube heat exchangers that are thermally grounded to each of the vapor cooled shields. The brazed copper neck tube heat exchangers (HEX) are split into two clamshells; the interconnecting stainless steel lines are bonded together with the four HEX'S after the HEX'S are bonded on opposite sides of the neck tube. Thus the vent flow is split into two paths; copper bridges thermally grounded the clamshells together to prevent uneven flow. The main tank vent line exited the vacuum shell at two locations: the ground vent test port and a set of parallel RAVs, which connected to the spacecraft attitude control thrusters. These RAVs were opened during launch, when outside the atmosphere, to initiate venting of the main tank.

The venting gas of the guard tank also vapor cooled the four shields. This tank is partially filled with normal boiling point helium at launch and is vented to space. To prevent putting unwanted torques on the spacecraft, the vent plume direction is set exactly opposite the spacecraft's center of gravity. To ensure good heat transfer at each of the four vapor cooled shields, a perforated copper plug with multiple holes parallel to the flow path is used since the vent line goes straight up the neck tube.

Emergency Relief

Emergency relief of the main tank in case of a catastrophic loss of the insulation vacuum space is done using two parallel 5.1 cm diameter cold burst discs installed on the tank. The effluent vapor from the main tank after rupture of the discs is through inflatable hoses that penetrate the insulation and connect to burst discs at the vacuum shell.

Porous Plug

The original concept was invented at Stanford in 1970. This design was modified to meet GPB's unique requirements. Superfluid helium has the unusual property of flowing from a cold area to a warm area. Thus as the liquid expands and cools as it passes through the porous plug, a liquid/gas interface is setup in the plug, with the liquid moving toward the warmer tank. The amount of gas venting is controlled by the downstream pressure in the vent line.

Requirements The porous plug, used during flight to retain the superfluid helium in the tank, must operate unchecked over a wide range of flow rates. Since the effluent vapor is used for supplying the necessary gas to the thrusters, it is required that the porous plug not choke over a range of 4-16 mg/s. These requirements make it unique in that the downstream flow conductance of the plumbing is not constant as with other space borne Dewars. A heater in the tank and a flow conductance valve are required in the vent line to provide the temperature control and variable flow rates required to 16 thrusters. High flow rates support the initial orbit trim of the space vehicle once on orbit.

Ground Test Results Different porous, sintered stainless steel samples were evaluated to select the one used in the Dewar (Ref PP-1). As the plug flow rate is increased by decreasing the back pressure, the temperature gradient increases until the plug achieves a choked condition. The flow rate at this point is referred to as the critical flow rate. As the flow rate is increased and subsequently decreased, the temperature gradient goes through a hysteresis loop. Figure 3.6 shows temperature gradient and back pressure profiles for various bath temperatures. The back pressure is measured in the ground support equipment of the Dewar. The slope of flow rate versus temperature gradient in the normal mode and the critical flow rate increases with bath temperature. Tests at various inlet hydrostatic heads were performed and the results were extrapolated to zero head to determine the critical flow rate on orbit. Figure 3.7 shows the plug meets the critical flow rate requirement of greater than 16 mg/s when operating at 1.8 K for the selected area of the plug.

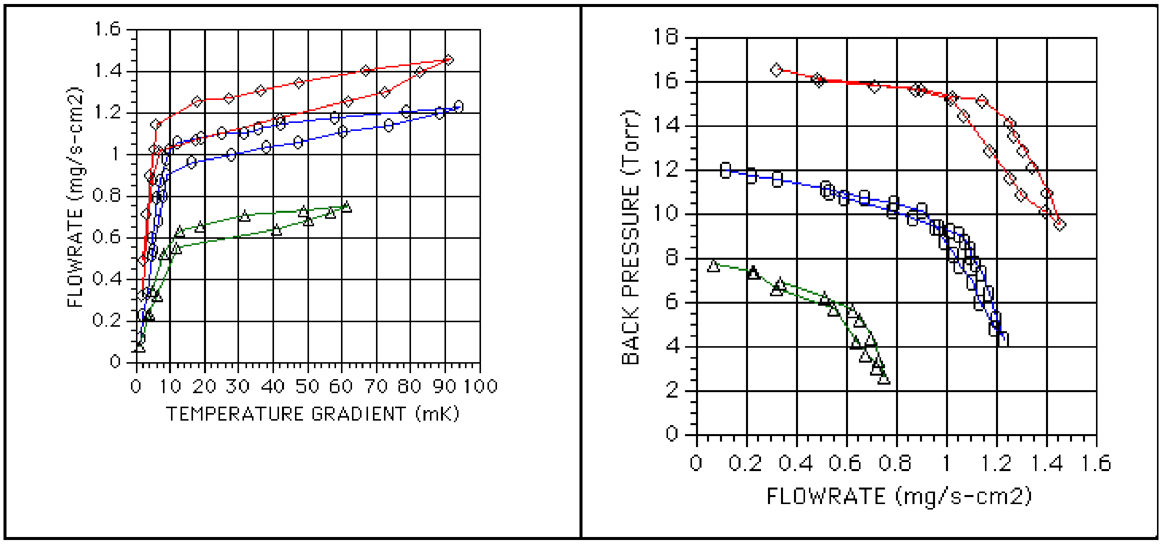


Figure 3.6 Effect of bath temperature on temperature gradient and back pressure of material (O 1.7K, □ 1.9K)

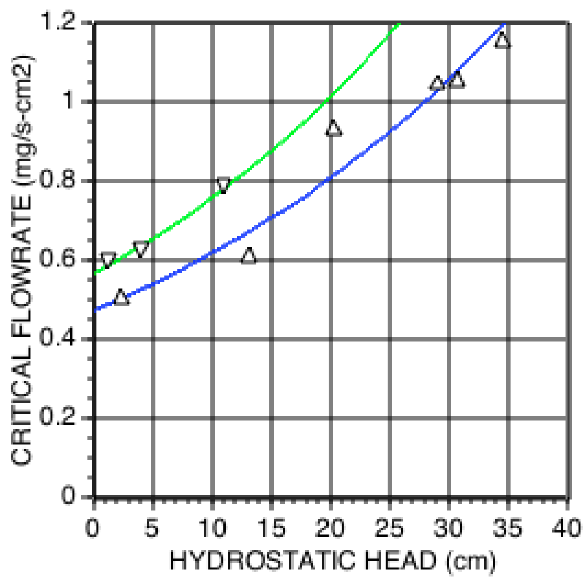


Figure 3.7 Effect of hydrostatic head on critical flowrate(⊗ 1.7K, ∉ 1.8K, □1.9K)

Design The material chosen from extensive tests has a diameter of 68.6 mm, a thickness of 6.35 mm and is made of 316L sintered stainless steel porous media (purchased from Mott Metallurgical Corp). The material has a permeability of 3.8 x 10^{-10} cm^2 and a bubble point of 19.3 cm Hg. The test porous plug is shown in Figure 3.8.

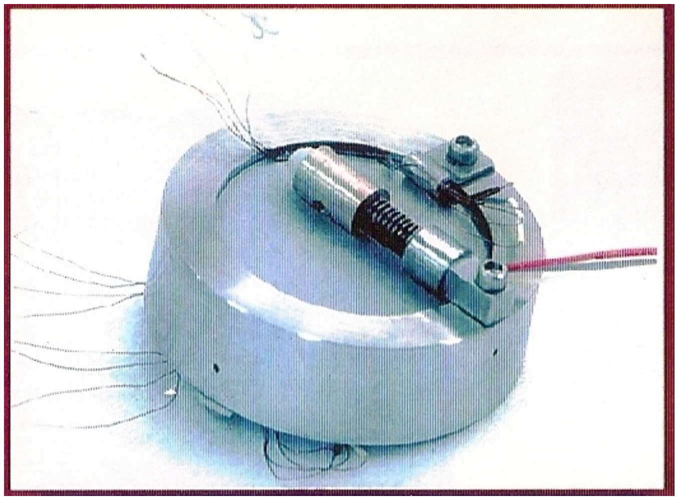


Figure 3.8Test Porous Plug

Instrumentation The Dewar's instrumentation is summarized in Table 3.1. Description of the custom made heat pulse meter and vent line flow meter are described in more detail below. In addition, the RAV's have position sensors to monitor their open or closed status. The attitude control system, which utilizes the effluent vapor from the main tank, has a set of instrumentation that includes pressure sensors at the inlets to the thrusters. On orbit, heaters were used to adjust the Dewar vent rate as required for the spacecraft attitude control, for the heat pulse meter, and for control of the temperatures inside the science probe. A number of heaters in the Dewar were used during the ground processing operations that included tank-to-tank internal transfers and external fills.

Table 3.1 Instrumentation

Measurement	No.*	No.*	Type	Manufacturer
	Grd	Flt		
Temperature	9 9	11 12	Germanium Resistance (lower temperatures) Silicon Diode (higher temperatures)	Lakeshore Cryotronics
Heaters	5	6	Resistance	Tayco Engineering
Liquid Level - Main Tank - Well - Guard Tank	7	0	Superconducting measurement wire encased in fiberglass tube	American Magnetics, Inc.
Liquid Point Sensor on porous plug	2	2	Superconducting measurement wire	American Magnetics, Inc.
Accelerometers	4	3	Triaxial accelerometers	Kistler
PODS (open or closed)	12	12	Electrical Resistance	----

* Some measurements are used in both ground test and in flight.

<u>Heat Pulse Meter</u> The primary method of determining the mass of helium remaining in the tank on orbit is the heat pulse meter. The meter utilizes a heater and temperature thermometers, which are in good thermal contact with the liquid in the tank. A pulse of heat is introduced into the liquid by use of the heater and the temperature response is recorded. Due to the high thermal conductivity of superfluid helium, the heat is evenly distributed. The response in the fluid temperature is primarily governed by the mass remaining in the tank and is determined from conservation of energy and mass.

In flight, a heat pulse large enough to increase the fluid by 0.005 K is utilized. In a ground test, heat pulses of up to 0.010 K were tested when the tank was half full. The liquid level sensors in the tank were used to measure the actual amount of fluid in the tank. Temperature drift of the fluid was measured before and after testing. Flow conductance of the plumbing downstream of the porous plug was kept constant during testing (i.e. the temperature control of the bath was turned off). The results of this test indicated a liquid residual of 52% while the liquid level sensors indicated 50%.

The heater in the main tank provides 33 watts of heat in flight. For a full tank, the pulse duration is approximately 2.5 minutes. Since pre and post data must be taken to determine the natural drift of the fluid temperature, the duration when the control system is off can be substantial.

Cold Flowmeter A vent gas flowmeter, used as a backup to the heat pulse meter, is based on the principle of convective heat transfer from a heated section of the vent line. This flowmeter is installed on the vent line before it reaches the first vapor cooled shield.

The flowmeter is a 1.9 cm long section of the 1.3 cm diameter plumbing line, heated to an isothermal condition with a 75 mW heater. Since the vent line is thin walled stainless steel, a clamshell of OFHC copper is bonded to the outside of the tube to insure a uniform wall temperature. The heater and thermometer are attached to this copper piece. The line is subsequently wrapped with multilayer insulation.

References:

PP-1: D. J. Frank and S. W. K. Yuan, Experimental Results of tests Performed on Superfluid Helium Phase Separators for the Relativity Mission; Advances in Cryogenics Engineering, Vol. 41, 1996, Pg.1195-1201.

Unique Thermal Features

In order to meet the lifetime requirements of 16.0 months in low Earth polar orbit, a number of new materials and designs were used to minimize the heat load to the superfluid helium. New materials were used with the lowest thermal conductivity known over the temperature range ambient to 2 K. The multilayer system was optimized based on extensive laboratory tests and the vacuum shell temperature was reduced using a 0.25 mm Teflon film silverized on the backside. Passive orbital disconnect struts (PODS) were used for supporting the main tank and four, rather than the normal three, vapor cooled shields provided an additional one month of lifetime. Details of these features follow.

Three composites were considered for use in the necktube and the PODS supports (for the main tank). Their thermal conductivity from ambient to 2 K is shown in Figure 3.9. Note the gamma alumina fiber/epoxy is the best compromise. Its conductivity is equal to the carbon fiber and lower than S-glass at low temperatures; at higher temperatures, it is lower than carbon and slightly higher than S-glass. The gamma alumina has excellent mechanical properties and consequently was selected for both the PODS supports and necktube.

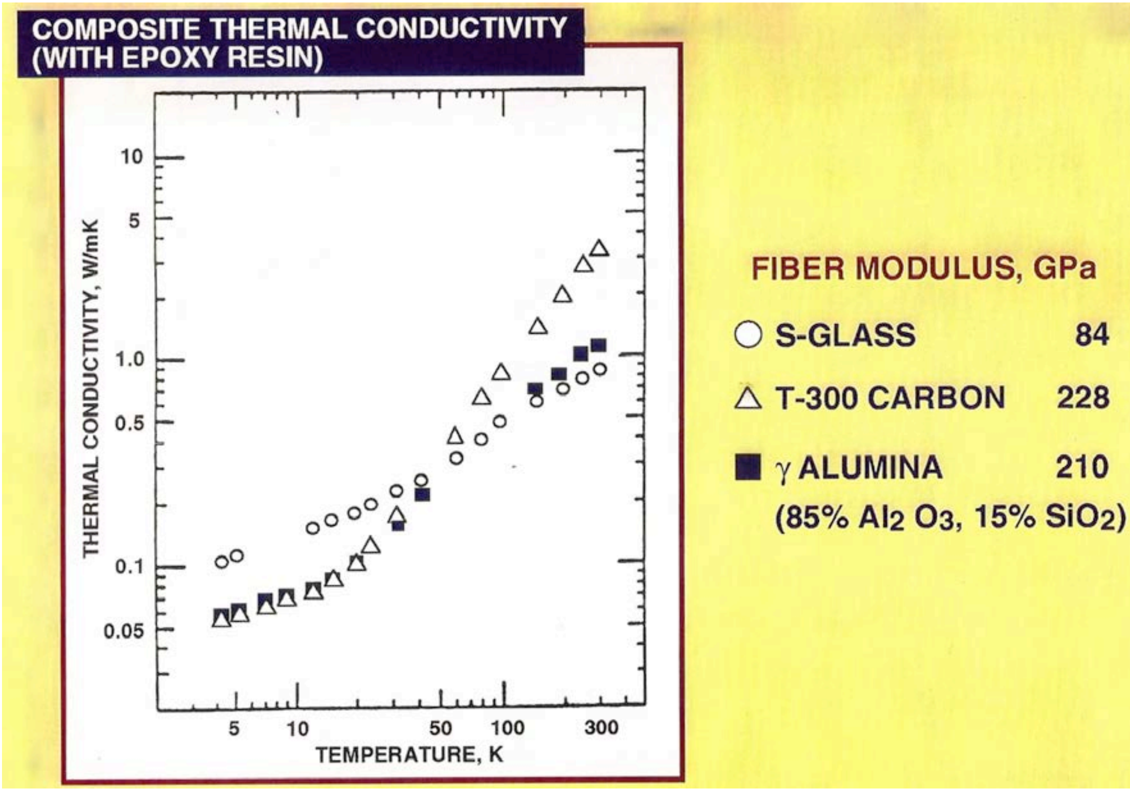


Figure 3.9 Gamma Alumina Properties (vs Carbon and Glass)

The necktube requires a vacuum barrier since it is sometimes filled with liquid helium for lead bag expansion and probe insertion.

The gamma alumina composite is too porous to helium so various metal alloys were examined as a barrier. The SR-71 aircraft used a very low conductivity titanium alloy 15V-3Cr-3A1-3Sn so we had it tested from 300 to 10 K. It turned out to have the <u>lowest</u> conductivity of <u>any</u> metal alloy over the entire range (See Figure 3.10). A 0.025 mm thickness provided a vacuum tight cylinder.

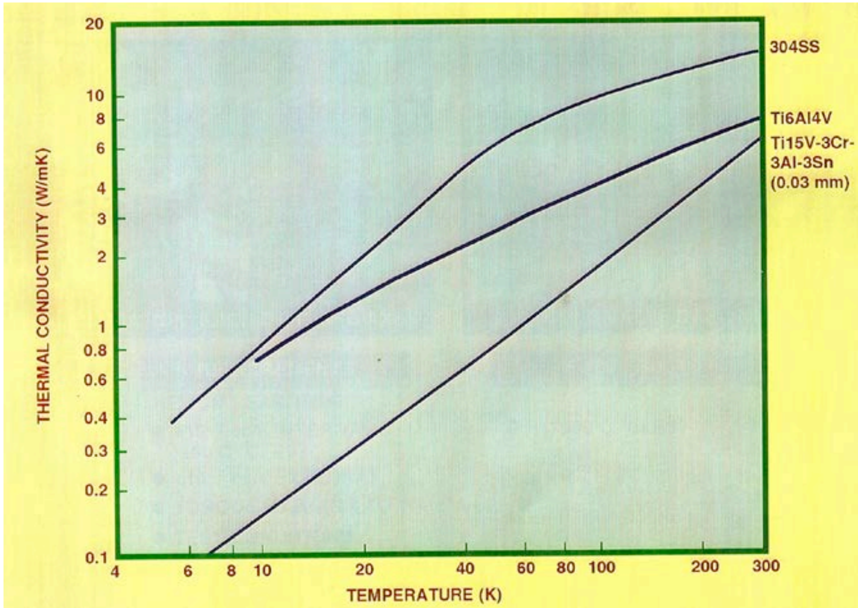


Figure 3.10 Thermal Conductivity of Metal Alloys

Extensive laboratory tests of multilayer systems showed the double aluminized Mylar/silk net spacers were the optimum choice (Figure 3.11). At the tank side, three silk nettings were used where solid conduction dominates. The number of nettings was reduced progressively down to one at the vacuum shell where radiation dominates.

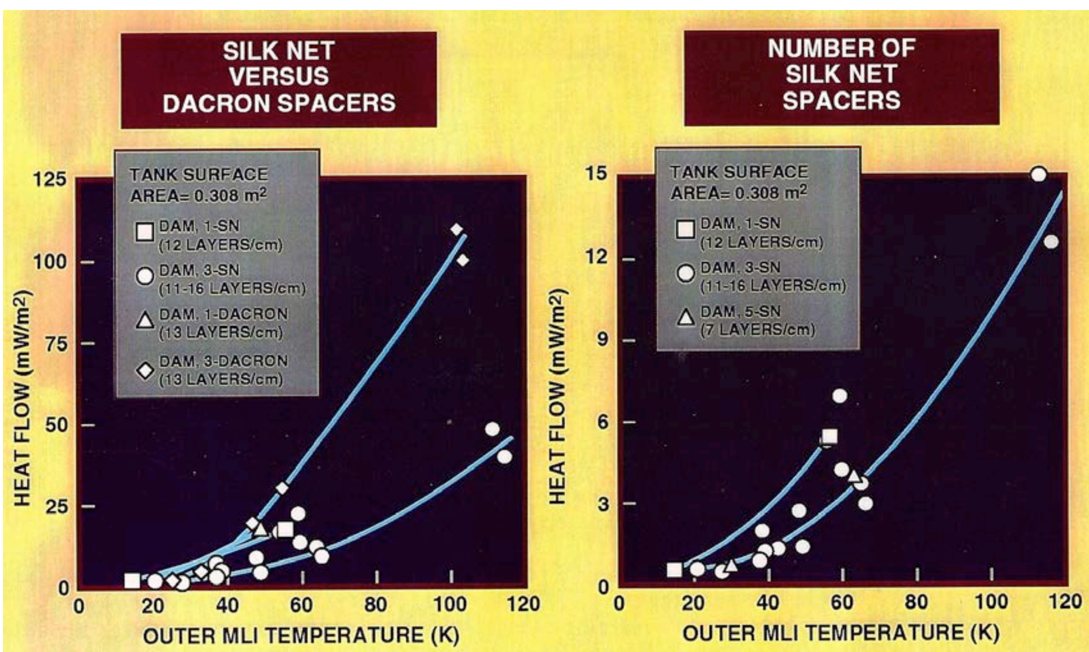


Figure 3.11 Multilayer Insulation Thermal Performance Comparisons

The insulation patterns were cut on a computer-controlled table (used in the clothing industry) and the sizes precisely increased for each layer. 139 radiation shields with spacers were installed.

The temperature of the vacuum shell has a strong impact on the Dewar lifetime as discussed later.

A second surface mirror, flexible optical solar reflector, (FOSR) is installed on the vacuum shell to lower its temperature in orbit. FOSR consists of a 0.25 mm Teflon film silverized on the backside. The silver provides low solar absorptance while the Teflon provides the high infrared emittance.

Multilayer insulation blankets are installed on the vacuum shell where it is not exposed to the Sun, i.e., covered by electronic boxes, etc.

Unique Mechanical Features

Main Tank Supports The main tank is supported by 12 passive orbital disconnect support (PODS) struts. These struts were developed over a number of years under several NASA/Ames contracts with Lockheed. Their heat leak drops dramatically from a high g to a zero-g environment (8 mW total). A cross section of the strut is shown in Figure 3.12.

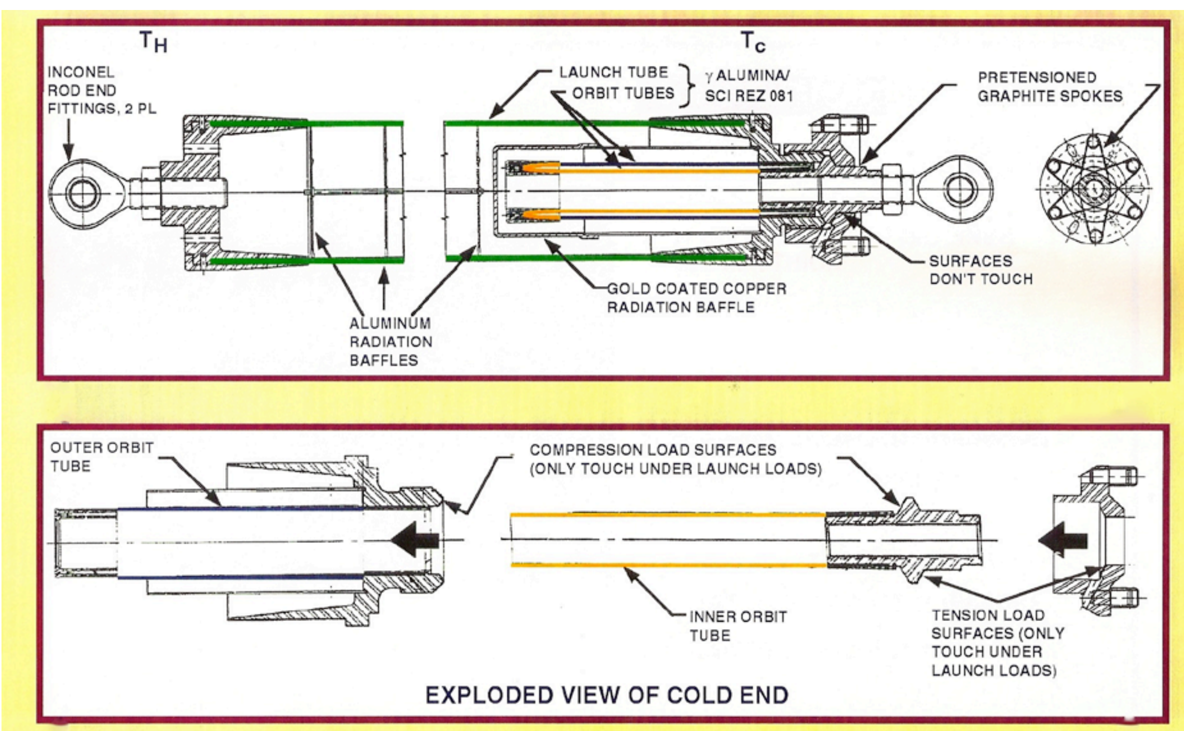


Figure 3.12 Passive Orbital Disconnect Strut Design

Gamma alumina/epoxy composite tubes with metal end fittings are used throughout the strut. Radiation baffles are installed inside the launch tube and graphite “spokes” keep the cold rod end centered. Note at the cold end (Figure 3.13), the metal gaps close under high tension or compression loads and the gaps reopen in zero-g. The two thin, small, folded orbit composite tubes at the cold end provide the high thermal resistance when the gaps open in orbit. The long composite launch tube is thermally grounded to and supports all four vapor cooled shields.

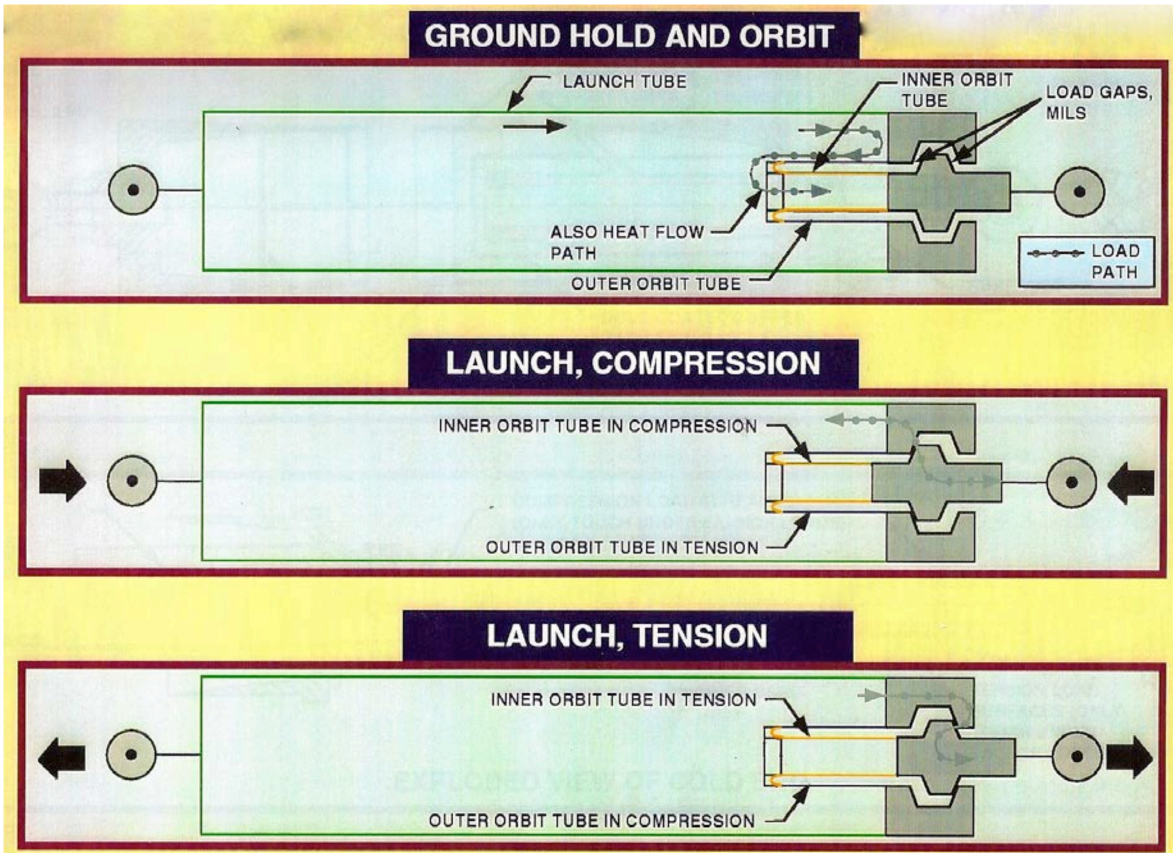


Figure 3.13 PODS Load Paths

Honeycomb Vapor Cooled Shields. To reduce weight, honeycomb vapor cooled shields were selected in place of the conventional monocoque design. The shields were constructed from perforated 5052 aluminum honeycomb core with bonded 0.1 mm 1100 aluminum, perforated face sheets. (See Figure 3.14). Prior to selecting this design, panels were constructed and tested to ensure the air could be evacuated from the core.

The following vacuum bakeout procedure was used on the Dewar. The Dewar was rotated upside down and placed inside a customized, insulated forced air oven (Figure 3.15). The upside down orientation allowed any minute creep of the aft PODS gaps to be in a favorable direction. The Dewar vacuum space was pumped down at a controlled rate to 1 torr in 29 hours while the oven was brought up to 317 K and held for 11 days. The temperature was increased to 322 K and held for an additional 6 days, based on the results of creep tests of heated PODS-V supports conducted in parallel. At the end of the bakeout period, the vacuum pressure read 5 x 10^{-4} torr at 322 K and 5 x 10^{-5} torr when cooled down to 294 K. Water vapor was the predominant gas left.

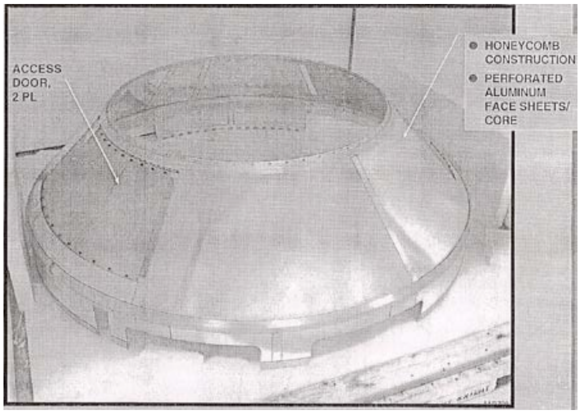


Figure 3.14 Vapor Cooled Shield Section

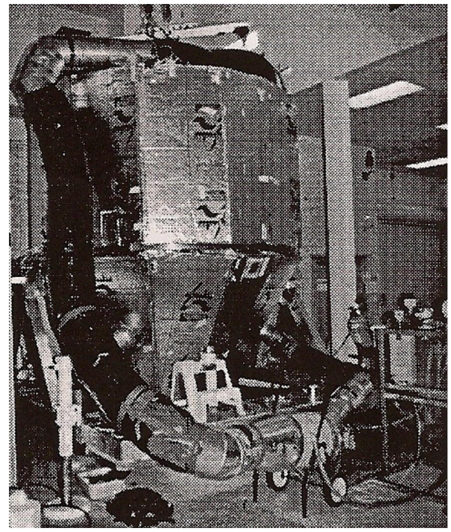


Figure 3.15 Bakeout Oven

<u>Star Tracker Mounts</u> Two star trackers were used for initially acquiring the guide star and later for roll control. Ideally, the star trackers should be mounted off the science instrument assembly (SIA) quartz block. Since this is not practical and the aluminum vacuum shell movement in orbit due to temperature changes is too large to be used as a mounting surface, we developed a very stable load path using low thermal expansion materials from the SIA through the vacuum shell.

Fortunately, the gamma alumina composite used in the PODS supports has a very low thermal expansion coefficient. Also, the aluminum main tank and probe at 1.8 K are very stable so if we put a large diameter graphite ring at the warm end of the six forward PODS with a low thermal expansion coefficient and attach the graphite ring to the inside of the vacuum shell with aluminum flexures (Figure 3.16), the star tracker mounts can be attached to the graphite ring. A post, attached to the graphite ring, penetrates the vacuum shell using a vacuum bellows to seal around the post. The star tracker platform is mounted on the end of the post. Two of these platforms are located on the graphite ring, 180 degrees apart. Analyses show this design meets the stability requirements.

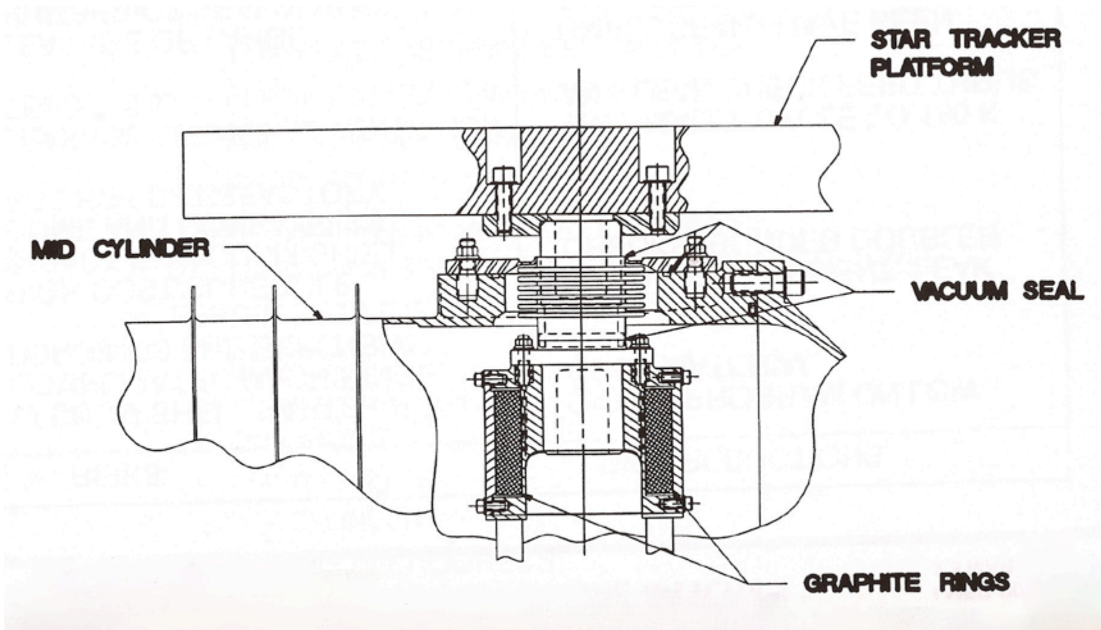


Figure 3.16 Star Tracker Pedestal

Retention/Thermal Sinking of Probe to Dewar The probe containing the SIA was designed so it could be inserted and removed from a cold Dewar through an air lock. Once inserted, it had to be supported and make excellent thermal contact at five places (1) the top of the superfluid helium main tank well (Sta 200), and the well itself, and (2) the four vapor cooled shield heat exchangers in the necktube.

A cross section of the probe to Dewar clamping design (Axial Lok at Sta 200) is shown in Figure 3.17.

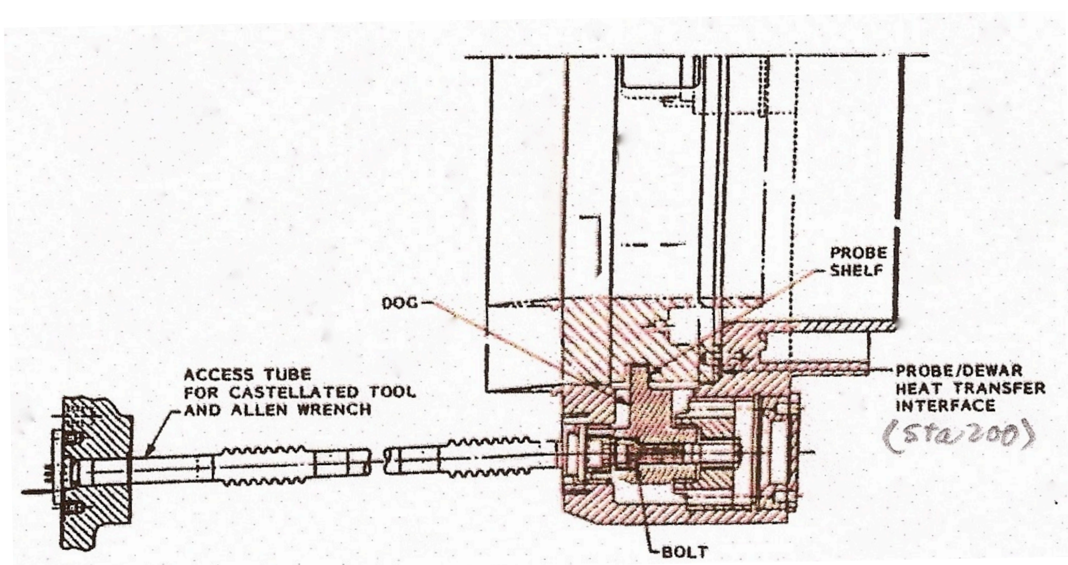


Figure 3.17 Axial Lok

At three locations 120 degrees apart, the dewar dogs are rotated into the matching slots in the probe using a long tubular castellated tool; the clamps are then tightened down using the Allen wrench inside the castellated tool. (These threads cold welded causing a different approach to be used, discussed later in this paper.) To keep the probe centered inside the dewar well, provide lateral support, and keep the lead bag supported and thermally grounded, 16 TiCu springs are flattened as the probe is pushed into the well (Figure 3.18).

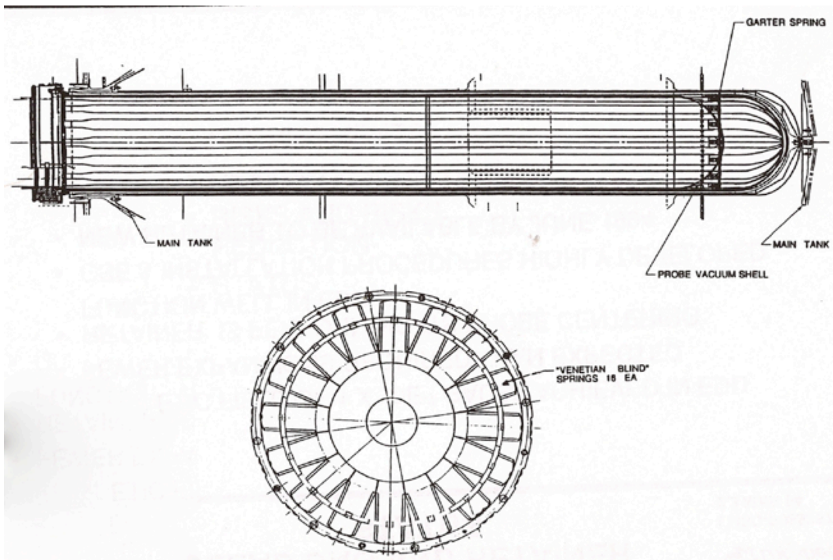


Figure 3.18 Lead Bag Retainer

Concurrently, six probe springs at each of the four dewar vent heat exchangers are compressed at the dewar copper stops (shown later in Figure 4-?). All springs are clocked with respect to each other so there is no interference. Therefore, the probe can be pushed straight down during insertion. Bolting down the probe top plate to the dewar provides the force necessary to compress all 24 springs**.**

<u>Emergency Vent Lines</u> In case of catastrophic loss of vacuum, the heat load could be so high as to rupture the helium main tank and vacuum shell. Previous flight helium dewars provide redundant burst discs on the tank and vacuum shell. If catastrophic venting occurs, the high pressure gas has to flow through the insulation and vapor cooled shields without plugging the burst discs on the vacuum shell with torn insulation or damaged shields.

One alternative is to provide large, redundant s.s. metal lines 5.1 cm in diameter through the insulation connecting the burst discs. Thermal analyses showed the radiation and conduction heat leaks were unacceptable for normal operations. Therefore, we developed, built and tested a unique low heat leak (3 mW) emergency vent line constructed from a Mylar/Dacron laminate that is folded flat when not in use and inflates if required (Figure 3.19).

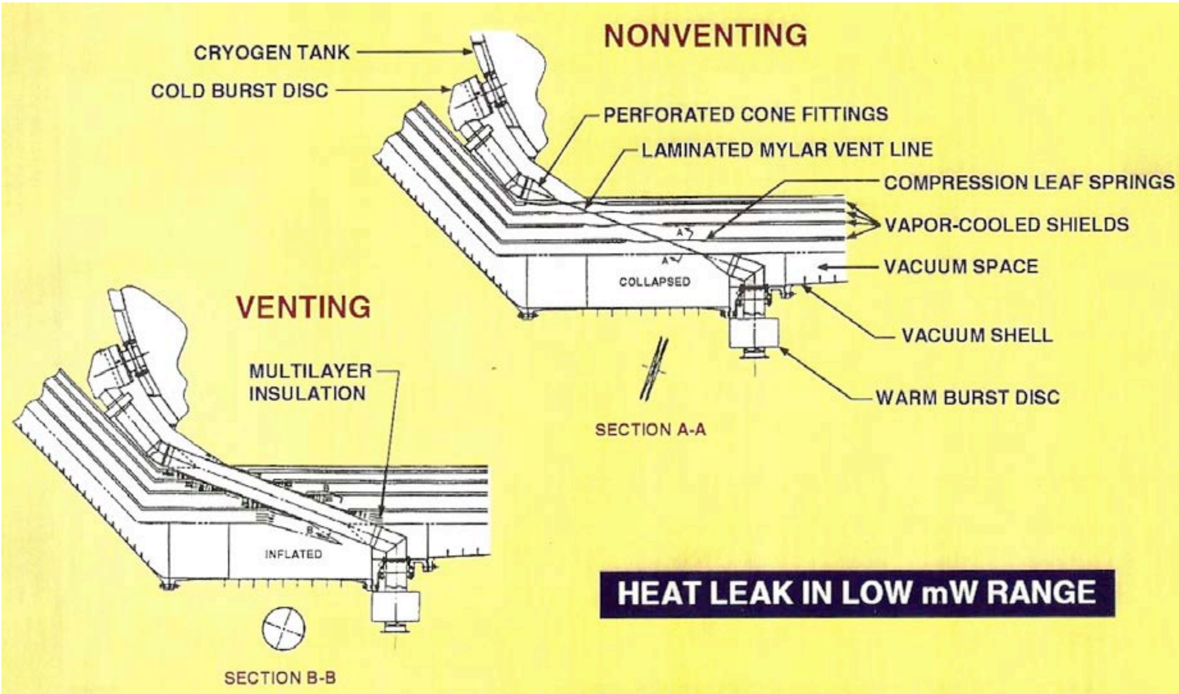


Figure 3.19 Main Tank Emergency Vent Line Design

Repeated tests with the line immersed in liquid nitrogen (Figure 3.20) showed almost no leakage when rapidly inflated with high pressure helium. Small vent holes in the metal end fittings allowed the lines to be evacuated along with the insulation during normal pump down operations.

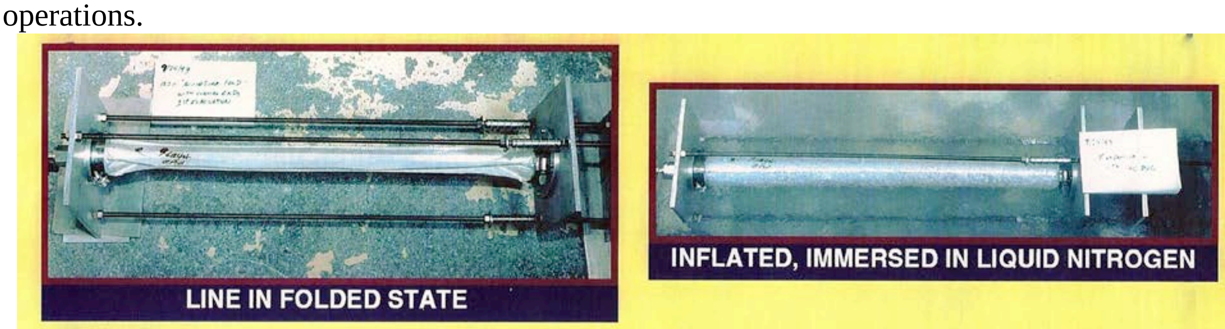


Figure 3.20 Inflatable Emergency Vent Line Tests

Weight Reduction

The measured dry mass of the flight dewar is 810 kg. This mass compares to a calculated value of 807.6 kg just prior to the measurement. The masses of all components were closely tracked throughout the conceptual and detailed design processes. Several significant program decisions can be directly correlated to the resultant low mass of the dewar, the principal contributors being light-weighted main tank and vacuum shell components and honeycomb vapor cooled shields. Although selecting waffled domes, ring-stiffened cylindrical sections and large curved honeycomb panels added 10% to dewar costs, these three areas significantly contributed to the lightweight dewar that has been produced. Table 3.2 illustrates the savings achieved in key areas.

Also of interest is, that since the weight savings are so significant, a more expensive and riskier option, using aluminum-lithium for the main tank and vacuum shell components, was deemed unnecessary.

Table 3.2 Weight Savings

Assembly	Flight Weight (kg)	Savings (kg)	Comment
Main Tank (including a 51-kg proton shield)	262	80	Waffle domes, ring-stiffened cylinder, 2219 aluminum
Guard Tank	15	4	Lightening holes in support cone
Vapor Cooled Shields	72	44	Perforated aluminum honeycomb shields
Vacuum Shell	345	100	Ring stiffened & waffle construction, 2219 aluminum

Leak Check and Proof Pressure Test Results

Extraordinary attention must be paid to making a superfluid helium system absolutely leak tight. Internal leaks can be so expensive to correct that they are program killers. Therefore, we used the following design criteria and leak testing procedures.

All the tanks and vacuum shell sections were electron beam welded. No leaks were found. We, then, epoxy bonded an aluminum doubler strip over the welds as a belt and suspender approach. Epoxy bonding of the composite necktube to the aluminum well and vacuum shell top plate also used an epoxied aluminum doubler. Glass beads, 0.08 mm in diameter, were mixed with the Epibond 1210 epoxy to maintain a constant bond line thickness. All tanks, lines, and the vacuum shell were proof pressure tested and leak checked as shown in Table 3.3.

All cold joints (welds, epoxy bonds, Helicoflex seals) were leak tested warm, cycled three times to 77 K and re-leak tested warm as the dewar was assembled. Following dewar assembly, the tanks and plumbing were leak checked as a system warm and at 4.2 K. No leaks were found.

Table 3.3 Proof Pressure and Leak Checks

Component	Proof Pressure, MPa		Leak Rate, cc/s STP He
	Internal	External	
Main Tank	0.39	0.25	$< 10^{-9}$ *
Well	0.20	0.39	$< 10^{-9}$
Guard Tank	0.56	0.25	$< 10^{-9}$
Plumbing	0.56	0.25	$< 10^{-9}$
Vacuum Shell	0.25	0.10	1×10^{-7} **

*	Lowest detection limit of leak detector
**	Air equivalent leak rate is 6 x 10^{-8} cc/s. Would deposit 20 angstrom ice coating on main tank if cold 8 years: no impact on lifetime.

Magnetic Considerations (Jim Lockhart)

IV. Probe Development

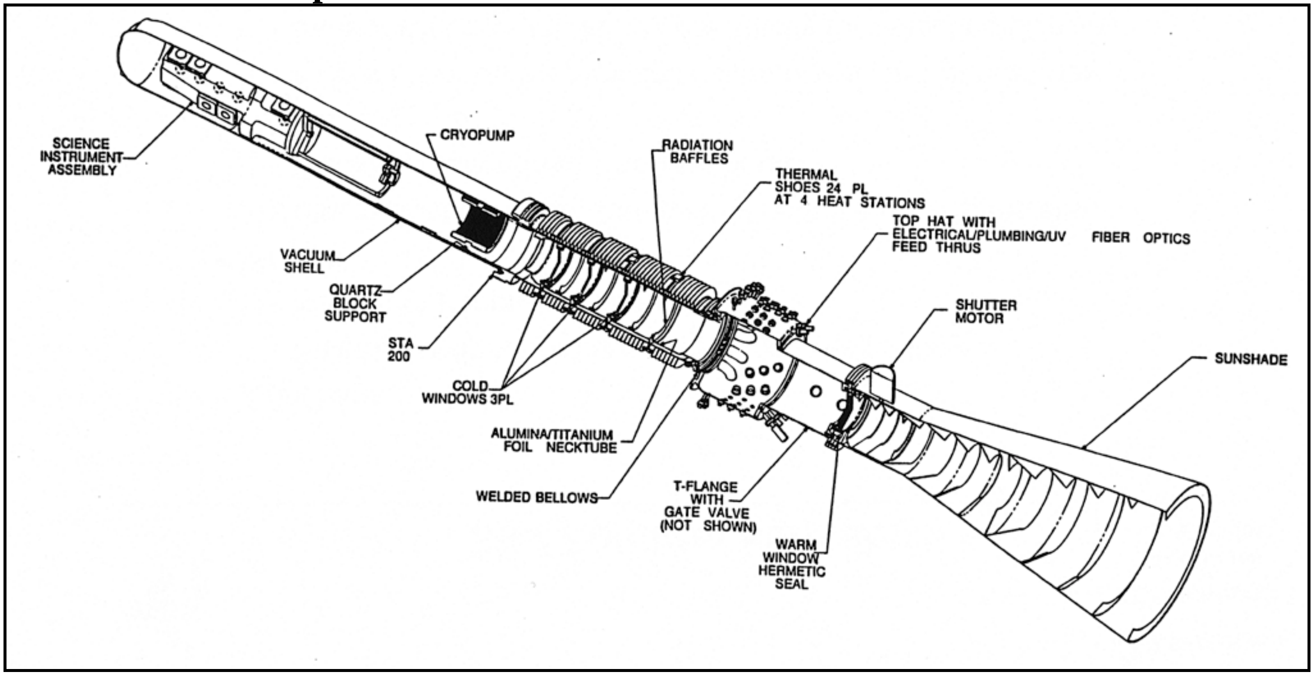


Figure 4.1 Probe

Probe introduction

The probe physically supported the quartz block/assembly containing the four gyros and the four SQUID London moment sensors inside a vacuum shell deep in the cold end of the Dewar (at the left of the figure). All of the electrical cabling, spin-up supply and exhaust plumbing, uv fiber optic cables (gyro discharge) led from the cold end through the necktube region to external feedthroughs in the top hat chamber. A 6" diameter aperture, capped with a sealing window allowed light from the guide star from the right of the figure to reach the primary mirror of the telescope. The sunshade/shutter assembly prevented off axis light from reaching the probe window.

The probe was assembled in a Class 100 cleanliness environment in a series of phases: cables were set first, then the Quartz Block Support, followed by necktube, top hat, and cross flange. The removable vacuum shell completed the closure of the Probe vacuum. All cables were thoroughly tested and the probe went through bake out at ?X °C and was leak tested. The outgassing rate was verified to specification.

The Probe was then shipped to Stanford where windows were installed, and the SIA itself integrated. After more verification, the Probe was integrated into the previously cooled Dewar. Finally, the Probe/Dewar was integrated with the spacecraft. The sunshade was installed before acoustic and thermal testing.

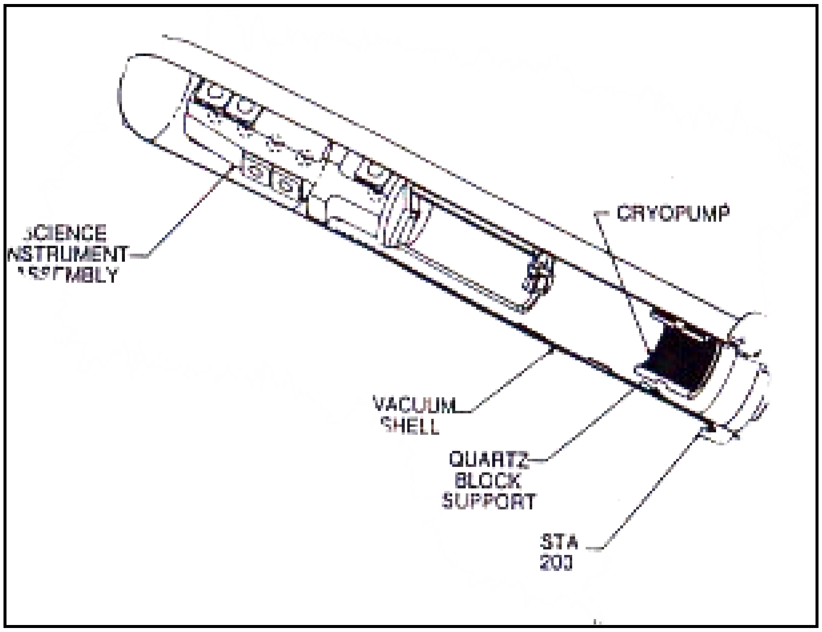


Fig 4.2 Cold End

The cold end included a Quartz Block Support (QBS), the Science Instrument Assembly (SIA), a passive, large surface area cryopump, and cold end cabling and plumbing. The vacuum shell assembly was removable to allow for repair or modifications to the SIA or probe. The cold end volume is within the superconducting lead bag magnetic shield which was expanded up against the Dewar well wall. The coldest part of the probe was at Station 200 where the Probe and Dewar are in thermal contact. This runs about 2.6K on orbit. The SIA is controlled by small heaters to within milliKelvin at a slightly higher temperature of XXX. The entire cold end is required to have extremely low remnant magnetic field for the gyros to read out correctly.

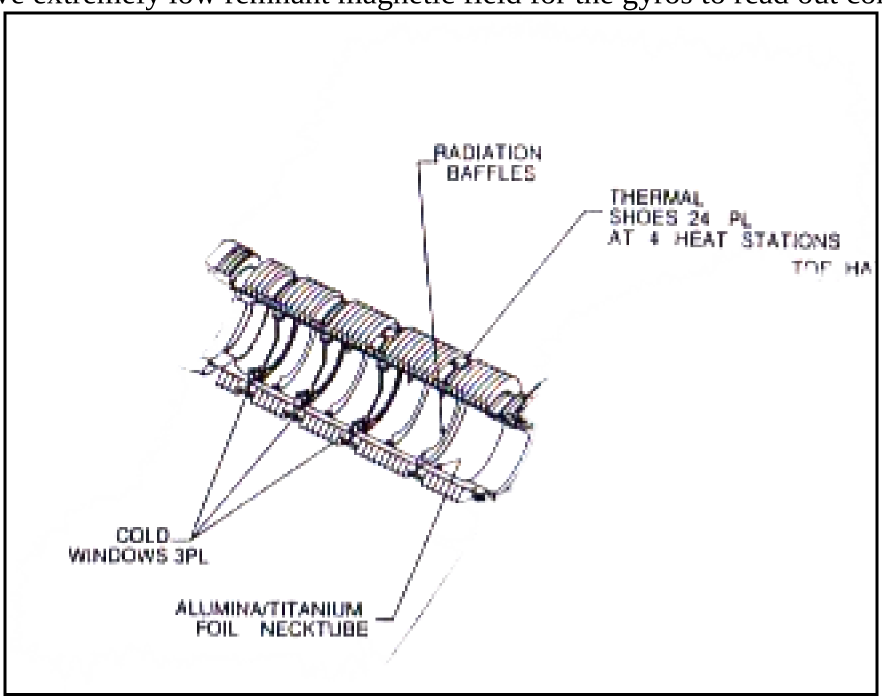


Fig 4.3 Necktube

The necktube region was concentric with the dewar necktube and was the area of the probe where everything was designed to control heat coming in from the top of the probe. The temperature gradient in this region was the difference between 2.5 K near station 200 and the top hat/cross flange region, which was essentially room temperature during ground operations and approximately 240 K in orbit. All the cables and plumbing lines and the necktube itself were required to have as low an axial thermal conductance as possible. The necktube was a highly optimized rib reinforced gamma alumina/epoxy wound tube with only 0.020 inch thick walls (similar to the Dewar neck tube). The dewar thermal control system of four heat stations and vapor cooled shields was connected to the four probe heat stations with mechanically activated contacts called thermal shoes.

All the cable and plumbing runs were thermally grounded at each heat station to intercept their conducted heat. The infrared absorbing Sapphire windows removed radiant energy and conduct it radially out through the heat stations to the helium vapor-cooled dewar system.

Radiant energy had to be trapped as much as possible, indeed heat maps showed very little heat passing through window 1, the coldest. At the same time, a cylindrical labyrinth had to allow spin-up leakage gas to have adequate passage to the top hat/cross flange and out to space.

Magnetics are less important in this section because everything was entirely outside the low field lead bag.

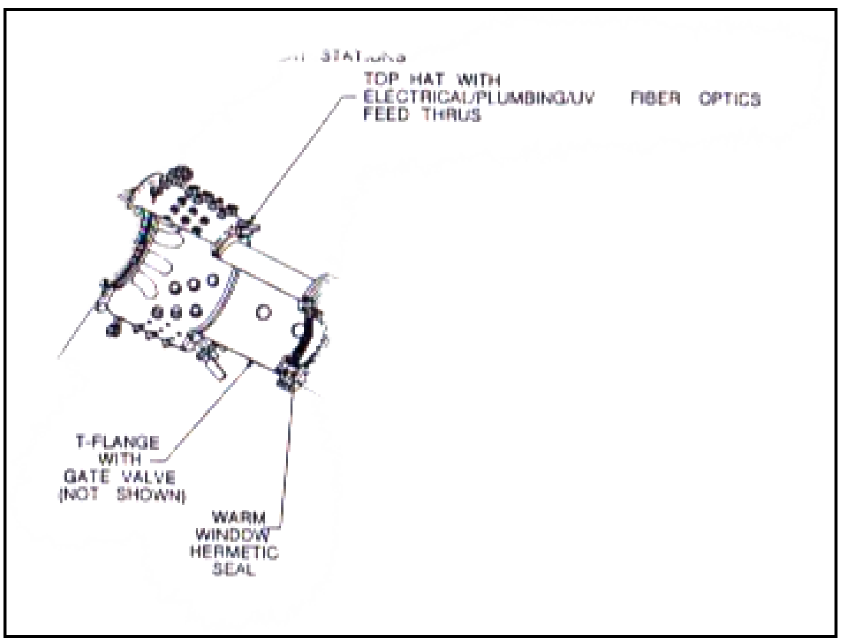


Fig 4.4 Top Hat/Cross Flange

The top hat/cross flange chamber provided all the hermetic feedthroughs required to connect the interior cables and plumbing to electronics and valving either on the exterior dewar vacuum shell or on the spacecraft. The two 6” probe venting valves and the vacuum sealed exterior window 4 are in the cross flange section. Thermal and magnetic considerations are minimal in this area.

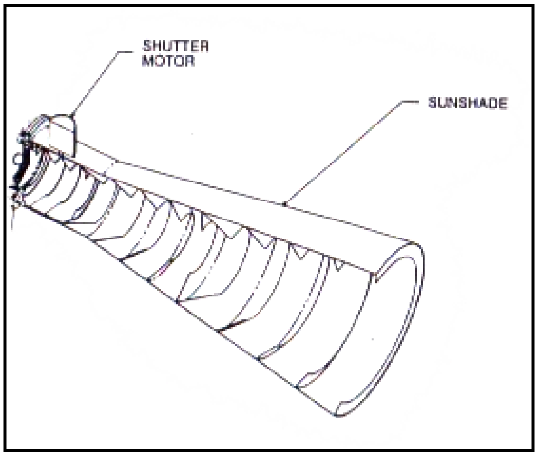


Fig 4.5 Sunshade/Shutter

The sunshade was a light weight “two stage” structure designed to trap off-axis light from stars other than the guide star from getting to the telescope. A shutter is designed to prevent thermal energy entering the probe during the 45 minutes per orbit that the view is of the relatively warm earth.

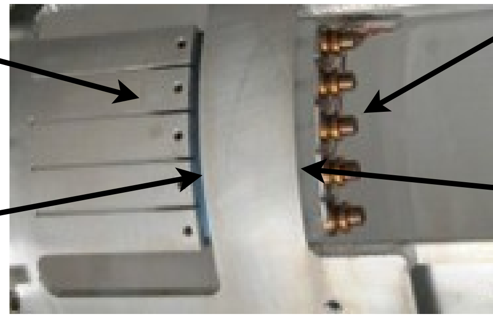
Probe Functional Description

The Probe high level probe requirements can be summarized in the following six areas: vacuum/cleanliness, magnetics, structural, thermal, cabling, and optical aperture.

***Structure and aperture*:**

The two primary driving requirements that created the basic form of the entire probe/dewar/spacecraft payload was that a maximum of guide star light within a 6 inch clear aperture would reach the telescope detectors, and that the SIA would be held securely in a ultra-high vacuum, within the nominally 2K dewar well. Furthermore, the physical support must have properties that allow the probe to survive transportation, cool-down of materials, and launch loads. The Quartz Block was machined from a boule of fused silica, with four mount lobes, drilled with five holes each, to provide 20 bolted contact points. The mating aluminum tube was machined with five slotted “fingers” at each of the four locations. This flexure arrangement allowed the high CTE (coefficient of thermal expansion) aluminum support to shrink in diameter, whereas quartz has a very low CTE.

Early prototype cold vibration tests indicated that the fingers were able to twist slightly under lateral vibration, develop heat by friction, and cause local spalling of the quartz. A redesign was affected for Probe-B that used machined Molybdenum “interface pads” as a low CTE intermediate element. Molybdenum was chosen because it has one of the lowest CTE of metallic materials.



The 6 inch aperture began at the shutter (see Probe Components; Shutter/Sunshade), through the vacuum sealed external window, and through three interior thermal radiation control windows held at each of the three coldest heat stations. At the same time, a radial gap had to be provided around the interior windows for He spin-up leakage gas to exit to exhaust valves in the top hat, without back pressure and possible arcing at the gyros.

Electrical and UV Fiber Optic Cables

The cables carried a variety of voltages, controls, and signals to and from the gyros, SQUIDS, and telescope detector. Temperature sensor information and heater current to control various temperatures for operations on the ground and in orbit.

In general, the cables had their own particular requirements, e.g. capacitance, shielding attenuation, breakdown voltage at certain He pressures, and round trip resistance. All the cables connect to an individual leak tight feedthrough in the Top Hat, down the necktube, through the QBS structure and to their final cold end connector.

Probe cable common requirements:
1) Nearly 100% shielding minimized interference and cross talk between any cables. The shielding was entirely “light tight” with the exception of very small vent holes to allow air out of trapped spaces within the cable or in the connectors. Shield performance requirements ranged from -80 dB to -110 dB effective attenuation.
2) Used thin walled, stainless steel shield assemblies in the necktube and top hat region to provide a high longitudinal thermal resistance (low parasitic heat leak).
3) Use non-magnetic Phosphor Bronze shields in the cold region essentially all running at the same 7K (normal He in tank) or 2.5 K (He superfluid).
4) Use either bare or polyimide coated .005 inch dia. Ph Br wire. A few heater wires were .010 in diameter to carry up to XXX milli-amps.
5) All required end to end electrical isolation for each conductor, and shield isolation from structure (ground loop prevention).
6) Must pass rigorous standard testing: capacitance, hi-pot (insulation breakdown), shield to wire shorts, shield to probe ground shorts, etc.

The table below shows more detail about the cable count, and conductor count, and the total conductors for the entire probe.

Cable Type	Cable Quantity	Conductors within one shield	Total Conductors	Comment
Suspension coax	35	1	35	6 cables + spare for each gyro, PM
Ground Coax	5	1	5	1 per gyro + PM
SQUID	24	4 each	96	2 twisted pairs each shield
Telescope detector	1	40	40	2 26-pin connectors at cold end
Instrument. Temp Sensors	3	55	TBF	total of 92
Instrumentation Heaters	3	55	TBF	
UV discharge	3	6 each	18	3 twisted pair per cable
Totals	71			

The Probe is required to keep the Science Instrument within a low vacuum, extremely low magnetic environment.

Vacuum/cleanliness

The probe vacuum was required to be capable of 10^{-9} Torr. This required leak tight seals and feedthroughs to prevent air from entering especially during ground testing. Furthermore, both virtual leaks and outgassing of materials had to be carefully controlled so that the required vacuum could be attained in a reasonably short time.

Virtual leaks are generally very small volumes that have air trapped in them with tiny escape passages. The most common are fasteners in blind tapped holes and electrical connectors with tight fitting parts. Most screws and bolts had to be drilled out down the centerline to allow air to exit. Connectors had multiple vent holes drilled to prevent close fitting parts from trapping air. Electrical cable shields had to have vent holes every inch or two.

Feedthrough design was restricted to all-metallic for the most part. Because every feedthrough had to have a (ceramic) insulator, we quickly determined that brazed assemblies were the best possibility. The ceramic was metallized by vapor deposition, and brazed into a stainless steel part that could be welded into a stainless steel top hat.

The plumbing feedthroughs likewise were welded. Only the multi stranded fiber optic cables were bonded.

The chosen seal design for the probe was Indium plated “c” seals (named for the shape of its cross section. The seals ranged from 1” dia. for small plumbing connections to 12” in dia. for the top hat to cross-flange seal. A titanium alloy created the basic circular spring, and then gold and indium coatings were applied. The seals were always replaced after any disassembly.

The two 6” diameter probe venting valves and the four 1.5” spin-up exhaust valves used a low permeability nitrile rubber seal in a “Vaterfly” valve (VAT Corp.) These were blanked off and pumped to prevent air permeation during leak testing operations. In space permeation was not an issue.

Cleanliness had three aspects: outgassing from materials or fingerprint oils, particles that might find their way into the gyro/housing gap, and magnetic particles that could migrate to the essentially field free zones near the gyros.

Materials were chosen very carefully throughout the probe. Metals were preferred, and insulators were either ceramic (fired alumina), PEEK, or polyimide (Kapton). Small amounts of teflon tubing were used to connect spin-up supply and vent lines to the gyro housings. Any bonded parts used Epibond, a proven cold temperature and extremely low outgassing material. Typically, epoxy was “degassed” in a vacuum to release air bubbles entrained in the two part mixing process.

The ultracleaning of parts was one of the major efforts in the build. Everything was subjected to manual cleaning, ultrasonic cleaning and high pressure spray cleaning using distilled water. Every part had to pass a particulate sampling test to level 100. The strategy was to clean everything to stringent standards and then use every technique available to keep items clean as they went in to higher and higher levels of assembly. All assembly work was done in a down-flow Class 100 clean room. All personnel used gloves, clean room suits, hoods, booties and masks. Often vacuum systems were employed to capture any particulates from very limited drilling, tapping and other operations that might generate particles. Solvents were high purity to prevent contaminants that might remain after evaporation.

The sealed Probe was leak tested by pumping with a leak detector in the line. An air heated shroud was used to bake out at 150° F for several days. The temperature was kept well below the epoxy glass transition points.

Magnetics

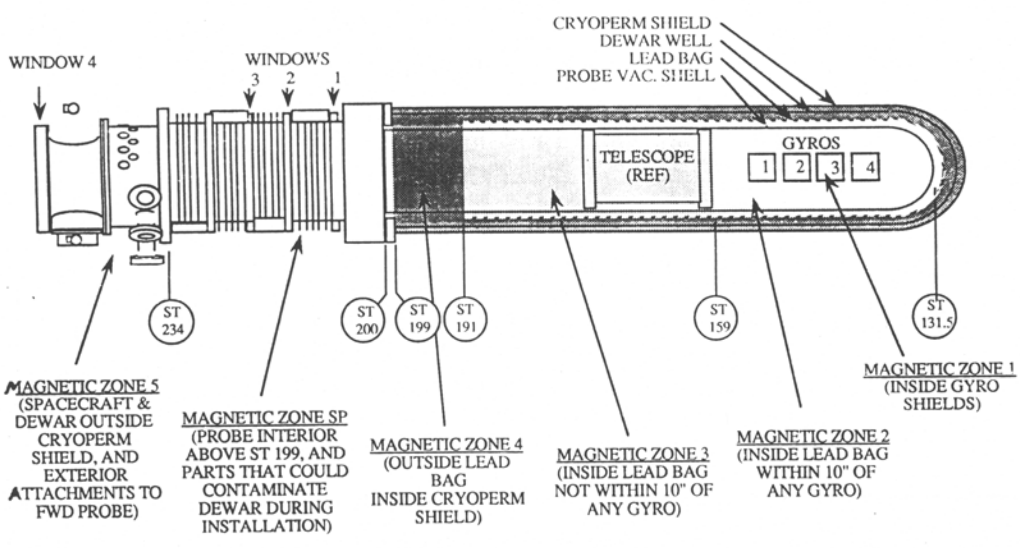


Fig 4.6 Magnetic Zone Map

The overall approach to magnetics was to divide the dewar/probe/SIA into six magnetic zones, each with its own requirements taking into account whether the part was within the low field zone created with the lead bag expansions and the distance from the gyros. Each and every part was tested individually for its zone requirements. Because joining and bonding processes might contaminate assemblies, they were further screened. The issue being that if even a one inch long cable bellows was out of range, then the entire cable would be out of range. If it was not detected at the assembly level, a cable for instance might actually get bonded, and possibly might have to be removed, an extremely difficult operation, with severe contamination issues. It was estimated that over 7,000 parts had to be screened, tracked, recorded etc. Fortunately very few failed.

Magnetic zone 5 had few requirements. Even permanent magnet motors were allowed.

Magnetic zone SP (interior of the probe above Station 199) had requirements that were not very stringent. The volume was completely outside the lead bag and would cause negligible magnetic dipole field at the gyros. Fortunately, this allowed stainless steel cable shields, which were the best material in terms of thermal resistance.

Magnetic zone 4 had similar requirements to SP. This was the area where the cable design transitioned to phosphor bronze shields.

Magnetic zone 3 and zone 2 had essentially the same requirements. We manufactured and tested everything to the more stringent zone 2, to be conservative.

Magnetic zone 1 was inside the niobium gyro shields; the probe had no items there. The approach after parts screening was to demagnetize anything that might slip through at the upper assembly levels. The entire completed probe except the demountable cross flange was shipped to a special facility at NASA Ames near Moffet Field CA, where a magnetics test set-up had been created for the Pioneer space probes. The probe was rotated about its long axis in a large helmholtz coil, to negate the earth's half gauss magnetic field. Then it was demagnetized using diminishing AC magnetic field.

In order to achieve low remnant fields in the cold end of the probe, we had to control the levels of iron and nickel that might be found in aluminum alloys, copper alloys, and electroplating materials. Furthermore even machining could embed tool particles.

Probably the most challenging was to find high purity Phosphor Bronze, the choice for the long cold end cable shields. Ultimately we had a small foundry in Ames Iowa cast and forge Phosphor Bronze (alloy B) with 5 nines pure copper and 5 nines pure tin melted in a in a graphite container. All the shield tubes, multi connector blocks etc were drawn from these billets. No problems ever occurred.

Thermal

The spacecraft and dewar outer vacuum shell received approximately 1366 Watts/meter^2 of solar radiation load, and the spacecraft power system supply XXX watts into the electronics boxes. Ultimately, the dewar vacuum shell temperature (293 K in the laboratory; 240K on orbit) was the source of heat reaching the He bath (related to lifetime) and to the heat reaching the Science

Instrument (required to be controllable just above 2.6 K). The heat was conducted by PODS support struts, layers of MLI, dewar and probe composite necktubes, electrical cables and gaseous He plumbing lines. Radiation occured between surfaces depending on their temperatures, view factors and emissivities.

The Probe and Dewar designs featured four key methods of preventing heat from the Dewar vacuum shell reaching the science instrument. These are minimizing conduction and thermal radiation, absorbing thermal radiation and helium vapor cooling. The figure below represents the design of various elements that explain the thermal control system in the critical neck tube region. Probe and Dewar are parts of an integrated design, especially in this area.

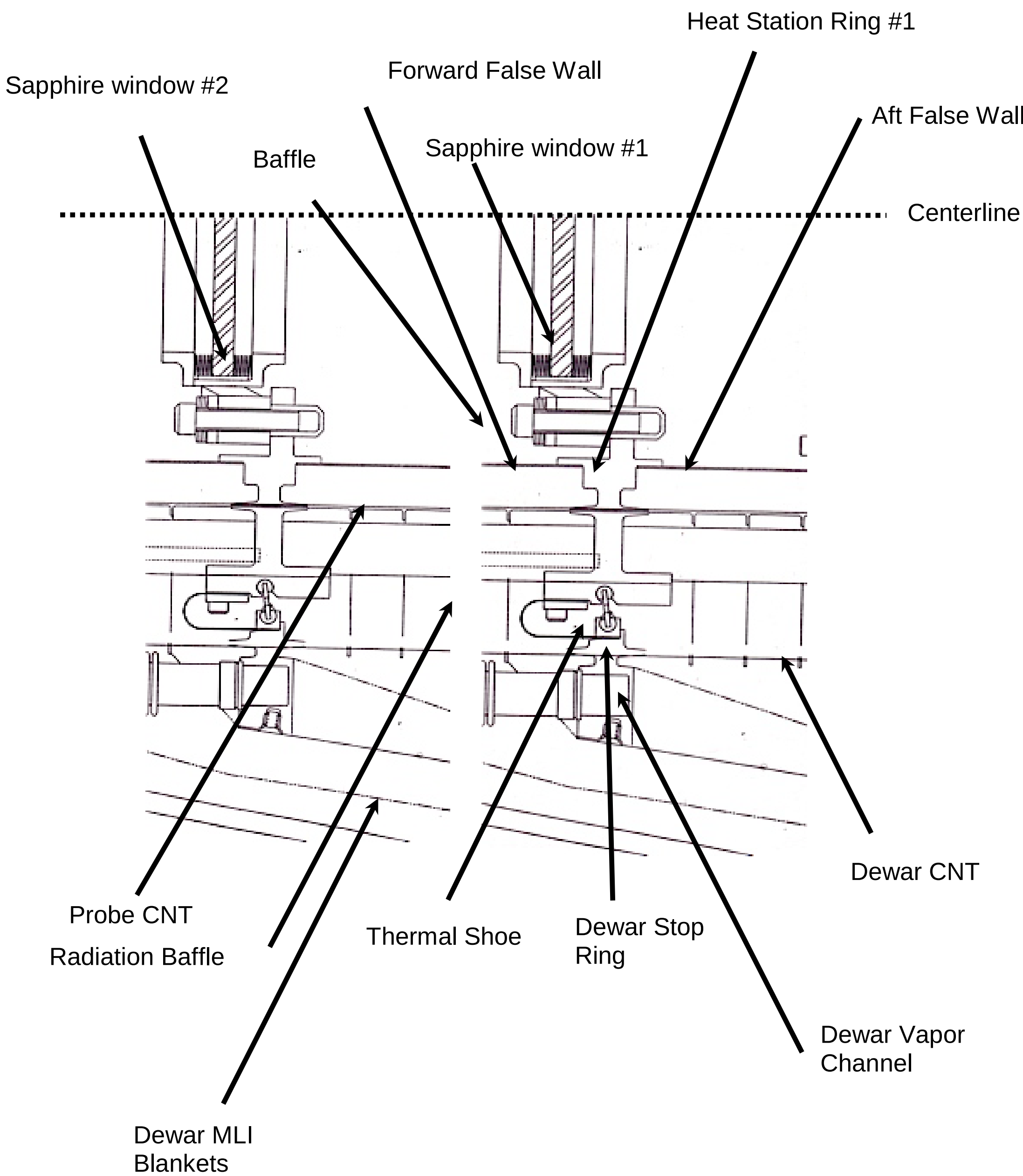


Fig 4.7 Section of Dewar and Probe in Necktube Region

Radiation from warmer areas of the probe (left side of the figure) was absorbed by the Sapphire windows and conducted to the probe heat station rings through the window frames, and bolted flexures. The baffles and false walls served to intercept radiation from penetrating around the window frames. The cables were bonded into the heat station ring, transferring heat conducted axially into the ring.

Outside the probe necktube was the heat exchanger rings which carried this collected heat to the thermal shoes and into the dewar stop ring via an Indium-plated interface. Heat was then carried through the dewar necktube into the circumferential cold vapor channels. The channels were interconnected with tubing. The vapor was brought from the main tank, through the guard tank, and then to three successive channels before exiting to the thruster attitude control system.

Every cable, plumbing line and structural element in the probe and dewar conducts heat from the dewar vacuum shell (293 K in laboratory conditions and about 240 K in orbit) to the coldest part of the system, the probe-dewar contact at station 200. The table below summarizes thermal design controlling conduction.

Item	Design
Cable shields	Thin walled stainless steel alloy tubes
Electrical Conductors	36 gauge (.005 inch dia.) Phosphor bronze
Plumbing lines	Thin wall Stainless Steel alloy tubing, high thermal resistance welded bellows
Vacuum necktube	Four layer layup, optimized wind angle, co-cured ribs for optimal reinforcement.
Vacuum necktube helium tight metallic liner	.001 inch thick low conductivity Titanium foil liner.
PODS	Low conductivity support struts.

Probe Components

False Walls

Radiant heat from the warm forward section of the probe including window four and the top hat and cables in the top hat area has a significant view factor to the cold end including the telescope, cables and the QBS.

The baffles were black anodized 1100 aluminum on the warm side to absorb infrared and conduct heat to the false wall cylinders and then to the heat station rings. The cold side was gold plated to minimize radiation to the cold areas.

The false walls were generally 1100 Aluminum, gold plated on the exterior (facing the cables and neck tube liner) and black anodized inner surfaces absorbed infrared radiation.

The axial labyrinth created by the succession of baffles, window frames and false walls was designed to allow gas leaking out of the rotor to cavity gap to escape through the probe interior to the 6 inch valves and out to space without excessive back pressure at the gyros, which could lead to arcing, damaging the gyros.

Construction: The false wall cylinders were made of highly conductive soft 1100 Al sheet that was spin formed on mandrels, re-annealed to a semi-soft condition, and either gold plated or black anodized (hard anodize with black dye). They were bonded to a circular interface of the heat station rings with Epibond epoxy. The baffles were made in three circular segments to allow removal and replacement when the windows were installed. Patches of Indium were plated at the fastener points to conduct heat.

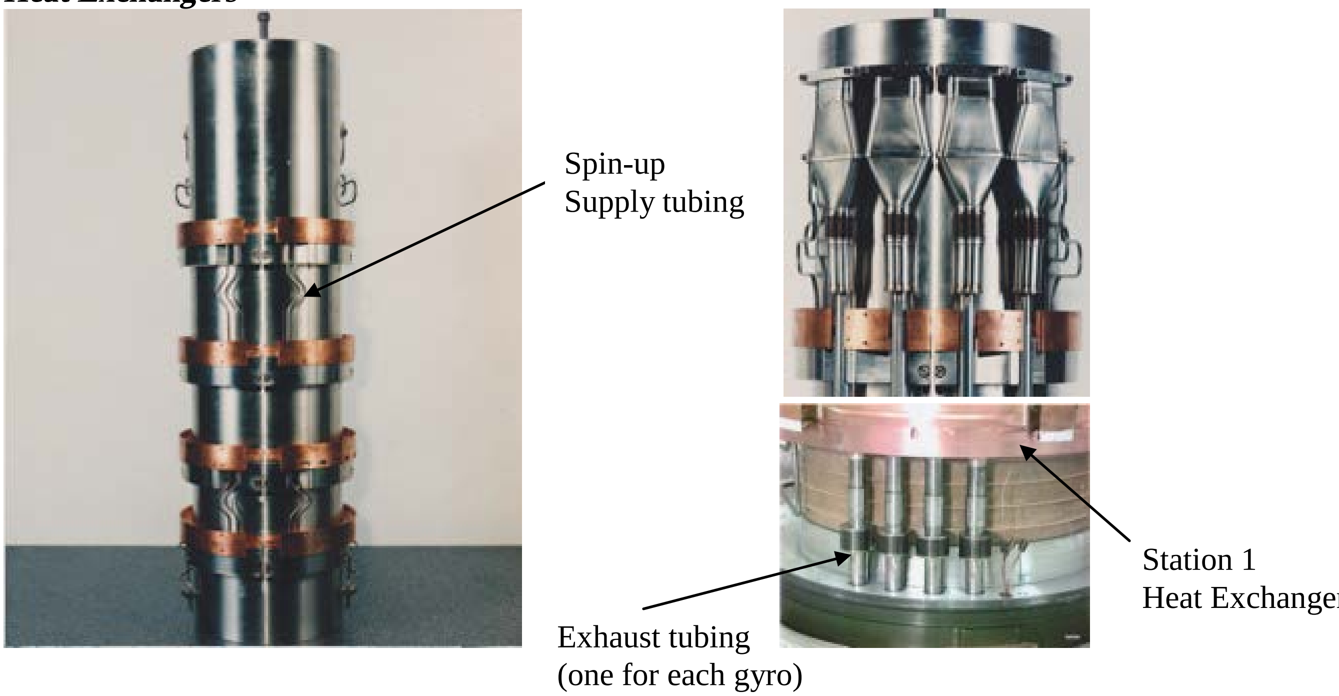
Thermal Shoes

Picture Needed

The thermal shoes were developed in order to make good thermal connections between the copper heat exchanger and dewar vapor cooling system as the Probe reached its final position in the dewar well (in full thermal contact at Sta. 200). An important requirement was that the probe had to be able to be removed, upgraded or repaired, and re-inserted for indefinite cycles, so the thermal shoes had to be re-aligned, and easily refurbished (new springs).

The outermost ring was bonded to the interior of the dewar necktube, against the titanium liner. This “stop ring” caught the thermal shoe itself as the probe came within .2” of Station 200. This forced the shoe to slide radially until contact was made and the spring compressed. The radius of curvature of the mating parts was the same. The stop ring side was plated with rhodium, an extremely hard surface to not allow any adherence of Indium from the thermal shoe.

Heat Exchangers



The gyro spin-up operation required Helium be plumbed down to the quartz block into the gyro cavity imparting spin the levitated gyro spheres. This gas was then carried back up to space through a series of circumferential plumbing channels and axial tubes that were gradually larger in the warm end to prevent back pressure at the gyro support electrodes. Thermally, the incoming gas from high pressure bottles was at about dewar vacuum shell temperature, and had to pass around channels in the heat exchangers, and channels in the QBS, cooling the gas to the required 2.5K before it impinged on the rotor. The cooled exhaust gas served to cool the heat exchangers and the incoming gas. This reduced thermal upsets caused by the incoming warm gas at the critical spin-up operation.

Windows

The windows intercept and attenuate infrared and EMI radiation that enters the optical aperture of the cryogenic payload before it reaches the science instrument assembly. There are four windows. Windows 1, 2, and 3 are located within the probe neck tube at Heat Station 1, 2, and 3. Window 4 is located between the T-Flange and the sunshade assembly and is hermetic sealed to maintain the integrity of the ultra-high vacuum within the probe. All four windows were made using single crystal sapphire 0.275 inches thick. Windows 1, 2, and 3 are 6.5 inches in diameter and Window 4 is 8.0 inches in diameter. The windows were tilted by 2 degrees to minimize ghosting and the crystalline axes of adjacent windows were opposed to minimize birefringence effects. By mounting the windows at the three heat stations and at the top of the T-Flange the heat from the intercepted IR radiation flows to the Dewar vapor cooled shields and vacuum shell.

The outer surface of each window has an anti-reflection coating to minimize surface reflections and ghosting while the inner surface coating varies depending on the window location. The inner coating on Window 4 is a combination EMI rejection/low emissivity coating while on

Windows 1-3 it is a low emissivity coating only to minimize IR radiation transmission window to window down the probe. The combined visible transmission of the four windows with coatings is about 37% (note: check this value).

Clamping the coated sapphire window between an upper and lower spring bellows in a circular mounting ring mechanically supports windows 1-3 but there is no vacuum sealing requirement for these windows (see Figure 4-xx1). The engineering challenges involved in developing the Window 4 mechanical mount and hermetic seal required many design iterations and a significant test effort to arrive at the final design. The solution was to support Window 4 between two Indium coated "C" seals with a thin layer of gold on the window surface and with the "C" seals maintained in compression by a spring bellows (see Figure 4-xx2).

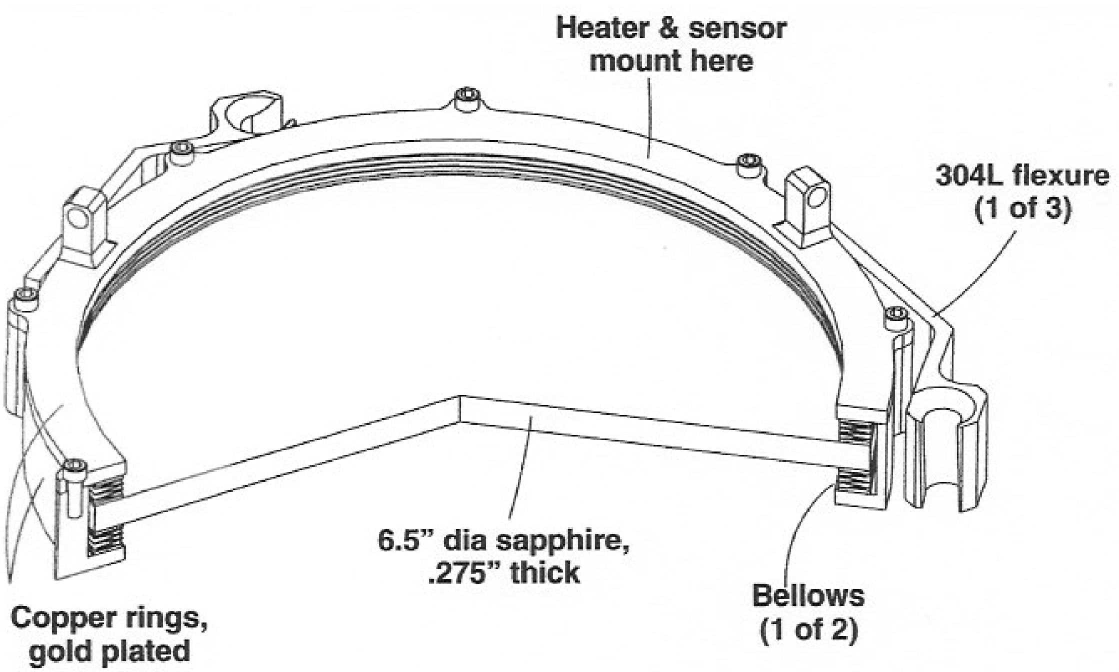


Fig 4.8 Windows #1-3

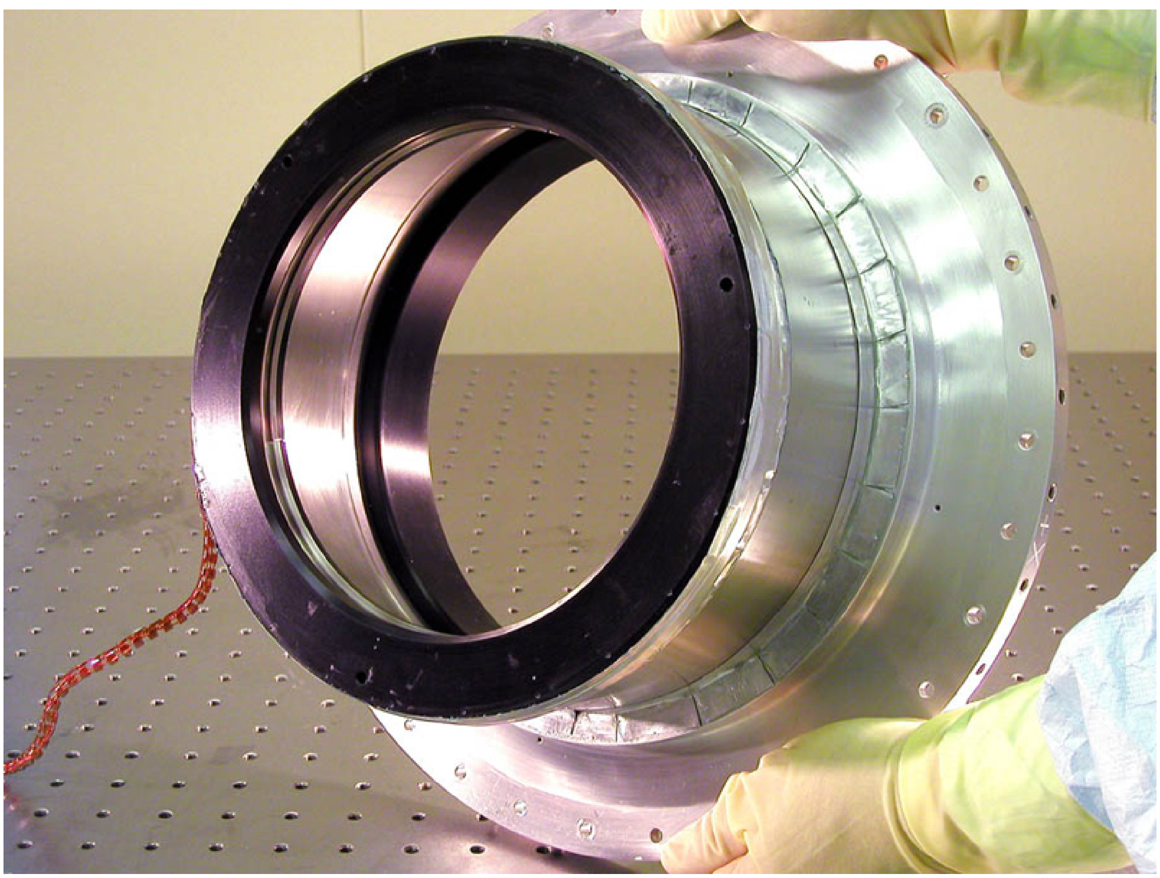
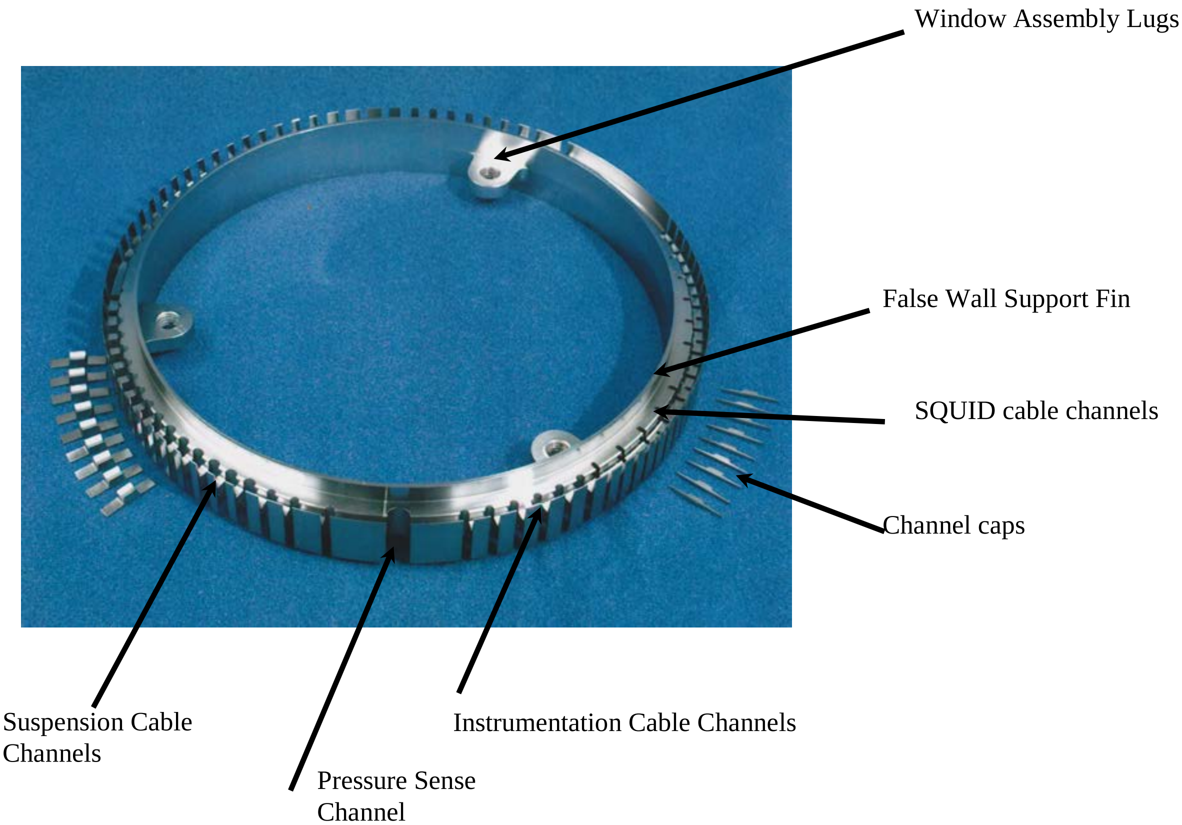


Fig 4.9 Window #4

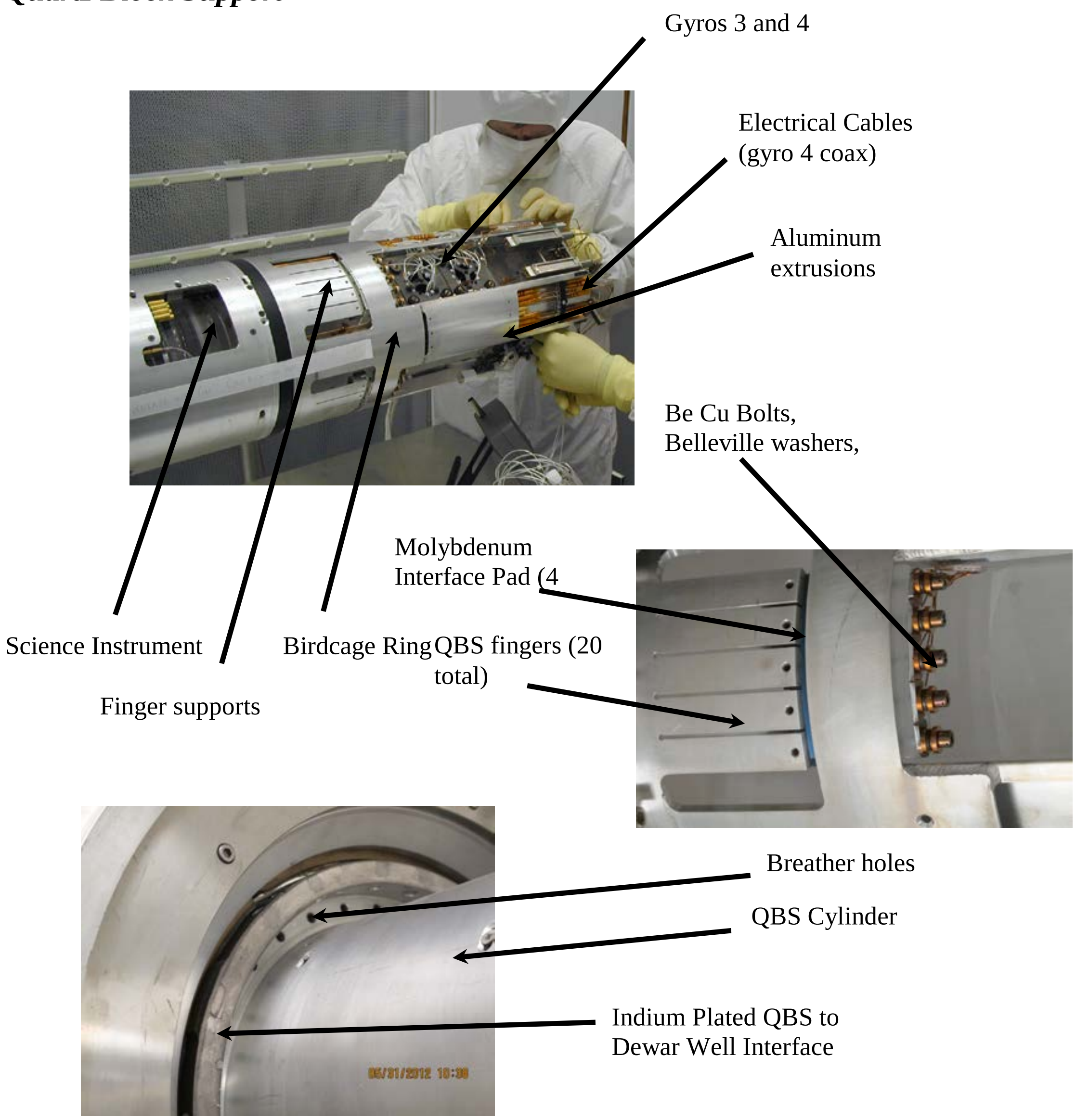
Heat Station Rings



The four heat station rings were placed just inside the composite neck tube at the same z-axis location as the heat exchangers, thermal shoes and dewar vapor cooling system. Beginning from the interior, the three lugs shown in Fig ZZ were attachment points for the window assembly. Next, the circular fin provided a bond surface for the false walls, forward and aft. U shaped cutouts were located around the circumference as bond locations for all the cabling. The very outside circumference was completed by bonding in channel caps, providing a continuous surface for the FM 73 bond to the interior of the neck tube.

The heat station rings were solid copper for good conductivity, and plated with rhodium (silver color) to provide an oxide free surface for the epoxy bonding. They were turned, milled to shape, and the cutouts were fabricated using wire EDM techniques.

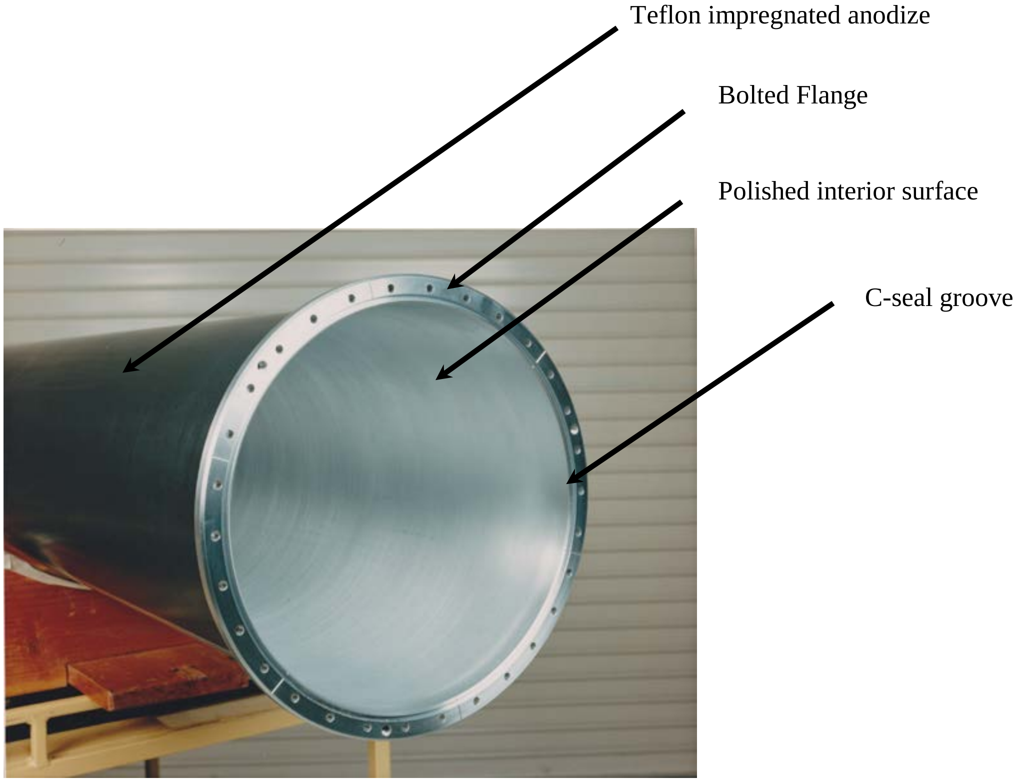
Quartz Block Support



The QBS was a long Aluminum cylinder welded to a Station 200 annular forging at the forward end, and extrusions used as cable trays to contain cables and plumbing. The Quartz Block/telescope was fastened to four lugs machined in the quartz. Flexible fingers allowed the aluminum (high CTE-Coefficient of expansion) to shrink without over stressing the Quartz, which has an extremely low CTE. The cylinder was designed to handle launch and shipping loads

A plated layer of Indium at the cold interface provided excellent conductivity to the Dewar well. Approximately xxxxx lbs of force was needed to crush the indium.

Vacuum Shell



The vacuum shell was a removable closed end tube that completed the vacuum tight probe chamber at the cold end. It was bolted into the QBS with a replaceable c-seal.
It served additionally to force the blades of the lead bag retainer tight up against the lead bag, and against the well (the coldest part of the probe/dewar interface). Surface heaters were bonded to raise the temperature of the well to 10K during the low temperature bakeout phase of the spin-up operation.

Cryopump

The cryopump is a welded assembly of 314 sintered titanium fins placed at the coldest area of the probe just below Window 1. The central opening was required to be slightly larger than the optical aperture and the outer diameter was constrained by QBS clearances.

Estimates of the total cold surface area in the probe that could be heated to 10 K were about 7.3 m^2. The decision was made to use a very high surface area passive cryopump that could have heaters and thermal isolation standoffs to bring it to 10K, driving off all the surface helium. This "regenerated" the component to scavenge Helium remaining in the probe. The vacuum requirement was $1x10^{-10}$ torr for the duration of the mission. Because vacuum predictions are so nebulous, and the vacuum level so critical to gyro spin-down speeds, as much material as was practical was used. Estimates were that the available surface area exceeded the derived requirement of 44 m^2 by a factor of five. The results were spectacular with vacuum estimated from spin-down rates to be 10^{-13} torr or lower.

The anticipated difficulty in cleaning the fins and assembly to level 100 standards required time and effort with high velocity DI water flush. Magnetics were less of an issue due to the unit being outside the lead bag volume.

Top Hat

The Top Hat included all the electrical, optical, and various plumbing feedthroughs welded into a stainless steel cylindrical structure. It supported the cross-flange/window 4 and was bonded to the warm end of the necktube assembly. A xx diameter flange sealed to the Dewar with an o-ring.

The electrical feedthroughs include three types:instrumentation, suspension/ground, and SQUID. Because of the Probe ultra-high vacuum requirement, each feedthrough had to be as leak tight as can be practically measured with a helium leak detector: 10-9 to 10-10 range. Generally, they were either vacuum or hydrogen brazed (fluxless) with silver/gold alloy solders. The suspension feedthroughs were triaxial structures with two ceramic sleeves as insulators. This provided a “floating ground” so that any desired voltage could be applied to the suspension shields. The SQUID feedthroughs had a six pin arrangement. The instrumentation feedthroughs used a military standard 55 pin arrangement with proprietary pin by pin glass insulators, fired to melt and form a hermetic seal. Each feedthrough was welded by hand into prepared locations from the inside, avoiding trapped volumes (virtual leaks). All pins were gold plated for excellent contact. Every internal part was drilled for venting.

The plumbing feedthroughs were generally made of tubing formed into a 45 degree bend and welded into the cylindrical area of the top hat for outer connections, and at the base of the top hat for bonded connections down to the cold end. The caging and spin-up supply lines were .25 inch diameter stainless tubing, and the large exhaust lines were 1.25 diameter pipes. A single pressure sense line was .375 inch diameter tubing.

Because the Dewar vacuum shell ran at very different temperatures throughout the build, ground test and space phases of GP-B, this lengthening and shortening was accommodated by a xxx diameter welded bellows, which could allow up to xxx inch excursions.

The interior of the top hat was entirely gold plated to provide a low-emissivity surface to control thermal radiation reaching the cavity down to window 3. In addition, an internal cylindrical gold plated radiation shield was fastened to the ring below the bellows, further controlling radiation to the cold end.

Cross Flange

The cross flange structure is a xxxx inch long cylinder primarily to provide two 6 inch diameter motorized butterfly valves. On the ground, one or both valves provided high gas conductance for laboratory pumps to evacuate the probe. In orbit, the valves evacuated to space. The window 4 assembly sealed to the cross flange at the forward end.

Because there were no welded elements of the cross flange, it was made of aluminum alloy to conserve weight. The probe burst disc and a pressure sensing port were made leak tight with c-seals.

Sunshade Assembly

The sunshade assembly, which is made up of the sunshade and shutter, is bolted to the cross-flange at the top of the flight probe. The primary function of the sunshade assembly is to prevent extraneous stray light from reaching the interior of the probe and interfering with the ability of the science telescope to accurately measure the position of the reference guide star. A secondary function is to prevent earth albedo from reaching the science instrument during the half of each orbit when the earth occults the guide star due to a concern about infrared heating of the cryogenic science instrument. A number of guide star candidates were considered during the development of the GP-B mission. The ideal guide star would be located close to the celestial equator (maximizes the frame dragging effect) and have an accurately known proper motion that has been measured relative to distant quasars at the edge of the universe. Potential guide stars considered during the development of the GP-B experiment included Rigel, HR 5150, and IM Pegasi (HR 8703). In the end IM Pegasi (apparent magnitude = +5.9, declination = +16.8 deg, and ecliptic latitude = 72 deg) was selected as the guide star for the GP-B science mission.

The sunshade assembly was designed, built, and tested by AlliedSignal of Teterboro, NJ under contract to Lockheed Martin. The sunshade assembly was designed and built prior to the final selection of the GP-B guide star. Requirements were developed to ensure that the sunshade assembly would provide the necessary stray light rejection from the sun and moon for all of the candidate guide stars under consideration. The sunshade stray light requirement is an attenuation of $> 10^9$ for sources > 18 deg from the optical axis. This was achieved using a two-stage sunshade design as shown in Figure 4-x. A two-stage design is higher performance in that stray light has to go through a minimum of two bounces to reach the sunshade exit aperture as opposed to one bounce for a single stage design. Shutter requirements were a lifetime of 8000 open/close cycles, failsafe to the open position, and an optical attenuation of 10^5 along the optical axis with the shutter closed. The forward end of sunshade assembly also served as mounting location for the spacecraft omni antennae and sun angle sensors. Additionally there was a mass constraint of $\leq$ 13 kg and a length constraint of 79 inches so that the sunshade would fit within the Delta II fairing envelope.

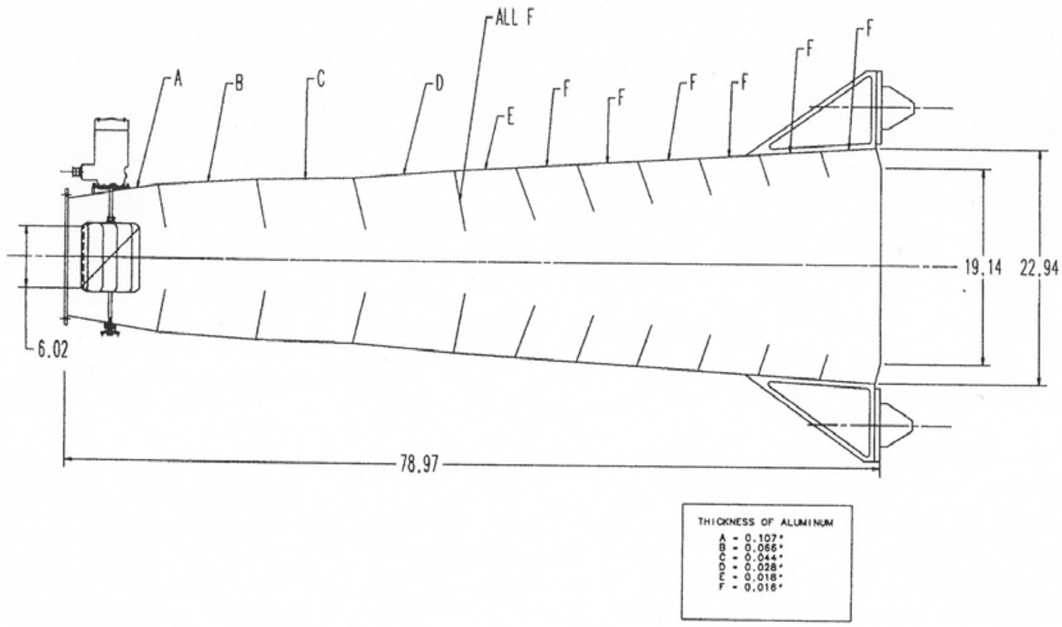
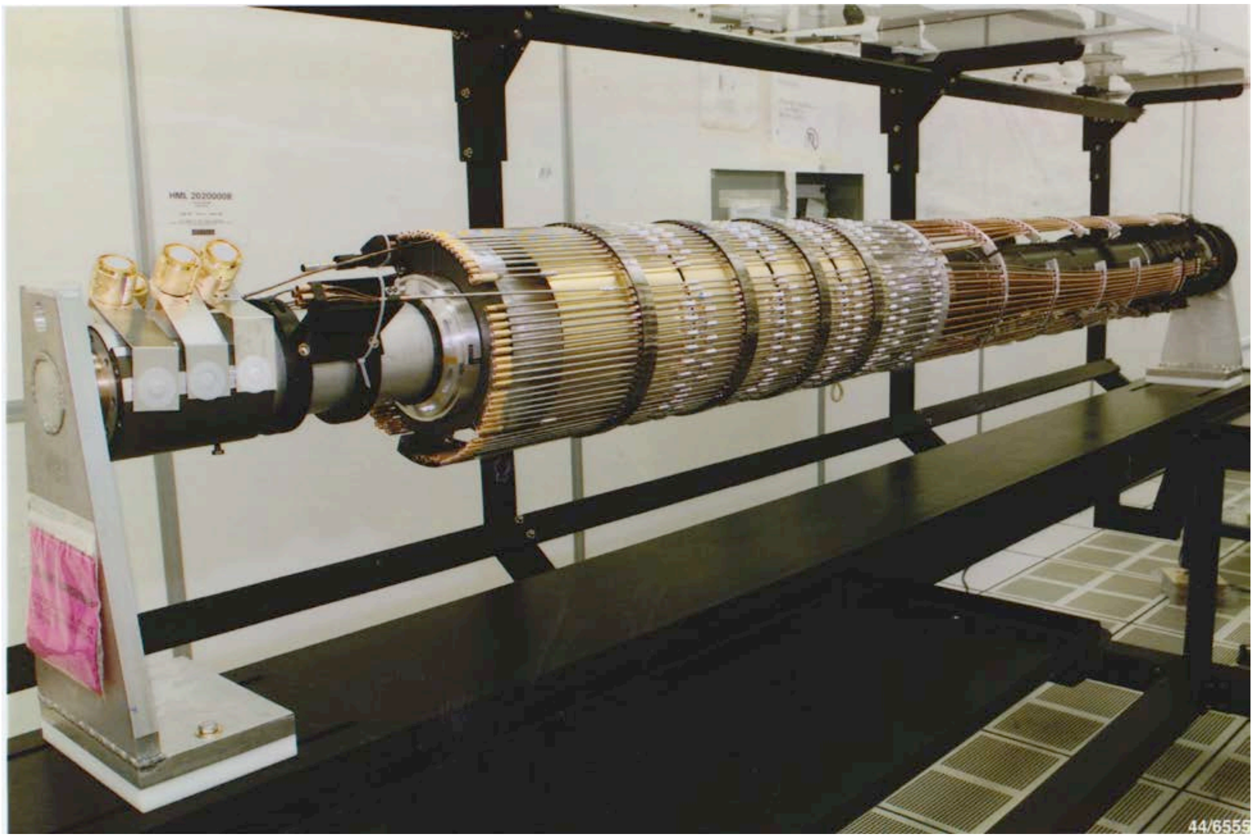


Figure 4-x: Sunshade Assembly

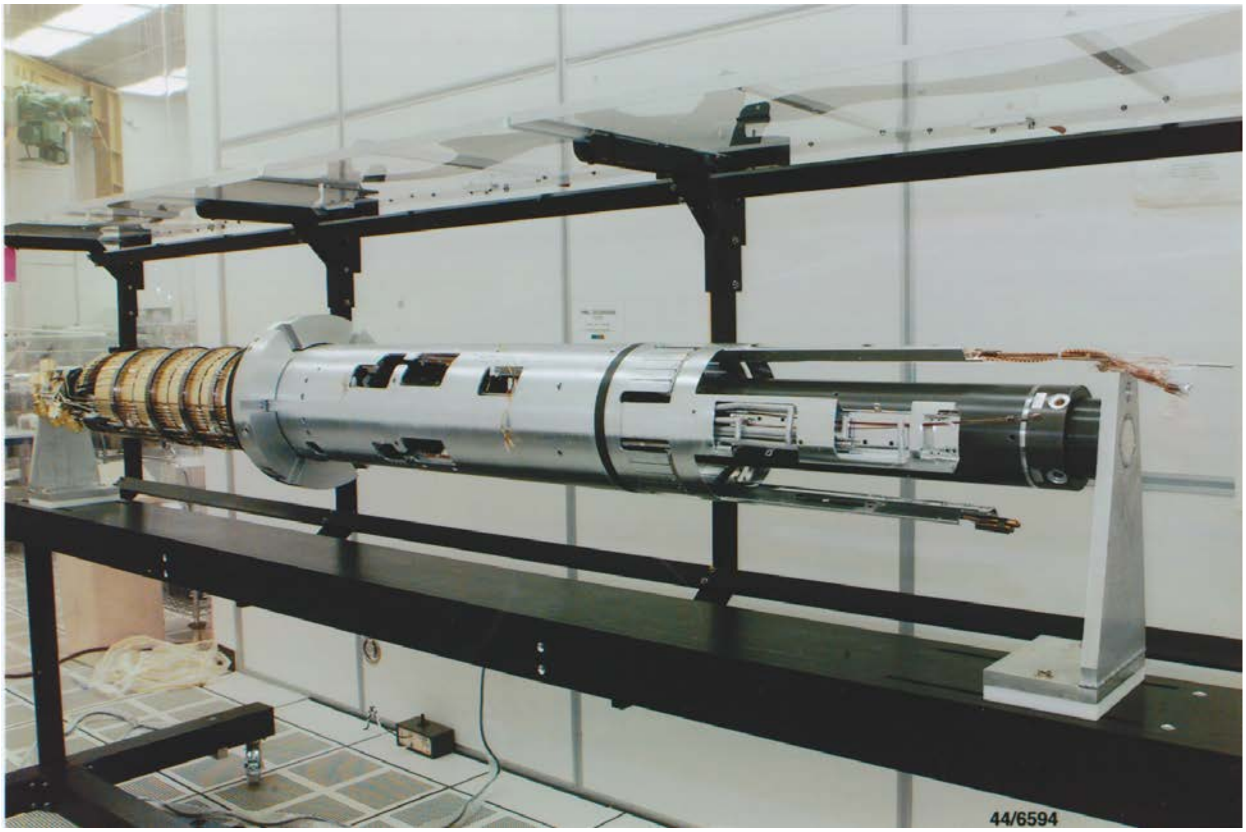
The sunshade housing (lower section) and baffle assembly (upper section) were made from machined aluminum and aluminum sheet respectively. Meeting the mass, structural frequency, and stiffness requirements was quite demanding and necessitated the iterative use of CAD and structural analysis tools to arrive at the final optimized design. The shutter was a shell with a hole cut through it that was rotated through 90° using an externally mounted DC motor to close. A spring inside the actuator housing drove the shutter to the open position when power was removed from the motor. This spring also served as the failsafe device to open the shutter in the event of a motor or electronics failure. The internal surfaces of the sunshade were painted using Z306 flat black paint to absorb internal reflections and meet the off axis attenuation requirement. The sunshade assembly completed thermal cycling, vacuum bakeout, shutter life cycle, modal, and vibration testing prior to delivery to Lockheed Martin and subsequent integration with the GP-B cryogenic payload.



The Probe was assembled from the inside out in a series of operations using a long tube to support and locate components consistent with following installations. The Probe Assembly Tool was a long, precision machined tube that could be rotated, positioned vertically or horizontally, cantilevered, and relocated for various operations.

All the suspension, SQUID and instrumentation and heater cables were bonded onto the heat station rings on the warm end and prepositioned saddles at the cold end. Picture n below shows the PAT tube supported with trunnions at far left and far right. At the left side (warm end), the gold plated 55-pin connectors are supported temporarily. Later, the top hat will be installed and these connectors will be mated to the vacuum feedthroughs welded into the top hat.

The four heat station rings are next towards the cold (right) end of the assembly. The cables are bonded one by one at each heat station ring and on saddles at the cold end. The cables are constructed with non-magnetic Phosphor Bronze at the cold end and low thermal conductance stainless steel at the warm end.



Picture 2 shows the Quartz Block Support (QBS) installed at the cold end. To accomplish this, the PAT was cantilevered and the QBS guided on rails over the cables and saddles.

The Composite Necktube (CNT) was installed in a vertical orientation using a specially made dewar/oven that brought the entire probe to LN2 temperature to shrink the entire probe. The warmed necktube was lowered over the heat station rings and the QBS interface which had FM73 epoxy tape applied. The LN2 was drained and heaters raised the temperature to cure the epoxy.

In a vertical orientation the top hat was installed at the warm end using cryogenically compatible liquid epoxy. The instrumentation/heater cable connectors were transferred to the welded feedthroughs in the top hat, and the PAT was pulled out, leaving the assembled structure, which was supported by the heavy central tooling ring attached to a modified fork lift fixture.

With the bore now clear, the cryopump, internal windows, various short cables in the top hat region were installed. All cables were checked for continuity, capacitance, high pot, and shield isolation (to defeat ground loops). No variances were found indicating a very successful build and assembly. The cross-flange with Vatterfly vent-to-space valves and vacuum tight window 4 was installed to complete the warm end.

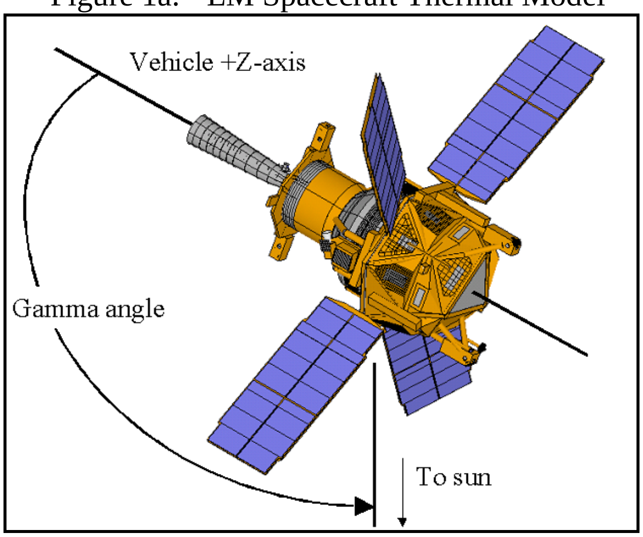
The Probe was transported and brought into the Stanford HEPL cleanroom and the Quartz Block/Telescope was installed. Finally, the vacuum shell completed the Probe.

V. Spacecraft Thermal Model

The GP-B spacecraft was designed to maximize the Dewar lifetime and provide the specified environments for the science and spacecraft electronic boxes. To achieve the lowest possible Dewar vacuum shell temperature, the exposed conical section of the Dewar external surface was covered with 10-mil thick silver-coated Teflon Tape. The aft and mid-sections of the Dewar vacuum shell were covered by the truss structure which provided mechanical support for the aft science and spacecraft electronics boxes. The aft truss structure was wrapped in Mulit-Layer Insulation (MLI) to prevent trapping of solar, albedo, and out-going long-wave radiator (OLR) under the truss structure and panels. The forward end of the Dewar housed the science electronics boxes in a Faraday cage and provides mechanical support for the GP-B telescope sunshade. These forward science boxes were placed in this location to minimize the distance to the Probe neck.

The sun-shade for the GP-B telescope was covered with 5-mil aluminized Teflon tape to provide a cold environment for the forward end of the Probe and the Dewar.
The GP-B was inertially-oriented, pointed at the guide star, HR8703, and spun about the Z-axis at 0.3 rpm. The orbit altitude was 640 km at and inclination of 90°. The spin about the Z-axis provided a benign environment for the Dewar vacuum shell radiating surfaces and electronics mounted to the exterior of the spacecraft by pointing the radiating surfaces out radially and normal to the Z-azis. Multi-layer insulation closes out the gaps between the boxes and the

Figure 1a. - LM Spacecraft Thermal Model



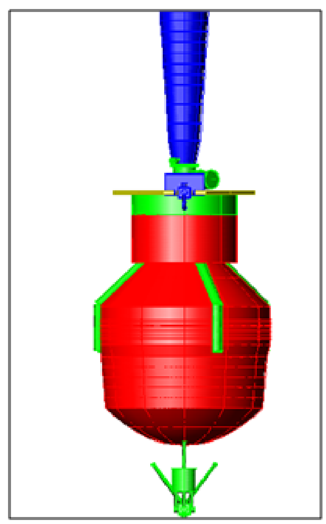
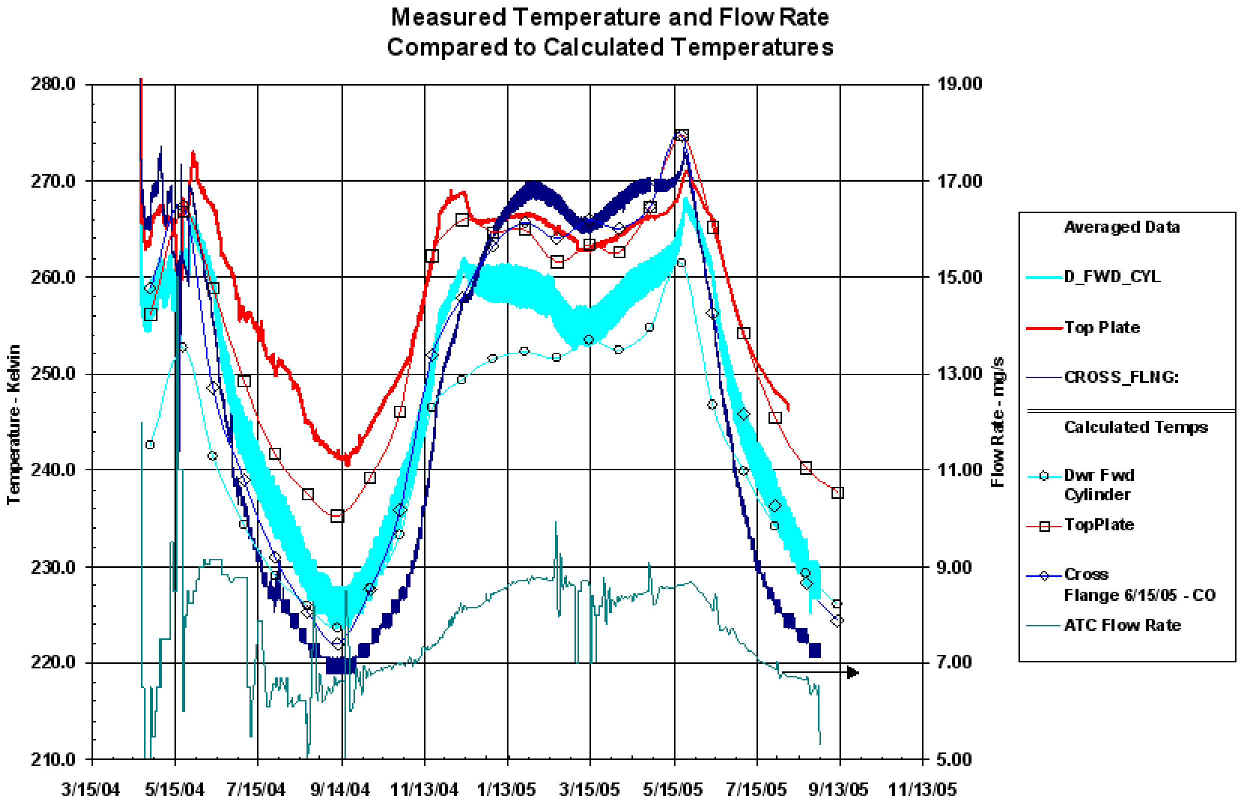


Figure 1b. - MSFC Dewar Thermal Model

The variation of Dewar vacuum shell temperatures over the life of the mission is presented in Figure 2. The Dewar vacuum shell was designed to radiate heat from the exposed forward cone of the Dewar and from the telescope sunshade. The gamma angle (angle between the vehicle Z-axis and the sun) ranged from 22° to 158° over the life of the mission. It can be seen in the Figure 2 that when direct sunlight falls on the forward cone of the Dewar, vacuum shell temperatures are at a maximum. When the aft end of the vehicle was pointed and the sun, vacuum shell temperatures are at a minimum.

Figure 2. - Calculated Versus Observed On-orbit Temperatures



GP-B Dewar Thermal Model

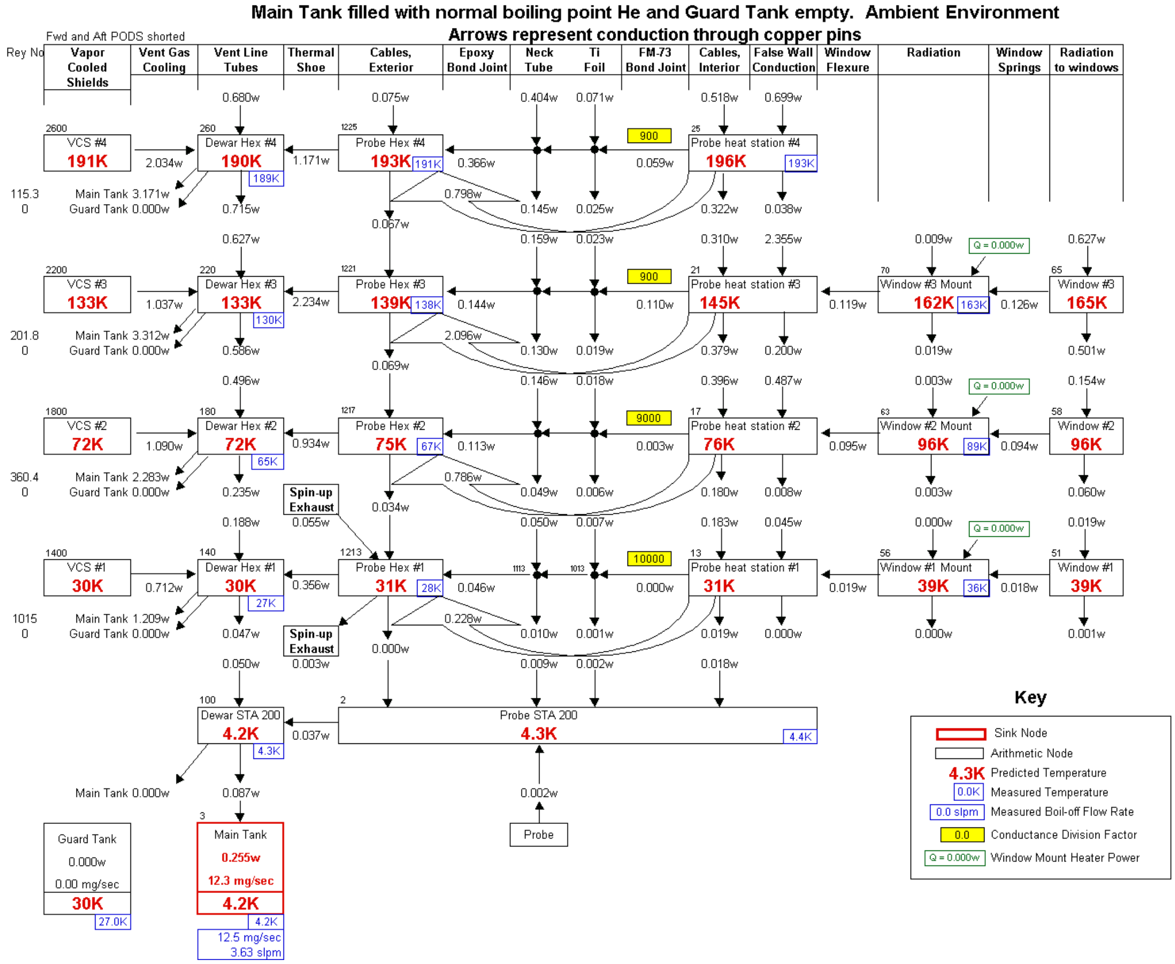
LM Ground Thermal Performance

The Dewar/Probe-C thermal model was correlated using data collected under a number of Dewar ground test fill regimes:

1. Main tank filled with normal-boiling point (NBP) He (4.2K), NBP He in well
   a. This occurred prior to repair of the Probe
2. Main tank filled with NBP He (4.2K) and guard tank empty
3. Main tank filled with super-fluid (SF) He (1.8K) and guard tank empty
4. Main tank filled with SF He (1.8K) and guard tank filled with NBP He

Figure 3 presents a heat map of the predicted Dewar performance with the vacuum shell at ambient temperature, main tank filled with normal boiling point helium, and with the guard tank empty. Excellent agreement was achieved between the measured Science Mission Dewar (SMD)/Probe C temperatures and the main tank helium vent flow rates. Predicted SMD/Probe temperatures were within 7K of measured temperatures and the predicted helium vent flow rate (a measure of the parasitic heat rate to main tank) is within 0.2 mg/sec of the measured value (12.5 mg/sec).

Figure 3. - Heat Map of Predicted Dewar Ground Performance



Main tank hold time, Guard tank hold time, and heat rate

The Dewar was designed for a main tank ground hold period of 90 days and a ground hold time of 7 days for the guard tank. The main tank was required to be initially cooled to 1.65K and the system was designed so that the maximum temperature did not exceed 1.85K over a 90 day period. The heat rate required to produce a 0.2K temperature rise in the main tank temperature over a 90 period, was 0.022 watts. The predicted main tank heat rate was 0.0175 watts. The guard tank intercepts the parasitic heat load to the main tank and must provide cooling for a minimum of 7 days after filling. The predicted guard tank lifetime was 7.6 days and includes a margin of 30%.

Dewar Vacuum Shell Temperature - Prediction vs. Actual

Predicted On-orbit Lifetime

After model correlation was completed, the margin was reduced from 30% to 10%. With 10% margin, the predicted lifetime was 17.1 months.

For on-orbit prediction of vent gas cooling, the He boil-off rate used to calculate vent gas cooling was not corrected for the residual gas in the tank due to the much lower external pressure.

On-orbit Temperatures

Figure 4 presents a heat map that compares Dewar on-orbit performance to predicted performance. The Dewar main tank is at 1.85K, the guard tank is empty, and the forward cone and aft dome of the vacuum shell are at 268K and 273K, respectively. The temperatures shown in blue are the observed on-orbit temperatures for June 10, 2004. On this date, the vehicle was at a gamma angle of 90°. The total predicted heat load to the main tank was 0.203 watts. The predicted on-orbit lifetime, using the correlated thermal model, was 18.8 months without contingency and 14.5 months with 30% contingency.

On-orbit, the Dewar vacuum shell temperatures were warmer than initially predicted by the space vehicle thermal model. A correlation of the space vehicle thermal model with on-orbit temperatures was performed. Figure 1 presents a comparison of the observed Dewar vacuum shell temperatures and those predicted by the space vehicle thermal model.

Figure 4. – Heat Map of Predicted On-orbit Performance Compared to Observed

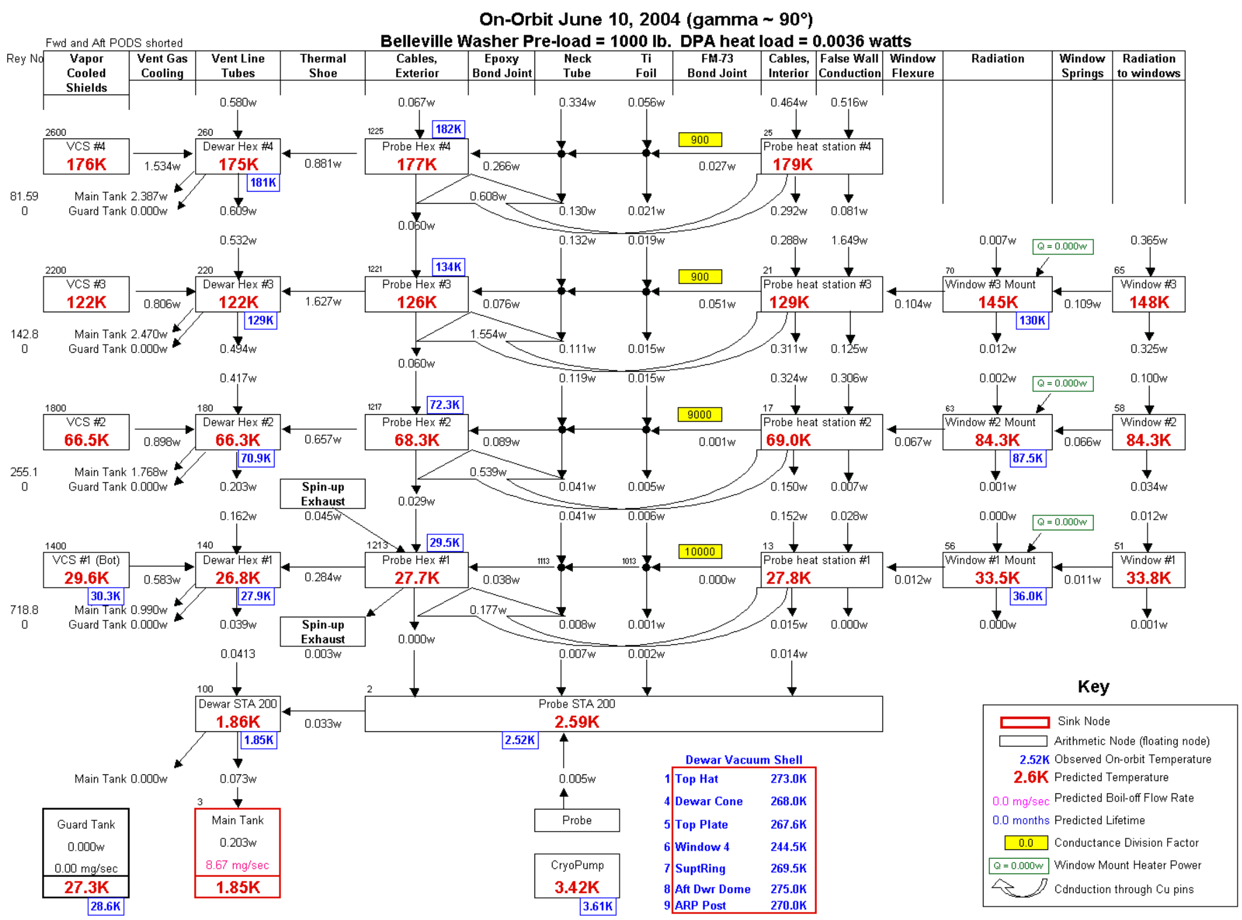
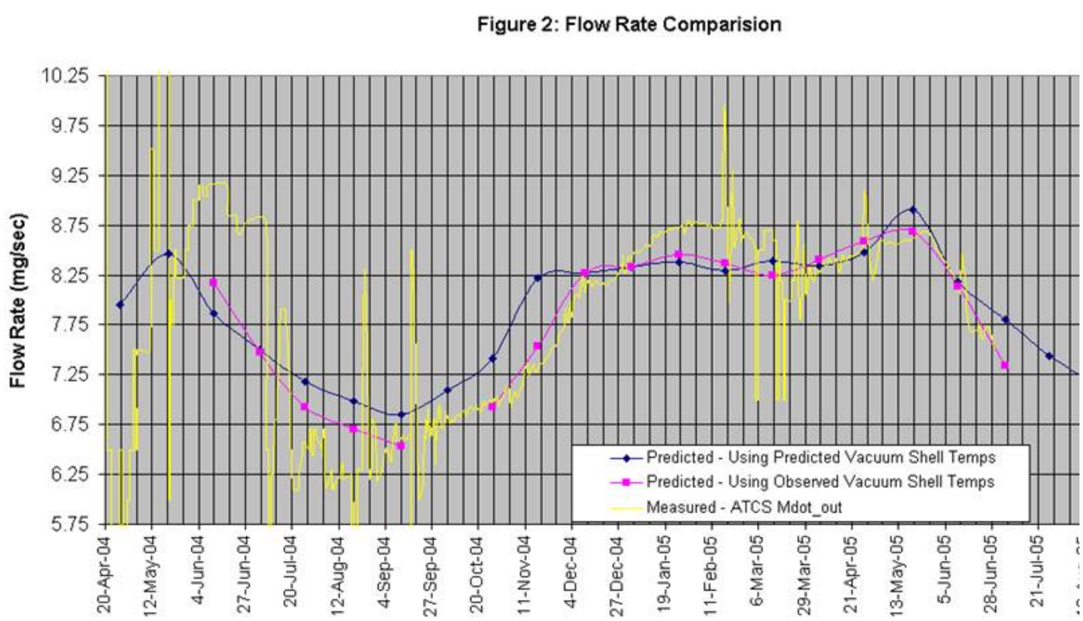


Figure 5 presents a comparison of predicted and observed helium flow rates:

1. Dewar vacuum shell temperatures predicted by the space vehicle thermal model were input as boundary conditions to the Dewar thermal model
2. Observed on-orbit vacuum shell temperatures were input as boundary conditions to the Dewar thermal model.
3. Flow rates measured by ATCS.

Figure 5. Comparison of Predicted and Observed Flow Rates



- Dewar vacuum shell temperatures are approximately 30°C higher than predicted for this time of year.
  - Dewar Vacuum Shell absorbed heat rates appear to be two times greater than predicted.
  - Possible Causes:
    - » Degradation of MLI blankets at aft end of FEE and between Dewar Support Ring and Truss Structure.
      - Blanket Installation
      - Depressurization of fairing during first minute of ascent changed blanket attachment
      - Observed material floating away from space vehicle prior to deployment from DELTA
    - » Degradation of FOSR (not likely)
      - FOSR survived 2 vehicle level thermal vacuum tests
    - » Temperature sensors not reading correctly
      - Two types of temperature sensors (SDTs and thermistors) give similar readings

VI. Ground Operational Experience and Performance

The design and assembly of flight hardware culminated 22 years of incremental prototyping, involving development of pre-flight hardware and critical lessons learned from their integration and test. Two pre-flight probes and one pre-flight dewar guided the design of flight hardware. Figure xx summarizes the ground test program.

In broad terms, ground operations spanned 1963 – 2004, with work during the first two decades focused on gyroscope development at Stanford and MSFC. In 1985, Lockheed Martin began work on the first large-scale probe and dewar. Combined with a pre-flight SIA, the hardware paved the way for the start of the flight probe and dewar in 1989. The flight dewar was completed in 1996, and the flight probe was completed in 1998. Integration and test spanned 1997 – 2003, first at Stanford with the integrated SIA, and then at Lockheed Martin with the spacecraft. After shipment of the vehicle to VAFB in 2003, ground operations concluded with launch April 20, 2004.

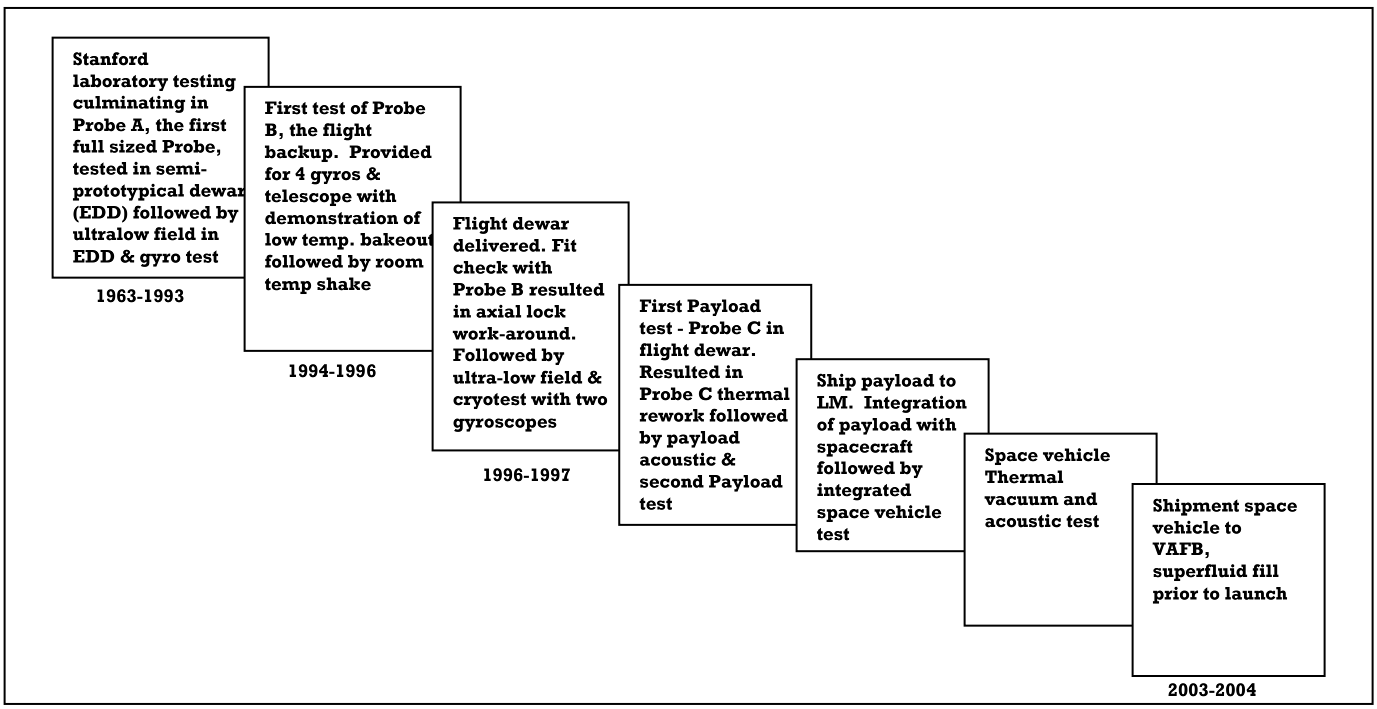


Figure: Ground operations overview

Precursors to flight hardware

The development of the EDD and the first full-sized probe, Probe A, allowed the mission to transition from an academic research effort to a full-scale flight program. Equally important, were two separate efforts: the design, fabrication, and test of the SIA (see Paper L), and the development of large-scale integration and test facilities.

Two large-scale facilities were built at Stanford University to support integration and test. Figure xx shows the 22-foot tall, class 10 clean room used to integrate the SIA into the probe. The order of integration was as follows:

1. Bonding of telescope to QB

2. Assembly of telescope/QB into probe
3. Installation of gyros and then SQUIDs.
4. Installation of vacuum can
5. Electrical and leak test verification

During this assembly process, both hardware and personnel were electrically grounded to prevent electrostatic buildup and the associated risk of electronics damage and contaminant attraction.


Figure xx: Probe in class 10 facility

The other facility, a 1200 m^2 class 10,000 high bay, was used to integrate the probe into the Dewar and to perform system tests. Integration of the probe into the Dewar required a 25-foot tall facility, dictated by clearance for the Dewar height plus twice the probe height. Significant floor space was required for the ground support equipment described below. An acoustic chamber and a thermal-vacuum chamber, both located at Lockheed Martin, were used for environment testing.

Probe A and Probe B, both with integrated SIA, were operated in the EDD. Whereas Probe A was clearly not intended for flight, Probe B was considered a flight backup unit, and if needed, could have been upgraded and flown if problems developed with the flight unit. Probe B provided for four gyroscopes, in which flight-like gyro performance was demonstrated including ultra-low magnetic field for London Moment readout, low temperature bakeout to limit differential damping torque, and tests of two competing gyroscope suspension concepts.

One final test was required prior to committing to the final flight Probe design, launch compatibility. Given the unforgiving physical nature of the SIA and the somewhat delicate construction of the probe, a shake test was performed in July 1996 using Probe B. The probe came though the test undamaged. Some quartz block damage at the SIA's interface with the probe finger attachment resulted in two hardware changes. Molybdenum pads were added at the probe-quartz block interface, and bumpers were placed at the bottom of the probe structure to reduce the size of the gap between probe and vacuum can. The follow-up vibration test was successful.

Flight Dewar completion and lead bag installation

The Dewar was delivered from Lockheed Martin to Stanford in November, 1996. After cooling the Dewar and measuring its heat rate with an insulating plug in the neck, the system was ready for lead bag installation. Lead bags [Cabrera] are sequentially installed in the Dewar well, ultimately yielding a magnetic field of < 10^{-7} gauss. Each bag starts at room temperature, tightly folded using a pleated construction (Fig. A). The first bag is lowered into the Dewar well, cooling to its superconducting state in the ambient field and ideally trapping only the flux penetrating the shield as it transitions. The bag is then expanded, increasing the shield volume by as much as a factor of 100. The total magnetic flux inside the bag is conserved as the bag is expanded, resulting in a large reduction in field strength. Iteration of this process is depicted schematically in Figure B. The procedure could be repeated many times to attain arbitrarily low field, but the field reduction is limited by thermal electric currents to ~5 pT due to thermoelectric currents generated by thermal gradient coupled with residual anisotropy in the Pb foil. To minimize these currents, cooling is performed slowly in a sealed cooling tube filled with exchange gas. The lead shield is a thin 63 µm (? 0.003-in) thick cylindrical lead shield closed on the bottom and lining the Dewar well. The shield is 254 mm diameter and 1.7 m in length with a mass of 1.1 Kg. The lead is alloyed with 0.2% Sn which suppresses surface lead oxide buildup (raises the superconducting transition temperature 0.1 K to 7.3 K).

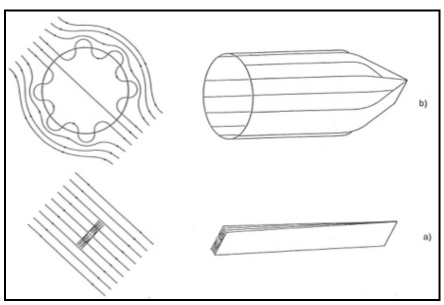


Figure A. Lead shield and magnetic field; a) prior to expansion and (b) after expansion.

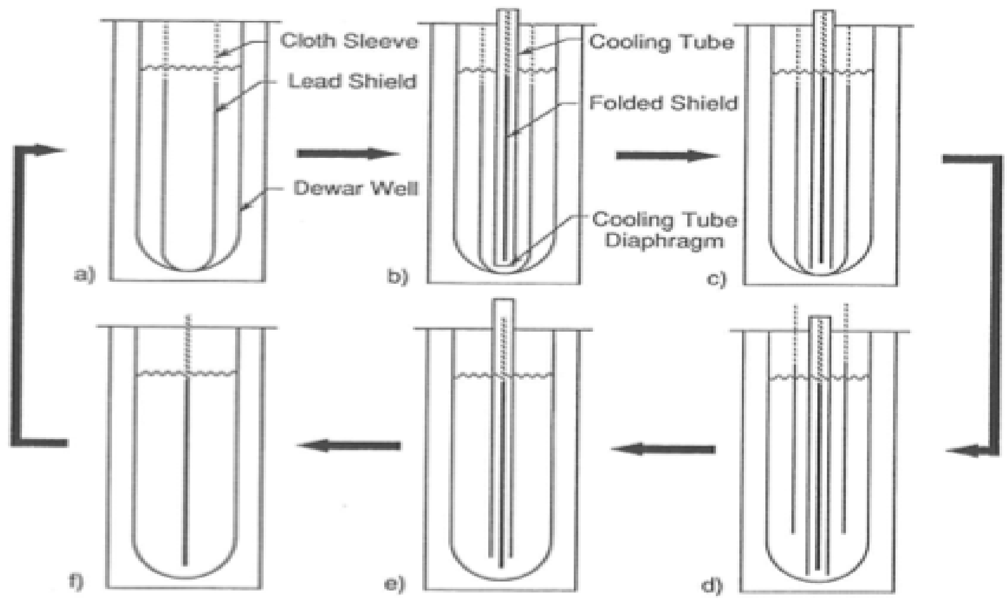


Figure B. Lead Shield (LS) field reduction technique: a) previous LS positioned in the well submerged in LHe, b) Next LS enclosed in cooling tube under controlled helium atmosphere is installed in the previous LS, c) after slowly cooling the new LS down the cooling tube diaphragm is cut out allowing LHe in, d) Remove the previous LS, e) remove the cooling tube, f) new LS is ready for expanding, a) new LS is in place.

As many of these lead bag operations are performed over open LHe in the well, a primary concern is to prevent air contamination of the well. Such contamination can cause Probe-Dewar mating surfaces to freeze together or interfere with clearances. To prevent this, several pieces of support equipment were built. These included a 0.7 x 0.6 x 2 m glove box, 0.38 m diameter airlock cylinder, and a 100 mm high sliding Mylar shutter mechanism.

The lead shield is installed into the cooling tube assembly (Fig. D). This assembly has two concentric Pyrex tubes; the outer tube is the vacuum tube, and the inner tube is cut-off so it can be lowered to pierce through a 25 μm thick aluminum diaphragm located at the bottom of the vacuum tube. This allows the lead shield egress out of the cooling tube after the controlled cool down is completed. The lead shield is supported by a string tied to its cloth sleeve; the latter is glued to the top of the lead shield. The cooling tube is leak checked and backfilled with 0.3 Pa (2 torr) helium. The hole cutter assembly is mounted in the cylindrical airlock and purged. The shutter is opened and hole cutter assembly is mated to the Dewar.

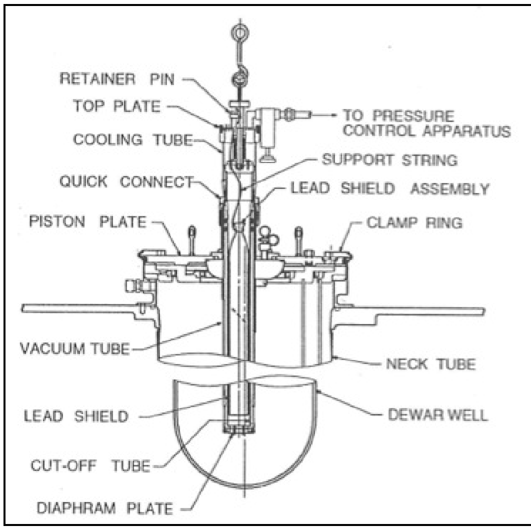


Figure D. Cooling tube with folded lead suspended inside cooling tube and the assembly inserted into well.

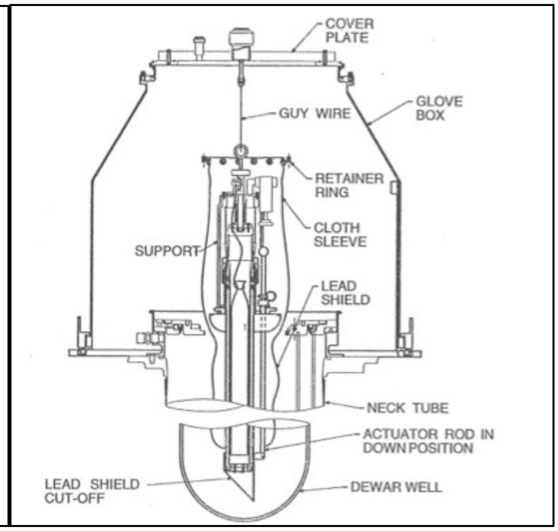


Figure E. Removal of the previous lead shield inside of helium-purged glove box.

The cooling tube is then slowly lowered through a sliding seal in the hole cutter to reach the configuration of Fig. D. A closed loop pressure controller controls the helium pressure in the cooling tube, such that the lead shield passes through the superconducting transition temperature slowly. A slow cool down is necessary to minimize the generation of thermoelectric currents and the consequent trapping of the flux generated by these currents. The cooling tube diaphragm is punctured and LHe admitted into the cooling tube. The removal of the previous shield is performed in the glove box as shown in Fig. E. The hole cutter is lowered to just below the bottom of the cooling tube and the previous shield is removed by pulling it up with the cloth sleeve; puncturing the bottom of the bag on the hole cutter.

The glove box is removed, and the cylindrical airlock is installed. The lead shield expansion is performed by lowering a triangular-shaped former, followed by spherical shaped former, through the airlock/shutter system into the shield with the cloth sleeve secured to the top of the Dewar neck. Following this, the field is checked using a SQUID-based flip coil magnetometer lowered into the lead shield to measure the transverse and axial fields at various locations. Table A gives the result of these measurements for two trial lead shields and the final four lead shield sequence.

Following the installation of the final bag, a mechanical retainer presses the shield against the wall of the Dewar well.

Table A. Flip Coil Measurements of several lead shields

Date	Shield	Field Value (10^{-10}T)	Direction
1/28/93	#1 6-in	NA	--
2/25/93	#2 6-in	1.0	Transverse
3/14/93	#3 6-in	0.32	Transverse
4/14/93	#4 10-in	0.07	Transverse

4/29/93	10-in with retainer	7.2	Axial
5/4/93	10-in without retainer	0.35	Axial

Material Selection and Handling
To eliminate the possibility of trace quantities of iron, nickel, or cobalt introducing excessive magnetic field inside the lead bag, 100 percent of the probe components in Magnetics Zones 1 & 2 (see Figure xx) were screened for magnetic contamination prior to assembly. All raw materials and the thousands of piece parts fabricated with these materials were screened using a low temperature SQUID-based system to ensure remnant magnetization of $< 10^{-7}$ gauss. Non-magnetic hand tools were used to ensure that the assembled piece parts remained magnetically clean.

Probe Insertion into cold Dewar
The Dewar must continuously be kept cold once the low field is established, thus requiring probe insertion into the cold Dewar. An elaborate 20 hour process, making use of specially fabricated support equipment, was needed to perform the insertion. A xx feet tall, xx feet diameter, helium filled airlock and piston prevents air from condensing in the well. Figure xx shows the probe insertion into the Dewar.

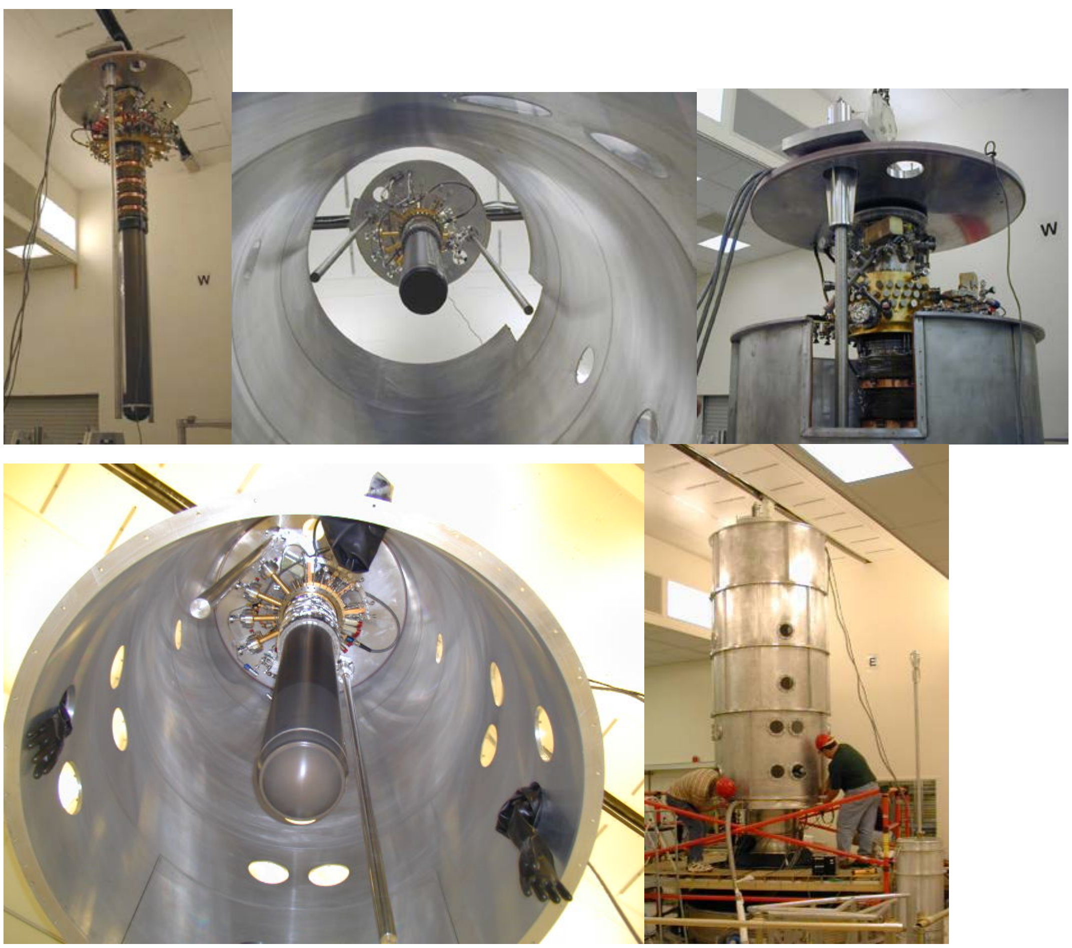


Figure xx: Probe Insertion into cold Dewar

To limit bag heating, the well is filled with liquid helium. To help maintain thermal equilibrium of the xx kg SIA with its surroundings, helium exchange gas is introduced into the probe. The probe is lowered inside the airlock a few centimeters at a time with the piston above the probe forming a helium tight seal. By moving the probe down a few centimeters at a time and then waiting, much of the SIA's thermal energy is safely removed prior to full insertion. After the probe had been fully lowered into the Dewar, the liquid helium in the well and the exchange gas in the probe are pumped out.

The next step in the integration process was to be actuation of the axial lock mechanisms. However, in testing the flight Dewar before installation of the lead bags, high running torque, due to galling in the threads, was observed when the axial lock mechanism was operated. Initially, this behavior was thought to be isolated to that individual lock, and that if not used, the remaining two axial locks would be adequate. However, when Probe B was later installed into the Dewar at Stanford, this problem reoccurred on a second lock. Separate laboratory tests demonstrated that high running torque resulted from too high a thread attack angle combined with the use of indium coating on mating surfaces. A solution was required to provide the needed thermal and mechanical characteristics at the four heat stations and at Station 200.

Rather than rebuild the axial lock system, the solution was to modify Probe C, still in construction at Lockheed Martin. Figure xx shows the Bellville Pre-load System (BPS). Mechanical loading is provided from the top of the probe by compressing three sets of stacked Bellville washers. Thermal analysis indicated a need for 2000 pounds of force to ensure adequate thermal conduction at the four spring-loaded heat stations and at Station 200. Tests performed on a non-flight test apparatus demonstrated adequate strength of the load-bearing, thin-walled neck tube. The as-assembled, BPS-supplied load was 2050 lbs.

Initial Payload tests

Probe C was delivered in mid-1998. The first cryogenic test verified the fit of the BPS system in probe-dewar system with the as-assembled, BPS-supplied load of 2050 lbs.

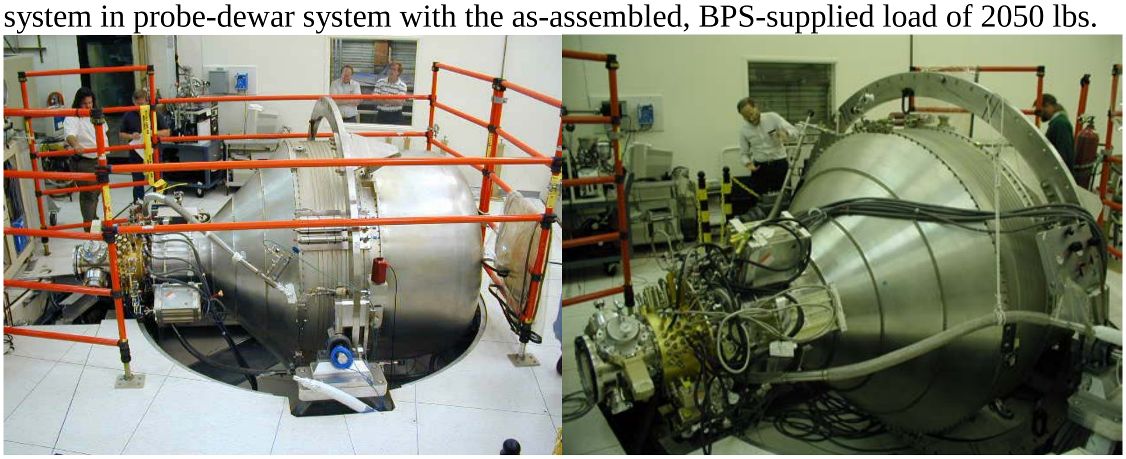


Figure xx: pick one…

Following the BPS verification, Probe C was removed from the dewar to install the flight SIA consisting of four gyroscopes, four SQUIDs, quartz block, and telescope. Figure xx shows the payload in test in the high bay laboratory at Stanford.

A probe thermal issue was discovered during the cool down of Probe C with the flight SIA. Excessive liquid helium boiloff gas was observed, indicating high heat rate into the main tank. In addition, the temperature profile in the neck region of the probe and dewar did not match the predictions (Figure xx). The temperature difference between probe and dewar at each heat station was expected to be small, consistent with the high thermal conductance required to remove heat from the probe. In practice, the differences were larger than expected, with dewar temperatures lower and probe temperatures higher than predicted. Uniform, radial temperatures inside of the probe's neck tube pinpointed the heat flow disruption to the interface between the Probe's necktube wall and interior heat station rings. These temperature measurements also suggested a lack of the structural integrity required for launch, and so, the probe was removed from the dewar for repair.

A mechanically clean and conceptually simple solution was implemented to fix the thermal and mechanical issues described above. 0.xx diameter holes, accurate to 1.3 μm, were machined through the outer heat station ring and probe necktube, into the heat station on the inside. High purity copper pins were press fit into the holes (Figure xx).

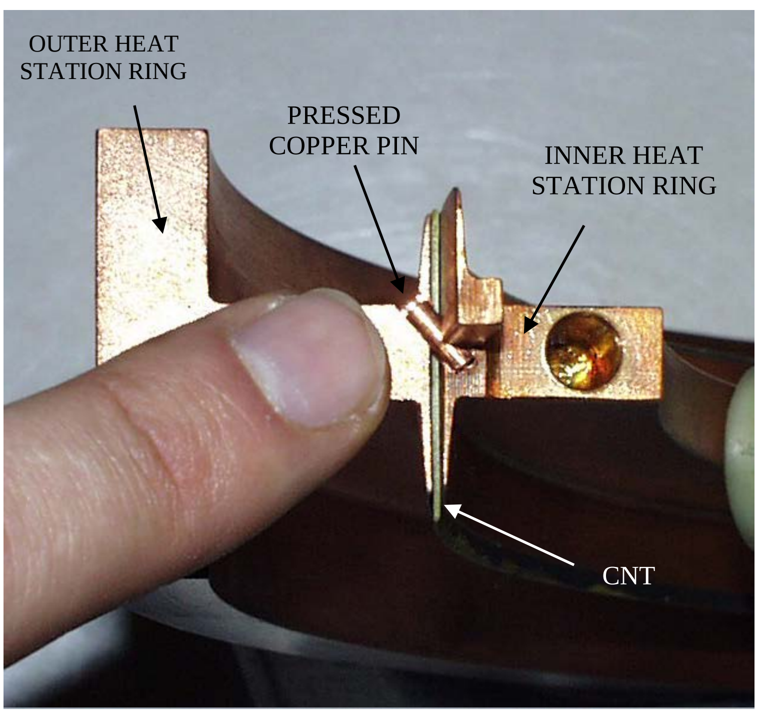


Figure xx: Cross section of angled copper pin

Each heat station required xx such pins. After completing the insertion of the final pin, the probe was leak tested and found to have a total leak rate of < 10^{-9} sccs.

After this eight-month-long repair process, the Probe was re-integrated with the dewar and the thermal performance was assessed. Figure xx gives the corrected temperature profile and Figure xx gives the full ground heat map. Full payload functionality was demonstrated and the trapped flux in each gyroscope, after a flux flush heat cycle described below, was shown to meet requirement. To demonstrate that the repaired probe would withstand the rigors of launch, the payload was shipped to Lockheed Martin for acoustic test. A check of the temperature profile after acoustic test, unchanged from the pre-acoustic result, demonstrated that the repaired probe would withstand the rigors of launch.

Final Payload test

Following acoustic test, the payload was shipped back to Stanford for science performance testing. To carry out these tests, many special purpose ground support hardware was developed. Some of this hardware, such as the previously described airlock, a temperature monitoring system, and large liquid helium transfer equipment, were needed for cryogenic operations. Other support hardware was required to verify the many science requirements. One example, a vacuum pumping station, was constructed to perform high speed gyroscope spin-up and Probe conductance tests using a dual set of the largest available commercial turbo molecular pumps.

A superfluid fill was carried out at Stanford, confirming the ability to fill the Dewar to 96% of its capacity at a temperature of 1.65 K. The process consumed 17 days, during which time the main tank was topped off four times with normal boiling point liquid and then pumped to reduce its temperature. A 300 cfm Roots blower pumped the main tank. With the guard tank full, a hold test demonstrated that the main tank could be kept below 1.85 K for 90 days at VAFB, without the need for super fluid operations.

When the tank was operated at sub-atmospheric pressure, extreme care was taken to prevent air incursion. Nonetheless, during the sub-atmospheric fill and at three other times prior to launch, air incursion resulted in plumbing blockages. The flowing of warm helium gas and the use of high power internal heaters restored proper operation. To reduce the risk of future occurrence, Dewar operating procedures were modified, including pressurizing the guard tank at all times to remain above atmospheric pressure, and improving leak detection tests of external plumbing. To further reduce risk, following completion of the super fluid test, the main tank was returned to atmospheric pressure, where it remained until shortly before launch.

~~?~~The dc magnetic field requirement was verified before and after acoustic test using the four gyroscope readout systems. As the superconducting niobium film on each gyroscope cools through its transition temperature, it locks in or traps magnetic flux. The amount of trapped flux is measured by levitating and spinning each gyroscope. Much like a flip coil magnetometer, the rotation of the rotor allows the dc trapped magnetic field to be measured with the gyro readout. The trapped field following initial cooldown from room temperature was elevated due to thermal gradients as the rotor transitioned to their superconductive state. The excess flux was removed by means of a heating and cooling flux flush procedure, with the best result achieved by levitating the gyroscopes, and then heating them with warmed exchange gas. After reaching the normal state, the gyroscopes were allowed to slowly cool, returning to their original temperature after an almost two day-long process.

The trapped flux in the rotors was re-measured following acoustic test. The result exceeded the requirement, thus confirming the need for an on-orbit flux flush. Importantly, the flush flux performed immediately after this measurement yielded low rotor trapped flux. This showed that the lead bag had survived acoustic test and therefore would retain low magnetic field during launch to support an on-orbit flux flush.

The ac magnetic shielding was measured following acoustic test by applying a varying magnetic field to the entire payload using an eight foot diameter coil set located outside the Dewar. The shielding factor was determined by comparing the gyroscope readout signal with the applied field. Two factors set the amplitude of the applied field. Choosing a large signal would improve simplify detecting any small magnetic leakage, however, too large an applied signal would cause the ferromagnetic shield to demagnetize at its top edge. In practice, a field similar in size to the Earth's field was selected.

The telescope was tested using an "artificial star" mounted on top of the probe. The artificial star, a 4-foot diameter, 3-foot tall evacuated chamber, simulated the guide star IM-Pegasi. The star contained a laser to illuminate the flight telescope. Precision mechanisms allowed 30 milliarcsecond precision scanning of simulated guide star position.

Operations at Lockheed Martin

The payload was shipped to Lockheed Martin in 200?, where it was integrated with spacecraft and then, as an integrated space vehicle, underwent environmental test.

The spacecraft consists of an open rib-like structure holding the 16 helium boiloff gas thrusters, attitude reference platforms with star trackers and rate gyroscopes, GPS receivers, helium gas supply, and other hardware(Figure xx). The sensitive analog payload electronics located near the top of probe were encased in a thin-walled Forward Equipment Enclosure (FEE) to prevent direct exposure to heating by the Sun. Additional flight electronics towards the bottom of the dewar interfaced to the flight computer which pre-processed the data for transmission to ground. With this electronics in place, much of the information regarding the state of the dewar transitioned from laboratory instrumentation to transmission through the flight hardware and software. Following checkout of this newly installed hardware and software, the vehicle was wrapped in second surface flexible mirror material in preparation for thermal vacuum (TV) test.

To perform TV, the boiloff gas for the dewar main and guard tanks had to be vented outside the chamber. In the initial test, a leak developed in the dewar vent inside the chamber, requiring a fix and repeat pump down of the facility.

Steady state dewar boiloff data, with reduced vacuum shell temperature, gave a TV lifetime prediction of 18.8 months. Hot and cold cycle stress tests demonstrated system survivability and a heat balance test provided a correlation with the thermal model. Payload electronics tests were performed to confirm thermal variation in the FEE of no more than 50 mK at roll frequency, 1 K at orbital frequency, and 10 K seasonally. High intensity heat lamps were cycled on and off to simulate thermal input at these three frequencies.

Following TV, the vehicle underwent acoustic test. The acoustic excitation lasts 60 seconds, during which time the power is slowly ramped up to the maximum level, simulating the maximum stress of launch - main engine cut off.

The final significant operation at Lockheed Martin was to perform a spin balance of the vehicle.

Operations at VAFB

The vehicle was shipped to Vandenberg Air Force Base (VAFB) for launch on xx 2003. After one of the electronics boxes had a small re-work, the main tank was conditioned to its pre-launch superfluid state. With the tank sealed off, there was added urgency to launch as soon as feasible. Guard tank fills continued every several days right up until launch. In addition, a small internal leak into the dewar well required continuous pumping to prevent excessive build up on helium and associated heat rate into the main tank.

Figure xx: The space vehicle installed on the Delta II with half of the fairing installed.

The cryogenic system was maintained on the launch pad for 56 days after completion of the main tank fill.

VII. On-orbit Operational Experience and Performance

Launch was at 09:57:24 PDT (17:57:24 Zulu) April 20, 2004. The dewar operational conditions were:

• Main tank: 95% full at 1.81 K, initially sealed off but opened to the S/C thruster system during the Launch Phase when the ambient pressure reached a value well below the ~ 12 torr tank pressure

• Guard Tank: 50% full at 4.18 K, vented to atmosphere and continuing to vent through a relief valve and flow control orifice through the Boost Phase and beyond.

Figure 7.2 shows the main and guard tank temperature profiles over the 4-day period April 17-21, 2004. The main tank reached its approximate final temperature after __ days, but with certain deviations discussed further in Section V and below. The on-orbit lifetime was 17 months 9 days, beating the original 16 month requirement by 39 days. The mission was divided into 3 Phases, explained further in Paper I. 1) Initial Orbit Checkout (IOC) planned for 60 days; taking in fact 128 days, 2) Science – 353 days; 3) Post Science Calibration – 63 days. Most active in operational considerations relevant to dewar performance was the IOC.

Figure 7.3 gives a timeline of the mission identifying key operations discussed below. Primary were: 1) flux flushing to check and remove any trapped magnetic flux in the rotors acquired through the vibration of launch; 2) gyro spin-up; 3) low temperature bakeout to reduce pressure.

The GP-B spacecraft was heavily instrumented, giving for the dewar a detailed timeline of pressure and temperature at numerous locations in the system.

Figure XX: Timeline of on-orbit operations

****

1st week
Launch
Pyro valves for dewar and well
Closed off stuck-open (but redundant) thruster

3rd week
Practice low temp bakeout

5th week
Flux flush
2nd thruster closed off

6th week

Slow spin of all gyros

9^{th} week
Increased spacecraft roll from 0.1 to 0.3 rpm allowing mass trim

10^{th} week
Increased roll to 0.9 rpm to allow bubble wrap

15^{th} week
Completed gyro spin up

16^{th} week
Low temperature bakeout

****

First week of experiment setup
Careful planning and optimization of on-orbit operations were needed from the start to achieve the best science result, given fixed helium lifetime. Experiment setup, entailing 35,000 software commands, began during the first day on-orbit with turn on of the gyroscopes, SQUIDs, and telescope. To take advantage of the vacuum of space, two pyrotechnic valves, one for the dewar and one for the well, were opened. The superfluid helium in the guard tank ran dry after one day, after which the system settled in to a fixed cryogenic configuration with boil off gas from liquid in the main tank venting through the ATC controlled thruster system. Towards the end of the first week, one of these helium gas thrusters got stuck in the open position. To prevent spurious gas flow, the upstream cut off valve to this redundant thruster was closed.

Practice Operations
To ensure smooth operations later in the experiment setup, the vatterfly valves were opened in the third week on-orbit. These valves would later be needed for flux flush, gyroscope spinup, and low temperature bakeout. Heaters to be used for these later operations were also operated. Interestingly, although no spin up gas was applied, all of the gyroscopes acquired a slow spin during this practice resulting from differential pumping of residual gas in the probe.

Flux Flush: Performed at Launch + xx days
With the gyroscopes slowly spinning, telemetry confirmed the need to remove launch-induced trapped flux. Figure xx shows temperature profiles at several locations within the payload. The thermal time constant of the quartz block is several hours, so that, including a thermal soak, the total duration of the heat cycle is 38 hours. A low inductance strip heater provides a mission maximum 1.xx W of heat at Station 200. The slowly ramped cool down minimizes risk of thermally generated magnetic fields. The rotors are levitated and a steady flow of helium gas, raising the probe pressure to ~ 5e-5 torr, ensures uniform rotor temperature. High helium mass flow commanded for xx days

prior to flux flush, combined with even higher flow during flux flush, limited the temperature rise of the liquid and minimized the maximum pressure of the boiloff gas.

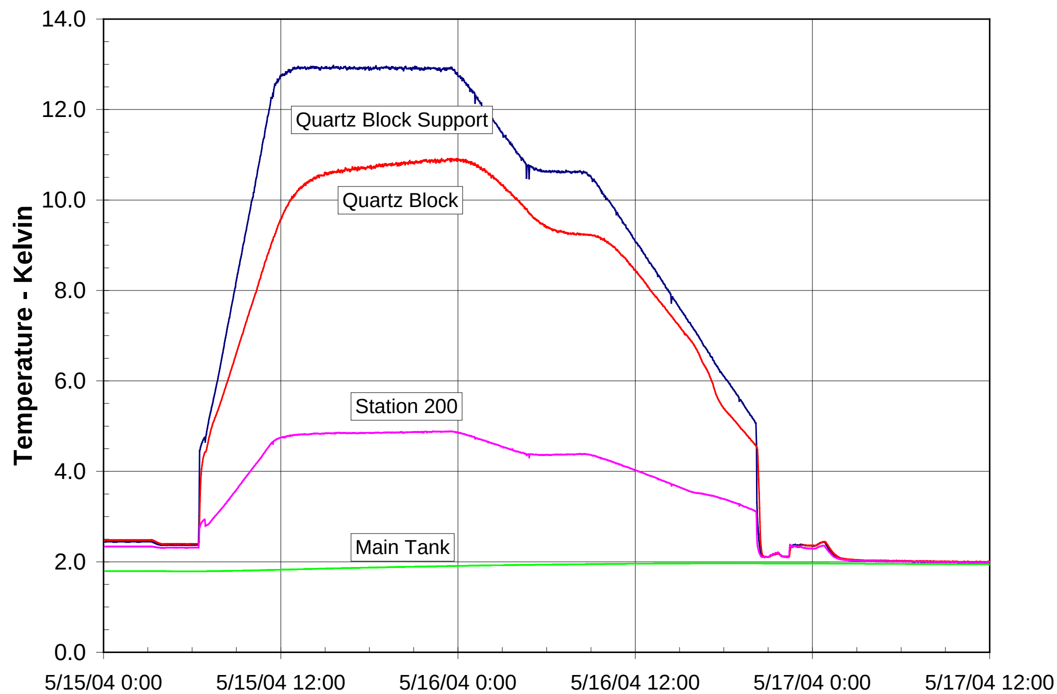


Figure xx: Flux flush temperature profile

Figure xx gives a one-week long profile of flux flush temperatures and pressures. During the five calendar days of elevated gas flow, eleven days worth of helium were consumed.

Porous Plug Performance: The porous plug worked well on-orbit. The typical temperature differential across the plug was ~4 mK . The Figure shows the one time during the mission when the porous plug choked. Although no breakthrough incidents were observed during the mission, choking did occur about a month into the mission, lasting several hours. Figure 3 shows system temperatures when the helium flow rate reached a mission maximum 27 mg/s. This incident occurred as a result of a thruster failure shortly after the main tank had started to recover from flux flush with a commanded helium mass flow of 15 mg/sec. The porous plug downstream temperature abruptly dropped by ~36 mK giving a porous plug differential of 40 mK. The shut off valve upstream from the failed thruster was closed by command and the abnormally high flow rate was corrected to 11 mg/s in about 5 hours. The porous plug spontaneously returned to nominal operation for the duration of the mission after about 14 hours.

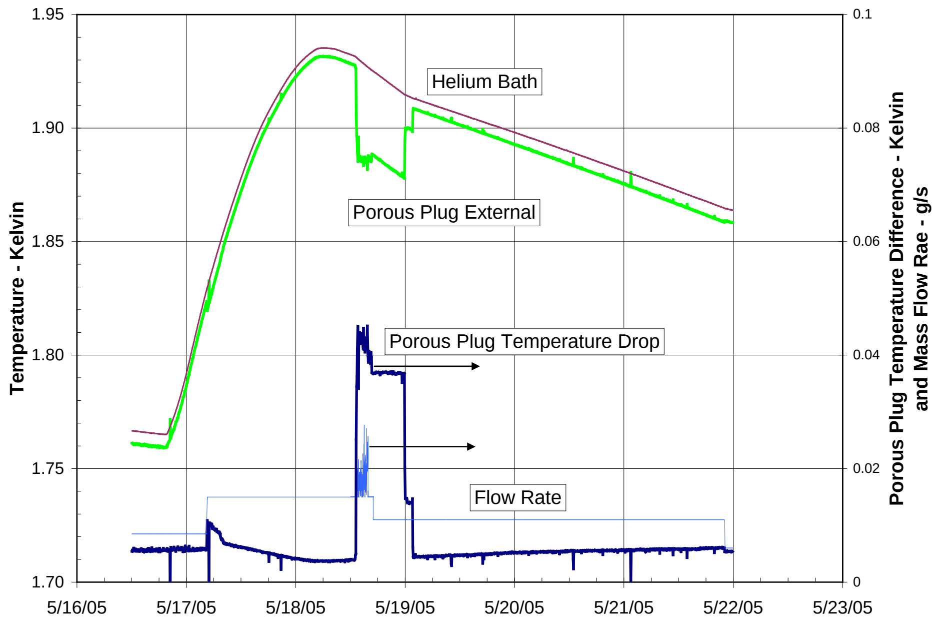


Figure 3**.** Temperature and flow history showing successful recovery of choked porous plug to normal operation.

Bubble Wrap: Launch + 9 weeks

Bubble wrap was carried out during the ninth week on-orbit. For four days the roll rate was maintained at its' mission maximum 0.9 rpm. After thirty three hours at this elevated roll rate a two-hour-long roll rate and helium mass flow transient signaled the successful completion of the bubble wrap operation. In two separate operations, the mass trim mechanisms were adjusted to move the mass center of the space vehicle to be c.

Gyroscope Spin Up: Performed from launch + xx days to launch + xx days

The gyroscopes were spun up individually. Using a series of progressively longer and faster spins for each gyro, all four units ultimately reached a final spin speed of 60 – 80 Hz. The final spin up for each gyroscope took about 1 hour to perform.

Prior to flowing helium gas for the spin up, one of the large leakage gas valves and the spin up exhaust valve for the gyro to be spun were opened. The gyroscope was positioned within its cavity to minimize the amount of leakage gas and a heater near the gyroscope was turned on to warm the gas to ~ 7 K. The gyroscope started spinning up when the valve to a helium gas source was opened. The pressure within the probe increased to xx mtorr during the spin operations due to gas leakage at the gyroscope.

Low temperature bakeout: Performed at launch + xx days

With the probe venting to space following spinup, the probe pressure decreased over the course of several hours to ~1e-5 Pa, necessitating LTB.

Figure xx shows temperature profiles at various locations. Although the entire SIA is warmed using the flux flush heater, additional heat is applied to the cryopump to provide the cleanest possible surface. The freed helium gas exits the probe through leakage and spin up valves. After 7 hours, the valves are closed, the heaters are turned off, and the probe cools to ~ 3 K. The small amount of residual helium gas is re-absorbed onto the cold, clean surfaces, creating a nearly perfect vacuum.

Probe gas pressure may be inferred from gyroscope spin down rate which varied by gyro from 1.4 to 0.29 μHz/hr. If we assume that all of the spin down was due to gas damping, 0.29 μHz/hr corresponds to 2.0 x10^{-9} Pa (1.5x10^{-11} torr). Note that this pressure measurement approach provides only an upper limit because the observed spin down may be due to factors unrelated to gas pressure. In fact, variation in observed gyro spin down rate suggests the spin down is due to a source other than gas damping and that the actual pressure is even lower.

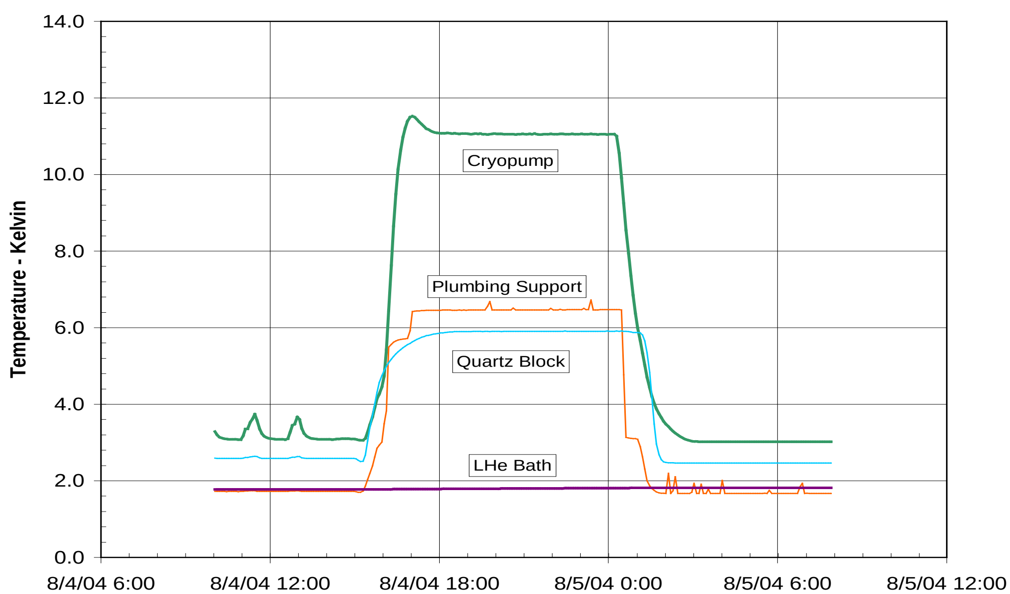


Figure xx: Low temperature bakeout temperature profiles.

A tighter limit for pressure was demonstrated by changing the probe's temperature. High pressure sensitivity to probe temperature variation results from the large binding energy of helium giving $\Delta P/P \sim 60\times\Delta T/T$. When the temperature is increased, the induced pressure change may be determined by measuring the change in gyro spin speed. A 10^{-10} fractional spin speed determination provided by TFM (see Paper L), combined with a lack of change in the gyroscope spin down when the SIA temperature was raised 0.080 K, confirmed a probe pressure upper limit of 10^{-12} Pa.

End of helium life (EOL)

For GP-B, EOL prediction is important to allow time towards the end of mission for cryogenic instrument calibration.

Two methods were used to estimate the remaining helium mass: integration of the measured mass flow rate, and mass determination using a Heat Pulse Measurement (HPM).

Remaining helium mass is measured with HPM by applying a 10 s long, xx Joule, pulse of heat to the liquid in the main tank. With perfect thermal conductivity and accurate knowledge of its specific heat, the liquid's resulting temperature step response would provide the remaining mass. In practice, conduction into the gas and to a lesser extent into the dewar structure, complicates this measurement.

Mass flow measurements provided a cross check with the occasional application of heat to the gas exiting the dewar's main exhaust line. Measurement of resulting temperature gradient provided the thermal conductivity and by inference, the mass flow. Integration of this mass flow rate provided the helium mass.

The liquid helium consumption rate, and therefore EOL, is dependent on the dewar shell temperature which varies over the course of the year. Two thermal models were constructed to predict shell temperature. One used calculated dewar shell temperatures and the other used measured orbital shell temperatures. The predicted rates are shown in Fig. 8 along with those measured by the thruster system.

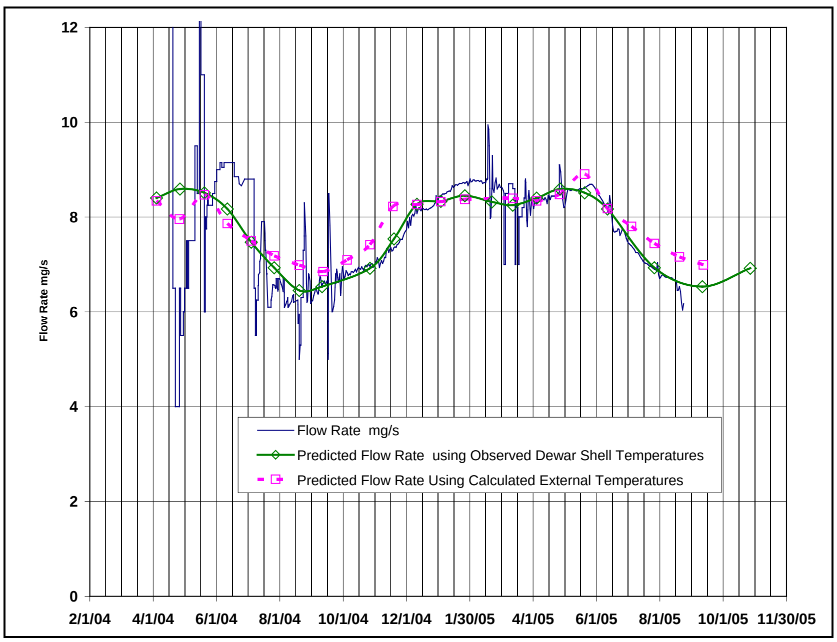
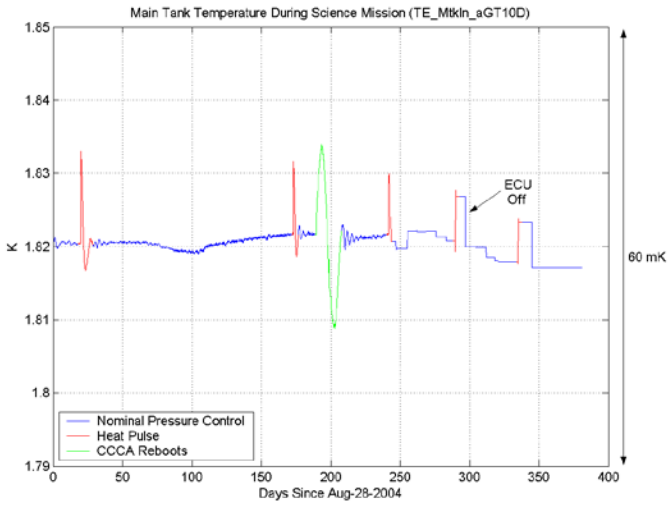


Figure 8. Observed flow rate and predicted flow rate for: 1) using observed external dewar shell temperatures giving EOL of 9/2/05; and 2) using calculated temperatures, giving EOL of 9/25/05. Actual EOL was 9/29/05.

Attitude and Translation Control and Dewar Temperature Control

Attitude and translation control (ATC) is provided by individualized division of the helium boiloff gas to the thrusters. This gas must also be pumped to space to maintain bath temperature. As predicted by thermal analysis, more gas is required to maintain temperature than to support ATC. This extra helium is "null-dumped" evenly among the thrusters, with the exact amount determined by temperature control software. See Figure xx. The temperature was held to 1.82 K +/- 3 mK other than for 5 heat pulse operations and one excursion midway through the mission. The average helium mass flow was 6.76 mg/s.

Figure xx shows the temperature of the liquid helium during the Science phase.



Two nested temperature control systems provide further thermal stabilization of the SIA. The probe attachment to the science instrument is to 1 mK. A germanium resistance thermometer and low inductance strip heater, both located near the probe attachment to the quartz block are operated using a PID control algorithm. To minimize the impact on helium lifetime, heater power was limited using ~ 50 mW of power to maintain a 0.050 K bias. The most thermally sensitive component in the SIA, the SQUID readouts, were further controlled using a PID algorithm combined with peaked gain at roll frequency to provide better than 2 μK control at this critical science frequency.

Probe and SIA Thermal Stability

Figure xx shows the thermal profiles for three locations in the probe and SIA. When the shutter is open at the top of the probe during GSI, earth shine near the poles causes orbital variation in the temperature profiles. When the shutter is closed during GSI, this orbital variation is much reduced. None-the-less, early in the mission it was decided to leave the shutter open during GSI because its' operation produced a significant mechanical impulse to the vehicle and gyroscopes. Evaluation of the shutter-open thermal variation found this variation did not significantly affect the science experiment.

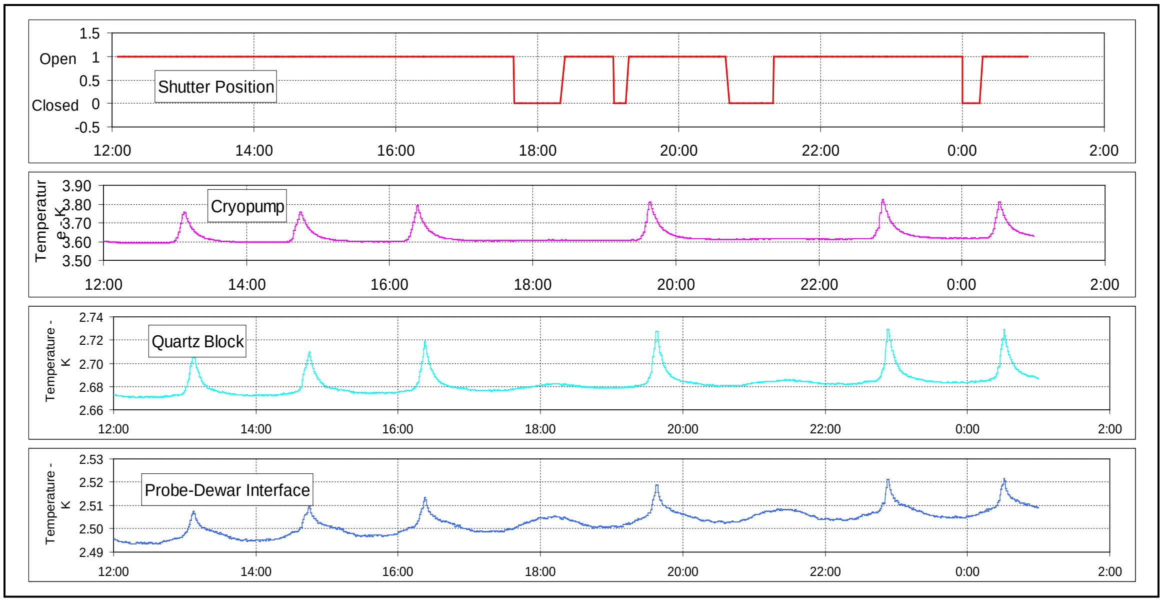


Figure xx: Thermal profiles for 8 orbits. Shutter status is shown at top of chart. Thermal variation with shutter open is due to heat radiating down neck due to earth shine. Thermal variation with shutter closed is due to expansion/contraction of the vacuum shell causing variation in BPS loading at Station 200.

There was little impact on science because the thermal transient occurs when the telescope points at the earth and precision science data is not required.

VIII. Performance Comparison of GP-B to Other Superfluid He Flight Cryostats

Comparisons of the GP-B cryostat to previously flown cryostats are made in three major areas: (1) weight, (2) launch pad performance and (3) thermal performance.

The dry weight/superfluid helium weight ratios of the dewars are plotted as a function of the superfluid helium weights in Figure 8.1. Note, the 30% weight savings achieved compared to the similarly sized ISO cryostat. Even larger savings are achieved if you eliminate the 51 kg proton shield dead weight.

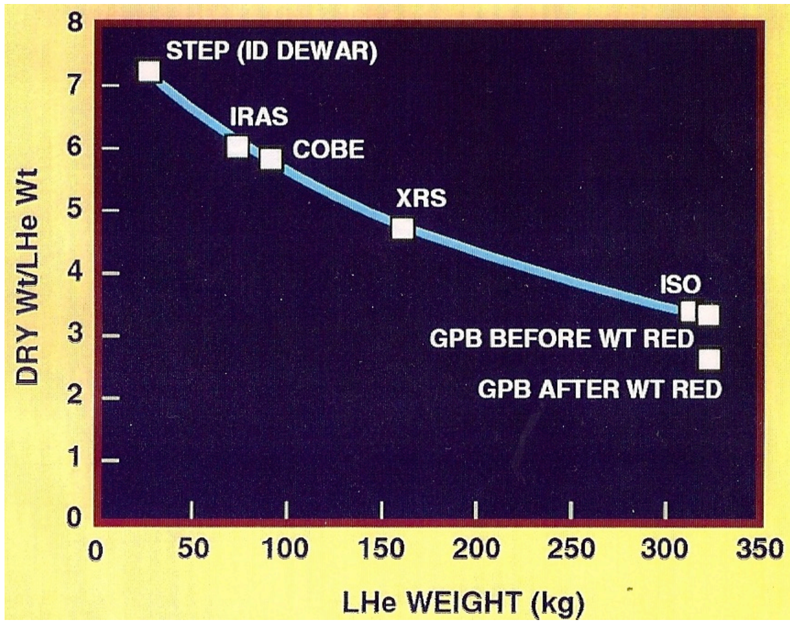


Figure 9.1 Dewar Weight Comparisons

The remarkable ground-hold performance of keeping the GP-B main tank non-vented for 90 days (Table 8.1) is due to the guard tank driving the inner vapor-cooled shield to 4.2 K (top) to 5 K (bottom); the main tank temperature rises from 1.6 to 1.85 K in this time period. The normal helium guard tank is filled every three days and no helium is lost from the main tank.

Table 8.1 provides a comparison of the acceptance test boil-off rates and the mission lifetimes. For equal warm boundary temperatures (acceptance tests), GP-B has the lowest percentage boil-off rate by a factor of three. However, mission lifetimes for some of the other cryostats are longer than GP-B because their space vacuum shell temperatures are so low. The reasons for the excellent thermal performance of the GP-B cryostat at such a high vacuum shell temperature are summarized in Table 8.2. Detailed discussion of each item listed is provided in the body of the paper.

Table 8.1 Superfluid Helium Flight Cryostat's Thermal Performance

Program	Acceptance Tests		Launch Pad				Space	
	% NHe Boil-off/Day (Th= 294 K, Science Instruments Turned Off)	Heat Rate (mW)	SFHe (kg)	Guard Tank Fill Cycle (Days)	SFHe Tank Non-vented Hold Time (Days)		Ave Vacuum Shell Temp (K)	Lifetime (Months)
					Max	Used		
IRAS	0.67	142	72	----	1.1		200	10
COBE	1.25	264	89	----	1.1			10
ISO	0.83*	650	331	1.9	5.6	5.6	112.6	28.3
GP-B	0.27*	216	337	3	90	56	255.6	17.3
SPITZER			50	----			50	69

*Guard Tank Empty

Table 8.2 Unique Thermal Features Contributing to the Low Heat Leak GP-B Cryostat

Unique Thermal Features	Dewar	Probe
Vapor Cooling		
- Four shields	x	
- Multilayer insulation	x	
- Plumbing lines	x	x
- Electrical lines	x	x
- PODS supports	x	
- Windows		x
- Baffles	x	x
Ultralow Thermal Conductivity Materials		
- Necktubes		
* Gamma alumina/epoxy	x	x
* Ti-15V-3Cr-3Al-3Sn	x	x
- PODS supports		
* Gamma alumina/epoxy	x	
- Emergency Vent Line		
* Mylar/Dacron laminate	x	
- Multilayer insulation with silk net spacers	x	
Special Coatings		
- Windows		x
- Baffles	x	x
Solar Protection		
- FOSR	x	
- Sunshade		x

Section IX. Conclusion

The GP-B Cryogenic Payload met or exceeded all requirements. See Table xx. The on-orbit lifetime of 17 months, 9 days, exceeded the 16 month requirement. The need for ultra-low magnetic field and ultra-high cleanliness mandated a Probe separate from Dewar. The hardware design and construction was followed by exhaustive ground testing. This ground test program included construction of special Dewar/Probe integration facilities and a large test laboratory at Stanford to verify the Science requirements. Next, the payload transferred to Lockheed Martin where it was integrated

Table xx

Parameter	***Dewar, Probe***	***Requirement***	***Achieved***
Lifetime	Dewar	16.0 months	17.3 months
Maximum helium temperature	Dewar	1.9 K	1.81 K
Ground hold	Dewar	90 day	xx days
Temperature stability	Dewar	< 30 mK	10 mK (?)
DC magnetic field	Dewar & Probe	< 1e-6 gauss	3e-7 gauss
AC magnetic field attenuation	Dewar & Probe	2e-12	2e-12
Gas flow conductance	Probe	xx	xx
Probe science pressure	Probe	< 1e-12 t	< 1e-14 t
Clear Aperture	Probe	14 cm	14 cm
Radiation attenuation	Probe	> 40 dB	60 dB
Proton shield	Probe	> 20 g/cm^3	21 g/cm^3
Off axis light attenuation	Probe	> 220 dB (?)	> 220 dB
Cross-track acceleration	Dewar & Probe	< 1e-11 g	1e-11 g
Helium slosh control	Dewar	Baffles	baffles
Maximum mass	Dewar & Probe	xx	xx

with the spacecraft and subjected to environment test. Ground operations required that the Dewar be kept cold for more than 6 years leading up to launch at Vandenberg Air Force Base. Two hardware issues were discovered during the ground test program. Modifications to the hardware allowed the program to progress without excessive delay. Following launch, the cryogenic system was set up for Science data collection. On-orbit set up activities included guard tank depletion, magnetic flux flush, gyroscope spin up, and low temperature bake out. Periodic heat pulse measurements of the liquid helium during the Science phase allowed estimation of mission end-of-life.