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Flight Performance of Gravity Probe B Cryogenic System

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Abstract

Gravity Probe B (GP-B), a cryogenic- and space-based test of Einstein's General Theory of Relativity by means of precision gyroscopes, was launched into a polar orbit from Vandenberg AFB on April 20, 2004. The launch and operation of GP-B represented the culmination of forty years of planning, technology development, hardware fabrication, and testing. Here, with the superfluid liquid helium now nearly depleted and the mission close to the end , we present a summary report on flight performance of the cryogenic subsystem. We start with a brief description of the cryogenic subsystem and its preparation for flight, proceed to a summary of key cryogenic measurements and operations performed during the mission, and finish with a summary of flight performance and a comparison to model predictions.

Introduction

Gravity Probe B (GP-B), a cryogenic- and space-based test of Einstein's General Theory of Relativity[1] by means of precision gyroscopes, was launched into a polar orbit from Vandenberg AFB on April 20, 2004. The flight dewar contained 2320 liters of 1.8 K super fluid helium at launch and houses precision gyroscopes which allow the science measurements to be made. Helium vent gas from the dewar is used to operate 16 thrusters which perform precision pointing on a fixed star and adjust the orbit to be drag free or true zero-g, on the order of 2 mNewton in any of the three body centered axes. The mission is now coming to an end with the depletion of the helium forecast to occur in the first part of September, 2005

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Dewar Description

The GP-B payload is shown in Figure 1[2]. The Science Instrument Assembly (SIA) which contains the 4 gyros, their SQUID read outs and the telescope optics and focal plane sits inside and is supported from the Probe. The Probe consists of a top hat section which interfaces with the dewar vacuum flange, a composite neck tube and a aluminum tubular vacuum shell which encloses the SIA. The sunshade mounts to the probe top hat and allows acquisition of a guide start for all seasons. The SIA Electronic boxes are mounted to the small diameter cylinder of the forward portion of the dewar vacuum shell and connect to the SIA via vacuum feed-through connectors mounted in the top hat. The plumbing to provide liquid helium to the main tank, guard tank and Well uses seven cold remotely actuated valves. Several of the valves allow for inter tank transfers and one valve is a bypass of the porous plug to allow low impedance venting of the main tank.

The dewar (2 meter diam. x 3 m length) without sunshade and probe is shown in cross section in Fig. 2. Two helium tanks are located inside the dewar vacuum shell: the guard tank (100 liter) used for ground servicing and long prelaunch hold capability (measured at 108 days) and the main tank (2400 liter). The main tank is supported by twelve

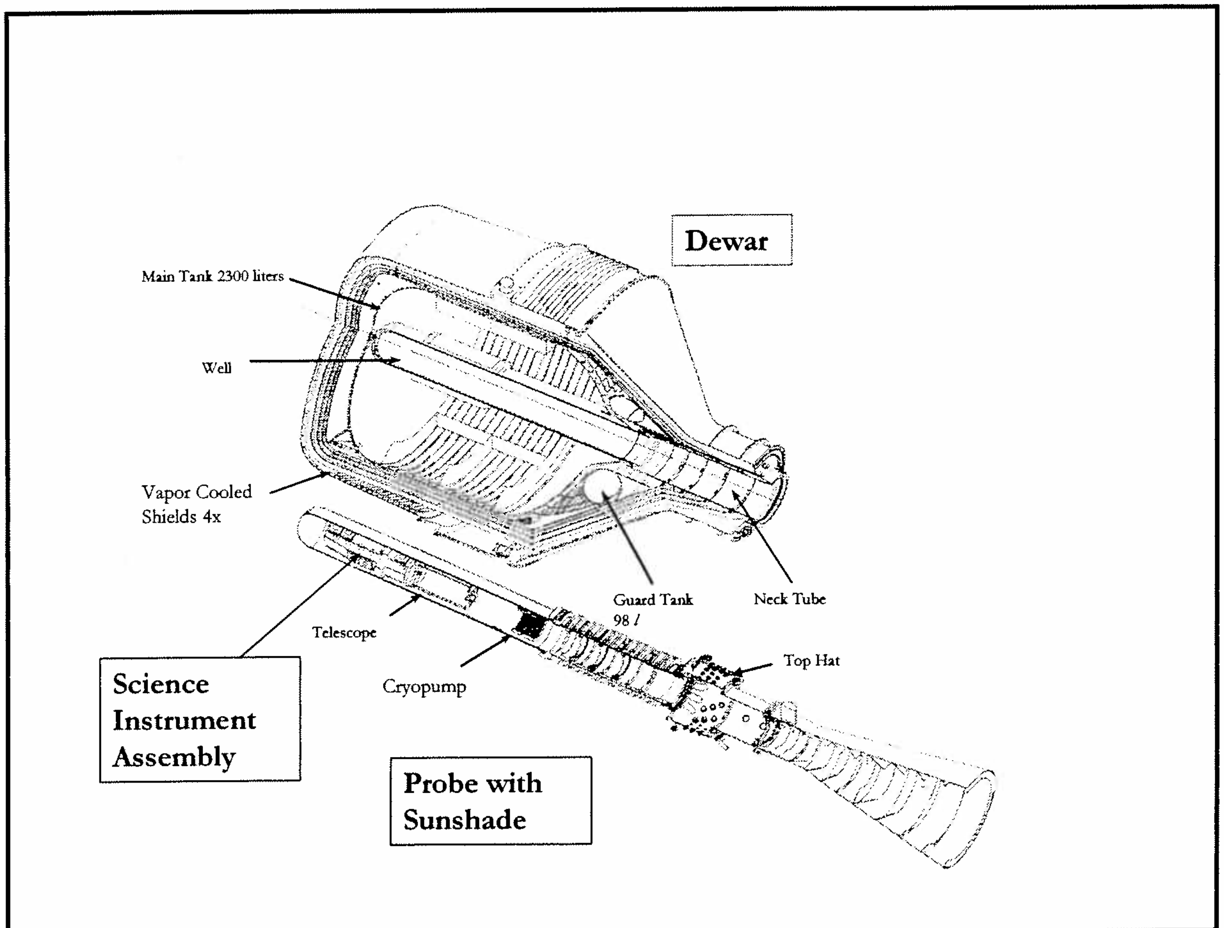

Figure 1. Payload components include the SIA (Science Instrument Assembly), the Probe with sunshade and the Dewar.

Passive Orbital Disconnect Supports (PODS) are designed to release in the low-G environment after launch and provide a low heat leak orbital support. The six forward PODS are installed in a plane and azimuthally stabilize the alignment of the SIA and reduce thermal expansion effects of the vacuum shell. Support of the main tank for ground test and launch loads is provided by the 6 aft PODS. A high compliance bellows connects the composite neck tube to the vacuum shell.

Four vent cooled heat exchangers are located on the neck tube and supply cooling to the four thermal shields. The latter are thermally protected by five Multilayer Insulation (MLI) blankets. Hinged flexures mounted on the probe make contact after probe installation (performed cold) with similar heat stations on the dewar. These provide vent cooling for the two neck tubes, the dewar MLI shields and the optical filters mounted in the probe neck tube. The neck tube inner surface is lined with a 1-mil titanium foil which serves to reduce the helium permeation into the vacuum space. A thin 63 µm (2.5-mil) layer of super conducting lead lines the inside the Well and was processed to provide the low 0.9 nT (9 µG) magnetic field required by the SIA. This shield after processing to the was kept below its 7.2 K superconducting transition temperature until the mission was completed, in this case about 9 years.[2]

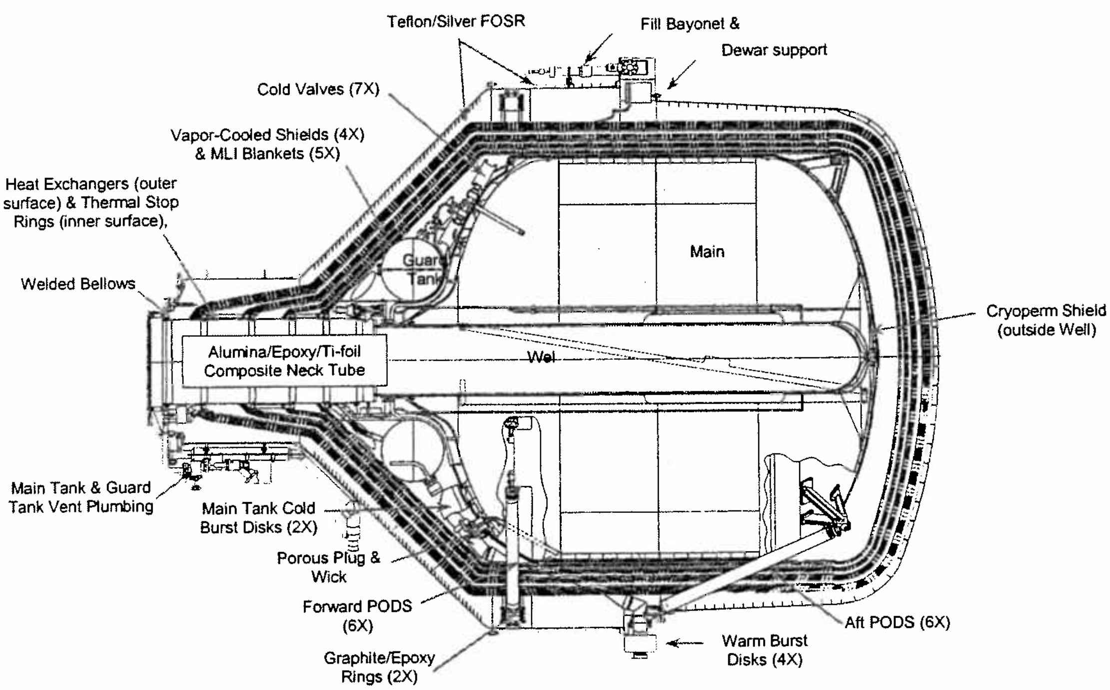

Figure2. Principal Dewar components and arrangement

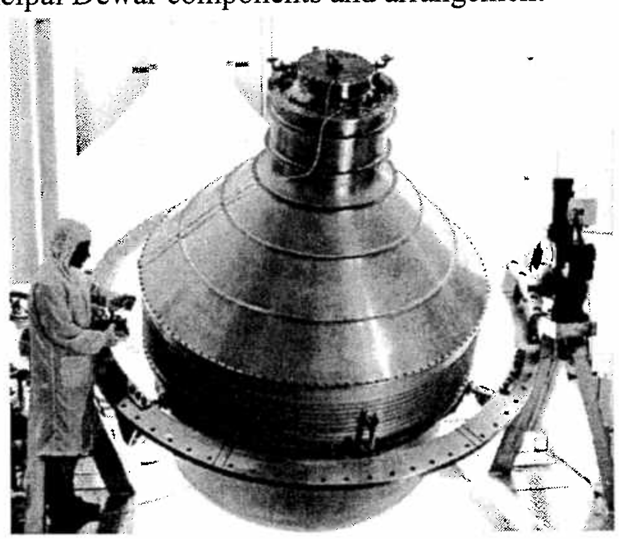

Figure 3. Dewar final assembly is completed and ready for acceptance testing

The dewar was integrated with the spacecraft and underwent acoustic vibration and thermal vacuum testing.

Pre-launch Operations
At VAFB (Vandenberg Air Force Base) with the dewar oriented vertical the main tank was filled to a 95% level over 16 days by periodically filling with normal liquid helium while continuously and pumping through valving which bypassed the porous plug. Topping off the guard tank was performed several hours prior to launch and was at an ideal 50% full at launch. The launch occurred 56 days after the final conditioning main tank final conditioning main tank during which time the temperature rose from 1.65 K to ~ 1.81 K.

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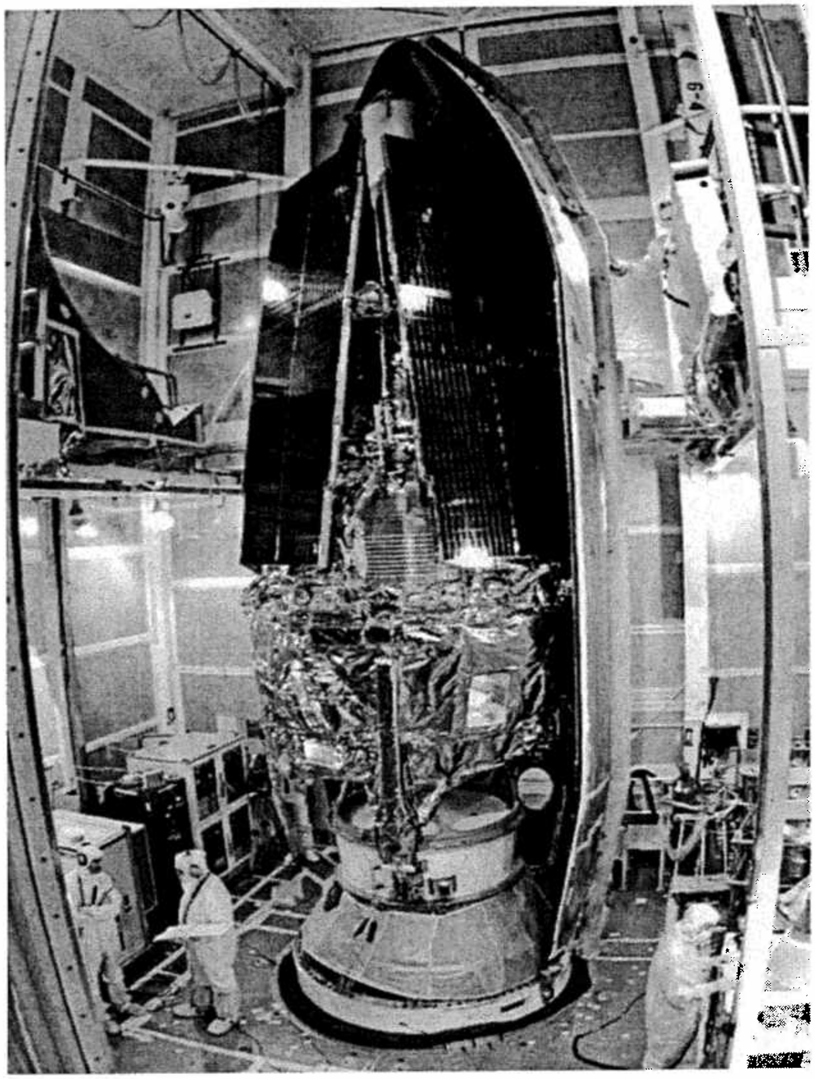

4. Figure 4. preparations for Delta 2 launch showing space vehicle with four double sided solar panels mounted. Dewar Ground Support Equipment (GSE) is in the lower left.

1.9 K was the maximum launch temperature. The Space Vehicle was launched on May 20, 2004. The pre-launch and initial post-launch temperature profiles are shown in Figure 5 (all times are in GMT). The first segment of data is prelaunch and the second segment orbital data. The pre-launch warming trend of the main tank is evident in both data taken prior to launch. The guard tank was launched with ambient venting and continued to vent to lower pressures through a flow control orifice throughout the launch and orbit. The main tank vent valve was opened by the thruster system when the ambient pressure was below the tank pressure (~12 torr) and the booster was accelerating. The small oscillations (~ 1 mK) of the main tank temperature with ~ 50 minute period in prelaunch configuration are of undetermined origin.

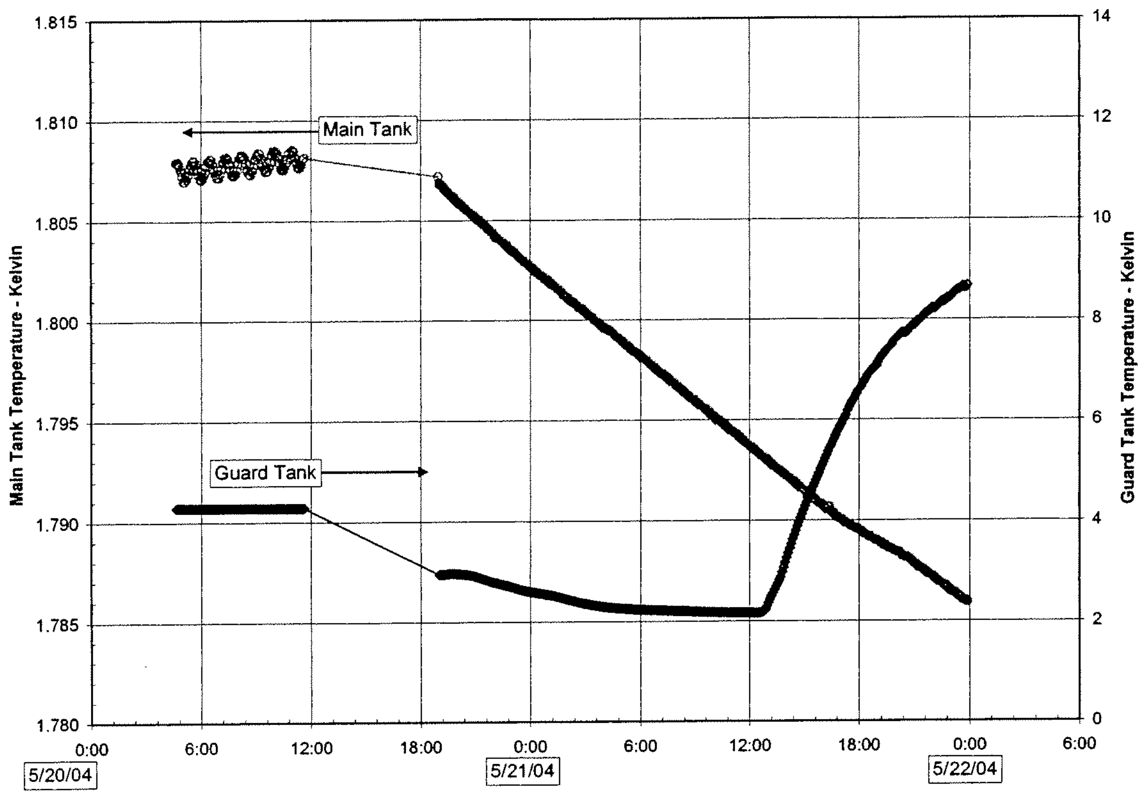

Figure 5. Cryogen Temperatures Pre- and Post-Launch

SIA Flux Reduction

It is the function of the SQUID based read-out to accurately determine the gyro rotation axis by processing signals from three pickup coils and thus determine the direction of the London (ref) moment generated in the rotor. The presence of extraneous signals such as those arising from trapped flux in the rotors must be reduced to very low levels. Although the rotors are de-fluxed prior to launch it was shown in flight verification testing that a disturbance such as that of an acoustic test environment resulted in adding trapped flux to the rotors. Reducing the trapped flux in the niobium thin films on the rotor and the local shield enclosing each gyro requires raising the Quartz Block temperature to above the nominal 9 K superconducting transition and then slowly cooling back through that temperature. To establish good thermal contact the conditioning is performed with a predetermined steady flow of helium gas, raising the probe pressure to ~5×10^{-5} torr.

A temperature plot of several of the probe components for the on-orbit flux flushing are show in Fig. 6. The heat sink for the Quartz Block Support (QBS) is at Station 200. The QBS closed loop heater controls the temperature of the QBS with the Quartz Block (QB) following at somewhat lower temperatures due to the coupling to the wall of the Well at LHe temperature. The procedure raises the QBS to 13 K where it is allowed to soak so that all QB components are at equilibrium values, it is then lowered to 10.5 K and soaked to bring the QB to just above the transition temperature. And finally the QB is slowly brought through the transition temperatures by controlling the QBS to cool at a rate of 0.5 K/hr. The resulting de-fluxing was successful yielding a maximum rotor trapped flux below 0.4 nT (4 uGauss).

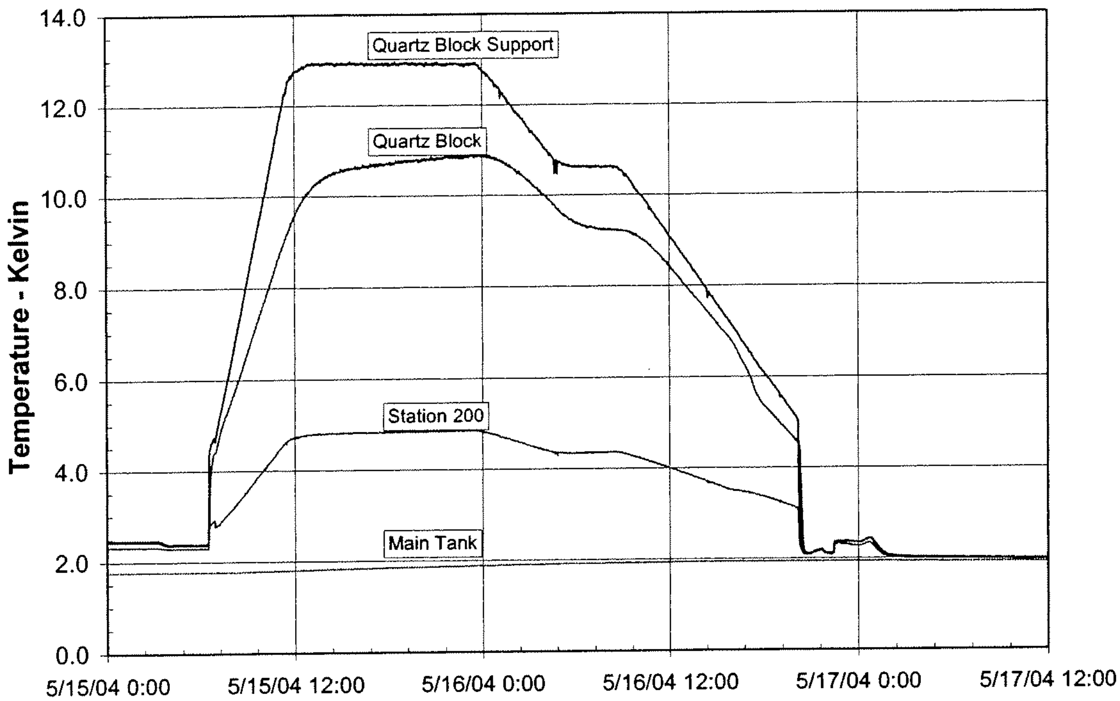

Figure 6. Removing trapped flux is performed by heating and slowly cooling the SIA

The main tank vents through a porous plug[3] that was designed to provide flow rates of 4 to 16 mg/s flows over temperatures of 1.6 to 2.0 K without choking or breaking through.[3] The hardware performed well in component testing as well as in the flight dewar during acceptance testing. For the mission this porous plug performed excellently with an average temperature differential of 4 mK.

No cases of break through and only one case of choking occurred. The latter happened when the space vehicle attitude and control system usage went up to approximately 15 mg/s. The temperature behavior during this excursion is shown in Fig. 7. The incident occurred as a result of a thruster failure shortly after the main tank had started to recover from the heat input of the flux flushing described above. The porous plug downstream abruptly dropped by ~36 mK giving a temperature drop of 40 mK. The abnormally high flow rate was corrected in about 12 hours and the porous plug returned to normal operation.

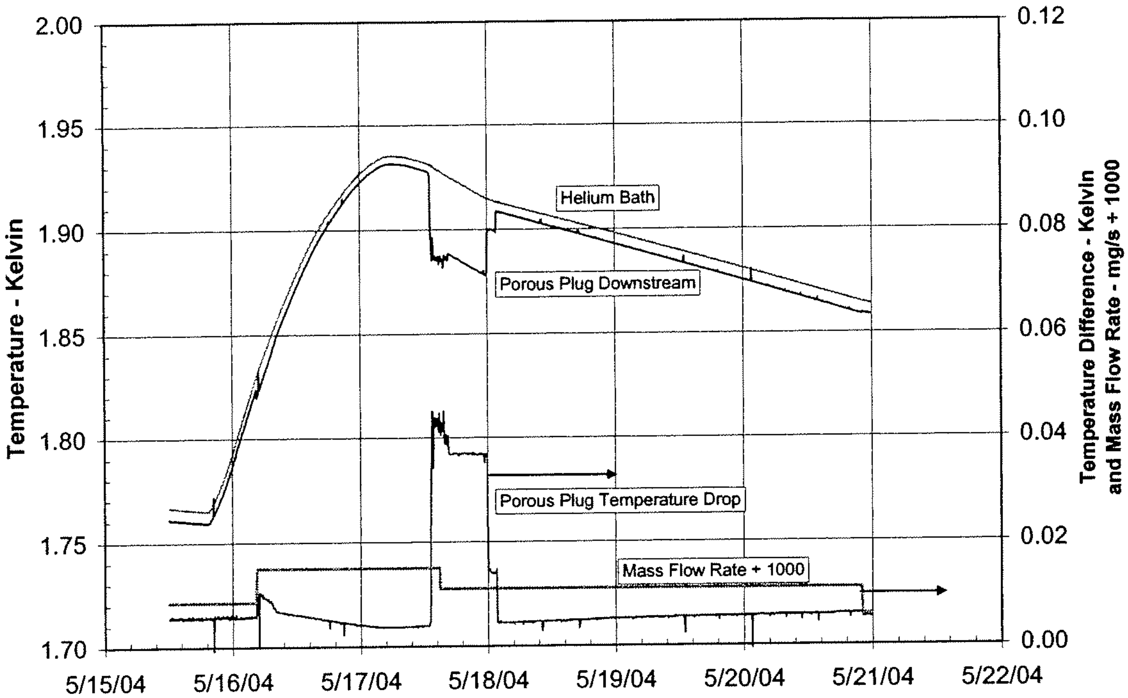

Figure 7. Temperature showing porous plug choking at flow rate >15 mg/s and recovering to normal operation.

Low Temperature Bakeout

At this juncture the rotors were suspended to clear the housing walls. They were then spun up to 60 to 100 Hz using helium gas introduced into the rotor housing to impinge tangentioally on the rotor. During this all internal surfaces become saturated with helium

The rotors require a very low spin down rate, on the order of 2 μHz/day. This requires lowering the pressure inside the probe to $<2.7\times10^{-8}$ Pa (2.0×10^{-10} torr). This is accomplished with a sintered titanium cryopump with a large effective surface area which is mounted in the forward end of the Well and thermally loosely tied to Station 200. The procedure used is to vent probe vacuum to space by opening two 6-in diameter probe vent valves. The cryopump and other internal probe components then undergo a low temperature bakeout. Heaters are used to raise the cryopump 11 K and the other critical surfaces to 6 K. This process drives the adsorbed helium from the cold surfaces while the vacuum vent valves are open to space. After the components have soaked at elevated temperatures the vacuum vent valves are closed and the components are allowed to cool. The cryopump can then produce pressures on the order of 2.0E-10 torr . This upper limit was demonstrated in payload verification testing. An indirect measure of pressure can be implied by the spin down rate of the gyros. In-orbit measurements gave a rate <2 μHz which is equivalent to a constant of on the order of 7000 years. Spin down rates of this size roughly correspond to a pressure <1.5E-11 torr.

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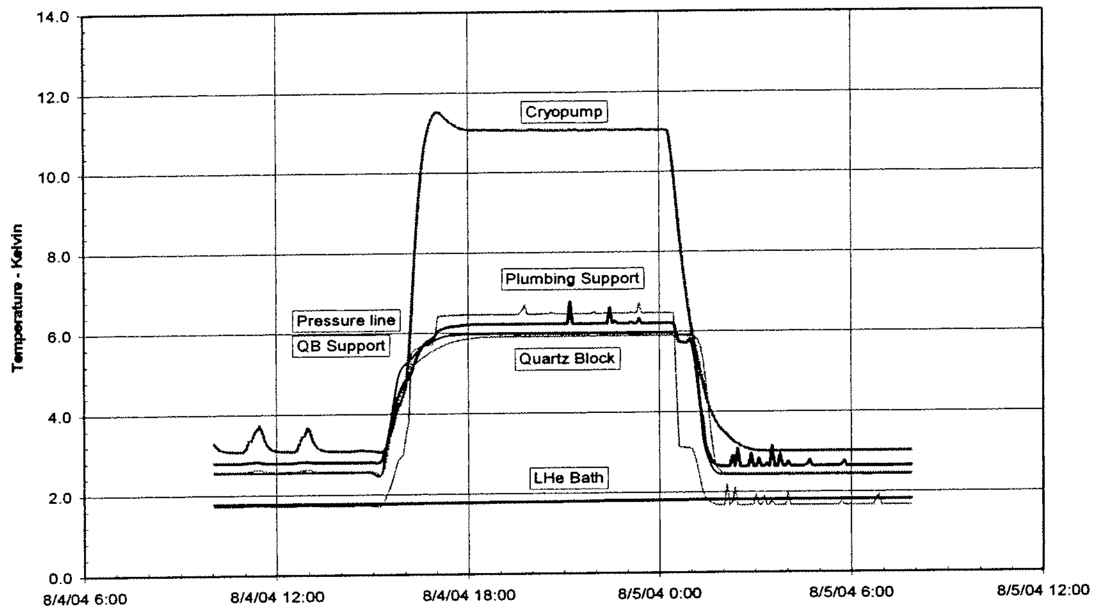

Figure 8. Cryopump and probe components are heated to remove adsorbed helium from surfaces and with subsequent cooling attain pressures <1E-10 torr.

Thermal Upsets

Early in the mission it became evident that with the sunshade open a transient heat input was produced in the probe. A trend of several probe components for May 29, 2004 is shown in Fig. 9 along with the shutter position. The heat pulses on all three items occur when the telescope points at the earth each orbit. Temperature fluctuations of this size upset the SQUID temperature control, which needs to be ~100 μK or better. Indeed the temperature control is only ~ +/- 3 mK during the heat pulses but quickly returns to a low value <30μK between pulses. Since at the time the telescope points at the earth , the guide star is not visible and no science data is present the temperature upset has no impact on the data collection.

Another effect seen in Fig.. 9 is with the shutter closed is the earth input is negligible for the cryopump but a small excursion on the probe components persists. This was determined to be caused by the vacuum thermal expansion/contraction as the space vehicle completes an orbit. The principal heat transfer interface of the probe to the LHe is between dewar Station 200 and probe Station 200. These are constructed of an indium coated aluminum surface on the probe and a are aluminum surface on the dewar. The contact conductance is controlled by the force the probe neck tube pushes the two parts together. Dewar shell temperature changes over an orbit produce periodic increase and decrease of the force holding the two components in contact. The cryopump, with its high thermal resistance to probe Station200 shows little effect of this second type variation.

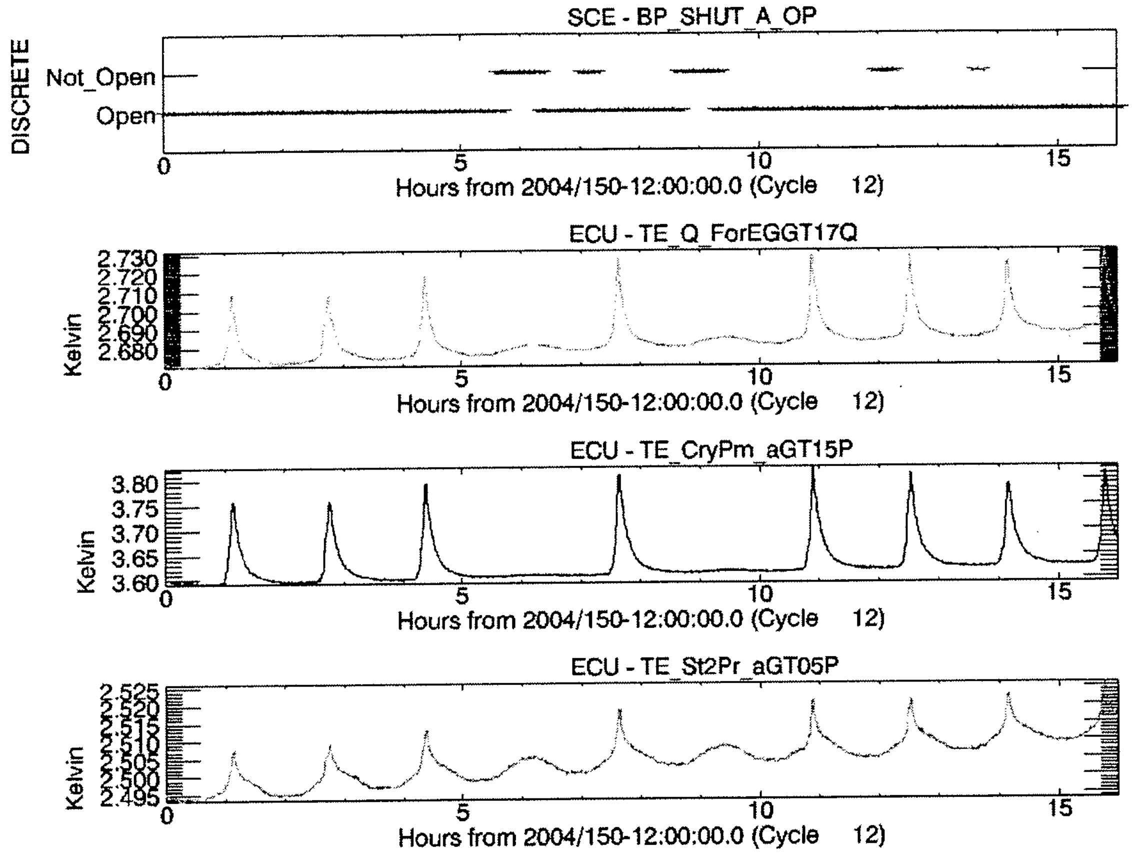

Figure 9. Temperature variations resulting from radiation into the optics with an sunshade shutter open and closed.

Remaining Mass Determination

The prediction of the End of Life (EOL) is very important for the GP-B mission as a certain period of time must be allotted at the end of mission for instrument calibration after the science data collection is stopped. The science data can not be restarted once calibration takes place. Thus, if the EOL is under-predicted the calibration period is insufficient to perform the required procedures. If the EOL is over predicted, the science data will have been terminated too soon. The length of the science data collection reflects directly on the accuracy of the result. To evaluate this parameter, two methods were used to predict the remaining mass: determine the loss in mass by integration of the measured flow rate and directly by conducting a Heat Pulse Measurement. (HPM).

The Attitude and Translation Control (ATC) of the spacecraft is by 16 micro thrusters which allow the helium vent gas to produce the required thrust. Each thruster vents gas through an orifice to space. Therefore, each thruster produces a flow that can be calculated from the temperature and pressure of the upstream gas. The total flow rate is then obtained by summing the over the 16 thrusters. In the commanded flow rate mode the requested flow is satisfied by null dumping if too much flow is commanded relative to ATC need. If too little flow is commanded, the thrusters take extra flow and the ullage pressure drops.

The HPM determines the remaining mass using a pulse of heat input to raise the temperature of the liquid helium. By evaluating the temperature change with the change in equilibrium conditions, a mass can be determined. The highest enthalpy components are the masses of liquid helium and gaseous helium and these will determine the temperature rise for a given heat input. The vapor does not affect the result when the vapor fraction is low but does have an appreciable contribution when the vapor fraction is high.
The determination of the remaining mass is produced using the liquid density at the average temperate times the volume determined from the following equation.

$$V_l = \frac{\Delta Q - V_t\left[\Delta(\rho_v e_v) - \left(\frac{\Delta\rho_v}{\rho_l - \rho_v}\right)(\rho_l e_l - \rho_v e_v)\right]}{\Delta(\rho_l e_l - \rho_v e_v) - (\rho_l e_l - \rho_v e_v)\frac{\Delta(\rho_l - \rho_v)}{\rho_l - \rho_v}}$$

ΔQ -is the change in the amount of heat input to the main tank due to the heater input
V_t - total volume
V_l - volume of liquid
ρ_v - density of vapor
ρ_l - density of liquid
e_v - internal energy per unit mass of the vapor
e_l - internal energy per unit mass of the liquid
Δ - operator that evaluates the change in any variable or combination of variables for temperatures at the beginning and end of the heater input.

This expression was derived by applying conservation of mass and energy over a control volume with the internal energy used for energy conservation.. (see for example Ref. 3)

The HPM procedure is conducted by disabling the closed loop pressure control, commanding the flow rate to a fixed value equal to the average over the last few hours, waiting several hours to obtain a good temperature trend, applying the pre-calculated heat input, and obtaining several hours of data after the heater input. Freezing the flow rate at a fixed pre-HPM value allows the vent flow from the liquid helium to maintain a value which equals the steady state heat input to the liquid helium. Therefore, to a good approximation, the ΔQ above the heater input. The HPM energy input is set to value estimated to be that necessary to produce a 10 mK temperature rise.

Heat Pulse Measurement Data Analysis
Temperature behavior for a HPM operation in the case of ullage volume (2.3 m^3 out of 2.4 m^3 is show in Fig. 10. In this case 868 joules were input to the tank heater over 60.1 seconds. A least squares fit to the pre- and post- heater input is used to determine the temperature rise by taking the difference of the two linear curves at the center of the 60 sec interval. Note that the data immediately after the heater operation is not used as this overshoot results from the vapor not being in equilibrium with the liquid.

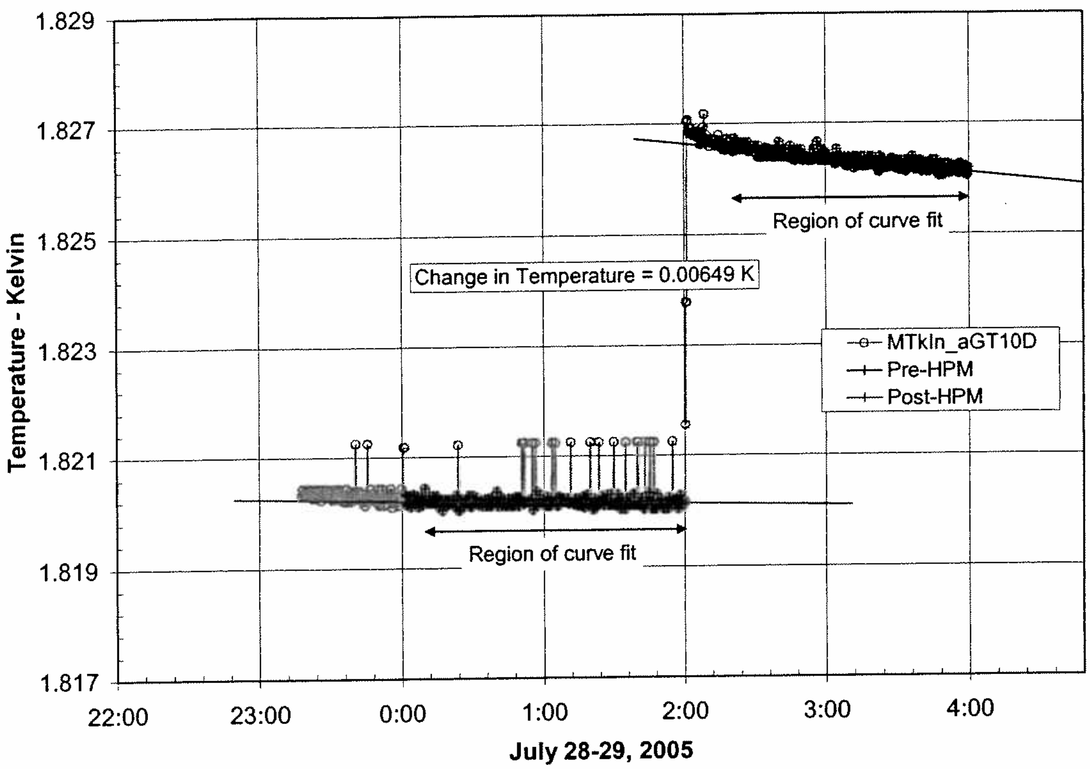

Figure 10. Heat Pulse Meter operation July 2005 using 868 joule heat input over a 60.1 second time period. Post-HPM shows some overshoot which must be ignored.

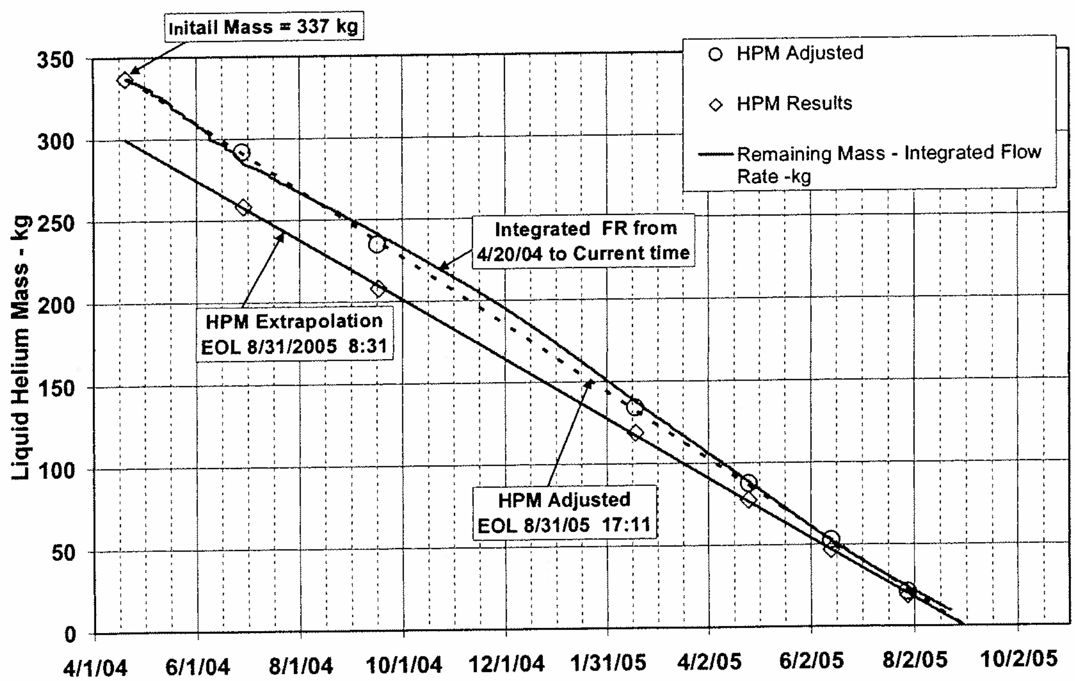

Figure 11. Remaining life using the flow meter and heat pulse meter. The HPM Adjusted values are obtained by scaling the heater voltage upward by 6%.

Fig. 11 shows the remaining mass estimation with results from both the method of integrated flow rate and HPM. The HPM adjusted values are reached by increasing the heater voltage by 6% over that indicated by the spacecraft telemetry. This is a likely error as the power supply for this heater was changed out just before flight and 6% is chosen so that the projection of the least squares fit to the launch date gives the initial as launched mass. (It should be noted that regardless of the heater scaling the error in predicted EOL becomes smaller the closer the end of life is approached.) As indicated the two curves project to an EOL date separated by just 11 hours. The integrated flow rate has followed the adjusted HPM curve closely throughout the mission.

A history of the recent EOL predictions are plotted in Fig. 13 along with the measured flow rate. The sudden change at July 29 in the predicted EOL curve was the result of normalizing to the July 29 HPM result rather than that of June 13. The various spikes in the flow rate are the generally the result of HPM operations, the flux flushing on 5/29/04 or the bakeout on 8/5/04. Other excursions, especially in the first four months are the result of attitude and translation control operations.

Another method is that shown in Fig. 12 where in the flow rate is integrated starting at the last HPM measurement and using one year ago data to projected flow rate to forecast the

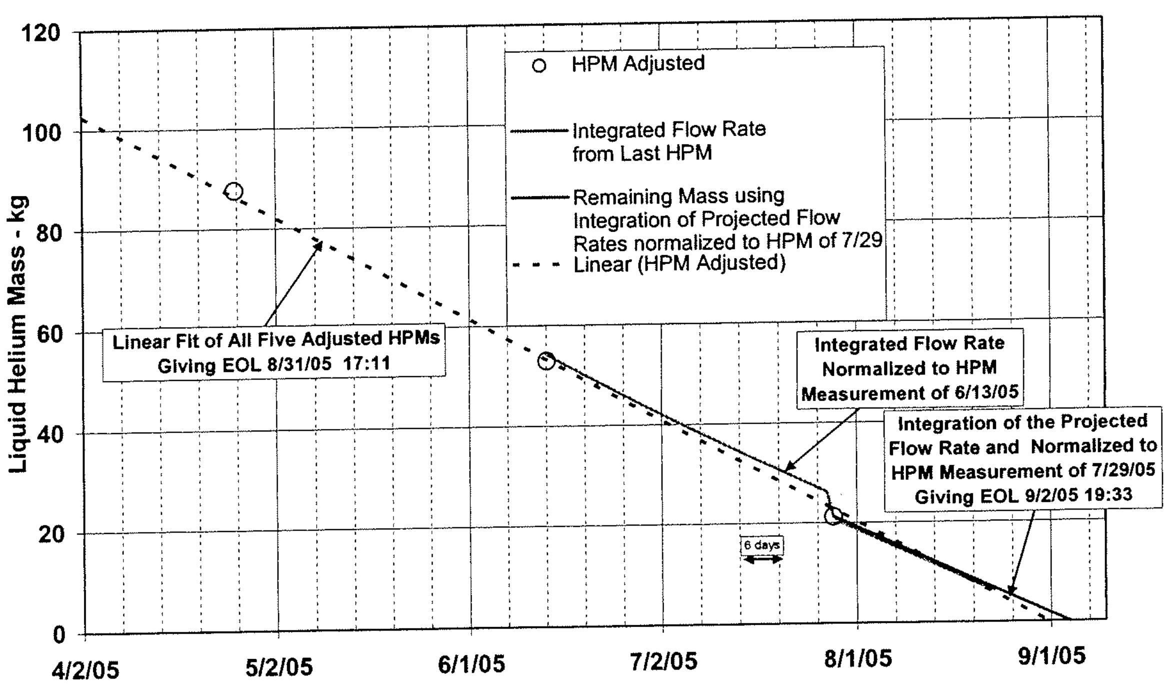

Figure 12. Prediction of EOL using HPM values and extrapolating using one-year-ago flow rates.

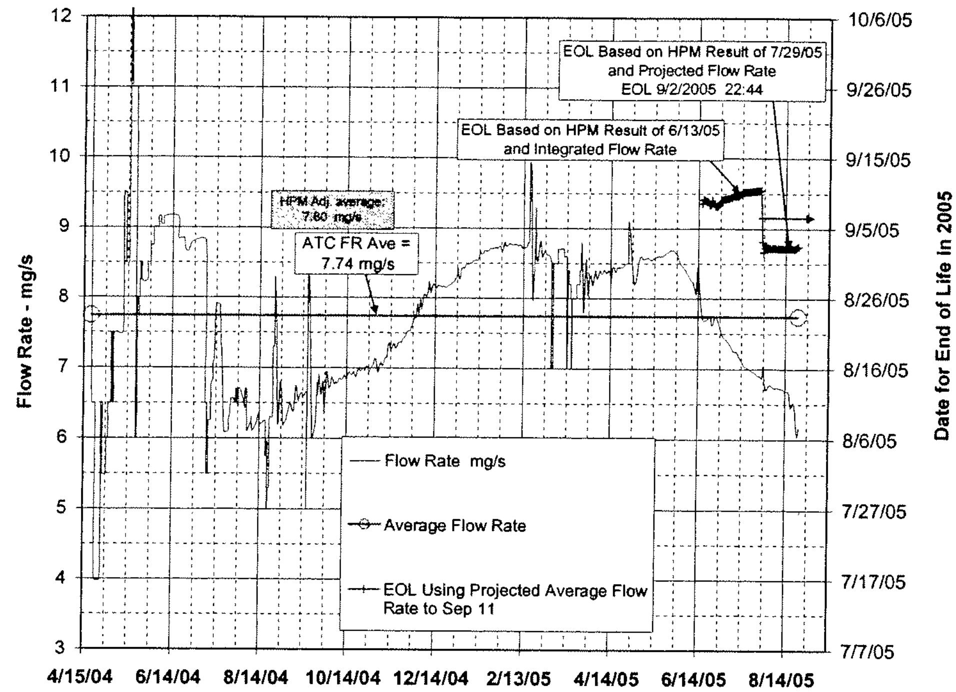

Figure 13. Flow rate and EOL prediction history. The drop in EOL at 7/29/05 is the result of adjusting to that days HPM result.

Two thermal models were constructed: one of the dewar shell to cryogen using prescribed shell temperatures and an integrated model for which the orbital shell temperatures were

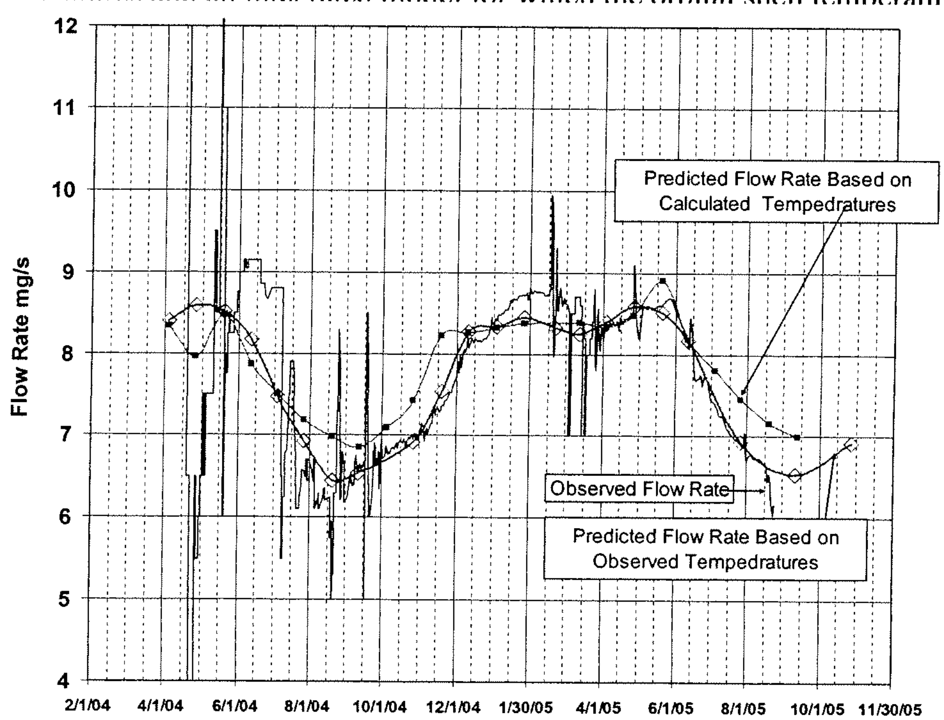

Figure 14. Observed flow rate and predicted flow rate for: 1) using observed external dewar shell temperatures and 2) using calculated temperatures.

calculated and used to predict dewar performance. The resulting flow rates produced by this modeling are shown in Fig. 14 along with those measured. The dewar only model uses the observed external dewar shell temperatures and the integrated model uses the calculated shell temperatures. It is clear the dewar only model is in good agreement with the observed data also the integrated model gives good agreement except it predicts slightly higher flow rates in the lower flow rate regions. This corresponds to the predicted temperatures being warmer than the observed.

Conclusions

The GP-B dewar orbital performance satisfied all temperature requirements and appears will meet the design lifetime of 16.5 months (16.4 months as of 8/31). The operation of the dewar was not as straight forward as one would have hoped, however, all upsets and surprises were easily handled. The HPM method was demonstrated to provide an accurate method of determining EOL and is especially useful for a mission which is so critically sensitive to the value.

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