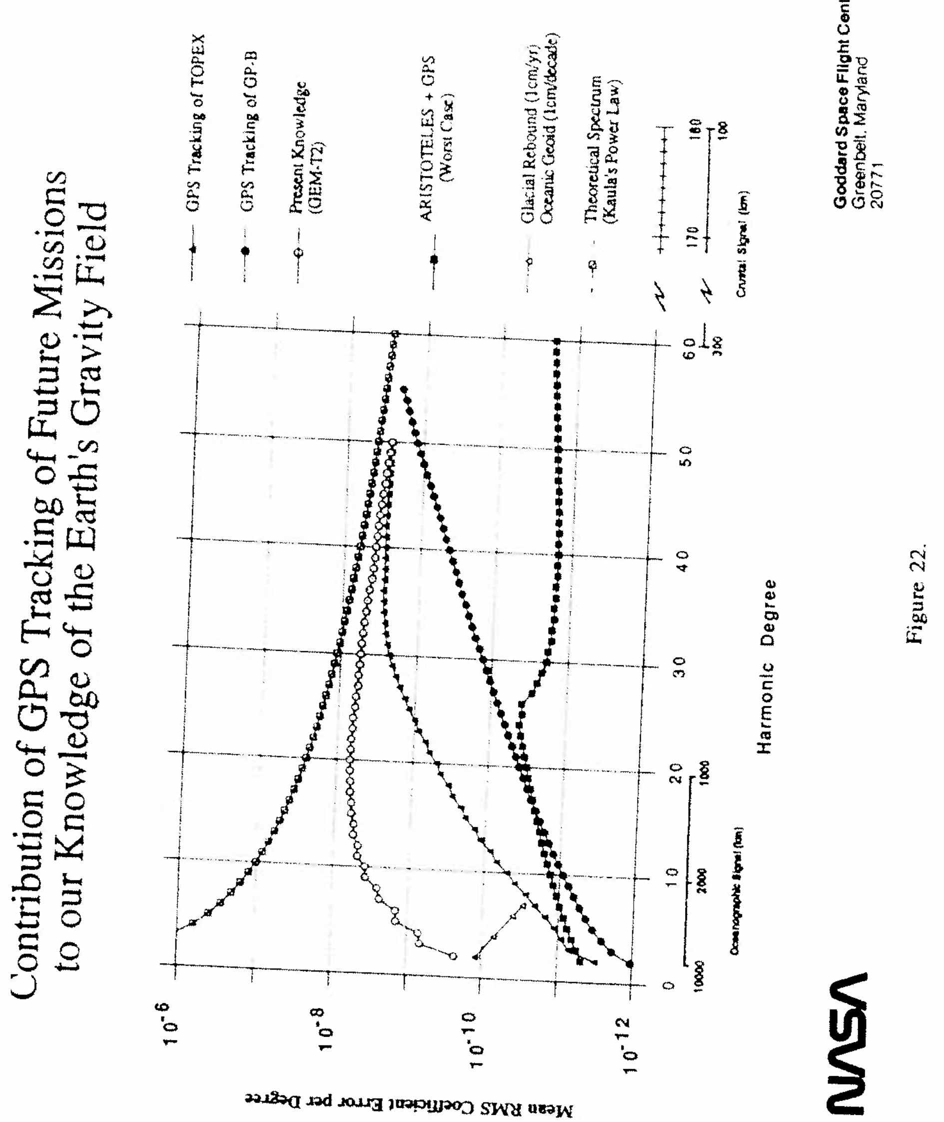

Figure 22.

Relativistic Gravitational Experiments in Space
ed. M. Demianski and C.W.F. Everitt (World Scientific, 1993)

GRAVITY PROBE B SUPERFLUID HELIUM DEWAR AND PROBE*

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ABSTRACT

The Gravity Probe-B Relativity Gyroscope Experiment (GP-B) will provide a precise and controlled test of Einstein's General Theory of Relativity by observations of the precession of nearly perfect gyroscopes in Earth orbit. For gyroscopes in a 650-km polar orbit, the theory predicts two orthogonal effects, known as the geodetic and frame-dragging precessions, with calculated rates of 6.6 arcsec/year and 0.042 arcsec/year, respectively. The goal of the experiment is to measure the geodetic effect to better than 0.01% and the frame-dragging effect to better than 1%. This paper summarizes the test performance of Probe A, in which the gyroscopes are mounted, and the Engineering Development Dewar, which provided the 1.8 K laboratory test environment. Predicted thermal performance of the Probe B and Science Mission Dewar concepts is also provided.

1. Introduction

Stanford University is developing a science instrument assembly (SIA) consisting of four gyroscopes, six SQUID readout devices, one drag-free mass and one quartz telescope, mounted on or inside a quartz block. The SIA will be flown in 1998 to provide an orbital test of Einstein's General Theory of Relativity. Lockheed is developing the probes in which the SIA is mounted and the superfluid helium dewars in which the probe is mounted (Fig. 1). Stanford University just concluded a series of successful laboratory tests on two gyroscopes mounted inside Probe A and the Engineering Development Dewar. Probe B is currently being designed to have the full complement of four gyroscopes plus the other equipment that makes up an SIA. Following Probe B tests, Probes C and D (one flight probe plus one spare) will be designed and fabricated. One more laboratory dewar called the Flight Component Development Dewar (Flicomp) will be built before the Protoflight Science Mission Dewar. This incremental hardware approach reduces the technical risk associated with such a demanding program.

* Work supported through Stanford University, via subcontract PR 4660 and NASA contract 8-36125 with the Marshall Space Flight Center.

(5)

2. Probe Configuration

The probe is part of the payload assembly consisting of the SIA, dewar, sunshade, and associated SIA electronics as shown in Fig. 2. The payload is then integrated with the spacecraft as shown in Fig. 3. The B version of the probe shown in Fig. 4 houses the SIA inside a 6061 aluminum vacuum shell. The SIA is structurally mounted and thermally grounded off a 6061 aluminum quartz block support tube through 20 indium coated fingers. This section of the probe runs at ~2.5 K. The necktube region temperature ranges from 2 K at the cold end to 220 K at the tophat in orbit.

The ring-stiffened composite necktube is constructed of four layers of ± 40 deg gamma alumina fiber/epoxy 0.5-mm thick with a 0.013-mm titanium alloy liner. The fiber was chosen because its high modulus, comparable to graphite, and low thermal conductivity, half that of glass at 15 K, minimizes the conduction heat leak down the neck by allowing the thinnest wall possible, yet allows the probe to be evacuated with a 1-atm external load. The titanium foil minimizes helium gas permeation during a cold probe insertion with liquid helium in the dewar well. The foil also minimizes absorbed gases, permitting a vacuum of 10^{-11} torr to be achieved after gyro spinup and a low temperature bakeout.

The counterflow heat exchangers on the outside of the composite neck cools incoming ambient temperature helium gas to 5 to 7 K for gyro spinup. The exhaust gas exits at 2 mg/s through 3.8-cm-diameter exhaust valves. (Each gyro has a separate inlet and exhaust line.) The 70-μg/s gas leaking into the probe during spinup exits to space through a 20.3-cm-diameter gate valve. Four optically coated calcium fluoride windows (magnesium fluoride antireflection coating on the warm side and protected silver on the cold side) provide a 15 cm aperture for the SIA telescope plus 80% transmission in the 0.3 to 0.6-μm range yet minimizes the infrared heat load down the probe neck. The probe aperture views the Earth a little less than half the time each polar orbit. The gold-coated and black-anodized false wall/heat station rings are also designed to minimize infrared heat loads on the SIA telescope and into the dewar. The silver-coated teflon (FOSR) sunshade with internal baffles minimizes solar reflections and infrared heat load down the aperture for a solar viewing angle of 30 deg off axis, minimum.

The tophat section, bolted to the dewar, contains all the electrical, optical, and plumbing feedthroughs. A welded bellows joins the tophat to the composite neck tube, allowing for differential contractions during cooldown.

3. Probe A Test Results

The quartz block with two gyroscopes and rf SQUIDS was integrated into Probe A, and installed into the Engineering Development Dewar (Fig. 5) at Stanford University. The dewar was tipped to 52.5 deg off the vertical, parallel to the earth's spin axis. Both gyroscopes were suspended and spunup, one to as high as 50 Hz. Their

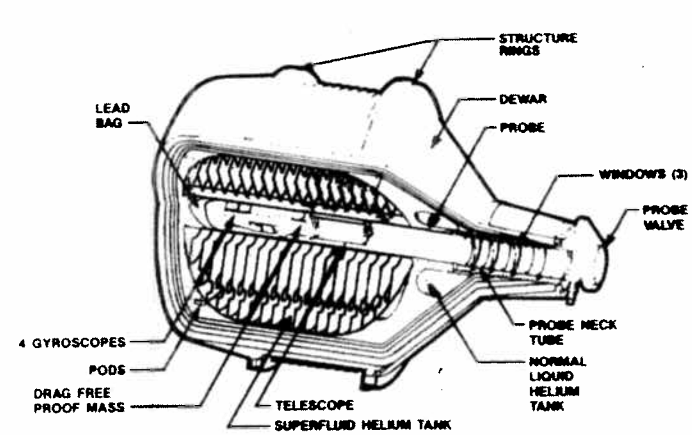


Fig. 1 Science Instrument Assembly Mounted Inside the Probe and Dewar (Early Version)

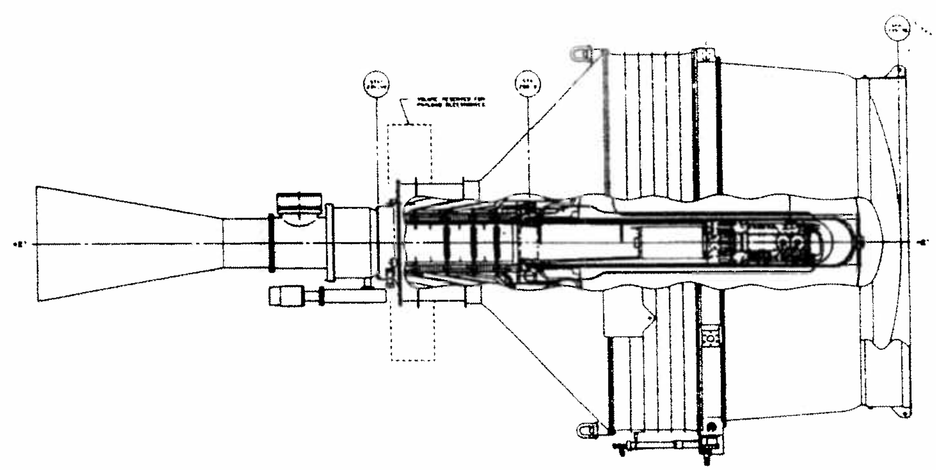


Fig. 2 Payload Configuration (Current Version)

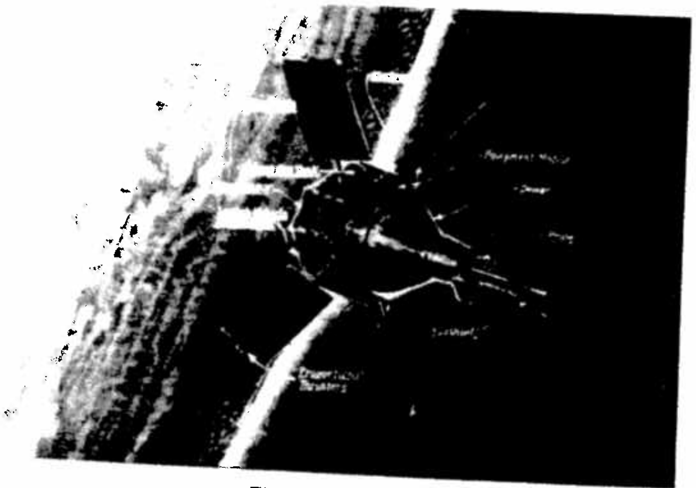


Fig. 3 Spacecraft

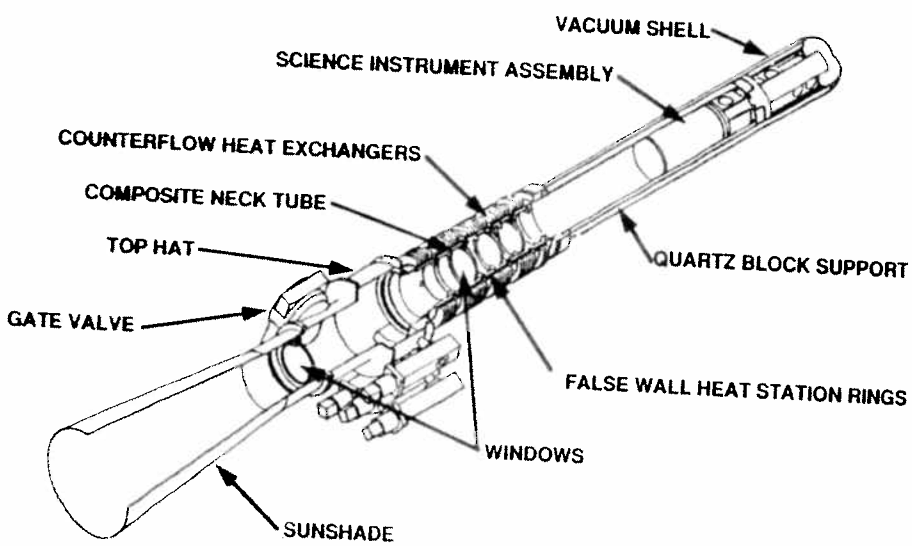


Fig. 4 Probe-B

performance and the SQUID's performance were checked out.[1] In addition, the probe's performance was measured as shown in Fig. 6.

The probe met all the performance requirements except two. The first is the 10^{-11} torr vacuum requirement. (A cryopump shown in Fig. 7 will be installed in Probe B to solve this problem.) The second is the pressure drop in the exhaust lines exceeds the 0.3-torr pressure drop requirement. (Line diameters will be increased at the cold and warm ends.) Note the leakage gas pressure drop through the probe and out the gate valve keeps the high-voltage suspension system out of the electrical discharge range of 10^{-3} torr. The separable probe/dewar thermal contacts at heat stations 1 through 4 produced very low temperature gradients, minimizing lifetime impacts to 2.1%. The infrared heat load on the quartz block was a remarkably low 0.12 mW, below the required 0.25 mW. However, the optically coated calcium fluoride windows were not installed for this test; gold-coated copper disks (coated side looking at the quartz block) were used.

4. Science Mission Dewar

The Science Mission Dewar concept is shown in Fig. 8. The dewar consists of (1) the main superfluid helium tank and well, into which the lead bag, lead bag retainer, and probe are mounted; (2) twelve passive orbital disconnect struts for tank support (PODS V); (3) the composite neck tube on the main tank; (4) the guard tank, mounted off the coldest heat exchanger, for ease of ground servicing; (5) four vapor-cooled shields and multilayer insulation; (6) plumbing; (7) vacuum shell; and (8) instrumentation.

During lead bag expansion and probe insertion into the dewar well, both the main tank and well are filled with LHe I at 4.2 K (Fig. 9). The fill level in the well is kept between heat station 1 and the top of the lead bag. During and following the lead bag expansion, the lead bags are never allowed to rise above 6.5 K (T_c = 7.2 K). To achieve this goal, a heat exchanger in the tank cools incoming topoff gas/liquid to ~4.2 K. (The lead bag expansions will take approximately 6 weeks and the plumbing will warm up between topoffs.) Once the final lead bag, lead bag retainer, and probe are installed in the cold dewar, the well is evacuated and valve V6 closed. Valve V8 assembly is then installed and the space pumped out between the two, as a safeguard against air leakage during launch.

Both the main tank and the guard tank are filled through the same line and vented through dual vent lines. Dual vent lines are used so heat exchangers and plumbing can be brazed and leak checked before bonding to the composite necktube (in two half assemblies). The main tank is filled by opening valves RAV1, RAV3, and RAV4 (Fig. 9). Once the main tank is filled with 4.2 K He I and the lead bag, retainer, and probe are installed as described previously, the tank is pumped down to 1.7 K through the vent lines. Approximately three to four topoffs and pumpdowns are required with near lambda point liquid helium from a supply dewar to achieve a 5% ullage at 1.7 K. Valves RAV1, RAV2, and RAV4 are closed and valve RAV2 is opened to fill the guard tank with 4.2 K He I.

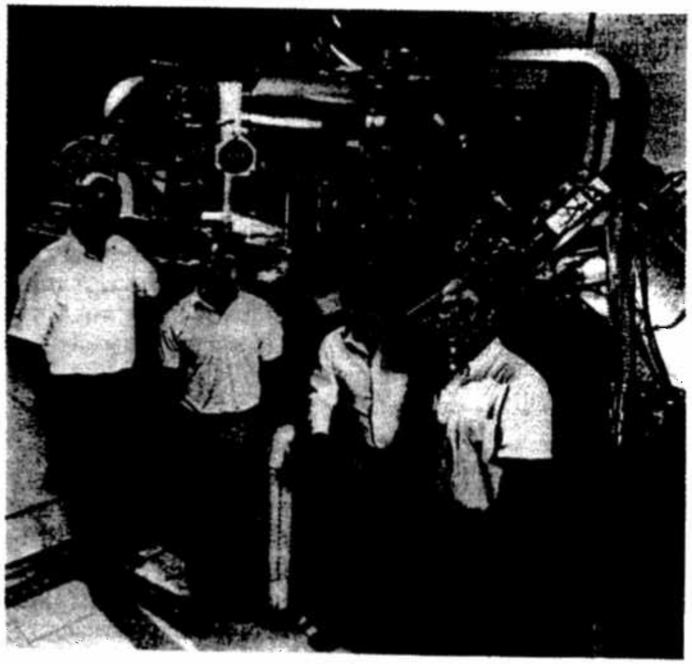


Fig. 5 Gyro Test Setup at Stanford University

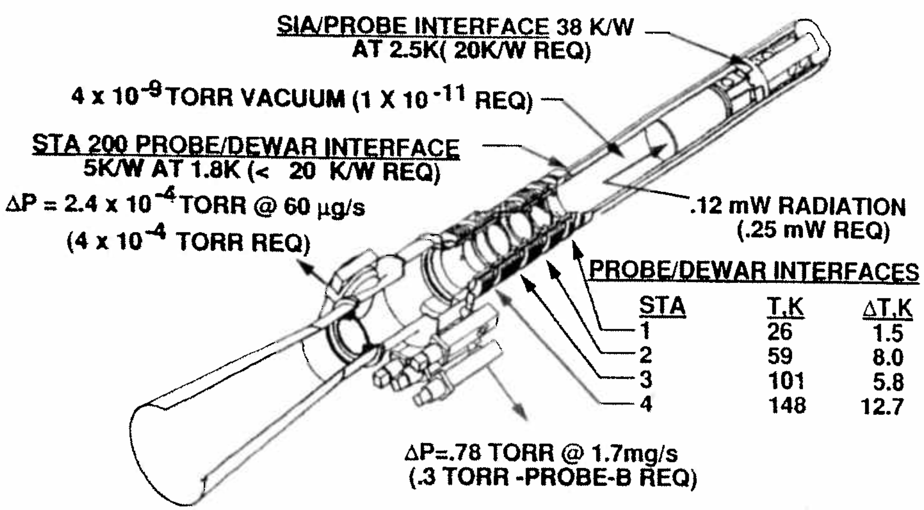


Fig. 6 Probe-A Performance/Probe-B Requirements

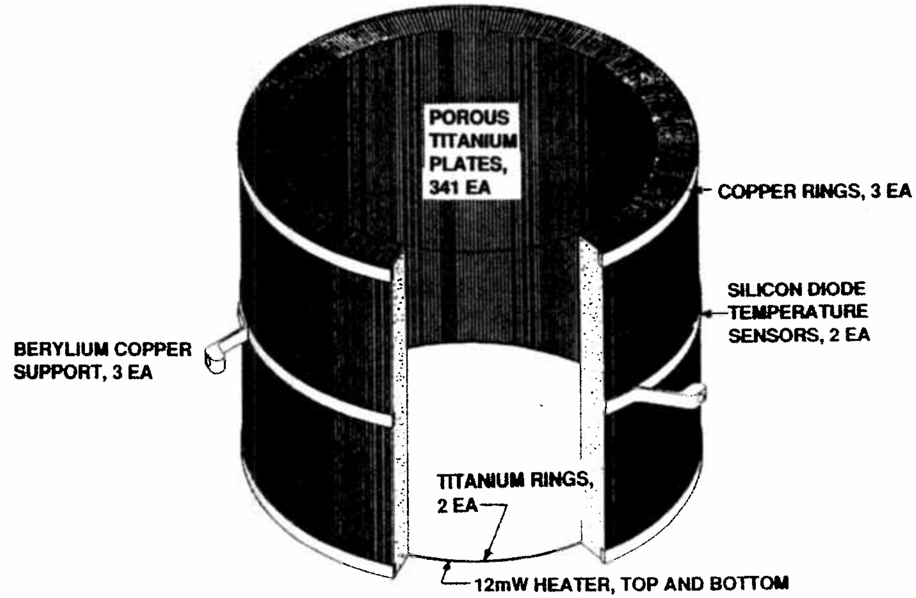
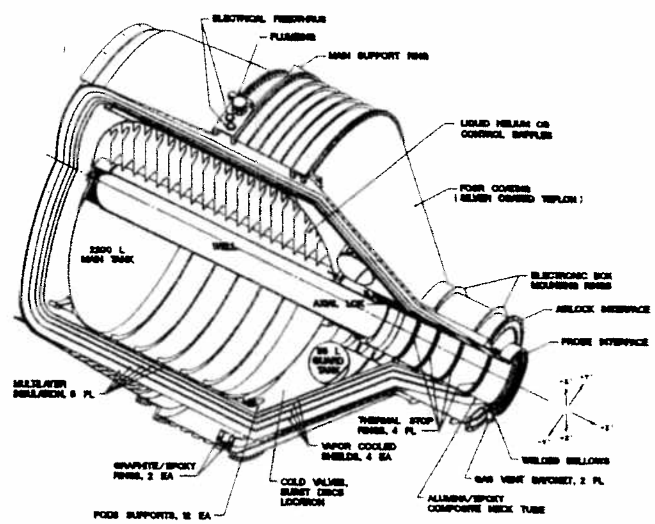


Fig. 7 Cryopump Design



WEIGHT	
DRY WT	1125 Kg
LHe	320 Kg
	1445 Kg
DIMENSIONS	
LENGTH	3.01 m
OUTER DIAMETER	2.17 m
RESONANCES	
LAUNCH	>35 Hz
ORBIT	>20 Hz

Fig. 8 Science Mission Dewar

The guard tank lifetime is shown in Fig. 10. As shown in Fig. 11, the nonvented ɿain tank temperature rises from 1.7 K to 1.75 K in 45 days with the guard tank at .2 K. During this time period, the guard tank is topped off every 9 days. Following the ınal guard tank topoff, valve RAV2 is closed, the fill line is pumped out, and valve V5 ; closed. The valve V7 bayonet assembly is installed and the space between V5 and V7 ; pumped out. Valve V7 provides added insurance against air leakage into the vacuated fill line during launch. The guard tank is emptied with a heater minutes ·efore launch.

After launch, redundant valves RAV4A–B are opened once the Delta II launch ehicle is outside the atmosphere, the fairing is jettisoned and the launch vehicle is still ccelerating. The main tank then starts venting through the porous plug, establishing ıe proper temperature gradient across the plug before orbit is achieved.

The main tank is supported with 12 PODS struts (Fig. 12). The forward PODS upports, mounted in a plane, are attached to two large graphite/epoxy rings, used as a table mount for two star blippers described later. The rings in turn are attached to the acuum shell through aluminum flexures (Fig. 13). The large graphite rings are stable imensionally from ambient to 220 K; as the aluminum vacuum shell cools down in rbit, the flexures take up the contraction differences between the stable graphite ring nd contracting vacuum shell. The forward PODS are designed for lateral, torsional, nd tilt loads in conjunction with the six aft PODS supports. The six aft PODS supports lso take all longitudinal loads along the z axis.

The graphite rings provide a very stable mounting platform for the two star lippers in order to meet the < 10 arcsec radial, random walk requirements between ıe star blipper and the quartz block (Figs. 14 and 15). The star blipper signals are ;ed to accurately control the spacecraft roll rate about the z axis at 0.1 rpm.

Four 6063 aluminum vapor cooled shields, silk net spacers, plus double uminized mylar radiation shields insulate the tanks. The inner shield is supported ıally and thermally grounded to the guard tank (Fig. 16). The second shield is pported in a similar manner off heat exchanger No. 2 on the composite necktube. ɔth shields are thermally grounded and supported radially off all 12 PODS with :xures (Fig. 17). The flexures allow differential movement between attached parts ıen cooled. The outer two vapor cooled shields are thermally grounded and pported off the aft PODS. Flexures at the forward PODS and heat exchangers ovide thermal grounding and radial support.

Thermal analyses show that vapor cooling the 0.5 mm thick 6063 aluminum ːelds at the composite neck (as opposed to isothermal cooling) only degrades ːtime by 0.6% and simplifies the vent plumbing routing.

The composite necktube is at its minimum wall thickness (four layers) for a 2×10^6 N/m^2 estimated load (emergency vent only). For launch, the external load emoved by evacuation of the dewar insulation. Consequently, a structural analysis ; performed on the composite neck tube to see how much mass can be supported in ·elta II launch environment. From Fig. 18 it can be seen that the weight of the guard

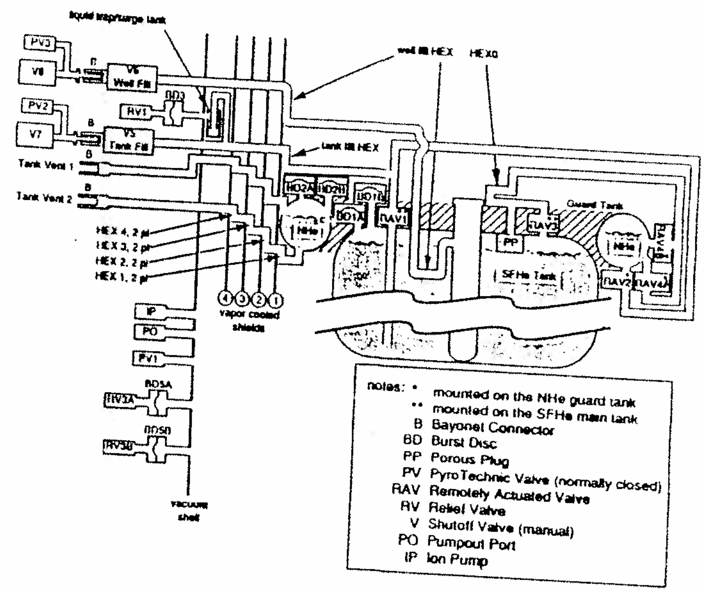


Fig. 9 Science Mission Dewar Plumbing Schematic

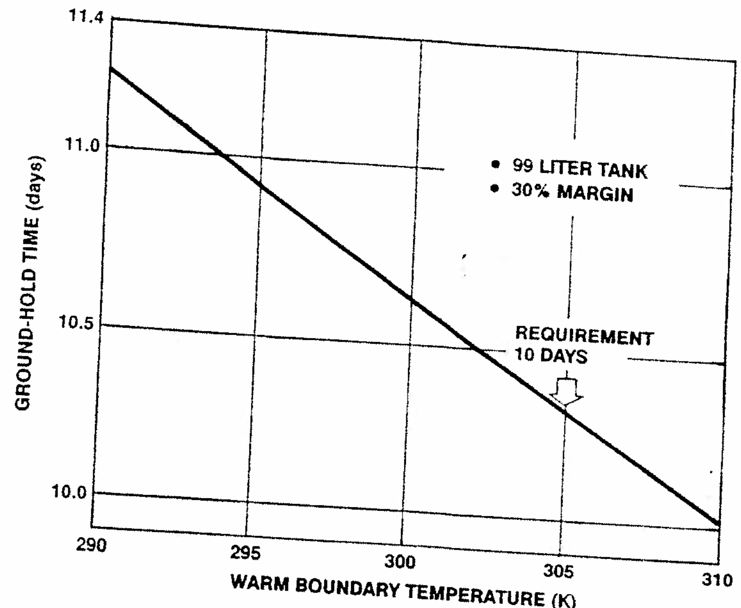


Fig. 10 Calculated Guard Tank Life Versus Warm Boundary Temperature

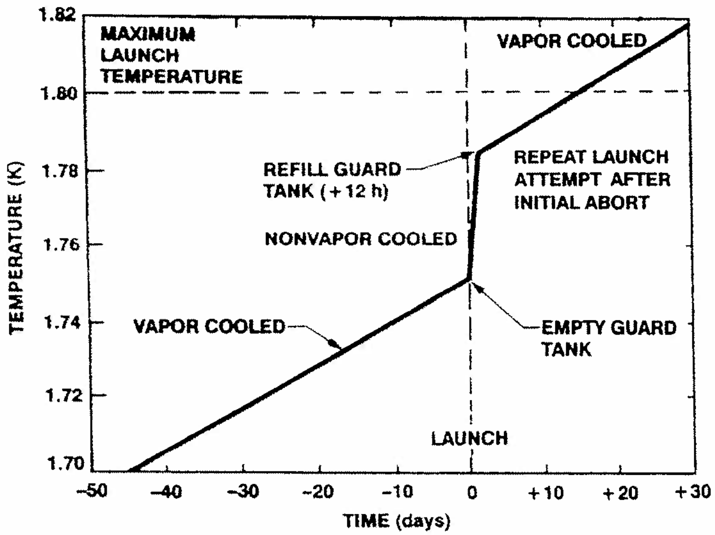


Fig. 11 Temperature Rise Rate of Nonvented Main Tank on the Ground

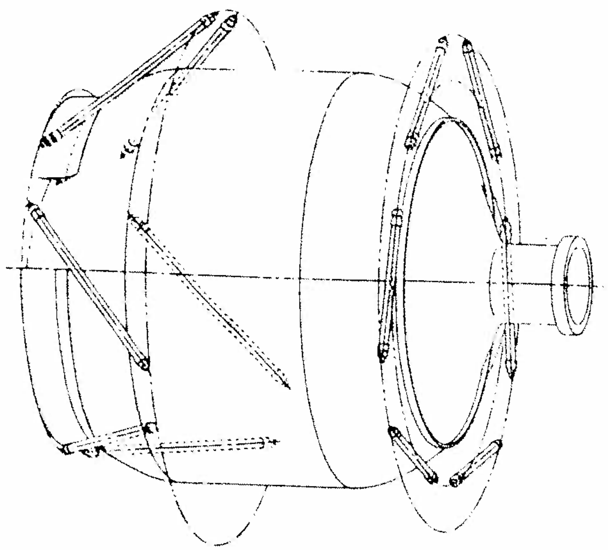


Fig. 12 PODS-V Supports, 12 Each

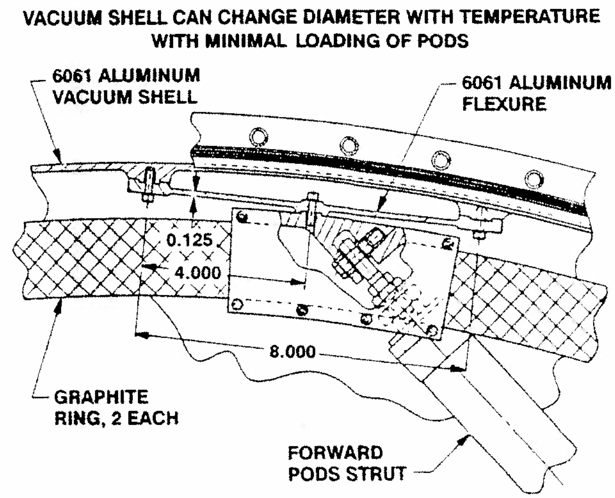


Fig. 13 Forward PODS Attachment to Graphite Ring/Flexure/Vacuum Shell

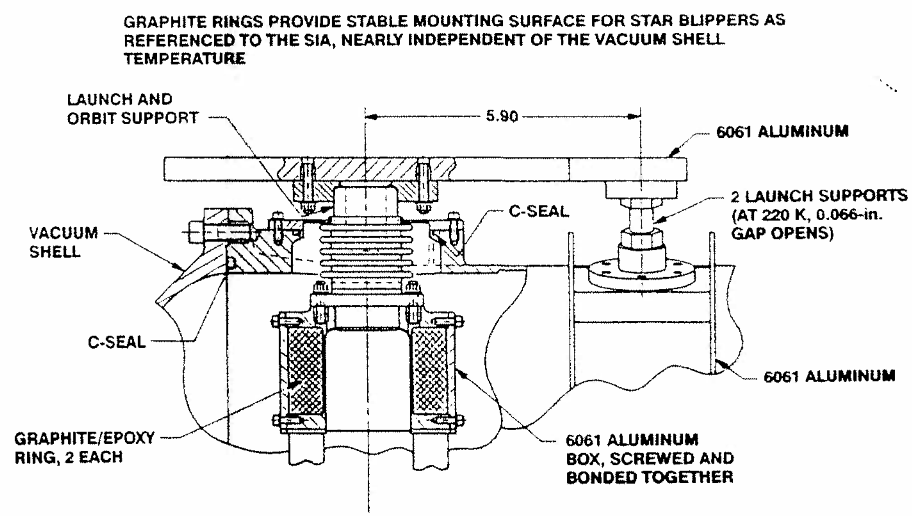


Fig. 14 Star Blipper Mount, 2 Each

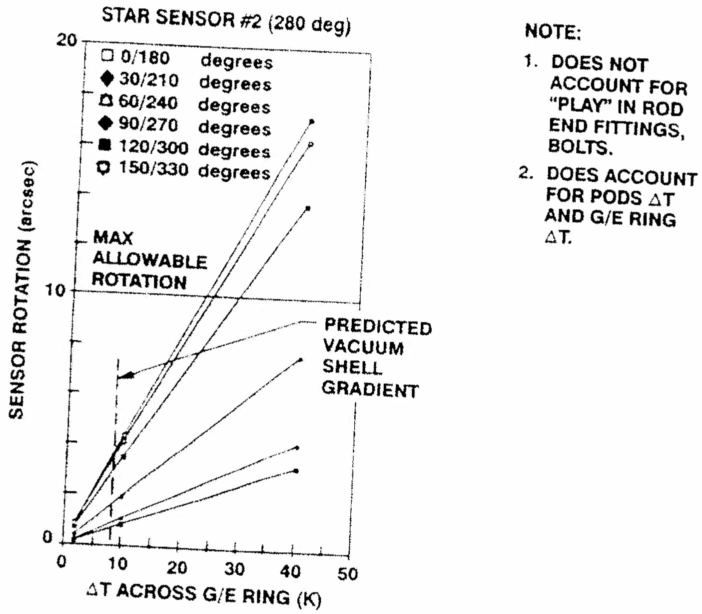


Fig. 15 Star Blipper Mount Point Errors Due to Circumferential Temperature Gradients

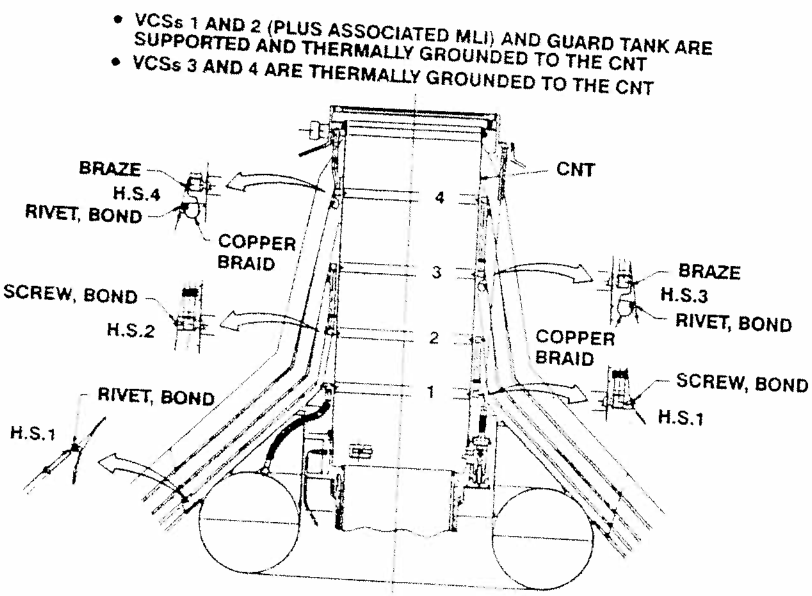


Fig. 16 Vapor-Cooled Shields (CNT Attachments)

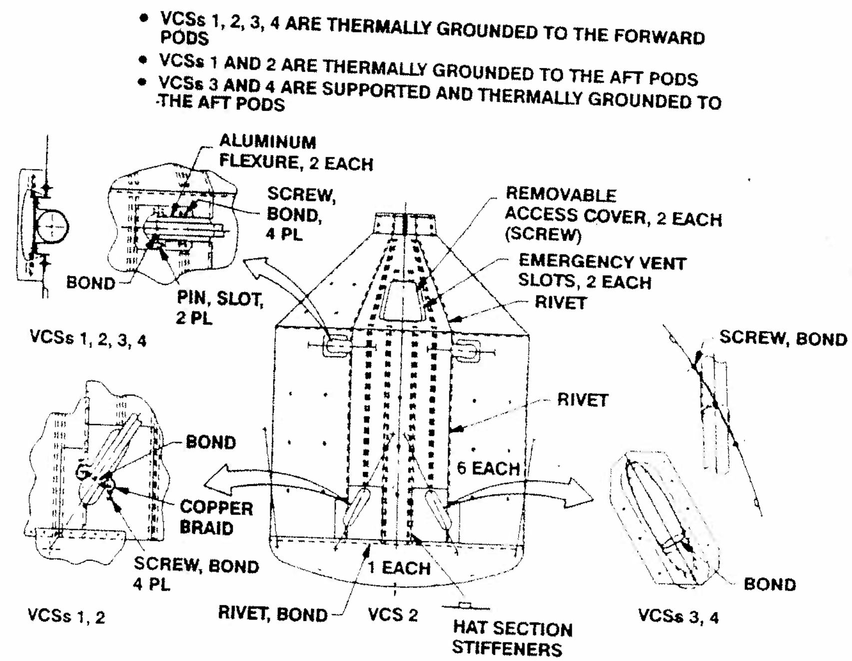


Fig. 17 Vapor-Cooled Shields (PODS Attachments)

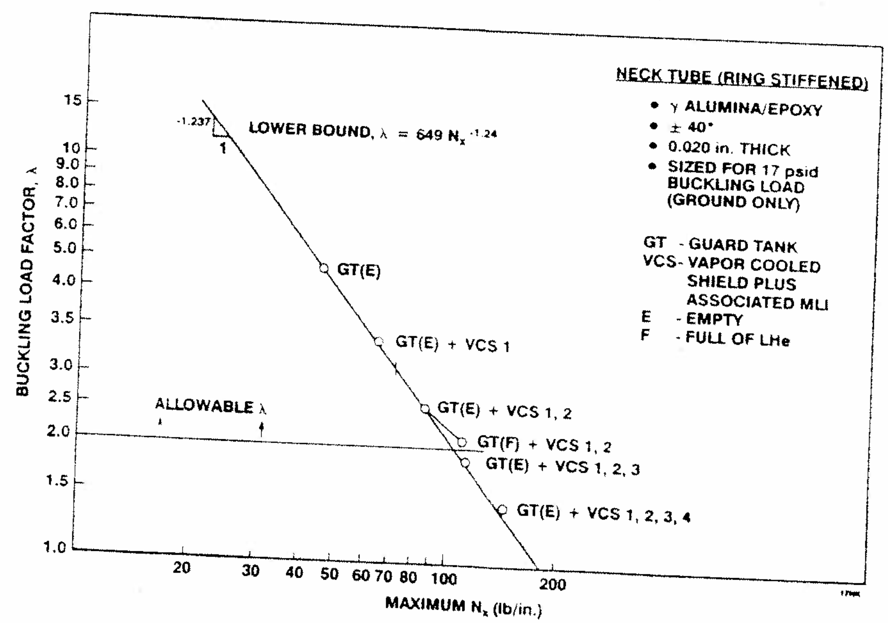


Fig. 18 Reference Dewar Neck Tube Buckling Versus Launch Loading

ε and first two shields (with their associated multilayer insulation) can be hung off necktube.

The ring stiffened, ± 40-deg, 0.5-mm-wall neck tube is of similar construction to probe, except for the liner. The 0.013-mm titanium alloy foil only extends from the plate to heat exchanger 3. Below heat exchanger 3, running at ~135 K, the nposite necktube helium permeation rate is low enough no liner is required for und operations. Consequently, when the well is filled with LHe, the dewar vacuum ce will not be degraded. For launch, the well is evacuated. This partial titanium r degrades lifetime ~1%, as compared to no liner.

The vacuum shell is constructed in four assemblies of ring-stiffened 6061-T6 minum; an aft dome section, a main support ring with plumbing and electrical d-throughs, a barrel section, and a forward conical/cylindrical section. The external face is covered with silver-coated teflon (FOSR) to reduce the shell temperature to inimum and maximize dewar lifetime. All sections are sealed with indium-coated onel C-seals. The indium provides a leak-tight gas seal, as demonstrated on the ng Life Cooler flight program.[2]

)rbital Performance

An orbital analysis was performed on a typical spacecraft configuration in a)-km polar orbit. The vacuum shell was assumed to be covered with FOSR to luce the shell temperature. The FOSR properties used in the analysis and the culated vacuum shell temperatures are shown in Fig. 19. Assuming a 300-W heat sipation from probe electrical boxes mounted around the dewar neck raised the ll temperature only 0.3 K.

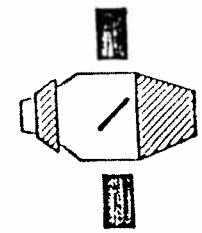
The parasitic heat load into the probe/dewar was then calculated using a 400-de SINDA model. The SINDA computer code is a software system used for solving nped parameter representations of physical problems governed by diffusion-type uations. The system is designed as a general thermal analyzer accepting nductor-capacitor (G-C) network representations of thermal systems. The results in . 20 show a 155-mW heat load at an average shell temperature of 220 K. Out of the 5 mW, 75 mW is coming through the probe due to the hundreds of wires, cables, at pipes and plumbing plus the radiation tunneling down the neck. These heat loads lude a 30% margin over the calculated values, based on prior dewar test margins uired. This heat load translates into an 18.4 month orbit lifetime (Fig. 21).

- FOSR PROPERTIES ON DEWAR VACUUM SHELL

	BOL	EOL	AVERAGE USED IN ANALYSIS
α_{SOLAR}	0.09	0.15	0.12
ϵ_{IR}	0.80	0.80	0.80

- VACUUM SHELL ORBITAL TEMPERATURE USING FOSR

VERNAL EQ.	223 K
SUMMER SOL.	212 K
AUTUMNAL EQ.	227 K
WINTER SOL.	219 K
AVERAGE	220 K



DEWAR + SOLAR PADDLES + EQUIPMENT SECTIONS + 300 W

Fig. 19 Orbital Analyses

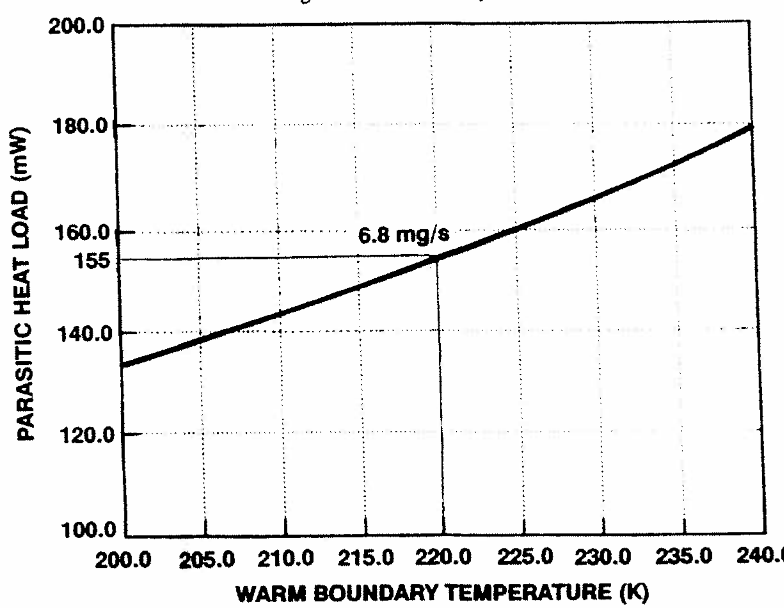


Fig. 20 Calculated Orbit Parasitic Heat Load Versus Warm Boundary Temperature (30% Margin Over Calculated Value)

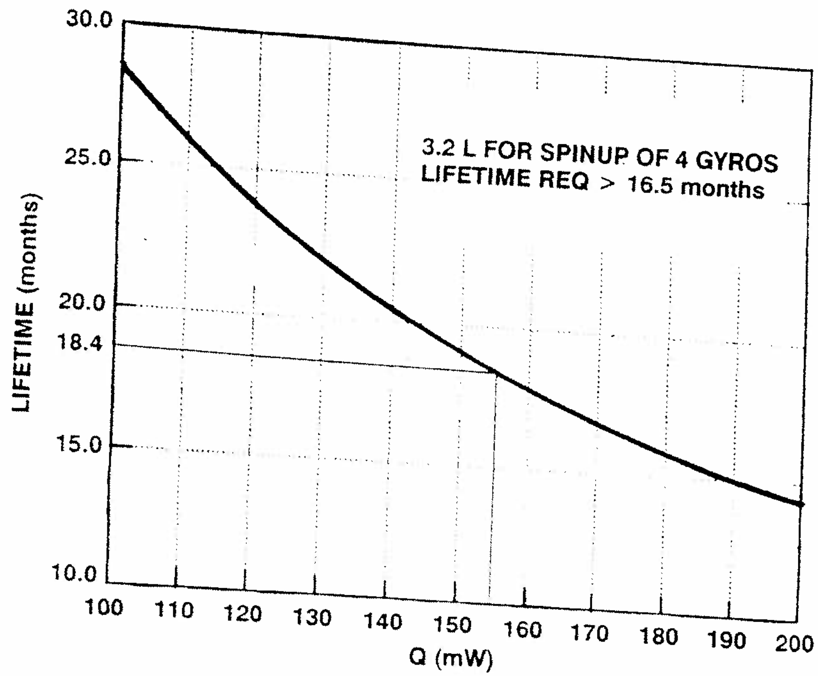


Fig. 21 Calculated Orbit Lifetime Versus Parasitic Heat Load, 5% Ullage

ummary

The Engineering Development Dewar and Probe A performed well in the initial) spinup tests at Stanford. The probes can be installed and removed from a cold ar. (Only a warm insertion has been demonstrated to date.) The launch pad icing is simplified by use of the guard tank and the dewar will meet the lifetime irements for the science mission.

eferences

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2. Long Life Cooler Program, Contract No. M9-309183-U4A.

PAST AND FUTURE TESTS OF RELATIVISTIC GRAVITATION WITH ATOMIC CLOCKS

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ABSTRACT

Highly stable atomic clocks are the basis of metrology for distance and time in tests of relativistic gravitation. Methods for using high stability signals to test theories of relativity and gravitation are described. The successful 1976 SAO/NASA GP-A redshift test has led to new ideas for microwave techniques using atomic hydrogen masers to measure gravitational and relativistic phenomena, including pulsed gravitational radiation, the PPN parameter β, (which describes the second order in the redshift), and a comparison of inertial frames defined by very long baseline interferometry observations and an inertial frame defined by the local velocity of light. Quantitative estimates are given of the limitations to the precision of such measurements from the frequency instability of the latest atomic hydrogen masers, now less than 1 part in 10^{15}.

1. Introduction

Atomic clocks occupy a unique position in the class of instrumentation for measurements of relativistic and gravitational phenomena. Today, the atomic hydrogen maser oscillator has frequency stability in the 10^{-16} domain for intervals of 10^4 seconds and further developments are in progress with cryogenically cooled atomic hydrogen masers operating at 0.5 K to generate even more highly stable signals.[1] New types of frequency discriminators using trapped and cooled ions and atoms are being developed that should be capable of controlling the frequency of oscillators for very long intervals reaching frequency stability in the 10^{-16} to 10^{-17} for periods of weeks and months.[1] The 1967 definition of the Systeme International (SI) second of time in terms of the hyperfine structure of the ^{133}Cs atom and the 1983 redefinition of the (SI) meter in terms of a defined velocity of light have led to new metrology based on frequency and time. These new concepts have made real and practical the clock and yardstick of the traditional "gedanken" experiments traditionally used to illustrate the behavior of relativistic and gravitational theories.

The best strategy for using clocks in testing gravitation and relativistic theory is to identify time varying measurable effects over intervals where clocks have optimum stability. A description of the frequency stability of a clock, or oscillator, must include the time interval over which the stability is measured, or represented.