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UNIQUE CRYOGENIC FEATURES OF THE GRAVITY PROBE B (GP-B) EXPERIMENT

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ABSTRACT

Gravity Probe B is an orbital test of Einstein's general theory of relativity using gyroscopes. The precession of the gyroscopes will measure both the geodetic effect (6.6 arc sec/yr) through the curved space-time surrounding the Earth and the motional effect (0.042 arc sec/yr) due to the rotating Earth dragging space-time around with it. To achieve the extraordinary accuracies needed to measure these small precessions, it is necessary to have the gyroscopes operating in the following environments: a vacuum of $<10^{-10}$ torr; an acceleration level of $<10^{-10}$ g; a magnetic field of $<10^{-7}$ gauss; and a temperature near 2 K. This paper discusses the current status of the cryogenic designs required to simplify launch-pad operations while achieving an orbital lifetime of 2 years, as well as the designs that allow the gyroscopes to be installed into or removed from a cold dewar.

INTRODUCTION

The scientific equipment in Gravity Probe B (GP-B) required to measure the geodetic and frame-dragging effects includes four gyroscopes, four superconducting quantum interference devices (SQUIDS) to measure the gyroscope precession, a quartz telescope to provide a frame of reference in space in conjunction with a reference star, and a drag-free mass used to obtain the low acceleration levels required. Boiloff gas from the dewar is used in conjunction with eight proportional gas thrusters to keep the drag-free mass centered in its housing. All this equipment is mounted in a quartz block assembly (QBA), which is mounted in a probe assembly. The probe assembly, in turn, is mounted inside the well of a 1580 L superfluid helium dewar (Fig. 1). The probe must be inserted while the dewar tank and well are filled with 4.2 K liquid helium, which requires the use of a helium-purged air-lock assembly. Once the probe is installed, good structural and thermal contact is required at five heat stations, four located at the vapor-cooled shields and the fifth at the dewar tank neck. An Axial Lok device, described below, provides this structural support between the probe and the dewar, as well as good heat transfer at the five heat stations.

Superfluid dewars that have flown require continuous pumping on the subatmospheric-pressure superfluid helium tank up until launch. For a

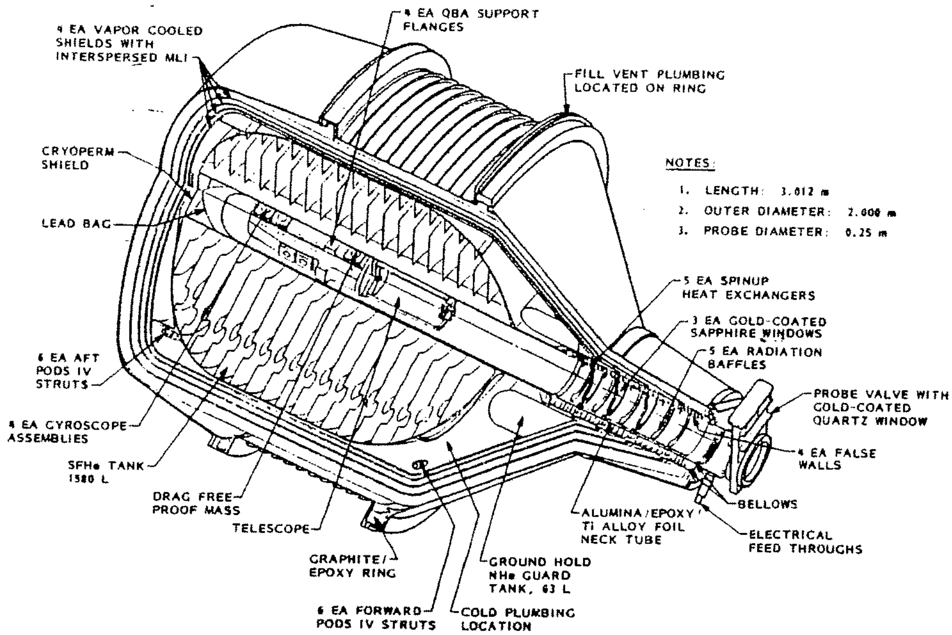

Fig. 1 GP-B Flight Dewar/Probe Concept

shuttle launch, a vacuum pumping system is located in the Orbiter bay; consequently, power is required continuously in the bay for the pumps during ground hold. The pumps have to be flight-qualified even though they operate only on the ground. Their extra weight is taken into orbit, and the potential exists for leaking oil contaminating other payloads. Loss of superfluid helium, which occurs in proportion to the length of the ground-hold period and bay temperature environment, shortens the orbital lifetime. To eliminate this servicing complication, a 63-L guard tank of 4.2 K liquid helium is mounted off the dewar neck tube and shorted to the coldest vapor-cooled shield. The superfluid-helium tank is serviced first followed by the guard tank. The servicing occurs before the assembly is loaded into the Orbiter, when access to the ground support equipment is much easier. A single fill and single vent line are required to service both tanks; only one additional valve, RAV2, and one burst disk, BD2, are required for the guard tank (Fig. 2). No servicing is required onboard the Orbiter for up to 2 weeks. If the launch is delayed beyond 2 weeks, the smaller guard tank is refilled with liquid helium at 1-atm vapor pressure, a much simpler procedure than servicing the superfluid helium tank. The nonvented, subatmospheric, superfluid-helium tank can go for over a month with a temperature rise of only 0.1 K (the superfluid tank is pumped down to 1.7 K). The tank is kept nonvented on the ground and in orbit until it reaches its operating temperature of 1.8 K. This design conserves all of the superfluid helium, maximizing the orbital lifetime.

Almost half the heat leak into the dewar by conduction and radiation is in the probe neck tube region. Consequently, to keep the conduction heat load to a minimum, both the probe and dewar necks are filament wound using a low-conductivity, high-modulus gamma alumina/epoxy composite. The probe neck also has a 0.025-mm titanium alloy liner to achieve the $< 10^{-10}$ torr vacuum required inside the probe. Gold-coated windows, walls, and baffles are used along with black

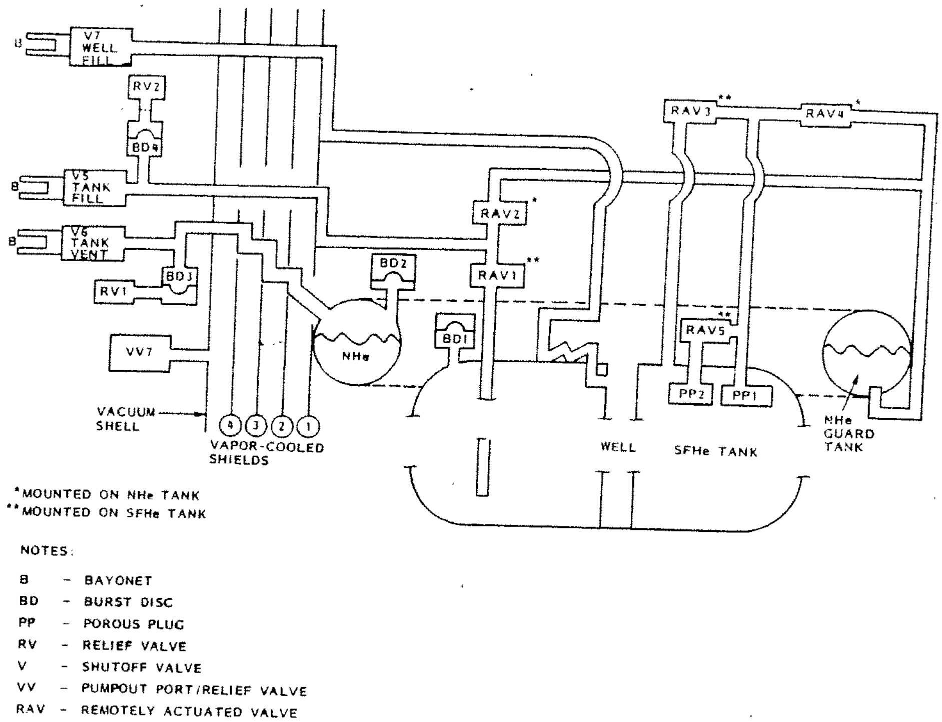

Fig. 2 GP-B Flight Dewar Plumbing

anodized aluminum walls and baffles to reduce the radiant heat load onto the telescope.

Twelve high-efficiency PODS-IV struts are used to support the superfluid helium tank to achieve a 2-year orbital lifetime. Gamma alumina/epoxy and graphite/epoxy composites are used in the strut design.

Details of the Axial Lok, alumina/epoxy neck tube, and PODS-IV supports are provided below.

AXIAL LOK

The Axial Lok provides structural support between the probe and dewar as well as good heat transfer at the five heat stations. It consists of a number of mechanisms, integrated to provide the required structural and thermal functions: (1) Three "dogs" (Fig. 3) hold the probe in the dewar providing the main structural support and heat transfer to the superfluid helium tank. (2) A lead-bag retainer (Fig. 4) presses the lead bag* against the inside of the dewar well as the Teflon-coated probe vacuum shell is inserted. The flattened beryllium copper springs provide the load required for good thermal contact between the lead bag and the well; the retainer also provides lateral support for the probe. (3) Eight thermal shoes (Fig. 5) at each of the four vapor-cooled shield locations (32 total) transfer heat conductively from the probe out to the dewar vent heat exchangers.

The dogs are rotated out of the way during probe insertion. A castellated tool, concentric with a specially designed long allen

*A series of expanded lead bags provides the ultralow magnetic field

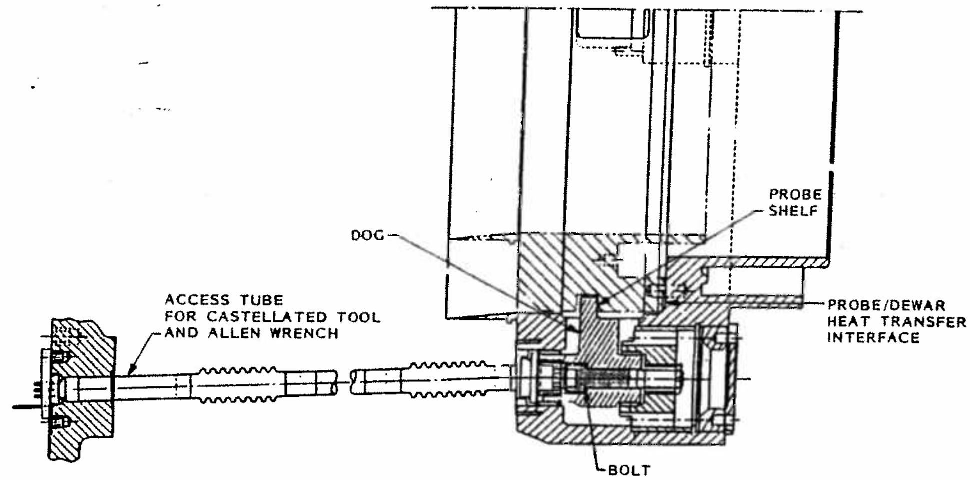

Fig. 3 Axial Lok

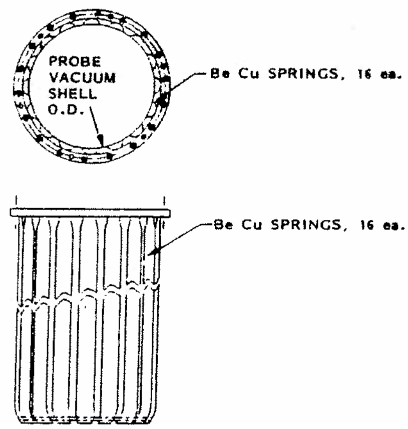

Fig. 4 Lead-Bag Retainer

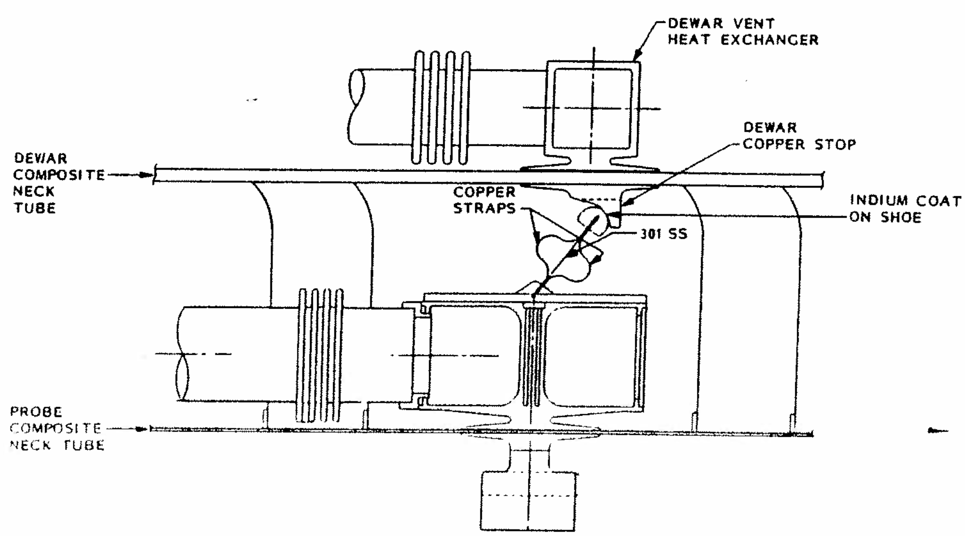

Fig. 5 Thermal Shoe Design

wrench, is inserted into a tube permanently located in the dewar. The castellated tool is used to engage and rotate the dog into the shelf machined into the probe ring. The three bolts on the dogs are then torqued down using the allen wrench. These bolts apply a 26,400 N load through the "dogs" to the probe/dewar-ring interface. The castellated tool and allen wrench are removed and a "shish kabob" of radiation disks mounted on a fiberglass rod is installed in the dewar tubes to reduce radiation tunneling. The probe side of the 6061-T6 Al interface is brush plated with indium (copper strike undercoat) to enhance heat transfer. The installation process is reversed when removing the probe.

As the dogs pull the probe against the dewar interface, each of the 32 thermal shoes engages a separate mating stop on the dewar neck. The thermal shoes are staggered at 11.25° intervals around the circumference so they don't interfere with each other during probe insertion. The 301 stainless steel spring used in the shoe is bent elastically and driven radially outward as the dogs pull the probe into the dewar.

Typical measured radial versus axial loads for each thermal shoe are shown in Fig. 6 as a function of the initial radial gap spacing between the probe shoe and the stop. A large number of these tests have been performed in the test apparatus shown in Fig. 7. Some additional testing remains. Thermal contact is made between an indium brush-plated copper rod brazed to the end of the spring and a concave cylindrical stop located on a copper ring, bonded to the inside of the dewar composite neck. Copper strap loops, 0.125 mm thick, are located on both sides of the spring. The straps are sized to keep the ΔT across the spring to less than several degrees K for the predicted heat loads.

ALUMINA/EPOXY-COMPOSITE NECK TUBES

The probe neck tube provides the aperture for the telescope and allows the probe to be evacuated and inserted or removed from a cold dewar. This design requires a separate neck tube for the dewar.

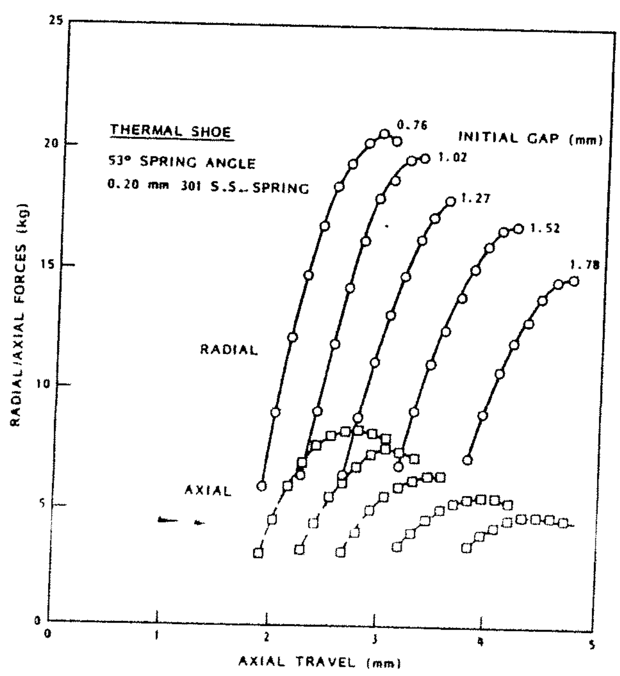

Fig. 6 Measured Thermal Shoe Radial and Axial Loads

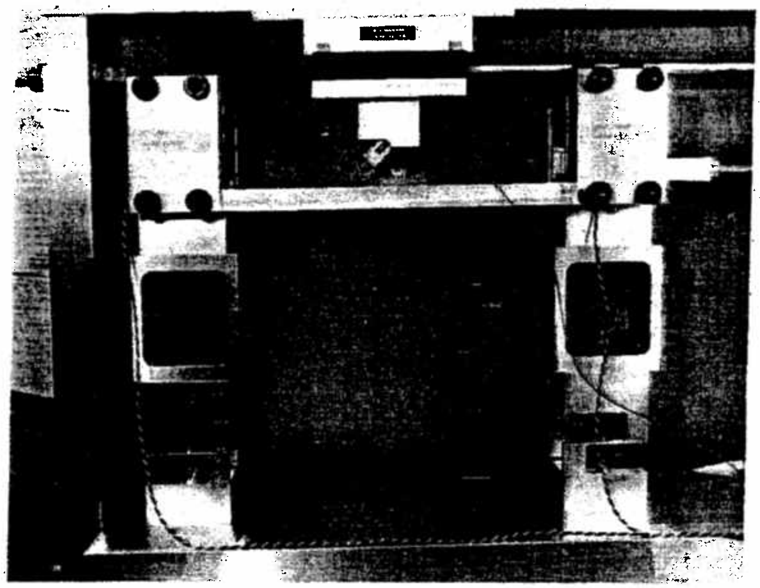

Fig. 7 Thermal Shoe Test Apparatus

The neck tubes for both the probe and the dewar must be designed to withstand a 1-atm compressive load during probe installation as well as 15-g flight loads with vacuum on both sides of the tubes. Because a high proportion of the total parasitic heat load in the dewar is from these tubes, various approaches were investigated to reduce the heat load. The first approach used folded composite neck tubes (to increase the conduction path length), with glass epoxy tubes at the warmer end and graphite epoxy tubes at the colder end (Fig. 8). Subsequently, a new fiber was reported[1] that has a thermal conductivity nearly as low as glass from 300 to 50 K and half that of glass and the same as graphite from 50 K to 0 K (Fig. 9). The modulus of the new gamma alumina/epoxy fiber is over double that of glass/epoxy and nearly the same as that of the graphite/epoxy. Consequently, the simpler single alumina/epoxy neck tube design was substituted for the more complex folded neck tube design, with only a slight increase in the heat load.

An extensive structural and thermal analysis was performed on the probe neck tube to optimize the wall thickness and winding angle. The wind angle was selected to minimize the axial thermal conductance while providing a structure that would survive the 1-atm ground-hold compressive load, 15-g flight load, and thermal strains induced during cooldown.

The thermal strains arise from (1) the mismatch in contraction between the fiber and the epoxy matrix over the temperature range from epoxy curing (414 K) down to operating (2 K) and (2) the contraction mismatch between the composite and the aluminum tank bond (cold end), the stainless steel bond (warm end), and the internal copper rings and external copper heat exchangers bonded at four locations along the composite tube. The best compromise to satisfy all these requirements is a $\pm 40°$ filament-winding angle with respect to the axis of symmetry, a probe wall thickness of 0.46 mm with a diameter of 244 mm, and a measured fiber volume fraction of 55 percent. Stiffening rings are wound at 15.5-mm intervals along the tube to minimize the wall thickness for thermal reasons, yet still provide a 1-atm compressive load

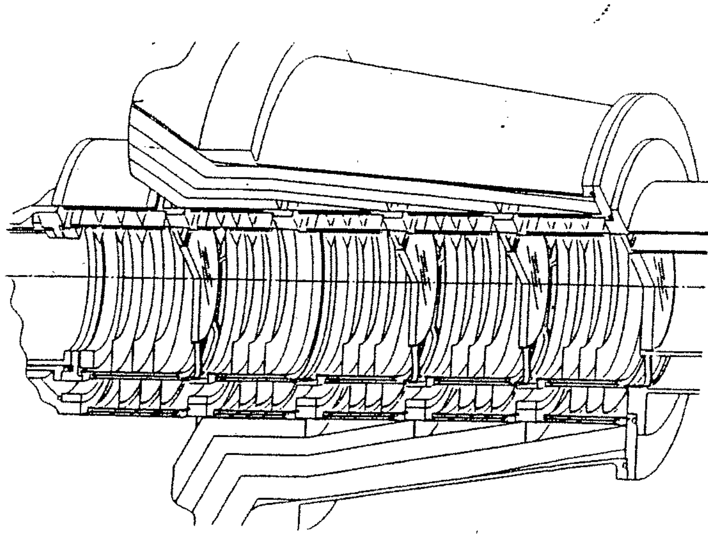

Fig. 8 Folded Neck Tube Design

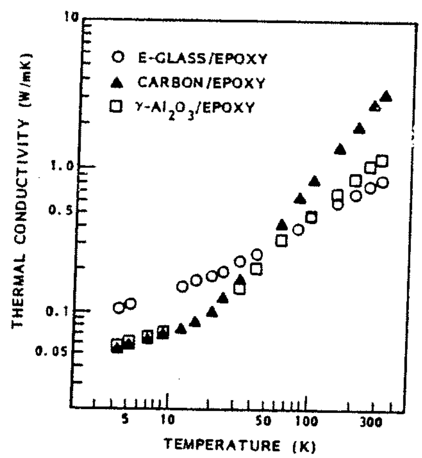

Fig. 9 Composites Thermal Conductivity

capability (with a safety margin of 4). The rings also provide a mounting surface for gold-coated Kapton radiation baffles. The baffles reduce the radiation tunneling in the annular space between the probe and dewar necks to < 1 mW.

A full-diameter, one-third-length test section of the composite neck tube was fabricated (Fig. 10) and thermally cycled from room temperature to liquid nitrogen and helium temperatures (Fig. 11). An external helium pressure of 1 atm was placed on the test section and the test article was evacuated. The permeation rate of helium gas was measured with a helium mass spectrometer leak detector. The low permeation rates measured are due to the 0.025-mm titanium alloy liner used. The thermal cycling is continuing. (Following probe insertion, the well is evacuated so there is vacuum on both sides of the probe neck for the remainder of the mission.) The tube has survived the thermal cycling to date with no structural damage. The thermal conductivity of the composite is currently being measured over the temperature range 300 K to 78 K to validate the literature values.[1]

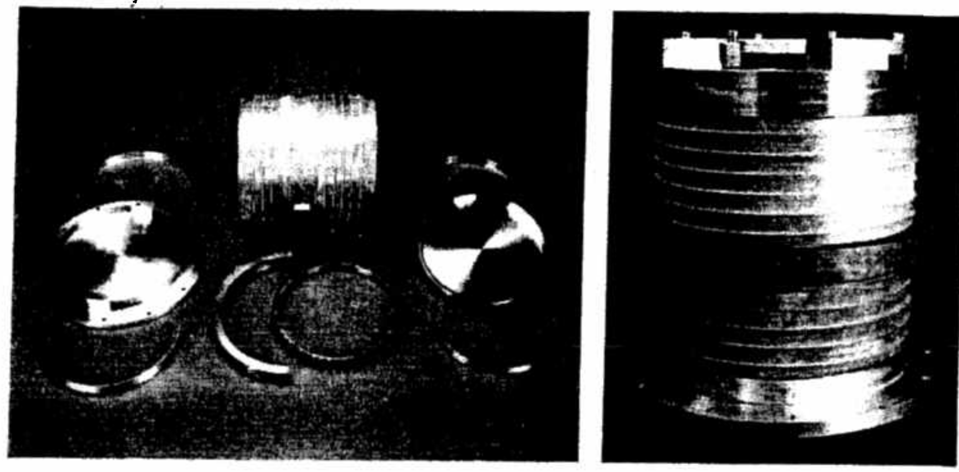

Fig. 10 Alumina/Epoxy Neck Tube Test Article

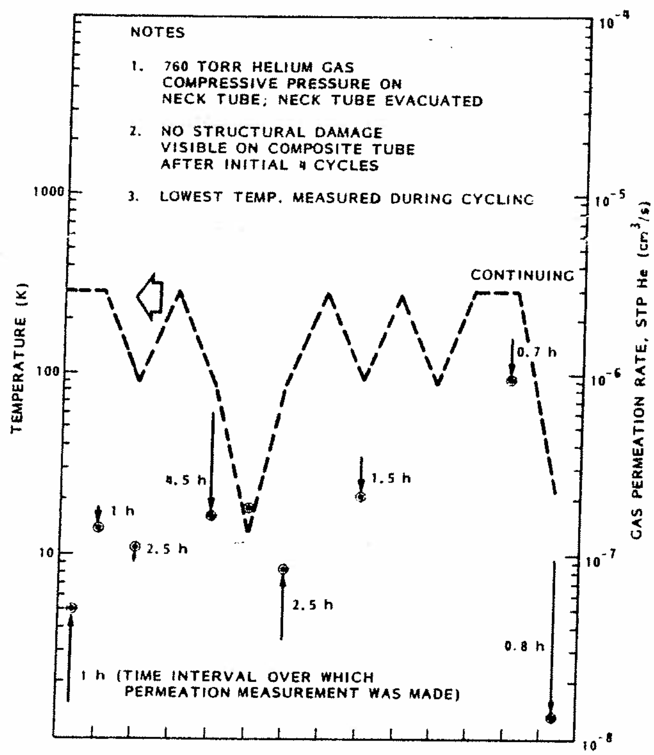

Fig. 11 Thermal Cycling Test Results of Alumina/Epoxy Neck Tube Test Article

PASSIVE ORBITAL DISCONNECT SUPPORTS (PODS-IV)

The PODS-IV struts are the most thoroughly ground tested support system to date for cryogenic flight dewars.[2,3,4,5,6] Tests have included thermal performance, static load tests, dynamic load tests, and creep load tests on the struts, both individually and as a system. Six supports can be used on smaller tanks, i.e., on a 200-L superfluid-helium flight dewar (Fig. 12), or 12 supports can be used for longer tanks, i.e., the 1580-L GP-B flight dewar (Fig. 13).

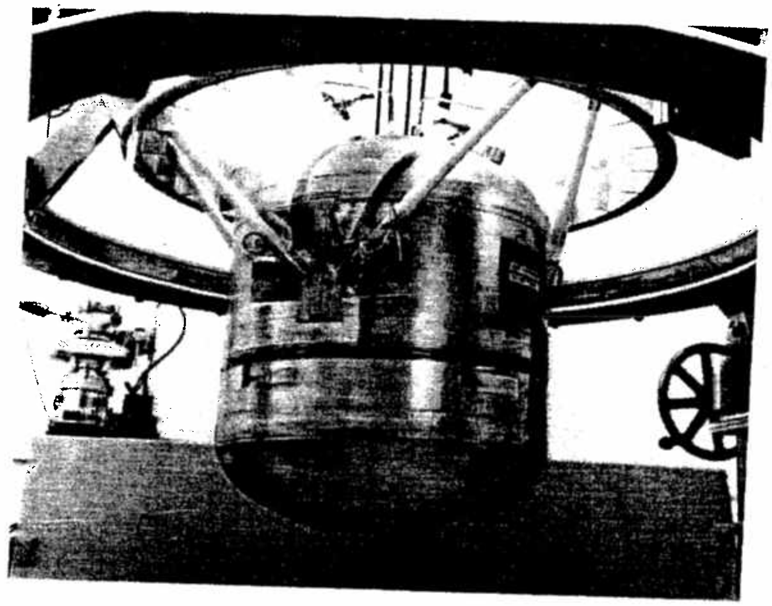

Fig. 12 Superfluid Helium Flight Dewar With Six PODS-IV Struts

The only true support-optimization program that has been developed for either PODS struts or tension support straps, DEWAR,[7] was used to size the PODS-IV struts (optimum number of struts, length, diameter, wind angles, number of layers, wall thickness, and mounting angle). The program minimizes support conductance within specified constraints (boundary temperatures, acceleration levels in all axes, minimum allowable frequency during launch or orbit, maximum allowable loads based on tube or strap fatigue strength, column buckling, localized buckling and dimensions of attachment hardware). The program accounts properly for coupling between lateral and tilting motion in the free vibration modes. The flexibilities of the dewar, vacuum shell, and supporting rings are also accounted for. Stress criteria in material coordinates for each lamina of a composite laminated support tube can become active constraints during optimization. Shell buckling is handled via a PANDA-type[7] of analysis for a composite cylindrical shell, rather than through use of the simple classical buckling formula. Thicknesses of individual layers in a laminated composite strut tube can be decision variables for optimization, rather than just the overall thickness of the tube being a decision variable. The conductivity is orthotropic, and the overall conductance now depends on the thicknesses and winding angles of the laminae in the composite strut tube wall.

Note that the 12-support configuration shown in Fig. 13 has the 6 forward supports located almost in a plane and attached to a graphite/epoxy support ring at the warm end of the struts. As the tank cools down, the thermal loads put into the struts are minimal with this arrangement. In orbit, changes in vacuum-shell dimensions due to temperature also put minimal thermal strains in the struts because of the ultralow expansion characteristics of the graphite/epoxy support ring. This ring is also used to mount the star blipper, providing a very stable mounting surface referenced to the telescope inside the probe. The aft six struts are sized for the axial launch loads. All 12 struts provide lateral, tilt and torsional load capability.

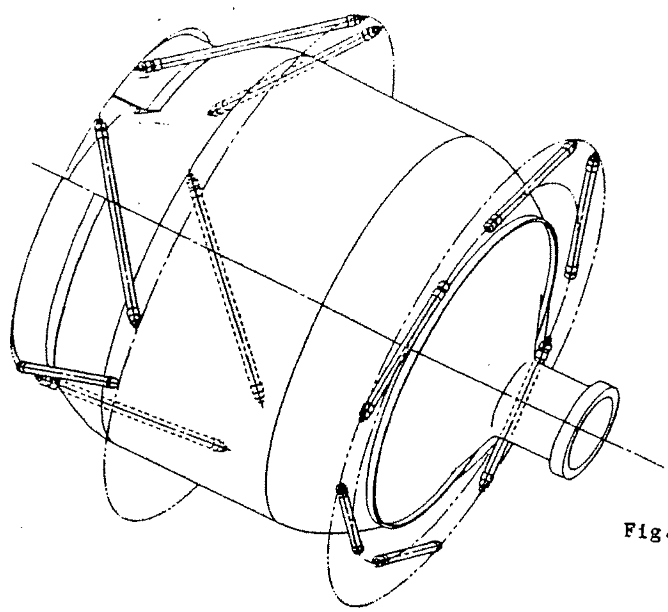

Fig. 13 GP-B Flight Dewar Support System Using 12 PODS-IV Struts

The four vapor-cooled shields are supported off the alumina/epoxy dewar neck described previously. They are thermally grounded and stabilized against side loads by the PODS-IV alumina/epoxy launch tubes. Substituting the alumina/epoxy for the glass/epoxy used previously allows the wall thickness to be cut approximately in half because of the alumina/epoxy's higher modulus. (Column buckling designs the tube.) The side load capability of the strut has been increased 700 percent going from the PODS-III to PODS-IV design; side loads put on the struts due to vapor-cooled shield contractions are well within the capability of the PODS-IV design.

The passive load bypass mechanisms of the strut described in earlier papers[4] does not close on the ground under 1 g (designed for 1.5 g) or in orbit, as demonstrated by ground tests of the complete support system.

A detailed 73-node thermal model of a vapor-cooled helium dewar verifies that the weight of the dewar can be cut in half[2] for the same lifetime by substituting PODS-IV struts for tension straps when both support systems are optimized using the same ground rules (shuttle launch) and the computer program described previously. The above analyses assume no internal instrument heat load.

CONCLUSIONS

A number of unique features have been designed into the probe and superfluid-helium dewar that are driven by Gravity Probe-B program requirements.

These features include: (1) the ability to load the probe into a cold dewar and provide good structural support and thermal contact after insertion, (2) elimination of the need for a pumping system during ground hold, and (3) use of a new composite, gamma alumina/epoxy, to minimize the parasitic heat loads into the dewar through the telescope aperture and the tank supports.

ACKNOWLEDGEMENTS

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Adolf Kratz developed the Axial Lok concept, Gary Reynolds developed the thermal shoe concept, Dave Donegan developed the lead-bag retainer concept, Mark Ferraro and Pat McCormack wound the alumina/epoxy tubes, Mary Wright and Marc Regelbrugge performed the structural analyses, Dave Bushnell developed the support optimization program DEWAR, and Jack Goodman performed the thermal analyses and the temperature cycling of the composite tube.

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