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PERFORMANCE OF THE RELATIVITY MISSION SUPERFLUID HELIUM FLIGHT DEWAR

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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 performed include (1) weight, (2) proof pressure and leak checks, (3) vacuum bakeout, (4) main tank fill with He I, (5) parasitic heat rate tests, (6) well fill with He I from both the main tank and an external supply dewar, (7) well depletion, (8) conditioning the main tank to He II, (9) porous plug tests, (10) heat pulse meter tests, (11) transferring He II from the main tank to the well with a fountain-effect pump, (12) guard tank fill with He I with a nonvented He II main tank simulating launch pad hold, and (13) guard tank emptying.

The measured performance is compared to the previously launched IRAS, COBE, and ISO cryostats. The Relativity Mission spacecraft will be launched in the time span 1999 to 2000.

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 arcsec/year) through the curved space-time surrounding the Earth and the motional effect (0.042 arcsec/year) 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 $<10^{-11}$ 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 acceptance test results of the flight dewar, which provides the <2 K bath temperature required for proper operation of the Science Instrument Assembly (SIA). The SIA consists of four gyroscopes, drag-free proof mass, superconducting quantum interference device (SQUID) readouts for measuring 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 (Figure 1); the sealed probe in turn fits inside the well of the dewar (Figure 2).

DEWAR FUNCTIONS

The flight dewar (1) maintains the SIA at <2.8 K for more than 16.5 months, (2) provides a magnetic field for the SIA of $<10^{-7}$ gauss using an expanded superconducting lead bag, (3) provides aluminum proton shielding for the SIA, (4) provides vent gas to 16 thrusters for spacecraft control, (5) provides two stable star tracker platform mounts off of graphite epoxy rings, (6) is capable of being operated in the vertical or horizontal attitude during ground tests, (7) has sufficient hold time for ground operations without losing any helium from the main tank, (8) dampens helium slosh motions, (9) measures the vent rate and amount of helium left in the main tank at any given time in orbit, (10) has multiple temperature sensors, heaters, liquid-level sensors, and accelerometers, and (11) can transfer He I or II from the main tank to the dewar well (see Figure 3).

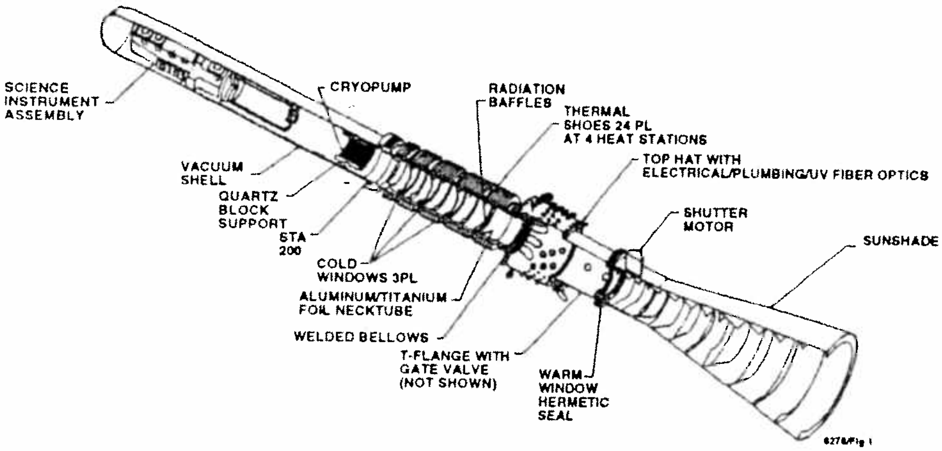

Fig. 1. The probe houses the science instrument assembly and provides all its service cables and lines.

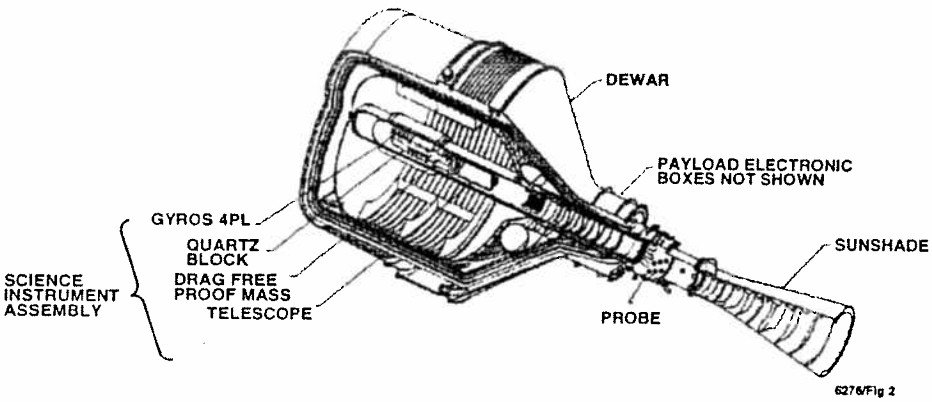

Fig. 2. The probe is inserted into a cold dewar through a helium-purged air lock.

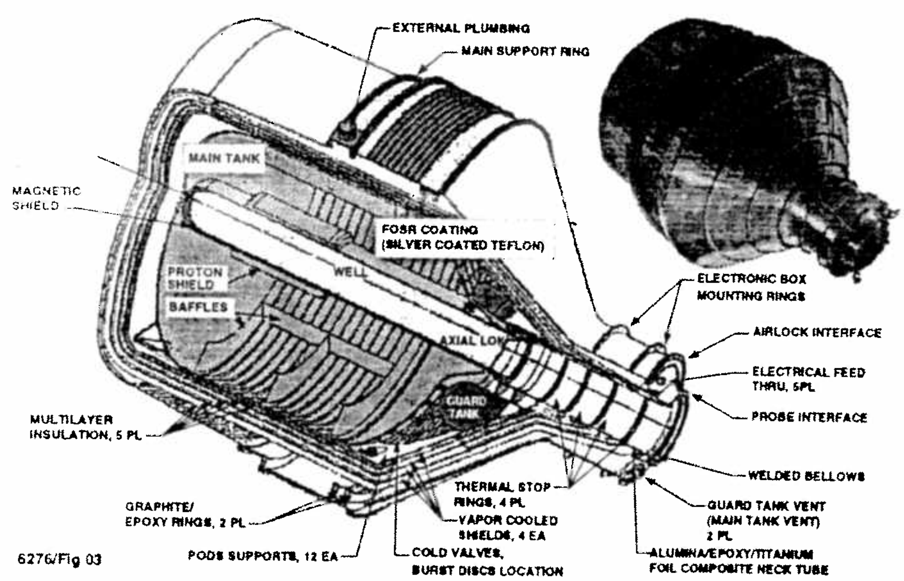

Fig. 3. Cutaway of dewar.

DEWAR DESCRIPTION

The dewar shown in Figure 3 is 3.0 m high, 2.2 m in diameter, and weighs 810 kg dry. The main tank contains 2328 liters of He II at 1.8 K, weighing 338 kg with a vapor ullage of 5%. The guard tank used to simplify ground servicing contains a maximum of 99 liters of He I at 4.2 K, which is reduced to 30 liters prior to launch by boiling off the liquid, using heaters.

The guard tank allows the He II main tank to be kept nonvented for months, while the guard tank only has to be filled once a week. Consequently, all of the helium from the main tank is available for use on orbit, as opposed to a system that pumps on the subatmospheric main tank right up until shortly before launch. The 30 liters left in the guard tank allows for two launch aborts plus launch separated by 24-hour intervals with no dewar servicing required.

The main tank is supported by 12 passive orbital disconnect strut (PODS-V) high-efficiency supports off the vacuum shell, while the guard tank is supported off the composite necktube. The γ alumina necktube with a 0.03-mm $TiV_{15}Cr_3Al_3Sn_3$ foil liner provides a low-heat-leak, vacuum-tight cylinder connecting the main tank to the vacuum shell. This cylinder allows the well to be filled with He I during lead bag expansions and probe insertion.

Four perforated 1100 aluminum face sheets with 5052 aluminum-honeycomb-core vapor-cooled shields plus double aluminized Mylar/silk net spacers provide thermal protection inside the evacuated vacuum shell.

A second surface mirror (FOSR) is installed on the vacuum shell to lower its temperature in orbit. FOSR consists of a 0.25-mm Teflon film silverized on the back side. The silver provides low solar absorptance while the Teflon provides the high infrared emittance.

The plumbing schematic is shown in Figure 4. The plumbing layout (1) allows the main tank and guard tank to be filled through the same bayonet and also to be pressure drained if required—the tanks are vented through separate lines, (2) allows the main tank to be nonvented while the vented guard tank is topped off once a week, (3) has a bypass line that allows the transfer line to be cooled down prior to main tank servicing, (4) allows the well to be filled with He I from the main tank using heaters or from an external supply dewar, (5) allows filling the well with 12-torr gas or He II, if required, using a fountain-effect pump, (6) vents the tanks and lines to space, and (7) provides overpressure protection for all trapped volumes (remotely actuated cold valve RAV6B is closed only on orbit, and the probe has a burst disc for well relief).

A thermal analysis using a vacuum shell temperature of 225 K shows that the major heat loads are from the probe (40%), multilayer insulation (22%), dewar composite necktube (11%), and dewar wires (11%), mainly due to the seven RAV cold valves.

ACCEPTANCE TEST RESULTS

Dewar Mass

The measured mass of the flight dewar is 810 kg. This mass compares to a calculated value of 807.6 kg just prior to the measurement. The masses of all components were closely tracked throughout the conceptual and detailed design processes. Several significant program decisions can be directly correlated to the resultant low

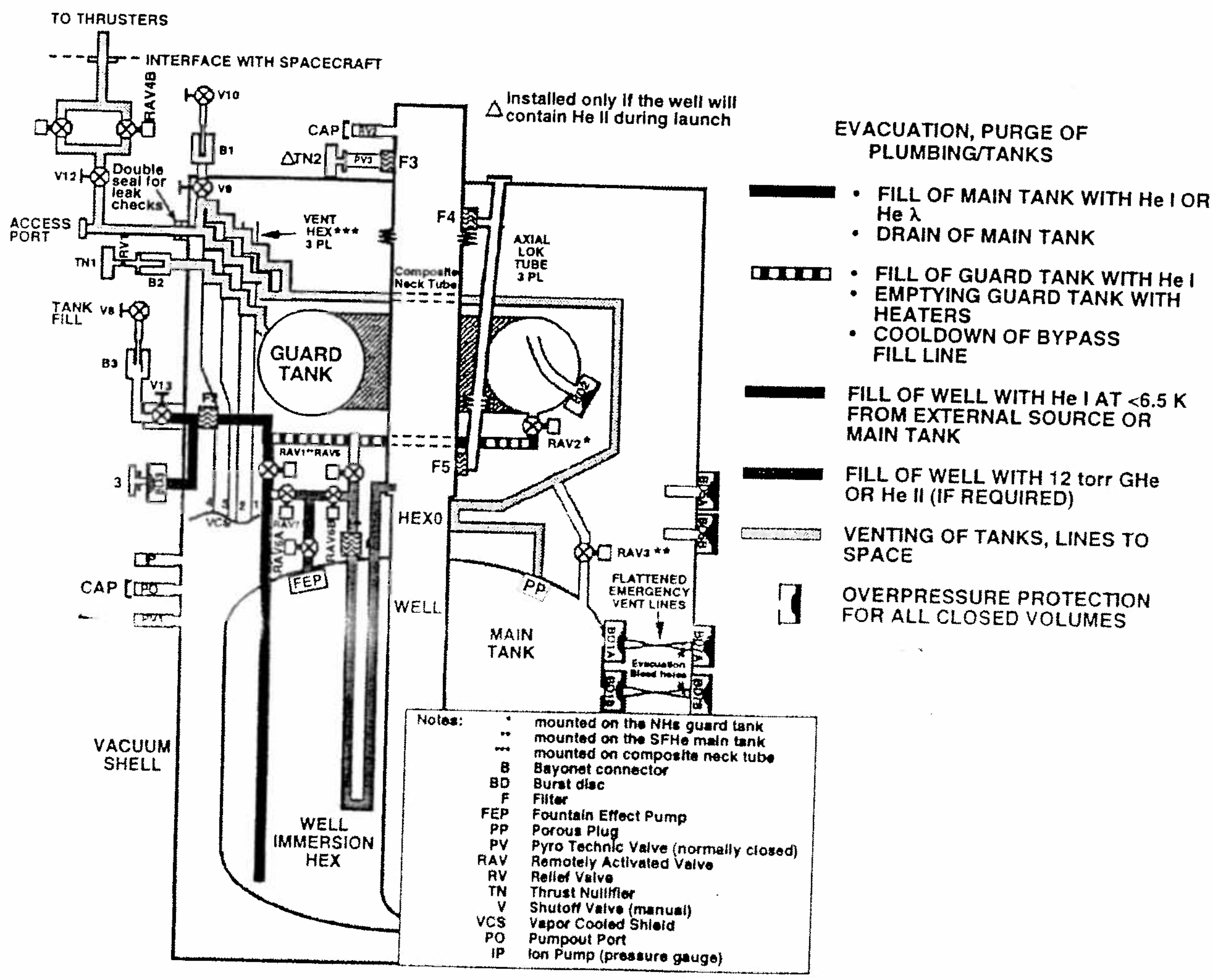

Fig. 4. Plumbing schematic.

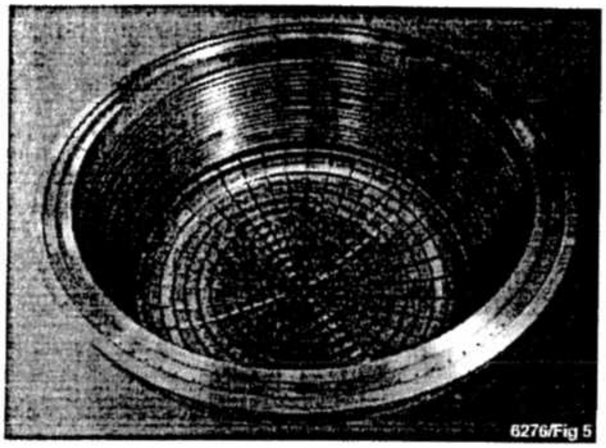

Fig. 5. Light-weighted aft vacuum shell.

mass of the dewar, the principal contributors being light-weighted main tank and vacuum shell components and honeycomb vapor cooled shields. Although selecting waffled domes and ring-stiffened cylindrical sections (Figure 5) and large curved honeycomb panels added 10% to dewar costs, these three areas significantly contributed to the lightweight dewar that has been produced. Table 1 illustrates the savings achieved in key areas.

Also of interest is that, since the weight savings are so significant, a more expensive and riskier option, using aluminum-lithium for the main tank and vacuum shell components, was deemed unnecessary.

Proof Pressure and Leak Checks

All tanks, lines, and the vacuum shell were proof pressure tested and leak checked as shown in Table 2.

All cold joints (welds, epoxy bonds, Helicoflex seals) were leak tested warm, cycled three times to 77 K and releak tested warm as the dewar was assembled. Following dewar assembly, the tanks and plumbing were leak checked as a system warm and at 4.2 K. No leaks were found.

Vacuum Bakeout

The dewar was rotated upside down and placed inside a customized, insulated forced air oven (Figure 6). The upside down orientation allowed any minute creep of the aft PODS gaps to be in a favorable direction. The dewar vacuum space was pumped down at a controlled rate to 1 torr in 29 hours while the oven was brought up to 317 K and held for 11 days. The temperature was increased to 322 K and held for an additional 6 days, based on the results of creep tests of heated PODS-V supports conducted in parallel. At the end of the bakeout period, the vacuum pressure read 5 x 10^{-4} torr at 322 K and 5 x 10^{-5} torr when cooled down to 294 K. Water vapor was the predominant gas left.

Helium I Tests

GSE modules (Figure 7) are connected to the well and vent line with plumbing lines at B1, plus electrical connections are made to the dewar, to accomplish the following tasks.

Main Tank Fill with Liquid He I. The main tank, guard tank and plumbing lines are evacuated and backfilled with GHe to 775 torr three times. The well, with radiation baffles installed, is evacuated. Supply dewars are connected to the fill-line bayonet B3. First the dewar bypass line is cooled through V13 and RAV2

Table 1. Weight Savings

Assembly	Flight Weight (kg)	Savings (kg)	Comment
Main Tank (including a 51-kg proton shield)	262	80	Waffle domes, ring-stiffened cylinder, 2219 aluminum
Guard Tank	15	4	Lightening holes in support cone
Vapor Cooled Shields	72	44	Perforated aluminum honeycomb shields
Vacuum Shell	345	100	Ring stiffened & waffle construction, 2219 aluminum

Table 2. Proof Pressure and Leak Checks

Component	Proof Pressure, MPa		Leak Rate, cc/s STP He
	Internal	External	
Main Tank	0.39	0.25	$< 10^{-9}$
Well	0.20	0.39	$< 10^{-9}$
Guard Tank	0.56	0.25	$< 10^{-9}$
Plumbing	0.56	0.25	$< 10^{-9}$
Vacuum Shell	0.25	0.10	1×10^{-7}*

* Air equivalent leak rate is 6×10^{-8} cc/s. Would deposit 10 Å ice coating on main tank if cold 4 years; no impact on lifetime.

with cold gas. RAV1 and RAV3 are opened and RAV2 is closed to redirect the cold gas to the main tank; the cooldown rate did not exceed 50 K/hour. Once the tank temperature is below 5 K, the delta supply pressure is increased to 0.03 MPa to start liquid transfer. After 6 hours, the main tank was 25% full. In later test sequences, the main tank was filled to 97%. The vacuum pressure dropped into the low 10^{-6} torr range with the main tank at 4.2 K.

Well Fill with Liquid He I. Expansion of lead bags in the well to achieve 10^{-7} gauss magnetic field at the SIA plus insertion or removal of the probe requires the well to be filled with 100 liters of He I.

The simplest method is to transfer helium internally from the main tank to the well. To achieve this transfer, the main tank vent is closed, valve RAV7 is opened (valve RAV6B is always open on the ground) and a 50 watt heater is turned on to pressurize the tank to 785 torr. When the well is vented, liquid transfer occurs. Liquid level sensors in the top of the well determine when the well is filled. The transfer rate attained was 0.3 liters/min.

Liquid helium was also transferred to the well from an external supply dewar through V13 and RAV5. Transfer rate was 3 liters/min.

Removal of liquid helium from the well after probe insertion is accomplished by pumping on the well with a Rootes blower/roughing pump system. This operation was demonstrated without the probe installed.

Parasitic Heat Rate Test. The parasitic heat rate test is used to establish a baseline performance datum and to validate the thermal mathematical model for the dewar. It is performed with a set of radiation baffles

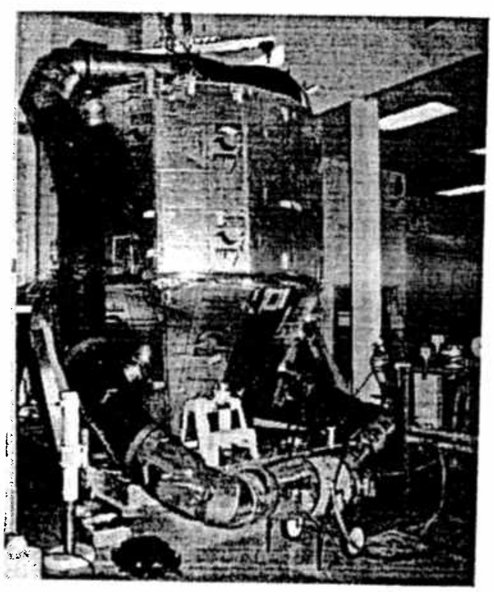

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Fig. 6. Dewar bakeout enclosure with hot-air circulation system attached.

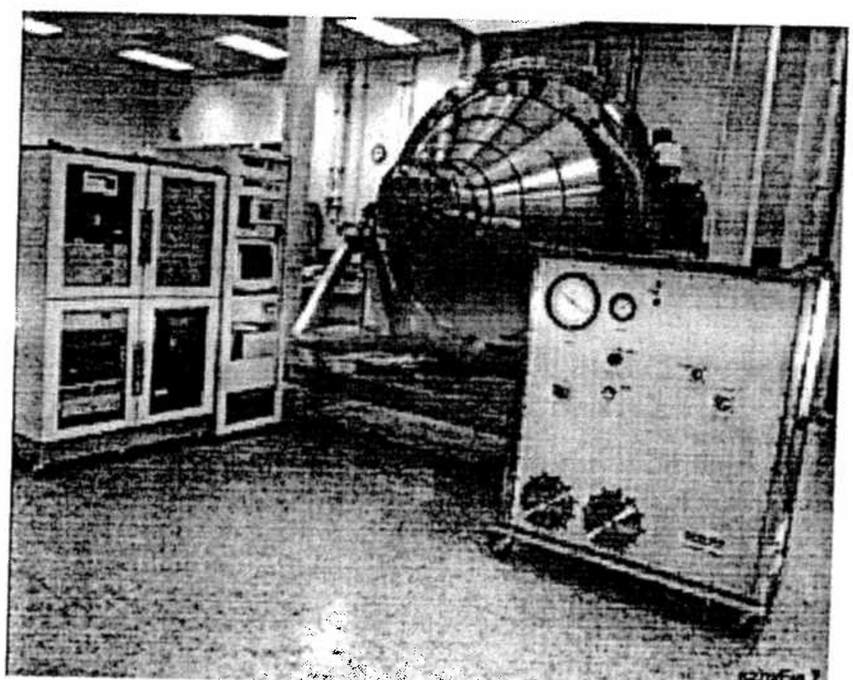

Fig. 7. Dewar with gas module, electrical module, and data acquisition system module.

installed in the dewar neck tube in place of the probe, which effectively reduces the radiation load to on the order of 11 mW. This resultant value, when combined with the dewar/probe thermal model, gives an updated lifetime prediction.

This test was performed with the main tank filled to 24% with normal boiling point liquid helium and the well and guard tanks evacuated.

The parasitic heat rate was measured after two weeks with a wet test meter (1% accuracy). The tank temperature remained stable to 4.280 ± 0.0005 K over a 20 hour period with a tank pressure of 776 torr. The remaining temperatures were 30, 55, 98, 170, and 294 K for the four vapor-cooled shields plus vacuum shell respectively. The vent rate was 0.040 ± 0.0016 l/s (6.6 mg/s) which translates into a heat rate of 136 mW. This measured value fell within the 30% margin added on to the calculated heat rate for the dewar test configuration, even if zero radiation was assumed to be coming down the dewar neck. Additional parasitic heat rate tests in 1997 with probe B installed will give a more accurate assessment of the payload lifetime and hopefully will allow the 30% margin to be reduced in the thermal model. The dewar with the probe meets the orbital lifetime requirements of >16.5 months.

Helium II Tests

Conditioning the Main Tank. Following the He I tests, the main tank was conditioned to He II by pumping on bayonet B1 with RAV3 open. The tank started at ~85% full at 4.28 K and was pumped down to 1.58 K and 51% volume in 6 days using a Rootes blower/roughing pump system. The purpose of the test is to demonstrate that the bath temperature could be reduced to 1.6 K. The multiple topoffs required with λ-point liquid from supply dewars, to bring the fill level back to 95 to 98%, will be demonstrated later, prior to the cold vibration test with probe B installed.

Porous Plug Tests. Operation of this porous plug is unique in that it is used to control the SFHe temperature, operate over a wide range of flowrate, and provide gas for spacecraft attitude control. Several sintered stainless plugs were evaluated to select the one used in the dewar (Frank, Yuan 1996). Data were taken during normal and choked flow conditions. The primary requirements that affected the design of the porous plug were to operate over a range of 4-16 mg/s without choking at 1.8 K, and operate with a sufficient back pressure so that the vented gas can be used for the spacecraft attitude control system. The predicted nominal flowrate during the science phase of the mission is 6.8 mg/s. The higher flowrates are required during the early phase or orbit trim.

These requirements make the porous plug unique in that the downstream flow conductance of the plumbing is not constant as on other spaceborne dewars. A heater in the tank and variable flow conductance valves in the 16 thrusters provides the temperature control and flowrates required for attitude control. Increases in venting are achieved by decreasing the downstream pressure of the porous plug and maintaining the bath temperature by turning on a heater.

The plug uses 316L sintered stainless steel porous media purchased from Mott Metallurgical Corp. The material had a permeability of 3.8 x 10^{-10} cm^2, a bubble point of 19.3 cm Hg, a thickness of 0.635 cm, and a diameter of 6.9 cm.

As the flowrate is increased by decreasing the back pressure, the temperature gradient increases until the plug achieves a choked condition. The flowrate at this point is referred to as the critical flowrate. As the flowrate is increased and subsequently decreased, the temperature gradient goes through a hysteresis loop. Figure 8 shows typical temperature gradient and back pressure profiles for various bath temperatures. The back pressure is measured in the ground support equipment of the dewar. As expected, the slope of flowrate versus temperature drops in the normal (linear) mode and the critical flowrate increases with bath temperature. Tests at various inlet hydrostatic heads were performed and the results were extrapolated to zero head

8.46t @1.7K
17.24t @1.9K

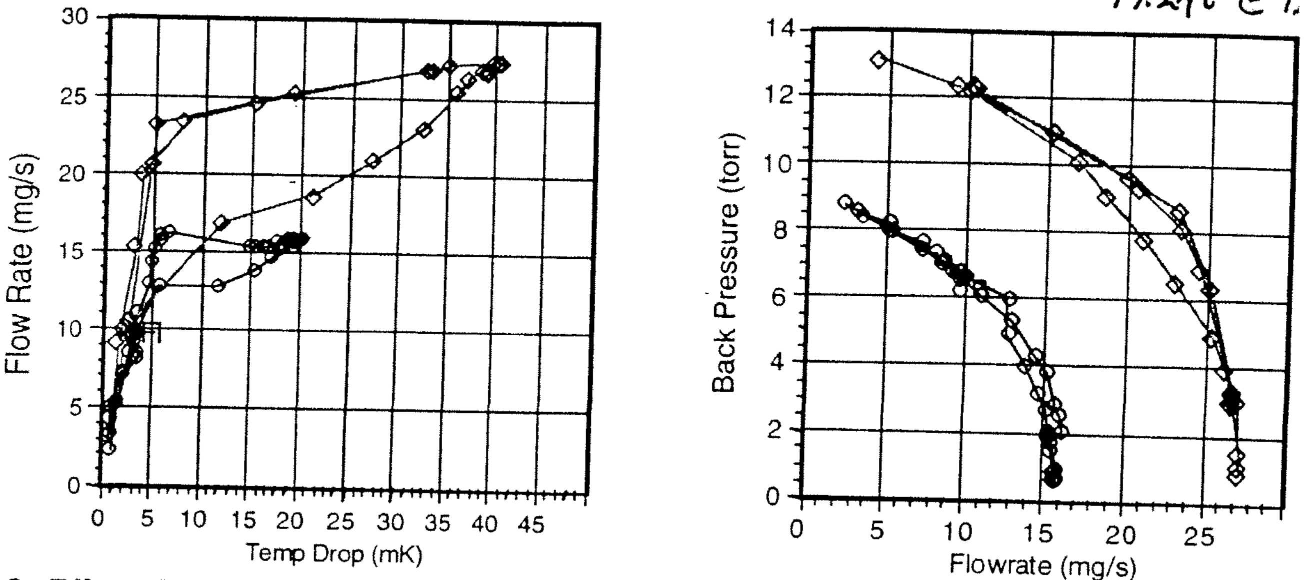

Fig. 8. Effect of bath temperature on temperature drop and back pressure (O = 1.7 K, ◇ = 1.9 K).

to determine the critical flowrate on orbit. Figure 9 shows that the plug meets the required flight maximum of 16 mg/s when operating at 1.8 K.

Heat Pulse Meter Test. The heat pulse meter is a method of determining the quantity of liquid in a tank by observing the temperature rise of the bulk liquid following a short pulse of heater power.

For this test, the dewar was vertical and the porous plug was not operating; the main tank pressure was controlled by pumping via V9 through the vent line. The temperature of liquid in the main tank was decreasing at 1 mK/hour. The temperature of the liquid helium is monitored before and after a 12.8 watt heater input over a 7-minute on time. The temperature offset caused by the energy input is thus determined and can be used to calculate the amount of liquid helium. With an energy input of 5800 joules and an observed temperature rise of 16.1 mK, the calculated mass is 171 kg. The reference mass was 167 kg, based on liquid level sensors. The accuracy of the calculated mass by the heat pulse method is affected by the measurements of heater power, time, and temperatures plus the stratification of the vapor in 1 g. The accuracy of the liquid-level sensor measurement is affected by the calculated volume versus measured liquid level in the main tank, the liquid volume to mass conversion based on temperature/density data, plus the accuracy of the liquid-level sensor itself.

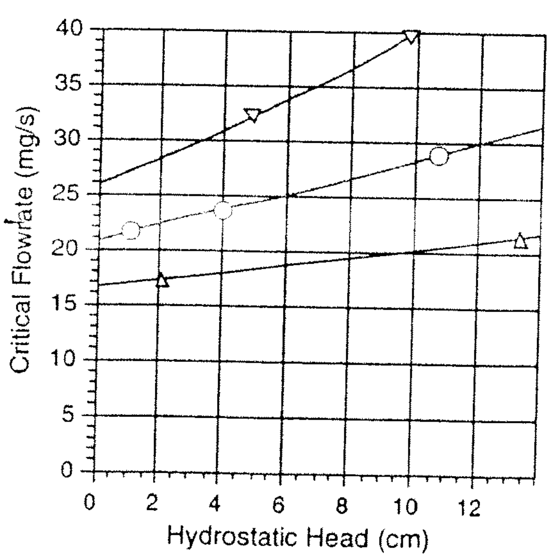

Fig. 9. Effect of hydrostatic head on critical flowrate(Δ = 1.7 K, O = 1.8 K, ∇ = 1.9K).

For flight operations, 33 watts of power will be used. For a full tank, the pulse duration will be approximately 2.5 minutes. The control system heaters will be off when pre and post data are taken to determine the natural drift of the fluid temperature.

Fountain Effect Pump (FEP) Test. The fountain effect pump (FEP) is designed to fill the well with He II from the main tank just prior to launch. This procedure is not a baseline but will be used only if the qualification vibration of dewar and probe show that the lead bag transition temperature has been exceeded with the well evacuated.

The test entailed the operation of the FEP and demonstration of a nominal transfer rate of 15 liters in 3 hours. The

Table 3. Thermal Performance Comparison of He II Flight Cryostats with Science Instruments Turned Off (T_H = 294 K)

Flight Payload	Tank Vol, Liters	% Boiloff / Day	Normalized Boiloff Rate
COBE	660	1.25 0.68[3]	4.6 2.5
ISO[1]	2300	0.83	3.1
IRAS	550	0.67	2.5
GP-B[1,2]	2441	0.27	1.0

1. Guard tank not used
2. Dewar boiloff measured. Probe/SIA heat leak calculated. 30% margin
3. Aperture cover actively cooled to 5 K with separate He I flow

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).

Table 4. Cryostats Ground Hold Performance at the Launch Pad

Cryostat	Helium Loaded (kg)	Percentage Ullage	Guard Tank		Initial Orbital Vent Rate (Compared to orbit equilibrium value)	Main Tank Nonvented Time (days)
			Used?	Fill Cycle, Days		
IRAS	72	7	No	—	Above	1.1
COBE	89	7	No	—	Above	1.1
ISO	331	1	Yes[1]	4	Above	Up to 4.2
GP-B[2]	338	5 Max. to 2 Min.	Yes[3]	7	Below	Up to 90

1. Mounted on main tank. Guard tank vapor cools inner vapor cooled shield to -30 K
2. Based on dewar acceptance test data. Includes calculated probe heat leak with 30% margin
3. Guard tank, inner vapor cooled shield run at 4.2-5 K

ACKNOWLEDGMENTS

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