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OPERATIONAL CRYOGENIC EXPERIENCE WITH THE GRAVITY PROBE B PAYLOAD

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ABSTRACT

The Gravity Probe B Relativity Mission is a satellite-based experimental test of two predictions of Einstein's General Theory of Relativity. The experimental design makes substantial use of cryogenic technology. The flight payload, which includes the dewar, the cryostat probe, and the science instrument, is now in final test in preparation for integration with the spacecraft. We review the unique aspects of the cryogenic subsystem and discuss the implications they have for cryogenic operations. We also review cryogenic performance of the payload and compare it to thermal model predictions.

INTRODUCTION

Program Objectives

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 with respect to a distant guide star (HR8703) while in Earth orbit. For gyroscopes in a circular polar orbit with the gyro spin vectors in the direction of the guide star and the guide star in the orbital plane, the theory predicts two orthogonal effects – geodetic precession and frame-dragging precession [1]. For a 650 km orbit, the former has a calculated rate of 1.0×10^{-12} rad/sec (6.6 arc-s/yr.) and occurs in the plane of the orbit, and the latter has a predicted rate of 6.5×10^{-15} rad/sec (.042 arc-s/yr.) and causes the gyros to precess out of the plane of the orbit. The goal of the experiment is to measure the geodetic effect to 0.01% or better and the frame-dragging effect to 1% or better.

Key Payload Features

The GP-B experiment is designed as a low temperature experiment in order to make use of superconductive technology for gyroscope readout and to achieve a high degree of mechanical and thermal stability. The payload portion of the space vehicle (FIG. 1) consists of four major subsystems: the Science Instrument Assembly (SIA), a removable cryostat probe (the flight version being designated as Probe-C) that houses the SIA, the Science Mission Dewar (SMD), and the payload electronics (not shown). Details of the GP-B experimental and engineering design have been described elsewhere [2]. In the following paragraphs we briefly review some of the more unusual aspects that are relevant to this paper.

The SIA consists of a telescope, four independent electrostatically-suspended gyroscopes, and SQUID (Superconducting Quantum Interference Device) readout systems

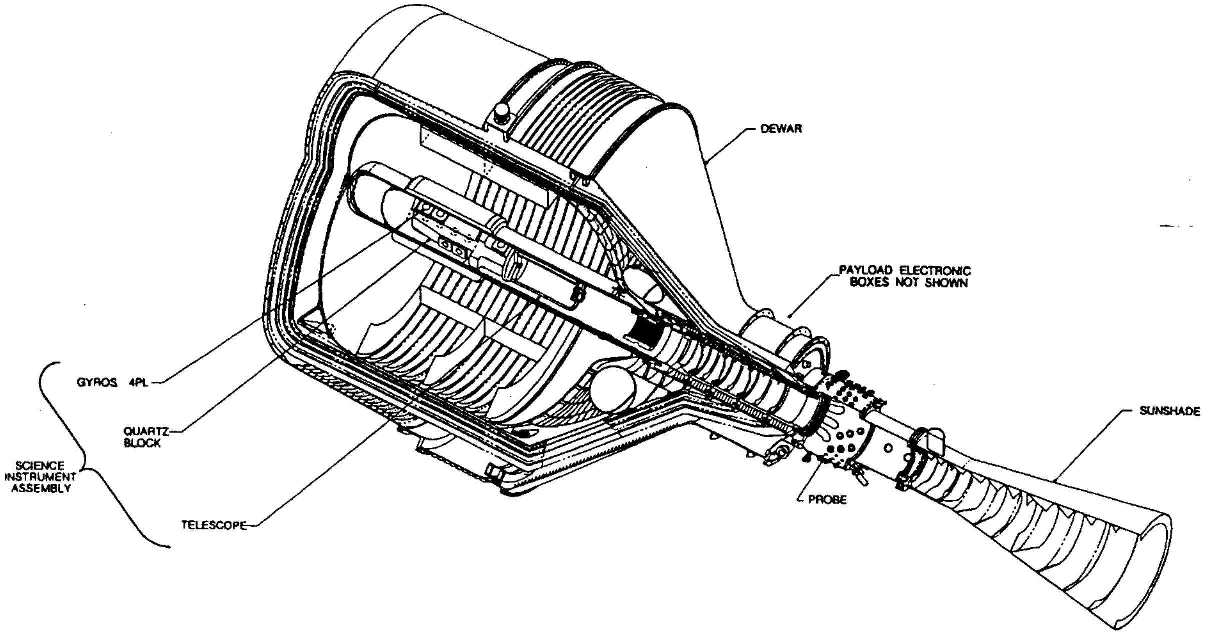

FIGURE 1. Cutaway view of the payload.

for each gyro. One of the unique aspects of the GP-B experimental design is that the readout of the gyroscopes is achieved by detection of the magnetic dipole moment generated by a spinning superconducting sphere (London moment). Each fused-quartz gyroscope rotor is coated with a thin layer of niobium (T_c = 9.2 K) for this purpose. The London moment, which is always aligned with the rotor spin axis regardless of the motion of the spin axis relative to the rotor body (polhode motion), is coupled to a SQUID sensor by means of a superconducting pickup loop located on the gyro housing. However, when the rotor coating is cooled through its transition temperature in an ambient magnetic field, the ambient field tends to become trapped in the body of the rotor. This trapped flux is coupled to the SQUID at the rotor spin frequency (~100 Hz). In order for the measurement of the London moment signal to achieve the necessary accuracy, the trapped flux must be small compared to the London moment. In our case, we require that the trapped flux level be less than 0.9 ntesla (9 μgauss, uniform field equivalent). In order to meet this rather stringent requirement, the magnetic environment provided by the dewar at the SIA must be at this level or lower, and the SIA and probe must be made from materials that have suitably low magnetic remanence.

The Science Mission Dewar (SMD) provides the thermal environment, mechanical support, and magnetic shielding for the probe and SIA. The flight thermal environment is maintained by a reservoir of 2300 liters (95% fill) of superfluid helium at a temperature of 1.8 K. The probe resides in a central well inside the main tank. The well volume is distinct from the main tank and may either be filled with liquid helium (before and during probe integration) or be evacuated (after probe integration). The exterior of the dewar well is enclosed by a cylindrical high-permeability ferromagnetic shield. The interior of the well is lined with a lead-foil superconducting ultralow magnetic field shield ("lead bag"). This shield is installed by means of a lengthy iterative process [3] and must be continuously maintained below its superconducting transition temperature (T_c = 7.2 K) in order to preserve the ultralow field environment. The lead shield currently in the SMD was measured to have an internal field of <10 ptesla (0.1 μgauss) in the gyro region before the installation of any additional hardware.

The SMD has other noteworthy features of a cryogenic and mechanical nature. The helium in the main tank is vented through a porous plug superfluid-vapor phase separator. after which it flows through a series of heat exchangers (HEX0 at the top of the main tank and HEX1-4 along the outside of the dewar composite neck tube) and then out to the spacecraft thrusters (FIG 2). The main tank heat exchangers, HEX1-4, are linked to four vapor-cooled shields in the dewar vacuum space as well as to heat exchangers on the probe[4]. Multilayer insulation is used in the regions between vapor-cooled shields. Just above the main tank is a 100-liter toroidal guard tank, which is thermally and mechanically tied to dewar HEX1. When the guard tank is filled with normal-boiling-point (NBP) liquid helium, dewar HEX1, which otherwise runs at ~30 K (on the ground), is maintained at 6 K, thus substantially reducing the heat input to the main tank. The purpose of this is to avoid having to refill the subatmospheric main tank once it is filled, conditioned to 1.65 K, and ready for launch. The guard tank vents via a separate vent line that has inline copper honeycomb heat exchangers that are coupled to the main tank heat exchangers, HEX1-4. The entire internal structure of the dewar is supported by low thermal conductivity struts [5]. For flight, the exterior surface of the SMD will be covered with flexible optical solar reflector (FOSR) material that will allow it to passively cool to an average temperature of 227 K.

Of importance to the operation of the dewar is the internal plumbing (FIG 2). A common fill bayonet and fill line is used to allow the external filling of any of the three vessels in the dewar. In addition, it is possible to internally transfer liquid from the main tank to either the guard tank or the well. The latter capability is particularly important since there are times when the liquid in the well is exposed to a high heat rate (e.g., during lead bag installation and probe insertion), and it is important that the lead bag be kept immersed in liquid. These features, as well as the ability to bypass the porous plug for fill operations, are implemented through the use of cold remotely actuated valves (RAVs).

CRYOGENIC OPERATIONAL EXPERIENCE

Over the past four years that the SMD has been kept continuously cold, a large range of operations in various configurations and conditions have been performed. Operations include external liquid helium transfers from supply dewars, partial main tank depletions, guard tank depletions, internal liquid transfers from the main tank to the well and guard

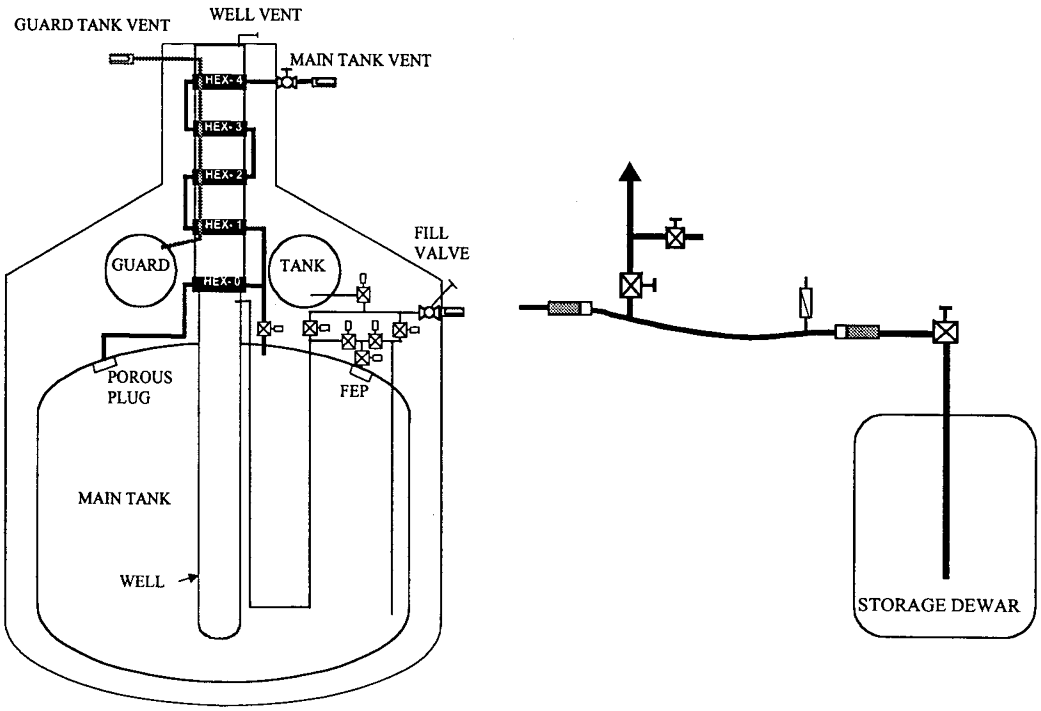

FIGURE 2. Schematic diagram of the SMD internal plumbing and external liquid helium transfer equipment. The 'FEP' is a fountain-effect pump that was included for a contingency that is no longer supported.

tank, lead bag installation, and probe insertion and removal. Configurations and conditions under which these operations were performed include well filled with liquid and well evacuated, probe installed and probe removed, guard tank full and guard tank dry, dewar vertical and dewar horizontal, and main tank at 4.2 K and at 1.8 K. During this wide range of operations and conditions, we have encountered a number of unanticipated situations that have caused us to make significant alterations to procedures and ground support equipment. These situations have been primarily due to two relatively unique aspects of the SMD: the presence of the guard tank and the presence of the lead bag, which we maintain below 6.5 K. We provide a few examples in the following paragraphs.

Guard Tank / Main Tank Interactions

The guard tank interacts more readily with the main tank than might be anticipated, and these interactions can have undesirable effects. In particular, there are three mechanisms that introduce coupling between the main tank and the guard tank:

Sharing of a common external vent In the initial configuration of the dewar ground support equipment (GSE), the main tank, guard tank and well were manifolded such that they vented through a common relief valve. The idea was that if the pressure in one vessel started to collapse, the other vessels would supply sufficient gas to maintain the pressure above atmospheric and prevent a possible introduction of air into the system. The problem with this approach is that it can be unstable to thermally driven gas flow oscillations between vessels. If, for some reason, there is a flow of gas from one vessel to another, the introduction of warm gas into the second vessel causes a heat input with an increase in pressure in the second vessel and a resulting counterflow. The first vessel then reacts in the same manner and an oscillation ensues. This mechanism is easily prevented by adding alternative vent paths for the guard tank and well with independent relief valves.

Coupling at HEX1 The temperatures of the heat exchangers in the dewar neck are strongly influenced by the vent rate from the main tank. Since the top of the guard tank is tied to HEX1, small changes in the HEX1 temperature can cause significant changes in the guard tank pressure. This is true even if the guard tank is partially filled with liquid. Under these conditions, a slight increase in the main tank vent rate can easily cause the guard tank pressure to collapse below atmospheric pressure. If there are any leaks in the guard tank vent manifold, air can be introduced into the guard tank vent. Because of the presence of the honeycomb heat exchangers mentioned earlier, even a small quantity of frozen air can block or severely restrict the guard tank vent. (The honeycomb apertures have an inscribed diameter of only 1.8 mm.) Recovery from a guard tank vent blockage is not easy because of the presence of the lead bag. In addition, it is not possible to snake a heater or source of purge gas down the guard tank vent to the blockage because of a complex geometry and the presence of the upper honeycomb heat exchangers.

We have, however, been able to clear the guard tank vent line on more than one occasion without warming up the dewar. This technique involved reintroduction of liquid into the well (to protect the lead bag), removal of the probe (to increase liquid reservoir in the well), and installation of a central vent tube in the well (to minimize heat exchange of the well vent gas with the dewar neck tube). Pressure from a source of warm helium gas was then applied to the guard tank through the fill line and maximum electrical power was applied to the guard tank heater. Gas flow rate, guard tank and HEX temperatures, and effluent gas composition were monitored to gauge progress. Once the blockage was cleared, the dewar temperature profile was normalized by performing an internal transfer of liquid from the main tank into the guard tank.

Avoiding a blockage of the guard tank vent line is obviously preferred over attempting to remove it. Leak checking of the GSE and connection to the SMD is an important first step. The first occurrence of air intrusion was found to be due to a leak together with a pressure collapse. However, no leaks were found after subsequent occurrences. As a second measure, we have taken procedural steps to make sure that the guard tank is maintained at a pressure above atmospheric regardless of whether there is liquid in it or not. When the guard tank is dry, for example, pressure is maintained by an external source of regulated helium gas. In cases where there are high extended vent flow rates from the main tank (such as when pumping on the main tank to reduce the temperature from 4.2 to 1.8 K), electrical power is applied to the guard tank heater to maintain positive pressure. In addition, the pressure is continuously monitored and an alarm is triggered if it drops to atmospheric. Since the introduction of these measures, there have been no additional occurrences of guard tank vent blockage.

Coupling through the SMD vacuum space The process of warming up the guard tank from 4 K to its normal operating temperature of ~30 K has been observed to trigger an unexpected chain of events. If the guard tank has been at liquid helium temperature for an extended period, its external surface and nearby surfaces can cryosorb a significant amount of gas. When the tank is warmed up, this gas is vaporized, causing degradation in the dewar insulating vacuum. This, in turn, can cause the vent rate of the main tank to increase and a subsequent recooling of the guard tank leading to a pressure collapse. Since this phenomenon has been observed, the procedure to empty the guard tank now calls for active pumping on the dewar vacuum.

External Transfer Initiation

The lead bag is most vulnerable when the well is evacuated because in that situation the temperature at its top is primarily controlled by the temperature of the He vapor in the main tank. Since much of the heat to the main tank comes from above, the main tank ullage tends to run a kelvin or so above the bath temperature. In addition, the ullage region has relatively low heat capacity and is sensitive to additional heat inputs. The presence of the lead bag requires special care in the initiation of external liquid helium fill operations. Even if the external transfer line is precooled, there is sufficient warm internal fill plumbing in the SMD (the fill bayonet, manual fill valve, tank fill filter) that the initial flow into the main tank rapidly heats the ullage temperature above 6.5 K. Fortunately, the external liquid helium transfer line has a vent valve located near the bayonet connection to the SMD. Thus, it is possible to close the guard tank vent, apply heater power, and precool the internal fill plumbing by forcing liquid helium outward from the SMD and through the transfer line vent. Once this has been accomplished, the manual fill valve, SV-13, can be closed and the valve from the external supply dewar can be opened to precool the external fill line. After the external line is precooled, the transfer line vent valve can be close, and SV-13 reopened to safely initiate the transfer. The main tank can also be used for precooling the internal fill plumbing when it is at atmospheric pressure. However, when the main tank is subatmospheric, as it will be prior to launch, this is not possible. This means that the liquid level in the guard tank cannot be allowed to go below the minimum necessary for the precooling operation (~15%) if any further guard tank fills are to be initiated.

PAYLOAD THERMAL PERFORMANCE

The primary figure of merit for thermal performance of a cryogenic payload is the length of time the science instrument is maintained at operating temperature on orbit. In our case, the mission lifetime requirement is 16.5 months. There are a number of factors that need to be verified in order to assure that the mission lifetime requirement can be met: initial cryogen fill level, cryogen temperature at launch, and average heat rate on orbit. During payload test, the first two factors can be verified directly. In the case of heat rate on orbit, the thermal environment in the laboratory does not adequately simulate orbital conditions. In this case, a numerical thermal model is validated by ground test and then used to predict on-orbit performance.

Initial Fill Level and Prelaunch Hold Time

In order to meet the lifetime requirement, the main tank must be ≤ 1.85 K and filled to ≥ 95% (2307 liters) at the time of launch, which may be up to 90 days after its final closure. We recently demonstrated the capability to reach 1.66 K at 95.5% full by alternately topping off the main tank with NBP helium and pumping on it. This took a total period of 18 days. We subsequently found that the heat rate to the main tank while the guard tank is at NBP (22 mW) is such that our hold-time requirement can be met if we achieve a temperature of 1.65 K at 95% full. We calculate that this can readily be met by additional pumping but without the necessity of additional fills.

It was originally required that the guard tank be able to hold NBP helium for at least 7 days for operational convenience. During payload testing, however, it was found that although it would hold for up to 8 days if the fill level were allowed to drop to zero, our requirement to have 20% in reserve for precooling reduced the useful hold time to 5 days. We have determined that this is still acceptable from an operational standpoint.

Lifetime Requirement

Although there is further thermal testing to be performed, the thermal model has been correlated with data taken while the main tank was at NBP, the guard tank dry, and the outer shell at room temperature. In general, both temperature and heat rate correlations are excellent. The largest temperature discrepancy was at probe HEX2 (67 K measured vs. 75 K predicted). The predicted boil-off rate was 12.3 mg/s while the measured rate was 12.5 mg/s. Projecting to on-orbit conditions (outer shell ~230 K, main tank at 1.8 K) the expected lifetime is 18.9 months with no contingency; with a 10% contingency placed on the heat rate estimation (appropriate for the current stage of maturity), the prediction is 17.1 months, which still exceeds the requirement of 16.5 months.

CONCLUSIONS

Through several years of experience with the GP-B dewar and payload, we have learned of a number of operational pitfalls and found procedural and hardware remedies to them. In spite of these challenges, however, results of ground tests indicate that the Gravity Probe B payload cryogenic system is performing as designed.

ACKNOWLEDGEMENTS

This work is supported by NASA contract NAS8-39225.

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