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# *Final Report The Cryogenic Gyroscope Program at Jet Propulsion Laboratory*

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# PREFACE

The Report is prepared under two covers. This first part, *Final Report*, contains the summary of the program; the second part, *Appendix to the Final Report*, includes all of the detailed documents to substantiate this concise summary. Only a limited number of copies of the *Appendix* have been printed. Those recipients of the first part who are interested in further details of the Cryogenic Gyroscope may receive copies of the *Appendix* by submitting requests to the Manager of the Guidance and Control Research Section, Jet Propulsion Laboratory.

The following is a list of the Appendixes contained in the second part:

A. The Cryogenic Gyro
B. Correspondence Re: Lapping Techniques for Niobium
C. Niobium Elastic Constants vs Temperature
D. Statement of Work for Study of Flux Trapping in Superconductors (facsimile)
E. A-C Losses in Superconductors
F. Low Frequency Magnetic-Field Losses in Superconductors
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# ACKNOWLEDGMENT

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# ABSTRACT

This Report is a technical account of the development of the superconducting gyroscope at the Jet Propulsion Laboratory from June 1958 to September 1965. The program, which began with levitating a superconducting ball with a single coil, has advanced to the point where total drift as low as one degree per day has been obtained with a research model of the gyro.

The Report describes the principal problems encountered in the program, namely: rotor fabrication, alternating magnetic field losses in superconductors, magnetic field configuration required for levitation, damping of rotor oscillation, refrigeration, spinup, and readout.

author

Because a multitude of reports has been issued during the course of this program, the text is concise and, for details, the reader is referred to previously issued reports, which are prepared under separate cover, entitled *Appendix to the Final Report*.

# I. INTRODUCTION

It is only recently that industry has realized the importance of research in cryogenics as a result of the rapid pace of discovery in both the theoretical and applied aspects of superconductivity. The cryogenic gyroscope program was initiated in 1958 at JPL to exploit the field of cryogenics. Work on the cryogenic gyroscope has been terminated, but research on other new applications of superconductivity continues to be an important part of the research work in the Guidance and Control Division at JPL.

The cryogenic gyro as described herein consists of a spinning superconducting sphere levitated in a vacuum by a magnetic field. The torqueless suspension of a superconducting sphere is based on the Meissner effect, which implies that magnetic forces on a superconductor are exerted normal to its surface (Appendix A). Furthermore, the lack of resistance allows high rotational speeds without eddy-current drag. The principal sources of torque in such a gyro are nonsphericity (including mass unbalance), trapped flux, ac losses and the London moment.

The program objective has been to determine the feasibility of the superconducting gyroscope concept, not so much on the basis of engineering and design limitations (such as the problem of readout from a spherical rotor) but primarily from a consideration of the fundamental limitations imposed by the physical phenomena involved (such as the forces, torques and dissipation produced in the interaction of a superconductor with a magnetic field).

The procedure chosen was to first identify those functions most likely to pose problems for the feasibility of the cryogyro, then to experimentally investigate each problem to assess its importance, and lastly, to propose and test various solutions to these problems. An alternative procedure would have been to design a test model of the gyroscope in the light of *a priori* knowledge of the technology involved in a superconducting gyroscope, then to revise the design as operation of the system revealed its shortcomings. It was felt that the technology of superconductivity was too primitive to favor such an approach. More than likely, the first naive design would have had so many defects that it would have been difficult to isolate them. Thus, it was decided to investigate each problem, one by one, before incorporating them all into a gyro system.

If all the technical problems proved tractable, the ultimate objective was to obtain meaningful drift data on a simplified model of the gyro to test the mathematical analysis. For this purpose it was decided not to compromise the gyro design by engineering considerations. Retaining a perfectly spherical rotor surface may cause difficulties in spinup, and elimination of gimbals may complicate readout, but if the inherent advantages of a gimbal-less spherical-rotor gyro are to be fully realized, it will be necessary to devise instrumentation specifically for the gyro, rather than adapt to state-of-the-art hardware.

The principal topics investigated in the JPL cryogenic gyro program have been:

1. The rotor: selection of an appropriate superconductor, its fabrication into an accurate sphere, and metallurgical treatments to eliminate flux penetration due to imperfections
2. Supporting field configuration: analysis of magnetic forces and torques exerted on an imperfect superconducting sphere
3. Spinup: techniques (necessarily non-magnetic) for torqueing a levitated sphere to gyro operating speed
4. Maintenance of cryogenic temperature: techniques for minimizing heat input to the vacuum isolated rotor
5. Damping: attenuation of translational oscillations of the suspended rotor imparted by motion of the gyro housing
6. Readout: determination of the direction of the angular momentum of a spinning sphere
7. Drift tests: measurement of angular deviation of rotor spin axis vs time for a research model of the cryogenic gyro

These items will be discussed one by one in the body of the Report.

The principal investigators on the cryogenic gyroscope program at JPL were John T. Harding[1] and Robert H. Tuffias[2]. The JPL program was based on the pioneering work of Ivan Simon (Refs. 1 and 2), of Arthur D. Little Inc., and the proposal of Culver and Davis of the RAND Corporation (Ref. 3). The project has benefited from periodic discussions with General Electric—General Engineering Laboratories, and Minneapolis Honeywell—Military Products Group, both of which have pursued independent cryogyro development programs.

# II. THE ROTOR

## A. Selection of a Superconducting Metal

### 1. Early Work with Lead

At the beginning of the program it was decided to choose a metal whose superconducting properties were known to be nearly ideal (as determined by the completeness of the Meissner effect). At that time (1958), for two principal reasons, only lead appeared to be a good choice for the superconducting surface of the rotor:

1. The metal was readily obtainable in pure form, such that it showed up to 97% flux exclusion during the

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[1] Presently at Ford Scientific Laboratory, Cryogenic Devices Department, Newport Beach, California.

[2] Presently at Stanford University, Department of Aeronautics & Astronautics, Stanford, California.

transition to superconductivity (unlike niobium which showed at most 10% flux exclusion with the grade of niobium that could be obtained commercially at that time).

2. It has a transition temperature of 7.2°K. At the convenient working temperature of 4.2°K (the atmospheric boiling point of liquid helium) the critical field is 550 gauss (adequate to support, at most, an 8.1-mm-radius solid-lead sphere[3]). Tin, indium, and mercury, which are common elements satisfying (1), all have transitions at, or below, 4.2°K, and have much smaller critical fields than lead.

Offsetting its advantages, lead, also, has serious shortcomings as a rotor material. Its mechanical properties, such as hardness and Young's modulus, are unsuitable for a precision high-speed rotor. Its surface corrodes readily in atmosphere, adversely affecting its surface conductivity. Lastly, its high density is disadvantageous for a field-supported rotor.

Nevertheless, lead was chosen as a starting material because the main interest centered on intrinsic superconducting properties. If lead could not demonstrate adequate flux exclusion and absence of losses while rotating in magnetic fields, then the cryogenic gyro concept would be infeasible, regardless of mechanical properties.

Thus it was that the first sphere to be levitated was a lead-coated[4] ping-pong ball, shown in Fig. 1. This photograph is of historic interest because it disproved the commonly held thesis that a single-coil support is unstable. An interesting sidelight is that initial attempts to photograph with flashbulbs were unsuccessful because the pulse of heat delivered to the thin ball was sufficient to cause the lead to go normal and the ball fell, even though it was immersed in liquid helium. A net force of only 4 grams was necessary to support this first ball. One-half-in.-diam solid lead balls have subsequently been levitated at 4.2°K.

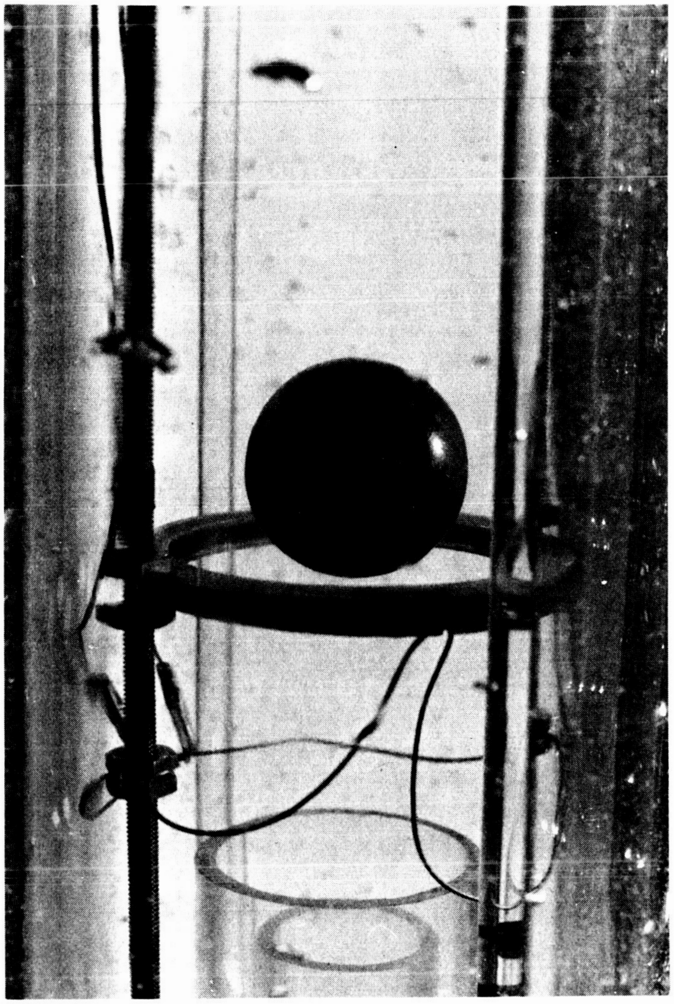

**Fig. 1. Levitation of lead-coated hollow ball with a single coil**

### 2. Change to Niobium

A switch to the use of niobium balls was made because of the following disadvantages of lead:

1. Lead is so heavy that, for balls over ½-in. in diameter, hollow or coated balls must be used to avoid exceeding the critical field. This requirement caused difficult fabrication problems, and also, the resulting superconducting properties were uncertain.

2. Even if the superconducting properties of lead proved adequate for gyro use, it would still be necessary to investigate and refine the superconducting properties of a metal like niobium, tantalum, vanadium, or some alloy because of the utter unsuitability of the mechanical properties of lead for a high-speed precision rotor.

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[3] Based on relation: Weight = projected area × $B^2_{\text{crit}} / 2\mu_0$

whence $R = 3\,B^2_{\text{crit}} / 8\rho g \mu_0$ $\quad$ Mass $= \pi \left(\frac{3}{4\rho}\right)^2 \left(\frac{1}{2\mu_0 g}\right)^3 B^6_{\text{crit}}$

$\rho$ = density $\quad$ $\mu_0 = 4\pi\, 10^{-7}$ (MKS units)

[4] The lead coating was formed by first condensing a conducting surface of silver on the plastic ball with the technique commonly used in coating a mirror. Then an adherent coating of copper was formed electrolytically. Finally, lead was deposited electrolytically.

Hence, a decision was made to utilize niobium as the rotor material because of its several advantages:

1. It is reasonably hard, similar to brass, though it machines like stainless steel. It can be lapped and polished to a high degree of sphericity and surface finish by standard techniques.
2. It has the highest critical temperature (9.2°K) of any element (except the rare technetium). The critical field at 4.2°K is 1500 gauss, which theoretically supports a 7.97-cm-radius solid-niobium ball weighing 18.2 kg (40 lb). (The largest ball actually levitated at JPL was 4-cm diam and weighed 290 g.)
3. It is resistant to atmospheric contamination at room temperature.
4. It has a body-centered cubic lattice which implies isotropic thermal expansion.
5. It can be anodized to produce an optical readout pattern.
6. It has become increasingly available from commercial sources as a result of its usefulness in reactor technology (low thermal neutron cross section), high temperature alloys, and superconductivity.

### 3. Verification of the Properties of Niobium

To realize drift rates below $10^{-3}$ deg/hr requires establishing the physical properties of the rotor material to a precision never before attempted with niobium. This required several investigations.

***a. Sphericity.*** A contract with Professional Instruments Company, of Minneapolis, was designed to determine what degree of sphericity could be obtained with niobium balls lapped and polished by state-of-the-art techniques. Two ½- and two 1-in. diam balls were prepared to a sphericity of 5 $\mu$ in. by Harold Arneson. His answer to the question of still further improvement in sphericity is answered in Appendix B.

***b. Dimensional stability and elastic constants.*** To what extent does a sphere of Nb deform when cooled to 4.2°K, or after temperature cycling? This question of dimensional stability to extreme temperature variations was the subject of a contract with Rice University. A related property, the elastic constants which are required for predicting centrifugal deformations of the spinning rotor, was also studied, and results were reported by Keith Carroll[5]; however, little information was gained with regard to dimensional stability. Graphs from the Report of the elastic constants ($C_{11}$, $C_{44}$, and $C_{12}$) as a function of temperature are displayed in Appendix C.

***c. Penetration of magnetic field into a superconductor.*** An implicit assumption in the proposal to employ a magnetically supported superconducting sphere as the rotor of a gyro was that the diamagnetism of the superconducting state would cause the magnetic field to vanish abruptly at the surface of the sphere at least within the few hundred Angstroms of *penetration depth.* To determine whether the *magnetic surface* of a niobium sphere coincides with its geometrical surface, a series of *static torque* tests was made. In these tests the ball was levitated by a pair of opposing (gradient) coils. Any initial oscillation was allowed to die out. The rotor was torqued with gas jets imparting a small amplitude rotational oscillation whose period was measured.

The restoring torques responsible for oscillation are presumably due to nonsphericity and trapped flux. The contribution due to trapped flux can be isolated by observing the period of oscillation before and after reversing the levitation field, inasmuch as torque due to trapped flux reverses sign when the field is reversed, whereas the torque due to nonsphericity is not affected. (In most tests the effect of trapped flux was negligible as a result of magnetic shielding during cool-down.)

An estimate of the upper limit on torque arising from nonsphericity is just $mg\delta r$, where $mg$ is the rotor's weight supported against gravity and $\delta r$ represents the maximum deviation of the surface from a true sphere. In highly purified rotors, periods are found to range from 25 to 50 sec. For small amplitude oscillations, the restoring torque is:

$$\tau = -k\theta = -I\left(\frac{2\pi}{T}\right)^2 \theta \leq -(mg\,\delta r)\,\theta$$

For one in. diam solid niobium spheres, $m = 70$ g, $I = 50$ g-cm$^2$, period $T = 35$ sec, the value for $\delta r$ is computed to be $> 2.3 \times 10^{-5}$ cm $\approx 9$ $\mu$ in. The sphericity of these rotors as measured on an Indi-Ron roundness tester is between 5 and 10 $\mu$ in., which suggests that the geometrical surface of a purified rotor does coincide with the surface that the magnetic field acts upon, at least within several $\mu$ in.

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[5] Carroll, Keith, "The Elastic Constants of Niobium Crystals and the Linear Expansion of Niobium," prepared for JPL (Purchase Order N1-120496, Requisition No. 51095), by the Department of Physics, William Marsh Rice University, Houston, Texas.

Other rotors which had been lapped without subsequent anneal, showed periods much less than those predicted from their measured sphericities. Furthermore an equilibrium axis could be found in almost any orientation of the rotor, which suggests a jelly-like behavior of the dirty *magnetic surface* in response to pressure.

***d. Flux trapping in niobium.*** The complete exclusion of flux from a specimen when it becomes superconducting is an idealized property of superconductivity. In practice, the Meissner effect is never complete; the specimen is always left with a residual fragment of the ambient field present during the transition. The residual field tends to be locked into the specimen once the entire specimen is below the transition temperature; hence, it is called *trapped flux*. Such a permanent magnetic moment trapped in a gyro rotor would interact with the levitation field to produce a drift torque. Accordingly, it is important to know how much flux trapping can be expected in a given specimen and how constant is the flux, once trapped; hence, the statement of objectives contained in Appendix D. The thesis[6] of Keith Carroll forms the final report of this investigation. The results of greatest interest are: (1) the trapped flux distribution does not necessarily coincide with the ambient field during transition, (2) rotation of the specimen during transition can cause a significant decrease in trapped flux, and (3) flux, once trapped, is extremely stable as long as the temperature remains constant. Unfortunately no investigation was made of the dependence of flux trapping on specimen purity and homogeneity. It would have been of interest, too, to determine whether the percentage of flux trapped remained constant, independent of ambient field, at fields below a milligauss.

***e. Alternating magnetic field losses in superconductors.*** One of the principal concerns from the onset of the gyro program at JPL was the possibility of minute eddy-current dissipation in a superconductor exposed to an alternating magnetic field. Such dissipation at rotor frequencies (50 to 400 cps) for specimens well below their transition temperature had never been observed by previous investigators (Refs. 4–6), but their techniques were insufficiently sensitive to reveal losses as small as $10^{-3}$ w/cm$^2$, while losses as small as $10^{-7}$ w/cm$^2$ are significant for a cryogyro. Dissipation due to rotation in a magnetic field not only produces a loss of rotational kinetic energy, but causes a drift of the angular momentum vector as well, inasmuch as the eddy current or hysteresis drag torque is not necessarily parallel to the spin axis. The first opportunity to measure ac losses in superconductors came with the first test of a rotor spinning about a horizontal axis (initial spin tests were about the vertical axis, which is the symmetry axis of the magnetic field). Losses in niobium and vanadium rotors while spinning in a vacuum were sufficient to cause the rotors to fall within 15 minutes due to exceeding the critical temperature. Tests on lead and tin superconducting specimens showed ac losses in these elements as well. This problem precluded resumption of gyro tests for two years, until techniques for reducing losses to acceptable levels were discovered. In the case of niobium, reduction of ac losses is accomplished by prolonged outgassing at 2000°C and $10^{-8}$ torr for 150 hr or more. This technique was developed in conjunction with Jaan Jurisson at Minneapolis-Honeywell. Outgassing not only reduces ac losses by two orders of magnitude, but also enhances the Meissner effect to the point where a Nb sphere will levitate when it cools through the transition in the presence of a levitation field. A record of rotor treatments is noted in Footnote 7. Appendixes E, F and G and Ref. 7 are reports of the study of ac losses conducted at JPL.

***f. The London moment.*** A spinning superconductor generates a magnetization (the London moment) parallel to the spin axis and of magnitude $2m\omega/e\mu_0$ (MKS). This magnetic moment interacts with the levitation field to give rise to a restoring torque. Although the effect on drift (about 1 deg/day) is too small to measure thus far, it is hoped that further testing will reveal its presence by virtue of its dependence on rotational speed.

## B. Fabrication of a Superconducting Rotor

A remarkable fact about field-supported gyros is that performance depends primarily on the perfection of the rotor. In fact, if the superconducting surface of the cryogenic gyro rotor is perfectly spherical, there will be no torque due to field, regardless of the supporting field configuration (provided only that the breakdown field is not exceeded). Because the rotor appeared to be a well-defined development problem and because JPL did not have the facilities or experience for such an effort, a decision was made to contract for the rotor. Appendixes H and I are the request for proposal and specifications,

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[6] Carroll, Keith J., "A Comparative Study of Flux Trapping in Superconducting Tin, Lead and Niobium Crystal Spheres," prepared for JPL (Purchase Order K2-181755, dated May 23, 1963; Change Order K2-18175 C/O H2, dated June 4, 1963), Rice University, Houston, Texas.

[7] JPL Section 345 File on Purchase Orders No. CG 4-312972, and No. BK3-211721.

respectively, for this contract. GE, Vitro Labs, IBM, Minneapolis-Honeywell, Arthur D. Little, and Nuclear Metals, Inc., submitted proposals. Nuclear Metals, Inc. (NMI), on the basis of their proposal (Ref. 8), was awarded the contract. Both quartz and Lucalox (GE alumina) were tested as substrate materials, and hold promise as acceptable materials, although further development is still required. The niobium coatings were prepared by pyrolytic deposition from $NbCl_5$ vapor. During deposition the substrate was heated and levitated in a gas bearing by a plasma torch. The film, thus produced, did exhibit traces of superconductivity (GE's subsequent experience with $NbI_5$, which does not require as high a temperature, has demonstrated good superconducting coatings on beryllia). Coatings obtained did not cover the substrate uniformly, due to preferential rotation in the gas bearing during deposition. Lastly, a technique for placing a pattern on the niobium surface was demonstrated and has proved very useful with solid niobium rotors. This involves photoresist techniques and anodization of the niobium. In retrospect, it is unfortunate that the Nuclear Metals contract was not extended to completion of the stated objectives, particularly in view of GE's success (including low ac losses) with a later very similar program. However, since at that time, ac losses had just been discovered, threatening the feasibility of the cryogyro concept, work on the coated rotors was terminated while an investigation of ac losses in bulk material was pursued. References 9 and 10 contain the results of the NMI contract.

## III. SUPPORTING FIELD CONFIGURATION

The initial attempt to analyze the forces exerted on a superconducting sphere by an array of current coils was accomplished by straightforward computer calculations described in Appendix J. Correlations between experiment and theory, utilizing computer techniques, are contained in a paper presented at the 1960 Cryogenic Engineering Conference (Appendix A). Subsequently, an analytical solution (Ref. 11, and Appendix K) was obtained for forces and torques acting on a spheroid in an axially symmetric magnetic field. This analysis has been extended to arbitrarily deformed spheres (Ref. 12) and to arbitrary magnetic fields (Ref. 13 and Appendix L). These latter calculations proceed from the philosophy that it is easier and more revealing to work in terms of the parameters describing the field, rather than in terms of the parameters of the coils which ultimately produce the field. The most significant result of this analysis is that torque due to rotor nonsphericity is the result of interaction between a symmetry mode of the rotor surface and a corresponding symmetry mode of the square of the magnetic field acting on the surface. In particular, if the field squared is expanded in a series of Legendre polynomials:

$$B^2 = a_1 \cos\theta + a_2(3\cos^2\theta - 1)/2 + a_3(5\cos^3\theta - 3\cos\theta)/2 + \cdots\cdots$$

then the torque appears in the form:

$T = a_1\,\delta_1 \sin\alpha + a_2\,\delta_2 \sin\alpha\cos\alpha + a_3\,\delta_3 \sin\alpha\,(5\cos^2\alpha - 1) + \cdots\cdots$ where $\alpha$ is the angle between the field symmetry axis and the rotor spin axis, $\delta_1$ is a coefficient describing rotor mass unbalance, $\delta_2$ describes rotor ellipticity, etc. This suggests setting all of the $a$'s equal to zero, but this obviously would eliminate levitation. In fact, the $a_1$ term alone is responsible for levitation, but even so, not all the remaining $a$'s can be zero since $B^2 = a_1 \cos\theta$ requires imaginary $B$. Nonetheless, it is possible to make certain $a$'s zero, which eliminates the torque due to the corresponding mode of nonsphericity. The elimination of torque due to ellipticity is demonstrated in Ref. 14 and is illustrated graphically in a motion picture taken during experimental verification of the theory.

Torque due to interaction between trapped flux and the levitation field is calculated in Ref. 15.

In all gyro tests the field configuration used was a uniform gradient field. This has the primary advantage of analytic simplicity and, by permitting a sizable gap between field and coils, it makes the gyro design much more flexible. However, it has the disadvantages of relatively low restoring forces and large sag which is awkward for readout. Figure 2 illustrates the suspension of a 1-in. Nb rotor in the field produced by a Maxwell gradient pair of coils.

A technique for reversing the levitation field without interrupting a gyro test has been demonstrated. This capability is useful for separating the effect due to trapped

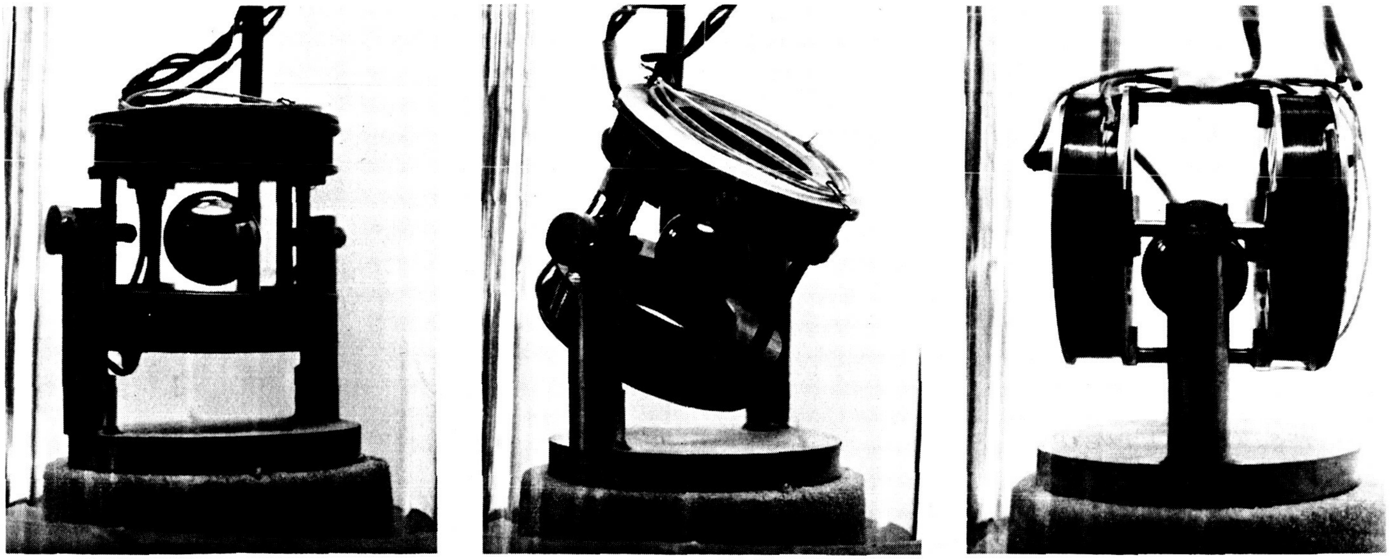

**Fig. 2. Levitation of 1-in. diam Nb rotor in field produced by Maxwell's gradient pair (7000 amp-turn/coil)**

flux (which depends on the magnitude and sign of the applied field) from the effect due to nonsphericity (which depends on the square of the applied field). To avoid dropping the rotor, the field must be reversed rapidly. This is done by causing the levitation coils to break down through application of a strong external reverse field. Reversals have occurred within 5 msec, without loss of levitation. Details are available in Ref. 16.

## IV. SPINUP

To accelerate the ball to operating speed, jets of helium gas are directed against the equator of the rotor. The gyro housing is a double-walled pyrex glass container depicted in Figs. 3, 4 and 5. Helium gas for accelerating the rotor is conducted down through the annular region, past the radiation baffles and exits through two tangentially directed jets located around the levitated rotor. The jets are 0.020 in. in diam and are drilled through the glass wall by a sand-blasting technique. In practice, a flow of 15 std ft$^3$/hr of helium gas is used to accelerate the rotor. It requires approximately 15 min to reach 100 cps, and 40 min to reach 200 cps. A speed of 300 cps appears to be the limit of the present design with the 15 std ft$^3$/hr flow. The 150 ft$^3$/min evacuation pump can maintain an absolute pressure of 3 mm Hg downstream and 5 cm Hg upstream from the jets at 15 std ft$^3$/hr flow.

When operating speed is reached, the two-way stopcock is rotated which stops the gas flow and initiates pumping on the annulus. (The jets are too restrictive to rely on for annulus evacuation.)

Since there is negligible friction, it is unnecessary to have a continuously operating spin motor. In a vacuum exceeding $10^{-6}$ torr, a rotor has been observed to have lost only 0.9 cps out of an original 200 cps during a period of 64 hr. At this rate the rotor would continue turning for 600 days.

It was found impractical to attempt to predict the rotor deceleration due to gas drag vs pressure on the basis of kinetic theory. This is because the accommodation coefficient for the rotor surface is not known and the pressure is also uncertain. The latter is due to the fact that the ion gauge is calibrated for air or nitrogen and not specifically for helium; and furthermore, the large temperature difference between the rotor and the ion gauge necessitates a correction for the thermomolecular pressure

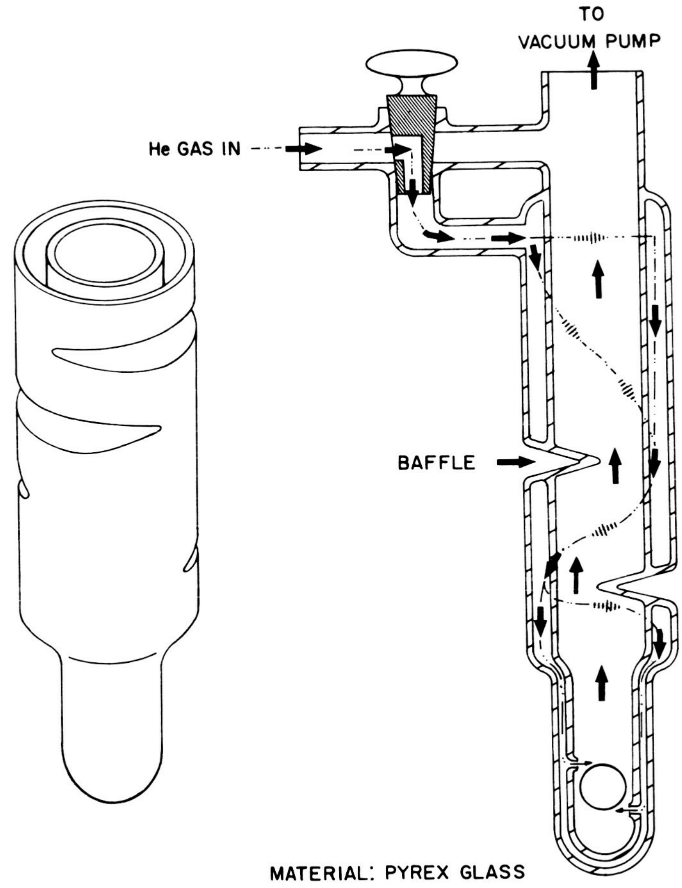

Fig. 3. Gyro housing schematic

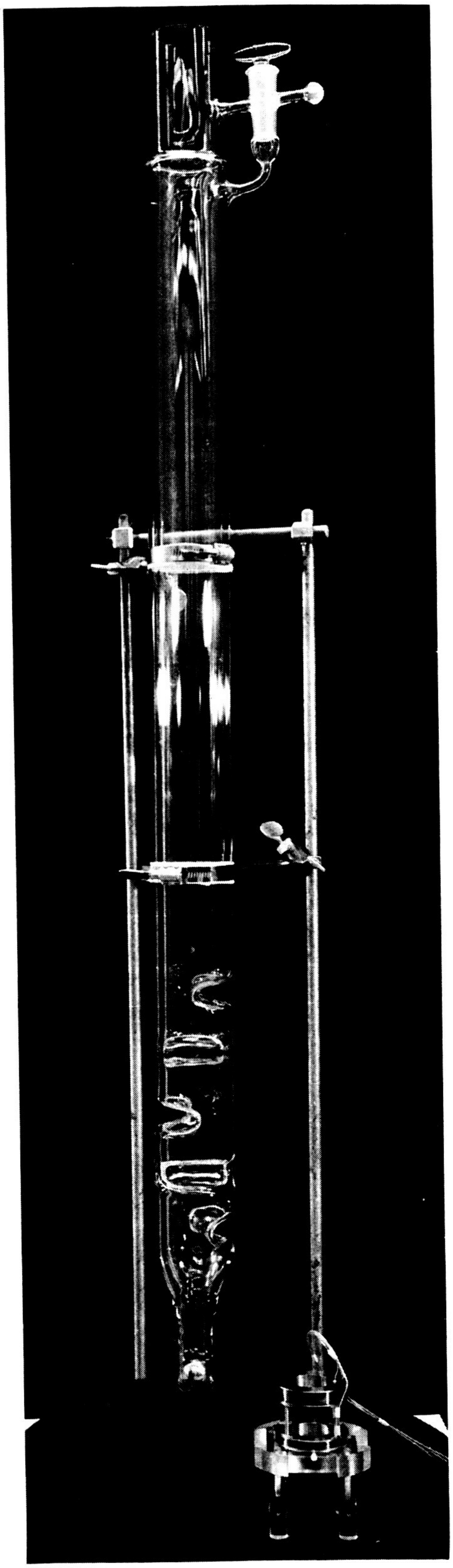

Fig. 4. Glass housing, full length

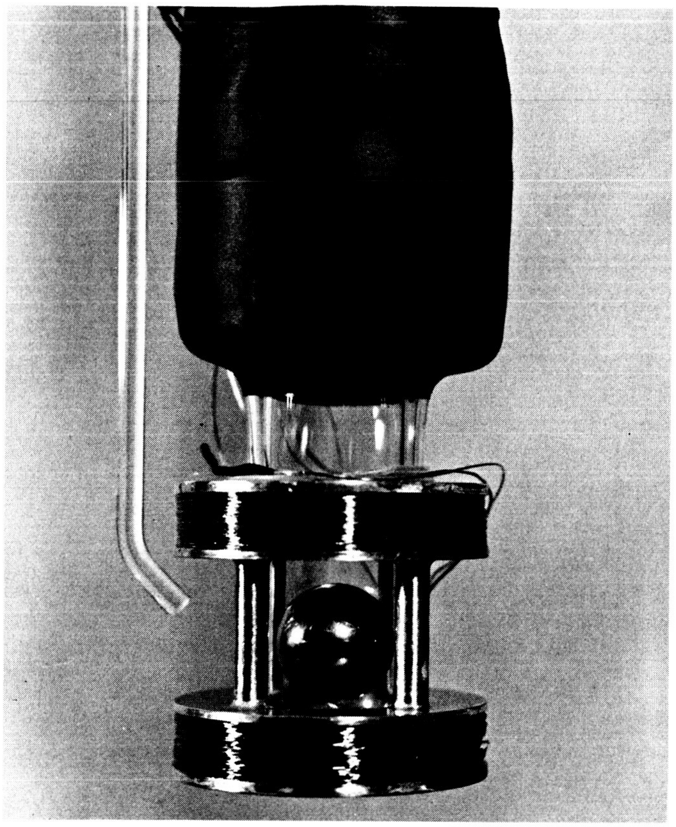

Fig. 5. Glass housing, detailed

difference at low pressures. Hence, it was prudent to have an actual calibration between deceleration and ion gauge pressure readings. In these tests, the rotation axis was vertical (parallel to the levitation field symmetry axis) to avoid ac losses. This condition was maintained by deliberately mass-unbalancing the rotor. The pressure was held constant by a Granville Phillips automatic pressure controller. The speed of the rotor was monitored by electronically counting rotor revolutions for 100-sec intervals by means of a photo-optical sensor. The calibration for a 1-in. Nb rotor is shown in Fig. 6. The linear region of deceleration vs pressure is identifiable as the Knudsen or free molecular range. The deceleration becomes independent of pressure in the continuum region of higher pressures.

Alternative techniques for rotor spinup were also investigated. For a time, plans called for spinning the ball by supporting it by ac levitation, in the normal state, just above the transition temperature, while torqueing it with a rotating magnetic field. Upon completion of spinup, the sphere could be cooled (e.g., by transfer gas) to less than $T_c$ and the levitation switched to dc. The high conductivity of metals at low temperature makes this appear feasible in that the eddy-current dissipation is of the order of $0.5\alpha$ watt in a 1-in. solid Nb ball (if the resistivity is given by $\alpha \times 10^{-6}\ \Omega$-cm). The optimum frequency is of the order of $30\alpha$ cps. However, the possibility of introducing trapped flux with this technique discouraged continuing its development. Another technique involved sealing the gyro rotor within a second rotor, which could be spun-up on a gas bearing. Cooling of the gyro rotor was accomplished by sealing some hydrogen gas in with the ball. This provides adequate gaseous conduction down to 6 or 7°K. Below 5°K the vapor pressure of hydrogen produces negligible viscous drag on the ball. Reference 17 gives a brief description of the gas bearing spinup system.

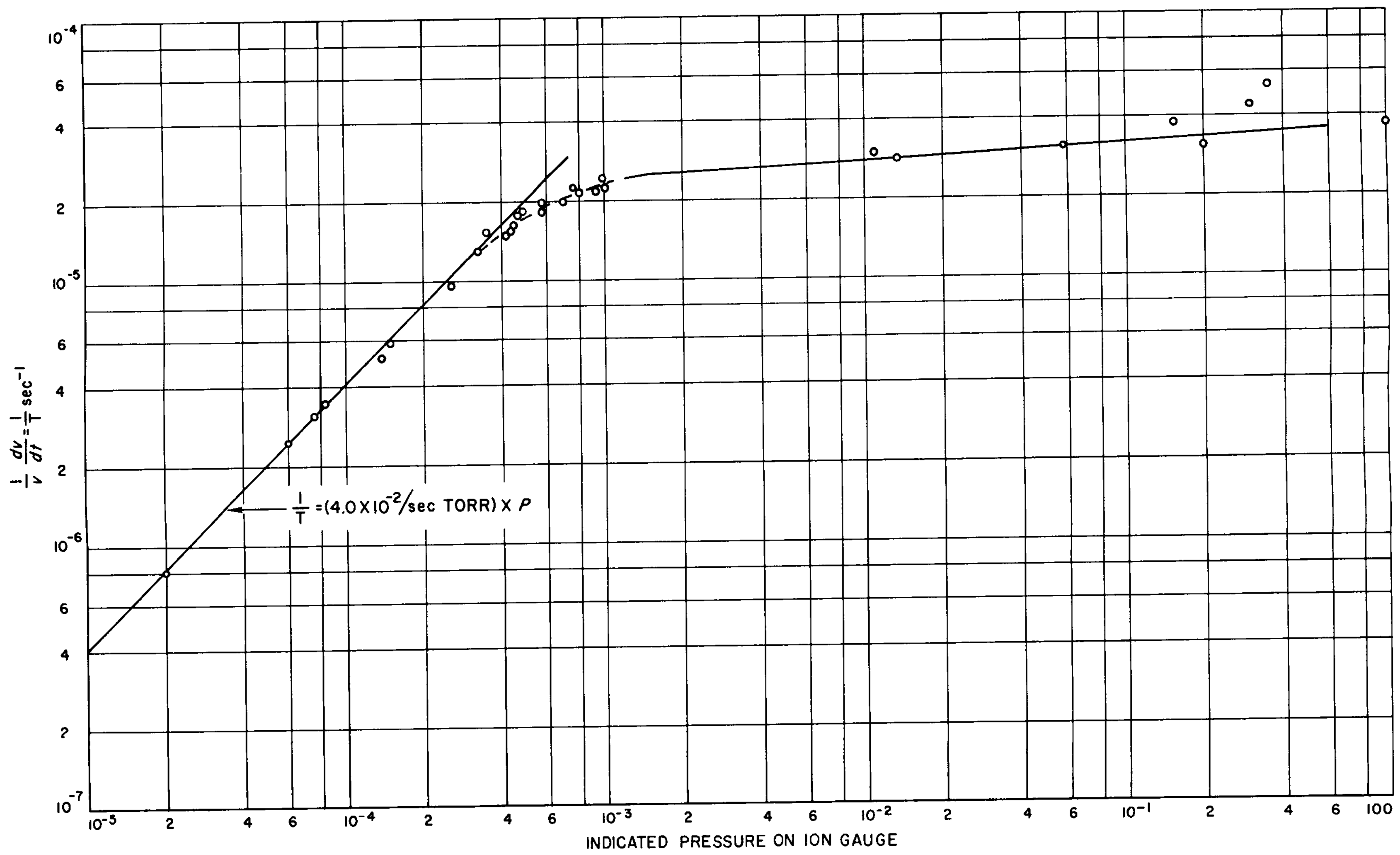

Fig. 6. Slowdown rate $[(1/v)\,(dv/dt)]$ vs pressure for 1-in. Nb balls in vertical spin rig

# V. MAINTENANCE OF CRYOGENIC TEMPERATURE

One of the principal concerns expressed by Simon in Refs. 1 and 2 was that it might prove very difficult to maintain the superconducting temperature of the rotor while it is exposed to electromagnetic radiation required for observation. If it were necessary to rely on radiation to dissipate heat, this would be so; but fortunately, it is possible to depend on gas conduction for heat transfer without expecting an excessive amount of deceleration due to gas drag. In fact, the ratio of heat transfer by radiation to heat conduction is:

$$\frac{Q_R}{Q_C} = \frac{\epsilon\,\sigma\,(T_2^4 - T_1^4)}{a_0\,\lambda\,p\,(T_2 - T_1)} = \frac{\epsilon}{a_0}\;7.5 \times 10^{-8}\ \text{torr}/p^{\dagger}$$

for an object at $T_2 = 5°K$, surroundings at $T_1 = 4°K$, and $\lambda = 280$ w/m$^2$°C torr (for helium), Ref. 18. If the ratio of emissivity to accommodation coefficient $\epsilon/a_0 = 1$, then the pressure would have to be less than $p^{\dagger} = 7.5 \times 10^{-8}$ torr before radiation exceeded conduction.

On the other hand, the exponential deceleration due to gas drag has a time constant given by kinetic theory as:

$$T = \frac{r\rho}{5p}\left(\frac{2\pi RT}{M}\right)^{1/2} = 325\ \text{sec torr}/p^{\dagger}$$

for a 0.5-in. radius, solid, niobium sphere ($\rho = 8.5$ g/cm$^3$) spinning in helium ($M = 4$ g/mole).

At a pressure of $10^{-5}$ torr$^{\dagger}$, the decay time is $T = 3.25 \times 10^7$ sec while the heat conduction from the sphere at 5°K to surroundings at 4°K is $5.7\mu\text{w} \times a_0$. Hence, if all other sources of heat influx are made negligible, several $\mu$w of heat due to readout illumination can be *conducted* away with a 1°K temperature rise and a gas drag decay time of one yr.

The most important other source of heat influx is thermal radiation from those parts of the apparatus surrounding the rotor which are not at liquid helium temperature. Ideally, the rotor would be completely enveloped by a black body at 4.2°K. This is not possible in practice because provision must be made for the transmission of electromagnetic radiation for readout purposes and an exhaust tube must be provided for evacuation. This tube ultimately connects to a higher temperature region. Without radiation baffles in the exhaust tube, the rotor has been observed to fall in only six min after evacuating the gyro chamber to $10^{-6}$ torr. This then, is one reason for the baffles shown in Fig. 3. They are staggered and painted black, providing an optical barrier to radiation travelling down the tube while permitting efficient evacuation of gas and insertion and removal of the rotor. The baffles serve two other purposes as well: (1) they act as a heat exchanger for cooling the spinup gas by virtue of the circuitous path they provide for the descending gas, and (2) the baffles join the inner and outer walls of the housing, so that the inner wall reaches the same temperature as the outer wall. Without this thermal contact, the temperature of the inner wall rises (due to heat flow from warmer regions) whenever a high vacuum exists in the housing.

The housing is immersed in liquid helium contained in a stainless-steel Hofman research Dewar shown in Fig. 7. A liquid-nitrogen shield surrounds the helium bath and both chambers share a common insulating vacuum jacket. It has been necessary to use a wad of glass wool between the glass housing and the liquid helium wall of

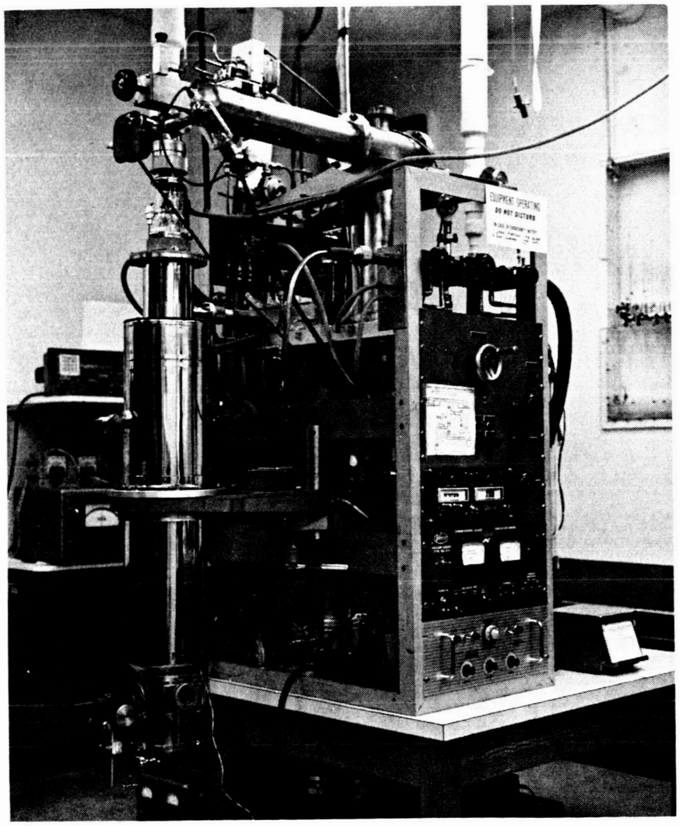

**Fig. 7. Cryogenic gyro in Dewar**

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$^{\dagger}$As read on a room-temperature pressure gauge. The thermomolecular pressure effect requires $p/T^{1/2}$ = constant in the free molecular pressure range.

the Dewar, above the liquid helium level; this is to attenuate Rayleigh thermal oscillations, which otherwise cause rapid liquid helium boiloff.

The Dewar was designed for general purposes and is equipped with 5 optical windows surrounding the experimental region at the bottom. Only two of these are used for readout, however, with the remainder blanked off with metal caps. Each port through the Dewar has three components: a pyrex or quartz, outer, room-temperature window. The inner, liquid-helium temperature window is sapphire, soldered to a Kovar retaining ring. Infrared radiation originating from room-temperature surroundings is prevented from reaching the experimental region by a middle window which is sealed into the hole provided in the copper liquid nitrogen shield. Originally this was a sapphire disk, coated with a partially reflecting layer of gold. (Gold is a very effective absorber in the infrared.) Recently it was replaced by Jena KG-3 heat-absorbing glass which absorbs infrared without any annoying reflection in the visible.

If the Dewar were to be redesigned, the tail of the Dewar should be considerably narrower to permit bringing the readout microscope closer to the rotor, thus reducing the working distance, increasing the magnification and improving the illumination.

With the present Dewar, about 7 liters of liquid helium are required for initial filling. Subsequently, the Dewar is topped off every 24 hr, which consumes 3 to 4 liters (including transfer losses).

## VI. DAMPING

A superconducting ball supported by a persistent current in a superconducting circuit is virtually a loss-less system. Translational rotor oscillations excited by transient or periodic accelerations of the gyro housing will persist almost indefinitely, if no provision is made for damping.

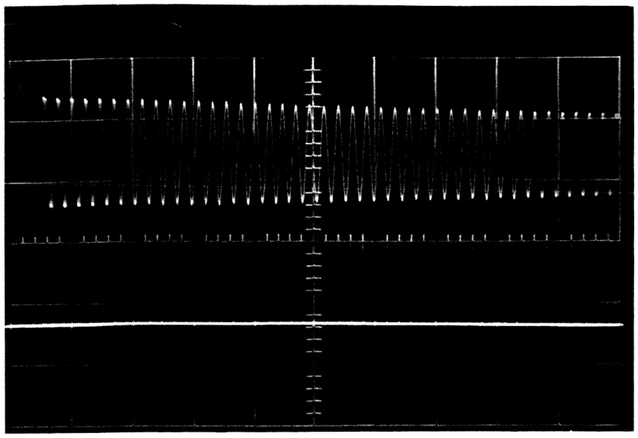
An active damping system involves a method for detecting the deflection of the ball and a feedback system for driving it back to a null position. This approach would require power and would add complexity to the otherwise simple persistent current suspension coils.

Alternatively, damping can be provided passively by means of eddy currents induced in a conductor placed in the levitation field. The excursions of the ball alter the magnetic field configuration; these changes in the field generate the eddy currents.

The dissipation produced by a thin, resistive spherical shell surrounding the rotor has been computed for the case where the shell radius is much larger than the rotor radius (Appendix M). The case of a conducting ring around the ball has also been studied and the calculations show that damping approaches critical as the radius of the ring approaches the radius of the sphere. Experimentally, an inefficient geometry was studied wherein the damping element is an oxygen-free high conductivity (OFHC) copper coil form, which also supports the niobium levitation coils (see Fig. 5). The effectiveness of high conductivity copper relative to brass in damping vertical oscillations is displayed in Fig. 8. The dimensions of the coil forms are nearly identical. It is important to note that the resistivity of the OFHC copper reduces by a factor of 100 between room temperature and 4.2°K, whereas the resistivity of the alloy hardly changes with temperature. The thickness of the copper flanges was reduced until the decay time for eddy currents induced in the ring at 4.2°K was equal to the natural period of oscillation of the rotor. Prior to the use of copper in the coil form, oscillations would build up during spinup of the rotor, which would occasionally become severe enough to cause the rotor to contact the housing. No buildup of oscillations has ever been observed with the copper forms.

The problem of obtaining maximum damping has not yet been solved in detail, although it is apparent from the arguments of Appendix N that the best geometry is a closely fitting resistive shell enclosing the levitated sphere. If the thickness and resistivity of the shell are properly chosen to make the decay time for eddy currents equal to the natural period of oscillation of the suspension, it should be possible to approach critical damping ($Q \approx 1$).

BRASS COIL FORM – 8.41 cps, $Q \simeq 1000$



OFHC COPPER COIL FORM – 8.31 cps, $Q \simeq 60$

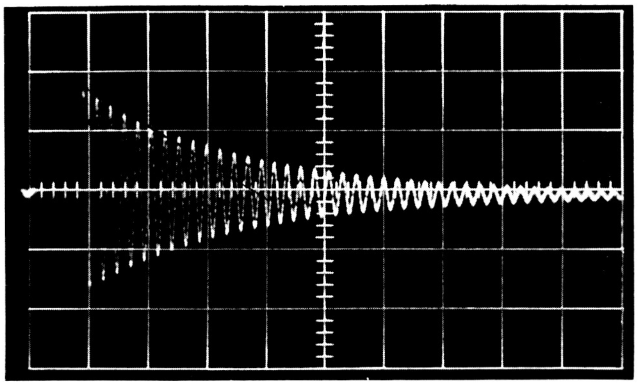


**Fig. 8. Decay of vertical rotor oscillations**

## VII. READOUT

A rotor possessing a perfectly spherical surface obviously presents a problem insofar as readout is concerned. However, this is a problem shared by the electrostatic gyro (ESG). Since the development of the ESG had several years lead on the cryogyro, it was decided at the onset of this program to concentrate on other problems and to avoid any independent development on readout, in the expectation that a suitable system would be available by the time drift tests could be initiated on the cryogyro. Visits to the University of Illinois Coordinated Science Laboratory, and to General Electric and Minneapolis-Honeywell, all of which were pursuing ESG development, indicated that a variety of promising solutions to the readout problem existed, and that most of the techniques were applicable to the cryogyro with little modification. All of these were optical systems and involved placing patterns on the rotor and using photocell pickoffs.

However, when the first tests of the high sphericity outgassed rotors in early 1964 revealed that drift rates were well below Earth's rate, no provision had yet been made for readout and it was necessary to improvise a

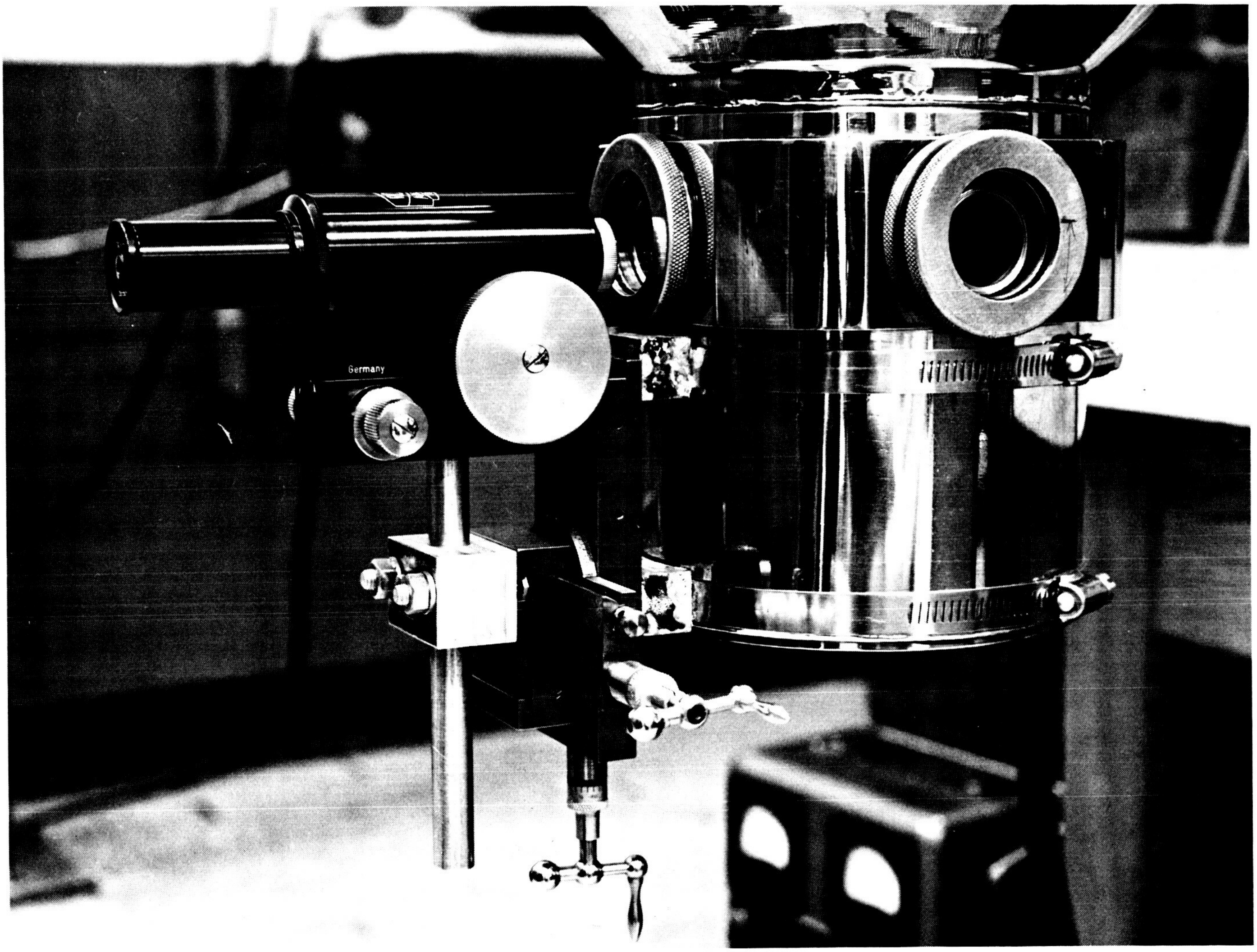


Fig. 9. Microscope for end axis readout

system which, while reasonably accurate in the data it did yield, provided only two measurements per day. This system consisted of a microscope mounted on the west window of the Dewar (Fig. 9). Since the rotor was spun-up about an east-west axis, the pole was initially visible in the field of view of the microscope and could be identified as the center of a series of concentric rings formed by the rotation of irregularities on the surface of the rotor. The cross hairs of the microscope were set on the axis and the time recorded. Subsequently, the pole would move out of sight in an apparent rotation about the Earth's axis caused by the diurnal motion of the Earth. Approximately 12 hr later the opposite pole would enter the field of view, and the times of crossing each crosshair were recorded. The amount of Earth's rotation in the interval since the setting of the cross hairs is readily computed. The difference between the Earth's rotation and 180 deg is the drift during the interval. Subsequent sightings of the poles crossing the crosshairs determined the cumulative drift every 12 hr or so. In this way drift data of the type shown in Fig. 10 were obtained for three 1-in. diam niobium rotors. Determination of the crossings is accurate to ±1 min of time which corresponds to ±15 min of arc.

In one test, rotation was obtained about an axis only a few degrees away from the Earth's axis[8]. The path of the pole was continuously visible in the field of view of a microscope mounted on the north Dewar window, and could be tracked by the vernier stage on which the microscope is mounted. The trace of the pole as shown in Fig. 11 was obtained in this way.

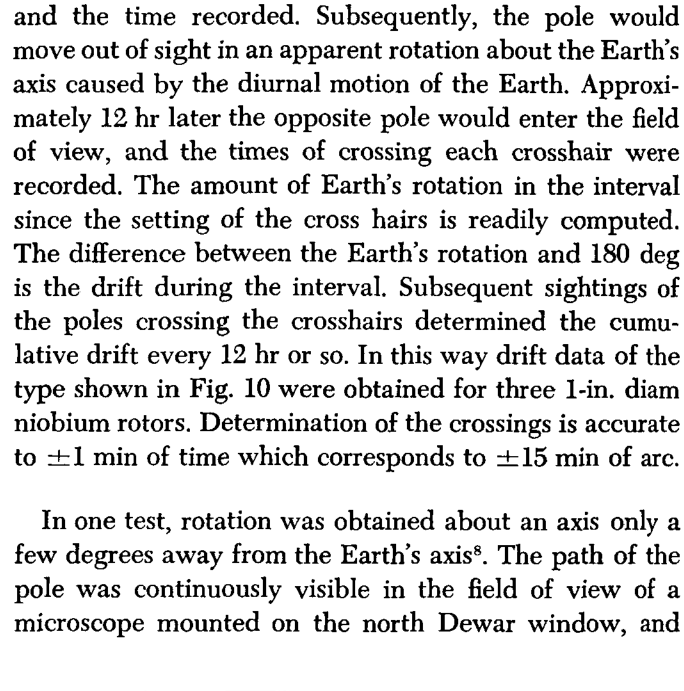


**Fig. 10. Drift vs time for three Nb rotors, equatorial mode**

To achieve an all-attitude readout applicable to a rotor not having a preferred axis, a number of techniques were conceived, of which some are discussed in Appendix O. Various constraints, such as manpower and time schedule, have led to adopting the following scheme, which, while being simple and quick to develop, may not have the accuracy capabilities required for an operational gyroscope. The basic idea is to deposit a phosphorescent layer on the surface of the rotor; an ultraviolet beam directed at the spinning ball will trace out a circle in a plane perpendicular to the spin axis. Determination of this plane is equivalent to determining the spin axis. This concept was proposed in a 1959 memorandum (Appendix P), but was not pursued until 1965 when Robert Tuffias at Stanford University demonstrated the tracing of a circle on a phosphorescent coated rotor (Ref. 19) at room temperature. Subsequently, the phosphor has been tested at JPL on an operating cryogyro rotor. Not only does the glow persist at 4.2°K but the phosphor does not appear to affect either the ac losses of the rotor or the drift rate.

Determination of the plane of rotation involves two dark field microscopes. The ultraviolet beam is focused at the center of a microscope's field of view by an annular illuminator surrounding the objective lens. Rotation of the phosphor-coated ball produces a glowing arc across the field of view. The orientation of the tangent to this arc at the intersection of the reticle crosshairs is read out on a protractor eyepiece. Since the glowing arc traces a latitude line on the spinning sphere, a great circle constructed perpendicular to the arc passes through the spin axis. It is clear that two such circles obtained from two separate microscopes will intersect at the rotor poles. This construction is done mathematically and requires only the two protractor readings to determine the orientation of the spin axis relative to the orientations of the two microscopes. In practice, the two microscopes are oriented with their optic axes east-west and north-south, both in a horizontal plane (Fig. 12). They are aligned by reference to *Polaris*. The overall accuracy of this technique is estimated to be ±5 min of arc which is adequate for preliminary drift data.

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[8] This was accomplished by aligning the housing so that the gas jets produced rotation about a horizontal N-S direction. The gas jets were activated twice, 12 hr apart, for equal periods; the resultant of which is a spin vector along Earth's axis (neglecting drift).

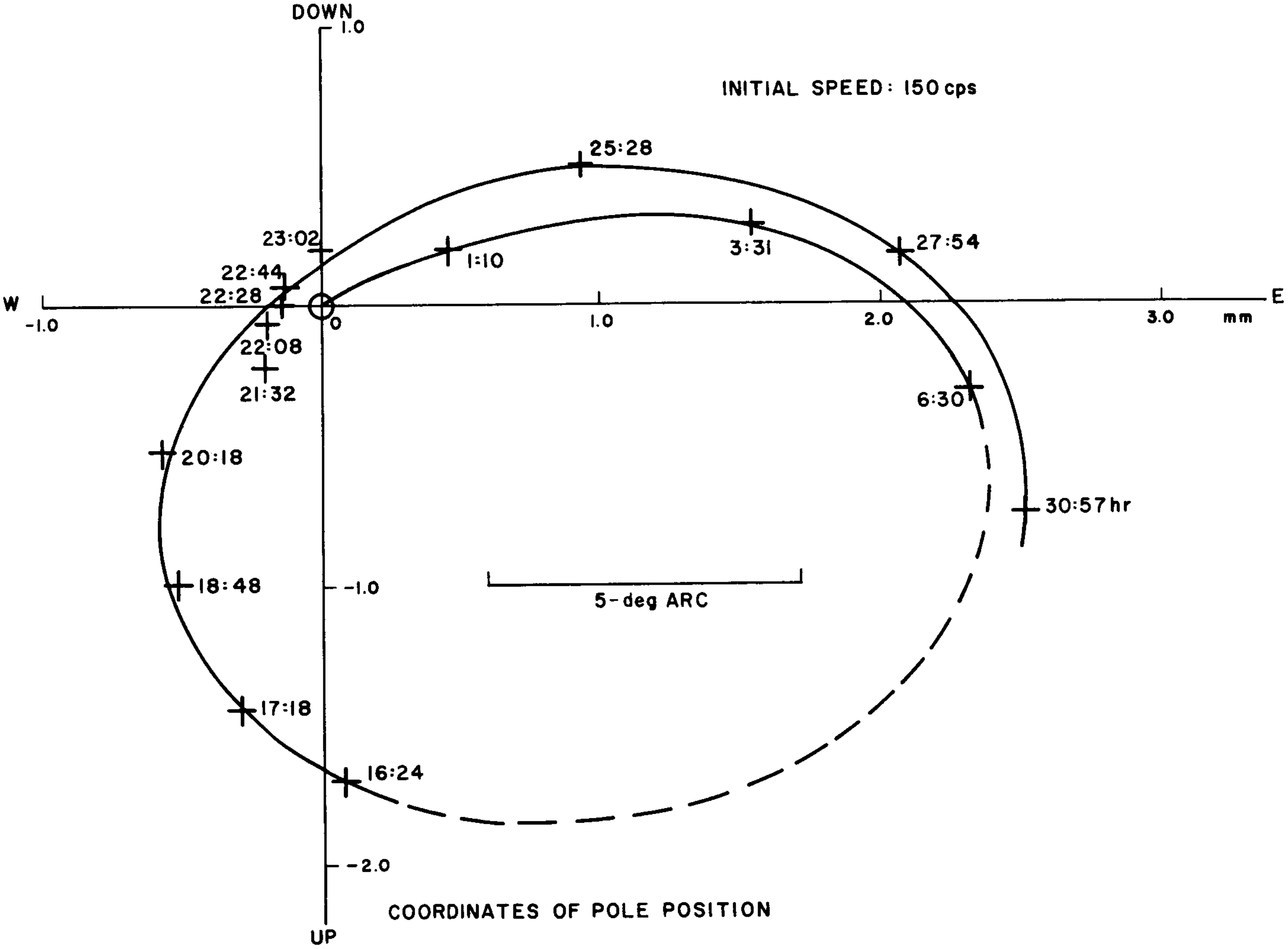

Fig. 11. Polar mode drift, Rotor MH6

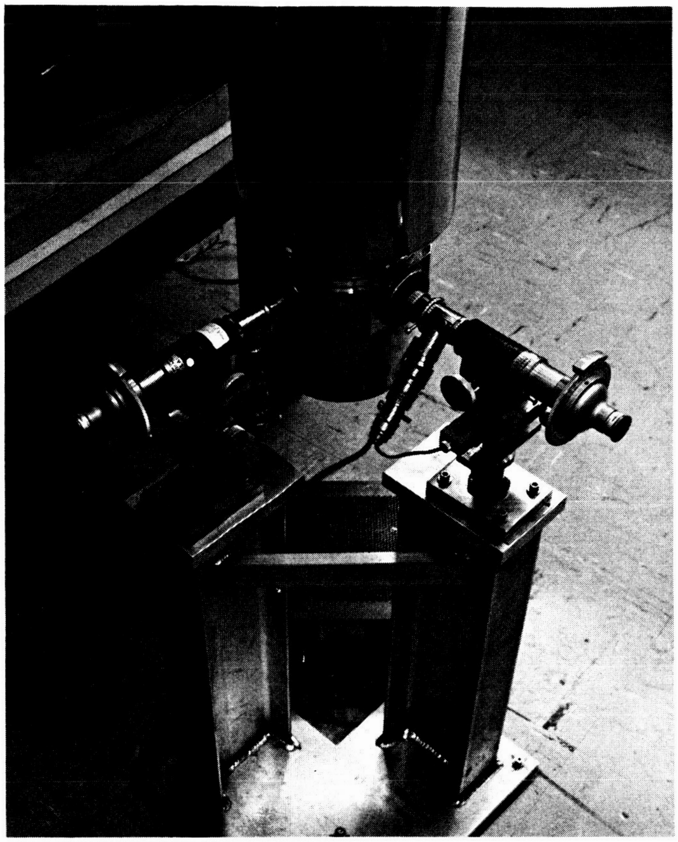

Fig. 12. Dark field microscopes for phosphor readout

## VIII. DRIFT TESTS

A drift test consists of measuring the angular displacement (in inertial space) of the gyro spin axis from an initial orientation. Ideally, one would like to have a continuous plot of displacement vs time to permit calculation of the time rate of drift as a function of the angle between the spin axis and the levitation field axis, thus testing the prediction of torque given by the mathematical model (Section III).

Lack of an all-attitude readout system has restricted data taking to only two points per day as described in Section VII. Thus only those effects which do not average to zero over a half-day period are observable. These include mass unbalance and uniform trapped flux.

Initial drift tests on three rotors furnished by Minneapolis-Honeywell are reported in Appendix Q and Refs. 20 and 21. These data are reproduced in Fig. 10 and summarized in Table 1. These tests are designated *equatorial* because the rotor spin axis was initially aligned

**Table 1. Drift data for three rotors**

| Rotor | Speed range, rps | Length of test, hr | Average absolute drift rate, deg/hr | Average torque required to produce drift* dyne-cm | Static period, sec |
|---|---|---|---|---|---|
| MH2 | 251–219 | 71.5 | 0.056 | 0.020 | 25 |
| MH3 | 240–196 | 92.3 | 0.562 | 0.19 | 45 |
| MH4 | 99–88 | 49.5 | 3.13 | 0.45 | 20 |

*$\tau = I\omega\Omega$.

parallel to the Earth's equator. The nature of the drift is such that the spin axis tends to remain in the equatorial plane, but to a first approximation, rotates uniformly in this plane. Superimposed on this are small amplitude cyclic displacements, both in the plane and perpendicular to it. The frequency of the cycle is Earth's rate (360°/sidereal day) plus the uniform component of drift rate. Only the equatorial drift is shown in Fig. 10. The uniform rotation is represented by the ramp function, which passes through points separated by one period (approximately one day). The intermediate data gives evidence of cyclic variations superimposed on the ramp. If continuous data were available, it would show the details of the cycle. The reason for the cycle, of course, is the cyclic motion of the (vertical) symmetry axis of the levitation field, relative to the drifting rotor spin axis, as a result of Earth's rotation.

The *static period* in Table 1 is the pendulous period of a levitated rotor before spinup. Mass unbalance, asphericity and trapped flux contribute to the restoring torque which is computed from the period T by the relation:

$$\frac{\tau}{\theta} = \left(\frac{2\pi}{T}\right)^2 I, \qquad I = \text{moment of inertia}$$

Thus for rotor MH2 with a static period of 25 sec, $\tau/\theta = 3.17$ dyne-cm/rad. In view of this calculation, it is surprising that the average torque acting on the rotor is only 0.020 dyne-cm. Equally surprising is the fact that MH4, with the longest static period, has the highest average drift rate. There appears to be no correlation between drift rate and static-restoring torque.

To test reproducibility of data, three drift tests were made with rotor MH2, with the results shown in Fig. 13.

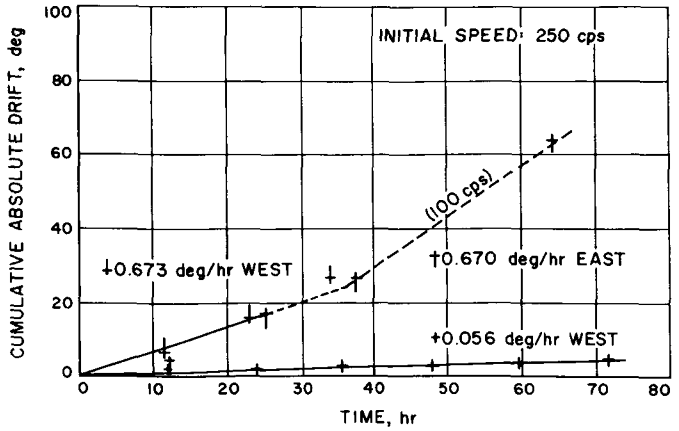

**Fig. 13. Equatorial mode drift; Rotor MH2**

The very low average drift (0.056 deg/hr) of the first test was not repeated on the subsequent tests. The latter showed average drifts over ten times as great. In one case the drift was eastward (i.e., in direction of Earth's rotation, while in the other two cases the drift was westward. Thus the data are not reproducible from test to test. However, the day-to-day reproducibility within a given test is excellent. A least squares fit of the data of Fig. 10 to a linear function yields the standard deviation of 0.28 deg in the case of MH2 and 0.53 deg in the case of MH3. Since these deviations from a linear estimate are the same size as the observational uncertainty (±15 arc min), the predictability is presently limited by an inadequate readout technique.

The lack of reproducibility from test to test is easily explained. The rotor has no strongly preferred axis and the method of gas spinup provides no control over choice of rotor axis. Thus, the initial axis of rotation within the rotor is random from one spinup to the next. Subsequently, the pole wanders around the surface of the rotor. The path of the pole, the polhode, is a closed curve in the absence of dissipation. Ordinarily, damping causes the pole's path to spiral into the maximum moment of inertia axis, but in the case of a superconducting sphere, loss mechanisms are rather scarce. Polhodes with periods of several minutes are observed during a typical gyro test. No significant deviation of the path on the ball's surface in a given run has been observed, even after several days of operation. Because most of the sources of torque are fixed within the rotor, it is clear that the polhode motion tends to average out the torque. If the polhode were a great circle, it would be expected that the torque averaged over the complete path would be zero (provided, of course, that the drift rate is much less than the polhode traversal rate). Indeed the three tests on rotor MH2 tend to confirm this theory—the greater the length of the polhode, the less was the drift. This theory also explains why the drift is less than that calculated from the static period, for the latter assumes a worst case example, wherein the ball spins steadily about the equilibrium axis. This requires that the equilibrium axis be a principal axis and that initial spinup occur about that axis—a most unlikely pair of circumstances. In fact the rotor is spun-up about an axis at right angles to the equilibrium axis, inasmuch as rotation is effected about the horizontal, whereas the equilibrium axis is vertical, once initial oscillations have died out.

In one test on MH2 after the drift was measured at an initial speed of 250 cps, the speed was reduced to 100 cps

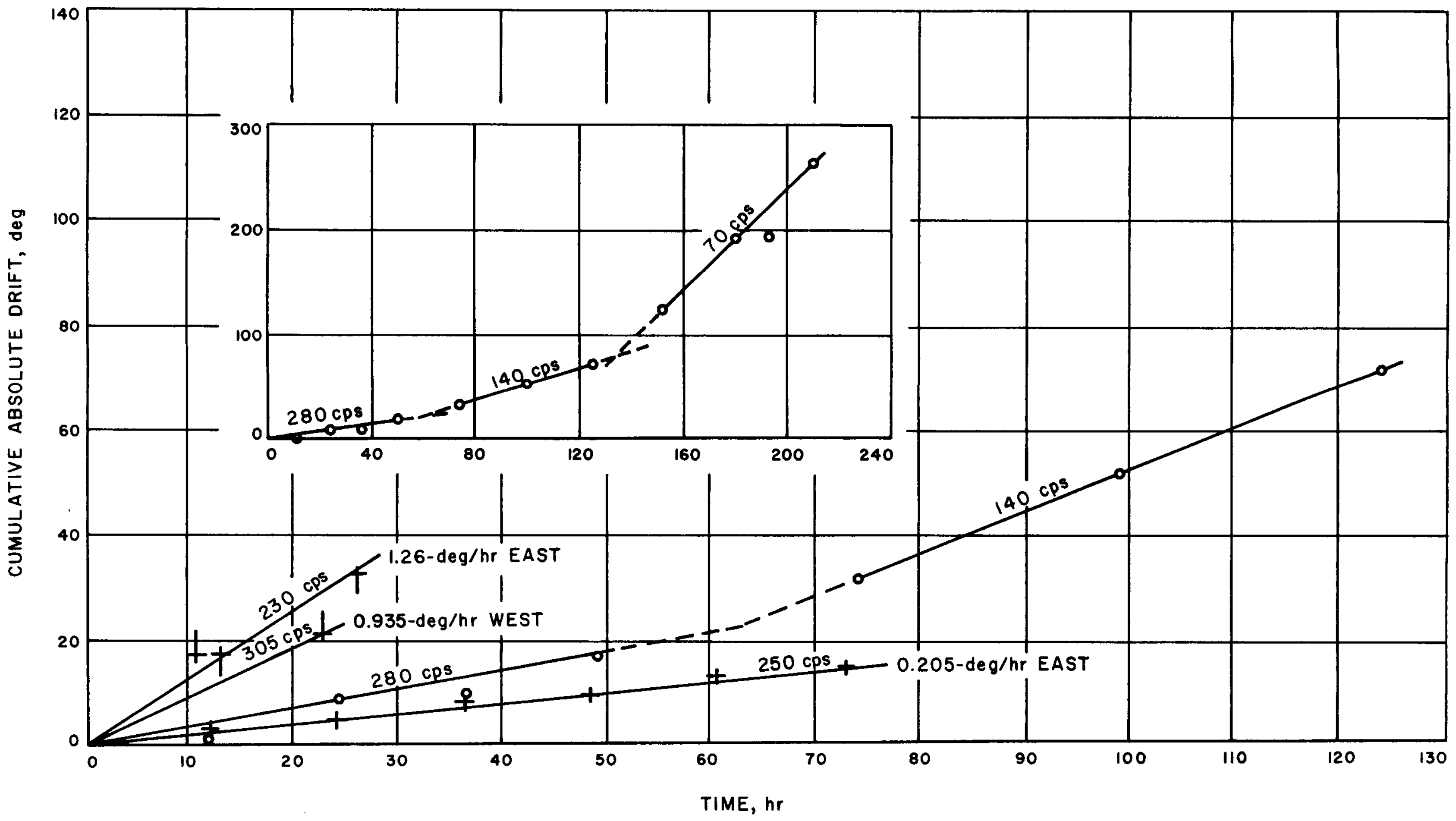

Fig. 14. Equatorial mode drift; Rotor MH6

(by temporarily increasing the gyro gas pressure) and the drift was measured to determine the effect of rotor speed on drift. As would be expected, the drift varies inversely with the rotor speed. This fact is demonstrated also by the long-term drift test of rotor MH6 shown in Fig. 14. The four tests of MH6 yield drift rates between 5 and 30 deg/day, again showing nonreproducible data from run to run.

If the spin axis of the rotor is nearly parallel to the Earth's axis, the diurnal excursion of the rotor pole relative to Earth-fixed coordinates will be slight, thus permitting continuous observation within the field of view of a single microscope. The trace of the rotor pole for such an *Earth's polar mode* test is displayed in Fig. 11. The pole was tracked by means of a vernier stage on which the microscope was mounted on the north port of the Dewar. The pole's path appears ellipsoidal because it represents the projection of the true, nearly circular, path about the direction of the Earth's axis onto a vertical focal plane. In the absence of drift, the path would have closed on itself at the end of one sidereal day.

## IX. CONCLUSIONS

The cryogenic gyroscope, as conceived by Culver and Davis (Ref. 3), was based on two main assumptions regarding superconductivity. The first is perfect diamagnetism, which implies that magnetic fields must vanish at the surface of a superconductor. This property makes possible the torqueless suspension of a superconducting sphere by a magnetic field. The second assumption is perfect conductivity, which permits spinning the sphere without eddy-current drag.

The most significant result of this investigation is that niobium, when suitably purified, is an ideal enough superconductor to make the gyro a reality. In addition, niobium has the necessary mechanical properties for use as a high speed rotor.

The other principal achievement of the program has been to solve the basic instrumentation problems, making possible the construction of a research model of the cryogyro. This system not only satisfactorily performed all necessary functions, but also yielded drift data which ranged as low as 1 deg/day total drift without compensation. It is felt that preliminary drift data of this order demonstrate the basic feasibility of the superconducting gyro concept.

Many difficult problems remain in making the gyro a practical piece of hardware, but these are engineering problems, not fundamental difficulties. Undoubtedly, the biggest obstacle to practicality is refrigeration. In pumping heat from 4 to 300°K, one is confronted on one hand by Carnot theoretical efficiencies of only 1 to 2% and on the other hand by an infant cryogenics technology where actual present-day efficiencies are nearer to 0.1%. There are two mitigating circumstances, however. Spacecraft application could reduce the rejection temperature to that of outer space (20 to 40°K), considerably improving the Carnot refrigeration efficiency; use of high efficiency insulation could make possible the use of storable refrigerants such as solid hydrogen. The discovery of high-temperature superconducting alloys, though apparently unlikely, would revolutionize the whole area of superconductor technology. In the meantime, however, the only practical prospect for the cryogyro appears to be in an application where it shares refrigeration with an all-cryogenic guidance, computer and telecommunications system.

The fabrication of a lightweight hollow niobium rotor is another important problem. This is essential to increase the tolerance to acceleration (which is only 4 g's with the 1-in. solid sphere) and it would permit a preferred axis for reproducibility. General Electric Co. has made considerable progress with both hollow and coated rotors.

A stiffer suspension system with critical damping may be important in an operational gyro for readout purposes, although a stiff suspension does not necessarily improve g tolerances. In this area also General Electric has made significant progress.

Any evaluation of the ultimate practicality of the cryogyro must take into account alternative gyroscope systems.

The principle competitor is the electrostatic gyroscope (ESG), but the gas bearing, laser, and nuclear gyros should also be considered. At the time the cryogyro was proposed by Culver and Davis in 1957, the ESG program had several years and several million dollars headstart. The main objectives of exotic gyro development were greatly reduced drift rate ($<10^{-4}$ deg/hr after compensation) and greatly improved reliability—up to several years mean time to failure. Since both of the field supported gyro concepts have similar limitations (rotor sphericity and mass balance) on their theoretical performances, there was little to recommend one program over the other. However, the ESG program in 1958 was having very serious materials problems involving high-field electron emission from the rotor surface and there was some question that these could be overcome. Hence the cryogyro program was considered to some extent as a hedge against the possible failure of the ESG program. Subsequently, the ESG has been brilliantly developed to close to its theoretical performance with outstanding reliability. It may well be asked if the cryogenic gyro, which can scarcely be expected to significantly improve on the ESG with respect to drift rate, has any prospective unique advantages to justify its parallel development with the ESG.

The cryogenic gyro appears to have the following advantages over the electrostatic gyro:

***a. Higher ultimate g capability.*** The maximum acceleration that a field-supported rotor can withstand is proportional to the square of the critical or breakdown field. For purposes of comparison, niobium, with a critical magnetic field of 1500 gauss, at 4°K, is equivalent to a conductor having a breakdown electric field of $4.5 \times 10^5$ v/cm or 1100 v/mil. This happens to be about the limiting value for the metals used in the ESG. Type II superconducting alloys exist with critical fields ten times that of niobium and with much higher transition temperatures. The prospects of finding such a metal with appropriate mechanical properties and suitably low ac losses and flux penetration are promising. Such a possibility of 100 to 1 acceleration tolerance advantage over the ESG is so significant that the immediate objective of future research in support of the gyro should be the search for a 10,000 gauss, 15°K, low ac loss, superconducting alloy. Needless to say, the discovery will have important impact on the technology of generating intense ac fields.

***b. Intrinsic levitation stability.*** Because the action of a magnetic field is repulsive rather than attractive, the levitation of a superconductor can be stable, whereas the electrostatic suspension is intrinsically unstable. As a result the ESG requires an electronic feedback system to prevent the rotor from impacting the electrodes. On the other hand the cryogenic gyro rotor is supported within a set of shorted superconducting coils which carry persistent currents without the slightest trace of dissipation. In fact once the cryogyro is started, no power is required for levitation. No power is required for maintaining the rotor speed, since it spins in a vacuum. No power is needed for maintaining a vacuum, because outgassing is nil at these temperatures. When it is necessary to interrogate the rotor, power is required to operate the readout and associated logic. To maintain the functioning of the rotor, all that is required is a supply of refrigerant to overcome the losses caused by imperfect insulation. The design and operation of the cryogyro is indeed a lesson in simplicity, and hence reliability.

***c. Intrinsic dimensional stability.*** Because of its very nature the superconducting gyro operates at low temperature, where coefficients of thermal expansion vanish; it also possesses the advantage of dimensional stability, an important factor in the drift of conventional gyros. (The ESG can also be operated at low temperature, but only by a considerable increase in complexity.)

Quite aside from any advantage the cryogenic gyro may possess over the electrostatic gyro, the most significant reason for pursuing research in support of the cryogyro is that the field of superconductivity is a very fertile one, engaging as it does a considerable fraction of the scientific community. That mutual benefit can result from doing applied research in such a field is hard to dispute, particularly in light of experience to date. The formulation of Type II superconductivity by the theorists during this period has had a profound influence on the course of superconducting materials investigation. Likewise, the discovery by cryogyro investigators of techniques for refining superconductors has had a corresponding influence by providing the reversible superconducting materials described by the theory.

Although this report covers the JPL cryogyro program to date, measurements of drift data are being continued. The objective is to obtain data throughout the drift cycle to permit analysis in terms of the mathematical model involving non-sphericity, trapped flux, and London moment. Donald Lawson is the engineer responsible for assembling the all-attitude readout system described in Section VII and for conducting the drift tests. A supplement will be issued when the tests are completed.

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