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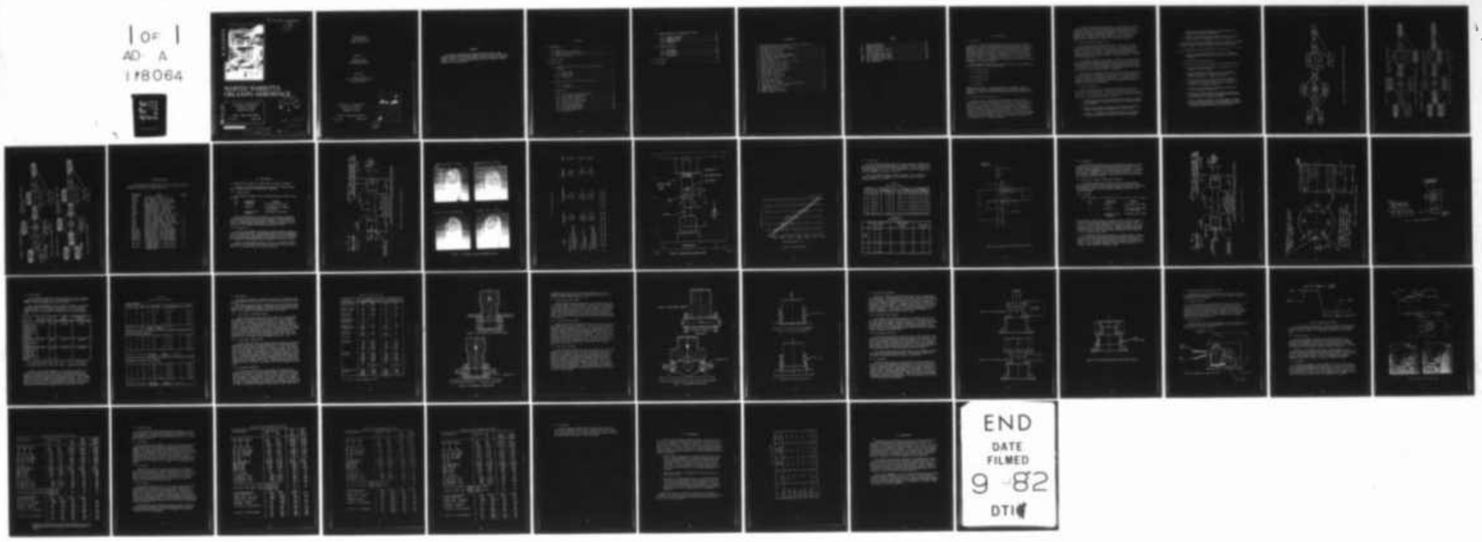

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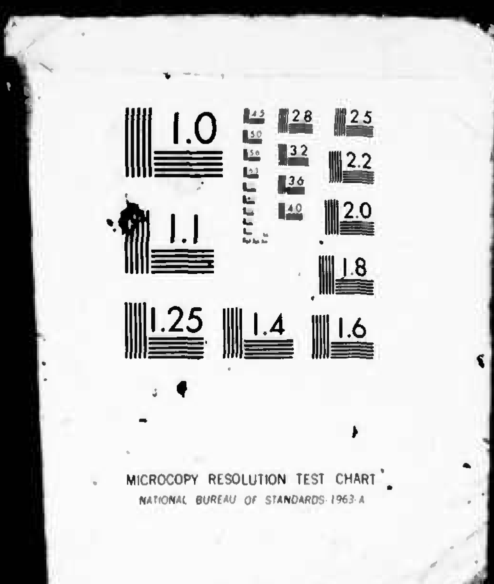

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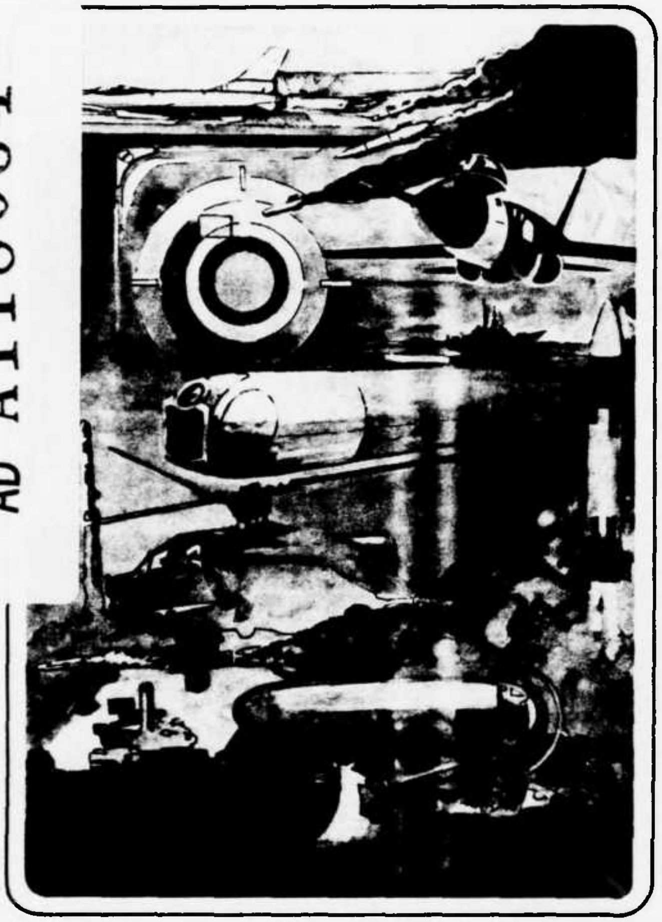

MARTIN MARIETTA ORLANDO AEROSPACE

Application of Powdered Metal Technology To Produce Titanium Gyro Parts

Volume I Overall Test Results

OR 16,766 March 1982

Contract DAAK-10-78-C-0070

MM&T Proj. No. 5794335

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FOREWORD

This report was prepared by Martin Marietta for the U.S. Army Armament Research and Development Command, Picatinny Arsenal, Dover, New Jersey. Work for the study reported herein was authorized under contract DAAK10-78-C-0070. This report concludes the effort of Project 5794335, Production Base Modernization.

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1.0 INTRODUCTION

1.1 Background

In 1979, a task was initiated aimed at reducing the cost of titanium components on a production program through the application of powder metallurgy technology. The Copperhead Engineering Development Program was essentially complete and Initial Production Facilitization was underway. Cost studies conducted during this time period showed that the cost of Copperhead titanium gyro components was excessive when fabricated using conventional machining techniques. Consequently, the task was organized to yield components at a considerable cost savings, the methodology of production, technical justification to incorporate the process, and design information for followon programs.

Martin Marietta addressed the problem of adapting a cost-competitive production process for five titanium parts:

1 Actuator housing

2 Gyro inner gimbal

3 Gyro gimbal ring

4 Gyro gotcha lock

5 Gyro base.

These parts, produced by conventional machining processes to tight tolerances, were tested and proven capable of surviving a maximum 9000-g design load sustained at cannon launch during ED testing at WSMR and at Huntsville.

1.2 State-of-the-Art Investigations

Initial efforts concentrated on investigating state-of-the-art powdered metallurgy (P/M) processes with the goal of accumulating data which could be compared to conventional production processes and quickly establish the applicability of the proposed processes. Accordingly, several companies involved in P/M were contacted. These companies were provided detailed technical information related to the gyro parts and requested to provide judgement on the producibility of these parts using P/M processes. Casting companies were also contacted as potential bidders to ensure competitive bidding. Results of these initial investigations are summarized in the following paragraphs.

All casting companies contacted said that casting technology was not sufficiently advanced to yield a near final part configuration. Most P/M contractors responded that short, erect parts could be fabricated but longer parts with final configuration dimensions along inside or outside surfaces would probably exceed their capability to produce the part. In essence, most companies with P/M experience had little confidence in their ability to produce all 5 parts. The one exception was TRW.

1.3 Material Technology Division of TRW

The Materials Technology Division of TRW, Cleveland, Ohio, expressed confidence in fabricating the major components. A technically feasible approach was provided to Martin Marietta and TRW demonstrated similar parts in support of the approach. Consequently, TRW was contracted to develop the processes and tools required to fabricate preforms to approved configuration and of sufficient strength to replace components "hogged-out" from wrought stock.

At the initial contact in Cleveland, the TRW facilities were toured, quality assurance procedures were reviewed, and technical considerations were established and accepted as well as program goals and plans. Critical surfaces of the final configuration (which requires expensive machining operations out of wrought material) were determined and were required to be final finished surfaces of the P/M preforms.

The proposed processing was established. Figure 1 depicts the variety of paths available in processing from raw material to final component; the path selected is determined as applicable to the material used, the strength desired, and the ultimate configuration. Figures 2 through 5 depict the operations required to deliver the strengths necessary of the material for each part configuration.

1.4 Report Organization

This report contains the results of tests conducted by Martin Marietta and the effort by TRW. Section 3.0 contains the test results and section 4.0 the conclusions. Work done by TRW has been documented and submitted to Martin Marietta. Copies of this report is submitted under separate cover. Work by Martin Marietta consisted of:

1 Determination of static tensile properties and impact properties of P/M specimens at +145°F, +70°F and -25°F, and bearing properties at +70°F.

2 Evaluation of apparent ultimate strength of tensile specimens during a dynamic high-g environment of a canister test.

3 Comparison of strength and compliance values of P/M specimens to wrought specimens and to analytical high-g requirements.

4 Evaluation of operating temperature and vibration effects on gyro assemblies made of P/M components.

5 Effects of high-g Copperhead acceleration profiles at temperature extremes on gyro assemblies made of P/M components.

The intent of the test program was to provide accurate data to support P/M use on future designs, and sufficient technical justification to support the replacement of wrought material in the production program.

The effort by TRW is covered in their final report. This effort was done by the Material Technology Division of TRW and covered:

1 Review part configuration in regard to proposed processing; submit configuration modification proposals if warranted by processing.

2 Order and characterize materials.

3 Evaluate test specimens fabricated to the planned processing.

4 Conduct preliminary investigations of preform behavior for insight to use in tool design.

5 Design and fabricate processing tools with documentation sufficiently detailed for competitive utilization and of durability adequate for a pre-production effort

6 Provide a Description of Manufacture specifying manufacturing procedures, process parameter control, raw material requirements, and ordinary and specialized equipment, etc., for each of the preforms fabricated.

7 Deliver to Martin Marietta test specimens representative of each process path for evaluation.

8 Demonstrate to Martin Marietta and ARRADCOM representatives that the Description of Manufacture indeed produces preforms to configuration and strength requirements.

9 Deliver finalized preforms in sufficient quantity to conduct component strength evaluations and gyro assembly evaluations over specified environments, and have an agreed-upon quantity in storage to support any followon evaluation needs.

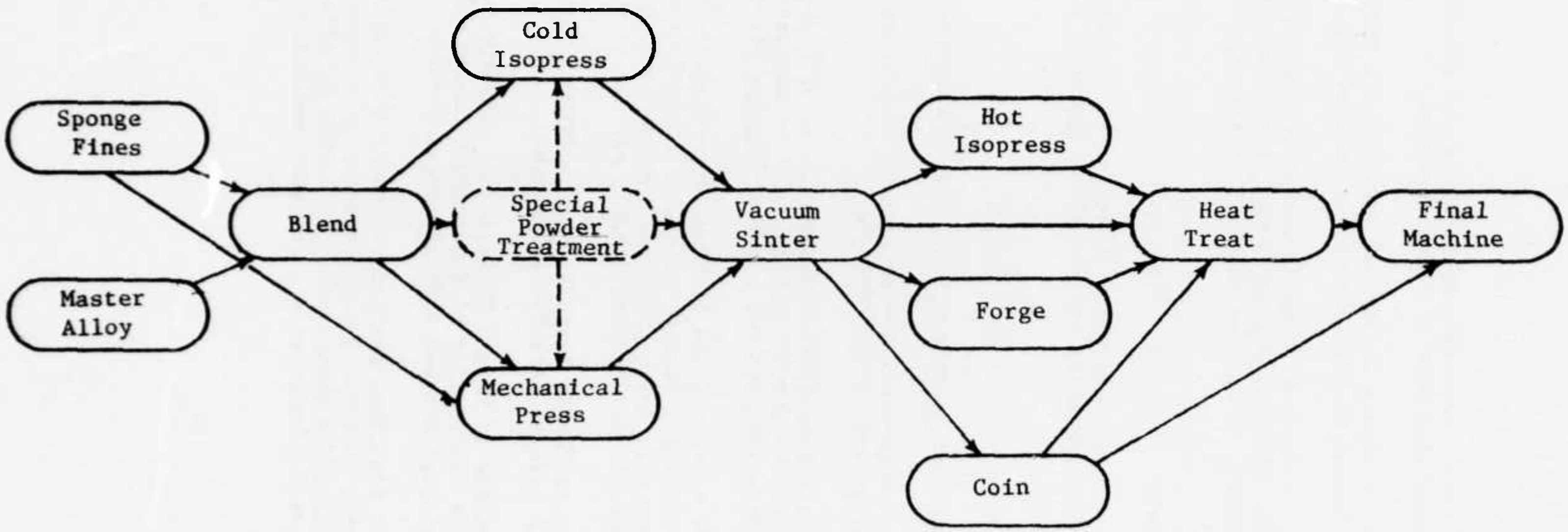


Figure 1 Operation Available For Powdered Metallurgy Processing

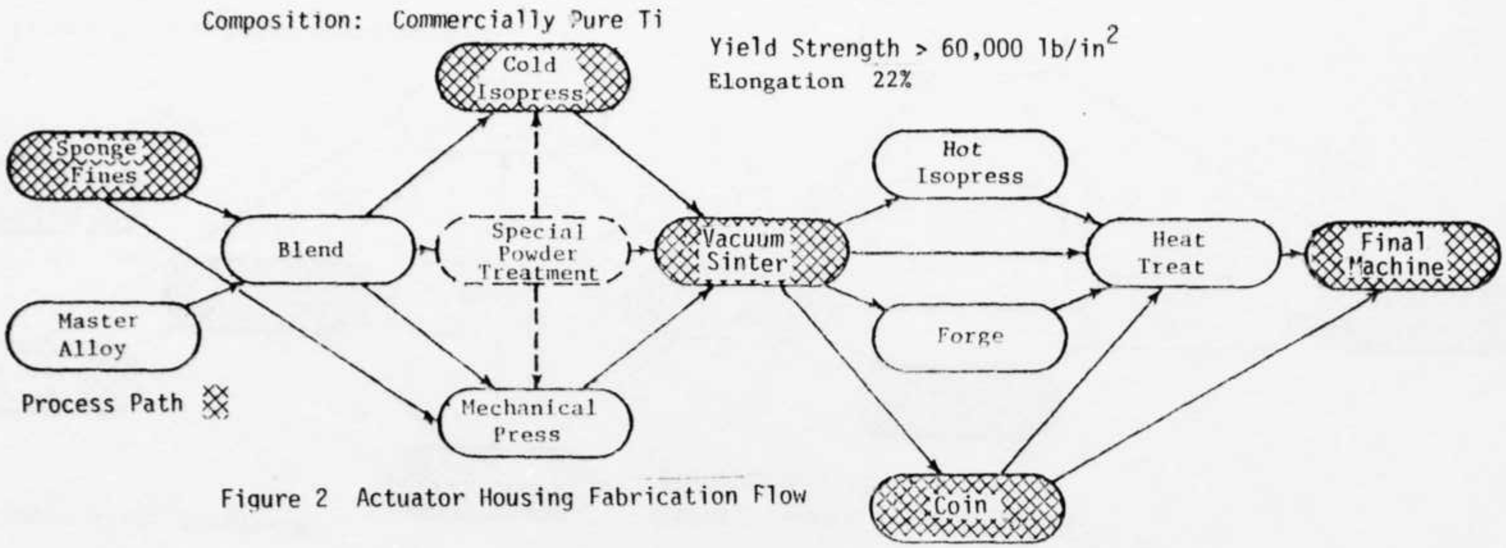


Figure 2 Actuator Housing Fabrication Flow

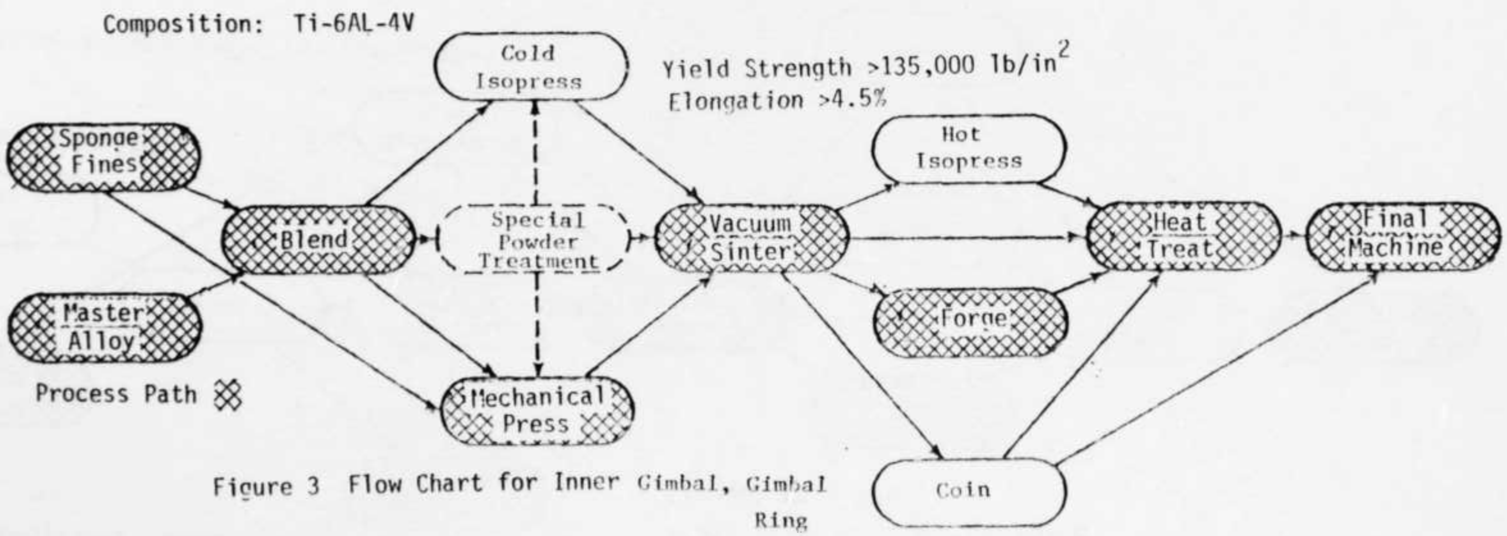


Figure 3 Flow Chart for Inner Gimbal, Gimbal Ring

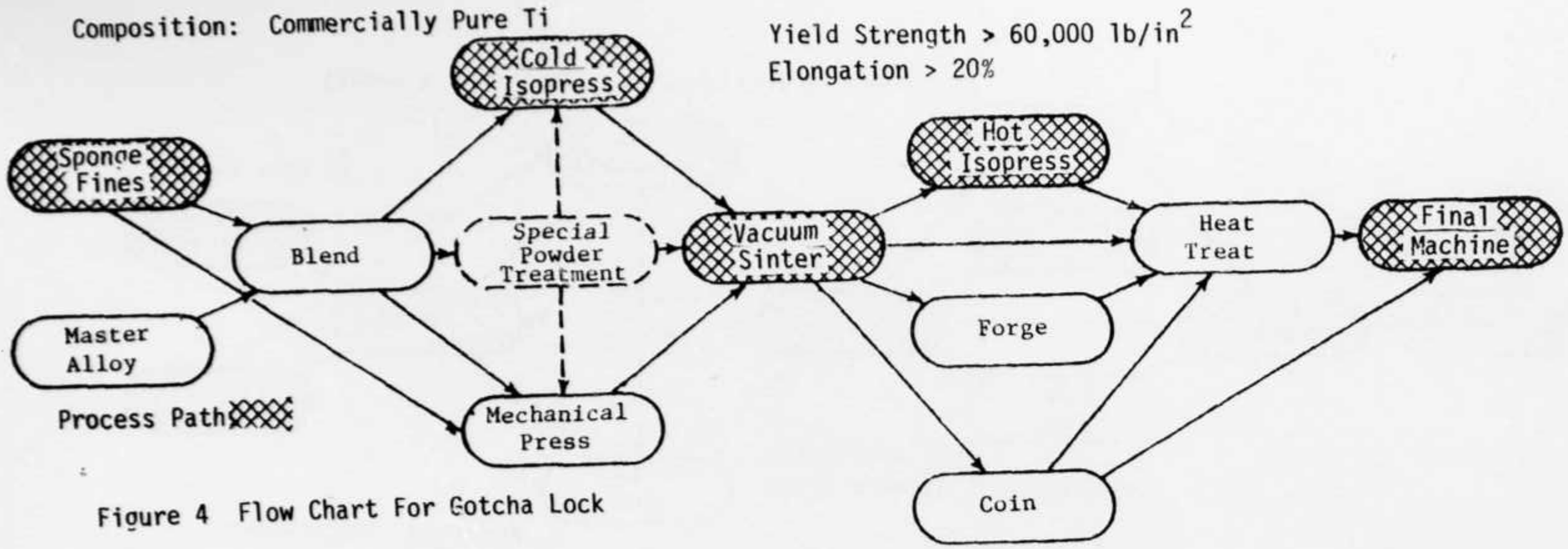


Figure 4 Flow Chart For Gotcha Lock

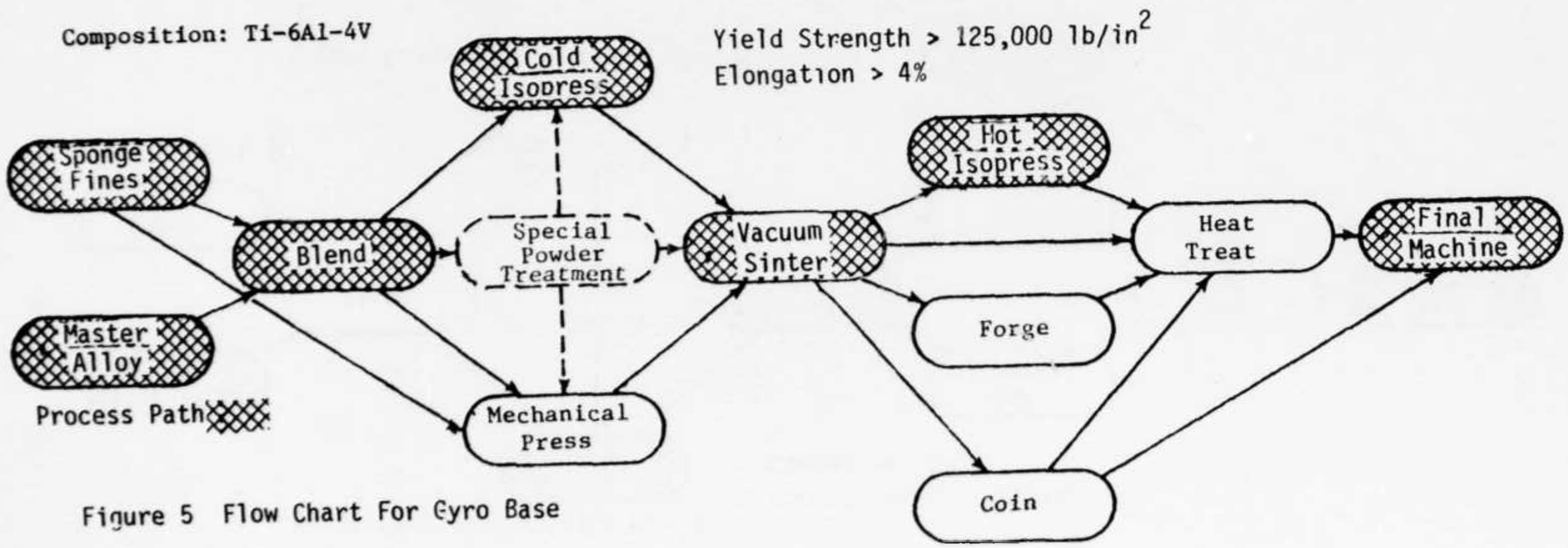


Figure 5 Flow Chart For Gyro Base

2.0 DRAWING PACKAGE

Machining preform drawings and associated tool drawings required to fabricate the preforms are listed below. Because of their size, these drawings are submitted as a separate package.

Drawing No.	Title	Sheet
407-T-2	CIP Mandrel for Gotcha Lock	
406-T-5	Bag & Mandrel for CIP of Gyro Base	1
406-T-5	Bag & Mandrel for CIP of Gyro Base	2
406-T-5	Bag & Mandrel for CIP of Gyro Base	3
406-1	Machining Preform - Gyro Base	
407-B	Machining Preform - Gotcha Lock	
408-C	Machining Preform - Actuator Housing	
409-B	Machining Preform - Gimbal Ring	
410-B	Machining Preform - Inner Gimbal	
409-FP-A	Forging Preform - Gimbal Ring	
408-A	Actuator Housing Preform - Preform Tools	3
409-A	Gimbal Ring Preform - Preform Tools	2
410-A	Preform - Inner Gimbal - Briq. Tools	1
410-A	Preform - Inner Gimbal - Briq. Tools	2
410-A	Preform - Inner Gimbal - Briq. Tools	4
408-A	Actuator Housing Preform - Preform Tools	4
408-A	Actuator Housing - Coining Tools	3
408-A	Actuator Housing - Coining Tools	4
409-A	Gimbal Ring Preform - Preform Tools	5
8851-265-1	Forging Die Set - Gyro Parts Assembly	1
8851-265-1	Forging Die Set - Gyro Parts Details	2
8851-265-1	Forging Die Set - Gyro Parts Details	3
8851-265-1	Forging Die Set - Gyro Parts Details	4
8851-265-1	Forging Die Set - Gyro Parts Details	5
8851-265-1	Forging Die Set - Gyro Parts Details	6
8851-265-4	Perishable Tooling - Forging Assembly Gimbal Ring	1
8851-265-4	Perishable Tooling - Forging Details Gimbal Ring	2
8851-265-4	Perishable Tooling - Forging Details Gimbal Ring	3

3.0 TEST RESULTS

3.1 Mechanical Properties of Titanium Powder Metallurgy Specimens

This section correlates mechanical properties of titanium powdered metal specimens against published wrought properties.

3.1.1 Tensile Tests

The following specimens of the configuration shown in Figure 6 were evaluated:

Qty	Composition	Process
21	Ti-6AL-4V	Die-Pressed, Warm Forged
21	Ti-6AL-4V	Cold Isostatically Pressed Warm Forged
21	Commercial Pure Titanium	Die-Pressed, Warm Forged

Tensile strength tests were preformed at the Materials Laboratory using laboratory fixtures and an Instron Machine. Seven specimens from the three compositions listed above were evaluated at -25°F, +75°F, and +145°F. Hi-magnification photographs of fractures are shown in Figure 7. Comparison of the average values obtained is given in Table I.

3.1.2 Bearing Test

This test was performed to evaluate and compare powdered titanium to wrought titanium in bearing. Four specimens were tested at room temperature of each material. The specimens were fixtured to the Instron machine and displacement gages were located on two surfaces as shown in Figure 8. The dimensions of the specimens and the direction of pull are also shown.

Loading of the specimens started at 300 lb. Displacement readings were taken at 300, 600, 900, 1200, 1500, and 1800 lb. Data are listed in Table II. The bearing load plot is shown in Figure 9.

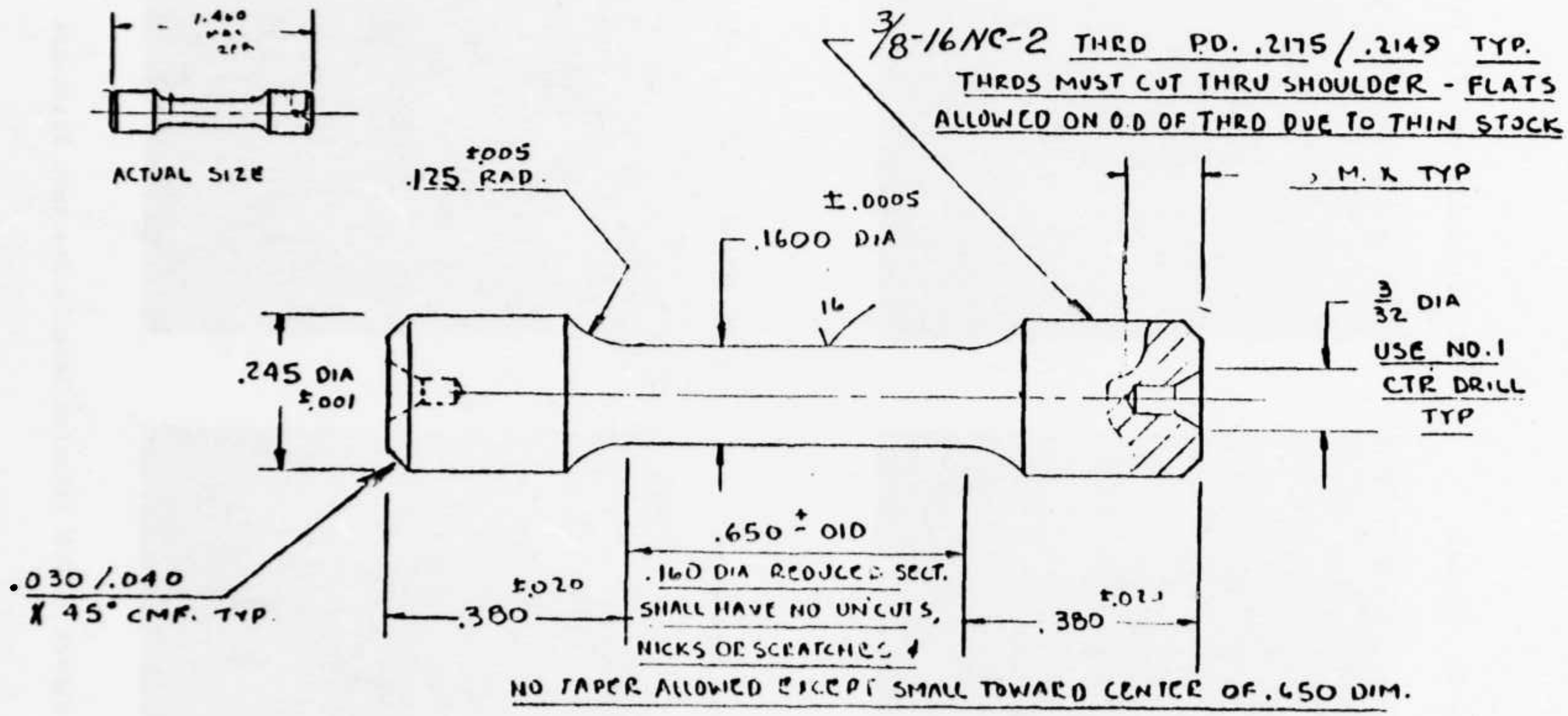
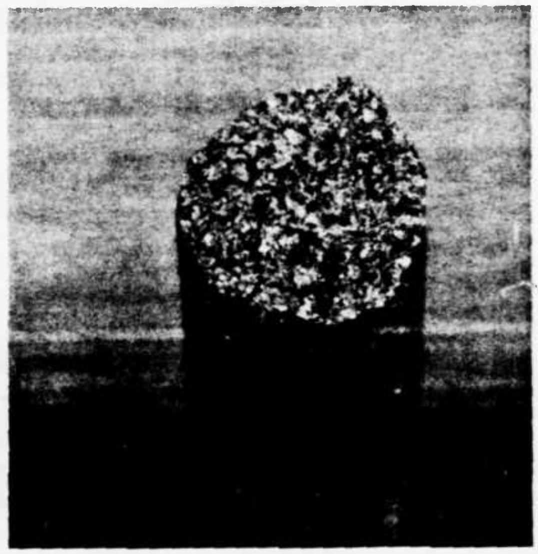


Figure 6 P/M Titanium Tensile Test Specimen

Commercially Pure Ti -25 Deg
10X

Commercially Pure Ti 145 Deg
10X



Ti-6Al-4V 10X Room Temperature

Ti-6Al-4V 10X -25 Deg

Figure 7 P/M Titanium Tensile Specimen Fractures

Table I Tensile Properties

Process	Yield Strength (Ksi)		Ultimate Strength (Ksi)		Elongation (%)		Temp. °F
Commercially Pure Ti	59.2		72.3		19.8		+145
Cold Isostatically Pressed, Sintered, Hot Isostatically Pressed (gotcha)	68.3	70*	82.2	80*	20.9	15*	+ 75
	81.0		96.4		21.3		- 25
Ti 6 Aℓ 4V	119.4		128.2		6.0		+145
Die Pressed, Sintered, Forged (gimbal)	126.9	120 **	134.2	130**	6.7	10**	+ 75
	141.9		152.5		7.3		- 25
Ti 6 Aℓ 4V	116.9		127.9		5.3		+145
Cold Isostatically Pressed, Sintered, Hot Isostatically Pressed (gyro base)	125.3	120**	137.3	130**	7.5	10**	+ 75
	142.6		152.4		13.2		- 25

* Room Temp. Properties of MIL-T-9046, Type I, Comp. B (MIL-HDBK-5C)

** Room Temp. Properties of MIL-T-9047, Comp. 6, Annealed (MIL-HDBK-5C)

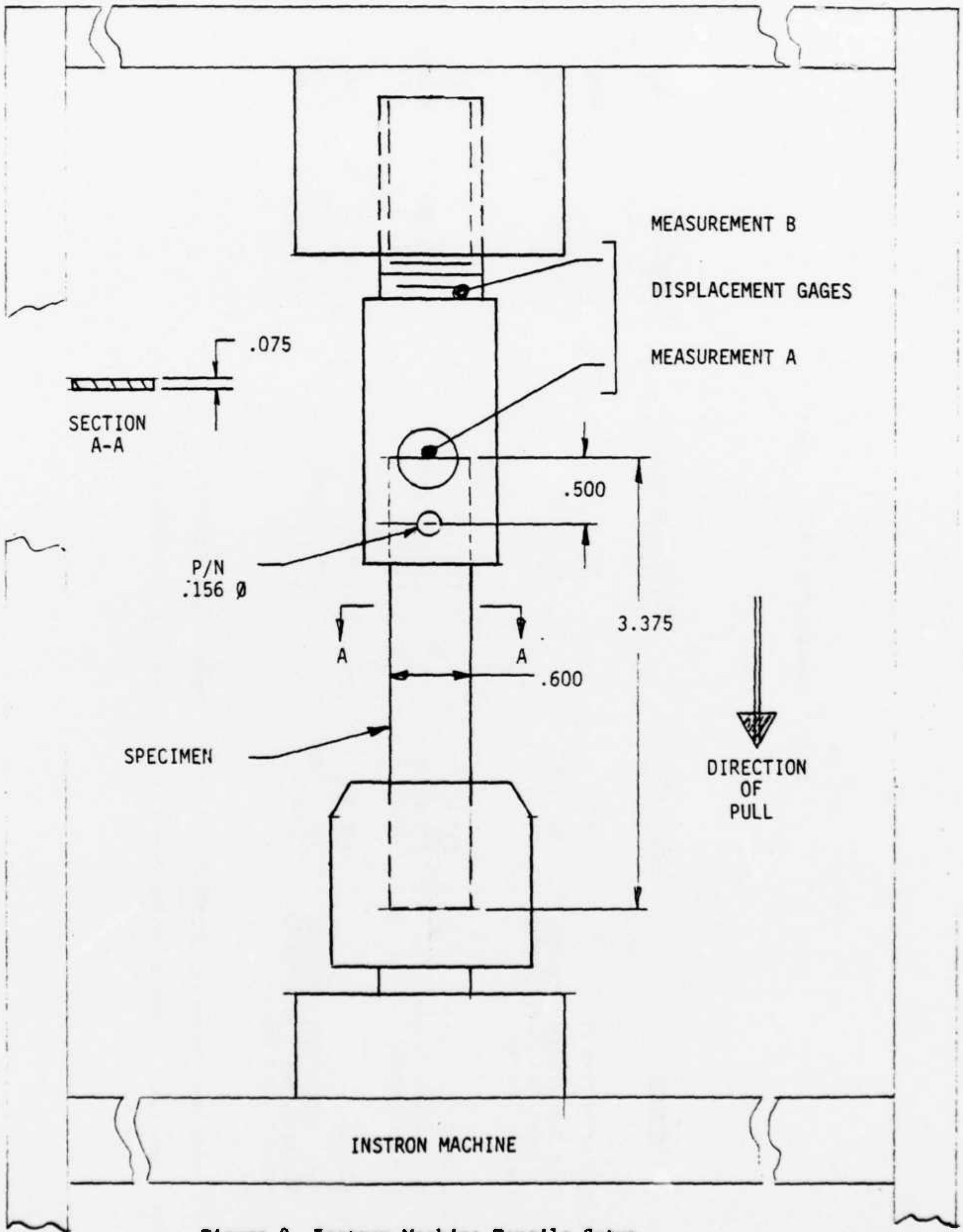


Figure 8 Instron Machine Tensile Setup

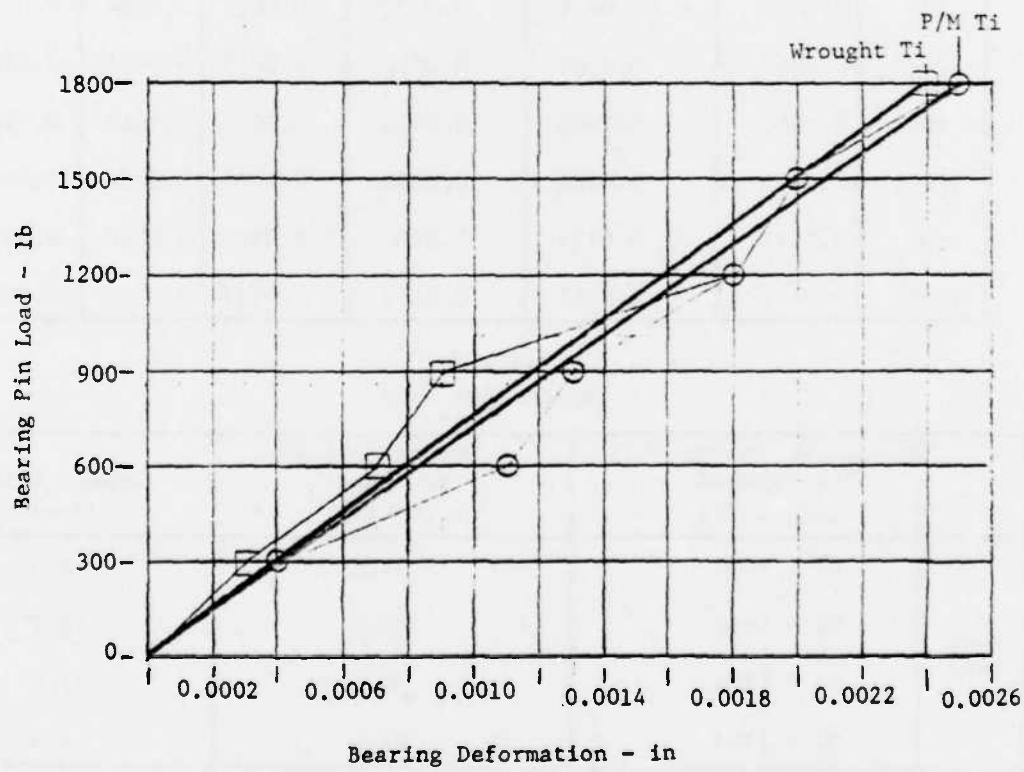


Figure 9 Bearing Load Data

3.1.3 Impact Test

The IZOD (cantilever-beam) impact test was performed to evaluate and compare powdered titanium (die-pressed) to published wrought titanium data. The machine used was the Tiniusolson Impact Tester. A total of seven P/M titanium specimens was tested. The dimensional size of the specimen used and the fixturing are shown in Figure 10.

Table III lists the results of tests performed. These values are judged acceptable when compared with the published impact strength of wrought TI-6AL-4V of 14 ft-lb.

Table II

Bearing Test Results

Applied Force (lb)	Gage A		Gage B		Elongation	
	PM	Wrought	PM	Wrought	PM	Wrought
300	0.0036	0.0034	0.0032	0.0031	0.0004	0.0003
600	0.0063	0.0062	0.0052	0.0055	0.0011	0.0007
900	0.0083	0.0084	0.0070	0.0075	0.0013	0.0009
1200	0.0105	0.0106	0.0087	0.0088	0.0018	0.0018
1500	0.0124	0.0124	0.0104	0.0104	0.0020	0.0020
1800	0.0142	0.0141	0.0117	0.0117	0.0025	0.0024

Table III

Impact Test Data

	Material Powdered Ti Die-Pressed (Tons - ^{0}F)	Energy Applied at Impact (in-lb)	Impact Value (in-lb)
Room Temp	40 - 1500	37.8	8.0
	40 - 1350	50.5	10.7
	40 - 1200	54.5	11.6
	30 - 1200	44.0	9.3
-25°F	40 - 1500	45.0	9.5
	40 - 1350	50.5	10.7
	30 - 1200	52.0	11.0

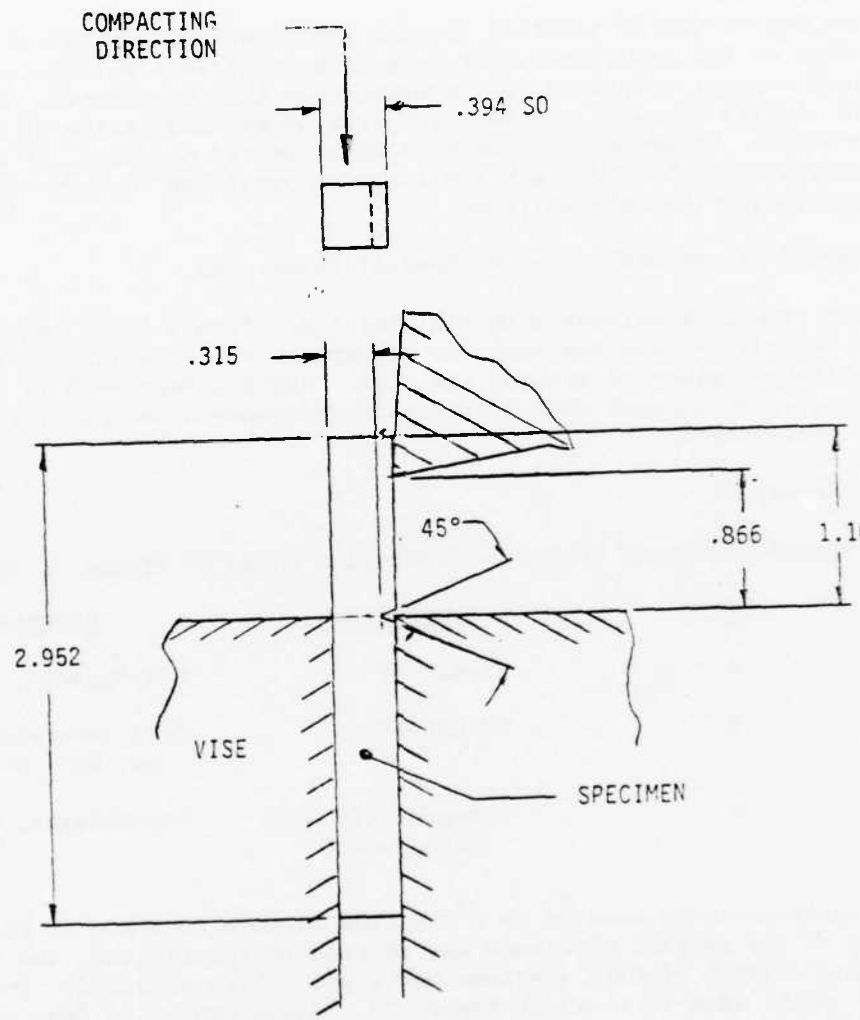


Figure 10 IZOD (Cantilever - Beam) Impact Test Setup

3.1.4 Conclusion

The evaluation of tensile, bearing and impact properties of specimens fabricated by the powder metallurgy process provides a portion of the technical support necessary for incorporation into Copperhead. The significance of data obtained was in the narrow spread indicative of a controllable process. Consequently, based on this limited sampling, it can be concluded with confidence that P/M titanium parts can be made with mechanical properties that are uniform.

3.2 Cannon Launch Effects on Mechanical Properties

Six tensile specimens were canister fired from a 155mm cannon to obtain material properties data for comparison with static test results and published values of wrought material. Results described in the following paragraphs indicate that P/M titanium components can survive the launch environment.

3.2.1 Procedure

Tensile specimens of the configuration shown in Figure 11 were provided:

Qty	Composition	Process
6	Ti-6AL-4V	Die-Pressed, Warm Forged
6	Ti-6AL-4V	Cold Isostatically Pressed, Warm Forged
6	Commercially Pure Titanium	Die-Pressed, Warm Forged

These specimens were mounted in a canister fixture as shown in Figure 12. One end of the tensile specimens was secured to the fixture, and the other end of each tensile specimen had a proof mass attached. The length of each proof mass is shown in Figure 13. Based upon data from static tensile tests, the intent was to bracket ultimate strengths attained during static tests by test specimens which would fail at ±20%, ±10%, and ±5% of the nominal static value.

Six different weights were fabricated; the average weight of these was to be determined. Based upon the static ultimate strength previously evaluated for a particular material/process variation, the desired g level at which to canister fire the units was calculated from the average weight. A material/process type whose static ultimate strength has a different value required a different g level.

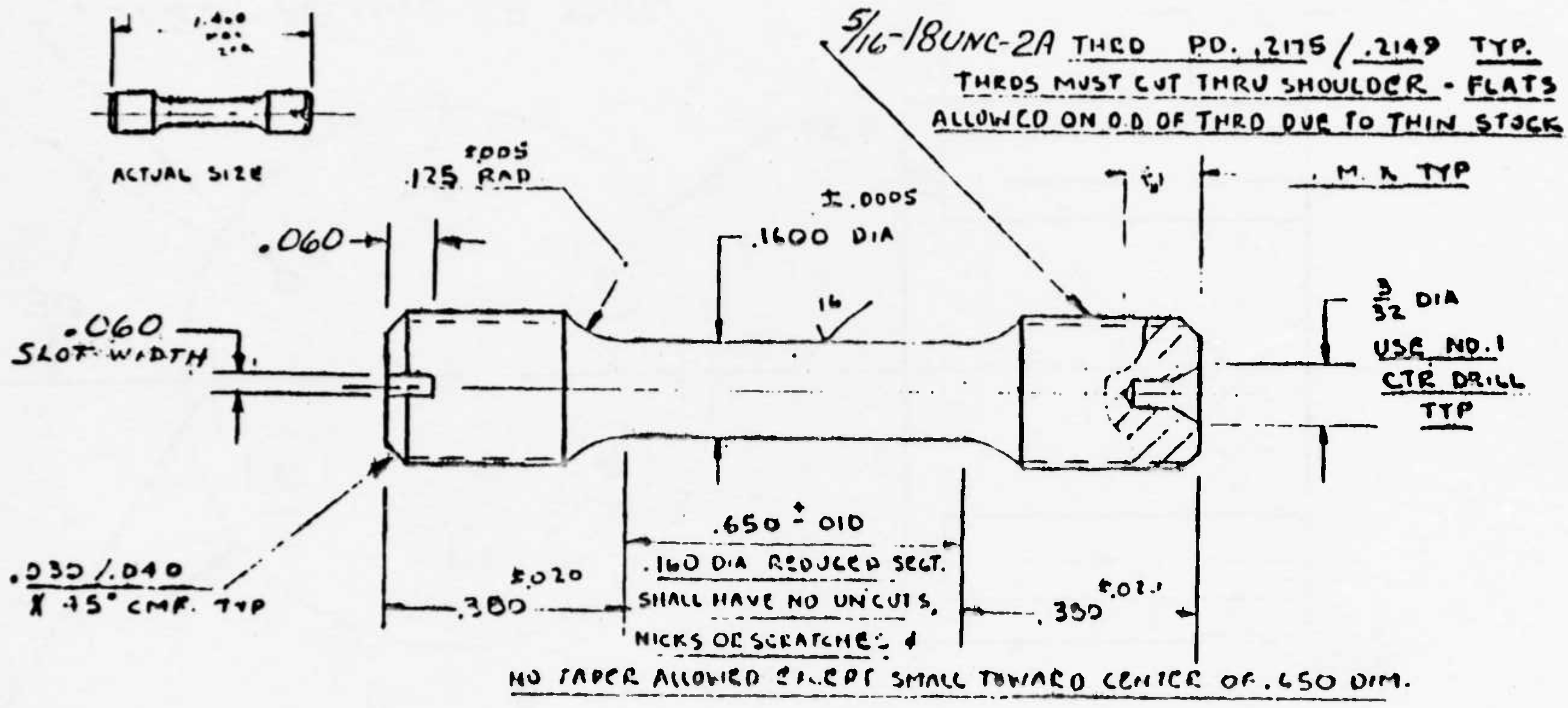


Figure 11 Canister Firing Test Specimens

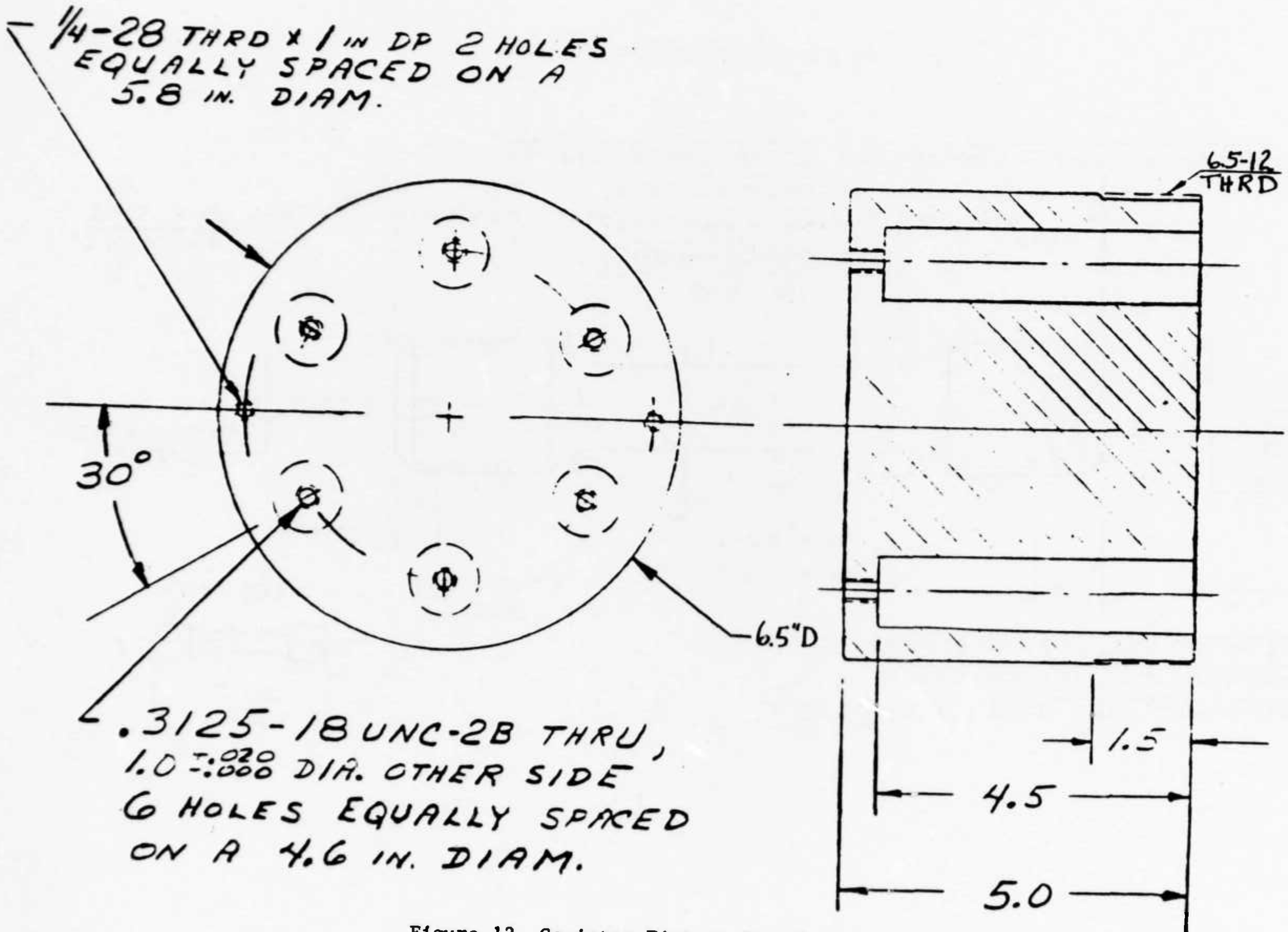
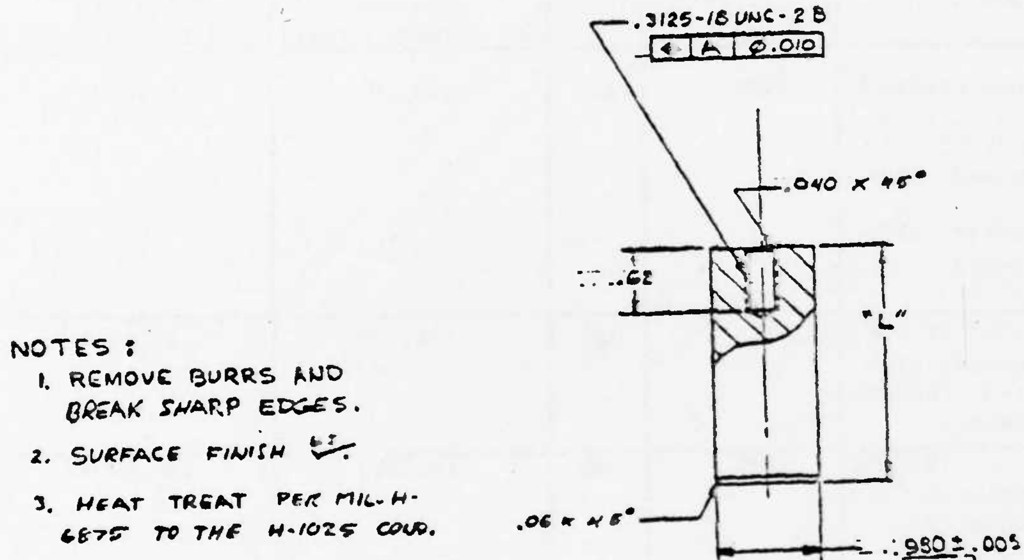


Figure 12 Canister Fixture Tensile Specimens



For lengths used, see Table IV.

Figure 13 Tensile Specimen Proof Mass

3.2.2 Test Results

Three canisters containing the P/M specimens were fired at Redstone Arsenal, Alabama, in August 1980. Parachute deployment on all three canister firings was normal and recovery was soft.

Since the transmissibility of the canister is unknown, an "apparent ultimate strength" was calculated (See Table IV) for each material/process variation, i.e., strength values were based on acceleration levels exerted on the canister, not actually felt at the test specimen mount.

Process	Acceleration (g)	Temp	P/M Apparent Ult Strength (psi)	Wrought Metal Published Ult Strength (psi)
Commercially Pure Ti Cold Isostatically Pressed, Sintered, Hot Isostatically Pressed (Gotcha)	8970	Amb	100,200	80,000*
Ti-6Aℓ-4V Die Pressed, Sintered, Forged (Gimbal)	8571	Amb	154,700	130,000**
Ti-6Aℓ-4V Cold Isostatically Pressed Sintered, Hot Isostatically Pressed (Gyro Base)	8783	Amb	140,800	130,000**

* Room Temp Properties of MIL-T-9046, Type I, Comp. B (MIL-HDBK-5C)

** Room Temp Properties of MIL-T-9047, Comp. 6, Annealed (MIL-HDBK-5C)

Assuming that the transmissibility of the canister launching fixtures to the P/M specimens is similar to the transmissibility of the Copperhead projectile to the gyro assembly, then stress safety margins based upon published values would be additionally safe by a factor approximately the ratio of apparent strength/published strength. That is, data does not imply that P/M parts are stronger than machined wrought parts; what is indicated is that a transmissibility of less than 1.0 effectively increases the designed safety margin on both P/M and wrought parts.

Table IV

Canister Launch Test Results

CP Ti - 8970 G's

WT #	LENGTH	PROOF MASS	+1/2 SPECIMEN (+1.9 Grms)	SPECIMEN
1	1.18	107.2 gms	109.1 gms	Broke
2	1.08	97.5	99.4	Intact
3	1.03	92.7	94.6	Intact
4	.94	83.5	85.4	Intact
5	.89	79.0	80.9	Intact
6	.79	69.7	71.6	Intact

Apparent ULT Strength = $\frac{99.4 \text{ g}}{454/\text{LBM}} \times \frac{8970 \text{ G's}}{.0196 \text{ in}^2}$ = 100,200 psi

Ti-6AL-4V C/H I P - 8783 G's

WT #	LENGTH	PROOF MASS	+1/2 SPECIMEN	SPECIMEN
7	1.90	173.8 gm + 3.13	176.93	Broke
8	1.76	157.5 ↓	160.63	Intact
9	1.65	149.0 ↓	152.13	Broke
10	1.55	141.0 ↓	144.13	Intact
11	1.40	124.9 ↓	128.03	Intact
12	1.26	113.5 +3.13	116.63	Intact

Apparent ULT Strength = $\frac{144.13 \text{ gms}}{454 \text{ g/LBM}} \times \frac{8783 \text{ G's}}{.0198 \text{ in}^2}$ = 140,800 psi

Ti-6AL-4V - Die Pressed Forged 8571 G's

WT #	LENGTH	PROOF MASS	+1/2 SPECIMEN	SPECIMEN
7	1.9	173.8 + 3.13	176.93	Broke
8	1.76	157.5 ↓	160.63	Intact
9	1.65	149.0 ↓	152.13	Intact
10	1.55	141 ↓	144.13	Intact
11	1.40	124.9 ↓	128.03	Intact
12	1.26	113.5 +3.13	116.63	Intact

Apparent ULT Strength = $\frac{160.63 \text{ gms}}{454 \text{ g/LBM}} \times \frac{8571 \text{ G's}}{.0196 \text{ in}^2}$ = 154,700 psi

3.3 Load Testing

This section documents the results of tests done to evaluate and compare compliances of gyro parts made of P/M titanium versus wrought titanium alloy.

Load testing was done at room temperature, using an Instron Universal Tester and other measuring divices. Two components of each type of material were used. Loads were applied as described in the following sections. Table V is a summary of deflections under the loads listed.

3.3.1 Inner Gimbal, Spin Bearing Thread

Analysis indicated that the spin bearing thread of the inner gimbal must support 200 pounds in tension before yielding. The P/M titanium inner gimbal was fixtured to the Instron Tester, as shown in Figure 14. It was seated at 100 pounds load and returned to 25 pounds to maintain seating. Load to the bearing thread was increased to 200 pounds with an indicated deflection of 0.0058 inch. Loading was continued to 400 pounds with an indicated deflection of 0.011 inch. The same procedure was followed for the wrought components and the amount of deflection recorded at 200 pounds was 0.006 inch, and at 400 pounds it was 0.0098 inch. The average spring rate for the P/M titanium was 40,403 lb/in. The average spring rate for the wrought titanium components was 48,571 lb/in.

3.3.2 Inner Gimbal, Trunnion Bore

Analysis indicated that the trunnion bores must support 406 pounds in bearing before yielding. The inner gimbal made of P/M titanium was fixtured to the Instron Tester as shown in Figure 15. It was then loaded to 200 pounds and returned to 100 pounds for seating purposes. Load to the gimbal was increased to 400 pounds with an indicated deflection of 0.0087 inch, and then loaded to 1000 pounds with an indicated deflection of 0.016 inch. The same procedure was followed for the wrought components and the amount of deflection observed at 400 pounds was 0.0085 inch, and at 1000 pounds it was 0.0158 inch. There was no apparent yield of material upon inspection of the load/deflection curve. The average spring rate for the P/M titanium was 71,428 lb/in. The spring rate for the wrought was 83,333 lb/in.

3.3.3 Ring Gimbal Compliance

The analysis indicates that the ring gimbal is subjected to 400 pounds load at launch in an out-of-plane bending. The P/M titanium ring gimbal was fixtured to the Instron Tester as shown in Figure 16, loaded to 100 pounds, and then returned to 25 pounds for seating. The load was then increased to 200 pounds with a deflection of 0.0041 inch recorded. The load was then increased to 500 pounds, and a deflection of 0.0080 inch recorded. The same procedure was followed for the wrought components and the amount of deflection indicated at 200 pounds was 0.0038 inch, and at

Table V Loading Test Data

Description	Wrought		P/M	
	Load (lb)	Deflect (in.)	Load (lb)	Deflect (in.)
Inner - Gimbal	200	.006	200	.0058
Spin BRG - THD	400	.0098	400	.011
Inner - Gimbal	400	.0085	400	.0087
Trunnion Bore	1000	.0158	1000	.016
Ring Gimbal	200	.0038	200	.0041
Compliance	500	.0073	500	.0080
Ring Gimbal	900	.011	900	.017
Trunnion Bore	-	-	-	-
See Note	2065f	-	2195f	-
Gotcha Lock	1100	.0046	1100	.0045
Forward Teeth	2000	.0075	2000	.0076
See Note	32150f	-	17925f	-
Gotcha Lock	1800	.0125	1800	.010
Aft Teeth	10000	.044	10000	.042
	21000f	-	12000f	-
See Note				
Gyro Base	100	.0006	100	.0005
Compliance	200	.0009	200	.0005
	400	.0009	400	.0013
	600	.0011	600	.0015
	800	.0012	800	.0020
	1000	.0014	1000	.0023
Gyro Base	1000	.0005	1000	.0013
Strength	2000	.0009	2000	.0015
	4000	.0022	4000	.0036
	6000	.0035	6000	.0054
	8000	.0049	8000	.0072
	10000	.0060	10000	.0095
	LBS.	Displacement (in)	LBS.	Displacement (in)
Gyro Base Yield	5000	.00195	5000	.00371
Strength	10000	.00530	10000	.00679
	50000	.02901	50000	.03124
	88500f	-	83350f	-

Note: Symbol f denotes component failed

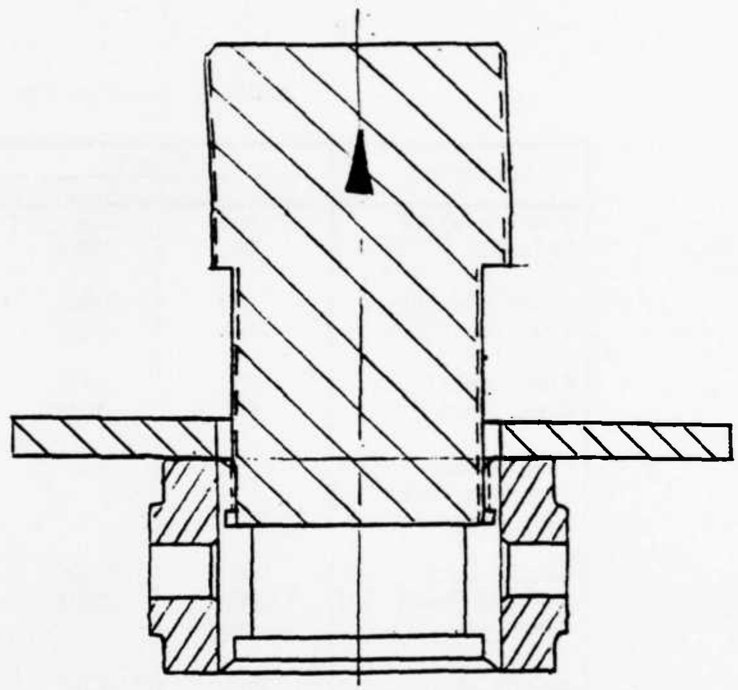


Figure 14 Inner Gimbal, Spin Bearing Thread

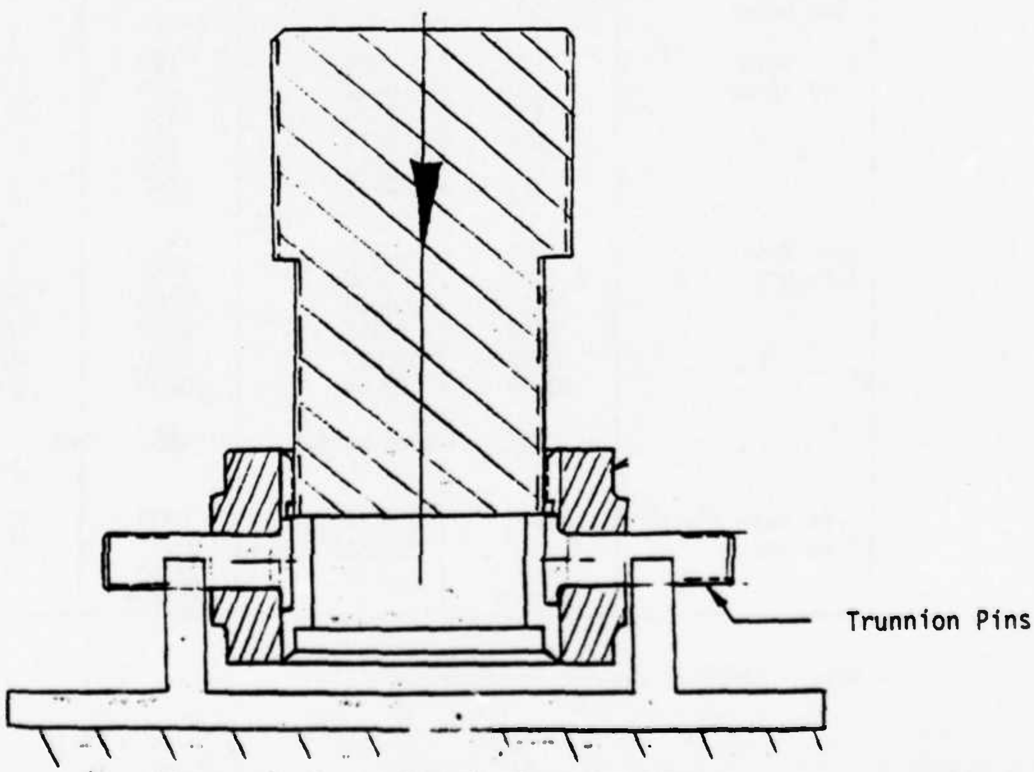


Figure 15 Inner Gimbal, Trunnion Bore

500 pounds it was 0.0073 inch. The average spring rate of the P/M titanium components was 61,526 lb/in. The average spring rate of the wrought titanium components was 66,724 lb/in.

3.3.4 Ring Gimbal, Trunnion Bore

Analysis indicates that the ring gimbal trunnion bores are subjected to 400 pounds bearing load during launch. The ring gimbal was fixtured to the Instron Tester as shown in Figure 17 and loaded to 900 pounds with an indicated deflection of 0.017 inch. Failure occurred at 2195 pounds. The same procedure was followed for the wrought titanium components and at 900 pounds the deflection was 0.011 inch. Failure occurred at 2065 pounds. The average spring rate of the powdered titanium components was 71,428 lb/in. The average spring rate for the wrought titanium components was 74,074 lb/in.

3.3.5 Gotcha Lock, Forward Teeth

Analysis indicates that the forward teeth that capture the gyro rotor must withstand 1092 pounds of shear load. The gotcha lock was fixtured to the Instron Tester as shown in Figure 18. The P/M titanium components used were made of commercially pure titanium to demonstrate that the less expensive commercially pure titanium possessed sufficient strength to replace the wrought alloy gotcha. The forward teeth were loaded to 1100 pounds with a deflection of 0.0045 inch recorded. At 2000 pounds another reading was taken with a deflection of 0.076 inch recorded. Failure of the forward teeth occurred at 17,925 pounds. The same procedure was followed for the wrought components and the deflection indicated at 1100 pounds was 0.0046 inch, at 2000 pounds it was 0.0075 inch. Failure occured at 32,150 pounds.

3.3.6 Gotcha Lock, Aft Teeth

Analysis indicates that the aft teeth which engage the gyro base must withstand 1774 pounds in shear. The gotcha lock was fixtured to the Instron Tester as shown in Figure 19. The P/M titanium components used were made of commercially pure titanium to demonstrate that the less expensive commercially pure material possessed sufficient strength to replace the wrought alloy gotcha. The aft teeth were loaded to 1800 pounds, yielding an indicated deflection of 0.010 inch. The load was increased to 10,000 pounds with an indicated deflection of 0.042 inch. Failure occurred at 12,000 pounds. The same procedure was followed for the wrought titanium components. At 1800 pounds there was a deflection of 0.0125 inch; at 10,000 pounds the deflection was 0.044 inch. Failure occurred at 21,000 pounds.

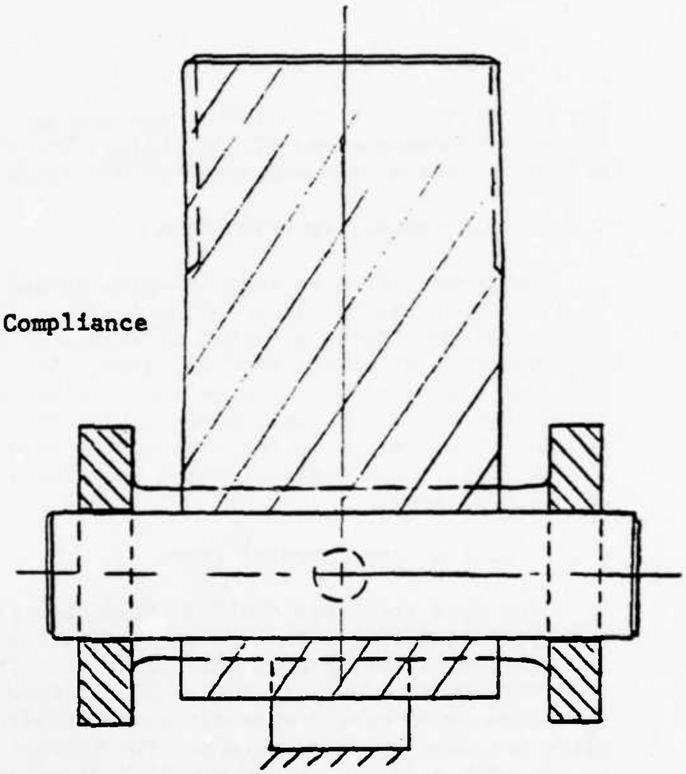


Figure 16 Ring Gimbal Compliance

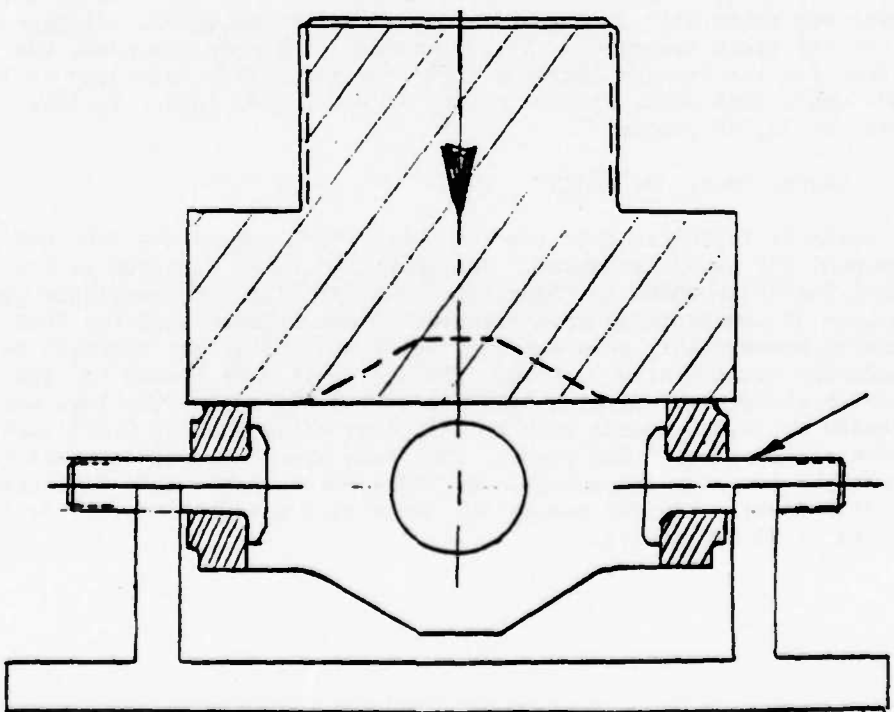


Figure 17 Ring Gimbal Trunnion Bore

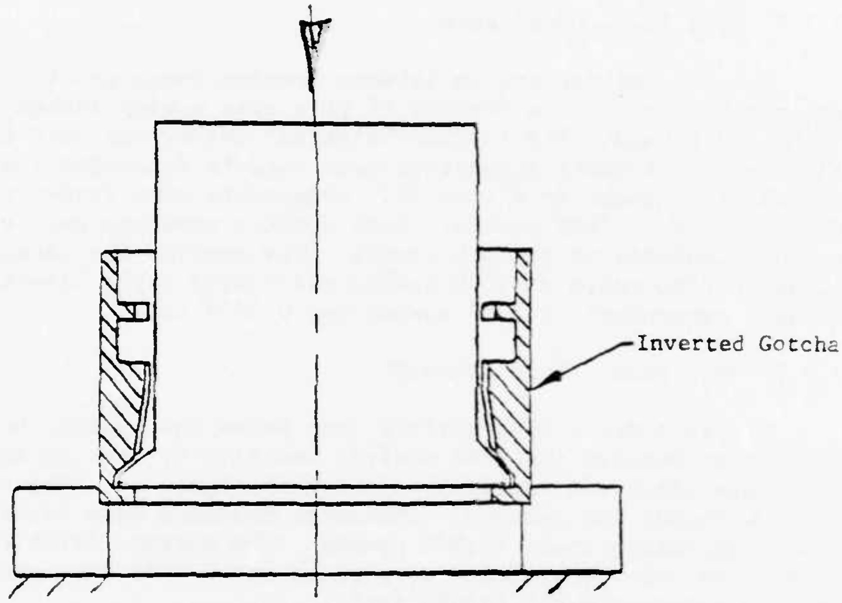


Figure 18 Gotcha Lock, Forward Teeth

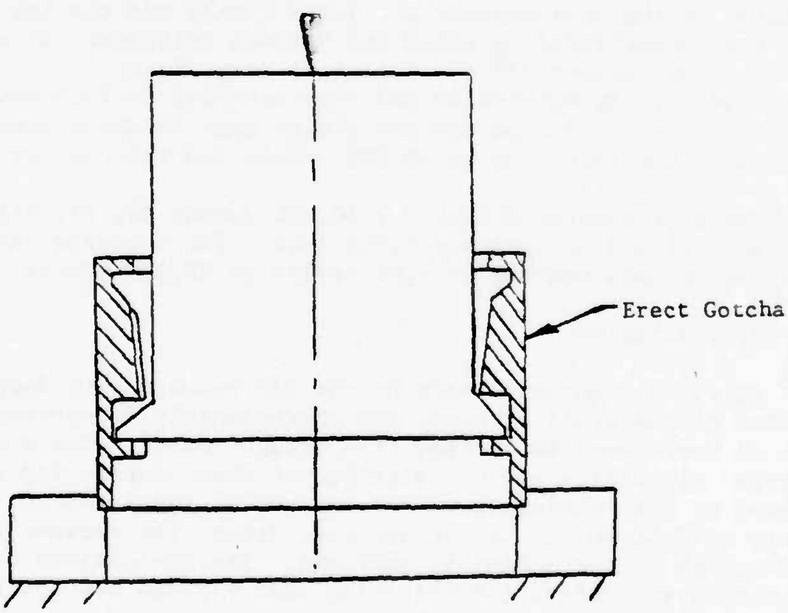


Figure 19 Gotcha Lock, Aft Teeth

3.3.7 Gyro Base, Compliance

The area of concern is between bearing bores and the forward edge of the gotcha teeth. The loading of this area during launch was determined to be 500 pounds. The Instron Universal Tester was used to apply the load, and two displacement indicators were used to determine the average displacement as shown in Figure 20. Components were loaded to 100 pounds and continued up to 1000 pounds. Displacement readings were recorded at 100 pound increments up to 1000 pounds. The average displacement of the P/M titanium components at 1000 pounds was 0.0023 inch; displacement of wrought components at 1000 pounds was 0.0014 inch.

3.3.8 Gyro Base, Yield Strength

By providing a flat surface just below the bearing bore holes, the deflection between the flat surface relative to the top surface of the gyro base teeth was measured as shown in Figure 21. The bases were loaded to 1000 pounds for seating. Indicator readings were recorded at 1000 pound increments up to 10,000 pounds. The average deflection at 10,000 pounds for the P/M titanium components was 0.0095 inch and the average for wrought components was 0.0060 inch.

3.3.9 Gyro Base, Compression

Analysis indicated that the base must support 13,200 pounds in compression in the area between the lower flange and the top shoulder. This test was accomplished by using the Baldwin Universal Tester and two SR-5 strain gages located 180 degrees apart (see Figure 22). The components were loaded to 20,000 pounds and then set-back to 1000 pounds for seating. Loading began at 1000 pounds and strain gage readings were recorded at 5000 pound increments up to 60,000 pounds and then to failure.

The average displacement at 50,000 pounds for P/M titanium was 0.0312 inch and for the wrought was 0.029 inch. The powdered titanium failed at 83,350 pounds and the wrought failed at 88,500 pounds.

3.3.10 Conclusion

Titanium components made by the P/M process have approximately 94 percent of the yield strength and approximately 92 percent of the spring rate of components fabricated from wrought stock. These differences in material properties are not significant when considering strengths as delivered by both processes versus analytical requirements. The factor of safety evident in the Copperhead gyro design far exceeds the structural differences of the materials analyzed. The evaluations described herein constitute sufficient justification that P/M can confidently be utilized for the Copperhead gyro application.

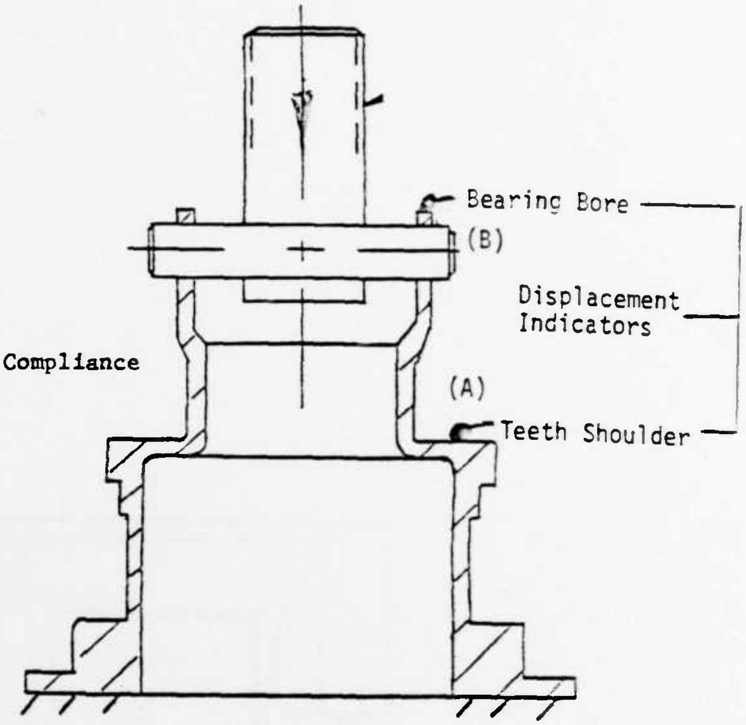


Figure 20 Gyro Base Compliance

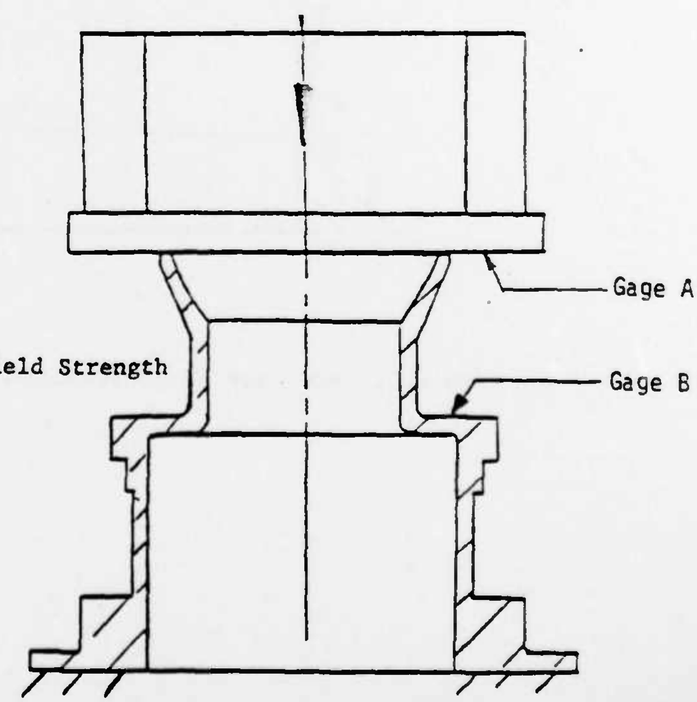


Figure 21 Gyro Base Yield Strength

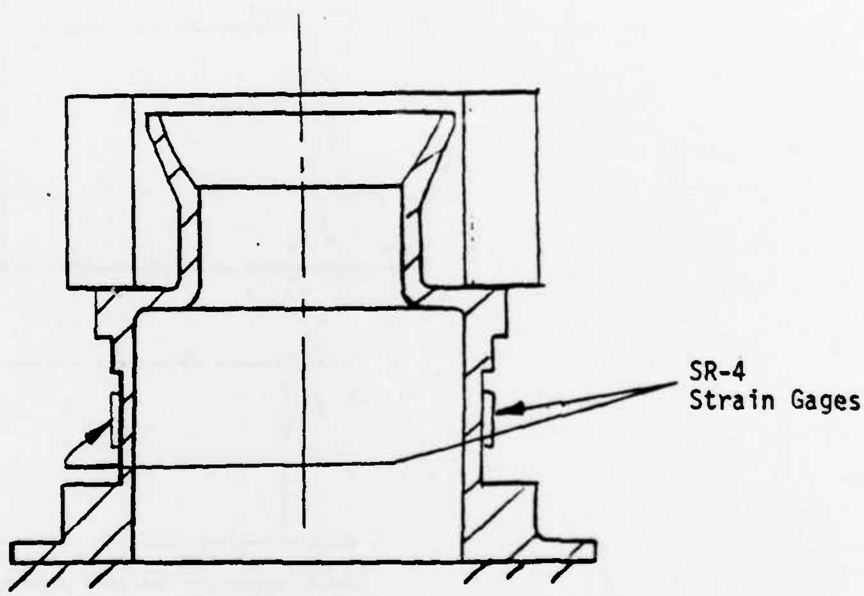


Figure 22 Gyro Base Yield Strength (Strain Gage Location)

3.4 Random Vibration and Temperature Cycling

The evaluations made are the mechanical and electrical functions of the Copperhead gyro before and after the gyro is subjected to temperature differences and random vibration.

3.4.1 Pretest Procedures

Five P/M titanium parts were dimensionally checked and recorded for the purpose of analysis in the event of gyro failure during testing cycle. Two gyros were assembled to the manufacturing process plan and subjected to the gyro acceptance tests. No problems were encountered. To assure that the gyros were completely operative, the gotcha squibs were electrically activated to test the gotcha release and drop mechanism which functioned as required. The squibs were replaced to permit re-activation after temperature cycle.

3.4.2 Temperature Test

The gyros were placed in the environmental chamber as shown in Figure 23. Data were recorded at ambient temperature, +145°F, -25°F and at ambient, cycled as shown in Figure 24.

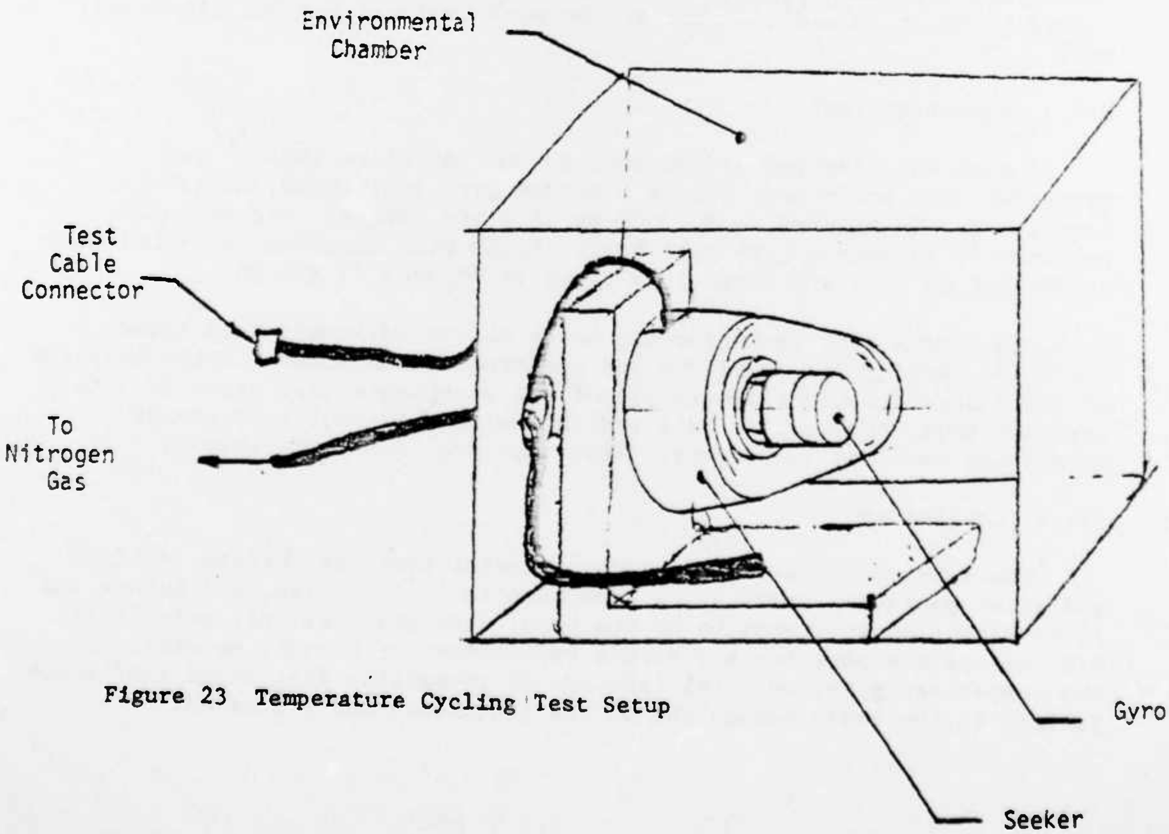


Figure 23 Temperature Cycling Test Setup

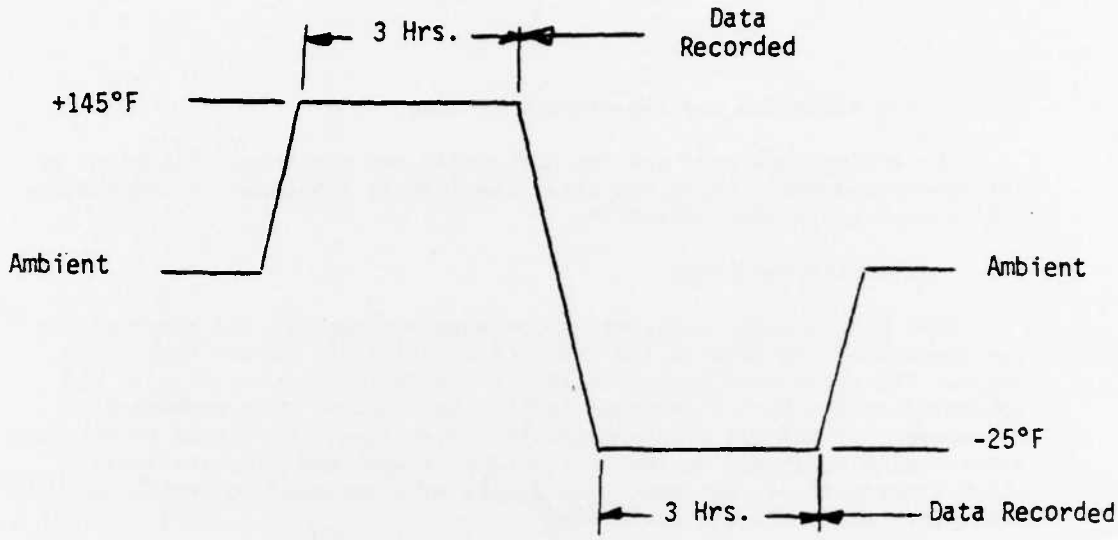


Figure 24 Temperature Cycling

Gyro performance was within spec. The gotcha squibs were activated after this test was completed and functioned as required. Test data are listed in Tables VI and VII. The squibs were replaced for the vibration test.

3.4.3 Vibration Test

A gyro was fixtured and mounted to the vibration table. Two exposures were performed; one at 0 degree gyro roll angle, horizontal position for 10 minutes at 20-2000 Hz (6 g rms target), and the other exposure at 90 degree gyro roll angle, horizontal position for 10 minutes at 20-2000 Hz (6 g rms target) as shown in Figures 25 and 26.

The gotcha lock mechanism was bench activated immediately after vibration testing was completed and performed as required. Cross coupling on P/M 2 deteriorated slightly from final acceptance test value of 3 to 6 percent; this, however, is well within the allowed post environment acceptance level of 10 percent. Test data are listed in Table VI.

3.4.4 Conclusion

The indepth evaluation of gyro parameter test data before, during, and after operating temperature environments on two gyros, and before and after vibration environments on one gyro, indicate that, not only is the P/M process adequate for the direct replacement of wrought material for the Copperhead gyro, but that data are so repeatable that added confidence is felt in the basic design and in the assemblers and processes.

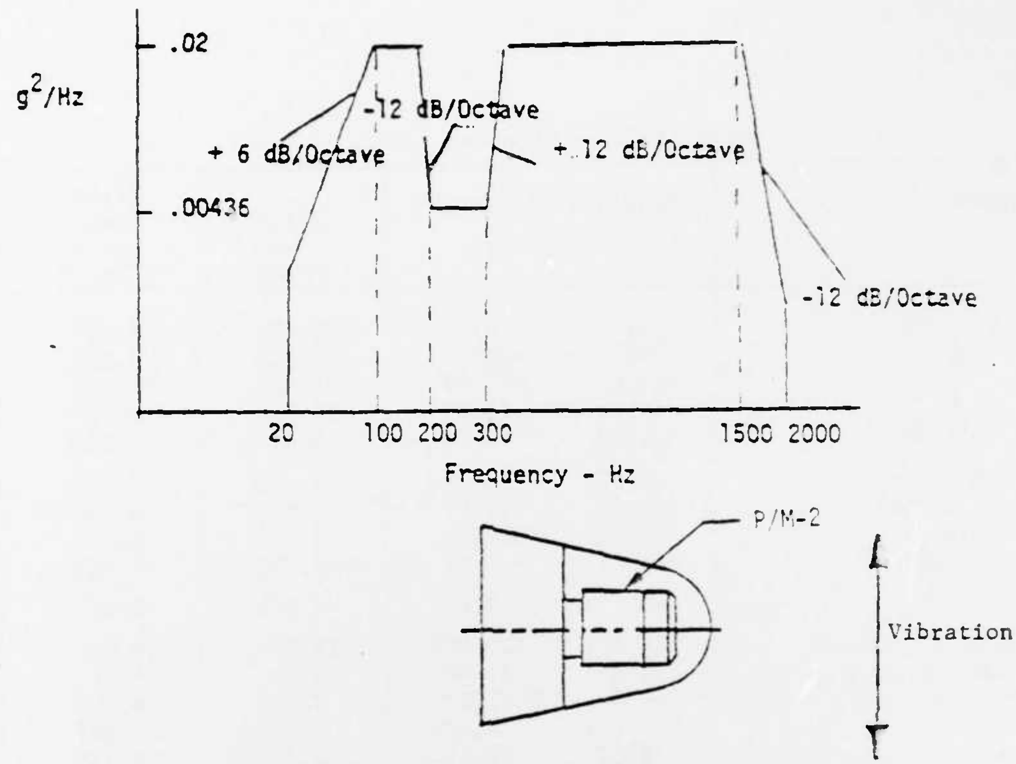
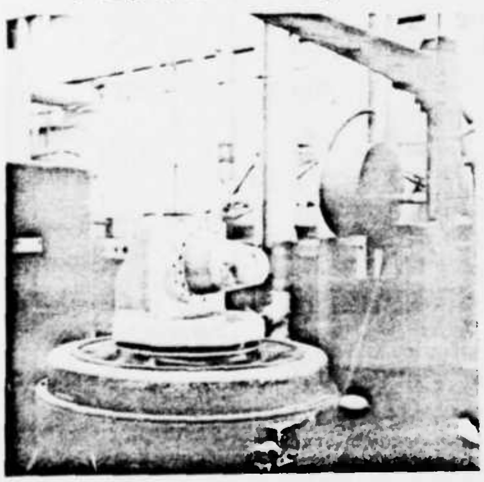


Figure 25 Random Vibration Spectrum

0 Deg Gyro Roll Angle



90 Deg Gyro Roll Angle

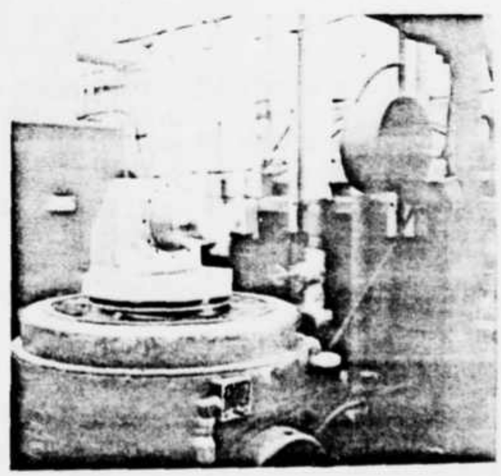


Figure 26 Seeker Vibration Test Setup

Table VI Gyro Acceptance Test (P/M-2)

Test Description	Baseline Limits Low	High	Final Test 1-9-82	After Temp. Cycle 1-28-82	After Vibration Cycle 2-25-82
Power Supply Voltage	+29V	+30V	29.650	29.400	29.600
	-29V	-30V	-29.850	-29.450	-29.250
	+14.6V	+15.4V	15.300	14.900	14.950
	-14.6V	-15.4V	-15.100	-14.940	-15.000
Power Supply Voltage	+4.8V	+5.2V	5.070	5.040	5.070
Max. Neg. Pitch Gimbal	+8.0V	+11.0V	8.715	8.715	8.760
Max. Pos. Pitch Gimbal	-8.0V	-11.0V	-8.670	-8.700	-8.745
Max. Neg. Yaw Gimbal	+8.0V	+11.0V	8.820	8.775	8.805
Max. Pos. Yaw Gimbal	-8.0V	-11.0V	-8.730	-8.685	-8.850
LEO Power	-2.20V	-3.20V	-2.600	-2.615	-2.635
Spin Speed Comm. #1	118 RPS	121 RPS	119.00	119.00	119.00
Spin Speed Comm. #2	118 RPS	121 RPS	119.00	119.00	119.00
Comm. #1 High	+4.6V	+5.4V	4.786	4.758	4.939
Comm. #1 Low	-.20V	+.80V	.053	.047	.050
Comm. #2 High	+4.6V	+5.4V	4.773	4.75C	4.934
Comm. #2 Low	-.20	+.8	.055	.050	.060
Dyn. Collimation	0.00"	0.15"	.050	.800*	.100
0° Free Drift - Pitch	.100V	/ 30 sec	.045	.058	.042
0° Free Drift - Yaw	.100V	/ 30 sec	.047	.057	.030
90° Free Drift - Pitch	.100V	/ 30 sec	.056	.032	.068
90° Free Drift - Yaw	.100V	/ 30 sec	.039	.053	.038
Pitch Drive, Yaw Couple = within 5%	pitch output of 3.4635 = .173		.074	.096	.184
Yaw Drive, Pitch Couple = within 5%	yaw output of 3.5293 = .176		.091	.104	.201
R1, R2 Torque Gain Res.	5.11K	40.2K	40.2K	38.30K	
Average Torque Rate	7.80/S	8.20/S	7.915	7.893	
G-Sens. Drift - Pitch Axis	.040/S	.040/S	.005	.010	.003
G-Sens. Drift - Yaw Axis	.040/S	.040/S	.012	.034	.032
Pot Noise - Pitch Axis	.00	.100V	.046	.036	.022
Pot Noise - Yaw Axis	.00	.100V	.066	.032	.011
Pitch Drive - Yaw Hysteresis	.00	.025	.012	.099	.012
	.00	.025	.014	.005	.009
	.00	.035	.026	.014	.021
Yaw Drive - Pitch Hysteresis	.00	.025	.008	.006	.011
	.00	.025	.016	.010	.012
	.00	.035	.024	.016	.023

* Unknown why collimation was shifted through temperature; most likely a handling problem, not associated with the unit being made by P/M process.

3.5 Canister Firings

On 19 January 1982, two P/M gyros were canister launched. The purpose of this test was to evaluate and compare the mechanical and electrical performance of the P/M gyro to the Copperhead production gyro. Comparisons made are the Baseline Limits/Final Acceptance Data/ Post Launch Data (Tables VIII and IX).

3.5.1 Pre-Launch

The five P/M titanium components of the gyro were each dimensionally checked and recorded for the purpose of analysis in the event of gyro failure after launch. Two gyros were then assembled to the normal gyro assembly line procedures and tested per normal procedures and acceptance criteria. The gotcha squibs were electrically activated to test the gotcha release and drop mechanism. New squibs were then installed and the gyros assembled to seekers with spring starters installed. Match line markings were scribed so as to check for any movement of assemblies after launch. One gyro was launched at 9,064 g and at +145°F; the other gyro was launched at 8,832 g and at -25°F. Recovery of both canisters was normal.

3.5.2 Post-Launch

Inspection of the match line markings showed that the assemblies were retained through launch. Shaking of the assembly and listening for any parts or hardware that might have loosened indicated no problem. The gotcha squibs were then bench activated, the gotchas dropped, indicating that the launch loads did not effect the components of that mechanism. The gyros were then disassembled from the spring starter and seeker housing, and fixtured to gyro final test set.

3.5.3 Test Results

The gyro P/M-3 (launched cold at -25°F) passed the performance test requirements after canister test firing. Gyro P/M-1 (launched hot at +145°F) passed all baseline test requirements except yaw drive pitch hysteresis. During the +145°F launch at 9000 g, gyro wires exiting the annular volume forward of the spring starter were torn. During the rework of the wires for test purposes, the spring starter was re-installed improperly, inadvertently affecting the gimbal alignment and correspondingly affecting the hysteresis plot. It is this error which was the cause of the yaw drive-pitch hysteresis being 0.007 volt beyond the flight specification of 0.050 volt.

Launch effects on gyro performance parameters listed in Tables VII and VIII have been compared to launch effects experienced on gyros made of wrought titanium; there is virtually no difference in the pre/post launch data for the two processes.

Table VII Gyro Acceptance Test (P/M-4)

Test Description	Baseline Limits Low	High	Final Test 1-9-82	After Temp. Cycle 2-18-82
Power Supply Voltage	+29V	+30V	29.650	29.600
	-29V	-30V	-29.580	-29.300
	+14.6V	+15.4V	15.300	14.950
	-14.6V	-15.4V	15.100	15.050
Power Supply Voltage	+4.8V	+5.2V	5.070	5.070
Max. Neg. Pitch Gimbal	+8.0V	+11.0V	9.120	8.970
Max. Pos. Pitch Gimbal	-8.0V	-11.0V	-8.850	-9.120
Max. Neg. Yaw Gimbal	+8.0V	+11.0V	8.625	8.595
Max. Pos. Yaw Gimbal	-8.0V	-11.0V	-8.685	-8.700
LED Power	-2.20V	-3.20V	-2.710	-2.730
Spin Speed Comm. #1	118 RPS	121 RPS	119.00	119.00
Spin Speed Comm. #2	118 RPS	121 RPS	119.00	119.00
Comm. #1 High	+4.6V	+5.4V	4.788	4.941
Comm. #1 Low	-.20V	+.80V	.050	.071
Comm. #2 High	+4.6V	+5.4V	4.770	4.933
Comm. #2 Low	-.20	+.8	.046	.051
Dyn. Collimation	0.00"	0.15"	.060	.040
0° Free Drift - Pitch	.100V / 30 sec		.032	.041
0° Free Drift - Yaw	.100V / 30 sec		.040	.044
90° Free Drift - Pitch	.100V / 30 sec		.066	.074
90° Free Drift - Yaw	.100V / 30 sec		.041	.036
Pitch Drive, Yaw Couple = within 5%	pitch output of 3.5352 = .176		.037	.065
Yaw Drive, Pitch Couple = within 5%	yaw output of 3.3274 = .166		.052	.037
R1, R2 Torque Gain Res.	5.11K	40.2K	40.20K	
Average Torque Rate	7.8D/S	8.2D/S	7.933	7.908
G-Sens. Drift - Pitch Axis	.04D/S	.04D/S	.034	.033
G-Sens. Drift - Yaw Axis	.04D/S	.04D/S	.018	.001
Pot Noise - Pitch Axis	.00	.100V	.030	.010
Pot Noise - Yaw Axis	.00	.100V	.016	.007
Pitch Drive - Yaw Hysteresis	.00	.025	.012	.011
	.00	.025	.014	.013
	.00	.035	.026	.024
Yaw Drive - Pitch Hysteresis	.00	.025	.006	.006
	.00	.025	.009	.008
	.00	.035	.014	.014

Table VIII Gyro Acceptance Test (P/M-3)

Test Description	Baseline Limits Low	- High	Pre-Launch 1-9-82	Post-Launch 1-29-82
Power Supply Voltage	+29V	+30V	29.65	29.4
	-29V	-30V	-28.85	-29.45
	+14.6V	+15.4V	15.30	14.9
	-14.6V	-15.4V	-15.10	-14.95
Power Supply Voltage	+4.8V	+5.2V	5.070	5.04
Max. Neg. Pitch Gimbal	+8.0V	+11.0V	8.88	9.315
Max. Pos. Pitch Gimbal	-8.0V	-11.0V	- 8.64	- 9.150
Max. Neg. Yaw Gimbal	+8.0V	+11.0V	8.55	9.630
Max. Pos. Yaw Gimbal	-8.0V	-11.0V	- 8.58	-9.675
LED Power	-2.20V	-3.20V	-2.67	-2.625
Spin Speed Comm. #1	118 RPS	121 RPS	119 RPS	119 RPS
Spin Speed Comm. #2	118 RPS	121 RPS	119 RPS	119 RPS
Comm. #1 High	+4.6V	+5.4V	4.766	4.74
Comm. #1 Low	-.20V	+.80V	.064	.071
Comm. #2 High	+4.6V	+5.4V	4.761	4.734
Comm. #2 Low	-.20	+.8	.038	.048
Dyn. Collimation	0.00"	0.15"	.020	.030
0° Free Drift - Pitch	.100V	30 sec	.040	.046
0° Free Drift - Yaw	.100V	30 sec	.016	.039
90° Free Drift - Pitch	.100V	30 sec	.084	.093
90° Free Drift - Yaw	.100V	30 sec	.037	.058
Pitch Drive, Yaw Couple =	Within 5% pitch output of 3.4302 = .171		.075	.094
Yaw Drive, Pitch Couple =	Within 5% yaw output of 3.3579 = .167		.110	.106
R1, R2 Torque Gain Res.	5.11K	40.2K	75.0K	82.5K
Average Torque Rate	3.8D/S	4.2D/S	3.966	3.954
G-Sens. Drift - Pitch Axis	.04D/S	.04D/S	.035	.004
G-Sens. Drift - Yaw Axis	.04D/S	.04D/S	.008	.027
Pot Noise - Pitch Axis	.00	.100V	.012V	.023
Pot Noise - Yaw Axis	.00	.100V	.065V	.005
Pitch Drive - Yaw Hysteresis	.00	.025 V	.016	.014
	.00	.025 V	.022	.016
	.00	.035 V	.034	.030
Yaw Drive - Pitch Hysteresis	.00	.025 V	.024	.029
	.00	.025 V	.023	.029
	.00	.035 V	.032	.057

Table IX Gyro Acceptance Test (P/M-1)

Test Oescription	Baseline Limits Low	High	Pre-Launch 1-9-82	Post-Launch 1-28-82
Power Supply Voltage	+29V	+30V	29.650	29.40
↕	-29V	-30V	-29.850	-29.450
↕	+14.6V	+15.4V	15.300	14.950
↕	-14.6V	-15.4V	-15.100	-14.950
Power Supply Voltage	+4.8V	+5.2V	5.070	5.030
Max. Neg. Pitch Gimbal	+8.0V	+11.0V	8.880	9.630
Max. Pos. Pitch Gimbal	-8.0V	-11.0V	-8.640	-9.450
Max. Neg. Yaw Gimbal	+8.0V	+11.0V	8.550	9.105
Max. Pos. Yaw Gimbal	-8.0V	-11.0V	-8.580	-9.420
LEO Power	-2.20V	-3.20V	- 2.670	-2.665
Spin Speed Comm. #1	118 RPS	121 RPS	119 RPS	120 RPS
Spin Speed Comm. #2	118 RPS	121 RPS	119 RPS	120 RPS
Comm. #1 High	+4.6V	+5.4V	4.766	4.761
Comm. #1 Low	-.20V	+.80V	.064	.060
Comm. #2 High	+4.6V	+5.4V	4.761	4.749
Comm. #2 Low	-.20	+.8	.053	.063
Dyn. Collimation	0.00"	0.15"	.020"	.120"
0° Free Orift - Pitch	.100V	30 sec	.016	.022
0° Free Orift - Yaw	.100V	30 sec	.046	.069
90° Free Orift - Pitch	.100V	30 sec	.039	.043
90° Free Orift - Yaw	.100V	30 sec	.045	.066
Pitch Orive, Yaw Couple = Within 5% pitch output of 3.4963 = .174			.007	.026
Yaw Orive, Pitch Couple = Within 5% yaw output of 3.8723 = .193			.058	.054
R1, R2 Torque Gain Res.	5.11K	40.2K	75.0K	64.90K
Average Torque Rate	3.8D/S	4.2D/S	3.986	3.974
G-Sens. Orift - Pitch Axis	.04D/S	.04D/S	.035	.036
G-Sens. Orift - Yaw Axis	.04D/S	.04D/S	.008	.016
Pot Noise - Pitch Axis	.00	.100V	.012V	.031V
Pot Noise - Yaw Axis	.00	.100V	.065V	.34V
Pitch Orive - Yaw Hysteresis	.00	.025V	.009	.007
	.00	.025V	.013	.007
	.00	.035V	.022	.014
Yaw Drive - Pitch Hysteresis	.00	.025V	.013	.018
	.00	.025V	.019	.012
	.00	.035V	.032	.031

3.5.4 Conclusion

Data from these two canister tests (at worst case spec limits of -25°F, +145°F temperatures and at 9000 g) indicate that the P/M fabrication process is adequate for the direct replacement of wrought material for the Copperhead gyro. The pre/post launch evaluations were comparable to pre-post launch evaluations of wrought components.

4.0 COST ANALYSIS

Quotations were submitted to Martin Marietta for preforms from TRW, and for machining from Speedring (division of Schiller Industries) for the five components in quantity of 4000 units. A listing of the quotations in comparison to current quotations of wrought components is given in Table X. Analysis indicates only a modest savings in utilizing the powder metallurgy process as opposed to normal wrought machining. However, additional economic support for P/M results when the following items are considered:

1 Best and final quotations by the machine shops are used in the table. These companies have delivered production components to the Copperhead Program for years and, therefore, have an established baseline from which to provide a best and final quotation. TRW, on the other hand, has delivered limited quantities of preforms against a development program and must be conservative in quotations until further experience is obtained.

2 Competitive bidding on providing P/M preforms is expected to help reduce costs.

3 At the start of this program, the cost of titanium stock was expensive and was expected to climb. However, the fact is that costs for wrought parts have declined during the life of the program thus making the savings modest. In a national emergency, the price of wrought stock might well sky-rocket again, while the price of preforms would only moderately increase.

Based on the results of this cost analysis, Martin Marietta recommends that powdered metallurgy be approved as an alternate fabrication process, and let the national economy dictate which process is used on cost-effective grounds.

Table X Cost Comparison

Part Description	TRW Preform	TRW Preform TRW Machining	TRW Preform Speedring Machining	"Hog-out" By Speedring Co.
Gyro base (9306406)	105.44	308.52	328.44	339.26
Gotcha Lock (9306407)	48.91	125.82	178.66	169.77
Gimbal (9306410)	4.39	104.53	100.52	104.74
Gimbal Ring (9306409)	15.02	120.00	127.38	104.40
Actuator (9306408)	3.37	66.09	89.32	80.88
Total	$177.13	$724.96	$824.32	$799.05

5.0 CONCLUSIONS

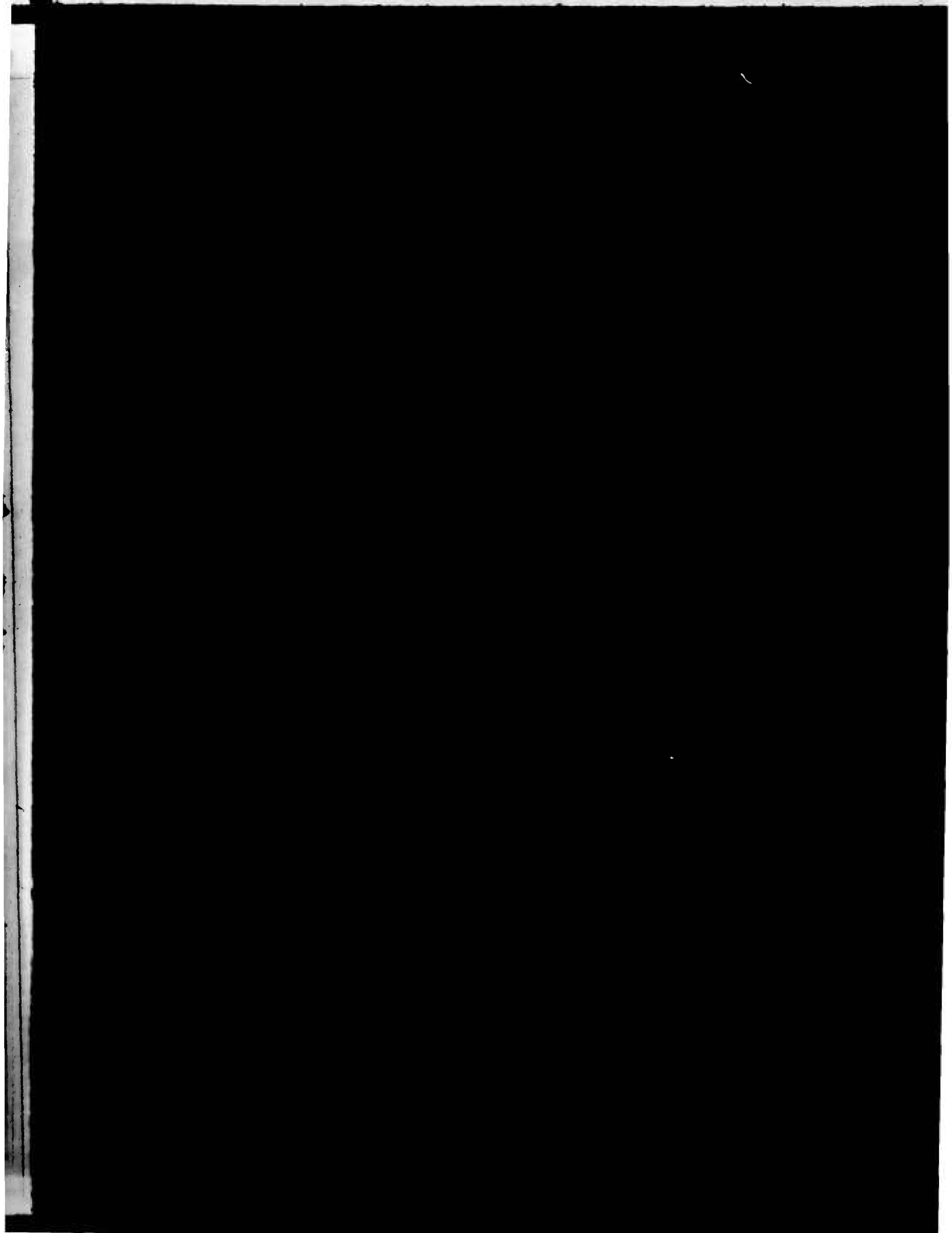
Components and test specimens produced by the powder metallurgy process have been demonstrated to possess approximately 94 percent the strength of components and specimens "hogged out" from wrought bar stock. The design of the components, made from either P/M or wrought stock, has a safety factor sufficient to alleviate concerns about the minor strength differences between the two processes. The large quantity of specimens evaluated had little variation in the data spread so that there exists a high confidence that the mechanical property values listed herein are accurate. Designers of followon programs can use these values.

The strength evaluations on components and specimens were believed to have been sufficient to justify P/M from a stress standpoint. The testing of gyros for function and parameter stability should satisfy concerns about part contact, interface, and operation. Minor parametric differences in pre/post environment exposure are attributed to handling errors by contributors outside the normal manufacturing realm whose influences are not controlled by approved procedures.

From a cost standpoint, the use of an approved alternate P/M process to fabricate gyro components will be a function of an ever-changing economic condition of the metals industry. Easy availability of wrought stock and scrappage losses from hog-out machining must be weighed against the costs of P/M preform processing. In a condition of urgency, the P/M alternative could prove invaluable.

DAT

FILM



G-Sens. Drift - Yaw Axis	.04D/S	.04D/S	.012	.034	[illegible]
Pot Noise - Pitch Axis	.00	.100V	.046	.036	.022
Pot Noise - Yaw Axis	.00	.100V	.066	.032	.011
Pitch Drive - Yaw Hysteresis	.00	.025	.012	.099	.012
	.00	.025	.014	.005	.009
	.00	.035	.026	.014	.021
Yaw Drive - Pitch Hysteresis	.00	.025	.008	.006	.011
	.00	.025	.016	.010	.012
	.00	.035	.024	.016	.023

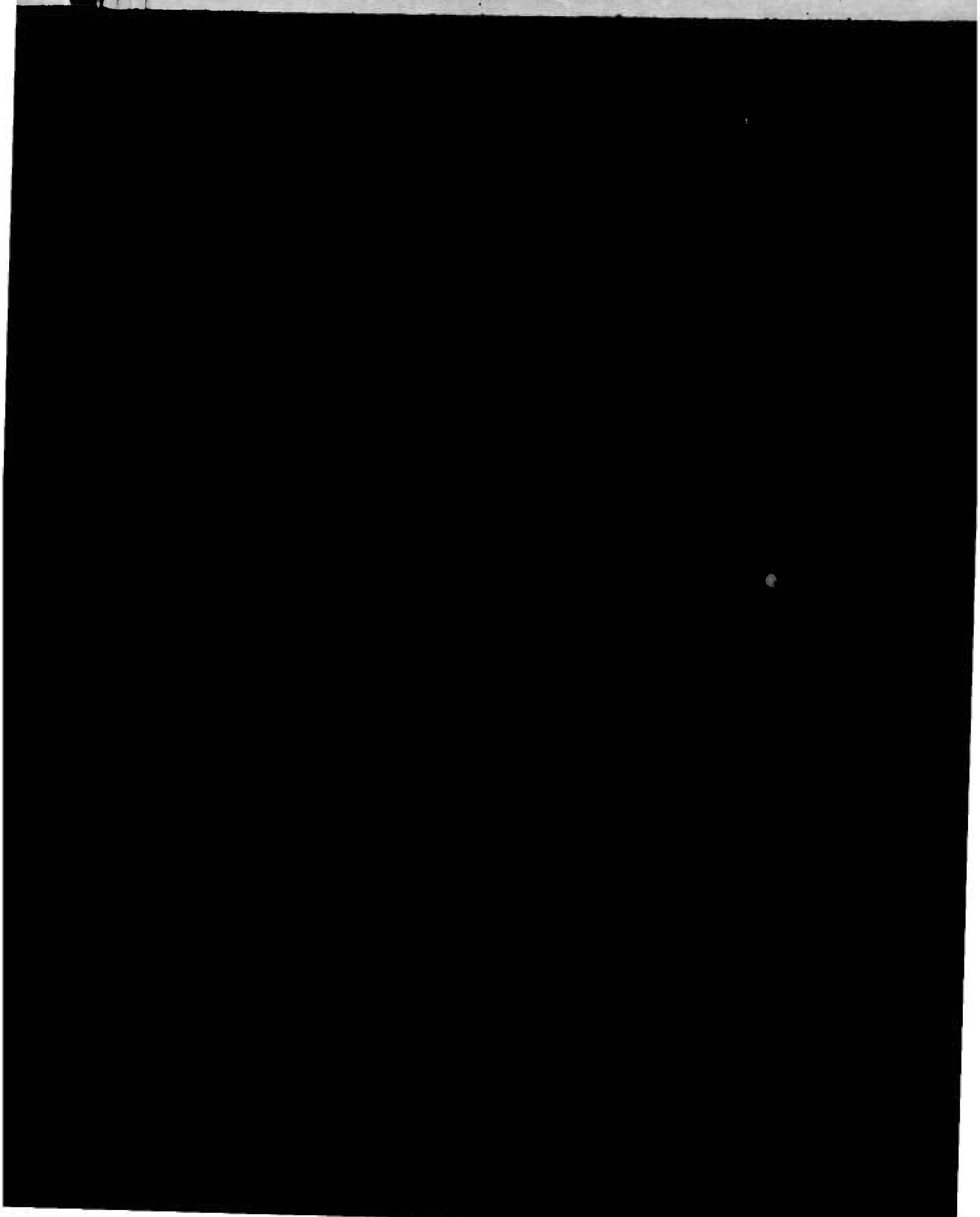
* Unknown why collimation was shifted through temperature; most likely a handling problem, not associated with the unit being made by P/M process.

Launch effecta on gyro performance parameters listed in Tables VII and VIII have been compared to launch effects experienced on gyros made of wrought titanium; there is virtually no difference in the pre/post launch data for the two processes.

Pitch Drive - Yaw Hysteresis	.00	.025	.012	.011
	.00	.025	.014	.013
	.00	.035	.026	.024
Yaw Drive - Pitch Hysteresis	.00	.025	.006	.006
	.00	.025	.009	.008
	.00	.035	.014	.014

	.00	.025 V		
	.00	.035 V	.034	.03
Yaw Drive - Pitch Hysteresis	.00	.025 V	.024	.02
	.00	.025 V	.023	.02
	.00	.035 V	.032	.05

Pot Noise - Pitch Axis	[illegible]	[illegible]	[illegible]	[illegible]
Pot Noise - Yaw Axis	.00	.100V	[illegible]	[illegible]
Pitch Drive - Yaw Hysteresis	.00	.025V	.009	.007
	.00	.025V	.013	.007
	.00	.035V	.022	.014
Yaw Drive - Pitch Hysteresis	.00	.025V	.013	.018
	.00	.025V	.019	.012
	.00	.035V	.032	.031



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