Apr 1st, 8:00 AM

Gravity Probe-B: the Stanford General Relativity Experiment as a Shuttle Payload

Gerald R. Karr
Associate Research Professor, University of Alabama in Huntsville

John B. Hendricks
Associate Research Professor, University of Alabama in Huntsville

Scholarly Commons Citation

Karr, Gerald R. and Hendricks, John B., "Gravity Probe-B: the Stanford General Relativity Experiment as a Shuttle Payload" (1981). *The Space Congress® Proceedings*. 3.
https://commons.erau.edu/space-congress-proceedings/proceedings-1981-18th/session-5/3

GRAVITY PROBE-B; THE STANFORD GENERAL RELATIVITY EXPERIMENT AS A SHUTTLE PAYLOAD*

Gerald R. Karr
Associate Research Professor
University of Alabama in Huntsville
Huntsville, Alabama 35899

John B. Hendricks
Associate Research Professor
University of Alabama in Huntsville
Huntsville, Alabama 35899

ABSTRACT

Gravity Probe-B (GP-B) is an experiment under Phase B study at Marshall Space Flight Center which is designed to measure general relativistic induced torques on a gyroscope in orbit about the earth. The measurement of the relativistic effects requires that the gyroscope be nearly perfect in spherical shape and be shielded from the influences of non-relativistic effects. To accomplish these requirements, the spacecraft design includes provisions for superconducting magnetic shields, superconducting readout electonics, drag free gyro suspension, a drag free spacecraft, and provision for gyroscope spin-up at cryogenic temperatures. The spherical rotor fabrication has resulted in advances in manufacturing and measurement techniques in order to meet the experiment requirements. An essential feature of the spacecraft system which will be launched by the Shuttle is a large volume liquid helium dewar which will supply cooling to maintain the gyros and shields at a few degrees kelvin for over a one year duration. The helium which is boiled off is used to maintain drag free control of the spacecraft. This paper will discuss the design requirements for the experiment, the essential features of the proposed spacecraft, the gyro manufacturing technology, the gas spin-up method, and the liquid helium technology.

INTRODUCTION

In 1960, L.I. Schiff[1] showed that a gyroscope in orbit around the earth would undergo a precession

$$\Omega = \frac{3GM}{2c^2R^3}(\underline{R} \times \underline{v}) + \frac{GI}{c^2R^3} \; \frac{3\underline{R}}{R^2}(\underline{\omega}\cdot\underline{R}) - \underline{\omega}$$

where $\underline{R}$ and $\underline{v}$ are the coordinate and velocity of the gyroscope and M,I, and $\underline{\omega}$ are the mass, movement of inertia, and angular velocity of the central body. Similar calculations were made independently at about the same time by G.E. Pugh[2]. The first term of the equation, called the geodetic precession, amounts to 6.9 arc sec per year in a 300 nautical mile orbit. The second term, called the motional effect, would amount to 0.05 arc second per year for a properly oriented gyroscope in a 300 nautical mile polar orbit. In a polar orbit, gyroscopes can be mounted so that the two effects are separated (Fig. 1).

In 1961, L.I. Schiff and W.M. Fairbanks, of the Stanford University Physics Department, made the first proposal for a space experiment. Work on the program, now called "A Gyroscope Test of General Relativity" or "Gravity Probe-B" (GP-B) has continued from that time. Reference 3 contains a complete history of the development of the project at Stanford University up until 1977. A shorter, but more widely available description is contained in Reference 4. In 1967, the management of the program was transferred from NASA Headquarters to the Marshall Space Flight Center (MSFC), and in 1972, MSFC contracted with the University of Alabama in Huntsville (UAH) to study certain problem areas in the GP-B program. In this paper we will first give a short description of the overall experiment, and then discuss three topics that have been of particular interest to the group at UAH.

THE OVERALL GP-B EXPERIMENT

A proposed overall assembly of the shuttle launched GP-B system is shown in figure 2. The system is essentially a large liquid helium dewar with the GP-B experiment package at the center. Figure 2 shows four gyroscopes, a proof mass, and a telescope at the center of the helium dewar. This central package is constructed of quartz and is shielded from external magnetic fields by superconducting shields. The gyroscopic motions of the four gyros is sensed by SQUID type magnetometers which measure the London moment produced by the spinning superconducting gyros. The motion of the gyros is referenced to the motion of a distant star which is tracked by the quartz telescope attached to the quartz block containing the gyros.

The experiment package is magnetically shielded using superconducting coatings and superconducting containers. The shields must be maintained at a temperature below the superconducting transition temperatures of the shield and coating materials. The cooling of these shields is achieved through the use of liquid helium at a temperature of 2K. The helium dewar utilizes vapor cooled shields and MLI lazers to maximize efficiency. The heat into the experiment package is transferred to the liquid helium which causes vaporization of helium. The helium vapor flow rate is controlled by a porous plug device which is discussed in a later section of this paper.

The vaporized helium which is heated during its passage through the vapor cooled shields is eventually used in the drag free control thrusters shown in figure 2. The firing of the drag-free-control thrusters is controlled by the position of the proof mass located near the gyros.

The dewar assembly also contains numerous valves which control the filling and venting of the liquid helium reservoir and for spinning the gyros. The gyros are spun-up after the shuttle has been launched. The dewar also contains internal supports which must withstand the launch load and must also produce minimum heat leak.

The GP-B experiment is clearly an ambitious task and requires careful consideration of error sources. Figure 3 gives a summary of the errors expected for the GP-B experiment and predicts that the maximum error in measurement of the motion of the gyros is expected to be less than 1 milli-arc-second per year. This level of accuracy is sufficient to verify the effects of general relativity .

The major error sources are listed on the left hand side of figure 3 and include the nonspherical shape of the gyro, error in measurements and control, and errors introduced by data transmission. Many of these errors can be identified and subtracted from the data during the data reduction. For example, the satellite is designed to rotate at a period of 15 minutes and the telescope is dithered in order to identify errors associated with solar panel disturbances, spacecraft control, and telescope errors.

The third column of figure 3 shows the expected errors remaining after data reduction due to the effects listed. The largest source of error is noted to be that due to the SQUID noise and other instrumentation associated with the data reduction. The total error due to data processing is expected to be .75 milli-arc second per year. A separate source of error is brought about by physical effects and is shown in figure 3 to be near .24 milli-arc-sec per year.

MANUFACTURE OF GYROSCOPE ROTORS

The gyroscope rotor should be spherical ($\frac{\Delta r}{r} < 5 \times 10^{-7}$), 1.5" in diameter, and have a uniform mass distribution $\frac{\Delta \rho}{\rho} < 3 \times 10^{-7}$

The mass distribution is measured using optical techniques, so a transparent material is required. Also, since the rotor is to be cooled to 2°K, the thermal expansion coefficients must be isotropic so as not to distort the figure of the rotor with temperature changes. For these reasons, the material selected for the rotor is high purity amorphous silica[4].

The first requirement for making the rotor is that we be able to measure the results. Fortuneately, developments in roundness measuring techniques in the past decade have resulted in machines that are adaquate for the job. Rank Taylor Hobson, Leicester, Engla , markets a roundness measuring machine (Talyrond 73) with a computer to correct the spindle errors (Talynova 12) that reduces errors in roundness to below 0.1×10^{6}in. The computer also allows the figure of the rotor to be determined in terms of shperical harmonics, and to generate maps of the errors for visual study. Stereo views of a rotor, generated with the Talynova 12, are shown in Figure 6. These views were generated by M. Debiche at Stanford University.

Thousands of years ago, the Chinese made beautiful spheres of ivory and other materials by first carving them round and then finishing them at the square ends of one or two sticks of bamboo. Our technique, developed by Mr. Wilhelm F. Angele,(Physics Dept., UAH), is similar but more sophisticated. A picture of the current lapping machine is shown in Figure 5. A study of the polishing process can be summed up as follows:

1. The polishing cups should cover as much of the rotor as possible. This is optimized by the "tetragonal" arrangement of the four cups (the three lower cups are in lined at 20° wrt horizontal).
2. The force between the ball and cup should be as uniform as possible around each cup. This is also best for the "tetragonal" arrangement.
3. The ball should always have a transverse motion with respect to each cup. If the cups were given a "random" motion, at certain time the ball would be stationary, and the polishing cup would cut a groove in the ball.

Thus a small period of time in this "bad" motion would overcome large periods of time of "good" motions. This has led to the use of cam programmed motors at constant speed so the "bad" motion can be eliminated. This more than compensates for the limited number of "good" motions.

The rotors are machine ground to rough shape; lapped with first cast iron, and then plastic laps to almost final size; and then ploished using pitch polishing laps. Our best rotors to date have roundness errors of 0.3×10^{-6} inch Peak-to-Valley. This represents a considerable improvement over existing practice, and is one of the major accomplishments of the GP-B program.

SPIN-UP OF THE GYROS AT CRYOGENIC TEMPERATURES

The GP-B gyros must be spun to a speed of approximately 100 revolutions per second in order to provide the signal strength needed for the readout system. After consideration that ordinary methods of gyro spin-up would violate the magnetic shielding requirements and the low temperature requirements, a gas spin-up system was proposed, developed, and tested successfully in the laboratory.

The gas spin-up method works on the principle that a gas flowing past a surface imparts a shear stress on the surface. Figure 4 shows the major design features of the gas spin-up system to be employed on GP-B. Gas at the ambient temperature of the system (2°K) and at a reduced pressure of near 1 torr is introduced at one end of the two spin-up channels. The cold helium gas is forced through the channels at the pressure of near one torr and exhausted into a low pressure region at the exit of the channel. Since the gyro surface makes up one side of the gas channel, the frictional forces act on the rotor, tending to spin the gyro about on an axis perpendicular to the plane of the spin-up channels. Analysis of the gas spin-up yields the following expression for the maximum obtainable spin speed, ω_{max}, as a function of an initial spin-up torque, Γ_i

$$\omega_{max} = \Gamma_i \left[\frac{\mu A_e r^2}{\delta} + \frac{P_c r^4}{\sqrt{2RT}} \right]^{-1}$$

where μ is the gas viscosity, A_e is an area of the lip of the channel which is closely spaced to the gyro rotor surface, r is the rotor radius, δ is the spacing between the channel lip area (A_e) and the rotor surface, P_c is the cavity background pressure, and T is the temperature. The spin-up torque level, Γ_i, is predictable on the basis of the fluid dynamics of the channel flow. For the pressure under consideration, the flow is in the transition flow region between laminar and turbulent.

The first term in the bracketed expression in the above equation is a viscous drag term resulting from the high pressure region between the channel lip area and the rotor surface. The second term is a rarefied gas drag torque resulting from the low pressure gas in the cavity region of the gyro. The lip area drag can be reduced by reducing the lip area but this would result in greater leakage of gas into the cavity, thus increasing the cavity drag term. The lip area must then be chosen to optimize the spin speed.

A prototype gyro was installed in a cryogenic system at MSFC to test the spin-up method described above. The results of a spin-up test are shown in Figure 7. The results show that a spin speed of 106 revolutions per second was achieved in 38 minutes. The figure also shows that the initial acceleration was near $6H_2$/minute. The initial torque is obtained from the relationship

$$\Gamma_i = I \, \dot{\omega}(0)$$

where $I = m \frac{2}{5} r^2 = 9.246 + 10^{-6} \text{Kg m}^2$ and $\omega(0)$ is the initial acceleration. We find that Γ_i was near 50 dyne-cm which is expected for the case when the rotor cavity pressure during spin-up is of order 10^{-3} torr. The temperature of the gas and gyro was 4°K for the tests reported here. The spin-up of the gyros on the shuttle will then require a period of nearly one hour to achieve the described spin speeds.

MAINTENANCE OF CRYOGENIC TEMPERATURES FOR GP-B

The GP-B experiment requires that the gyros and the magnetic shields be maintained near 2°K for a period of about one year. This requirement can be met with an efficient dewar of liquid helium. The amount of helium needed will depend on the dewar design and the performance of a superfluid plug device used to act as a phase separator. The superfluid plug was first proposed for application to the GP-B experiment[4] and since has found application to the problem of liquid vapor phase separation in zero gravity of space[5]. The device works on the principle that superfluid helium experiences a thermomechanical pressure due to a temperature gradient. Thus, by maintaining a negative temperature gradient in the direction of helium flow, the superfluid experiences a positive pressure gradient which restricts the superfluid flow. The flow can be reduced to the point that only enough liquid flows through the plug to remove heat from the dewar by evaporation at the plug surface. Experiments have been performed in the laboratory to test various types of superfluid plugs[6]. Figure 8 shows the laboratory set-up used to test a prototype plug system. The figure shows a schematic of the experiment in which the plug is stationed at the bottom of the liquid helium container. The liquid-to-vapor phase change takes place at the plug's lower surface, thus generating a lower temperature at that point. The liquid above the plug is at a slightly higher temperature which causes a pressure to develop across the plug which is in the direction needed to keep the fluid from dropping through the plug.

Figure 9 shows results obtained from one such experiment showing that the plug operates over quire a wide range of temperature, pressures, and flow rates. At 2.17°K the plug no longer operates as a superfluid plug and liquid readily passes through the plug. The plug needed for GP-B will be required to operate at relatively high pressures due to the need to use the helium boil-off for drag free control of the satellite. Plug studies presently in progress at MSFC and UAH are expected to provide the needed plug design for the experiment.

CONCLUSIONS

The above discussion has summarized the important design features of the GP-B experiment. The experiment is complex and delicate, qualities which make the shuttle launch of this experiment attractive. Prior to ejection from the shuttle bay, the gyros can be levitated and spun-up to speed and the entire data collection system can be exercised. since these tests can not be performed in the one-g environment prior to launch, the shuttle bay tests will insure that the system is in operating order. The shuttle operations will also provide time for thermal stabilization of the liquid helium and dewar in the zero gravity of space.

REFERENCES

1. L.I. Schiff, Proc. Nat. Acad. Sci. 46,871 (1960).

2. G.E. Pugh., WESG Research Memo No. 11, Weapons System Evaluation Group, The Pentagon, Wahington 25 D.C. (November 12, 1959).

3. W.M. Fairbank, C.W.F. Everitt, and D.B. DeBra, Final Report on NASA Grant 05-020-019, W.W. Hansen Laboratories of Physics, Stanford University (July, 1977).

4. Everitt, C.W.F., Part I, Experimental Gravitation (B. Bertotte ed., New York, Academic Press, 1974),pp. 331-360.

   Lipa, J.A., Fairbank, W.M., Everitt, C.W.F., Part II, pp. 361-380.

   Wordon, P.W. and Everitt, C.W.F., Part III, pp. 381 - 401.

5. Karr, Hendricks, Urban, Katz, & Ladren, Proceedings of the Eigth International Cryogenic Engineering Conference, pp. 38-42, 1980.

6. Urban, Katz, and Karr, Low Temperature Physics LT14, (Krusius & Vuorio, eds.), Worth Holland, 1975) vol. 4, pp. 37-40.

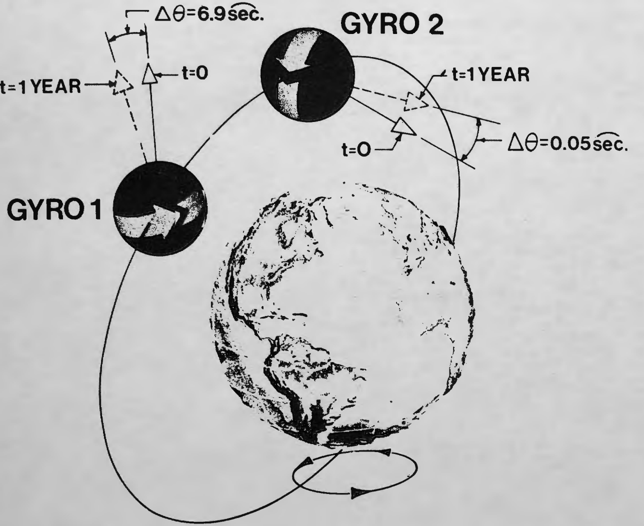


Figure 1. Expected Precession Due to General Relativity Effects for Two Gyro Orientations.

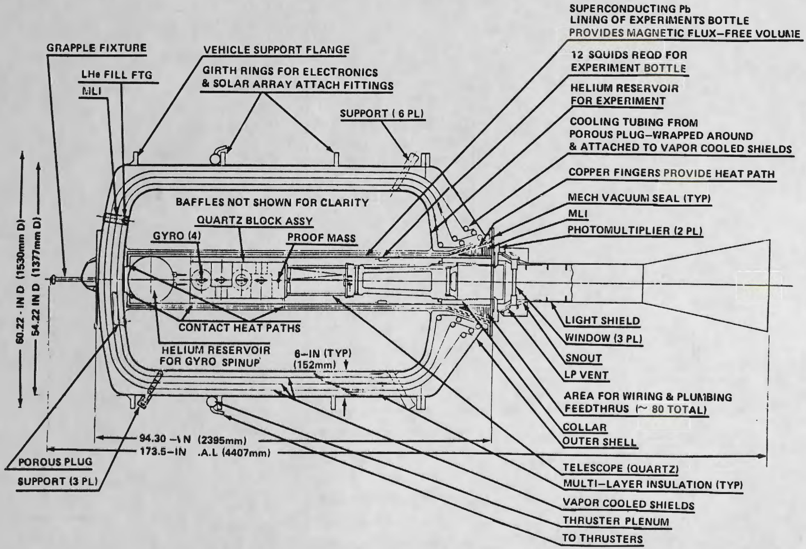


Figure 2. The GP-B Dewar Assembly

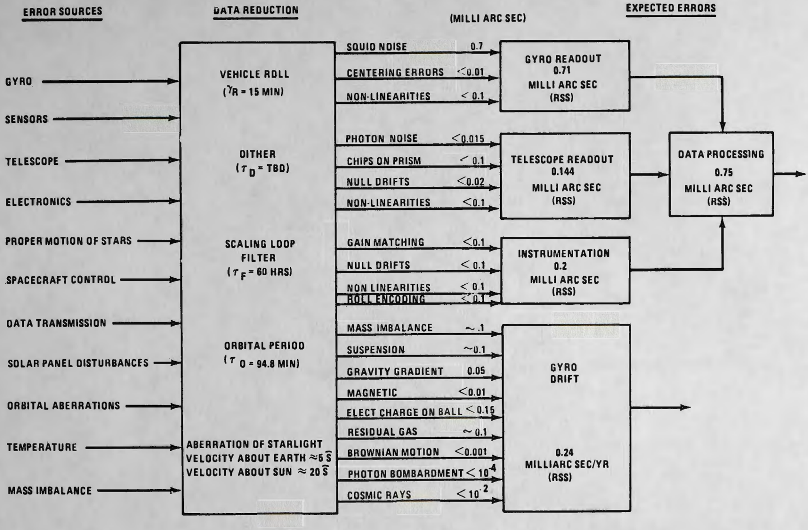
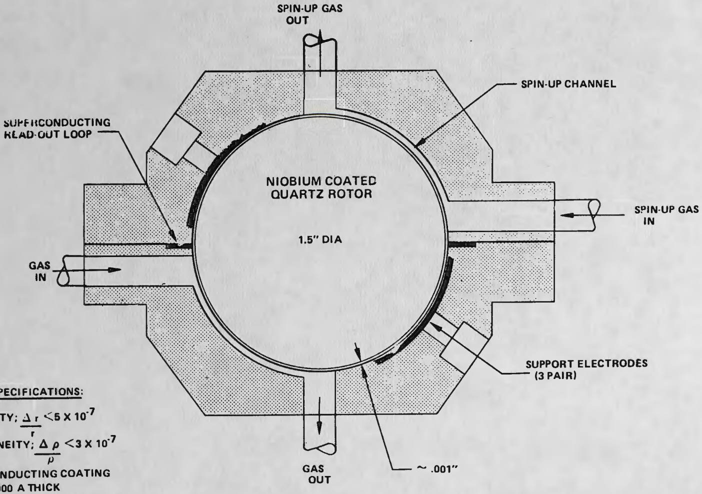


Figure 3. The GP-B Preliminary Error Budget



ROTOR SPECIFICATIONS:

SHPERICITY: $\frac{\Delta r}{r} < 5 \times 10^{-7}$

HOMOGENEITY: $\frac{\Delta \rho}{\rho} < 3 \times 10^{-7}$

SUPERCONDUCTING COATING
$\sim$5000 A THICK
3 % UNIFORMITY

Figure 4. The GP-B Gyroscope Design

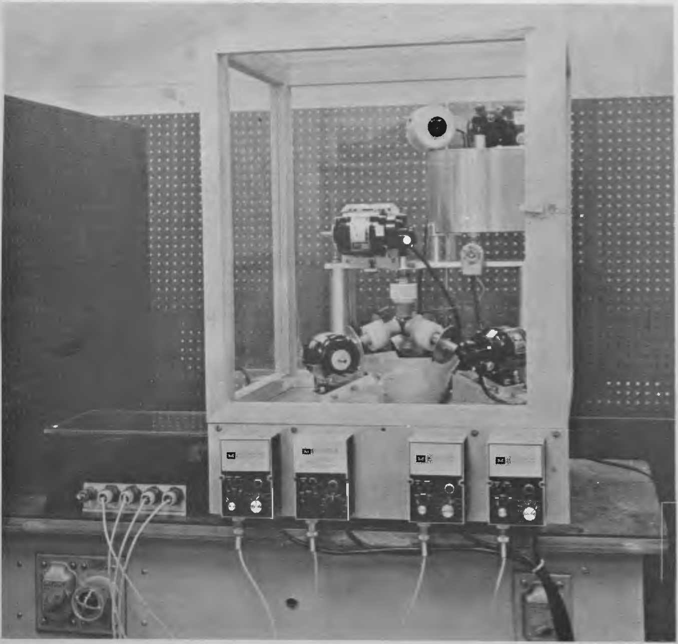


Figure 5. The Rotor Grinding Machine

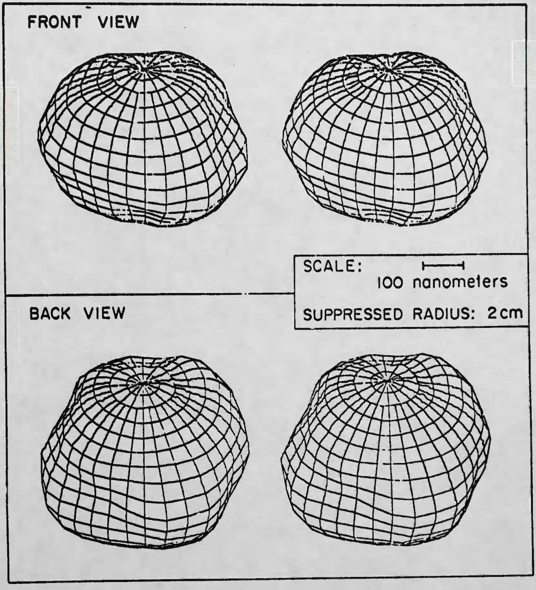


Figure 6. Stereo Views of Quartz Rotor

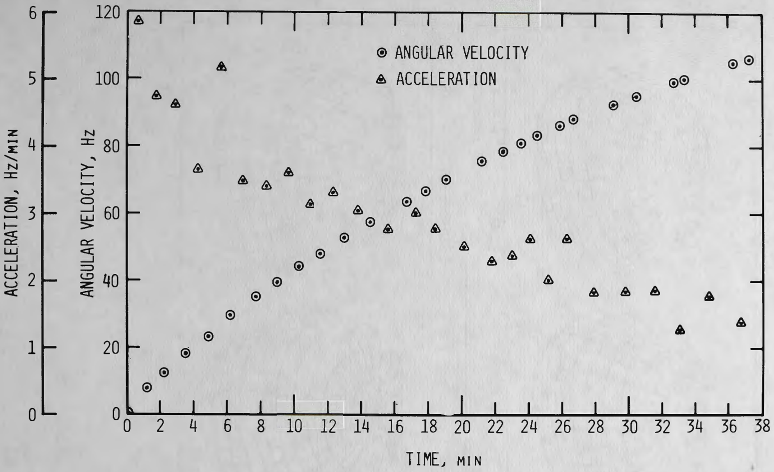
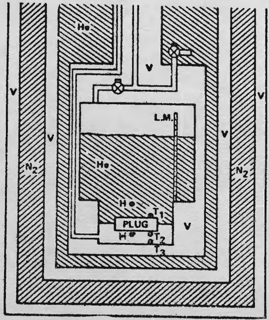


Figure 7. Angular Velocity and Acceleration History. Helium Gas at 4K, .8 torr, and 40 scc/min



LEGEND

H	HEATER
H_e	LIQUID HELIUM
L.M.	LEVEL MONITOR PROBE
N_2	LIQUID NITROGEN
T	THERMOMETERS
V	VACUUM

Figure 8. Schematic of MSFC Superfluid Plug Experiment

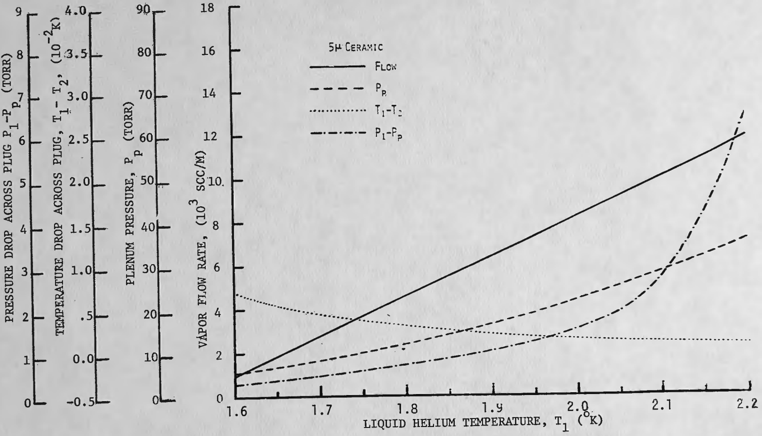


Figure 9. Results for Steady State Operation of 5 µm Ceramic Super Fluid Plug.