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APOLLO

GUIDANCE, NAVIGATION AND CONTROL

E-2557

APOLLO II GYRO PROCUREMENT
FINAL REPORT TASK ORDER 33

by

R. J. Cooper

JANUARY 1971

MIT

CAMBRIDGE MASSACHUSETTS 02139

**CHARLES STARK DRAPER
LABORATORY**

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GUIDANCE, NAVIGATION AND CONTROL

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The publication of this report does not constitute approval by the National Aeronautics and Space Administration of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

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APOLLO II GYRO PROCUREMENT
FINAL REPORT

TASK ORDER 33

ABSTRACT

The report constitutes the final report of the development and production effort involved in producing a quantity of 40 Apollo II gyros at MIT/DL and Bendix Corporation.

The report content includes a description of the Apollo II gyro, a history of activity at both MIT/DL and Bendix during the period of the Task Order, statistics of the important parameters of the gyros produced and conclusions and recommendations for possible improvement applicable to future procurements.

by

R. Cooper
January 1971

1.0 INTRODUCTION

This document is the final report for Task Order No. 33 of Contract NAS-9-4065, the Apollo support contract with MIT. It covers a period from March 1968 through August 1970.

Task Order No. 33 was implemented effective March 16, 1968 by a supplemental agreement definitized by modification 47S of the contract, dated January 10, 1969. The purpose of the Task Order was to produce a total of 40 Apollo II inertial reference integrating gyroscopes. In detail it stated that: - the contractor shall provide the materials, facilities, personnel, management and all other items necessary to deliver forty (40) 7A series IRIG's in accordance with a delivery schedule starting in October 1968, and ending September 30, 1969. It further required that MIT/CSDL build eight units and subcontract the remaining thirty-two units.

This report is divided into five additional sections as follows:

2.0 DESCRIPTION OF THE APOLLO II IRIG

This section includes a general description of the instrument, an identification and description of the changes in design configuration which have evolved during the course of the program, a general description of gyro operation and the specific elements involved in applying the instrument in the Guidance and Navigation Inertial Subsystem.

3.0 DESCRIPTION OF THE TASK ORDER 33 PROGRAM

This section describes the principal significant activities which took place during the period of performance, and presents summaries developed from the results achieved.

4.0 GYRO STATISTICS

This section provides summaries of certain important parameter values obtained on the gyro population represented by this Task Order.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This section presents some conclusions and recommendations subdivided as applicable to design or documentation. The impact on possible follow-on production is given special emphasis.

6.0 APPENDIXES

The appendix section consists of references to periodic progress reports, status review meeting reports and other sources of detailed information.

2.0 DESCRIPTION OF THE APOLLO II IRIG

2.1 GENERAL

The Apollo II gyro is a single degree of freedom, floated, integrating instrument and has the primary function of stabilizing the platform in the Inertial Measurement Unit of the Apollo Guidance and Navigation System. It consists of a spherical beryllium float containing an electrically driven, ball bearing mounted wheel, signal generator and torque generator microsyns and temperature control sensors all contained within a fluid filled, thermally and magnetically shielded housing. A line schematic is shown in Figure 2-1.

A cutaway view of the Apollo II gyro is shown in Figure 2-2. The wheel is a symmetrical structure rotating about a fixed shaft on an integral R2 size, pre-loaded ball bearing inner race. It is driven by a two-phase hysteresis motor at 24,000 ~~rpm~~ ^{RPM}. The wheel is shaft mounted within a hermetically sealed float where a dry helium atmosphere of approximately 7 psia inhibits corrosion, promotes thermal transfer and minimizes windage torques. The float carries the rotors associated with the TG and SG ducosyns and contains provisions to permit the float to be balanced about the input and spin axes. The float is suspended within the gyro housing by matching the float density to the density of a bromotrifluoroethylene floatation fluid and by the magnetic suspensions incorporated in the ducosyns. This fluid has the required viscosity necessary to provide the proper output axis damping. To eliminate extraneous torques resulting from possible fluid separation or stratification, the molecular weight distribution of the fluid is rigidly controlled.

The end housings, TG and SG, contain the stators for the ducosyns in potted assemblies, seal the gyro housing at each end and provide mounting for the electrical terminals. A bellows assembly is attached at each end to compensate for fluid volume changes with temperature.

2.1.1 IRIG Characteristics

Important IRIG characteristics are summarized in Table 2-I.

2.1.2 Operation and Performance

The operating elements of the Apollo II gyro consist of the spinning wheel, magnetic suspension elements, an angle to voltage transducer (SG), a torquer (TG), and a temperature control circuit. The magnetic suspensions and the SG and TG are configured as ducosyns. A ducosyn combines the signal or torque transducer with a magnetic suspension in a single coaxial and coplanar structure.

TABLE 2-1

Element	Type	Specification
Wheel	28V, 2 phase, 800 Hz	Speed - 24,000 rpm H - 0.434×10^6 gm cm ² /sec
Damping	Viscosity 2400 Centipoise at 137°F	Damping OA - 4.75×10^5 dc/rad/sec IA - 1.5×10^9 dc/rad/sec SRA - 1.5×10^9 dc/rad/sec
SG	8 pole E connected microsyn 4V 3200 Hz	Sensitivity - 10 mv/mr
TG	12 pole modified E connected microsyn with reset and bias compensation windings	Sensitivity - 0.6 dc/ma ²
Magnetic Suspension	20° included angle taper	Stiffness Axial 0.8 gms/0.0001 in. Radial 6 gms/0.0001 in.
Temperature Sensors	2 thermistors in series mounted on end housing each end.	Total Resistance 345 ohms at 137°F Gradient 6 ohms/°F/sensor

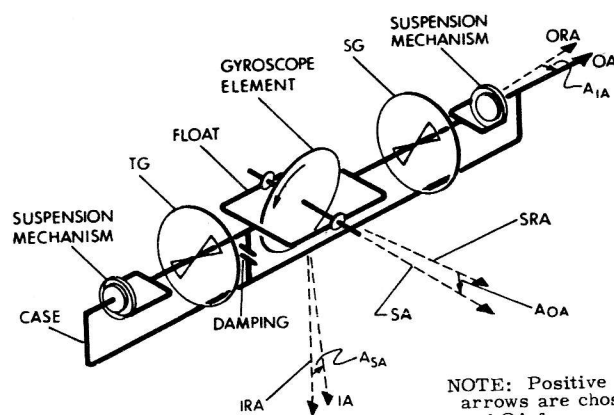


Fig. 2-1. Line schematic of SDF floated integrating gyro unit.

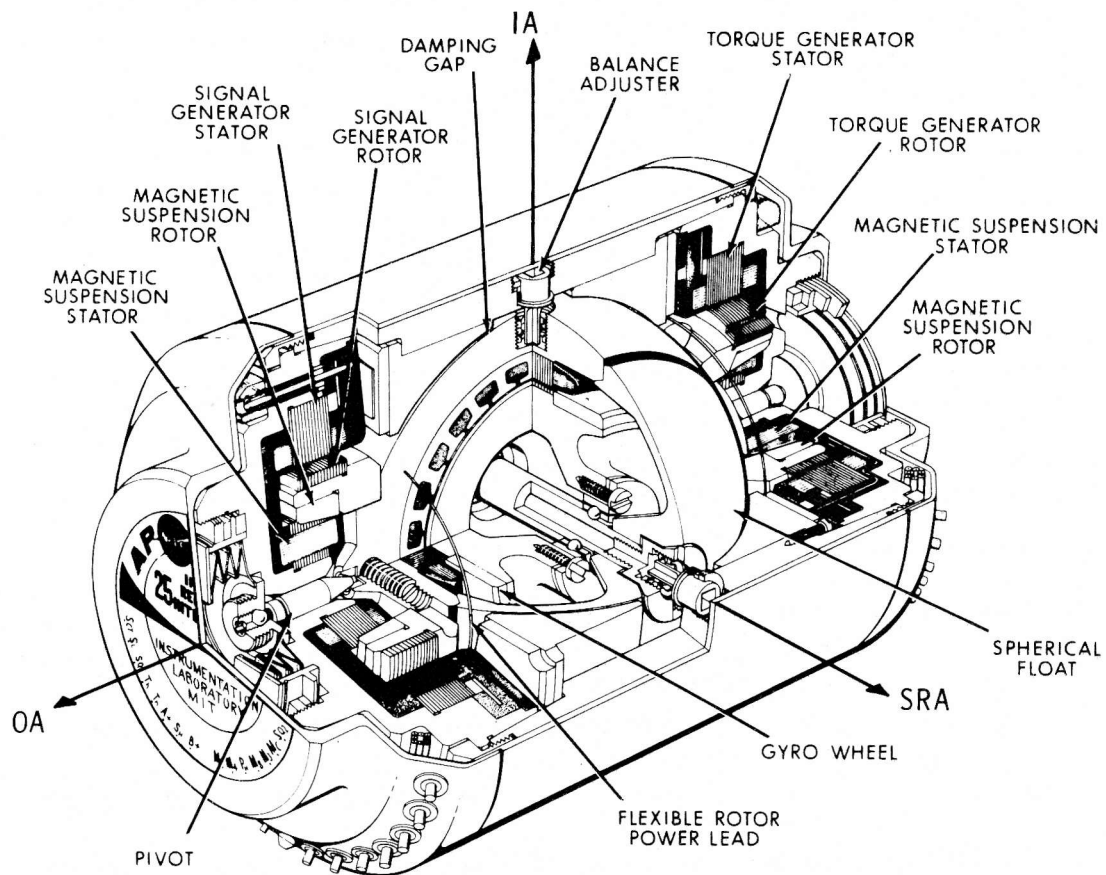


Fig. 2-2 Apollo IRIG

An angular velocity input to the gyro results in an output signal proportional to the integrated input as in any single degree of freedom floated unit. Performance is determined by the stability of the location of the center of mass of the wheel, the stability of the float balance and the stability of the residuals of a large number of minor torque producing phenomena.

The acceptance values for performance of the shrouded gyro assembly are summarized in Table 2-II.

TABLE 2-II

Parameter	Value	Stability
UBD	35 meru	5 meru
ID	20 meru	—
RD	25 meru	—
ADIA	20/meru/g	10 meru/g
ADSRA	15/meru/g	5 meru/g

where:

- UBD = Total uncompensated bias drift rate at normal excitation
- ID = Uncompensated bias drift rate independent of microsyn and suspension excitation contributions
- RD = Uncompensated bias drift rate contributed by microsyn and suspension excitation
- ADIA = Acceleration sensitive drift rate due to 1 g case acceleration along the IA gyro axis
- ADSRA = Acceleration sensitive drift rate due to 1 g case acceleration along the SRA axis

Further limitations pertaining to the magnitude of short term deviations permitted during the conduct of a test are invoked to prevent the use of data with an excessive spread in the calculation of the several drift parameters.

2.1.3 Normalized Gyro Configuration

The Gyro Shrouded Unit Assembly, Part No. 2021602, is prealigned and normalized for interchangeability in the Apollo Guidance and Navigation system. The prealignment package, which mounts on the Signal Generator end of the shrouded gyro contains the following components:

1. Ducosyn suspension capacitors
2. Temperature control circuit normalization resistors
3. End mount with prealignment slot and end mount heaters
4. Torque Generator normalization resistors
5. Signal generator preamplifier with gain normalization resistors

The prealigned gyro constants are:

1. Suspension current phase angle - $45^{\circ} \pm 3^{\circ}$ lagging
2. Temperature Sensor Resistance at 137°F - 769.6 ± 1.0 ohms
3. Bias Drift (BD) - 0 ± 5 meru
4. Gyro Transfer function - 1200 ± 30 mv/mr
5. Torquer Scale Factor - $\pi/2^{20} \pm 500$ ppm/rad/pulse

The network diagram is shown in Figure 2-3.

2.2 EVOLUTION OF THE GYRO CONFIGURATIONS

Task Order No. 33, as issued, specified delivery of gyroscopes defined as Part No. 2021602-021. This configuration called for a wheel bearing assembly which was an "improved" element introduced in September 1967, at the beginning of the Delco gyro repair program. This new bearing assembly compared to the assembly previously employed is shown in Table 2-III.

On August 26, 1968, approximately five months after the start of Task Order No. 33, the configuration was changed to Part No. 2021602-041. This configuration represented an attempt to return to the previous bearing because of the poor experience with the "improved" bearing. The retainer material continued to be nylasint.

On January 29, 1969, the configuration was again changed; to Part No. 2021602-071. The effect of this change was to identify a supplementary lapping operation on the wheel bearing races of same bearing hardware. No other significant changes were involved.

On July 8, 1969, the final change in the gyro configuration was made. The new part number is 2021602-081. This configuration retained the use of the -071 wheel bearing hardware with the relapped races, and, in addition, introduced SRG 160 lubricant with almost three times the viscosity of the previous V-78 oil, reduced the nominal preload from 3 pounds to one pound and incorporated a gravity transient test into the acceptance procedures.

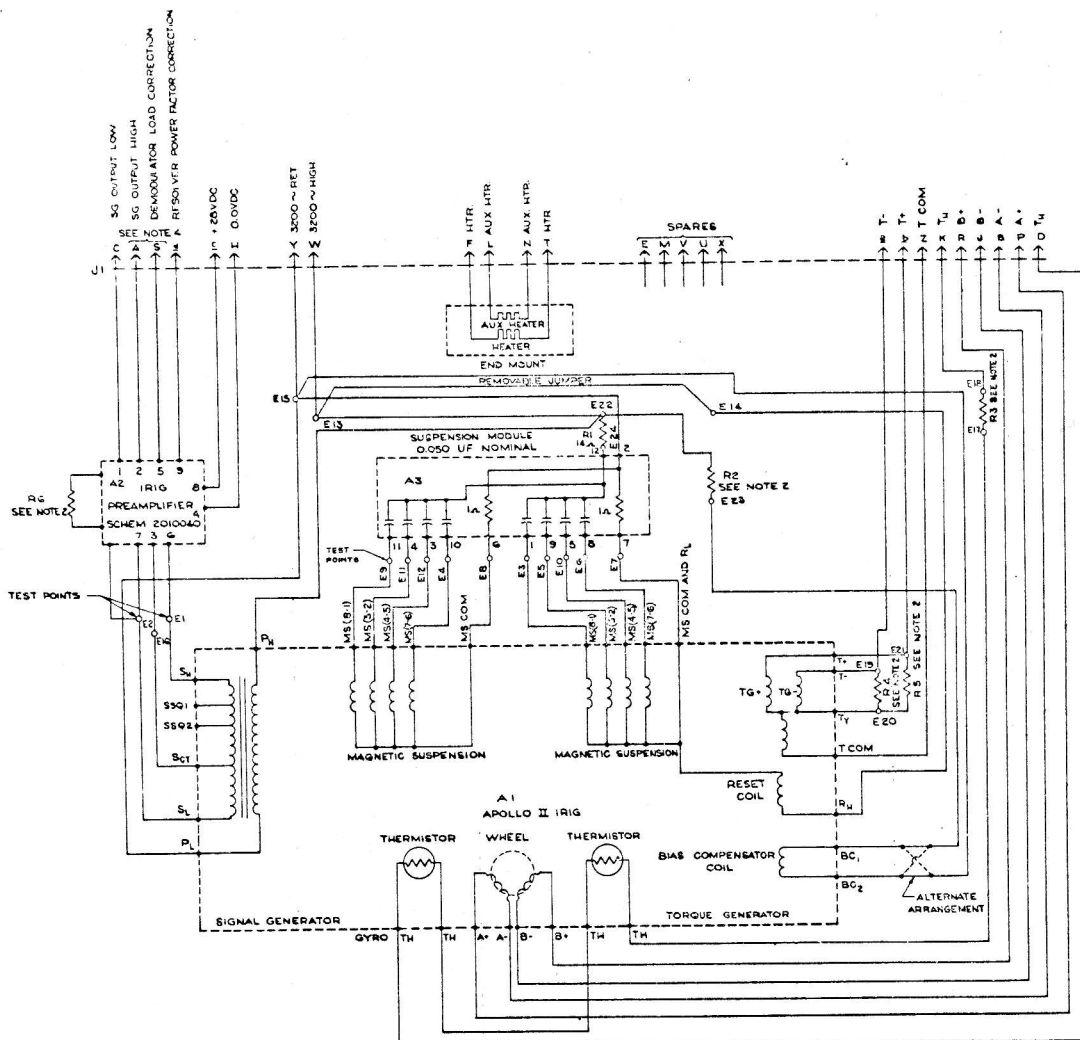


Fig. 2-3 Apollo II IRIG Prealignment Network

TABLE 2-III

TABULATION OF BEARING IMPROVEMENTS

	FEATURE	APOLLO II Z179X26	REPAIR PROGRAM Z179X32
Geometry Improvements	Ball Match per row	10 μ in	5 μ in
	Ball Roundness	5 μ in	3 μ in
	Inner Race Roundness	50 μ in	40 μ in
	Outer Race Roundness	50 μ in	50 μ in
Improved Sur- face Finish	Outer Race Finish	lap	Double Hone Ball Lap
	Inner Race Finish	lap	Double Hone Ball Lap
	Surface Con- ditioning		TCP
Special Clean- ing & Wett- ability	Metal Parts Cleaning Solutions	Varsol Spray Engsol Wipe	Engsol, Toluene, Freon, Methanol, Methanol- Acetone
	Wettability Test after TCP Soak		Outer & Inner Races, Detail Process in MC 25-879
TCP	TCP Surface Treatment		15 Day Storage in TCP at $225 \pm 5^{\circ}\text{F}$
Screening	Visual Screening	MC 25-865	MC 25-887 (Somewhat Tighter)
	Dynamometer & Wattmeter Screening	No Dynamometer (Direct Float Build)	Dynamometer Run & Critical Interpretation of Traces
Matl.	Retainer Material	Synthane	Nylasint

3.0 DESCRIPTION OF TASK ORDER NO. 33 PROGRAM

3.1 ORIGINAL PLAN

The original plan for Task Order No. 33 contemplated a straightforward development of a second source for an instrument which had, in one variation or another, been manufactured successfully by several manufacturers and in substantial quantities. Bendix was to create tooling and test equipment, order parts, generate internal assembly and test documentation, assemble and test instruments. A reliability and quality control program including failure analysis was included. It was assumed that the wheel bearing problems which had plagued both ACE and MIT during the immediate past would be identified and corrected before this new contract could be impacted. To insure maximum coordination MIT was to build eight of the required 40 units. Experience by MIT in the production of flightworthy equipment for NASA, especially with respect to the Quality Control features, permitted a confident approach to this new challenge.

3.2 WHEEL CONFIGURATION DEVELOPMENT

During the early period of performance, through July 1968, both MIT and Bendix initiated the first phases of Gyro production. At MIT an important item was the build activity. From May through September thirty wheels using Barden double honed bearings, two wheels with Miniature Precision Bearing Co. (MPB) ball lapped bearings, seventeen wheels with residual New Departure bearings and three wheels with the new Barden bearing, X44, were completed. All failed dynamometer testing except one wheel with a Barden bearing, and three wheels with New Departure bearings. The former subsequently ran without catastrophic failure for over 1400 hours. These unsuccessful wheels contained all or most of the new procedures and materials which had been introduced, including wettability testing, oil absorption, TCP coating, more precise metrology, improved cleaning, and selected nylasint retainer material.

Bendix started testing wheels in September 1968. By the end of October, thirty wheel assemblies had been tested; all failed.

As the result of this poor record of wheel assembly success at MIT and Bendix, coupled with similar results at ACE and Nortronics, direction was provided by NASA, on 21 October 1968, authorizing MIT and Bendix to continue work in the wheel area aimed at development of a hardware/process combination that would provide a reasonable yield and yet not cause an excessive reduction in gyro performance. Full scale production would be discontinued after 20 November 1968, and persist until this condition had been achieved. As a result of this direction MIT set up a program at MIT and Bendix designed to develop the maximum volume

of useful information before 20 November 1968, at which time a NASA review of the wheel build situation was scheduled. The program consisted of the following elements and objectives:

1. Evaluate the effect of the difference in cleaning procedures used on the earlier bearing assemblies and the current X44 units.
2. Evaluate the effect of using staggered pocket retainers to reduce the incidence of retainer instability.
3. Evaluate the effect of using available outer races from the earlier bearing (X26) in combination with the X44 shafts and balls.
4. Evaluate the effect of a ball relapping operation, using alumina and TCP, on the races of the current bearing.
5. Evaluate the effect of a stick relapping operation, using alumina and TCP, on the races of the current bearings.
6. Continue to build wheels using residual New Departure bearings to provide a basis for comparison.

MIT was to build nine wheels during the period and Bendix was to build nineteen (subsequently referred to in Task Order documents as the "Build 19 Program").

The limited degree of success attained by the time of the Review Meeting held at MSC on 20 November 1968, prompted MIT to propose that production activity on Task Order No. 33 be partially suspended until 1 March 1969, and the three months be used to develop an X44 bearing raceway surface condition that would provide a wheel yield of at least 30%. The Bendix portion of the resulting activity was identified as the "Build 27 Program." A wheel evaluation program was added at this time. It consisted of a sixteen wheel life test including periodic monitoring of selected parameters.

At the completion of the wheel build evaluation period on 1 March 1969, the results were not conclusive. The cumulative yield during the period was well under 30%, but was improving steadily. The hardware loss was drastically reduced and the almost instantaneous failure no longer occurred. Much of the improvement was attributed to the improved bearing surfaces obtained from the lapping operation.

This period resulted in the eventual completion of two gyros and three evaluation wheels by MIT and two gyros and four evaluation wheels by Bendix to the wheel configuration identified with the 2021602-071 gyro configuration, i.e., relapped races with alumina and TCP, V78 oil and 3-pound nominal preload.

The possible improvement in the operating environment of the R2 bearing as used in the Apollo II Gyro by increasing the viscosity of the lubricating oil and reducing the preload level of the assembly was recommended by NASA. At a meeting at MSC, on 24 April 1969, NASA requested MIT to investigate the possible effects resulting from a reduced preload. At a NASA review meeting held at MIT on 17 May 1969, with Mr. Max Holley, it was directed to incorporate the use of a wheel configuration using a more viscous oil, a one-pound preload and an inner race riding retainer. During the following week MIT began to assemble wheels using SRG-160 lubricant, inner race riding retainers, one-pound nominal preload and X45 bearings lapped with TCP and alumina. This configuration gyro was identified as Part No. 2021602-081. Bendix was directed to change over to the new configuration as soon as parts were available.

Bendix was also authorized to run an evaluation program on a new lot of Barden bearings identified as X52. This evaluation was eventually accomplished with a total of twelve bearings assembled to the -071 configuration with no relapping on the first build cycle. A process yield of 8% and a hardware yield of 16% resulted. Thereafter, all X52 bearings were relapped prior to wheel assembly.

Bendix was also authorized to build a preproduction sample lot of wheels to the -081 configuration. Assembly was started on 26 May 1969. By the end of June the -081 wheel was in production. Fifteen assemblies had been completed with a process yield of 21% and a hardware yield of 50%.

3.3 PRODUCTION HISTORY

Once the wheel problems had been alleviated by the implementation of the 2021602-081 configuration, gyro production activity was able to proceed. The delivery status at that time stood at: MIT - 4; Bendix - 1.

Gyro assembly revealed its own set of problems, some typical and expected; some unusual and unanticipated. The individual problems are summarized for MIT and Bendix with an indication of the severity and the corrective action in each case.

3.3.1 MIT Gyro Production Problems

3.3.1.1 Contamination. The first gyro 0811 delivered to test failed early in the test sequence. Teardown revealed a metallic chip 0.015 x 0.005 inch on the SG spring mount, probably from the plated spring during the dry centering operation. Similar problems occurred on 0818. One delivered unit, 9A8, failed at Delco for float freedom. It has not been torn down to confirm the failure cause. No method is currently known to eliminate this failure mode. Contamination control is a disciplinary problem requiring continuous and meticulous regard for cleanliness in the

assembly process. The following improvements in processing procedures were instituted to minimize the contamination problem:

1. Provide final cleaning of all gyro parts, fixtures and equipment using a "Waterpik" and clean, virgin freon just prior to starting the final assembly operation.
2. The laminar flow work cabinets used for the gyro flushing operation were fitted with a rigorous double filtering system using 0.45 micron Millipore final filters.
3. The filter used to provide the contamination count for flushing qualification was changed to black, 0.80 micron.
4. The fluid filters used in the filling operation were changed to 5-7 micron Millipore and 17 micron stainless steel mesh.
5. A fill fluid effluent evaluation with a maximum contamination level specification was added to the filling procedure.

3.3.1.2 Magnetization. The second gyro failed for instability in bias drift. Since this is an unusual and unexpected condition, all aspects of the magnetic elements were investigated thoroughly with no conclusive results. Later evidence suggests that the instability could have been caused by a change in the magnetic condition of magnetic portions of the wheel assembly due either to lack of complete degaussing prior to assembly or subsequent guassing by unidentified sources, possibly vibration exciters.

3.3.1.3 Gravity Transient and Hot Storage Sensitivity. These two problems appear to be different manifestations of the same phenomenon, i.e., small cavities existing on the float assembly are not completely filled with damping fluid. If the volume is such that the fluid within can flow relative to the axis on which it is initially located, it exhibits a test characteristic identified as gravity transient. Depending on the flow rate, the transient may show a time constant as short as 15 minutes or one extending over many hours. Hot storage sensitivity can be considered a logical extension of the gravity transient in that the cavity(s) are slowly collecting additional fluid. This process may continue at a perceptible rate at elevated temperature which in the instrument reduces the viscosity of the damping fluid by an order of magnitude and doubles the pressure.

The first gyro delivered to Delco showed a gravity transient condition. The second had an ADSRA ramp. Both the third and fourth instrument also failed for a gravity transient condition. A subsequent unit at MIT, 0816, failed for hot storage sensitivity. The sixth unit showed the same indications at Delco but appeared to be settling out.

The first corrective action taken was to impregnate the rotor assemblies. This action was dictated by the desire to avoid scrapping parts which had been completed with a resulting impact on the delivery schedule. A preferred method is to perform the assembly operation in such a way that a clear path for the entry of fluid is provided without introducing other deleterious effects on the ferrite, rotor roundness or other features. The development of an optimum design for this element is still in process under other auspices.

3.3.2 Bendix Production Problems

3.3.2.1 Contamination. Bendix also started out with a float freedom failure. Three more occurred at Bendix and two gyros, 9A9 and 9A10, delivered to Delco during the early months of the production program, failed there for float freedom test anomalies. As the result of this series of failure, process improvements were initiated at Bendix. The first of these improvements was identified as the "Freon Vapor Build: as reported by Bendix to NASA at a meeting in Houston called for the purpose of reviewing the Bendix performance with respect to contamination control. Only two additional units have failed for float freedom due to contamination and only one delivered unit has been found to have float freedom indications to date. Two separate NASA R&QA visits were made to Bendix in support of this problem. Details are provided by the reports covering those visits and the resulting Bendix actions are set forth in their monthly progress reports.

3.3.2.2 Balance Weight Adjustments. Three units exhibited problems associated with proper operation of the final balance weight adjustment element. Teardown revealed no condition which might have caused the problem except for one unit in which the float had been assembled into the main housing in a reversed orientation. The corrective action was to apply more stringent inspection to assure smoothly operating balance weights prior to final assembly and to provide an inspection check-point for the orientation of the float.

3.3.2.3 Gravity Transient and Hot Storage Sensitivity. The same problem of partially filled, slowly filling cavities in the rotor assembly which affected MIT production was the cause of many failures at Bendix as well as problems with delivered units at Delco. As many as twelve failures in-house may be attributed to this cause, although teardown data is not always sufficient to confirm it. At Delco one unit, 9A16, was a confirmed gravity transient failure. A large quantity of units were discovered to have long time constant gravity transients of relatively small magnitudes. This condition has been determined to be acceptable for system use. The corrective action is identical to that described under MIT.

3.3.2.4 Excessive Unbalance. This failure mode may possibly be attributed to the unfilled cavity problem. Four units showed an initial unbalance which was beyond the capability of the balance adjustment provided. Since there is no specific effort made at the float balancing operation to insure that any existing cavities are filled with fluid, the initial unbalance at test includes the effect of any fluid picked up during the filling operation. This operation includes a 40-hour pressurization cycle at 10 atmospheres. Statistics are not available to correlate the failures noted with the float weight change. It is possible that an outgas and pressurization period in the balancing tank added to the procedure would eliminate these excessive unbalance conditions.

3.3.2.5 Wheel Problems. Four gyro failures occurred at Bendix due to wheel problems. The symptoms were identical in each instance, bimoding of the milliwatt power trace with a corresponding OOS condition in the deviation of individual drift measurements from the rms average. No observable discrepant conditions nor wear indications existed in any of the wheels at teardown. The bimoding is presumed to be caused by an unstable lubricant flow condition coupled with excessive lubricant volume. No corrective action has yet been devised.

3.3.2.6 Megger Failures. Two delivered units, 9A18 and 9A27, failed the insulation resistance requirement when tested at Delco. Teardown analysis showed a pinched wire in the end shroud on 9A18 and a small chip under the cement coating of one of the feed-through terminals in the end shroud of 9A27. Bendix agreed to repair these units at their expense under the terms of the incentive fee arrangement.

3.4 TERMINAL STATUS

3.4.1 Technical

3.4.1.1 Wheels. The final cumulative yield for the -081 wheel build operation at Bendix was 45% for X52 bearings and 35% for X44 bearings. At MIT the yield was 26% using a mix of X44 and X45 bearings. In each case the accumulative yield values were adversely affected by low yields during certain portions of the build period especially in the beginning. Retainer rejections appear to correlate with these periods of low yield but the retainer parameter causing the condition has not been identified. Although confidence is expressed that wheel yields approaching 50% can be expected in a new program, the statistics from Task Order No. 33 experience do not unequivocally confirm this opinion.

3.4.1.2 Rotor Assemblies. The optimum design of this assembly and its attachment to the float has not yet been determined. An evaluation technique which does not

require building and testing a gyroscope is a prerequisite for the successful development of an optimum design.

3.4.1.3 Gyro Assembly and Test. Many of the problems which have existed in the past seemed to be under control as the program came to an end. Three problems persist to some degree. The first, float freedom, is perennial and probably can never be completely eliminated. However, with the procedures and equipment which have been incorporated and the current status of the clean room discipline and control, its impact is minimal. During the period April through August, a total of 33 gyros have been assembled and tested with only one float freedom failure. Only one failure for this cause has as yet been reported on the units shipped. The second and most prevalent failure cause is the balance shift due to incomplete fill in the rotor assemblies. It provides such symptoms as excessive drift deltas, excessive drift maximums, excessive initial unbalance and gravity transients. Twelve of the twenty failures are attributed to this cause. No one assembly technique applicable to the rotor assembly is associated with a major percentage of these twelve failures. The comment made for Rotor Assemblies (paragraph 3.4.1.2, above) applies.

The third failure cause is a wheel associated phenomenon identified as bi-modding. The test symptom is failure to meet the requirement that the root mean square average of the drift rates with IA vertical shall not exceed three meru. Failure analysis has not yet identified a cause for this condition and its effect on the reliability of the wheel package is unknown. Whether the three meru specification is necessary for the Apollo mission requirements should be evaluated.

3.5 CONTRACTUAL SUMMARY

16 March 1968	Effective starting date for Task Order No. 33
26 August 1968	Revision 2. Part No. Change, 2021602-021 to 2021602-041
25 September 1968	QA Representative changed from Smellgrove to Lewandoski and Technical Representative from Biggs to Swingle
10 January 1969 \$2,919,000	Definitization of Task Order No. 33
29 January 1969 \$3,592,627	Effectivity of CCA No. 62, changing 37 units to Part No. 2021602-071, introducing two supplemental wheel build programs and a wheel design verification program, and changing delivery period to 8 January 1969 through 31 December 1969
8 July 1969 \$4,392,565	Effectivity of CCA No. 62 Ammendment No. 1. Changes remaining units to Part No. 2021602-081, implements gravity transient test and provides continuing wheel engineering support by MIT

19 September 1969 \$4,428,526	Effectivity of CCA No. 66 authorizing "Signature Analysis" of 32 evaluation program wheels by G. E., VFPTC, Philadelphia
4 November 1969 \$4,489,627	Effectivity of CCA No. 75 providing for teardown and analysis of 9A2, 3, and 4 gyros and rebuild and retest three gyros and deliver at least two units to ACE by 1 February 1970. Part No. 2021602-081. FAR reports required
18 December 1969 \$4,505,953	Effectivity of CCA No. 78 providing for failure analysis of 25 IRIG Serial No. 7C111
13 April 1970 \$4,710,535	Overrun associated with stretchout to 30 June 1970. Proposal 70-134
2 July 1970 \$4,830,530	Overrun associated with stretchout to 31 July 1970. Proposal 70-181
— \$4,839,239	Overrun associated with stretchout to 15 August 1970. Proposal 70-246, gyro tooling and documentation for gyro repair program at Northrup.

3.6 PRODUCTION YIELD AND REJECTION CAUSE SUMMARY

3.6.1 MIT

A total of sixteen gyros were built and submitted to test. The quantity of final assembly parts was eleven. The remaining five were rebuilds. Five gyros were accepted direct from the original assembly. This quantity includes 9A5 which was outside the specification limits on ADIA but stable and was used for system testing at MIT. Of the remaining four, two subsequently failed at Delco for gravity transient. There were seven rejections in-house. These rejections can be subdivided into the following classifications:

A — 43% — Float Freedom	3	Nos. 811, 818, 819
B — 43% — Fluid	3	Nos. 816, 820, 814
C — 14% — Miscellaneous	1	No. 810

There were five field failures at Delco. Failure cause was in two classifications:

A — 20% — Float Freedom	1	9A8 (813A)
B — 80% — Fluid	4	9A1 (811A), 9A2 (812) 9A3 (810A), and 9A4 (813)

Production yield was 56%. Field failure rate to date is 50%.

3.6.2 Bendix

A total of 78 gyros were built and submitted to test. The quantity of final assembly parts provided for 39 assemblies. The remaining quantity, amounting to

39, were rebuilds. Thirteen gyros were accepted direct from original assembly. This quantity includes gyro No. 1, the engineering unit, which was not delivered. There were 45 in-house rejections. These rejections can be subdivided into the following classifications.

A - 18% - Float Freedom	8	Mech 3, 5A, 13, 12, 12A, 4A, 23, 30
B - 47% - Fluid (Gravity transient and hot storage sensitivity)	21	Mech 2, 7, 3A, 5B, 7A, 15, 12B, 17, 20, 22A, 31, 32, 26A, 17A, 38, 35, 32A, 33, 30A, 32B, and 10
C - 18% - Wheel ($\Sigma 10 > 3$ meru and rundown deviation and wheel power shifts)	8	Mech 6, 14, 5C, 5D, 12C, 36, 12D, 5E
D - 18% - Miscellaneous (Bal. Wts hung up, Elastic Restraint OOS, radial recovery, Bias shift, gaussing, End Shake excessive, Radial voltage OSS)	8	Mech 5, 22, 21, 26, 21A, 29, 39, 4

There have been eight field failures at Delco. Failure causes are in five classifications:

A - 25% - Float Freedom	3	9A9, 9A10, 9A17
B - 13% - Fluid	1	9A16
C - 25% - Megger	2	9A18, 9A27
D - 25% - Shroud Discrepancies	2	9A33, 9A37
E - 13% - Bias Drift	1	9A26

Production yield was 42%, field failure rate to date is 25% on the total of 32 units delivered to Delco. However, the gyros in classifications C and D are readily repairable without disassembly of the basic gyro. Eliminating these four units from the failure list results in a more respectable 12.5% field failure rate to date.

3.7 SCHEDULE AND DELIVERY SUMMARY

The original schedule developed for Task Order No. 33 was the following:

1968					1969				
Mfg	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
MIT		1	1	2	1	1	2		
Sub	2	3	5	5	5	5	5	2	
Total	2	4	6	7	6	6	7	2	

The first firm schedule following the contract award to Bendix was:

68 *1969*

Mfg	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
MIT			1	1	2	1	1	2			
Bendix	3	3	3	3	3	5	5	5	2		
Total	3	3	4	4	5	6	6	7	2		

Amendment No. 1 to the Bendix subcontract was dated 9 May 1969. The resulting schedule became:

68 *69*

Mfg	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
MIT			2							1	2	3	2		
Bendix								1	2	4	5	5	5	5	5
Total			2					1	2	5	7	8	7	5	5

Amendment No. 2 to the Bendix subcontract was dated 21 November 1969. The resulting schedule became:

	1968	1969							1970						
Mfg	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb
MIT	2			1	2	3	2								
Bendix				1		2	4	5	5	5	5				
Total	2			2	2	5	6	5	5	5	5				

Although several additional amendments were processed extending the period of performance, the schedule for gyro delivery was not changed. Delivery of gyros to destination has been as follows:

	1968	1969											1970	
Mfg	Dec		Feb		June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	
MIT	2		1		1			1				1	1	
Bendix						1		1	1				8	
Total	2		1		1	1		2	1			1	9	

1970						
Mar	Apr	May	June	July	Aug	Sept
2	1					
3	3	3		4	4	4
5	4	3		4	4	4

NOTES:

- MIT deliveries includes 8 units and 2 repairs — total 10.
- Bendix deliveries total 32.
- A delivery hold was in effect from November—January 1970, while waiting for shroud inclusion resolution.

4.0 GYRO STATISTICS

4.1 CRITICAL PARAMETER SUMMARY

4.1.1 MIT

Gyro No.	Float Weight	Bellows Length	Thermistor	
			SG	TG
*9A1	183.225	3.618	341.8	342.2
*9A2	183.682	3.560	349.1	350.1
*9A3	183.775	3.583	336.1	336.5
*9A4	183.773	3.576	348.8	351.9
9A5	183.861	3.564	349.3	362.5
*9A6	183.814	3.565	336.7	341.0
9A7	183.720	3.565	344.2	342.3
9A8	183.956	3.548	348.8	347.7
9A41	184.002	3.566	344.7	342.3
9A42	183.826	3.567	338.2	336.3

* Part No. 2021602-071. All other gyros are 2021602-081.

Gyro No.	Microns Effluent Count				°F Flotation Temp.	seconds RDT		dyne-cm Wheel T.	% by wt. Retainer Oil Content		End Shake in. x 10 ⁻⁴
	5-25	26-50	51-75	76-		\bar{x}	RMSD		#1	#2	
9A1					135.3	152.5	4.7	1100	14.8	15.3	12.0
9A2					134.9	130.5	3.8	1500	14.7	15.4	11.5
9A3					136.0	118.7	4.7	1400	15.1	15.6	11.5
9A4					136.7	116.5	4.6	1375	16.4	15.5	16.0
9A5					133.6	166.2	2.0	975	20.0	20.0	11.0
9A6					135.6	136.6	3.4	1200	17.8	16.7	14.5
9A7					134.5	190.2	5.2	675	18.5	15.9	13.0
9A8	14	13	2	0	135.2	169.5	1.7	800	15.6	17.6	10.3
9A41	40	8	4	3	133.7	162.3	6.8	975	18.1	17.5	11.8
9A42	25	3	0	7	134.9	154.1	2.7	860	17.3	18.1	9.3

Gyro No.	Minimum Start Voltage Wheel	Seconds Run Up Time	Torquer SF	
			+	-
9A1	28.0	76.8	9.320	
9A2	28.0	74.8	9.182	
9A3	28.0	85.0	8.952	
9A4	28.0	116.9	9.361	
9A5	28.0	72.5	9.378	9.345
9A6	28.0	68.0	9.180	
9A7	26.6	70.1	9.412	9.384
9A8	26.6	89.2	9.378	9.345
9A41	—	—	—	—
9A42	—	—	—	—

4.2 CRITICAL PARAMETER SUMMARY

4.2.2 Bendix

Gyro No.	Grams Float Weight	Inches Bellows Length	Ohms Thermistor		Grams Rotor Weights	
			SG	TG	SG	TG
*9A9	183.7728	3.6230	341.91	358.84		
*9A10	183.9129	3.6167	341.80	344.41		
9A11	183.8740	3.5668	343.40	352.06		
9A12	184.0016	3.5702	345.18	361.61		
9A13	183.9551	3.5775	377.72	366.62		
*9A14	183.8557	3.5860	345.31	333.19		
9A15	183.9019	3.5742	350.97	351.28		
9A16	184.1214	3.5742	350.29	350.20		
9A17	183.8401	3.5986	343.57	356.18		
9A18	183.9674	3.6050	360.65	349.48		
9A19	183.9058	3.6102	369.98	364.40		
9A20	183.8764	3.5847	358.73	335.76		
9A21	183.9319	3.6061	377.68	353.75		
9A22	183.7263	3.6191	369.84	372.36		
9A23	184.0082	3.5875	357.03	361.58		
9A24	183.9311	3.6326	364.40	339.59		
9A25	183.8505	3.6129	350.38	350.76		
9A26	183.8789	3.5872	363.70	347.07		
*9A27	183.7474	3.6094	371.52	372.86		
9A28	183.9891	3.6217	367.85	363.25		
9A29	184.0504	3.5796	354.89	359.64		
9A30	184.0382	3.5940	362.42	359.66	16.4870	16.5250
9A31	183.9417	3.6216	362.76	363.18		
9A32	183.9739	3.6098	348.53	368.96		
9A33	183.8361	3.6120	352.06	362.33		
9A34	183.9944	3.5836	347.05	353.02	16.4010	16.4025
9A35	183.7658	3.5576	376.95	366.36		
9A36	183.9345	3.5900	349.47	344.76	16.4425	16.3540
9A37	184.0375	3.5895	355.74	346.47	16.5405	16.5155
9A38	184.1367	3.5851	339.41	361.07	16.5265	16.4025
9A39	184.0312	3.5950	330.74	340.56		
9A40	183.7844	3.5985	358.07	352.51		
*Part No. 2021602-071. All other gyros are 2021602-081.						

Gyro No.	Microns Effluent Count			
	5-25	26-50	51-75	76-
9A9				
9A10				
9A11				
9A12				
9A13				
9A14				
9A15				
9A16				
9A17				
9A18				
9A19	8	5	1	1
9A20	28	2	1	0
9A21	6	1	0	0
9A22	6	0	0	0
9A23	35	3	0	0
9A24	57	3	0	0
9A25	35	2	0	0
9A26	67	10	0	0
9A27	46	3	0	0
9A28	65	8	2	0
9A29	112	5	4	0
9A30	323	8	4	0
9A31	87	7	1	0
9A32	136	8	2	0
9A33	478	12	5	0
9A34	144	10	1	0
9A35	185	13	2	0
9A36	219	6	1	0
9A37	310	9	4	0
9A38	435	8	2	0
9A39	368	5	0	0
9A40	193	4	1	0

Gyro No.	°F Flotation Temp.	Volts Minimum Wheel Start Voltage	Seconds Run Up Time	Torquer Scale Factor		Seconds Run Down Time
				+	-	
9A9	133.05	20.5	67.1	9.3893	9.7119	128.0
9A10	135.55	20.0	66.2	9.2661	9.3092	152.9
9A11	135.45	19.0	72.5	9.1581	9.1528	159.9
9A12	134.42	19.0	69.9	9.4585	9.5284	157.7
9A13	135.74	18.0	76.7	9.4581	9.3996	156.5
9A14	134.90	21.0	75.7	9.4953	9.4859	110.6
9A15	135.65	18.0	73.1	9.3436	9.5222	181.7
9A16	134.58	19.0	77.6	9.0757	9.1038	150.5
9A17	135.35	19.0	70.7	9.4536	9.4716	153.6
9A18	135.40	18.0	68.1	9.0726	9.1001	193.3
9A19	135.70	18.0	67.5	9.3110	9.2213	141.4
9A20	135.20	18.0	63.7	9.1661	9.1687	147.0
9A21	135.10	18.0	60.9	9.4508	9.4398	187.3
9A22	135.00	19.0	73.8	9.2080	9.2085	127.1
9A23	135.30	19.0	69.3	9.4623	9.5421	128.9
9A24	135.50	19.0	63.8	9.1755	9.1700	185.5
9A25	134.45	19.0	73.4	9.3427	9.5393	147.2
9A26	135.10	19.0	67.1	9.2319	9.2127	119.6
9A27	136.10	20.0	67.3	9.1504	9.1469	137.3
9A28	136.25	19.0	73.6	9.0783	9.1785	141.2
9A29	135.00	19.0	68.4	9.2384	9.2771	145.2
9A30	135.55	19.0	70.2	9.1612	9.2461	148.5
9A31	135.95	18.0	74.1	9.1178	9.0637	125.0
9A32	135.08	18.0	70.4	8.9453	8.8673	150.4
9A33	135.15	19.0	70.3	9.1827	9.2194	154.0
9A34	135.80	18.0	73.2	9.5684	9.5794	143.8
9A35	136.20	19.1	83.5	9.4208	9.4747	140.8
9A36	135.05	19.0	75.6	9.7614	9.7056	143.3
9A37	136.38	18.0	69.4	9.2117	9.2832	139.6
9A38	134.40	18.0	68.3	9.3403	9.2052	138.8
9A39	134.55	18.0	74.6	9.2529	9.2731	169.1
9A40	134.42	18.0	72.1	9.7807	9.7070	139.7

4.3 PERFORMANCE

The Contract No. 377 between MIT and the Bendix Corporation provides for the target fee to be paid to Bendix subject to the following criteria:

The full amount, if 32 gyros are delivered, each of which: a) maintains operational level performance for 2500 hours of operation following acceptance, or b) maintains operational level performance for eighteen months after acceptance of the last gyro, or c) is used in a successful flight or otherwise destroyed by anyone other than Bendix. This total shall be reduced \$3,000 for each gyro up to a total of nine which fails to meet these requirements. Beyond that quantity, the entire performance portion of the fee shall be forfeited. Failed units may be re-qualified by repair at Bendix expense through 31 March 1971.

Currently two units, 9A9 and 9A10, which failed float freedom requirements and were torn down for failure analysis by Delco at NASA direction, qualify under (c) above, and two units, 9A18 and 9A27, which failed the insulation resistance requirements, have been repaired at Bendix expense and reaccepted. One failure, 9A16, for excessive gravity transient, one failure for float freedom, 9A17, one failure for bias drift shift, 9A26, and one wheel-oriented failure, 9A29, are charged against Bendix as of 1 December 1970. Total fee at this time, therefore, is base fee 141,698.59 plus performance fee remaining 90,834.03 or 232,532.62. The 1500-hour point for all units except 9A18 and 9A27 will arrive on 4 March 1972 and for those two units by the end of June.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 DESIGN

5.1.1 For future production, both shroud end covers will be fabricated from Mumetal, an effective magnetic shielding material. The background associated with this change is summarized in MIT Letter 70-3836-1, dated 2 January and Bendix Letter GC: 5-69-188, dated 18 November 1969.

5.1.2 The requirement for a vacuum condition between the shroud and the gyro case should be changed to a dry Nitrogen and helium mixture at atmospheric pressure. The performance difference due to any change in thermal conditions will be imperceptible. The simplification of assembly operations and the resulting convenience of the leak test procedure justifies the introduction of this change.

5.1.3 Bearing retainers have always been recognized as critical elements in the assembly, performance and life of gyro wheel packages. Experience at both MIT and Delco has developed practical methods for improving these characteristics of retainers. The kind of activities undertaken to achieve these results has been described in Section 5.4 of the Apollo II 25 IRIG Repair Program Final Report published by Delco in March 1970. The choice of optimum clearances between ball and pocket and the retainer guiding diameter and the bearing land diameter as a means of minimizing retainer disturbances had been identified at MIT. Specific recommended proportions were utilized at MIT and later at Bendix during later phases of the Task Order No. 33 wheel build program. Generally the results were comparable to those experienced at Delco.

It is possible therefore to recommend that future -081 configuration wheel build programs be advised to incorporate the following additional requirements for retainer/bearing match:

- a) The ball to pocket clearance range to be 0.0035 to 0.0040 inches.
- b) The retainer ID (for inner race riding retainers) to bearing land diameter clearance range to be 0.004 to 0.005 inches.
- c) The range of difference between (a) and (b) above to be 0.003 to 0.0013 inches.

No drawing changes are required. With a normal distribution of dimensions within the allowable tolerance 99% of the parts will be usable.

5.1.4 Rotor Assembly

The major cause of gravity transient and hot storage failures in the Task Order No. 33 production program has been ascribed to the slow accumulation of fluid in the various joints of the rotor assemblies. A description of the process is included in Laboratory Report E-2486, Fluid Effects in Floated Inertial Instruments. The problem is best avoided by attaching the parts with the minimum of cement and insuring that a relatively free flow path is provided into every cavity. This condition permits the fluid to fill all the cavities completely during the filling and pressurizing procedures.

To maintain this condition without introducing changes which would require requalification of the instrument, the following is recommended:

5.1.4.1 Install the inner rotor to the rotor holder by applying three spots of LCA-9 adhesive equally spaced in the holder grinding relief.

5.1.4.2 Slide the inner rotor into the rotor holder until the front surfaces are flush.

5.1.4.3 Apply three spots of LCA-9 adhesive equally spaced in the groove formed by the 0.015/0.020 x 45 chamber and the 0.020/0.030 x 45 chamber.

5.1.4.4 Cure the adhesive.

5.1.4.5 Assemble the microsyn rotor to the inner rotor assembly as in 5.1.4.1 through 5.1.4.4 above.

5.1.4.6 It may also be desirable to update the stacking procedure for the microsyn rotor. Current practice uses a Bondmaster adhesive of very low viscosity and capillary action to bond the stack. This method replaced the earlier method (used on Apollo II gyros) of painting or spraying a more viscous Cycleweld adhesive and bonding under pressure. The resulting glue line thickness with Bondmaster is about 40 μ inch compared to about 300 μ inch typical of the Apollo II gyro. Use of the current technique for Apollo gyros would reduce the available volume for fluid pickup in the microsyn rotor by a factor of eight and effectively eliminate this assembly as a possible source of gravity transient or hot storage sensitivity problems. This change can be accomplished without affecting any other parts, assemblies or procedures.

5.1.4.7 The foregoing eliminates the rotor assembly fill problem insofar as joint access by the fluid is involved. Porosity of the materials, especially the ferrite, can contribute to progressive unbalance changes. For this problem there are at least two possible corrective actions:

1. Impregnate the piece parts with epoxy under high pressure (\cong 2000 psi) prior to assembly.
2. Increase the length of the pressurization cycle in the fill procedure. There are drawbacks to each of these actions. For (1) machining which may be required after impregnation may negate the sealing effect and the high pressure may result in a reduction in the magnetic properties of the ferrite. For (2) a rotor saturated with damping fluid requires a major cleaning effort in a rebuild cycle.

5.1.5 Bearing Evaluation

In order to predetermine that the bearing assemblies procured for the program will result in wheels capable of long life and good performance and produce a reasonable process and hardware yield, a bearing qualification specification is being added applicable to each bearing configuration from each vendor. This new qualification test requires that a 25% minimum hardware yield be achieved through dynamometer testing in the three-pound preload, V78 oil wheel configuration. The degree to which the race surfaces are finished by the bearing vendor or subsequently by the gyro manufacturer is left to the gyro manufacturer.

APPENDIX

MIT Quarterly Reports

Report No. 1	31 July 1968
Report No. 2	30 September 1968
Report No. 3	31 December 1968
Report No. 4	30 June 1969
Report No. 5	30 September 1969
Report No. 6	30 April 1970

Bendix Monthly Progress Reports

Report No. 1	30 June 1968
Report No. 2	31 July 1968
Report No. 3	31 August 1968
Report No. 4	30 September 1968
Report No. 5	31 October 1968
Report No. 6	15 December 1968
Report No. 7	15 January 1969
Report No. 8	15 February 1969
Report No. 9	15 March 1969
Report No. 10	30 April 1969
Report No. 11	15 May 1969
Report No. 12	16 June 1969
Report No. 13	16 July 1969
Report No. 14	20 August 1969
Report No. 15	15 September 1969
Report No. 16	15 December 1969
Report No. 17	29 January 1970
Report No. 18	1 April 1970
Report No. 19	1 May 1970
Report No. 20	1 June 1970

Bendix Fiscal Reports

The first report covers the initial period through 30 June 1968. One report is available for each month thereafter terminating in a report for August 1970. The material presented consists of DD 633 forms covering Summary, Engineering, Manufacturing and Test Equipment and a cumulative cost and forecast graph.

GE Reports

Document No. 70SD4230 dated 16 April 1970

Final Report on an Acoustic Signature Analysis of 32 Gyro Wheel Assemblies

Bendix Reports

TR 1865 dated 7 December 1969

Final Report on 25 IRIG Gyro S/N 7C-111 Apollo Gyro Bearing Analysis Program

MIT/DL Reports

FBM/IC 032 dated September 1970

Apollo II IRIG Ball Bearing Wheel Design Verification Test Program

ISS Memo No. 743 dated 28 August 1969

Apollo II IRIG Wheel Design Verification Test Plan

ISS Memo No. 739 dated 8 September 1969

Proposed Failure Guidelines for Bearing Verification Test Program

STG Memo No. 1473 dated 27 February 1970

System Level Test Performed on Gyro S/N 814 (Heavy Oil Unit)

Delco Reports

Summary Final Report on Qualification Test of Bendix and MIT 25 IRIG gyros dated 15 April 1970.

E-2557

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