Report No.: WAED64.73E

Second Quarterly Report

For a

Brushless D. C. Torque Motor

(25 September 1964 - 25 December 1964)

Contract No.: NAS5-3934

Prepared by

Westinghouse Electric Corporation

Aerospace Electrical Division

Lima, Ohio

For

Goddard Space Flight Center

Greenbelt, Maryland

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ABSTRACT

This report covers the work performed on NASA Contract NAS5-3934 during the second quarter of work commencing September 25, 1964 and ending December 25, 1964. This contract covers the development of a brushless DC torque motor.

During this period, all manufactured and purchased components were procured, test procedures were prepared, and some general design considerations which arose after the initial design period were resolved. A research report prepared by Westinghouse Engineering Laboratories on the solid lubricant bearings to be used in these motors is included. In general, the work is proceeding according to the original schedule and plan.

author

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LIST OF FIGURES

I. INTRODUCTION

This report is the second quarterly report on NASA Contract NAS5-3934 - Brushless D. C. Torque Motor. It covers the period from September 25, 1964 to December 25, 1964. This period covers the manufacturing and procurement of components and the preparation of test documents. Some general design considerations which arose subsequent to the first quarter report will also be covered. A report on the solid-lubricant bearings is given in Appendix II.

As of the end of the reporting period, all purchased and manufactured components have been procured. Some design considerations were evaluated. General test procedures for laboratory tests and for engineering tests have been written.

II. DISCUSSION

A. Procurement and Manufacture of Components

No severe problems arose in the procurement and manufacture of components for the motor and reluctance switch. The following material substitutes were allowed by engineering because of procurement difficulties.

1. Double build ML enamelled wire of 0.0056 bare diameter was substituted for triple build ML enamelled wire of the same diameter. The double build wire will be satisfactory in this application.

2. A silicon rubber grommet was substituted for a Viton A grommet.

A design change was made in the control circuit. All type 2N2102 transistors were changed to RCA type 34381. This transistor has the same characteristics as the 2N2102 except that the sustained collector to emitter voltage is approximately 30 percent higher. This transistor is a stock item and will not present a procurement problem.

B. Test Procedures

The first available unit will be utilized for testing by engineering to check out the design of the control. This checkout will be generally in line with the procedures given in Appendix I. Any changes necessary in the design of the control will be made at this point.

Subsequent to this, all of the motors will be subjected to the General Test Procedure described in Appendix II except that only one unit will be tested for performance curves at all voltages. The others will be tested at only 40 volts. At the end of these tests, two units will be delivered to NASA.

C. New Design Considerations

1. Ripple Torque

The present torque motor design uses a 3-phase bridge with a wye-connected winding. The switching mode used is such that alternately 3 legs of the winding and then 2 legs are in the circuit. The question has been raised as to whether eliminating the 3-leg conduction and using just 2-leg conduction might be a better mode of switching from a ripple standpoint. To resolve this, an analysis similar to that shown on Pages 9 through 11 of the First Quarterly Report was performed for just 2-leg conduction using a 60 degree skew.

It is now only necessary to analyze 3 positions corresponding to connection 2 (refer to Figure 1) since all switching intervals are identical. If one per unit current was previously allowed on connection 1, it is now necessary to allow one per unit current on connection 2. The per unit current on connection 2 before was 0.75. It would be necessary to decrease Zph to lower the resistance. At the same time, the conductors would increase in area since more room is available.

Therefore, to keep the two switching modes on the same basis so that they can be directly compared, Zph must decrease by $\sqrt{0.75} = 0.866$. Therefore, every per unit torque calculated must be multiplied by 0.866 with one per unit current assumed.

Referring to Figure 2, using the general equation with all values in per unit

Torque = (Flux density)(Current)(Conductors)(Length)

<u>Position 1.</u>

Torque = 1.5 x 1 x 0.866 x 1.416 x Zph = 1.841 Zph

<u>Position 2.</u>

Torque = 1.5 x 1 x 0.866 x 1.667 x Zph = 2.16 Zph

<u>Position 3.</u>

Torque = 1.841 Zph

where Zph is the original value assumed for the previous switching mode.

Average Torque = 1.947 Zph

$$\text{Ripple} = \frac{0.319 \times 100}{1.947} = 16.4\%$$

Other values of skew were investigated and found to give worse results.

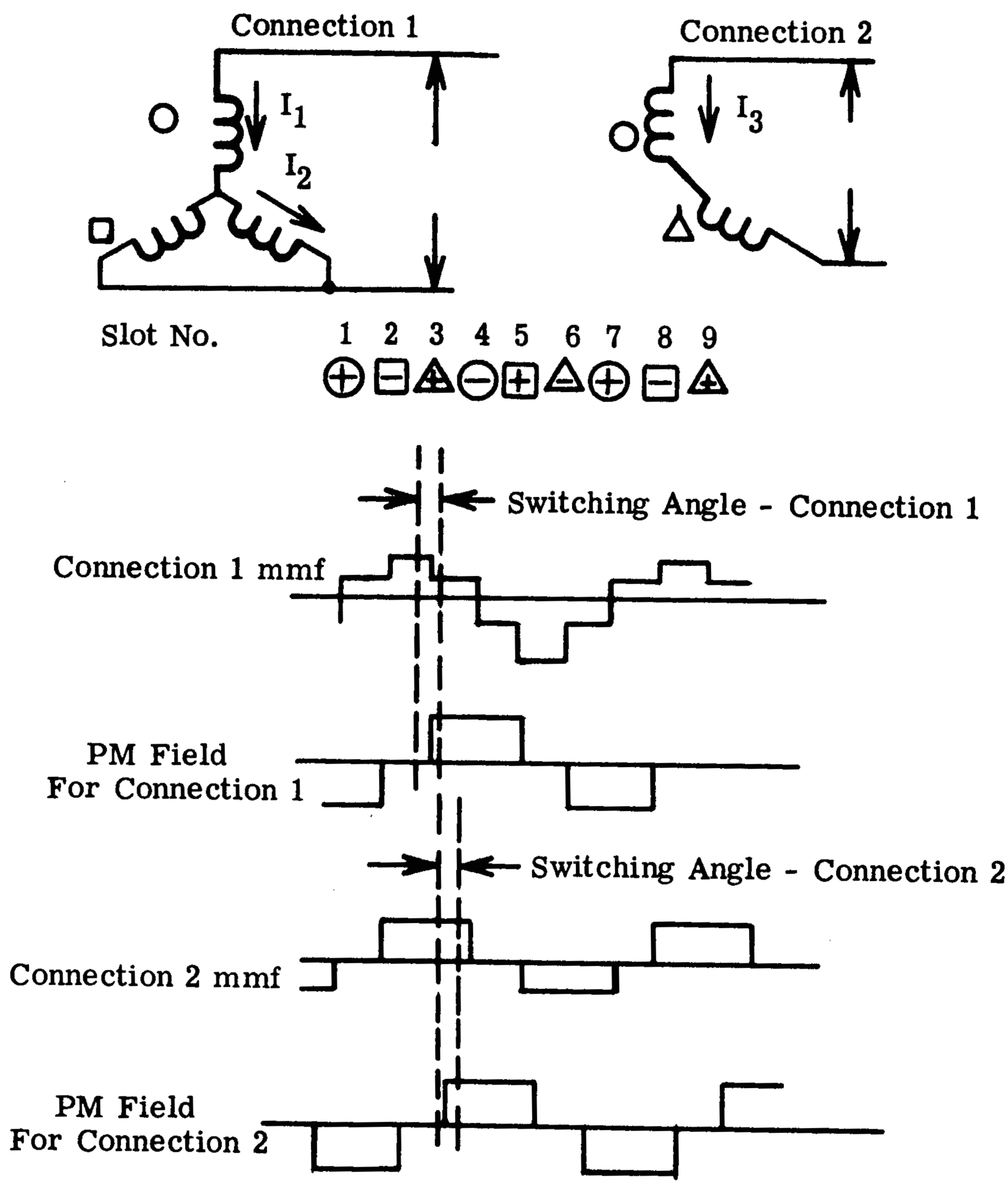


FIGURE 1. Connection and Magnet Lineup Diagram

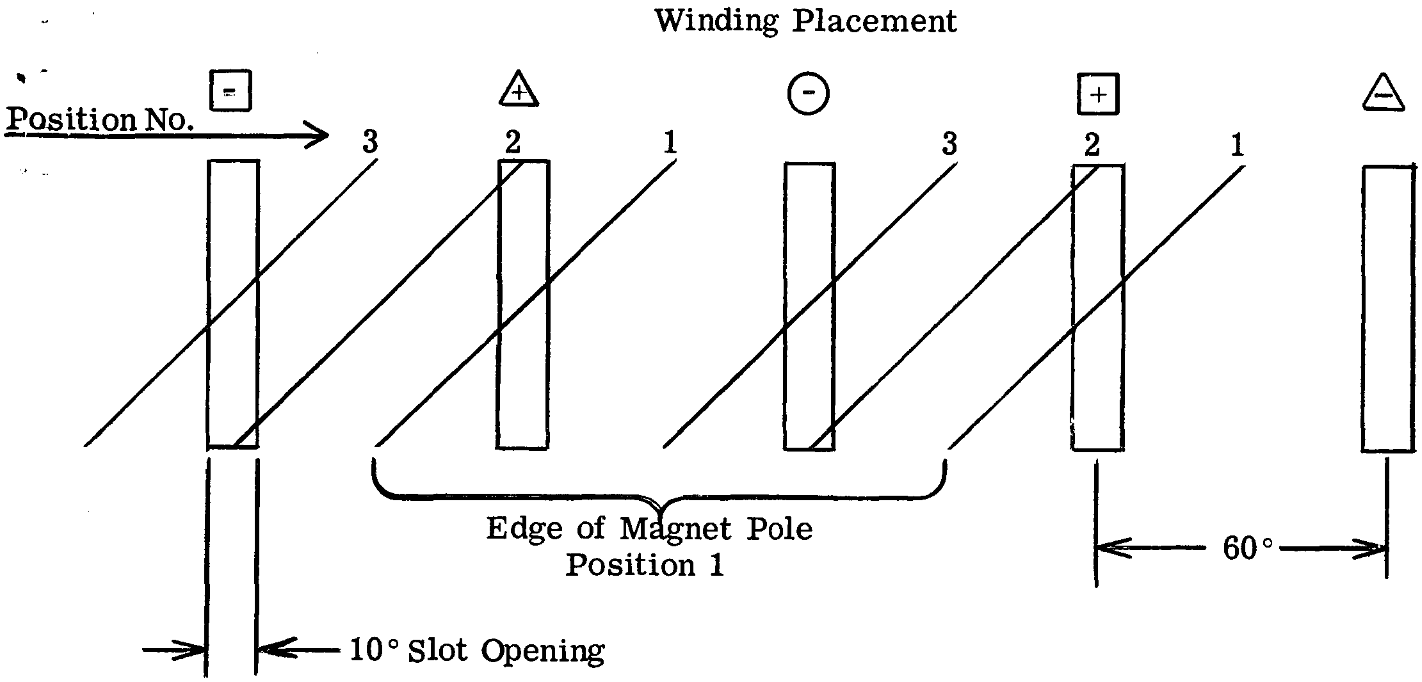


FIGURE 2. Layout of 60° Skew For 60° Switching Angle

On the same basis, the average per unit torque of the original switching mode was 2.17 Zph and the ripple was 6.92 percent. It is concluded that the original mode of switching gives lower ripple and higher torque.

2. Squaring Circuit

The voltage waveform across one output winding of a sample reluctance switch is shown in Figure 3. The switch was driven from a resistive coupled oscillator similar to the one which is used in the final design. The amplitude modulated voltage is applied to the input terminals A and B of the squaring circuit shown in Figure 4.

It can be seen from Figure 3 that the voltage waveform has a steep wavefront and then decays approximately 25 percent before switching occurs. The question has been asked whether this type of waveshape will cause premature turn-off of the SCR. This could happen if the voltage across the filter capacitor C_1 does not decay at a faster rate than the output voltage of the reluctance switch. To resolve this, a discharge characteristic of the RC combination used in the "squaring" circuit was

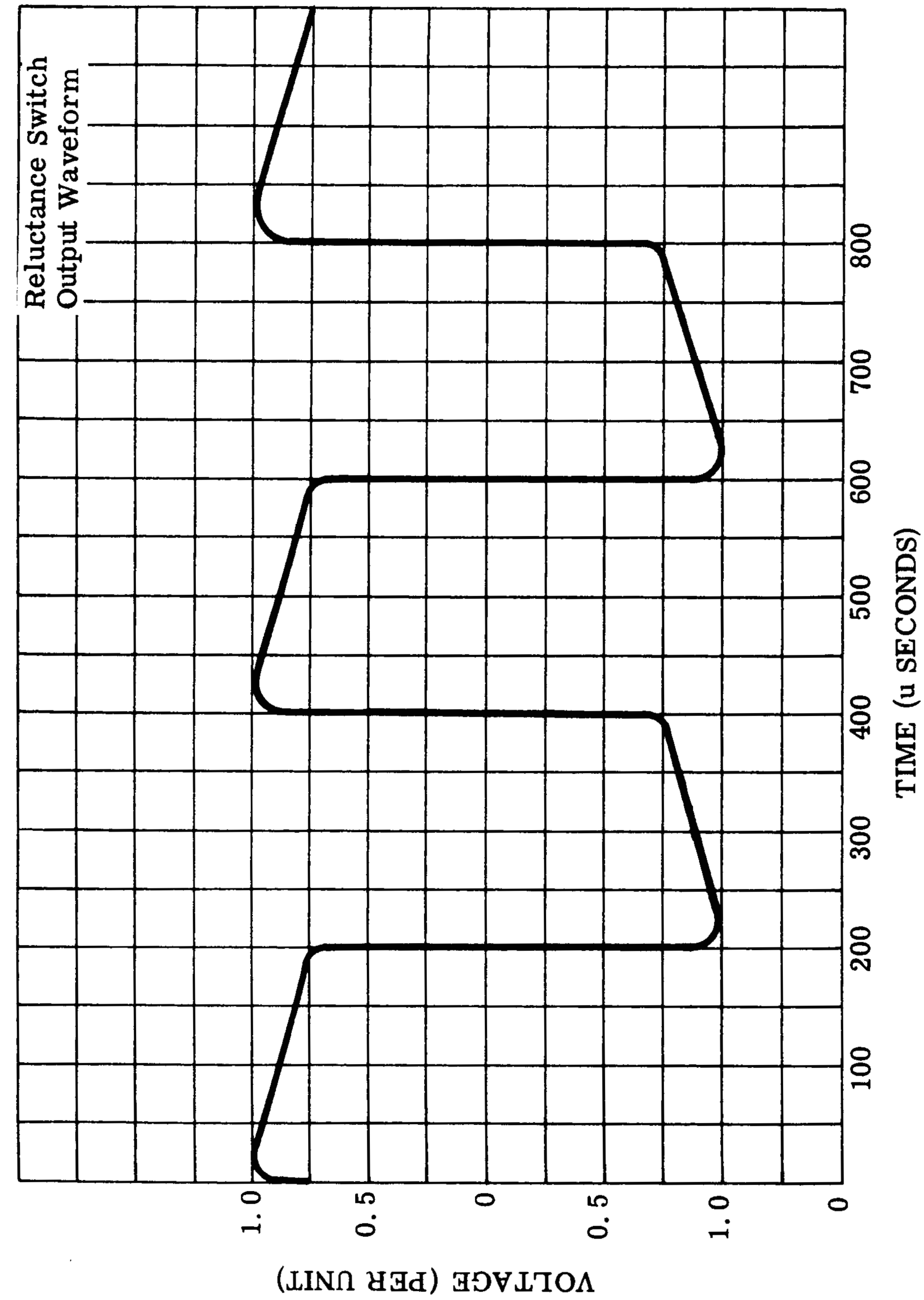


FIGURE 3. Reluctance Switch OUTPUT Waveform

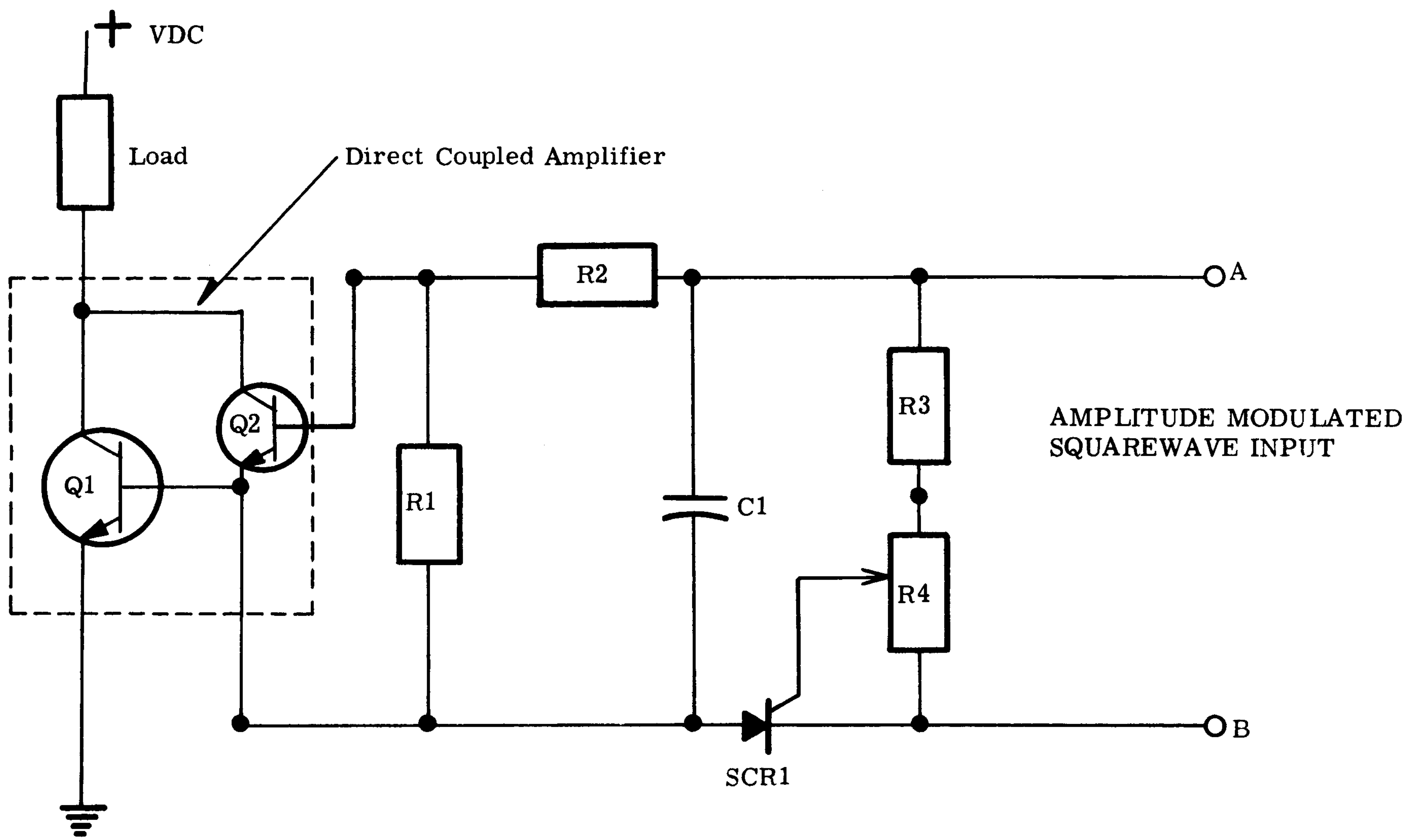


FIGURE 4. Squaring Circuit

calculated. The parameters used in the design are as follows:

$$C_1 = 0.47 \mu fd$$

$$R_1 = 681 \text{ ohms}$$

$$R_2 = 464 \text{ ohms}$$

The base to emitter resistance of transistor Q_2 was determined to be 75 ohms for the conditions of circuit operation. Capacitor C_1 will discharge through R_2 in series with the parallel combination of R_1 and the base to emitter resistance of Q_2. This combination was calculated to be 532 ohms. Using the equation

$$V_c = E\, e^{-t/RC}$$

the discharge characteristics for two values of C_1 were calculated. A plot showing the discharge characteristics is shown in Figure 5. Figure 5 shows that the capacitor voltage will decay at a faster rate than the output voltage of the reluctance switch. Based on this characteristic, it has been concluded that premature turn-off of the SCR in the present design will not result. It is also concluded that capacitor C_1 could be increased to one μfd without any problems.

D. Solid-Lubricant Bearings

A report of an investigation made by D. J. Boes and G. R. Kelecava of the Westinghouse Research Laboratories on the solid-lubricant bearing materials used in the bearings for this motor is given in Appendix III. This investigation and the bearings were purchased as part of this contract. The investigation was conducted to find the cage composition which would give the maximum mechanical strength without an appreciable sacrifice in lubricating properties. The composition selected was a 15% Teflon - 85% silver-mercury amalgam.

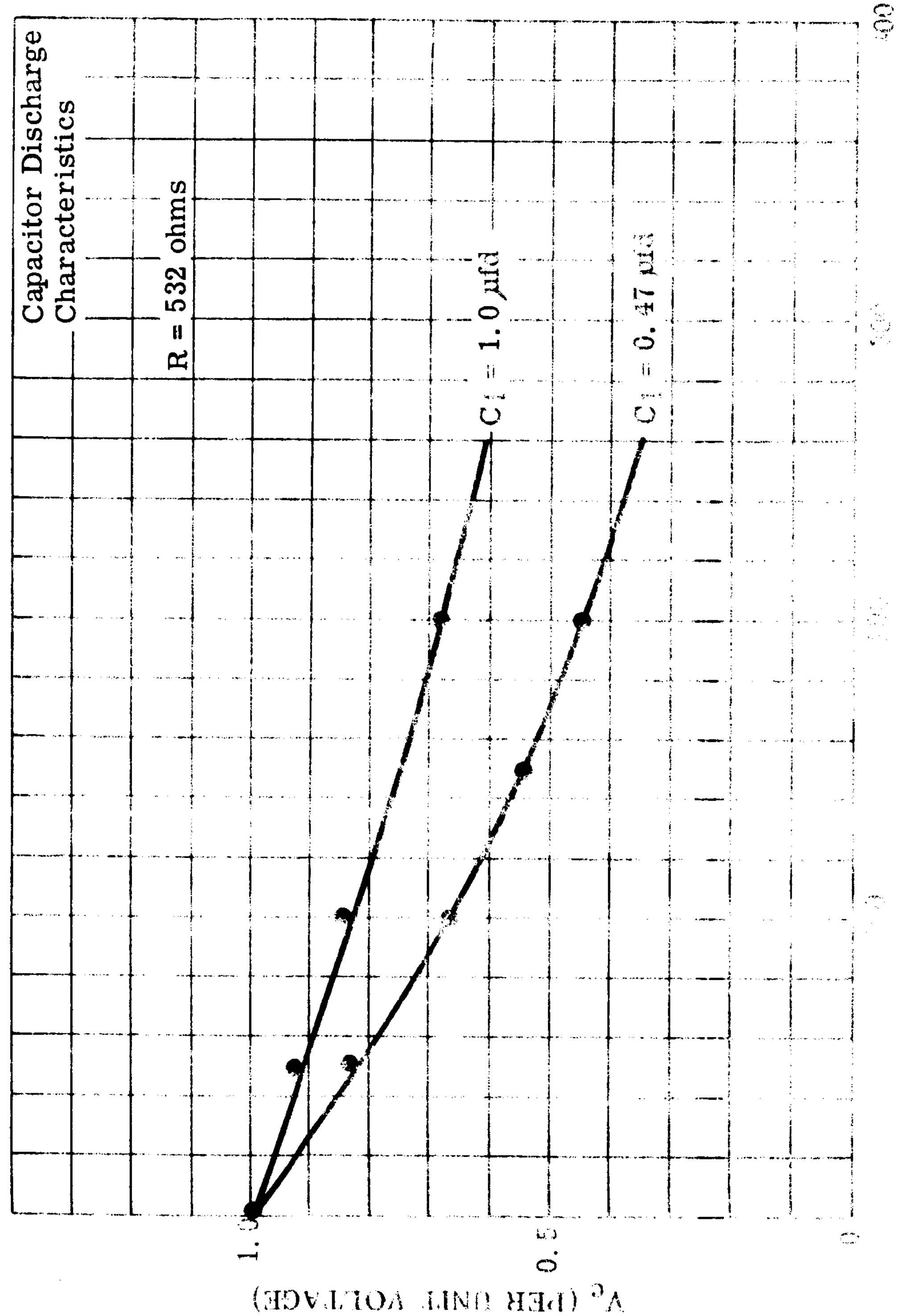


FIGURE 5. Capacitor Discharge Characteristics

III. NEW TECHNOLOGY

There is no new technology to report for this period; however, the following is included to amend the items which were reported in the First Quarterly Report, No. WAED64. 55E, Pages 80 through 85.

The above referenced report listed five (5) reportable items as generated under the subject NASA contract. They were Disclosure Numbers 63411, 64622, 64621, 64500 and 64620. Three (3) of these disclosures should not have been listed as reportable items.

Patent Disclosure 64622, Book 7738, Page 16 discloses the use of a reluctance switch to control a torque motor to provide a position indicator or controlled torque applicator.

Patent Disclosure 64621, Book 7738, Page 17 discloses the use of two or more reluctance switches in combination with two or more torque motors to provide two or more shafts which perform precisely in unison with no more than electrical couplings between units.

Patent Disclosure 64620, Book 7738, Page 20 discloses the use of a reluctance switch to control a torque motor having a different number of poles than the reluctance switch. This will provide a position indicator or controlled torque applicator with angular speed and displacement reduction or gain.

None of the inventions disclosed in the above patent disclosures are used in the brushless DC motor being developed under the subject contract. Because they all use the reluctance switch being developed on that contract, they were erroneously classified as having been made on that contract. This resulted in classifying them as reportable under the "New Technology" clause in the contract. Since the reluctance switch, as such, is not new and none of the inventions disclosed are used in the performance of the subject contract, all three patent disclosures should be removed from the reportable classification.

IV. PROGRAM FOR NEXT REPORTING INTERVAL

In the next quarter, the motors and controls will be assembled and subjected to tests in accordance with this report. Modifications to the units will be made as necessary and the two complete motors will be delivered to NASA. A final comprehensive report will be written.

V. CONCLUSIONS AND RECOMMENDATIONS

It is concluded that the design as conceived and described in the First Quarterly Report is still the most practical. The design at present is fixed by the procurement of parts. Some changes in the control circuitry may be necessary after final tests.

VI. NOMENCLATURE

Symbols and Abbreviations

C - Designation for capacitor

e - Logarithmic constant 2.71828

E - Designation for source voltage (peak)

I - Designation for current

Q - Designation for transistor

R - Designation for resistor

t - Time

T - Symbol for transformer

V_c - Designation for capacitor voltage

Zph - Total series conductors per phase

VII. APPENDIX I

General Engineering Test Procedure

Note: Figure 6 is used for reference in Appendices I and II for terminal and component designation.

The following is a general engineering test procedure which will be followed to determine the operation of the control circuit and verify the component values selected for the design. This test procedure will be performed on the first available unit. Design changes determined to be necessary will be made at this point in the program and will be incorporated in all units.

The investigations will be made with the motor and control connected together. Voltage will be applied to the reluctance switch drive oscillators only and will not be applied to the main motor windings.

A. Resistance

Make resistance check in accordance with paragraph B of General Test Procedure (Appendix II).

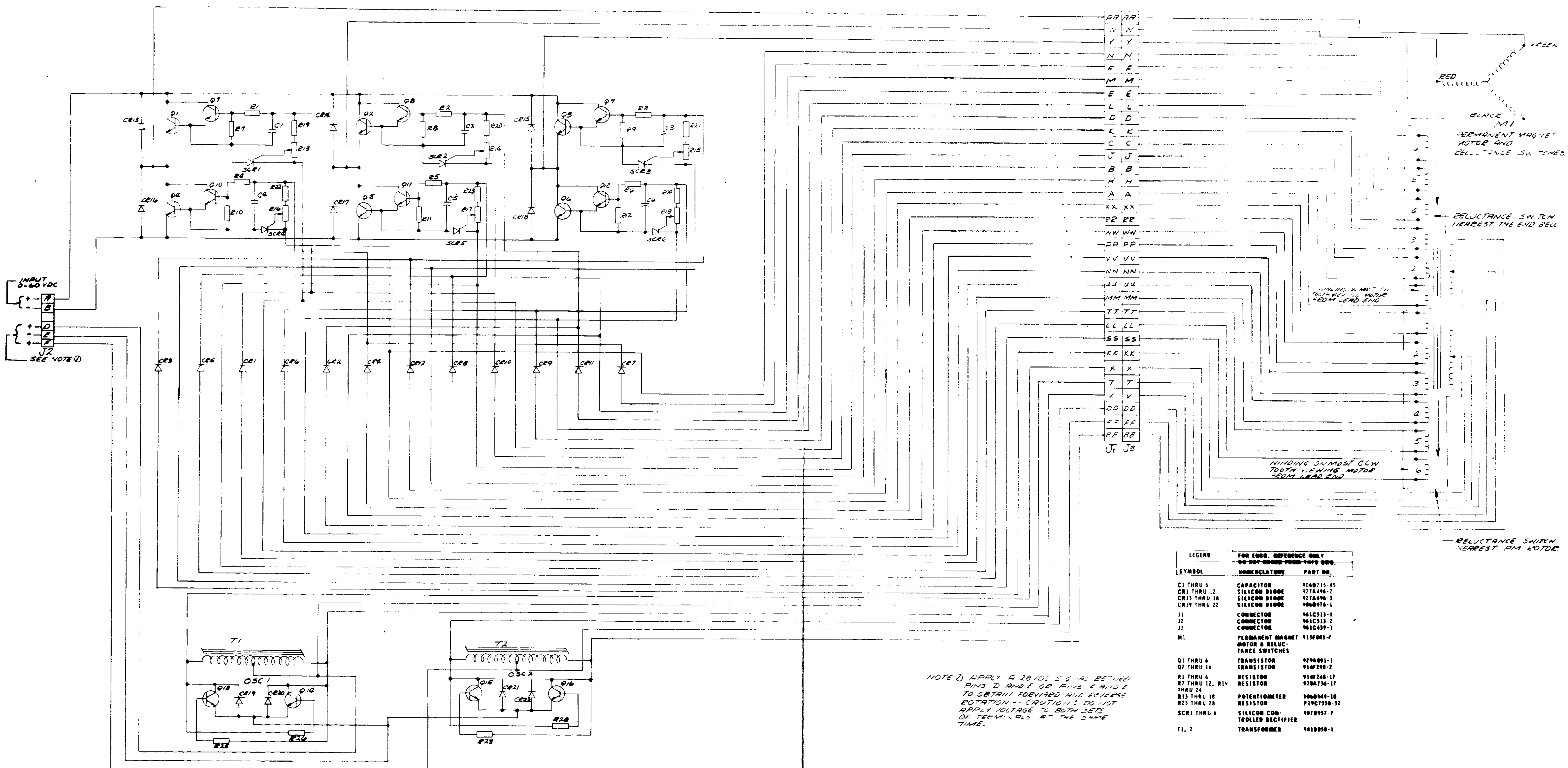
B. Oscillator Frequency and Base Drive

1. Connect the motor and the control together. Apply 28 volts D. C. (±0. 1 volts) to input terminals D and E (+ to D). Using an oscilloscope, view the waveform across saturation transformer T_1. The magnitude of 1/2 cycle should be approximately 56 volts and the frequency should be approximately 5000 cps. Using a current probe, measure the oscillator peak collector current. Calculate the required base drive and compare to the actual.

2. Repeat paragraph 1 for the second oscillator. Apply 28 volts D. C. across pins F and E (+ to F) and view waveform across transformer T_2.

C. Trigger-Trimmer Adjustment

Adjust the trigger-trimmer resistors in accordance with the procedure of Part D, paragraphs 1 through 5, of the General Test Procedure, Appendix II.



LEGEND	FOR ENGR. REFERENCE ONLY ~~DO NOT ORDER FROM THIS DWG.~~	
SYMBOL	NOMENCLATURE	PART NO.
C1 THRU 6	CAPACITOR	906D715-45
CR1 THRU 12	SILICON DIODE	927A496-2
CR13 THRU 18	SILICON DIODE	927A496-3
CR19 THRU 22	SILICON DIODE	906D976-1
J1	CONNECTOR	961C513-1
J2	CONNECTOR	961C513-2
J3	CONNECTOR	961C439-1
M1	PERMANENT MAGNET MOTOR & RELUCTANCE SWITCHES	915F043-4
Q1 THRU 6	TRANSISTOR	929A091-1
Q7 THRU 16	TRANSISTOR	914F290-2
R1 THRU 6	RESISTOR	914F248-17
R7 THRU 12, R19 THRU 24	RESISTOR	928A736-17
R13 THRU 18	POTENTIOMETER	906D949-10
R25 THRU 28	RESISTOR	P19C7558-52
SCR1 THRU 6	SILICON CONTROLLED RECTIFIER	907D957-7
T1, 2	TRANSFORMER	941D058-1

NOTE ① APPLY A 28 VDC SIGNAL BETWEEN PINS D AND E OR PINS F AND E TO OBTAIN FORWARD AND REVERSE ROTATION -- CAUTION: DO NOT APPLY VOLTAGE TO BOTH SETS OF TERMINALS AT THE SAME TIME.

FIGURE 6. Schematic Diagram

WAED64. 73E-15

D. Darlington Base Drive

Determine the base current supplied to each transistor Q_7 through Q_{12}. This is done by exciting one of the oscillators with 28 volts D. C. and measuring the base current, using a current probe, when the associated controlled rectifier just turns ON. Compare this value with that required to switch maximum current in the power transistors (approximately 2. 1 amps). Also view the base emitter voltages of Q_7 through Q_{12} while rotating the motor shaft to determine sharpness of turn-on and turn-off.

Note: If any component changes are made, recheck the trigger-trimmer adjustment to determine if any shift has taken place.

VIII. APPENDIX II

General Laboratory Test Procedure

A. Dielectric Tests

Test in accordance with drawings.

B. Resistance

Disconnect motor from control. Measure ohmic resistance of motor stator winding Pin AA to W, AA to Y, and W to Y. Measure reluctance switch primaries Pin BB to FF, FF to DD, BB to DD, V to T, T to X, and V to X. Measure all twelve secondaries, Pin N to F, M to E, L to D, K to C, J to B, H to A, XX to RR, WW to PP, VV to NN, UU to MM, TT to LL, and SS to KK.

C. Run-in

Drive motor at approximately 1700 RPM for 4 hours. Do not apply voltage to motor.

D. Trigger-Trimmer Adjustment (Engineer to be present)

1. Connect the motor to the control.

2. It is necessary to measure the angle through which the shaft is turned to the nearest 1/4 degree. Therefore it is necessary to lay out a circular angular scale with a pointer on the shaft.

3. The cover of the control will be removed and points brought out as directed by the engineer. Apply 28 volts DC (±0.1 volts) to terminals D and E (+ to D).

4. Apply the output of each of the six trigger circuits in turn on a scope. Adjust the trimmer until the trigger has output for 37.5 degrees (±0.25 degrees) of shaft rotation in any one "on" period. (The trigger will have output 4 times in one shaft revolution. If the 4 conducting periods are different in angular length, the average should be adjusted to 37.5 degrees.) <u>The input voltage must be maintained constant during this adjustment.</u>

5. Record the angular lengths of conduction with voltage applied to terminals E and F (+ to F). Do not change trimmer adjustment unless advised to do so by the engineer.

E. Reluctance Stator Coarse Adjustment (Engineer to be present)

1. Set both reluctance switch stators in the approximate center of their adjustment.

2. Apply 28 volts to terminals D and E. Slowly apply D. C. voltage (up to 10 volts) to terminals A and B (+ to A) until motor starts to rotate. Check (as directed by engineer) which reluctance switch is excited and make a note associating the direction of rotation with that reluctance switch.

3. Lock the rotor of the motor to a suitable torque measuring device. (Maximum torque will be approximately 210 oz. in.) Hold the stator in a V-block such that it is possible to obtain 90 degrees of stator rotation by loosening the restraints. With 28 volts D. C. (±0.1 volts) applied to terminals D and E and 30 volts applied to terminals A and B (current will be approximately 0.7 amp at terminals A and B), loosen the holding screw on the reluctance switch stator and adjust the excited reluctance switch until torque is a maximum in the proper direction. The torque should be constant at this maximum over an angular excursion of the reluctance switch stator of 7.5 degrees. Set the reluctance stator approximately in the center of this span.

4. Free the stator and turn in a direction to obtain maximum torque. Simultaneously adjust the reluctance stator to keep the same angular relationship with the rotor. (Turn stator 2 degrees, turn reluctance switch stator back 2 degrees, for example.) Continue until the torque is the maximum obtainable.

5. Tighten reluctance switch in place. Increase voltage at A and B to 40 volts. Move stator through measured angular increments of 5 degrees for 90 degrees recording minimum and maximum torque readings. Average the torque readings and compute the difference between the maximum and minimum torque readings.

F. Stabilization (Engineer to be present)

With the same voltages as used in the previous step and the rotor locked, adjust the motor stator until all 3 phases are excited. (Check this on a scope as directed by the engineer.) Continue turning the stator until the unit just switches out of the 3-phase conduction mode to a 2-phase conduction mode. Turn the motor stator back until the 3-phase conduction just starts again. Determine the direction of the voltage and currents in the motor stator phases at this point. Lock the rotor and stator in place. Remove all voltages and disconnect the control.

Apply a variable D. C. voltage to the motor stator in such a manner as to duplicate the current flow and voltage directions applied to the motor stator with the control connected. Raise the voltage until 2.1 amps are attained in the circuit. (Do not exceed this value by any amount for any length of time.) This will require approximately 90 volts. Do this quickly to avoid overheating the stator. Once the current is obtained, immediately remove the voltage.

G. Other Reluctance Stator Adjustment

Repeat Part E, paragraphs 3 (except use 40 volts at terminals A and B), 4, and 5 for the other reluctance switch. Connect the 28-volt control voltage to terminals E and F.

H. Reluctance Stator Fine Adjustment

1. Repeat Part E, paragraph 5, for the reluctance switch associated with control voltage terminals F and E with the reluctance switch stator position adjusted in increments of 2 degrees until the average torque is a maximum and the ripple torque is a minimum. Turn stator 2 degrees in one direction and measure values. If the values improve, move another 2 degrees; if not, go back 4 degrees and repeat measurement. Continue adjusting in the direction of improvement until the best position is found.

2. Repeat above for the other reluctance stator (attach control voltage to terminals D and E) except repeat the zero adjustment measurements.

I. Voltage Tests

Take speed-torque curves including no load, locked torque and 3 intermediate points with 3, 5, 10, 20, 30, 40, and 60 volts applied to terminals A and B. Take locked torque at 60 volts quickly to avoid overheating the motor. Do not allow speed to exceed 1700 RPM.

IX. APPENDIX III

Westinghouse Research Laboratories

Report on Solid-Lubricant Bearings

Note: This report is a typed copy of the original written by Westinghouse Research Laboratories.

Research Memo 64-8B5-347-M1 December 3, 1964

SELF-LUBRICATED TORQUE MOTOR BEARINGS FOR ULTRA-HIGH VACUUMS

D. J. Boes & G. R. Kelecava
Chemical Technology
Insulation & Chemical Technology R&D

INTRODUCTION

Sixteen ball bearings were equipped with high strength, self-lubricating retainers for use in an ultra-high vacuum of 10^{-9} torr under interworks requisition #39G1-338904. The work was sub-contracted by Lima AED under NASA contract NAS5-3934 from Goddard Space Flight Center. Prior to the fabrication and installation of the retainers, a short laboratory program was conducted to establish:

1. The optimum self-lubricating composite formulation from a mechanical strength consideration, and

2. the outgassing characteristics at 70°C and 10^{-9} torr of the candidate materials.

The dry lubricated bearings are to be used in a torque motor capable of prolonged operation in an ultra-high vacuum environment. They are required to meet the following specifications:

1. 0 to 100 RPM - inner race rotation with majority of life near zero RPM.

2. Rotor weight - 1 lb.

3. Shock - 50 G's of 2 millisecond duration in each of three mutually perpendicular directions.

4. Vibration - 5 minutes of random vibration from 20 to 2000 CPS at 15 G's RMS in each of three mutually perpendicular directions.

   Peak Force = 21.2 lbs. total on two bearings.

5. Vacuum of 10^{-9} mm Hg for a period of one year.

6. Ambient Temperature: -10 to +70°C.

7. Bearings to have minimum static friction torque.

SUMMARY

The sixteen bearings were equipped with a high strength self-lubricating composite retainer composed of a sintered silver-mercury amalgam matrix containing homogeneously distributed pockets of Teflon (PTFE). Screening tests indicated that for maximum mechanical strength both the Teflon and silver powder - before amalgamation - should consist of equal parts of sub-micron and coarse particles (PTFE-100 mesh; Ag-325 mesh). The blanks from which the retainer were machined were formed under a combination of heat and pressure into 1 1/2" long rings 1 1/2" O. D. x 3/4" I. D. The retainers were not shrouded and weighed approximately 20 grams each.

EXPERIMENTAL

Bearing Design

The MRC-1905 bearings selected for this application are an extremely thin series of an ABEC-1 non-precision grade. It was decided to employ as a retainer material a composite of maximum mechanical strength in view of (1) the high shock loading and vibration which the bearing must withstand, (2) the small cross-section of the ball retainer resulting from the narrow bearing design, and (3) the inability to encase the retainer in a reinforcing metal shroud.

Retainer Composition

As mentioned previously, it was necessary to determine the optimum retainer composition prior to fabrication. This was achieved by evaluating the friction, wear and mechanical properties of a number of candidate compositions of the silver-mercury type. A prior in-house program had already demonstrated that this composite exhibited the highest mechanical strength of the available Westinghouse self-lubricating materials. It was necessary, however, to establish what adjustments were necessary in the (1) particle size of composite components, (2) Teflon content, and (3) solid lubricant content that would provide a material best qualified to meet the unique requirements of the proposed application. A series of experiments were conducted to define the effect of the parameters on composite performance. Teflon and solid lubricant content was varied from 0-25% (vol) and 0-5% respectively. In addition, two particle size distributions were investigated for both Teflon and silver. All test specimens were 1/2" dia x 1" long and fabricated at 260°C under a load of 60,000 psi. Holding time at temperature and pressure was 3 minutes. Optimum conditions of fabrication had been established during the previous program.

Outgassing Tests

In order to establish that the 70°C/10^{-9} torr environment to which the bearings will be subjected would not cause appreciable material losses through evaporation, outgassing tests were run on four composite formulations. The samples were held at 70°C and 10^{-6} torr for one week, after which the pressure was reduced to 10^{-9} torr by means of a cryopump and maintained for 72 hours. Following this period, the specimens were removed from the vacuum chamber and weight loss measurements made.

RESULTS

Table 1 lists the various material combinations studied in the optimization program and the effect of particle size and lubricant concentration on friction, wear and tensile strength characteristics.

The following pertinent points were brought out by these experiments.

Mechanical Properties

1. Tensile strengths vary inversely with the quantity of Teflon incorporated in the composite.

2. For a given composition, the substitution of as little as 5% solid lubricant (WSe_2) as a replacement for a corresponding amount of PTFE causes a substantial reduction in tensile strength.

3. Composites incorporating 325 mesh silver are at least 50% lower in tensile than a corresponding composition using a 50-50 combination of 325 mesh and sub-micron silver.

4. Maximum tensile strengths are obtained when the particle size distribution for both silver and PTFE is evenly split between submicron and 325 or 100 mesh respectively.

Lubricating Properties

1. The use of small quantities of solid lubricant (WSe_2-5%) resulted in a substantial reduction in friction coefficients.

2. Increasing PTFE contents did not improve appreciably composite friction coefficients at either 530 or 940 psi loads.

3. Low tensile properties do not result in a corresponding increase in composite wear rate.

Based on this information, a composite containing 15% (vol) PTFE in a silver-mercury amalgam matrix (No. 12-Table 1) was selected as that offering the best combination of properties for the proposed application. The authors do not believe the excessive wear rates experienced by this composite at 940 psi will cause any difficulty in view of the low bearing loads ($\sim$1 lb.) and speeds (0 to 100 RPM) involved. In this particular case, the more important consideration is the ability of the self-lubricating composite to carry moderate loads and withstand severe shock loadings. The physical properties of this material are given in Table 2.

The results of the outgassing experiments are given in Table 3. None of the four samples evaluated showed any significant weight loss from the exposure. The ability of these materials to successfully withstand ultra-high vacuum-moderate temperature environments has also been demonstrated during 100 hour functional tests at 10^{-8} torr on roller bearings utilizing these composites as retainers. The bearings carried a 3000 lb. load at 100 RPM and a temperature of 50°C. Bearing wear was negligible during the 100 hour run.

MRC-1905 Retainer Design & Fabrication

Figure 1 presents a detailed drawing of the bearing retainer and the bearing dimensions pertinent to its design. It is an inner race riding cage containing eleven ball pockets, and is designed to provide a 0.005 inch diametral clearance between its inner diameter and the O. D. of the inner race. Figure 2 is a photograph of the machined retainer and an assembled 1905 ball bearing utilizing the retainer as the self-lubricating member.

Ins. & Chem. Tech. R&D - Chemical Technology - D. J. Boes
- G. R. Kelecava

TABLE 1. Friction-Wear-Mechanical Strength of Silver/Mercury Composites
(80 Ag-20 Hg)

Sample No.	Composition-Vol % Alloy	PTFE	WS_2	Particle Size-Mesh	Tensile Strength (psi)	530 psi Fric. Coef.	530 psi Wear gm/hr	940 psi Fric. Coef.	940 psi Wear
1	100	--	--	Ag- 1/2-1/2*	35, 450	--	--	0.52	0.008
2	85	15	--	Ag- 1/2-1/2 PTFE 100	5, 650	0.15	0.005	0.18	0.003
3	80	20	--	Ag- 1/2-1/2 PTFE 100	4, 650	0.23	0.004	0.18	0.002
4	75	25	--	Ag- 1/2-1/2 PTFE 100	3, 150	0.19	0.006	0.22	0.003
5	80	15	5	Ag- 1/2-1/2 PTFE 100	3, 800	0.13	0.002	0.22	0.005
6	75	20	5	Ag- 1/2-1/2 PTFE 100	2, 650	0.14	0.003	0.13	0.003
7	85	15	--	Ag-325 PTFE 100	2, 450	0.21	0.008	0.20	0.016
8	80	20	--	Ag-325 PTFE 100	2, 100	0.21	0.001	0.26	0.002
9	75	25	--	Ag-325 PTFE 100	1, 400	0.23	0.002	0.17	0.002
10	80	15	5	Ag-325 PTFE 100	2, 700	0.13	0.006	0.18	0.004
11	75	20	5	Ag-325 PTFE 100	600	0.16	0.003	0.15	0.008
12	85	15	--	Ag- 1/2-1/2 PTFE 1/2-1/2**	7, 600	0.21	0.001	0.22	>0.5

*50% 325 mesh-50% sub-micron
**50% 100 mesh-50% sub-micron

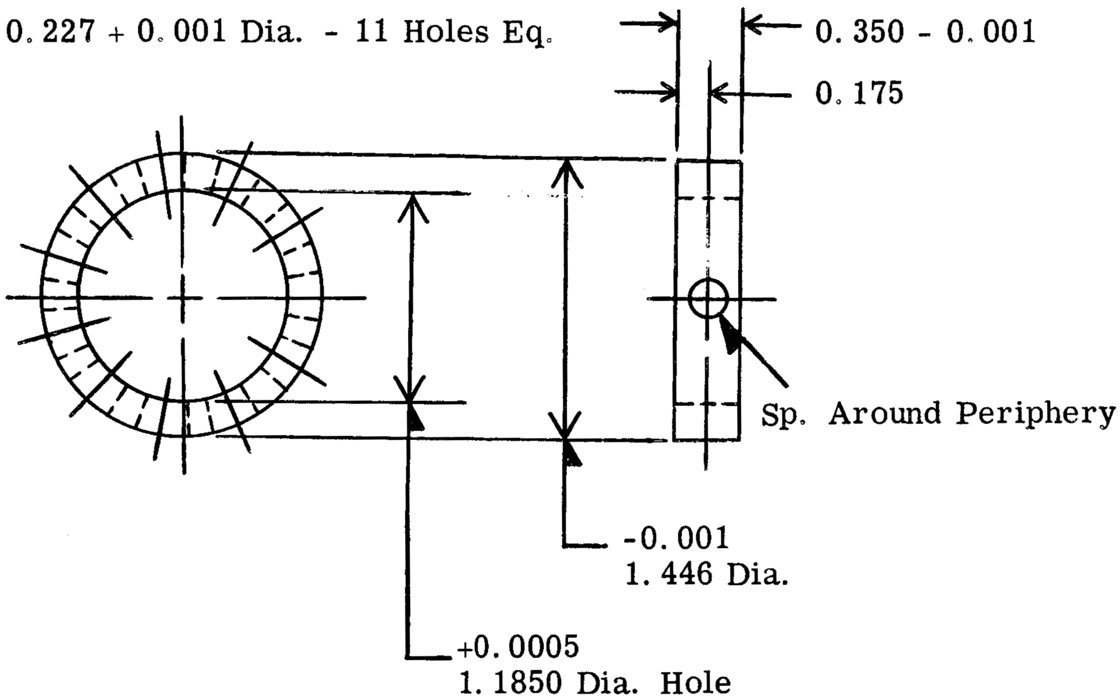
TABLE 2. Physical Property Data on Self-Lubricating Retainer

Composition-Vol %	85 Alloy (80 w/o Ag-20 w/o Hg) 15 PTFE
Particle Size Distribution	Silver - 50 w/o 325 mesh 50 w/o sub-micron PTFE - 50 w/o 100 mesh 50 w/o sub-micron
Pressing Conditions	260 C - 60,000 psi - 3 min hold on 1/2" Ø
Tensile - psi	7600
Shear - psi	7325
Flex. Modulus - psi	4.4×10^6
Coef. Thermal Expansion (75° to 300°F)	11.62×10^{-6} inch/inch °F
Friction Coefficient*	
170 psi	0.17
530 psi	0.21
940 psi	0.22
Wear - gm/hr - (30 min run)	
170 psi	0.002
530 psi	0.001
940 psi	.5

*Measured on Westinghouse Hydrostatic Friction-Wear Tester Against 440-C Stainless Steel.

TABLE 3. Composite Outgassing Tests

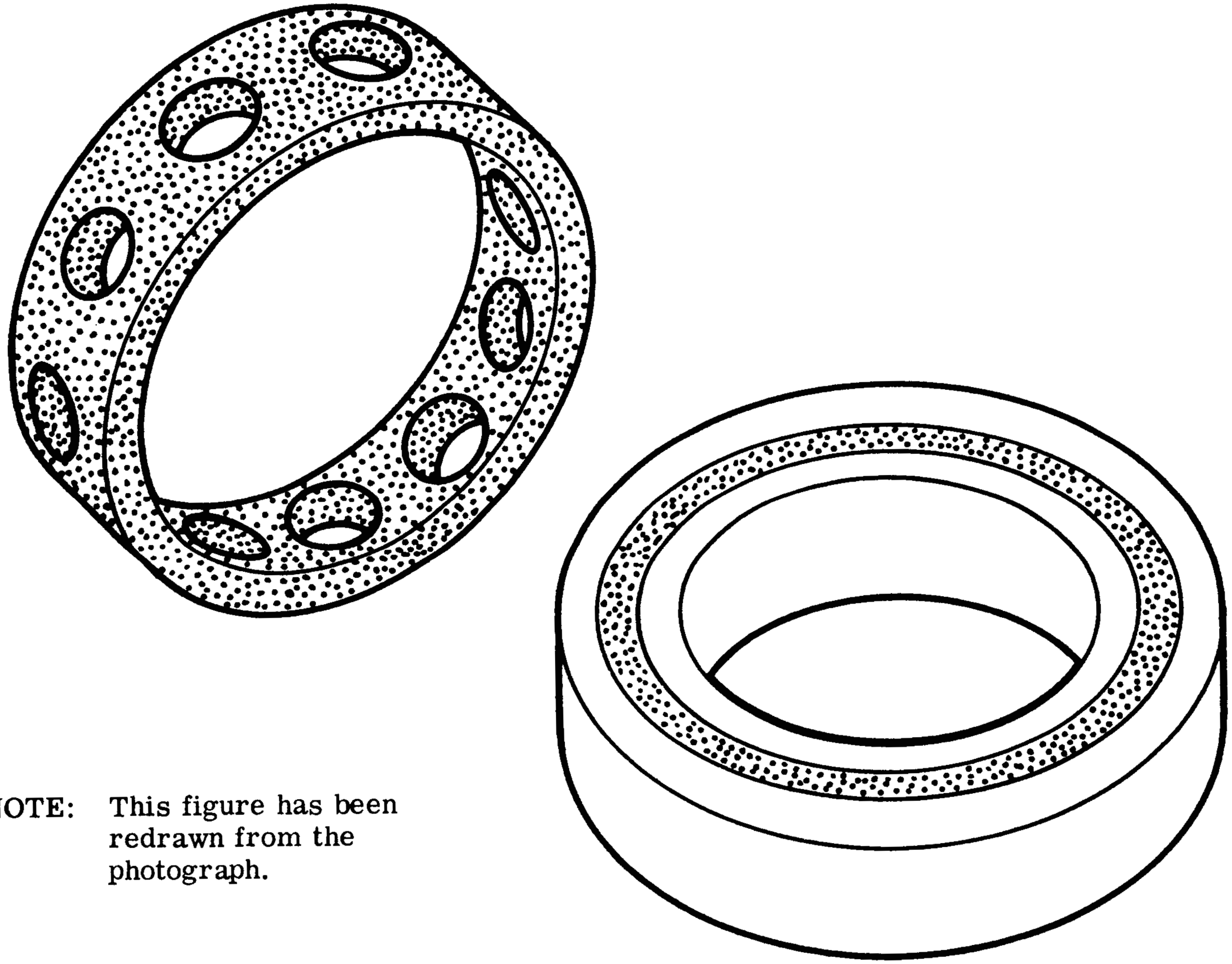
	Sample Description	Initial Wt. (Grams)	Final Wt. (Grams)
1.	85% AgHg (1/2-1/2)-15% PTFE (100 mesh)	0.6502	0.6500
2.	85% AgHg (1/2-1/2)-15% PTFE (1/2-1/2)	0.6871	0.6870
3.	80% AgHg (1/2-1/2)-20% PTFE (100 mesh)	0.6815	0.6815
3.	80% AgHg (1/2-1/2)-20% PTFE (1/2-1/2)	0.7712	0.7711



1905 Bearing Dimensions

Outer Race O. D.	= 1.653
Outer Race I. D.	= 1.468
Inner Race O. D.	= 1.180
Inner Race I. D.	= 0.9843
Ball Dia.	= 0.2185
Width	= 0.355

FIGURE 1. Self-Lubricating Cage Design - MRC-1905 Ball Bearing



NOTE: This figure has been redrawn from the photograph.

FIGURE 2.