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Status of the relativity mission superfluid helium flight dewar[1]

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Abstract

The world's largest capacity helium flight dewar has been assembled for use on the Relativity Mission, also known as Gravity Probe-B (GP-B). Acceptance tests have been successfully performed and the dewar has been delivered to Stanford University. The science mission dewar (SMD) is the first piece of flight hardware delivered for GP-B. It will be used in testing to demonstrate payload functionality with a prototypical Science Instrument Assembly, the flight spare probe (Probe-B), and prototypical electronics.

Since delivery to Stanford, the flight dewar has undergone preparations for integration of Probe-B with the dewar. This involved filling both the main tank and the well with liquid helium and installing a superconducting ultralow magnetic field shield. This shield consists of 63-μm-thick lead foil which lines the inside of the dewar well and provides an ambient magnetic field environment of < 10 pT (0.1 μG) in the region of the science instrument assembly. The installation of the shield is an iterative process which will be described briefly. Once the shield is installed, the dewar and the shield must be kept cold through to the end of the science mission. The ambient field inside the shield that has just been installed has been measured to be 5 pT or less in the gyro region. After completion of testing with Probe-B, the flight probe (Probe-C) will be integrated in early 1998 in preparation for testing the flight payload.

This paper reviews the key design features of the dewar, especially those driven by the ultralow magnetic field requirements. The measured mass, helium boil-off, and ground hold performance are compared to those of the previously launched superfluid helium cryostats (IRAS, COBE, and ISO).

Keywords: Space cryogenics; Superfluid helium dewar; Gravity Probe-B

1. Introduction

The Relativity Mission 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-s/year) through the curved space–time surrounding the Earth and the motional effect (0.042 arc-s/year) due to the rotating Earth dragging space–time around with it. To achieve the extraordinary accuracy needed to measure these small processions, it is necessary to have the gyroscopes operating in the following environments: a vacuum of $< 10^{-11}$ torr, an acceleration level of $< 10^{-10}$ g, a magnetic field of < 10 pT, and a temperature near 2 K. The flight dewar is critical in meeting the acceleration, magnetic field, and temperature requirements for proper operation of the science instrument assembly (SIA), and it must provide a minimum orbital lifetime of 16.5 months in order to achieve the required experimental accuracy. The SIA consists of four gyroscopes, superconducting quantum interference device (SQUID) readouts for measuring the gyroscope precession, and a telescope that, in conjunction with a guide star, provides a frame of reference against which the precession can be measured. The SIA fits inside a long cylindrical container called the Probe (Fig. 1); the sealed probe in turn fits inside the well of the dewar (Fig. 2).

2. Dewar overview

2.1. Dewar description

The dewar shown in Fig. 3 is 3.0 m high, 2.2 m in diameter, and weighs 810 kg dry. The main tank con-

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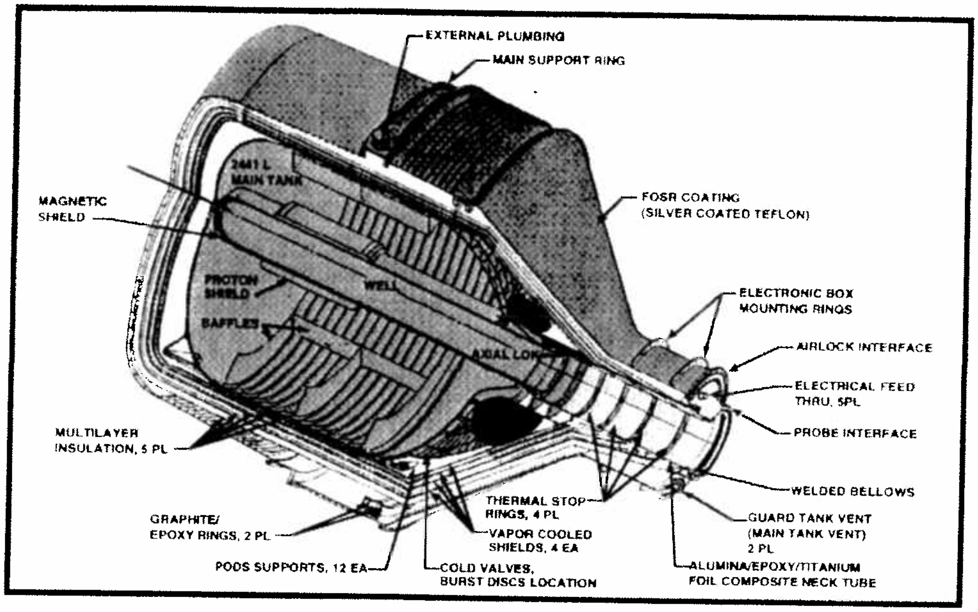

Fig. 3. Cutaway of science mission dewar (SMD).

The requirements that have the most profound influence on the GP-B dewar design are the ultralow magnetic field requirement, cold insertion of the probe, meeting the mass and lifetime requirements, and providing a stable mounting platform for the star trackers.

The ultralow magnetic field is achieved by the successive expansions of superconducting lead magnetic shields. This technique will be described briefly in this paper and has been discussed extensively in previous papers [1]. This expansion must be performed when the shield is below the superconducting transition temperature (< 7.2 K) of the lead and in a very stable thermal environment. Once the expansions are completed and the desired magnetic field is achieved, the remaining lead shield must be maintained in a superconducting state or the low field is lost. Therefore, the gyroscopes must be inserted into the low field environment while it is at helium temperatures without increasing the temperature of the lead shield above its transition temperature.

To perform these operations, the dewar must provide a separate volume, called the well, for the expansion of the lead bags. This volume must be accessible from the ambient environment and must be capable of being filled with liquid helium. The well volume cannot contain superfluid helium in a zero-*g* environment since it communicates thermally with the warm vacuum shell, hence it must be filled and evacuated separately from the main tank. Since it is filled with helium during lead bag operations, it must be isolated from the guard vacuum even though the well volume is evacuated once the probe is installed. This vacuum isolation is accomplished with a titanium-foil-lined composite neck tube. The composite neck tube also provides thermal isolation, since it must seal at the main tank well (1.8 K) and at the vacuum shell (230 K). The probe must be inserted through a helium-purged air lock into the liquid helium filled well containing a lead bag magnetic shield. As part of the insertion process the probe is thermally/structurally attached to the helium tank, thermally grounded at four stations in the composite neck tube and sealed to the vacuum shell. Axial lock clamps [2] provide the necessary clamping force for good thermal contact and structural support between the probe and main tank at 2 K. All this must be done without increasing the temperature of the magnetic shield above 6.5 K

Mass and lifetime are always design drivers for a space cryogenic system, and significant effort was expended to meet the lifetime while minimizing mass. The helium lifetime is dominated by parasitic heat loads so an efficient thermal isolation system is critical. Twelve passive orbital disconnect struts (PODS) [3] are used to support the main tank and minimize the support heat leak. The gamma alumina/epoxy neck tube with a 0.03-mm 15-3-3-3 titanium alloy foil liner provides a low-heat-leak, vacuum-tight cylinder connecting the dewar well to the ambient environment. This neck tube has the thermal stop rings [4] which are the thermal/mechanical interface to the probe and allow the probe to be vapor cooled, improving lifetime performance. The insulation system of alternating layers of double aluminized Mylar and up to three silk net spacers was selected based on subscale test results showing this construction to have the minimum heat leak compared to other spacers, such as polyester.

Dewar mass was minimized by a highly optimized structural design on the main tank and vacuum shell and the use of honeycomb vapor cooled shields [5]. The vacuum structures were optimized for both internal and

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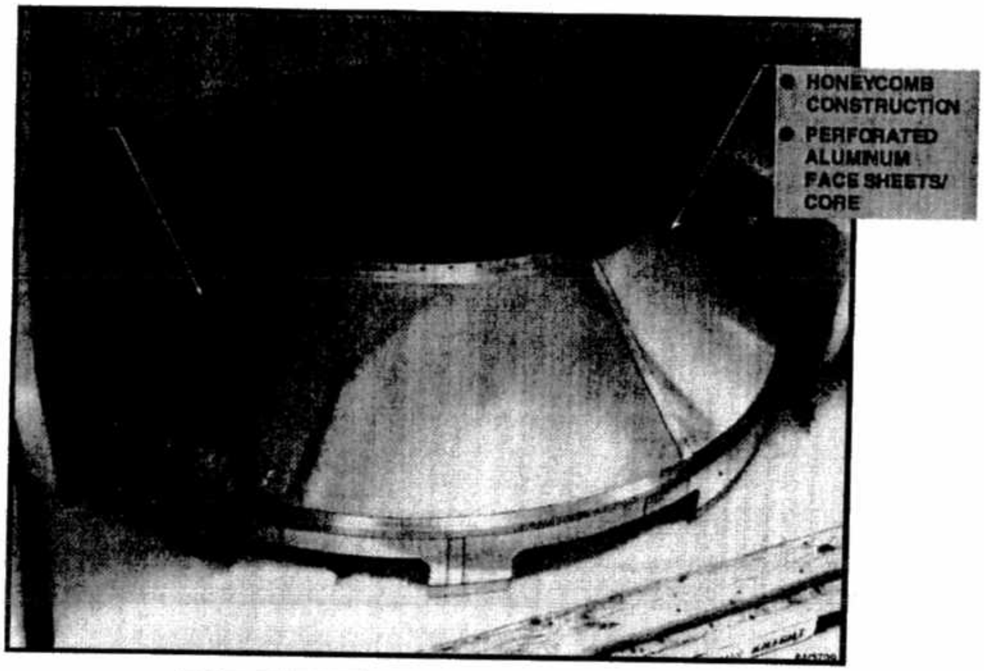

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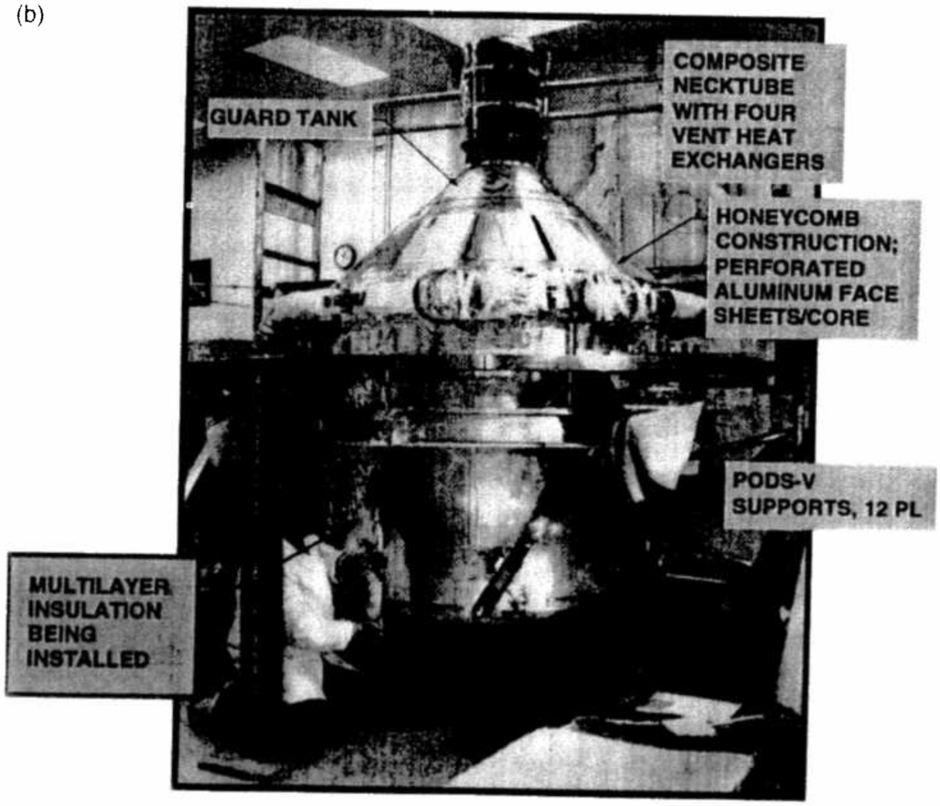

Fig. 5. (a) Cone section of first vapor cooled shield. (b) First (of four) vapor cooled shields.

that refurbishment of the dewar after a loss-of-vacuum will be easier, since the multilayer insulation (MLI) and vapor-cooled shields will not be damaged. Venting directly into the vacuum space would require a rebuild of the thermal protection system.

4. Performance summary

Acceptance test results have been reported previously [6]. The critical performance parameters of mass, para-

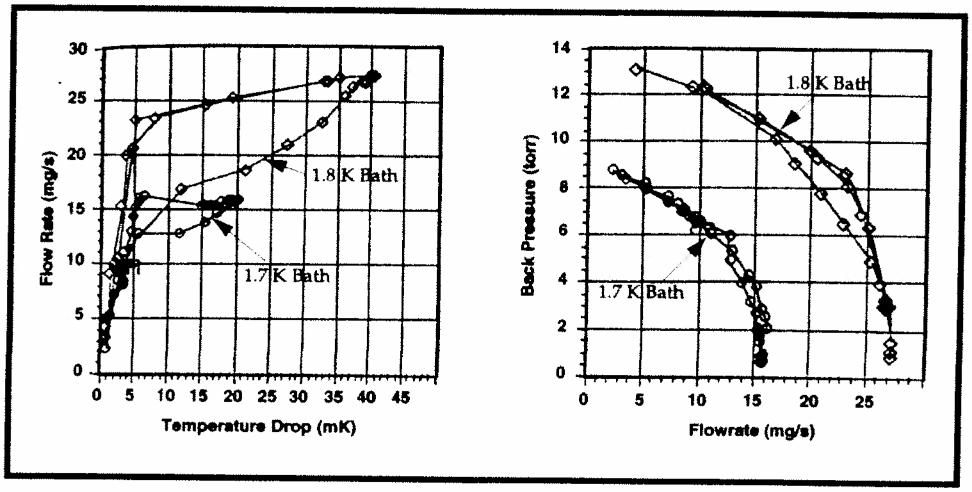

Fig. 7. Effect of bath temperature on temperature drop and back pressure.

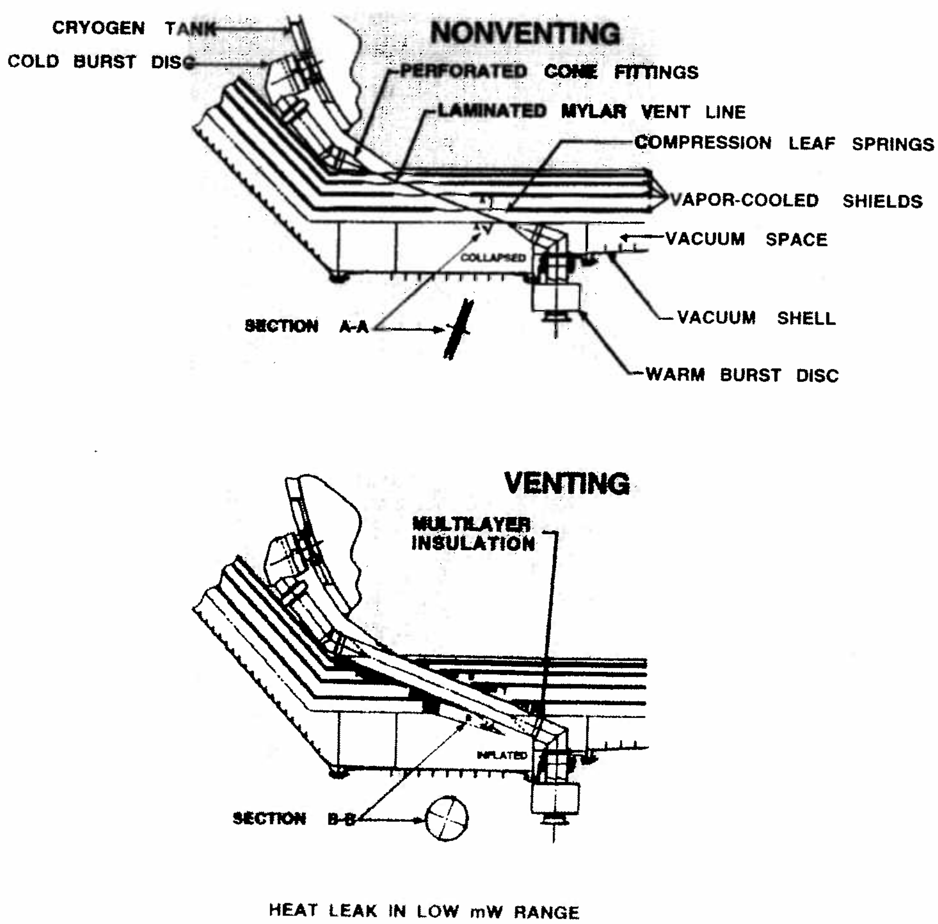

Fig. 8. Cryogen tank emergency vent line is shown in both nonventing and venting configurations.

at the vacuum shell) plus the use of four vapor-cooled shields.

The remarkable ground-hold performance of keeping the GP-B main tank nonvented for 90 days (Table 3) is due to the guard tank driving the inner vapor-cooled shield to 4.2 K (top) to 5 K (bottom); the main tank temperature rises from 1.6 to 1.85 K in this time period. The He I guard tank is filled once a week and no helium is lost from the main tank. Both IRAS and COBE pumped on the main tank up to 26 h before launch. Consequently, they had less helium for use in orbit.

Table 3
Cryostats ground hold performance at the launch pad

Cryostat	Helium loaded (kg)	Percentage ullage	Guard tank Used?	Guard tank Fill cycle (days)	Initial orbital vent rate (compared to orbit equilibrium value)	Main tank nonvented time (days)
IRAS	72	7	No	–	Above	1.1
COBE	89	7	No	–	Above	2 to 3
ISO	331	1	Yes[a]	4	Above	Up to 4.2
GP-B[b]	338	5 max to 2 min	Yes[c]	7	Below	Up to 90

[a]Mounted on main tank. Guard tank vapor cools inner vapor cooled shield to ~ 30 K.
[b]Based on dewar acceptance test data. Includes calculated probe heat leak with 30% margin.
[c]Guard tank, inner vapor cooled shield run at 4.2–5 K.

shield is then installed in the dewar well inside of a previously installed shield. The new shield can then be warmed and cooled through the superconducting transition temperature of lead (7.2 K) by controlling the partial pressure of helium exchange gas in the cooling tube. Once the new shield is cooled in this manner, it will essentially pin the ambient magnetic flux. The previous shield is now removed from the dewar, the bottom of the cooling tube is opened, and the cooling tube is then removed, leaving the new shield hanging in the dewar well. The new shield is mechanically unfolded using an expansion tool so that the shield assumes its cylindrical shape. Since the magnetic flux is pinned in the lead foil, it now becomes spread over a much larger volume thereby reducing the magnitude of the field. The magnitude of the field can be measured by means of a SQUID-based magnetometer. Field reductions by a factor as large as 100 can be achieved by this technique, and it can be repeated as many times as necessary to achieve our requirement (10 pT). This process is depicted schematically in Fig. 11. The shield that was recently installed in the science mission dewar was obtained after four iterations. After the internal field is determined to be acceptable in the final shield, it is detached from its cloth sleeve and left in the bottom of the dewar well (see Fig. 12). Measurements of the field in the flight lead shield after completion of installation have indicated that the radial component of the field is ≤ 5 pT (0.05 μG) in the region that will be occupied by the science gyroscopes. In addition, the axial component, which in the absence of physical defects in the shield will be much smaller than the radial components, has been measured to be constant to within 5 pT over the same region. These results are consistent with the field magnitude being well below the requirement of 10 pT. Future measurements will also be made to verify that the shield meets its ac field attenuation requirements.

Before a probe can be integrated into the dewar, a device called a lead bag retainer is installed inside the shield (Fig. 13). This device consists of a number of linear leaf springs (much like Venetian blinds) made of titanium copper alloy which hang inside the shield. It serves to protect the foil shield and to center the probe during probe insertion, and it also insures good thermal contact between the shield and the cold well wall while providing thermal isolation to the probe shell. In addition to the leaf springs, there is a basket-shaped structure to support the bottom of the shield during launch accelerations.

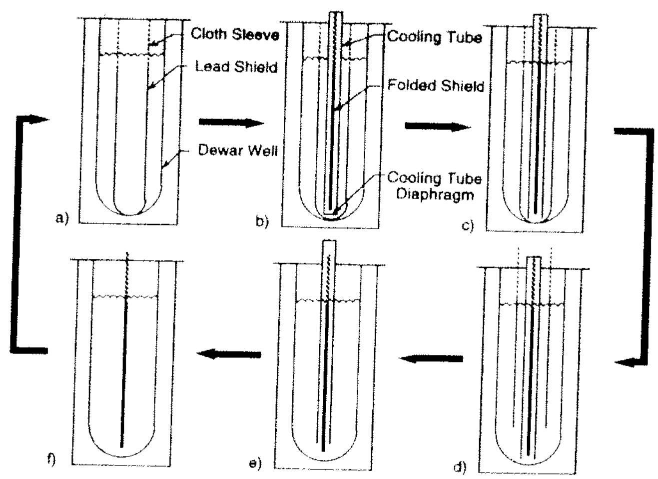

Fig. 11. Lead Shield (LS) field reduction technique: (a) previous LS positioned in dewar well; (b) next LS enclosed in cooling tube under controlled helium atmosphere and installed inside the previous LS; (c) cooling tube diaphragm cut out; (d) removal of previous LS; (e) removal of cooling tube; (f) LS ready for expanding; (a) LS expanded.

7. Conclusions

The SMD acceptance test results show that the dewar meets all relativity mission requirements. The use of advanced technology in weight reduction techniques, PODS-V supports, multilayer insulation, vapor-cooled shields, and guard tank design make this dewar the lightest, per unit mass of He II stored, the most thermally efficient, and the easiest to service at the launch site (compared to the three previous free flight cryostats that have been launched, IRAS, COBE, and ISO). The magnetic field achieved meets the program requirements for the SIA.

Acknowledgements

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