Gravity Probe B cryogenic payload

C W F Everitt1,4, R Parmley2, M Taber1, W Bencze1, K Burns2, D Frank2, J Kolodziejczak3, J Mester1, B Muhlfelder1, D Murray1, G Reynolds2, W Till3 and R Vassar2

1 Hansen Experimental Physics Laboratory, Stanford University, Stanford, California 94305-4085, USA
2 Lockheed Martin Corporation, Sunnyvale, CA 94089, USA
3 NASA George C. Marshall Space Flight Center, Huntsville, Alabama 35808, USA

E-mail: francis@relgyro.stanford.edu

Received 8 September 2015
Accepted for publication 15 September 2015
Published 17 November 2015

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, and ground and on-orbit performance will be discussed, culminating in a 17 month 9 day on-orbit liquid helium lifetime.

Keywords: GP-B, cryogenic payload, gyroscope, spacecraft, NASA, Stanford, Gravity Probe B

1. Introduction

For its dual test of Einstein’s theory of gravity, general relativity, the NASA Gravity Probe B Mission required a Dewar and 1.8 K Probe with on-orbit cryogenic hold-time of 16 months. This paper covers the design, construction, and flight operations of the Dewar/Probe system, the features that distinguish it from all prior Flight Dewars, and the ground-based program to develop it. Essential were constraints detailed in section 2 on cleanliness, stability, ultra-high vacuum, ultra-low magnetic field, etc. The actual on-orbit hold-time was 17 months 9 days. The cryogenic payload was the joint product of two institutions, Stanford University and Lockheed Martin, with review and technical contributions from NASA Marshall Space Flight Center.

4 Author to whom any correspondence should be addressed.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Figure 1. Cutaway diagram of Flight Dewar, showing 2319 ℓ main tank with baffles against helium slosh, and inner well into which the Flight Probe of figure 2 is inserted.

Figure 2. Flight Probe and Science Instrument Assembly, showing the cryopump, welded bellows, top hat, sunshade, and the albedo shutter mechanism which had to be left permanently open.

Figure 1 is the Dewar in section (length 3.0 m, diameter 2.2 m, helium capacity 95% full ~2319 ℓ). Figure 2 is the Probe and Science Instrument Assembly (SIA). The construction process, commenced March 1985, was intensely interactive, Stanford building the SIA and Lockheed the Dewar and Probe, with final assembly and testing in two unique facilities in the University’s Hansen Experimental Physics Laboratory: an 11 ft high horizontal-flow Class 10...
clean room for SIA/Probe assembly, and a 22 ft high, 12 000 ft² Class 10 000 first integrated systems test (FIST) laboratory for Dewar/Probe operations. The Dewar was relatively straightforward; the challenge was the Probe—meeting GP-B’s unique requirement to enclose the SIA in a separate, sealed, ultra-clean, ultra-low magnetic field, ultra-high vacuum chamber inserted into the Dewar well, incrementally prototyped, with extensive ground-based testing of three successive units: Probe A, a laboratory workhorse in which designs were reduced to hardware; Probe B, a flight backup, run initially in an Engineering Development Dewar (EDD) then the Flight Dewar; Probe C, the flight unit. The next six sections cover design and requirements, Dewar development, Probe development, the thermal model, and ground-based and on-orbit performance. We conclude with a comparison of the GP-B Dewar with other flight cryostats.

2. Cryogenic payload design and requirements

2.1. Overview

Considerations of three kinds, science, assembly, and launch, shaped the payload layout, leading in turn to seven distinct design issues:

- **Science:** the specific operating temperature, cryogenic lifetime, telescope aperture, gyro configuration, acceleration levels, satellite roll rate, pressure, magnetic field levels, etc required to allow the SIA to reach its planned on-orbit performance;
- **Assembly:** crucial as against all earlier Flight Dewars was isolation; the SIA had to be enclosed in a separate sealed Probe, capable of repeated insertion into and removal from the 1.8 K Dewar during ground testing;
- **Launch:** a payload/Spacecraft design of mass, size, mechanical robustness, etc capable of accommodation in the proposed Delta II launch vehicle.

The seven issues were: (1) cryogenic lifetime; (2) fixed pointing; (3) Spacecraft roll; (4) gyro spin-up; (5) ultra-low field technology; (6) ultra-high vacuum; (7) rotor charge control.

2.1.1. Cryogenic lifetime. The solar heat incident on the Dewar was ∼10 kW; the allowed input into the helium was 150 mW, a formidable ratio met by first lowering the vehicle skin temperature to ∼260 K with flexible optical solar reflector (FOSR) and then circulating the helium boil-off gas through four shields in the Dewar vacuum space. The latent heat L of helium at 2 K is 21 J g⁻¹; the specific heat of the gas 5.2 J g⁻¹ K⁻¹; to raise one gram of gas from 2 K to 260 K takes 62 L. Table 1 details computed gains in hold-time for one, two, and three optimally located shields, over a Dewar with no shields. Applied to the scaling of lifetime τ with skin temperature Ts, the same model made τ ∝ Ts⁻¹.₃₃, as against T⁻² for standard radiative transfer. With four shields the lifetime gain at Ts 260 K was 28, the fourth shield increasing the hold-time by ∼6%—about a month.

| # of shields | Gain factor G | Shield temperature in K |
|--------------|--------------|-------------------------|
| One          | 11.1         | 62.5                    |
| Two          | 19.9         | 41                      | 128                      |
| Three        | 25.5         | 25.5                    | 87.5                     | 185                      |
2.1.2. Fixed pointing, solar radiation and the Earth’s albedo. GP-B’s guidestar was occulted each half-orbit, exposing the SIA to albedo light from the Earth. For the resulting 40 mK SIA temperature swings and their impact, see section 7.3.3.

2.1.3. Spacecraft roll, SIA layout, and helium ‘bubble wrap’. Two constraints, gyro readout noise and ATC stability, led to a spacecraft roll rate, settled on orbit, of \( \sim 0.013 \, \text{Hz} \) (77.5 s period), with the four gyroscopes in line within 50 \( \mu \text{m} \) of the telescope boresight, the mean cross track acceleration on each was \(< 10^{-10} \, \text{g}\). A ‘bubble wrap’ to be described in section 7.2.5 symmetrized the distribution of helium in the Dewar.

2.1.4. Probe diameter, telescope aperture, SIA mounting, and gyro spin-up. Requirements of all three kinds, science, assembly, and launch, fixed the Probe diameter. First, the 0.14 m telescope aperture called for a 0.18 m diameter SIA. Second, assembly and launch required robust SIA mounting within the Probe frame. Finally, \( 10^{-3} \, \text{Torr} \) differential pumping for the gyro spin-up system imposed a minimum 0.25 m inner diameter for the Probe.

2.1.5. Probe length, Dewar hold-time, and ultra-low field shielding. Two factors, hold-time and magnetic shielding, fixed the Probe length. Shielding had two aims: low trapped flux in the rotors and \( \sim 234 \, \text{dB} \) attenuation of varying external fields. The ultra-low field technology described in section 6.3.3, based on expanding a superconducting lead bag in the Dewar well, imposed magnetic constraints on probe materials. The 234 dB attenuation came via: (1) a cryoperm shield; (2) the lead bag; (3) transverse superconducting shields around each gyroscope; (4) the rotor’s own self-shielding. Long hold-time made for a large Dewar with an overall Probe length (excluding sunshade) of 3.3 m.

2.1.6. Ultra-high vacuum via ‘low-temperature bakeout’. At 2 K, all gases except He\(^3\) and He\(^4\) are frozen out. Spin-up injected large quantities of He\(^4\) into the Probe, with spin down times after pump-out of 40–50 yr. ‘Low temperature bakeout’ (i.e. heating the SIA from 2 K to 6 K for a few hours and then letting it cool down) followed that, after which spin-down times ranged from 7000 to 25 900 yr depending on the gyroscope. For details see section 7.2.7. The actual on-orbit pressure approached \( 10^{-14} \, \text{Torr} \). Had that been the only damping, \( \tau_s \) would have been \( \sim 2 \times 10^8 \, \text{yr} \).

2.1.7. Rotor charge control. The maximum allowed electric charge on each rotor was \( 3 \times 10^7 \) electrons. A study based on the ESA Geant model called for heavy attenuation of cosmic ray charging; hence the increase seen in figure 1 in wall thickness of the Dewar well from 5 mm to 38 mm over the 0.5 m length surrounding the SIA. Each gyroscope had an elegant UV discharge system, reviewed in paper 7 [1], actuated on-orbit for a few hours.

2.2. Summary with table

The Dewar/Probe assembly was a unity with many cross-connections. Take ultra-low magnetic field versus hold-time. Lead bag expansion was a Dewar issue but even more effort went to the shielding and non-magnetic requirements of the Probe. Long hold-time took the most rigorous thermal link between the four Dewar/Probe heat stations, and optimizing the Probe heat load. Table 2 summarizes the principal design requirements, along with the on-orbit values, discussed in section 7.4.
3. Flight Dewar

3.1. Overview

To maintain the SIA at 2.6 K for 16 months the Dewar utilized: (1) passive orbital disconnect struts (PODS) combining rigid launch support with low on-orbit heat leak; (2) a 98 ℓ toroidal ‘guard tank’ filled during ground operations with normal helium at 4.2 K; (3) aluminum shielding of the science gyros against ∼200 MeV cosmic ray protons; (4) the lead bag low field shield; (5) two graphite-epoxy mounted attitude reference platforms (ARPs); (6) built-in damping of helium slosh. For ground tests the Dewar had to operate in any orientation, horizontal to vertical, and be capable of transferring normal or superfluid helium from the main tank to the well. With the guard tank refilled every three days, the main tank could be kept sealed at the launch pad below 1.86 K for 90 days.

3.2. Design principles

The Dewar comprised three vessels: main tank, guard tank, and shell; figure 3 is an open view of it partially assembled. The design had five aspects: vessels, plumbing, instrumentation, thermal/mechanical considerations, and weight. In what follows, the term ‘Station 200’ denotes the location on the engineering drawing coordinate system of the Dewar/Probe mounting flanges at the upper end of the Dewar main tank.

3.2.1. Main tank and well. The main tank, constructed from 2219 aluminum, an alloy with excellent mechanical properties and weldability, held 2319 ℓ of superfluid helium with vapor ullage of 5%. Extensive use of ring-stiffened and waffle structures minimized its mass. Internal features included fill and vent plumbing, liquid level sensors, temperature instrumentation, heat pulse meters, and baffles to damp helium slosh and keep the helium and ullage axially symmetric about the SIA. The Dewar’s 0.28 m alumina epoxy necktube joined the central well in the main tank at Station 200 to form a continuous, cylindrical vacuum-tight region into which the Probe was inserted. The well was fabricated from 6063 aluminum, which has low remanent magnetization and sufficiently high thermal conductivity.
to hold the final $10^{-7}$ gauss lead bag below 7.2 K through launch. The cryoperm shield provided a $\sim 10^{-3}$ gauss starting volume for the expansion process and prevented the upper edge of the bag from going normal.

3.2.2. Guard tank. The 2219 aluminum guard tank, tied to the lowest shield on the Dewar neck, held up to 98 ℓ of helium at 4.2 K. Its purpose was to eliminate superfluid helium transfer at the launch pad. With the guard tank empty, the vapor-cooled shield ran at $\sim 27$ K; with it full the heat load on the main tank dropped by a factor of 20, allowing it to be kept non-vented for 90 days. Filling the guard tank with normal helium every few days was a much simpler operation. After launch, as the guard tank emptied, it cooled the Dewar’s four shields below their normal running temperatures, providing a further small gain in on-orbit cryogenic lifetime.

3.2.3. Vacuum shell. The Dewar shell, also from 2219 aluminum, was in three parts, aft dome-cylinder, support ring, and forward cylinder-cone, kept vacuum-tight with the largest known Inconel seals. The seal material, soft aluminum, allowed triangular ridges above and below to be crushed for single-use assembly, providing vacuum isolation during ground operations and launch. Like the main tank, it was optimized for both internal and external pressures to minimize mass.

3.2.4. Plumbing. The plumbing had four functions: (a) filling the three helium vessels, main tank, guard tank, and well; (b) normal venting; (c) on-orbit control of helium boil-off by the porous plug; (d) emergency venting. Remotely actuated valves (RAVs) developed by Mission
Research Corporation, Logan, Utah controlled all operations. Figure 4 is the plumbing schematic showing fill lines to both tanks, transfer paths to the Dewar’s inner well and emergency over-pressure protection valves.

Figure 4. Dewar plumbing schematic.
3.2.4.1. Filling. All three vessels were filled from an external supply Dewar via a single bayonet/manual valve port. To prevent magnetic contamination, the incoming liquid passed through a filter inside the shell. The single fill line could supply each vessel through RAVs 1, 2, and 5; also the plumbing was designed to allow the guard tank and well to be filled with normal helium with a total of seven RAVs internal to the shell. Given the severe magnetic requirement, the well fills were always done by transfer from the main tank through a second cold internal filter.

3.2.4.2. Venting. On the ground the main tank was vented through bypass valve RAV-3, and in space through the porous plug. Cooling came at five locations starting at the coldest attachment point Station 200, and then at each of four necktube heat exchangers (HEXs) tied to the four vapor-cooled shields. Each HEX was split into two clamshells with stainless steel lines bonded to them after the HEXs had been bonded to the necktube, splitting the flow into two paths linked by copper bridges. On Earth, the main tank vent-line exiting to a high-vacuum system maintaining the shell < 10^{-7} Torr. In space the guard tank and well were vented through ports opened pyrotechnically once altitude was reached, and the main tank via parallel RAVs connected to the ATC. The main vent-line went straight up the necktube; a perforated copper plug with multiple holes parallel to the flow path ensured good heat transfer at each shield.

3.2.4.3. Porous plug. The porous plug controlled the flow of superfluid helium from the Dewar. To provide control authority for the ATC thrusters, it had to operate over a much wider range (4–16 mgs^{-1}) than the plugs used in other space-borne Dewars. A flow valve in the vent-line, and heater in the tank, gave the necessary temperature stability and flow rate. For details of this GP-B invention and its application here, see paper 14 [2]. Additional important background work is given by Frank and Yuan [3].

3.2.5. Instrumentation. Table 3 lists Dewar instrumentation. Heaters had several functions: on the ground to manage helium fills and internal tank-to-tank transfers; on-orbit to control the Probe temperature and adjust the flow rate. Other instrumentation included position sensors to monitor the open or closed status of the plumbing RAVs, and two units, a heat pulse meter and vent-gas flow meter, to provide continuous independent measures of the Dewar’s residual on-orbit hold-time.
3.2.5.1. Hold-time measure 1: the heat pulse meter. This unit comprised a heater and thermometers in good thermal contact with the main tank, with the high thermal conductivity of the superfluid ensuring even heat distribution. As the tank emptied, heat transfer to the ullage gas increased. In one check toward the end of the Mission, 14.5 W were injected for 60.1 s, giving a temperature rise of 6.49 mK.

3.2.5.2. Hold-time measure 2: the vent-gas flow meter. Based on convective heat transfer from a 19 mm long multilayer insulation (MLI)-wrapped vent-line section heated to an isothermal condition by a 75 mW heater, the vent-gas flow meter provided a second lifetime prediction. An OFHC copper clamshell bonded to the stainless steel vent line ensured uniform wall temperature and a thermally stable mounting for the heater and thermometer.

3.2.6. Unique thermal/mechanical features. The finished system required: (a) materials for the two necktubes and PODS with low thermal conductivity over the full temperature range ambient to 2 K: (b) an optimized MLI system: (c) optimized honeycomb vapor-cooled shields: (d) good PODS design: (e) proper retention/thermal sinking of the Probe to the Dewar: (f) stable ARP mounts: (g) emergency venting. We discuss each in turn.

3.2.6.1. Low thermal conductivity materials. The two necktubes, Dewar and Probe, had to be leak-tight and combine low thermal conductivity with strength. We compared the thermal conductivities of three materials for them and the PODS over the range 2 K to ambient: gamma alumina fiber/epoxy, T-300 carbon fiber, and S-glass. Best was gamma alumina fiber/epoxy, which combined excellent mechanical properties with conductivity 4 K–50 K equal to T-300 and lower than S-glass; and at higher temperatures lower than carbon and only slightly higher than S-glass. Since gamma alumina is porous to helium, a vacuum barrier was needed. We checked various low thermal conductivity alloys, comparing in particular the conductivities from 300 K to 10 K of 304 stainless steel, Ti-6Al-4V, and the Ti-15V-3Cr-3Al-3Sn titanium alloy developed by Lockheed for its SR-71 aircraft. Best by far over the entire range was the Ti-15V-3Cr-3Al-3Sn. A 0.025 mm thickness of this created a vacuum-tight cylinder with minimal additional heat load.

3.2.6.2. Multilayer insulation. Double aluminized Mylar with silk net spacers was found in tests at Lockheed to be the optimal MLI, with three layers of netting at the tank side, reduced progressively to one at the Dewar shell. The patterns were cut on a computer controlled table from the clothing industry, with sizes precisely increased for each layer. In all, we installed 139 MLI shields. See also Nast [4].

3.2.6.3. Honeycomb vapor-cooled shields. To reduce weight the vapor-cooled shields had a honeycomb structure, combining perforated 5052 aluminum honeycomb core with bonded 1100 aluminum perforated face sheets 0.1 mm thick. Trial panels were constructed and tested to ensure the air could be evacuated from the core, before settling on this design.

3.2.6.4. Passive orbital disconnect struts. A Flight Dewar must combine rigid support through launch with low heat leak on orbit. Figure 5 illustrates how Lockheed’s PODS achieved this. Each PODS had a central flanged aluminum piston fitting with <2 mil (0.05 mm) clearance into an aluminum cylinder set within concentric low thermal conductivity alumina epoxy ‘orbit tubes’. Under launch load the piston locked against the cylinder’s mating surface. On orbit the spring relaxed to gain low thermal conduction through the orbit tubes. Surrounding this was a larger diameter ‘launch tube’, containing radiation
baffles and graphite ‘spokes’, grounded thermally to all four vapor-cooled shields in the Dewar. The PODS heat load was expected to drop on orbit by a factor of 6, but with the Belleville washer redesign to be described in section 6.3.3.3, six had to be shorted and the reduction was only a factor of 2.

3.2.6.5. Retention/thermal sinking of Probe to Dewar. Tied to the Dewar at Station 200, the Probe held the lead bag firmly against the inner surface of the Dewar well, besides making excellent thermal contact there and at the four necktube HEXs. A retainer with 16 titanium copper springs flattened against the lead bag and Dewar well provided firm lateral support as the Probe went in.

3.2.6.6. Emergency vent-lines. Any rapid loss of Dewar vacuum will cause a huge main tank heat load, resulting in an explosion. Earlier Flight Dewars had burst discs, but since the escaping high pressure gas has to flow through the MLI and shields, that risked blocking the discs with torn MLI or damaged shields. Figure 6 shows GP-B’s unique 3 mW line, with a 51 mm diameter Mylar/Dacron laminate capable of rapid inflation but folded flat when not in use. Tests with the line immersed in liquid nitrogen showed little leakage when rapidly inflated. Small holes in the metal end fittings allowed the lines to be evacuated along with the insulation during normal pump-down.

3.2.6.7. Attitude reference platforms. Each gyroscope’s roll phase \( \varphi \) had to be known with respect to GP-B’s orbit plane to <10 arc-s, ideally by transverse star trackers and rate gyroscopes on the SIA, but in practice by two reference platforms outside the Dewar, each with its own star tracker and rate gyroscope, connected by the graphite pedestals shown in figure 7 to the Dewar’s internal graphite ring. The ARP pedestals were 120° apart; the thermal load path was as follows. First, at 1.8 K, where the expansion

---

**Figure 5.** PODS load paths featuring passive thermal disconnect which reduces the heat leak.
The coefficient of aluminum is vanishingly small, the connection from Probe/SIA to the Dewar main tank was stable. Next, the gamma alumina composite in the PODs had very low thermal expansion. The same high stability continued through the graphite ring.
(figure 3) to the ARP pedestals, protected from Dewar shell motions by their flexible seals.

3.2.7. Weight reduction. With the Delta II launch vehicle, weight saving was critical. Initially the Dewar mass was 1330 kg. The waffled domes and ring-stiffened cylinders of the main tank and shell, and honeycomb shields, reduced this to 810 kg. Table 4 lists the main savings. Earlier we had examined the riskier option of using aluminum–lithium for the tank and shell, but since the 228 kg reduction of table 4 met Mission requirements, we did not pursue it.

3.3. Overall checks

3.3.1. Leak check and proof pressure verification. Superfluid helium systems must be absolutely leak-tight. Given the extreme difficulty of correcting internal leaks, we established rigorous design and test procedures. First, all the tanks and vacuum shell sections were electron beam welded; no leaks were found. Next, we epoxy-bonded aluminum doubler strips over each weld and over the bonds of the composite necktube to the vacuum shell top plate and main tank well. Epibond 1210 was the epoxy selected; with it we mixed 0.08 mm glass beads to maintain a constant bond line thickness. All tanks, lines, and the shell were pressure tested and leak checked. For cold joints (welds, epoxy bonds, HelicoFlex seals) our procedure was to leak-test them warm, cycle them three times to 77 K, retest them as the Dewar was assembled, and then after assembly, leak-test the tanks and plumbing as a system, both warm and at 4.2 K. No leaks were found.

3.3.2. Vacuum bakeout. For vacuum bakeout, we set the Dewar upside down within a customized, insulated forced air oven, making any creep of the aft PODS in a favorable direction, pumped down the shell to 1 Torr in 29 h, while the oven was brought up to 317 K and held there for 11 days. Following creep tests of heated PODS we raised the temperature to 322 K and held it there for six additional days. At the end of the bakeout, the pressure was $5 \times 10^{-4}$ Torr at 322 K and $5 \times 10^{-5}$ Torr at 294 K. The predominant remaining gas was water vapor.

4. Flight Probe

4.1. Overview

The Flight Probe supported the SIA mechanically, optically and electrically, provided the required thermal, vacuum, and cleanliness environments, and upon integration with the Dewar met all GP-Bs low heat leak, low magnetic field, and launch load requirements.

Three SIA issues, flow conductance, telescope aperture, and designing a secure quartz block support (QBS) framed the layout, with electrical cables, spin-up plumbing, and UV fiber optic cables routed through the necktube to external feedthroughs. The hardware spanned three regions: thermal gradient necktube, ambient temperature, and low temperature. Cables and plumbing bridged all three, and the telescope’s 0.14 m diameter clear aperture, capped at the upper end with a warm sealed window, ran the length of the Probe. Two features in the ambient temperature region above the Dewar were the top hat containing electrical and optical feedthroughs, and the T-flange with a gate valve and warm vacuum window. Next in design came vacuum/cleanliness and magnetics, and finally the assembly
process. Overriding all was the grand requirement of a total Dewar/Probe heat load <220 mW.

Figure 8 shows Probe C in fabrication at the LMSC Palo Alto Research Laboratory, with a 3.35 m long Probe Assembly Tool mounted in trunnions at each end, with gold plated 55-pin connectors temporarily placed at the warm end on the left and the aluminum QBS for the SIA installed at the cold end.

4.2. Cryogenic layout

4.2.1. Thermal gradient necktube region. The Probe heat load comprised, in addition to conduction down its gamma alumina/epoxy necktube, radiation from the top hat and conduction in the plumbing and leads, all tied through heat stations to the Dewar’s four vapor-cooled shields. Incoming radiation met reflective windows and heat-absorbing false walls at the three lower stations, with the conductive loads sunk to all four. Thermal shoes linked the Probe stations to those in the Dewar. Cables and plumbing were bonded into heat station mounting rings, bonded in turn with the HEXs and shoes to the necktube inner wall. Figure 9 shows the layout, with forward and aft false wall cylinders which limited radiation to the QBS and telescope, while leaving space for differential pumping of the leakage gas during gyro spin up. Heat station mounting rings, one of which is seen in figure 10 provided a bond surface for the false walls, forward and aft, with U-shaped cutouts around the circumference serving as guides for the cables. Channel caps, bonded over them, provided a continuous face to the necktube’s inner surface. The rings were solid copper, plated with rhodium to provide an oxide-free surface for the epoxy bonds. They were turned, milled to shape, with the cutouts fabricated by wire electrical discharge machining techniques. Outer rings on the Probe necktube provided a conductive and mechanical connection to the Dewar stop rings via the thermal shoes.

4.2.1.1. False walls. The false wall cylinders were 1100 aluminum sheet, spin-formed on mandrels and re-annealed, black anodized on their inner surfaces to absorb radiation, and gold plated on the outside to minimize re-radiation. They were bonded to the mounting rings with a low outgassing material, Epibond. A set of baffles, made in three circular segments, also
4.2.1.2. Thermal shoes. The thermal shoes in figure 9 provided thermal and mechanical connection between the HEXs and Dewar cooling system as the Probe reached its final installed position. A stop ring in the Dewar necktube caught the shoe as the Probe came within 5 mm of Station 200, forcing it to slide radially and compress the spring. Mating parts had the same radius. The ring was plated with rhodium to create an extremely hard surface, preventing transfer of indium from the shoe. To enable multiple insertion and removal of the Probe, the shoes could be re-aligned and refurbished with new springs.

4.2.1.3. Cold windows. The Probe had three single crystal sapphire necktube windows (figure 11(a)) tilted 2° to reduce ghosting, with the crystalline axes of adjacent windows black-anodized on the warm side and gold-plated on the cold side, conducted heat to the false wall cylinders.
opposed to minimize birefringence effects. The windows, clamped between spring bellows in the heat station mounting rings of figure 10, were 7 mm thick and 170 mm in diameter. Each had an anti-reflective coating on its warm surface and low emissivity coating on the cold surface to minimize infrared transmission. The optical transmission was 37%; the three lugs of figure 10 were the attachment points. The topmost window, #3, is seen in location from the view into the Probe of figure 12.

4.2.1.4. Window #4. Window #4 (figure 11(b)) also of single crystal sapphire but 0.2 m diameter, sealed the Probe. Tilted at 2°, it was gripped between two indium-coated C-seals at the upper end of the T-flange, a development that took multiple design iterations and prototype testing. Heat intercepted by the window flowed to the T-Flange and then to the Dewar shell. A thin gold coating on its inner surface rejected EMI and provided low thermal emissivity.
4.2.1.5. Top hat and T-flange. The top hat and T-flange chambers, bonded to the warm end of the necktube, together housed plumbing feedthroughs, electrical feedthroughs, and a set of motorized valves to allow gas to exit the Probe. The electrical feedthroughs, each leak tested to $10^{-9}$ sccs, were of three types: suspension, instrumentation, and SQUID, with ceramic-insulated conductors and shields, brazed after metal vapor-deposition with fluxless silver/gold alloy solders into stainless steel housings welded into the top hat. The suspension feedthroughs were triaxial with two insulating sleeves. The SQUID feedthroughs had six pins; the instrumentation ones had 55, using proprietary pin-by-pin glass insulators fired to melt and form a hermetic seal. Each was welded into the top hat from the inside. All pins were gold plated to provide good electrical contact. The fiber optic cables were epoxy-bonded into the top hat. During Probe/Dewar integration, an O-ring flange sealed it to the Dewar.

Figure 12 is a view into the Probe from the top hat, showing the many electrical feedthroughs, and also the plumbing feedthroughs welded into the top hat and bonded inside the Probe to stainless steel tubes from below, along with an internal gold plated radiation shield and window #3. The caging and spin-up supply lines were gold plated to minimize thermal radiation. The supply line diameters were 6.4 mm, the exhaust lines 32 mm. Welded bellows in the cables and plumbing accommodated thermal expansion and contraction from varying Dewar shell temperatures. The T-flange, built without welds from a weight saving aluminum alloy, had four spin-up exhaust valves, one for each gyroscope, and two Vatterfly valves with low permeability nitrile rubber seals to allow the spin-up gas to be exhausted to space. For ground operation, the valves were capped and pumped to prevent air permeation; also installed in the T-flange for safety were a Probe burst disc and pressure sensing port.

4.2.2. Low temperature region

4.2.2.1. Quartz block support. Figure 13 presents three views of the cylindrical aluminum QBS, designed to support the SIA through launch, welded at its upper end to a ring-forging at Station 200, and at its lower end to extruded trays for cables and plumbing. The SIA had four lobes extending outward 90° apart, each with five holes for a total of 20 bolted support points. The two upper photographs show five slotted ‘finger attachments’ at each location, allowing
the aluminum support to shrink without overstressing the SIA. Early launch level vibration tests indicated that the fingers could twist under lateral vibration, causing local spalling of the quartz, a problem corrected in Probe C by adding molybdenum interface pads. For good thermal connection, part of the QBS at Station 200 was coated with indium, as seen in the third photograph of figure 13.

4.2.2.2. Vacuum shell. The Probe vacuum shell was a closed-end tube attached to the QBS after SIA/Probe integration. During Probe/Dewar integration, the shell pushed the ‘venetian blind’ lead bag retainer blades outward, pressing the bag against the Dewar well. Surface heaters raised the temperature to the appropriate values for on-orbit flux-flushing and bakeout.

4.2.2.3. Cryopump. The cryopump (figure 14) was an 0.28 m outer diameter cylindrical welded assembly of 314 sintered titanium fins with surface area 2400 ft², 5 times the
requirement, cleaned during assembly to Class 100 standards with a high velocity DI water flush. Heaters and thermal standoffs allowed it to be raised to 10 K for the low temperature bakeout.

4.2.3. Electrical cables, spin-up plumbing and general considerations

4.2.3.1. Electrical cables. A total of 71 electrical cables, connected to leak-tight feedthroughs in the top hat and cold end connectors just below the QBS, ran the gyro suspension systems, SQUID readouts, telescope readout, thermometers and heaters. Specifications for capacitance, shielding attenuation, breakdown voltage and resistance were defined for each. Signal conductors were bare or polyimide-coated 5 mil phosphor bronze wire; heater wires were 5 or 10 mil diameter. Phosphor bronze shields minimized magnetic contamination, the use of nearly light-tight shielding minimized interference and crosstalk. The electrical isolation of the conductors and shields was checked as the cables were built and integrated into the Probe. The use of thin walled stainless shields in the necktube and top hat was critical. See table 5.

4.2.3.2. Spin-up plumbing. Figure 15 is the spin-up plumbing. Incoming gas cooled to 2.5 K as it passed through channels in the HEXs and QBS, then reheated to 6.5 K just before the gyroscope. The exhaust gas was routed upward through circumferential channels and axial tubes, with larger diameter in the warm section, cooling the incoming gas in the aforementioned HEXs.

4.2.3.3. Vacuum/cleanliness considerations. For ground testing the Probe required leak-tight feedthroughs and seals, and rigorous control of virtual leaks and outgassing, with indium plated C-seals ranging from 25 mm diameter for small units to 0.3 m for the top hat/T-flange seal. Mating surfaces were coated with gold and indium, new C-seals being used whenever a
| Cable type          | Cable quantity | Conductors within one shield | Total conductors | Comment                                                                 |
|--------------------|----------------|------------------------------|------------------|-------------------------------------------------------------------------|
| Suspension coax     | 33             | 1 each                       | 33               | 6 cables + spare for each gyro + 5 (not actually used) for a separate proof mass |
| Ground coax         | 5              | 1 each                       | 5                | 1 per gyro + (proof mass)                                               |
| SQUID               | 24             | 4 each                       | 96               | 2 twisted pairs in each shield                                          |
| Telescope detector  | 1              | 40 each                      | 40               | 2 26-pin connectors at cold end                                         |
| Instrument temp sensors | 3        | 55 each                      | 165              |                                                                         |
| Instrumentation heaters | 3          | 55 each                      | 165              |                                                                         |
| UV discharge        | 3              | 6 each                       | 18               | 3 twisted pair per cable                                                |
| Totals              | 72             | —                            | 522              |                                                                         |
connection was needed. Well placed vent holes staved off virtual leaks. Fasteners had holes along their centerlines; electrical connectors had multiple holes to release gas trapped in close-fitting parts; cable shields had holes every 25–50 mm, depending on the cable type. To limit outgassing most parts were metal or insulators of ceramic, polyether ether ketone (PEEK), or polyimide (Kapton). Short lengths of Teflon tubing joined spin-up supply and vent-lines to the gyro housings. Epibond, ‘degassed’ in vacuum to release air entrained in the mixing process, was used throughout. Parts were cleaned to Class 100 level prior to assembly, all being subjected to manual cleaning, ultrasonic cleaning, and high pressure spray cleaning with distilled water. Assembly was in a downflow clean room, using vacuum systems to capture particulates from drilling, tapping, and other operations. The completed Probe was sealed, evacuated and leak tested, and—using an air shroud—heated to 150°F for several days to desorb water before shipment to Stanford for SIA/Probe integration.

4.2.3.4. Magnetic considerations. The two magnetic requirements <9 × 10⁻⁶ gauss trapped flux in the rotors and 234 dB ac shielding; along with Johnson noise, magnetic susceptibility, and trapped flux distortion, severely constrained the remanent magnetism, permeability and thermoelectric properties of the Probe. Probe C fabrication was a three year process run in daily coordination with LMSC under a four part magnetic control plan; (i) cryogenic screening of all materials; (ii) cryogenic screening of all finished parts in critical areas; (iii) room temperature gradiometer screening of the completed Probe; (iv) full integrated system ground test of rotor trapped field levels. It involved three separate test facilities, a commercially available Quantum Design MPMS SQUID system for rapid measurement of small parts and coupons, a unique ultra-low field cryoscreener for parts up to 10 cm diameter, and a Cryotron SQUID gradiometer mounted in a special magnetically shielded facility for room temperature testing of large parts. Over 7000 parts and assemblies were screened. Table 6 summarizes the critical measurements and the suppliers of the materials. The copper
Table 6. Magnetic properties of materials.

| Material                  | Supplier                        | Remanent (emu) | Susceptibility (emu g⁻¹) |
|---------------------------|---------------------------------|----------------|--------------------------|
| **Structural metals**     |                                 |                |                          |
| Al 6061                   | Alcoa, Reynolds                 | ≤4.0 × 10⁻⁷    | 7.0 × 10⁻⁷               |
| Ti 99.6%, Grade 2         | Goodfellow, TiCo                | ≤2.5 × 10⁻⁷    | 3.1 × 10⁻⁶               |
| Nb Type 1                 | Teledyne Wah Chang              | ≤4.0 × 10⁻⁷    | 2.5 × 10⁻⁶               |
| Copper 10100 99.99%       | Sequoia Copper and Brass        | ≤3.0 × 10⁻⁷    | 2.5 × 10⁻⁷               |
| BeCu 25 C17200            | Brush Wellman, NGK              | ≤3.1 × 10⁻⁶    | 4.0 × 10⁻⁷               |
| BeCu 125                  | Brush Wellman                   | 1.7 × 10⁻⁷     | 1.5 × 10⁻⁷               |
| Binary BeCu               | NGK Beryco                      | ≤1.9 × 10⁻⁷    | 2 × 10⁻⁸                 |
| Binary BeCu               | Ames Research Iowa St.          | ≤9.7 × 10⁻⁸    | 4.3 × 10⁻⁸               |
| BeCu 3HP                  | Brush Wellman                   | ≤6.5 × 10⁻⁷    | 8.3 × 10⁻⁸               |
| TI Cu unschild900         | Yamaha Metals                   | ≤3.0 × 10⁻⁷    | 3.7 × 10⁻⁷               |
| Si Bronze                 | Sequoia Copper and Brass        | 0.3–2 × 10⁻⁴   | −4.5 × 10⁻⁷              |
| Phos Bronze C-51000       | Copper and Brass Sales,         | ≤2 × 10⁻⁵      | ≤3.0 × 10⁻⁶              |
| Phos Bronze Custom        | Ames Research Iowa St.          | 1–4.7 × 10⁻⁷   | 1 × 10⁻⁶–3 × 10⁻⁶        |
| Molybdenum 99.97%         | CSM Industries                  | ≤4.5 × 10⁻⁷    | 9.6 × 10⁻⁷               |
| **Structural dielectrics**|                                 |                |                          |
| Teflon                    | Dupont                          | ≤9.0 × 10⁻⁷    | −5.0 × 10⁻⁸              |
| Delrin                    | Laird Plastics                  | ≤5 × 10⁻⁸      | −4.7 × 10⁻⁷              |
| Kapton                    | Dupont                          | ≤2.0 × 10⁻⁷    | 1.6 × 10⁻⁷               |
| Vespel                    | Dupont                          | ≤6.6 × 10⁻⁷    | 8 × 10⁻⁷                 |
| PEEK                      | E Jordon Brooks                 | ≤9.2 × 10⁻⁷    | 1 × 10⁻⁷                 |
| Sapphire                  | Saphikon Inc.                   | ≤7.4 × 10⁻⁸    | −1.2 × 10⁻⁷              |
| Quartz                    | Corning, Hereas Amersil         | ≤1.5 × 10⁻⁷    | −1.1 × 10⁻⁷              |
| **Wire and ribbon**       |                                 |                |                          |
| Manganin .005′            | Lakeshore Cryotronics           | 2.4 × 10⁻⁴     | 1.8 × 10⁻⁴               |
| Phosphor bronze           | California Fine Wire            | ≤2.5 × 10⁻⁶    |                          |
| Copper 38 gauge           | Belden                          | 4.0 × 10⁻⁷     | −3.7 × 10⁻⁸              |
| Platinum-tungsten         | California Fine Wire            | 1.4 × 10⁻⁶     | 3.3 × 10⁻⁶               |
| Nb/Ti .005′/ .010′        | California Fine Wire            | ≤1.8 × 10⁻⁶    | 2.0 × 10⁻⁶               |
| Silver ribbon .004′       | California Fine Wire            | 1.5 × 10⁻⁸     | 2.7 × 10⁻⁸               |
| **Special**               |                                 |                |                          |
| Si Diode Therm            | Lakeshore Cryotronics           | 1.0 × 10⁻⁶     |                          |
| Ge Therm 1500B            | Lakeshore Cryotronics           | 0.5–2 × 10⁻⁶   |                          |
| Permaly 55145-A2          | Magnetics Corp.                 | 2 × 10⁻⁵       |                          |
| Indium 99.99%             | Indium Corp. of America         | 3.0 × 10⁻⁷     | 7.8 × 10⁻⁸               |
| Indium #150 Solder        | Indium Corp. of America         | 7.0 × 10⁻⁸     | 2.3 × 10⁻⁷               |
| PbSn 60-40 Solder         | Kester                          | ≤7.0 × 10⁻⁷    | 2.5 × 10⁻⁸               |
| Poly shrink tubing        | Advanced Polymers Inc.          | ≤8.0 × 10⁻⁷    | 1.3 × 10⁻⁶               |
| Trabond 2115 Epoxy        | Tra-Con                          | ≤2.4 × 10⁻⁷    | −3.5 × 10⁻⁷              |
| Stycaet 1266 Epoxy        | Emerson and Cuming              | ≤7.1 × 10⁻⁸    | −4.6 × 10⁻⁷              |
| Silver Epoxy 83-C         | Emerson and Cuming              | ≤2.3 × 10⁻⁶    | 8.8 × 10⁻⁷               |
arm on which the niobium box containing the SQUID was mounted had to be coated with superconductor to ‘shield in’ Johnson noise currents.

The Probe had six zones (figure 16) with different requirements: \(<10^{-7}\) gauss remanent fields for parts in zones 1, 2, 3; \(<10^{-6}\) gauss in zone 4, and in zone 5 \(<10^{-1}\) gauss—low enough to guard the cryoperm shield while allowing permanent magnet motors in some areas. Most complex was zone SP, the necktube area, with competing low heat leak/low magnetic field limits: far enough from the SIA to allow gyro suspension and readout cables made from low thermal conductivity stainless steel but needing great care to prevent magnetic particles migrating from it to zones 1, 2, 3. Throughout the construction we tested parts to their zone requirements, and monitored joining and bonding procedures. The many thousands of piece parts for zones 1, 2, and 3 were screened in one of the three cryogenic facilities and chemically etched prior to screening to remove any embedded machine tool contaminants. The cold end cable shields were fabricated from high purity phosphor bronze, cast and forged from 99.999% pure copper and 99.999% tin, melted in a graphite container by a small foundry in Ames, Iowa, with all shield tubes and multi-connector blocks drawn from the resulting billets. Specially built non-magnetic phosphor bronze wrenches and screwdrivers were essential. A final grand demagnetization was performed via a diminishing ac magnetic field within a three-axis 20 ft diameter Helmholtz coil system, set up years earlier for the Pioneer space probes at NASA Ames. Final full Probe screening was by a combination of fluxgate and SQUID gradiometers, with the Earth’s field nulled prior to shipment to Stanford for SIA integration and installation into the Dewar.

4.2.4. Probe assembly. Probe assembly had two phases: primary at LMSC using the Probe Assembly Tool of figure 8, then integration with the SIA at Stanford. First at Lockheed, the suspension, instrumentation, heater and SQUID cables were bonded into the heat station rings. Next the QBS was installed and the cables bonded into saddles there, followed by a step known to Lockheed engineers as ‘the miracle’: integrating the heat station/QBS/cable assembly, mechanically and thermally with the necktube. FM73 epoxy tape was applied to the QBS interface and heat station rings. With the Probe vertical, a custom cold/warm chamber was used to heat the necktube and cool the inner assembly. The expanded necktube was lowered over the shrunk assembly; at thermal equilibrium, they bonded. For Probes A and B, the miracle worked; for Probe C it did not. Section 6.4 below explains how the
resulting drastic loss of thermal contact between the inner and outer copper rings on the Probe was resolved.

After assembly, the top hat was installed using a cryogenically compatible liquid epoxy. The various cable connectors were bonded to feedthroughs in it. The Assembly Tool was removed, support during its removal being provided by a tooling ring attached to a fork lift. With the Probe’s bore clear, the cryopump, internal windows, and top hat jumper cables were installed. During integration, cables were checked for continuity, capacitance, breakdown voltage, and shield isolation. The T-flange, six Vatterfly valves, and window #4 were installed prior to shipment to Stanford. Table 7 illustrates the interconnectedness of the design. Details of SIA integration, Probe/Dewar assembly, and final laboratory testing are in section 6.

### 5. Thermal model

#### 5.1. Introduction

The thermal model had two parts, Spacecraft and Dewar–Probe; the two key issues were on-orbit helium life and ground hold-time. The Spacecraft model, confirmed by observation,
gave the Dewar’s on-orbit skin temperature. The Dewar–Probe model gave helium lifetime for a given temperature. Ground hold calculations checked the Dewar–Probe model. The work here was by Lockheed; a model from Marshall Space Flight Center gave similar results.

5.2. Models

5.2.1. Spacecraft. The Spacecraft faced two thermal constraints: Dewar skin temperature and holding certain electronics boxes within the ranges dictated by science: 10 °C per year, 1 °C per orbit, 0.05 °C per roll cycle. Issues were: (1) surface properties of materials; (2) power dissipation for each box; (3) orbit and pointing. The Spacecraft was covered with the FOSR mentioned earlier: a 10 mil Teflon film silvered on the back to reflect visible light but radiate strongly in the infrared. The front-end boxes were mounted within a thin-walled structure to stop direct illumination by the Sun. The Spacecraft aft section consisted of a truss structure for electronics boxes, solar panels, spin-up gas pallet, thrusters, and plumbing. The boxes and pallet were wrapped in MLI to guard against albedo and earthshine. The aft electronics boxes were mounted with their base radiating surfaces pointed outward and normal to the Spacecraft roll axis.

5.2.2. Dewar–Probe. The Dewar–Probe model drew on prior Lockheed experience1, with radiation, conduction, and vent-gas cooling modeled using a finite difference numerical approach, both Dewar and Probe being taken as axially symmetric. Radiative heat exchange in the Dewar vent-lines and Probe necktube was calculated using Monte Carlo techniques, with radiation neglected for temperatures below 30 K. The low thermal conduction of the MLI was modeled using a semi-empirical algorithm developed from extensive testing2. The flow rate of the boil-off gas was corrected for the corresponding increase in ullage gas.

Figure 17. Predicted on-orbit lifetime margin relative to 16 month requirement.
5.3. Results

5.3.1. Pre-launch. The required Dewar hold-time was 16 months. At the August 1993 Preliminary Design Review this was met with a 64% margin, which evolved with maturing hardware design and test data to a final prelaunch margin of 15%. See figure 17.

The Dewar/Probe C model comparing predicted temperatures and flow rates was correlated with measurements in four steady-state conditions: (1) main tank and well filled with 4.2 K helium; (2) main tank 4.2 K helium, guard tank empty; (3) main tank 1.8 K helium, guard tank 4.2 K helium; and finally (4) the nominal science state, main tank 1.8 K helium, guard tank empty. Updates included using the final number and dimension of wires and tubes in the necktube, and radial heat conduction through the heat station rings. The predicted and measured Dewar/Probe temperatures for case 4 agreed to 7 K, the flow rates to 1.6%.

The 90 day ground hold requirement dictated <0.2 K temperature rise in the main tank after cooling it to 1.65 K and then sealing it off: a 0.022 watt heat rate. The model prediction after correlation with test data was 0.0175 W or a 26% margin. The predicted guard tank lifetime was 9.7 days—a 28% margin.

5.3.2. Post-launch. Figure 18 compares the annual variation in Dewar shell temperatures from the Spacecraft model with the on-orbit values, taking into account the varying line of sight to the Sun. From July to November, with the aft end of the Dewar towards the Sun, the forward Dewar-cone was cooler; from December to June it was warmer. Either from over-optimistic values for absorptance (0.07) and emissivity (0.87), or from gaps in the Spacecraft FOSR coverage, the overall Dewar shell temperature was warmer than expected. On orbit, during science the Dewar main tank was at 1.82 K, the guard tank empty, and the forward cone and aft section of the vacuum shell at 268 K and 273 K, respectively. The mean predicted main tank heat load was 0.203 W, with a variation over the year in good agreement with computations from both the Spacecraft model and observed shell temperature.
Also of interest are main and guard tank temperature profiles over the 4 days 17–21 April 2004 before and after launch presented in figure 19.

6. Ground operational experience and performance

6.1. Background

The incremental prototyping by means of tests on three Probes A, B, and C, started with the procurement from an established Dewar manufacturer, Kadel Engineering, of a 400 ℓ EDD.
6.2. Probe A, FIST, and ground test unit 0 (GTU-0) (1986–1993)

Probe A ran two tests, with the EDD sometimes vertical, sometimes (figure 20) aligned with the Earth’s axis: from 1986 to 1989 FIST and from 1990 to 1993 GTU-0. FIST had a preliminary quartz block, two gyroscopes, no telescope, no cryopump, metal baffles not quartz windows in the Probe neck, standard readout and support cables, and rf SQUIDs. The aim was Probe/SIA design, and included: (i) warm Probe insertion into the EDD verifying interfaces, assembly procedures, and hold-time, (ii) checks of gas flow, spin-up pressure, and vacuum performance, (iii) gyro spin at 2 K–50 Hz. GTU-0 had prototype quartz windows, a $10^{-6}$ gauss lead bag shield in the EDD, and again two gyroscopes, one with a dc SQUID of the type that would be used on orbit. With it we demonstrated ultra-low field operation with warm Probe insertion, subatmospheric helium transfer, and London moment readout in the integrated system. Crucially, it confirmed the workability of a 10 in (0.25 m) inner diameter Probe.

6.3. Probe B, GTUs-1 and -2, and shake test

Probe B, delivered in 1994, was far more advanced, and could have been upgraded and flown. It had three stages, first with the EDD, then the Flight Dewar: GTU-1, a shake test, and finally full Probe/SIA insertion into the Flight Dewar.

6.3.1. GTU-1 (1994–1996). GTU-1 had a flight QBS, four gyroscopes, a mass-model telescope, sintered titanium cryopump, and flight-style readout and support cables. It demonstrated good coupled dc SQUID gyro readouts, $<10^{-6}$ gauss trapped field in the rotors, use of the cryopump to produce ultra-high vacuum in the Probe, overall emi stability and flight quality lead bag retainers in the EDD well.

6.3.2. Probe/SIA shake test (1997). In 1997 we ran a warm Delta II qualification test of the Probe B/SIA assembly in Lockheed Martin’s Sunnyvale acoustic test facility, with an important result. Our original plan was for each gyroscope to be caged during launch by a flexible bellows mechanism inflated with helium gas. Two of the mechanisms leaked; those gyroscopes had to be left uncaged. Both survived the Delta II test, so following further offline tests we removed the caging mechanisms, significantly accelerating the assembly of Probe C.

6.3.3. GTU-2 (1997–1998). GTU-2 was decisive in GP-B’s overall development, with three interconnected steps following delivery of the Flight Dewar: (a) creation of an ultra-low field shield in the Dewar, (b) construction of the helium ‘airlock’ shown below in figure 22 for inserting the warm Probe into the Dewar, (c) the test and redesign of the Probe axial-lok described in section 6.3.3.3.

6.3.3.1. Ultra-low field shield. The lead bag expansion process for generating ultra-low magnetic fields (figure 21) exploits the fact that magnetic flux, the quantity conserved in a superconductor is $\mathbf{B} \times \mathbf{A}$. Each bag starts as a tightly folded pleated structure (figure 21(A)). It is cooled, goes superconducting, traps the ambient field, and is then expanded with an increase in area $\sim 100$ and corresponding reduction in field. A second bag is cooled in the field of the first, and so on (figure 21(B)) to reach the desired level (limited by thermoelectric currents to $5 \times 10^{-8}$ gauss). The final flight bag was 1.95 m long and 0.28 m in diameter; it weighed 1.1 kg.
During the expansion process the Dewar well, in addition to the Dewar, was filled with normal helium. Each successive bag was set in a closed cooling tube, which with the aid of a glove box, 0.38 m diameter airlock, and 0.09 m high sliding Mylar shutter could be lowered into the well with no risk of air contamination. Helium gas at 2 Torr made the cool-down slow and uniform, with only the flux penetrating the bag being trapped. Once a folded bag was superconducting, the tasks were to remove the tube and expand the bag. The tube was sealed below by a thin diaphragm. Removal meant lowering an open-ended inner tube to puncture the diaphragm, then lifting both tubes away while holding the bag from above. Expansion was a two-stage process, lowering first a triangular plunger, then a spherical one into the bag. The flight shield took four expansions: three of 0.15 m bags and then the final 0.28 m one.

The field levels on three dates over the 14 months, 11/20/1998 – 01/07/2000, are in table 8. For gyroscopes 2, 3, and 4 the fields were predominantly along the vertical axis and somewhat above $10^{-7}$ gauss. For gyro 1, it was close to horizontal and nearer $10^{-6}$ gauss. The higher than expected fields, due probably to residual magnetism in the lead bag retainers, still met the Mission requirement.

**Table 8.** Flight Dewar dc magnetic field measurements over 14 month period.

| Position          | 11/20/1998 | 07/14/1999 | 01/07/2000 |
|-------------------|------------|------------|------------|
| 3.25° above Gyro 1| 1.69 μG (74.4°) | 1.56 μG (78.8°) | 1.65 μG (75.5°) |
| Gyro 1            | 0.58 μG (71.7°) | 0.51 μG (64.3°) | 0.50 μG (70.7°) |
| Gyro 2            | 0.24 μG (52.5°) | 0.33 μG (47.2°) | 0.30 μG (49.2°) |
| Gyro 3            | 0.20 μG (47.3°) | 0.32 μG (45.0°) | 0.37 μG (40.0°) |
| Gyro 4            | 0.57 μG     | —          | 0.68 μG (35.8°) |

During the expansion process the Dewar well, in addition to the Dewar, was filled with normal helium. Each successive bag was set in a closed cooling tube, which with the aid of a glove box, 0.38 m diameter airlock, and 0.09 m high sliding Mylar shutter could be lowered into the well with no risk of air contamination. Helium gas at 2 Torr made the cool-down slow and uniform, with only the flux penetrating the bag being trapped. Once a folded bag was superconducting, the tasks were to remove the tube and expand the bag. The tube was sealed below by a thin diaphragm. Removal meant lowering an open-ended inner tube to puncture the diaphragm, then lifting both tubes away while holding the bag from above. Expansion was a two-stage process, lowering first a triangular plunger, then a spherical one into the bag. The flight shield took four expansions: three of 0.15 m bags and then the final 0.28 m one.

Field levels on three dates over the 14 months, 11/20/1998–01/07/2000, are in table 8. For gyroscopes 2, 3, and 4 the fields were predominantly along the vertical axis and somewhat above $10^{-7}$ gauss. For gyro 1, it was close to horizontal and nearer $10^{-6}$ gauss. The higher than expected fields, due probably to residual magnetism in the lead bag retainers, still met the Mission requirement.

**6.3.3.2. Probe insertion.** Inserting the warm Probe into the cold Dewar was a 20 h process using the 11 ft high helium airlock of figure 22. The Probe was lowered in stages, a few inches at a time, with 2 Torr helium exchange gas in it and liquid helium in the Dewar well to cool the SIA safely. When the Probe top flange reached the top flange of the Dewar, it was fastened down, the liquid in the well and Probe exchange gas were removed, and ground-based testing began.
6.3.3.3. Axial-lok failure and replacement. Our original Probe mountings at Station 200 were axial-loks with Dewar dogs at three locations rotated and tightened into matching slots in the Probe. Early tests revealed high running torque on one lok, traceable to galling in the threads. Analyses indicated that two loks would hold, but when Probe B was installed, a second failed. The high running-torque was traced to the use of indium coatings and a too-high thread angle. With Probe C under construction, we redesigned the system to hold the Probe in another way, by compressing three sets of stacked Belleville washers 120° apart through the Probe necktube. Tests on a non-flight unit demonstrated that the necktube could withstand the load; in Probe C the new mounting worked well.

Figure 22. Probe insertion into cold Dewar.

Figure 23. Integrated Probe C and Flight Dewar in payload test.
6.4. Probe C (1999–2000): initial flight payload test

Probe C, delivered in mid-1998, constituted with the Dewar and SIA, the flight payload. After one cool-down to check the Belleville washer system, we withdrew the Probe to install the completed SIA: telescope, quartz block, four gyroscopes, four SQUIDs, and cryogenic support equipment. Figure 23 shows the payload in test in the FIST laboratory at Stanford—but first, a deadly thermal issue. The heat load, radiative and from conduction down leads and pumping lines was heavy; only met by making full use of the cooling power of the boil-off gas via the four HEXs, HEX-1–4. For Probes A and B the miraculous bonding of section 4.2.4 worked; for C it did not. Table 9 gives temperatures at the three windows and HEXs for Probes B and C. The window/HEX differences for B are 7–28 K, with the lowest window at 21.79 K. For C, the lowest window ran at 86.47 K.

Reworking the epoxy bond, with disassembly, a new necktube, a second miracle, and more would have taken two years. Instead, keeping the Probe assembled, we drilled 16 precision-machined holes (four for each HEX) through the outer HEX ring and necktube into but not through the inner ring, after which tightly fitting soft copper pins were forced into the holes for good thermal contact to the necktube and HEX. This operation required an elaborate drilling and reaming procedure developed in trials on a dummy necktube, using different tools for copper and fiberglass with no fewer than 30 penetrations run in a variety of ways. Great credit belongs to Mr Mark Molina of Lockheed, who carried the final rework through in the HEPL Class 10 clean room with rigorous exhaust control to prevent dirt or drill turnings entering the Probe. The result was rigorous metal-to-metal contact with excellent conductive power. Tests after completion showed the Probe leak-tight (leak rate <10⁻⁹ sccs). In the final operating state with Dewar heat Station I at 30 K, HEX-1 was at 31 K and the HEX/window difference was 8 K. An acoustic test demonstrated that the reworked Probe would withstand launch; the payload was returned to Stanford. This rework took eight months.

6.5. Second flight payload test (2001)

Re-spinning the gyroscopes after the acoustic test showed a ∼500 increase in trapped flux levels. We reheated the rotors above their superconducting transition and let them cool down over ∼38 h. The trapped fields returned to ∼10⁻⁶ gauss. This result had two implications: (1) given the similar acceleration levels in the acoustic test and launch, the low field bag would survive launch, and (2) almost certainly an on-orbit flux flush would be needed. Other tests included verifying the 234 dB ac shielding, re-verifying the telescope, and full-speed gyro spin. To carry them out took a great deal of special ground support hardware. Largest was a vacuum pumping station comprising a dual set of commercial turbo molecular pumps, used in
the Probe conductance tests and high speed gyroscope spin. The 234 dB ac shielding was measured by applying a time varying magnetic field roughly equal to the Earth’s field using external eight foot diameter coils. The telescope had already undergone extensive testing with the ‘artificial star’ described in paper 12 [5]. To recheck it in the assembled system, a smaller ‘star’ contained in a 4 ft diameter 3 ft high evacuated chamber was mounted on the Probe, using laser illumination and a scanning mechanism which allowed 30 marc s motion of the star position.

Filling the Dewar to >95% at 1.65 K took 17 days, during which the main tank was topped off with normal helium four times and then pumped down with a 300 cfm roots blower. With the guard tank full the main tank could be kept below 1.9 K without superfluid transfer for 90 days. Despite all care to prevent air incursions plumbing blockages did occur then and at three other times prior to launch. Warm helium gas and high power internal heaters restored proper operation. To reduce the risk of re-occurrence, the main tank was returned to 4.2 K for the ensuing tests. With each blockage, operating procedures were reviewed. Improvements included pressurizing the guard tank to stay above atmospheric pressure and upgrading leak tests of external plumbing.

6.6. Operations at Lockheed Martin (2002–2003)

In October 2002, the fully-tested payload was shipped to Lockheed Martin for integration with the Spacecraft, an open rib-like structure holding the 16 thrusters, two ARPs, GPS receivers, gyro spin-up gas supply, the sunshade, and other hardware. The sunshade designed, built, and tested by AlliedSignal, Teterboro, NJ, had two sets of baffles: inner with narrow cone angle, outer with a wider angle, so that entering stray light had at least two bounce, with substantial attenuation at each. Most important for helium life was the attenuation of incoming thermal radiation. Figure 2 indicates an automatic shutter to be closed against albedo each half-orbit. On-orbit, the shutter caused unacceptable shocks and had to be left open.

The payload electronics had two locations: analog units in the Dewar’s thin-walled forward equipment enclosure, digital units and the flight computer at the Dewar’s lower end. Tests with high intensity heat lamps confirmed that the thermal variation in the forward equipment enclosure would be in the ranges stated in section 5.2.1. In an acoustic test, excitation was slowly ramped up to a maximum, consistent with main engine cutoff and maintained there for 60 s, with no damage to the flight hardware. The final Lockheed Martin operation was to spin balance the vehicle.

6.7. Operations at Vandenberg Air Force Base (2003–2004)

The vehicle was shipped to Vandenberg Air Force Base on 10 July 2003, and installed in the 30 ft high Block House RLCC Building 8510. Following some work on the experiment control unit electronics; the main tank was conditioned to its superfluid state. Continual pumping was required to prevent excessive helium build up from a small internal leak into the Dewar well. The Spacecraft was hoisted to the top of the Delta II rocket on 1 April 2004. Guard tank fills continued every several days, right up until launch, 56 days after completion of the final main tank fill. Figure 25 shows the vehicle atop the rocket.
7. On-orbit operational dewar experience and performance

7.1. Introduction

Launch was at 09:57:24 Pacific daylight time (17:57:24 Zulu) 20 April 2004, with the Dewar main tank 95% full at 1.85 K (opened during ascent when ambient pressure fell below \(~12\) Torr) and the guard tank 50% full at 4.18 K, vented through ascent and beyond as discussed in section 3.2.4.1. The 526 day on-orbit lifetime had three phases: (1) initial orbit checkout (IOC)—128 days; (2) science—353 days; (3) post science calibration—45 days. During IOC the main tank temperature ranged from 1.69 K to 1.94 K stabilizing to 1.82 K just before science. The Spacecraft instrumentation gave Dewar temperature and pressure at numerous locations, transmitted to ground and fed to the Stanford Mission Operations Center. Commands to the vehicle were sent from the MOC; IOC alone required 35 000.

7.2. Initial orbit checkout

Table 10 lists key events over the first 16 weeks, primary among them being: gyroscope flux flush, guide star acquisition, gyroscope spin-up, and low temperature bakeout.

7.2.1. Experiment setup: week 1. Setup began on day 1 with turn-on of electronics for the gyroscopes, telescope, and SQUIDs, and pyrotechnic valves for the Dewar shell and well opened. With the guard tank depleted, the system was defined by liquid in the main tank, gas in the porous plug, and venting through the Spacecraft’s 16 thrusters. The temperature difference across the plug was \(~4\) mK; the mass flow \(6\)–\(7\) mg s\(^{-1}\). Towards the end of week 1, one thruster got stuck in the open position and its upstream cut off valve was closed to prevent spurious gas flow.

7.2.2. Practice operations: week 3. Early in week 3 the Vatterfly valves were opened and heaters operated to practice flux flush, gyroscope suspension, and low temperature bake out. Owing to pumping of residual gas from the Probe, the gyroscopes all acquired a slow spin.
Figure 25. Space vehicle installed on the Delta II during fairing installation.

Table 10. IOC highlights.

| Week # | Activity                                      |
|--------|-----------------------------------------------|
|        | Launch                                        |
| 1      | Open pyrotechnic values for Dewar and well    |
|        | Turn on all electronics                       |
|        | Close off stuck-open (but redundant) thruster |
| 3      | Practice low temperature bakeout              |
|        | Flux flush                                    |
| 5      | Close off second thruster                     |
| 6      | Slow spin of all gyroscopes                   |
| 7      | Acquire guide star                            |
| 9      | Spacecraft roll rate increased to 0.3 rpm from 0.1 rpm |
| 10     | Spacecraft roll rate increased to 0.9 rpm for bubble wrap |
| 15     | Final gyro spin-up                            |
| 16     | Low temperature bakeout                       |
7.2.3. Flux flush: week 5. As expected from the Probe C acoustic test, on-orbit data confirmed that launch vibration, while leaving the lead bag unaffected, raised the trapped flux levels in the rotors. Low flux was restored by applying 1 W at Station 200 with a low inductance strip heater, and running a steady flow of helium gas at \(5 \times 10^{-5}\) Torr over the levitated rotors, reducing the temperature slowly afterwards to lessen the risk of thermally generated magnetic fields. The whole process took 38 h. The five days of elevated gas flow shortened the time available for science by 11 days.

7.2.4. Porous plug performance, including event of week 5. Except for one event on 16 May 2004, shortly after the main tank had started to recover from the flux flush, the porous plug performed as desired for the full Mission. Figure 26 shows the event, several hours of choking after a thruster failure. The plug’s downstream temperature dropped by \(36\) mK, and the helium flow rate reached \(27\) mg s\(^{-1}\), five times its normal value. We closed the thruster’s upstream shut off valve and after \(5\) h, the flow rate corrected to \(11\) mg s\(^{-1}\); 14 h later the plug spontaneously returned to normal operation.

7.2.5. Bubble wrap: week 9. The bubble wrap to symmetrize the distribution of helium in the Dewar was achieved during IOC by gradually increasing the Spacecraft roll rate to 0.9 rpm. After 33 h, a mass flow transient and two-hour tidal period signaled completion of the wrap. The result was greatly improved symmetry of the helium distribution and improved ATC performance.

7.2.6. Gyroscope spin-up: week 15. The gyroscopes were spun one at a time, in steps, until all four had reached 60–80 Hz. The final spins each lasted \(\sim 1\) h. Paper 8 [6] describes the technique. The gyroscope was moved over in its housing toward the spin channel, 95% of the gas ran through the channel at \(3\) Torr, with the rest at \(10^{-3}\) Torr exiting through the Probe necktube by opening the spin-up exhaust valve and one of the two large leakage valves in the T-flange. A heater near the gyroscope warmed the incoming gas to \(7\) K. A higher spin speed and lower leakage pressure would (and should) have been achieved by opening both leakage valves during spin-up.

Figure 26. Temperature and flow history: return of choked porous plug to normal operation.
7.2.7. Low temperature bakeout: week 16. After spin-up, an on-orbit low temperature bakeout warmed the SIA from 2 K to 6 K for several hours and then allowed it to cool down. Desorbed helium was vented to space through 6 T-flange valves in the top hat; with the valves closed and heaters turned off, the minute residue of helium gas was re-absorbed in the Cryopump, reducing the pressure to an extremely low level. How low is hard to tell. One check was spin-down rate; the observed rates ranged from 1.4 to 0.29 $\mu$Hz h$^{-1}$, a factor of five difference which meant that some other mechanism than gas damping was at work. A binding energy investigation by Turneaure set an upper limit on the pressure of $10^{-14}$ Torr. The most likely cause of the higher observed spin-down is torques between patch effect potentials on the rotor and housing [7].

7.2.8. Spin-axis alignment: weeks 17 and 18. During the last two weeks of IOC before science, we continued close observation of gyro performance and did a careful alignment procedure on each gyroscope to bring its spin axis within $\sim$10 arc-s of the telescope boresight.

7.3. Post-IOC considerations

7.3.1. Tidal slosh and bubble wrap. On 29 September 2004, one month after the start of science, we observed a growing 4.6 mHz oscillation in the gyro suspension control effort in a direction perpendicular to the roll axis. The drag-free control system was pumping energy into a gravity wave in the helium as it depleted. The frequency decreased until the frequency of the wave came into resonance with the drag-free control loop, leading to a pumping action. Figure 27 is a history of the resonance, peaking on 29 September (day-of-year 273). At the peak, the transverse acceleration on the gyroscopes reached $1.2 \times 10^{-6}$ m s$^{-2}$. For the relation between tidal slosh and bubble wrap see paper 15 [8].

7.3.2. Dewar temperature control and ATC. During science, as in IOC, the Dewar bath temperature was actively controlled by regulating the venting of helium boil-off gas to space through the 14 active ATC thrusters. At 642 km altitude, the available thrust exceeded the ATC requirement, the excess being ‘null-dumped’ evenly among the thrusters in amounts determined by temperature control software. The average helium mass flow was 6.76 mg s$^{-1}$. Other than for five heat pulse operations and one excursion midway through the Mission, the temperature was held to 1.82 K $\pm$ 3 mK.

7.3.3. Study of shutter mechanism. The shutter mechanism indicated in figure 2 caused large on-orbit mechanical shocks and had to be left open. The only effect on science was a short,
easily handled gyro readout offset at the beginning of each half-orbit, with the loss of about 1 min worth of science data.

7.3.4. ARP stability. Initially when IM Pegasi came out of Earth eclipse, the ARP had a roll phase error \(\sim200\) arc-s, and took \(\sim15\) min to recapture the phase reference. By deactivating an autonomous control-gyro bias estimator, and replacing it with manual adjustments, the delay was reduced to \(<2\) min. Analyses by Kolodziejczak and Li reduced the roll phase error to \(\sim8\) arc-s.

7.3.5. Probe and SIA thermal stability. Two nested temperature control systems provided further thermal stabilization of the SIA. The QBS was controlled, using its measured temperature as input to PID software and hardware which powered the low inductance strip heater. To minimize the impact on helium lifetime, a 0.050 K thermal bias was achieved with \(\sim50\) mW of heater power. A second, nested control system regulated the most thermally sensitive component in the SIA—the SQUIDs. These devices were further controlled using a PID algorithm combined with peaked gain at roll frequency to provide better than 2 \(\mu\)K control.

7.3.5.1. Effect of Dewar shell temperature on helium lifetime. The heat rate into the main tank varied with the Dewar shell temperature. The 10 K higher than expected shell temperature, discussed in section 5.2.1, had a 2.1% impact on Mission life. Figure 18 shows the seasonal trend.

7.3.5.2. End of helium life. The on-orbit helium hold-time was 17 months 9 days. The residual helium estimates from the heat pulse and vent gas flow meters, agreed to within a day or so, but the actual hold-time exceeded the predictions by more than two weeks, a fact of great value in strengthening the final post science calibration phase.

7.4. Summary of requirements versus on-orbit performance

All cryogenic payload requirements were met. The longer than expected on-orbit helium lifetime partially offset the extra time required to set up the experiment. Figure 28 is a heat map of the measured on-orbit performance, showing the good agreement with predictions from the models.

8. Conclusion and comparison with other on-orbit helium Dewars

Comparisons of this cryogenic payload with other previously flown cryostats cover three areas: weight, launch pad and thermal performance. GP-B, after the weight reduction was 30% lighter than the similarly sized Infrared Space Observatory (ISO) cryostat, launched 1995, despite the need for a 51 kg proton shield. Table 11 compares acceptance test boil-off rates and mission lifetimes of various Flight Dewars. For equal warm acceptance test boundary temperatures, GP-B had the lowest boil-off rate by a factor of three. Some of the other cryostats had longer mission lifetimes because of a lower shell temperature. COBE, for example, was able to maintain a shell temperature \(\sim50\) K by continually pointing away from the Sun. The table indicates reasons for the GP-B cryostat’s excellent thermal performance with its 260 K mean shell temperature.

The GP-B guard tank made it possible to keep the Dewar main tank non-vented for 90 days eliminating the great difficulty of a superfluid helium transfer at the pad. The normal-
Figure 28. Heat map of predicted and measured on-orbit system.
| Program | He boil-off %/day | Heat rate (mW) | SFHe (kg) | Guard-tank fill (days) | Max | Actual | Vacuum shell temp (K) | Lifetime (months) |
|---------|------------------|----------------|-----------|------------------------|-----|--------|----------------------|------------------|
| IRAS    | 0.67             | 142            | 72        | —                      | 1.1 |        | 200                  | 10               |
| COBE    | 1.25             | 264            | 89        | —                      | 1.1 | <180   | 112.6                | 10               |
| ISO     | 0.83             | 650            | 331       | 1.9                    | 5.6 | 5.6    | 255.6                | 28.3             |
| GP-B    | 0.27             | 216            | 337       | 3                      | 90  | 56     | 50                   | 69               |
| SPITZER |                  |                | 49        | —                      |     |        |                      |                  |

Table 11. Superfluid helium flight cryostats’ thermal performance.
helium transfers to the guard tank at the pad took place every three days. In the 55 days from the last main tank fill until launch, the main tank temperature rose from 1.6 to 1.85 K. The payload’s 17 month 9 day cryogenic hold-time allowed determinations of two previously unmeasured physical phenomena: the geodetic and frame-dragging effects of general relativity only made possible by running the SIA at 2.6 K.

References

[1] Marcelja F, DeBra D B, Keiser G M and Turneaure J P 2015 Precision spheres for the Gravity Probe B experiment Class. Quantum Grav. 32 224007
[2] Li J, Keiser G M, Lockhart J M, Ohshima Y and Shestople P 2015 Timing system design and tests for the Gravity Probe B relativity mission Class. Quantum Grav. 32 224014
[3] Frank D J and Yuan S W K 1996 Experimental results of tests performed on superfluid helium phase separators for the relativity mission Adv. Cryog. Eng. 41 1195–201
[4] Nast T C 1993 A review of multilayer insulation, theory, calorimeter measurements, and applications Recent Advances In Cryogenic Engineering ASME HTD vol 267, ed J P Kelley and J Goodman (New York: ASME) pp 29–43
[5] Bennett N, Burns K, Katz R, Kirschenbaum J, Mason G and Shehata S 2015 Gravity Probe B spacecraft description Class. Quantum Grav. 32 224012
[6] Wang S et al 2015 The design and performance of the Gravity Probe B telescope Class. Quantum Grav. 32 224008
[7] Buchman S and Turneaure J 2011 The effects of patch-potentials on the Gravity Probe B gyroscopes Rev. Sci. Inst. 82 074502
[8] Conklin J W et al 2015 Precision attitude control of the Gravity Probe B satellite Class. Quantum Grav. 32 224015