sanders associates,inc.

[redacted]

INSTRUMENT DIVISION

creating new directions in electronics

FINAL REPORT

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

DESIGN OF RECTILINEAR ACCELEROMETER

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GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

Contract No. NAS 8-20519

DESIGN OF A RECTILINEAR ACCELEROMETER

Submitted by:

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Instrument Division
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November 10, 1965

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FOREWORD

The Instrument Division of Sanders Associates has successfully completed the requirements of the Contract NAS 8-20519 for the design of a Rectilinear Accelerometer. This accelerometer is used for the lateral control of the Saturn Launch Vehicle. The details of the design and a discussion of the performance of the evaluation prototype are included herein. Sanders is confident of providing operational hardware and enthusiastic about continuing this program.

FINAL REPORT

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FINAL REPORT

INTRODUCTION

On July 1, 1965, the Instrument Division of Sanders Associates, Inc., received NASA Contract NAS 8-20519 for the design of a Rectilinear Accelerometer. The design to be pursued is Alternate #2, Rectilinear Accelerometer, as proposed in Sanders' Proposal No. 42KC submitted May 13, 1965. The program to be followed will be Phase I of the Program Plan described in the proposal.

The Rectilinear Accelerometer is a spring mass accelerometer used to measure the lateral acceleration on the Saturn Launch Vehicle during the passage of the launch vehicle through the jet streams. The acceleration information is then used to direct the engines for the proper angle of attack.

The goal of the program is to establish a design for a Rectilinear Accelerometer based on analytical studies and tests of actual components.

I. WORK STATEMENT

A design will be presented at the George C. Marshall Space Flight Center with the necessary documentation of analytical studies and component test results to indicate successful performance of a Rectilinear Accelerometer. As a result of the presentation at the George C. Marshall Flight Center, a final design will be established and final documentation provided. It is understood that this final documentation will not be used for production purposes, but should adequately delineate the design.

II. SUMMARY

Since receipt of the contract for the Development of the Rectilinear Accelerometer, Sanders Associates has designed, and analytically and empirically evaluated, the accelerometer components. In addition, limited assembly testing has been accomplished. Minor modifications to the existing prototype hardware will allow the prototype accelerometer to meet the design goals as set forth. A summary of design performance is given in Table I on the next page.

The design of the accelerometer is as shown in Sanders' Drawing 30312 and discussed in Section IV. It should be pointed out that this design does not put forth the minimum of size for the accelerometer. For instance, with the test data already accumulated, it was found that the self-test forcer was approximately three times stronger than required. In subsequent designs the permanent magnet material will be reduced in volume, and it is felt that a single permanent magnet mounted in a soft iron carrier to close the flux path across the moving coil would be sufficient to develop the necessary force. In addition, preliminary tests on the "S" springs indicate that reduction of the "S" spring diameter from the present 2-1/2" diameter to 2" in diameter is very feasible.

The output of the IRC Linear Variable Differential Transformer (LVDT) has a considerable quadrature output; however, the prototype design was tailored to meet the expected travel of $\pm.125$. In future units, the Sanborn LVDT, which operates at 7KHz with zero phase shift, will be incorporated. (Test Data Appendix A)

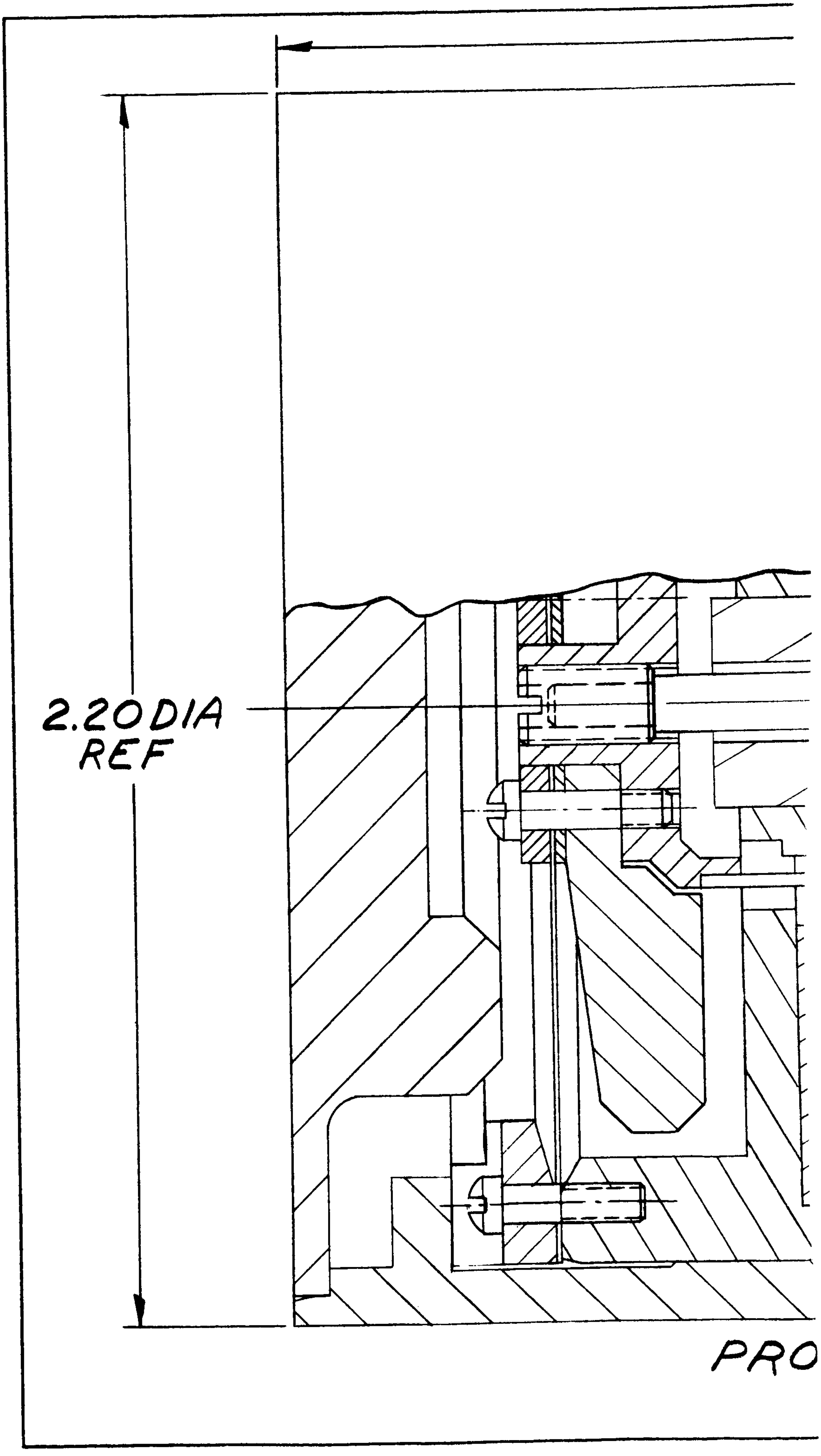
It is predicted that with these changes and the incorporation of the Sanborn LVDT, the package size can be reduced to a length of 2.6 inches and diameter of 2.2 inches, the limits of the proposed design in Figure 1.

SUMMARY OF DESIGN PERFORMANCE

PARAMETER	DESIGN GOAL	PROTOTYPE PERFORMANCE	REMARKS
RANGE	$\pm$10 meters/sec^2	Greater than $\pm$10 meters/sec^2	
OUTPUT	.5 volts/meter/sec^2 min.	.38 volts/meter/sec^2	Determined by amplifier
NULL VOLTAGE	15 mv max	less than 15 mv	
PHASE LAG	2.5° max	Greater than 2.5° with IRC LVDT	Within limits with Sanborn LVDT
STATIC ACCURACY	$\pm$1/2% - 1/2 scale $\pm$1% - 3/4 scale $\pm$1.5% full scale	see remarks	Within design goals unfilled. Filled unit exhibits non-linearity greater than design goals. "S" spring positioning in assembly must be accurately controlled.
NATURAL FREQUENCY	9 $\pm$1 cps	5 cps	Increase "S" spring spring rate
DAMPING	.6 to 1.0	.55	Corrected by damping fluid or gap change.
FORCE COIL CALIBRATION	15 ma/meter/sec^2	6 ma/meter/sec^2	Change by number of turns or magnetic flux density
ENVIRONMENTALS		Not Tested	

SUMMARY OF DESIGN PERFORMANCE (Cont'd)

PARAMETER	DESIGN GOAL	PROTOTYPE PERFORMANCE	REMARKS
WEIGHT	Unspecified	3.15 lbs.	Can be reduced by change in size and change in materials.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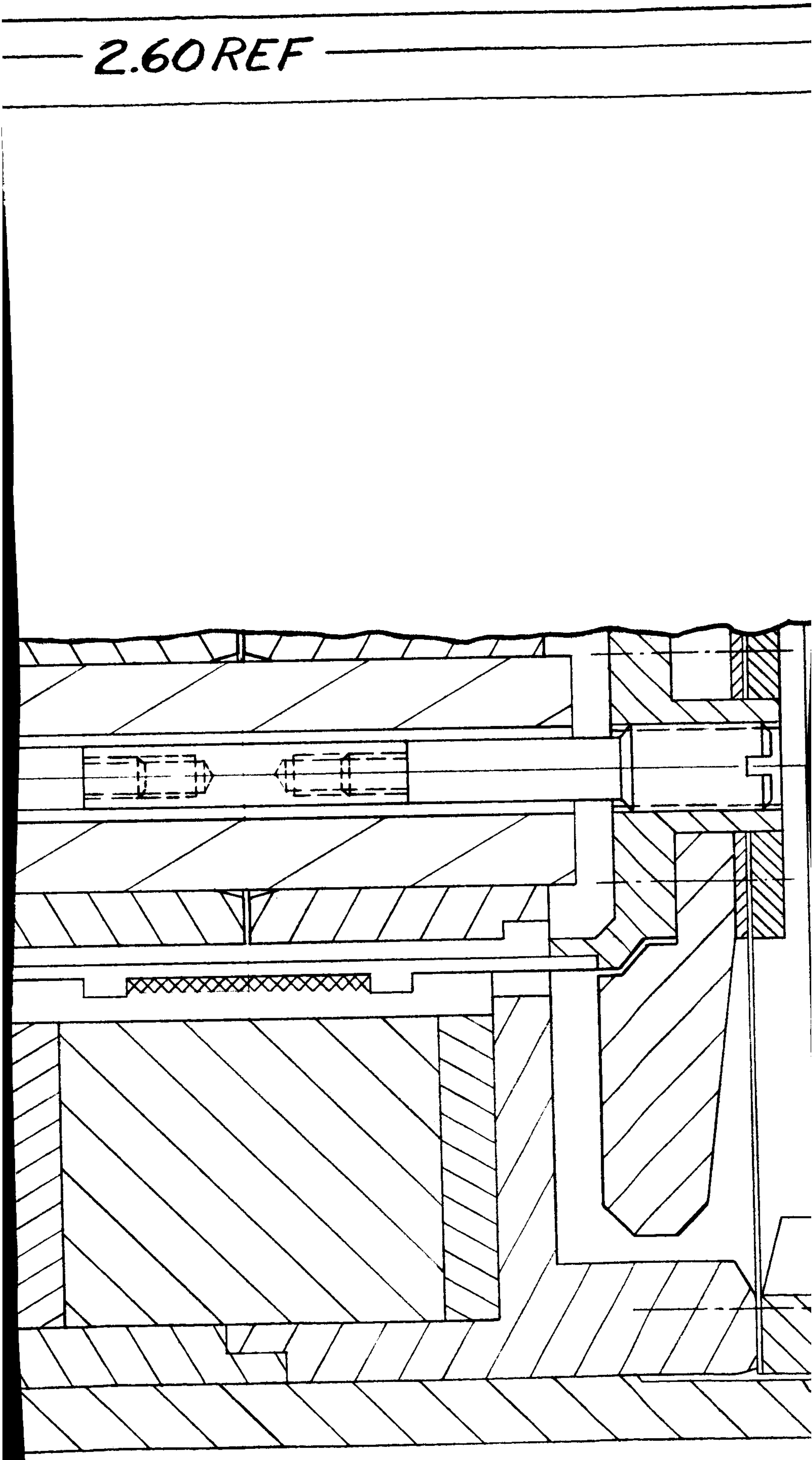
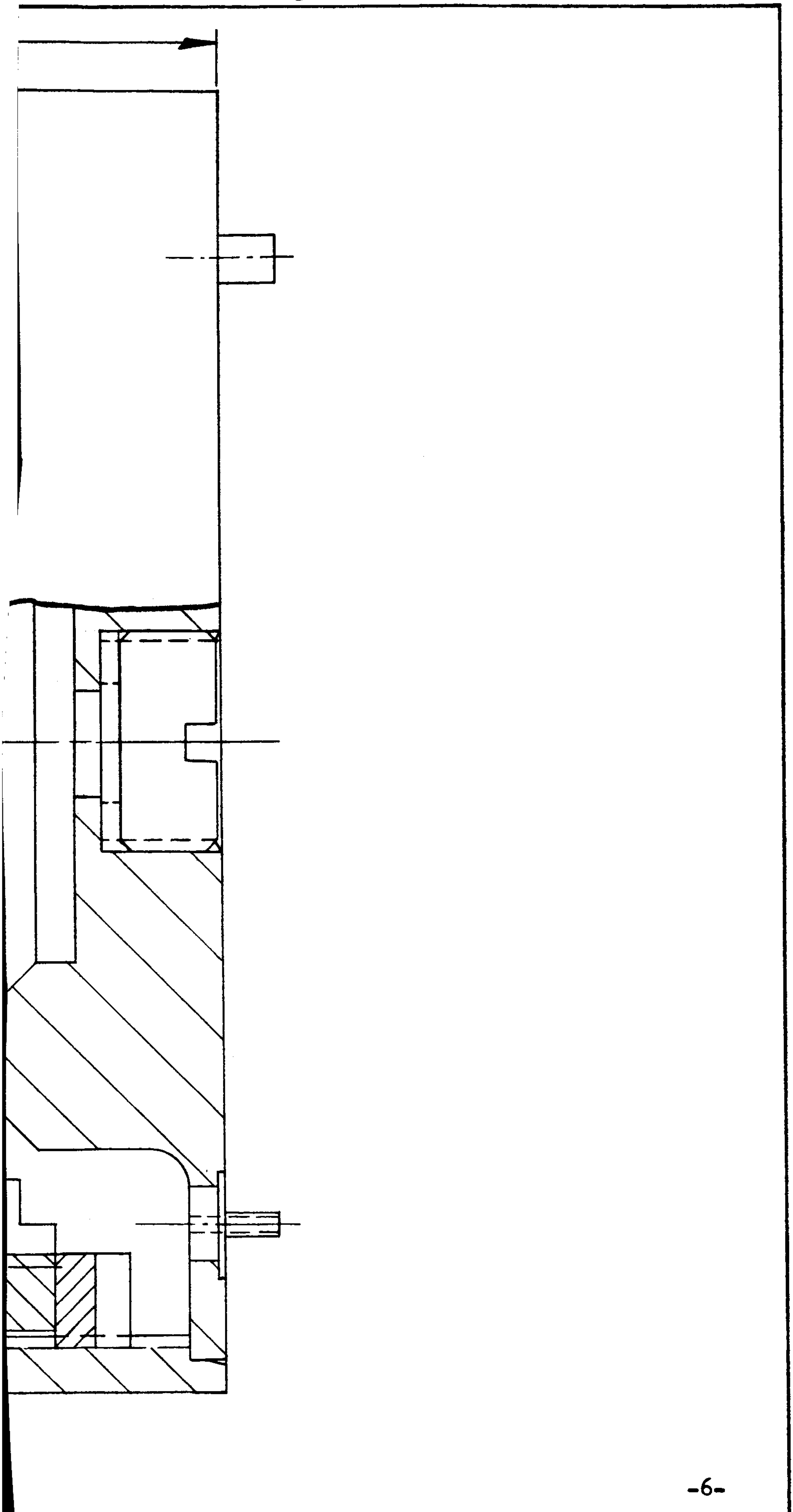
REF
PRO



POSED ASSEMBLY

FIGURE 1

3



III. DESIGN GOALS

The Rectilinear Accelerometer will operate from an AC source with a phase sensitive AC voltage output proportional to applied accelerations. In addition, the unit will have an independent circuit for self-test which will provide sensor output simulating acceleration applied to the sensitive axis.

The accelerometer will be designed to meet the following goals:

Range

$\pm$10 meters/sec/sec.

Output

0.5 volts rms/meter/sec/sec.

Output Load

20,000 ohms resistive.

Output Impedance

2,000 ohms maximum as a voltage generator.

Null Voltage

With instrument level, total residual voltage shall not exceed 15 millivolts at 75°F, no more than 20 millivolts between 40°F, and 110°F and shall not exceed 25 millivolts at any temperature in the operating range.

Electrical Phase Lag

The electrical output shall be in phase or 180° out of phase with the input except in addition, it may lead or lag the input up to and including 2-1/2° or where in excess of 2-1/2°, the quadrature voltage shall be less than 15 millivolts.

III. DESIGN GOALS (Cont'd)

Residual Voltages

Providing the input voltage is harmonic free, the quadrature and harmonic content of the output voltage together at any "G" input within range shall not exceed 1-1/2% of the full scale voltage output.

Grounding

The instrument must operate with its case grounded; however, all circuits must be isolated from ground.

Static Accuracy

Including the effects of linearity, hysteresis, friction, and scale factor, the inphase component of the output voltage shall be proportional to the above specified output within the following percentages of full scale with a 20,000 ohm resistive load.

		+40°F to +100°F	-20°F to +160°F
a.	Between +5 and -5 meters per/sec^2	±1/2%	±1%
b.	Between +5 and +7.5 and between -5 and -7.5 meters/sec^2	±1%	±1-1/2%
c.	Between +7.5 and +10 and between -7.5 and -10 meters/sec^2	±1-1/2%	±2-1/2%

Temperature Range

a. Operating: -20°F to +160°F

b. Storage: -65°F to +185°F without damage

III. DESIGN GOALS (Cont'd)

Natural Frequency

Nine cycles per second ±1 cps, at 90° phase angle, over the operating temperature range.

Damping

Between 0.6 and 1.0 of critical over the temperature range of -20°F to +160°F.

Cross Sensitivity and Axis Alignment

Within 0.002 G/G with respect to instruments mounting provisions when cross acceleration is applied in any direction perpendicular to the sensitive axis.

Force Coil Calibration

With the instrument level and no acceleration applied along the sensitive axis, a d.c. current applied to the force coil from an external 28 volt d.c. source shall deflect the seismic mass in both directions and be proportional to the inphase component of the instrument output voltage as follows:

a. Including linearity, hysteresis, friction, scale factor, and repeatability, within ±6% of reading at 75°F ambient temperature.

b. Change in sensitivity not to exceed 0.15% of reading per degree F over the ambient temperature range of +25°F to +125°F.

c. Zero shift not over 0.08% per degree F over the temperature range of +25°F to +125°F.

d. Desired scale factor approximately 15 ma/meter/sec^2.

III. DESIGN GOALS (Cont'd)

Insulation Resistance

Greater than 200 megohms with 500 volts d.c. applied between any internal circuit and case ground.

Weight, Size, Construction

Hermetically sealed case with weight and size as required for initial design. These parameters become restrictive in later phases of program.

Steady-State Acceleration

Fifty (50) "G's" along any axis without damage.

Shock

Fifty (50) "G's" along any axis for 10 milliseconds duration with 0.4 millisecond rise time without damage.

Vibration

a. Along any axis, 1/2 inch double amplitude or 20 G peak sinusoidal, whichever is smaller, from zero to 2,000 cps without damage.

b. Less than 4% of full scale output shall result from vibration in any axis of 1/2 inch double amplitude or 20 G peak sinusoidal, whichever is less, from zero to 2,000 cps. Less than 2% of full scale output at 10 G peak sinusoidal. This shall not apply to the sensitive axis at frequencies below 80 cycles.

IV. PROTOTYPE DESIGN

Evaluation prototype design is shown in Drawing 30312. The components are shown in Figure 2. With an acceleration applied to the sensitive axis, the acceleration sensitive mass, Items 6, 7, 9, 13, 16, 17, 18, 19, 28, and 31 will deflect until the acceleration force on the sensitive mass is equalled by the deflection force in the "S" springs, Item 20. This deflection is measured by an output from the LVDT, Item 27, which is a phase sensitive differential transformer. The accelerometer is damped by the nylon damping pistons, Item 19, which form temperature compensating dashpot damping in conjunction with the silicone oil damping fluid.

For self-test capabilities, a series wound coil, Item 31, is mounted on the self-test coil carrier, Item 6; and the winding is positioned between the two permanent magnets, Item 4 and Item 5. A direct current passing through the winding causes a reaction force, which is proportional to the current, magnetic flux density, the number of turns on the coil, and the direction of the current.

The assembly is mounted within a cylindrical housing, Item 1, and secured in position by the lock ring, Item 22. End caps, Items 21 and 10 are mounted to each end and solder sealed. The assembly is then filled with a Dow Corning Silicone damping fluid and hermetically sealed. All electrical connections terminate at the terminals, Item 24, on one end of the assembly. Being an evaluation prototype assembly, there is no provision in the prototype for expansion bellows; however, space is provided in the end caps, where material has been added to simulate the volume of the bellows.

V. COMPONENT DESIGN

Sensitive Mass

The sensitive mass, shown in Figure 3, consists of nylon damping rings, coil carrier supports, and the coil carrier with its winding. In addition, the core of the transducer and its null adjustments are also included in the sensitive mass. From the calculations and actual weight of the hardware, it was found that the sensitive mass weight is 50 grams; however, when the unit is filled with silicone oil, the effective mass that is acceleration sensitive is 38 grams because of the buoyant effect of the damping fluid.

"S" Springs

The "S" spring is shown in Figure 4. Two (2) "S" springs are used in the assembly and are symmetrically mounted, one on each end of the sensitive mass. The sensitive mass is mounted to the ID of the "S" spring which in turn is securely positioned to the magnet carrier. These springs are fabricated from Ni-Span steel which has very low change of spring rate with temperature and exhibits extremely low hysteresis with deflection. The fabrication of the "S" spring was by Photo-etch technique.

Linear Variable Differential Transformer

The Linear Variable Differential Transformer (LVDT) is shown in Figure 5. In operation, the core links flux lines from a primary winding into two balanced opposing secondary windings. With the core at electrical null, the inphase signal and out-of-phase signal cancel leaving an electrical zero. With motion in either direction, an output signal proportional to the core position is achieved. Because the core is part of the sensitive mass and thus travels or deflects with it, the output signal indicates the mass position.

V. COMPONENT DESIGN (Cont'd)

Self-Test Forcer

The self-test forcer comprises three components--the forcer coil carrier, Figure 6; the forcer magnets, Figure 7; and the magnet carriers, Figure 8. In design, the coil carrier is positioned within the flux gap located between the two permanent magnets. When a current passes through the winding, a force is developed which deflects the forcer in either direction depending on the direction of the current flow. The magnets are mounted in Armco Iron magnet carriers, which provide the magnetic flux path around the two permanent magnets.

The forcer coil carrier is an aluminum drum of very thin cross section. On the OD of the aluminum drums are two ribs within which the series wound self-test coil is mounted. The coil is 400 turns of #38 wire and is potted in a casting resin.

The two forcer magnets, inner and outer, are of a plastic permanent magnet material, (Plastiform) which is easily formed into any cylindrical shape. This material has a very high coercive force and a coefficient of change in magnetism of less than .105%. However, the magnet material itself is not strong enough to hold dimensional stability; therefore, the magnets are encased in aluminum shells. These shells mount on the ID of the outside magnet and the OD of the inside magnet to provide the necessary mechanical support. In addition, the aluminum shell also forms spacers at the end of the magnets so that they cannot come into physical contact with the magnet carriers, thus preventing the shorting-out of the magnetic fields.

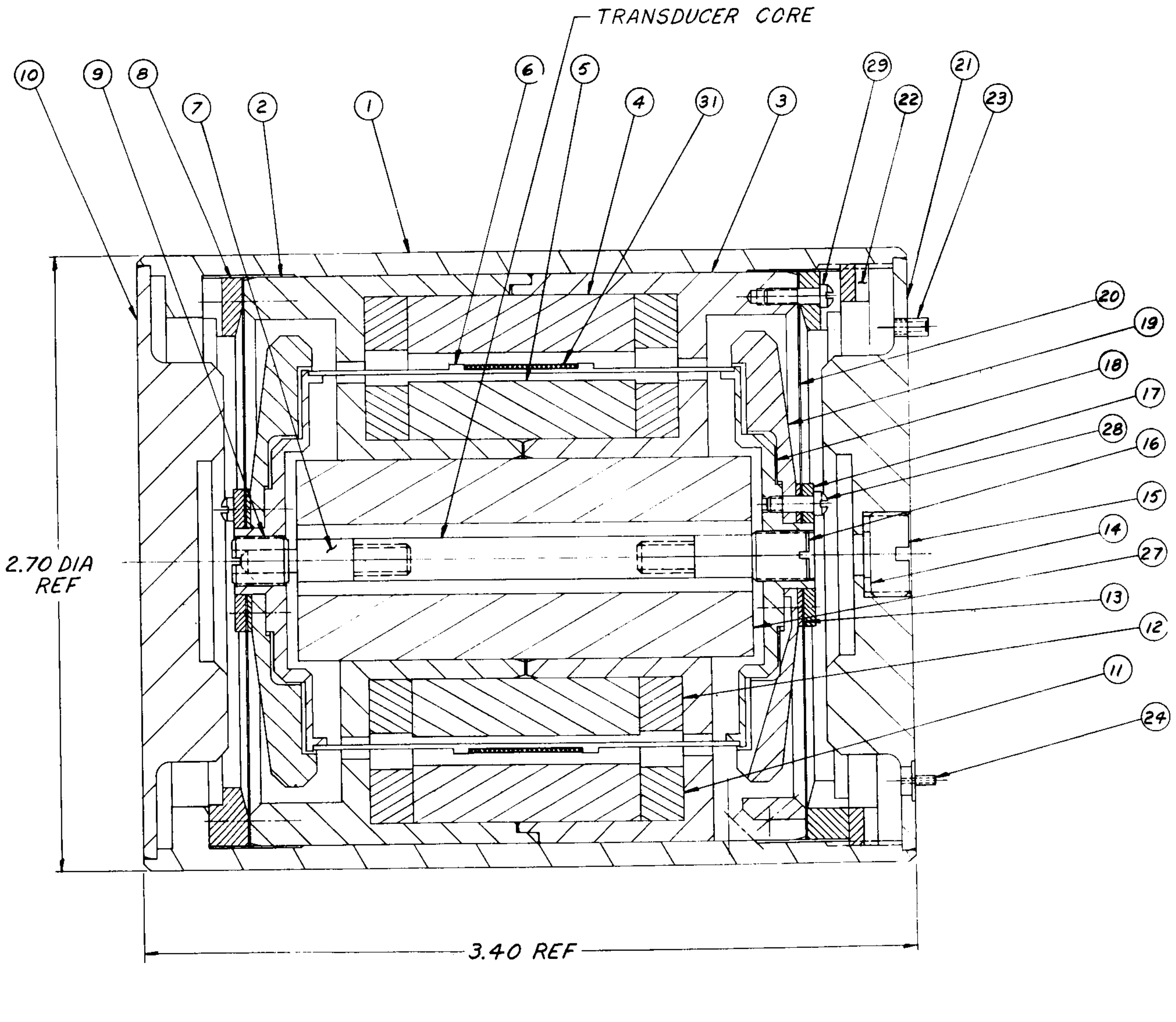
Coil Supports

The coil supports shown in Figure 9, are fabricated from 303 stainless steel. These supports mount on the ID of the "S" springs. Dimensions are very close to guarantee concentricity of the assembly. In addition, the coil supports also carry the coil carrier, the null adjustment of the LVDT, and the nylon damping pistons.

V. <u>COMPONENT DESIGN</u> (Cont'd)

Damping Rings

The damping nylon rings are shown in Figure 10. The dashpot damping leakage gap is between the ID of the magnet carriers and the OD of the nylon damping rings. To compensate for the change of fluid viscosity with temperature, the nylon was chosen because it has a temperature coefficient of expansion much higher than the Armco Iron used in the magnet carriers. In other words, when the the temperature increases and the oil viscosity decreases, the nylon damping rings increase in size closing down the damping gap and thus compensating for the change in fluid viscosity. When the temperature decreases, the damping fluid viscosity increases and the nylon damping ring OD decreases, opening the gap and again compensating for the change in viscosity.



GENERAL NOTES

6 5 4

94117-SVH-100X

APPLICATION		REVISIONS			
NEXT ASSY	USED ON	SYM	DESCRIPTION	DATE	APPROVAL

2

	33			
	32			
AR	31			WIRE, HEAVY FORMVAR #38 (.0049)
	30			
6	29			SCREW, MACH, FIL HD. 1-72 X .250
8	28			SCREW, MACH, FIL HD. 1-72 X .22 APPROX.
1	27		MODEL #70-3903	TRANSFORMER (ROBINSON HALPERN CO.)
	26			
	25			
7	24	A	775A01-21	TERMINAL
1	23	A	11964-P1	FILLER TUBE (MODIFIED)
1	22	B	SVH-114XP1	LOCK RING
1	21	C	SVH-109XP1	END CAP TERMINALS
2	20	C	PCD 2511	S-SPRING (5.6X)
2	19	C	SVH-111XP1	NYLON PISTON
2	18	C	SVH-116XP1	COIL SUPPORT
2	17	B	SVH-117XP2	WASHER
1	16	B	SVH-118XP1	NULL ADJUST
1	15	B	SVH-122XP1	PLUG (END CAP TERMINALS)
1	14	A	SVH-123XP1	SEAL (PLUG)
2	13	B	SVH-117XP1	WASHER
2	12	A	SVH-125XP1	FILLER SPACER
2	11	A	SVH-125XP2	FILLER SPACER
1	10	C	SVH-119XP1	END CAP
1	9	B	SVH-121XP1	BUSHING
2	8	B	SVH-113XP1	SPACER
1	7	B	SVH-120XP1	CONNECTOR CORE
1	6	C	SVH-112XP1	COIL CARRIER
1	5	B	SVH-108XP1	FORCER MAGNET
1	4	B	SVH-108XP2	FORCER MAGNET
1	3	C	SVH-110XP1	SHELL-MALE
1	2	C	SVH-124XP1	SHELL-FEMALE
1	1	C	SVH-115XP1	HOUSING
G6 G5 G4 G3 G2 G1	ITEM	SIZE	PART NO	DESCRIPTION
REQD PER ASSY				LIST OF MATERIAL

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
XX DECIMAL ± XXX DECIMAL ±
ANGLES ± SURFACE QUALITY √ MAX
INTERPRET DRAWINGS PER 815002
MFG DATE

DRAFTING: DR R. H. Sauvant DATE 10-8-65
APPD
ENGINEER: CHK / DEV / ELEC / MECH
PROJ L.D. Daley 10-8-65
APPD

SANDERS ASSOCIATES, INC.
NASHUA, NEW HAMPSHIRE

TITLE
RECTILINEAR ACCELEROMETER

SIZE	CODE IDENT NO	DWG NO	REV
E	94117	30312	A

SCALE 4:1 CONT NO SHEET 1 OF 1

DO NOT SCALE PRINT

D C B A

3 2 1

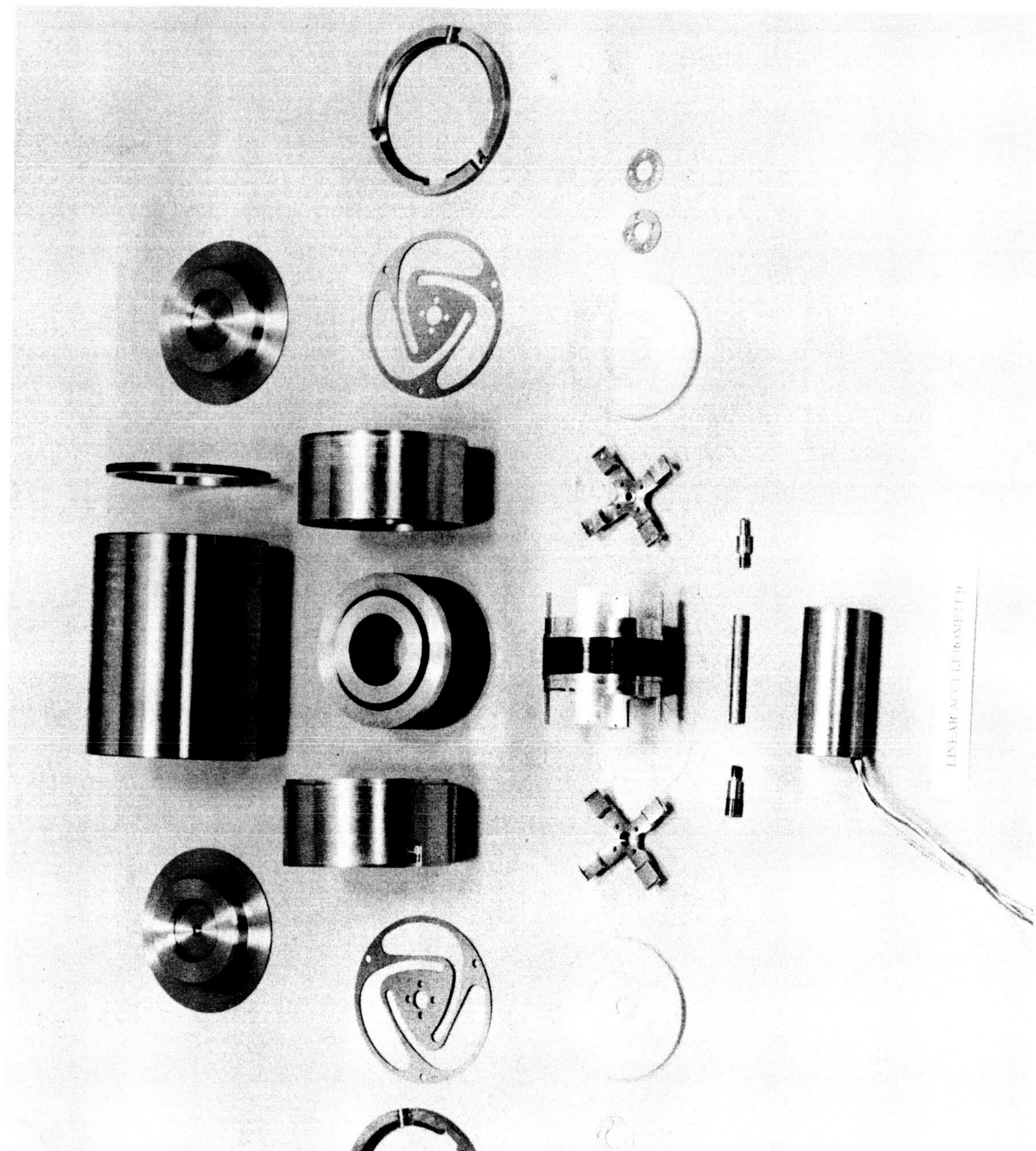


Figure 2 - Rectilinear Accelerometer Components, Page 16

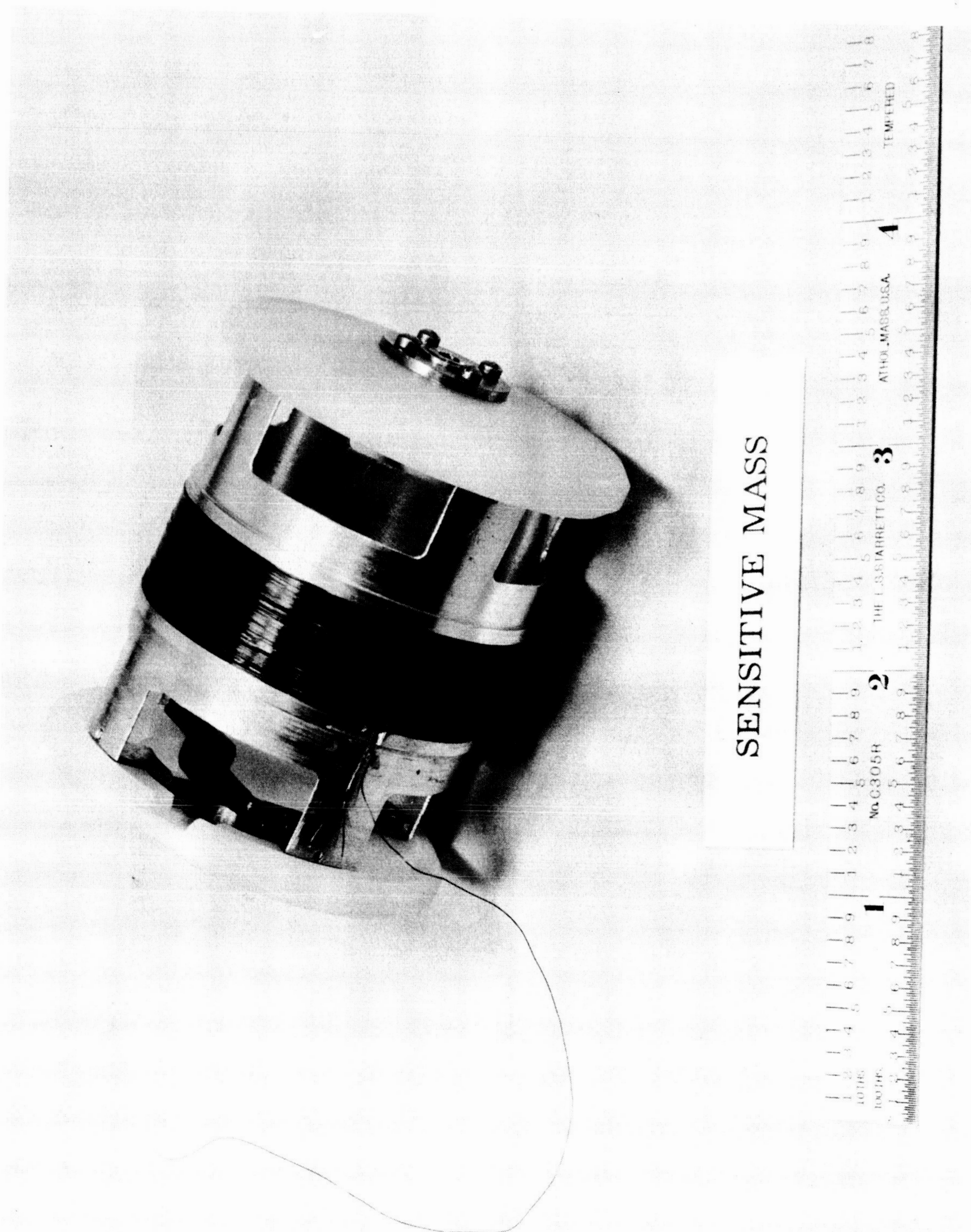


Figure 3 - Page 17

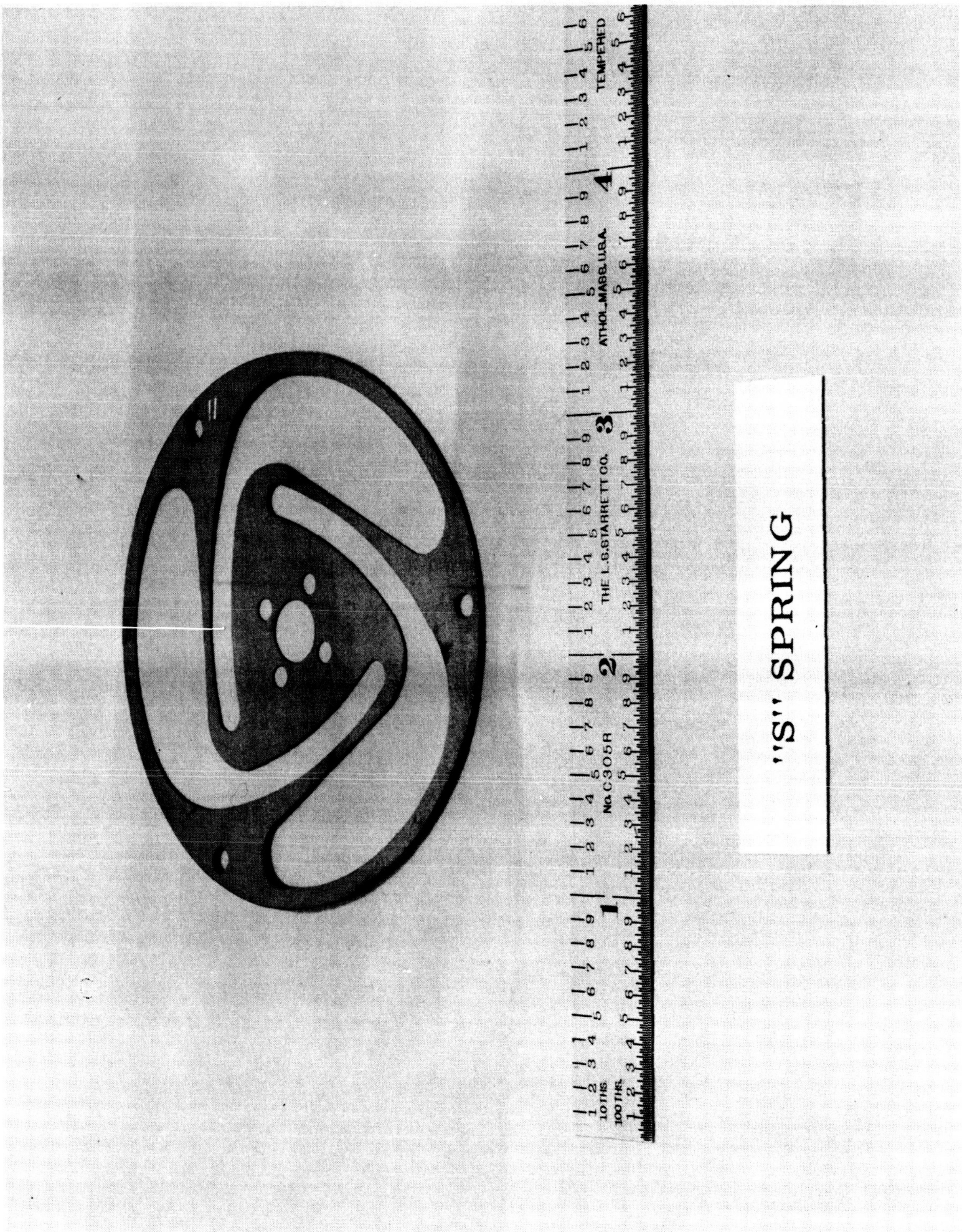
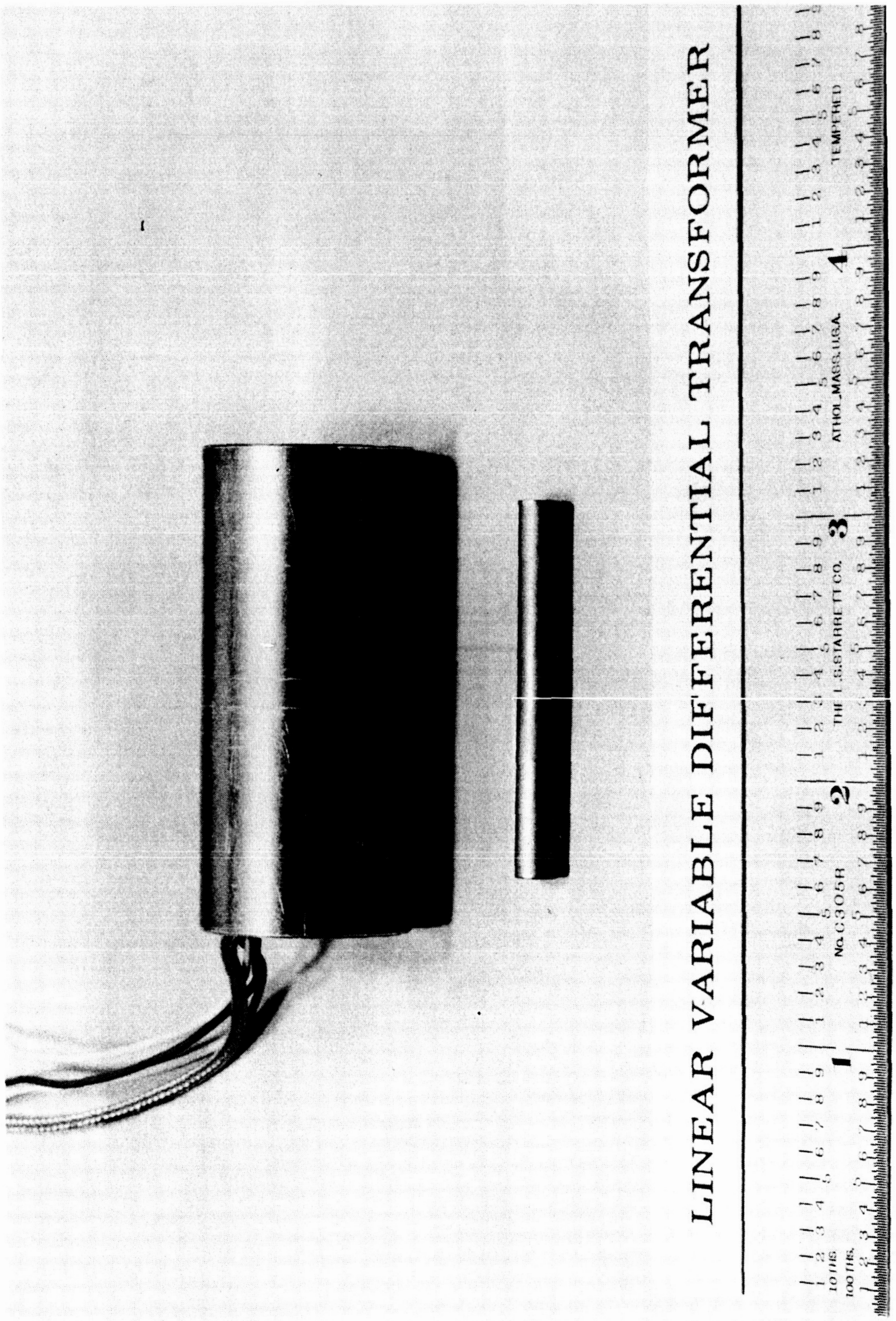


Figure 4 - Page 18


LINEAR VARIABLE DIFFERENTIAL TRANSFORMER
No.C305R
THE L.S.STARRETT CO.
ATHOL, MASS. U.S.A.
TEMPERED

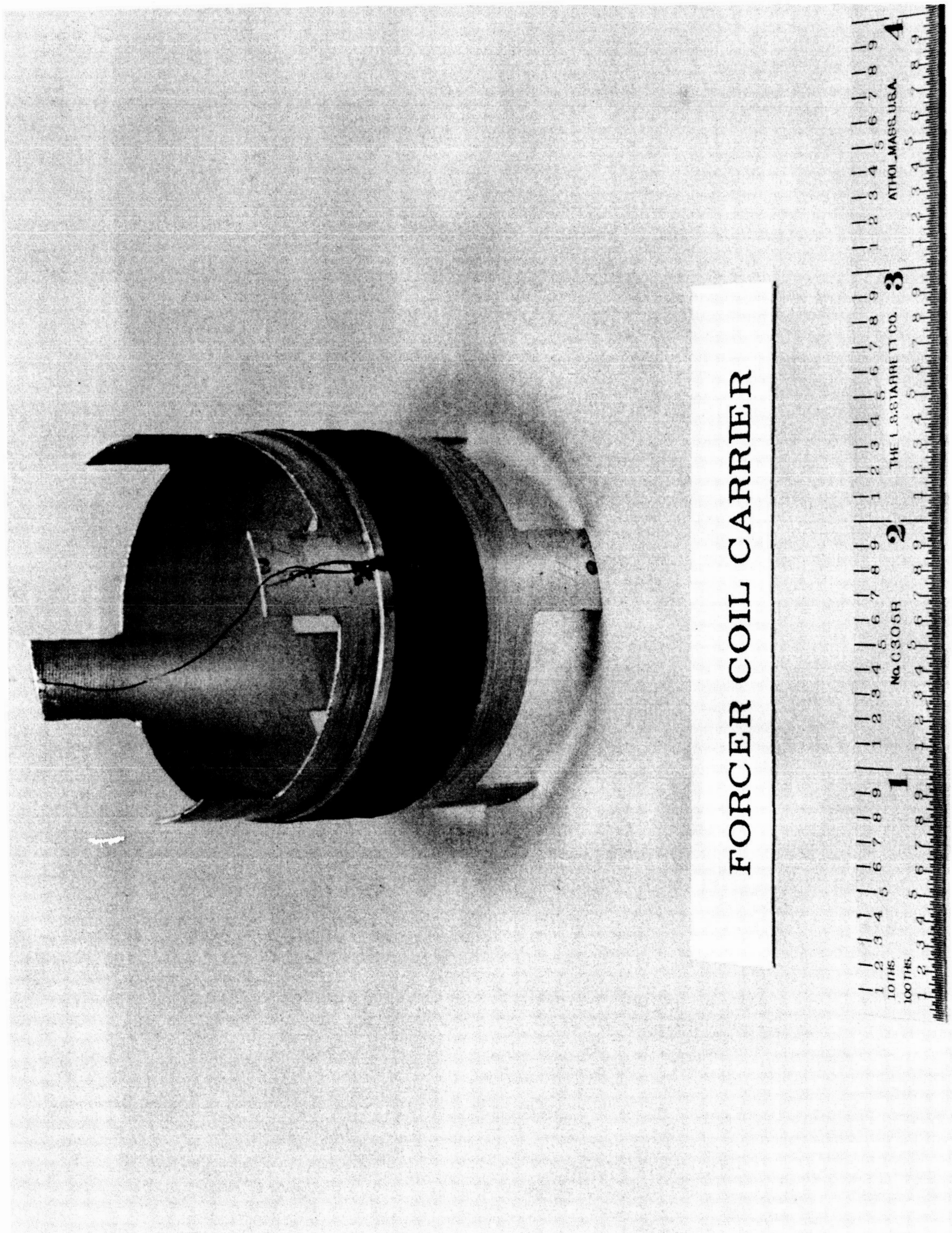


Figure 6 - Page 20

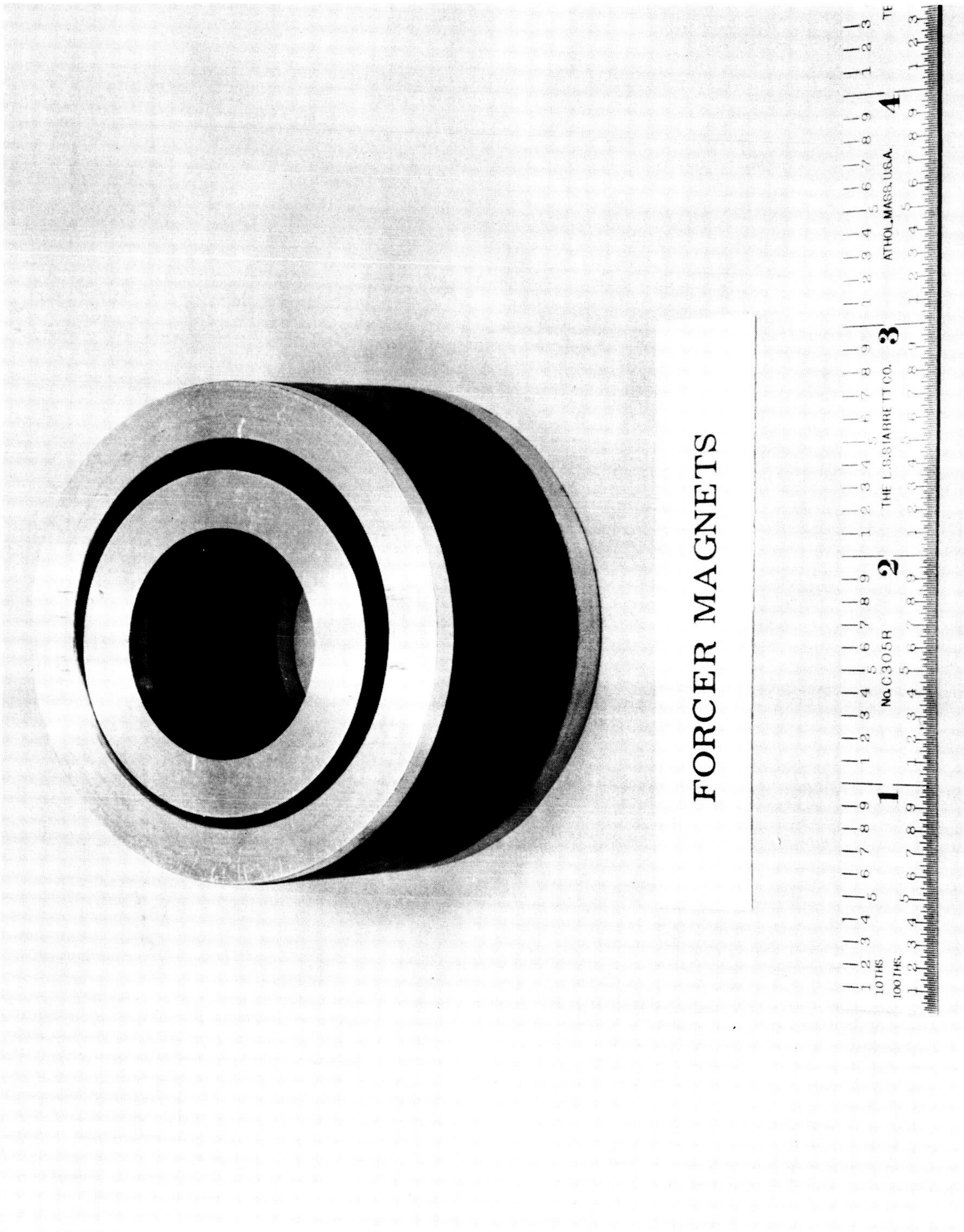


Figure 7 - Page 21

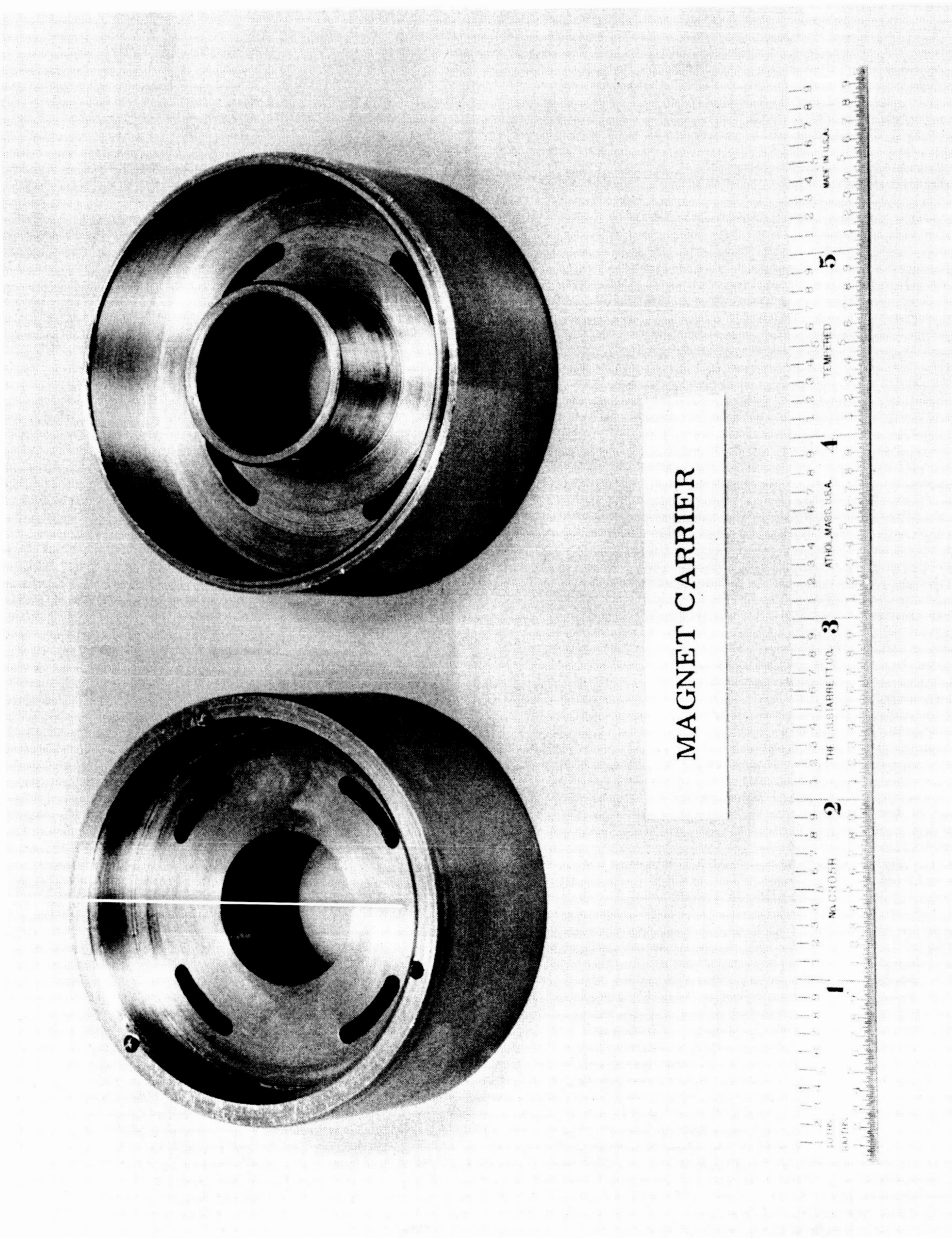
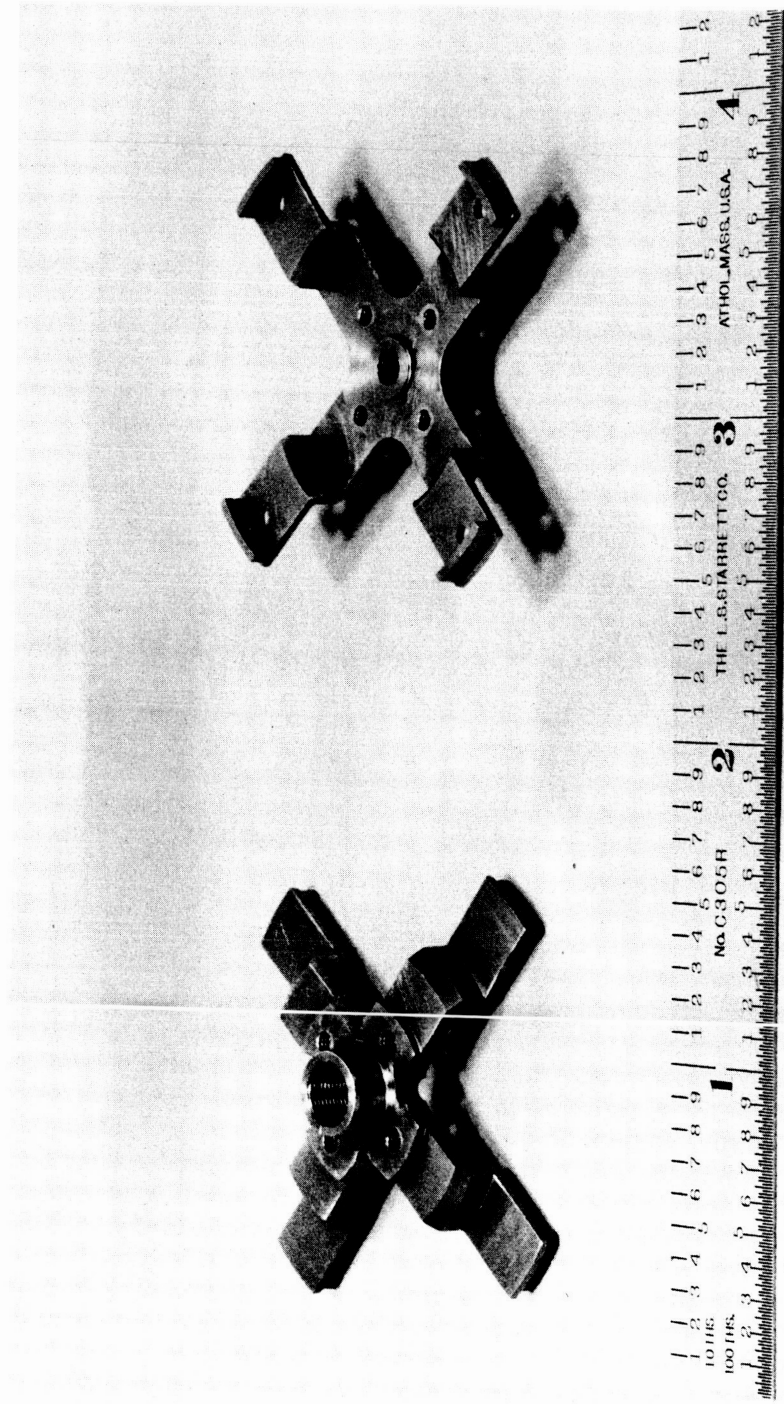
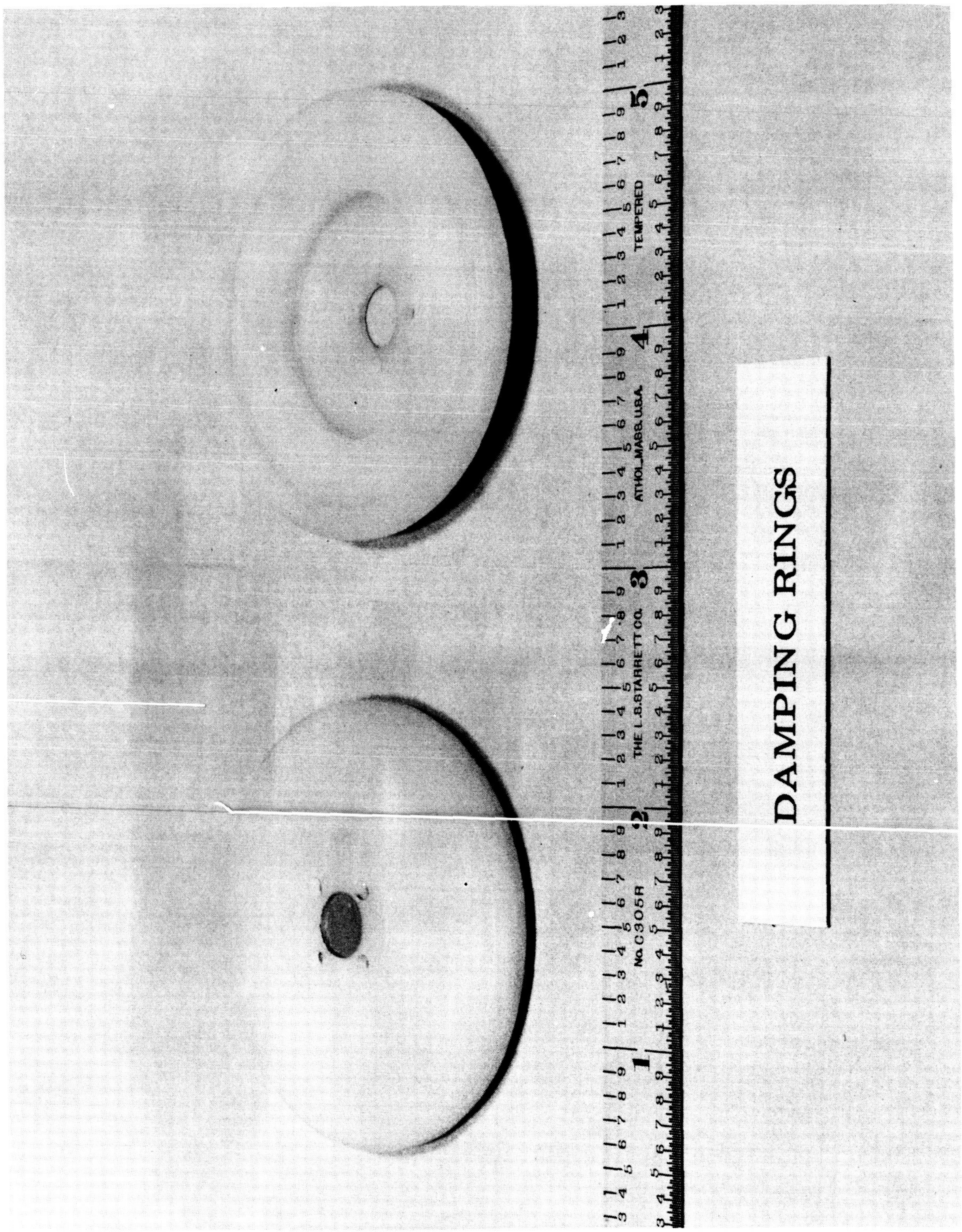


Figure 8 - Page 22



COIL SUPPORT


DAMPING RINGS

VI. PERFORMANCE EVALUATION

The evaluation components of the Rectilinear Accelerometer were assembled and limited test data was obtained. Testing was done to determine the performance of the unit in the areas of:
1) Linearity unfilled, 2) linearity filled, 3) null stability, 4) damping and natural frequency, 5) self-test forcer.

1. Linearity Unfilled

The unit was built up to the point of soldering the end caps on and at this point, linearity of the unfilled unit was determined. It should be pointed out that the full scale acceleration applied was $\pm .75$ g's since the sensitive mass was not submerged in the damping fluid. The mass unsubmerged weighs 50 grams and submerged the buoyant force is 12 grams. Therefore, .75 g's corresponds to 1 g acceleration when the unit is filled.

The accelerometer was mounted on a rate-of-turn table at a radius of 10 inches and acceleration was applied by the following formula for radial acceleration.

$$a = r\omega^2$$

where a = acceleration
r = radius
ω = applied angular velocity in rad/sec

The output of the accelerometer was monitored with the circuitry of Figure 11. The output signal was reduced to a null voltage by applying a cancelling signal which bucked off the output. Both the inphase output and the quadrature output was cancelled so that the total signal was a null voltage. In the unfilled linearity test only the inphase cancelling voltage was measured and recorded. This data is shown in Chart 1 and plotted in Figures 12 and 13. Calculation of the linearity is shown in Chart 2. The error calculation shows that the accelerometer is well within the specification limits as outlined in the design goals.

VI. PERFORMANCE EVALUATION (Cont'd)

2. Linearity Filled

The prototype instrument was then sealed and filled with Dow Corning Silicone fluid (DC 200 - .65 centistokes). When the unit was connected to the monitoring equipment, a very high null was present (.8 volts). The seal port was opened and the unit was renulled and output data was taken. This data is listed in Charts 3 and 4 and plotted in Figures 14 and 15. The output was not symmetrical and in one direction the output was quite unlinear. The linearity is calculated in Charts 5 and 6 and shows the wide range of nonlinearity.

After the assembly was torn down to change the damping gap, linearity was again tested. This data is listed in Charts 7 and 8, plotted in Figures 16 and 17 and calculated in Chart 9. The error is much less than in the previous test and no null shift was noted after filling. The linearity is still in excess of the specification limits.

In comparing the techniques in the filling of the accelerometer, it was found that the first time a rapid decompression occurred during the evacuation and backfill. Apparently this caused the "S" springs to shift slightly to give a condition known as oil canning. It is apparent that the mounting of the "S" springs is extremely critical and causes the nonlinearity. Proper assembly techniques will eliminate the nonlinearity problem.

VI. PERFORMANCE EVALUATION (Cont'd)

3. Null Stability

With the accelerometer on the rate table, an input rate was applied which caused a full scale deflection. The rate table was allowed to coast to a smooth stop and the null was noted. There was no measureable change in null output with this test. It should be pointed out that this instrument is extremely sensitive to its mounting orientation and as such provision will be made in the future for accurate and repeatable mounting.

4. Damping and Natural Frequency

By driving the forcer with a sinusoidal input and monitoring the point at which the driving signal was at 90° to the response signal from the LVDT, the natural frequency was determined. The damping factor was determined by plotting the amplitude ratio versus the ratio of the input frequency to the natural frequency. By setting up an oscilliscope so that the input signal was a known magnitude and the output signal was adjusted to have an equal magnitude. The frequency was increased in steps and the ratio of the output to input was measured at each step. The data obtained is in Chart 10 and plotted in Figure 18. By comparing Figure 18 with Figure 19 (amplitude ratio for various damping values in a second order system), it can be seen that the damping ratio is approximately 0.15. In addition, the 6 cps natural frequency is verified as the 0.15 damping curve peaks at approximately the natural frequency. From this data and other measured constants, the effect of the fluid mass can be calculated.

Unfilled mass--M = 50 grams = .11 lbs.

Total travel (stop to stop) = .0985

Total acceleration input stop to stop = 1.60 g's +1.36 = 2.96 g's

Sensitive mass weight filled = 38 grams = .0838 lbs.

$$\text{deflection at 1 g} = \frac{.0838}{2.96} = .0333 \text{ inches}$$

$$K = \#/\text{in} = \frac{.0838}{.0333} = 2.5\#/\text{in}$$

now

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M + M_f}}$$

where f_n = natural frequency

K = spring rate

M = mass of sensitive weight

M_f = fluid mass

$$6 = \frac{1}{2\pi}\sqrt{\frac{2.5\#/\text{in } 386 \text{ in/sec}^2}{(.11 + M_f)\ \#}} = \text{cps}$$

squaring both sides

$$36 \times (2\pi)^2 = \frac{2.5 \times 386}{.11 + M_f}$$

$$\frac{1420}{965} = \frac{1}{.11 + M_f}$$

$$1.47\ (.11 + M_f) = 1$$

$$1.47\ M_f = 1 - .162$$

$$M_f = \frac{.838}{1.47} = .570 \text{ lbs.}$$

VI. PERFORMANCE EVALUATION (Cont'd)

In addition, the low damping constant is partially caused by the low natural frequency as

$$C_c = 2\sqrt{KM}$$

K = spring rate

M = total mass (including fluid)

but $\frac{K}{M} = \omega_n^2$

where ω_n = natural frequency rad/sec

then $C_c = 2\sqrt{\frac{K^2}{\omega_n^2}} = \frac{2K}{\omega_n}$

therefore

$$C_c = \frac{2(2.5)}{6 \times 2\pi} = \frac{5}{37.7} = .132 \text{ \#sec/in}$$

and damping calculations were based on a damping constant of .0975# sec/in. Two inserts were fabricated to reduce the damping gap from .073 to .050.

The damping was again measured to find the effect of reducing the gap from .073 to .050. The frequency response was practically identical to the previous test indicating no increase in the damping coefficient.

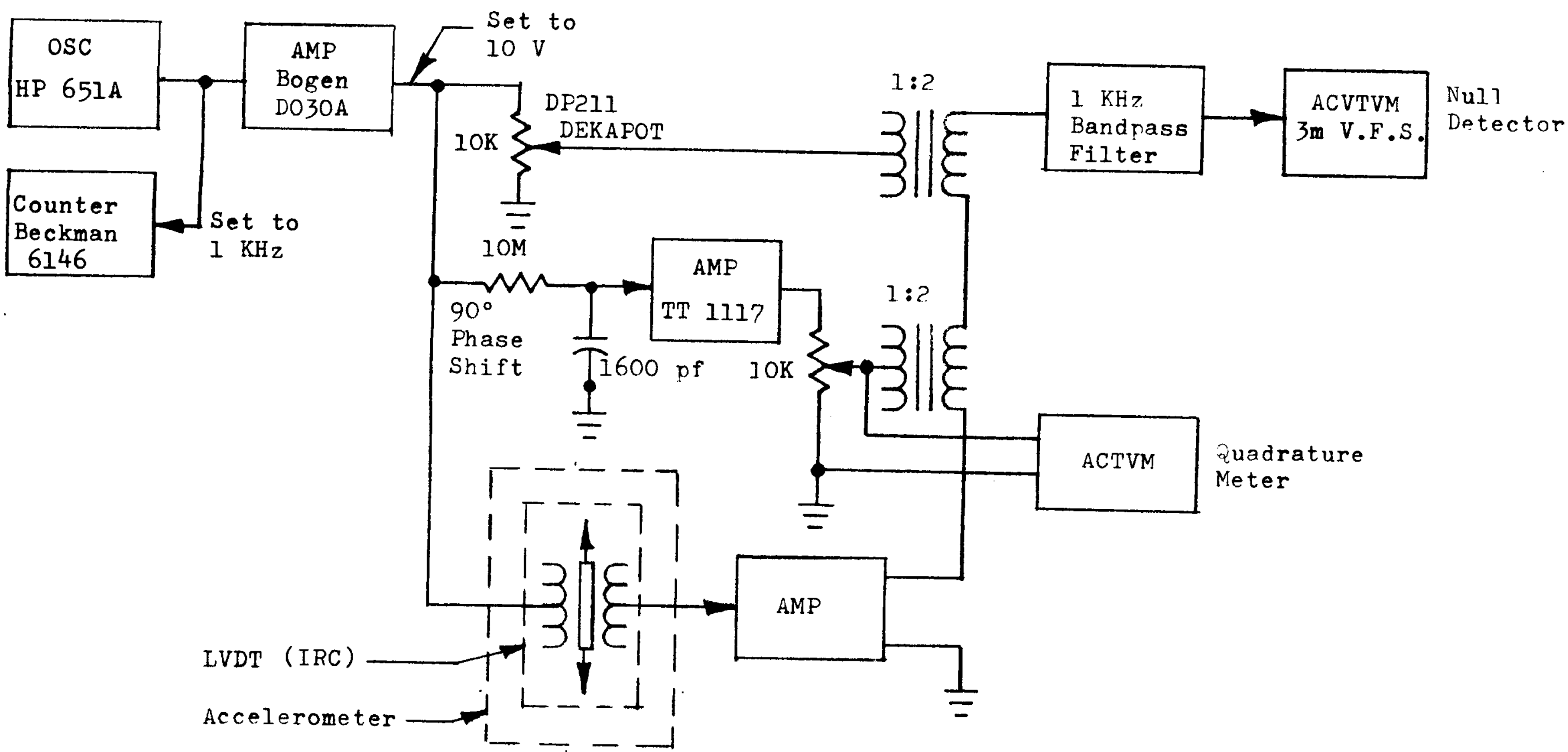
A re-evaluation of the damping calculations as presented in Status Report No. 2 revealed an error in this calculation. In transposing from the viscosity in centistokes to units of #sec/in., an error of 10^{-2} was introduced. The section should read

.46 centistokes = .506 x 10^{-7} #sec/in instead of
.46 centistokes = .506 x 10^{-5} #sec/in.

The unit was then refilled with 10 centistokes Dow Corning Silicone oil and the frequency response data of Chart 11 was taken. This data is plotted in Figure 20 indicating a damping of .55. With 10 cs oil, the shear layer is thicker, which increases the fluid mass and lowers the natural frequency from 6 cps to 5 cps.

Self-Test Forcer

The self-test forcer was tested by applying a current to the self-test forcer coil and matching the output as determined in the linearity test. This data is listed in Charts 3 and 4 and plotted in Figures 14 and 15. The full scale output is attained with less than 60 ma **indicating self-test forcer approximately three times stronger than the requirements in the design goals.**



ACCELEROMETER LINEARITY TEST CIRCUIT

FIGURE 11

LINEAR ACCELEROMETER

OUTPUT VERSUS INPUT
Unfilled Unit

10/20/65

INPUT		OUTPUT (Decapot Reading)	
°/sec	g's	Away From Header	Towards Header
113	.1	263	-268
160	.2	545	-537
195	.3	809	-809
226	.4	1079	-1081
252	.5	1350	-1356
276	.6	1619	-1625
298	.7	1892	-1900
308.5	.75	2022	-2026

CHART 1

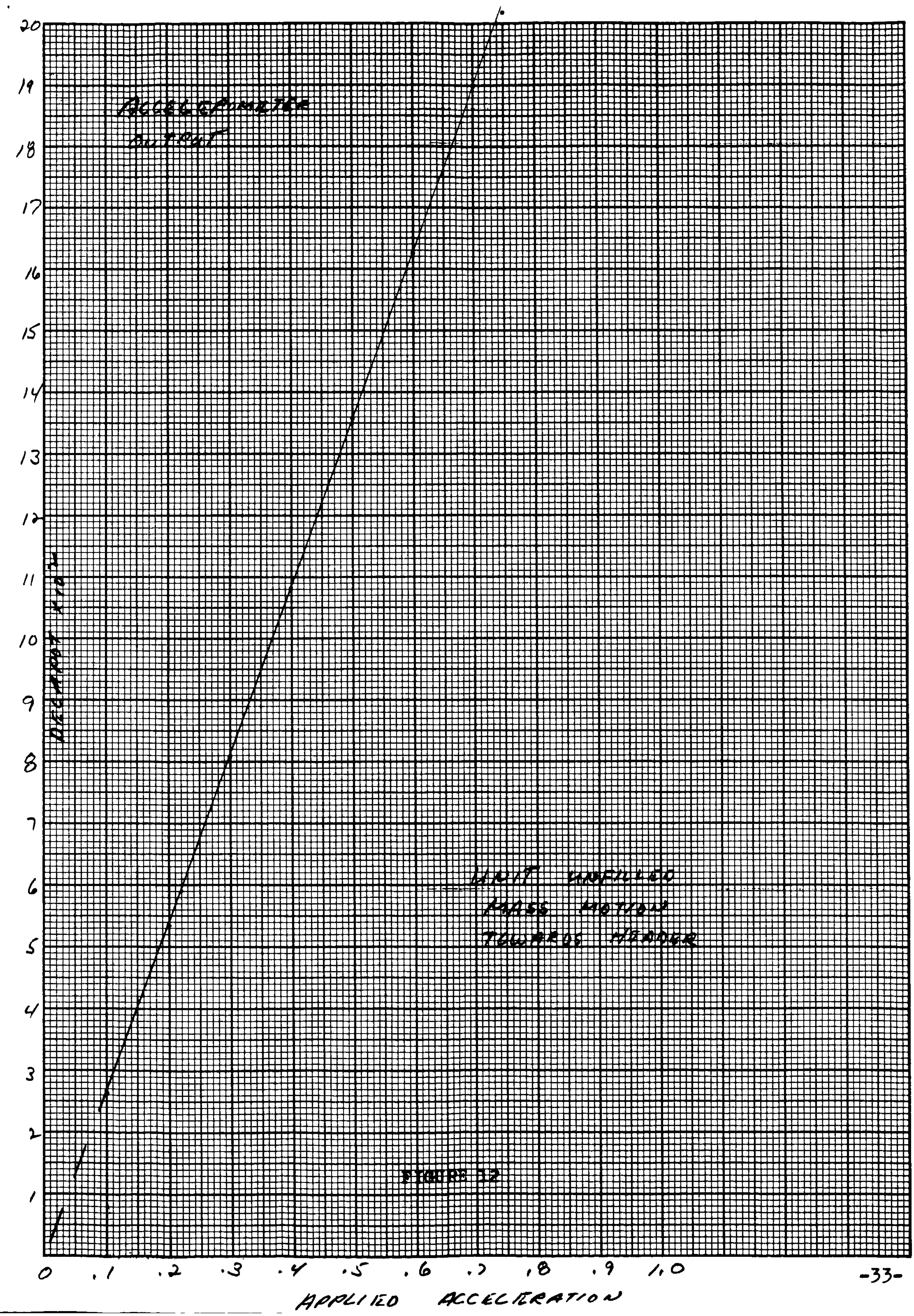

ACCELEROMETER
OUTPUT
UNIT UNFILLED
MASS MOTION
TOWARDS HEADER
APPLIED ACCELERATION
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

FIGURE 12

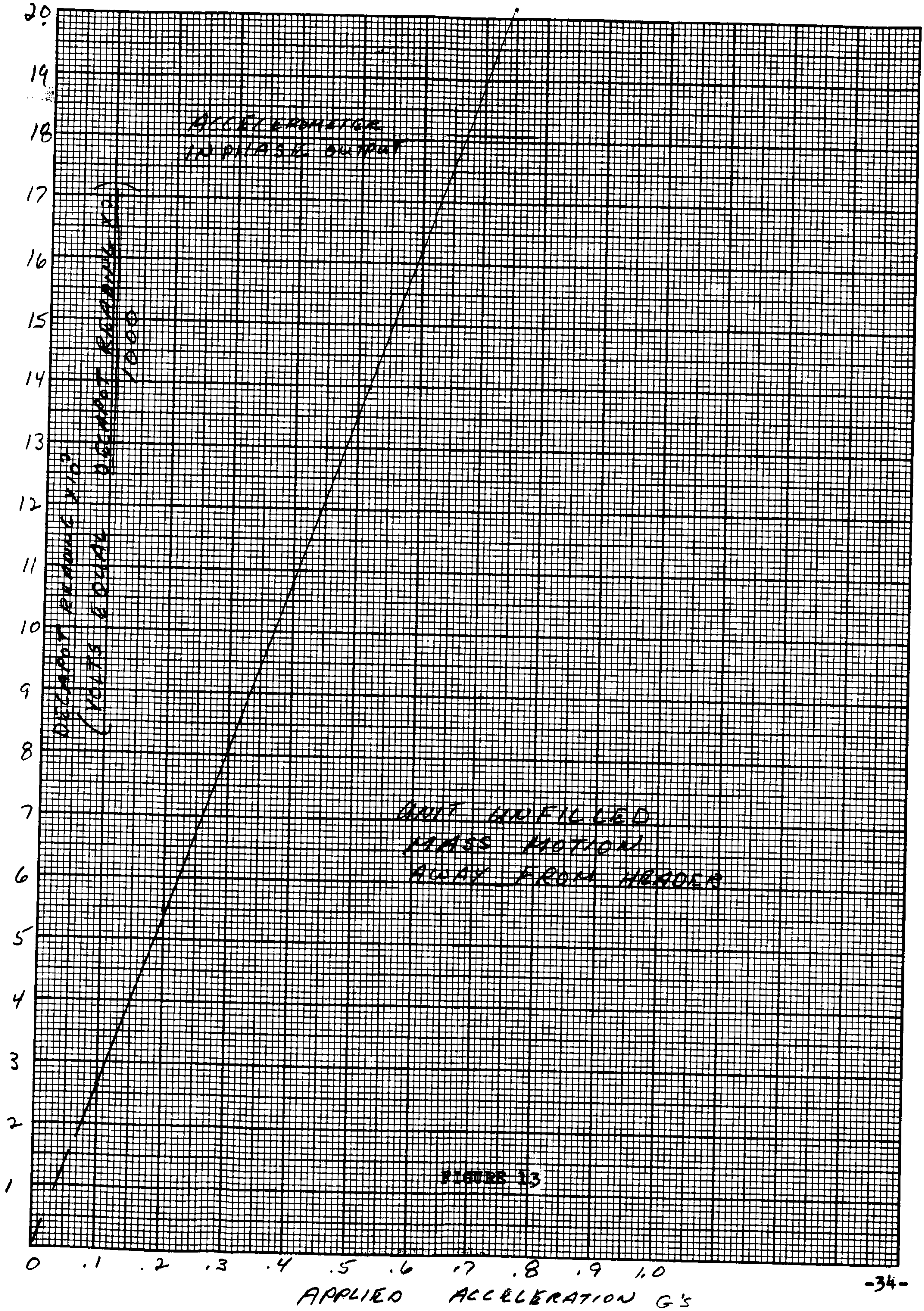

ACCELEROMETER
IN PHASE OUTPUT
DECADPOT READING X10²
(VOLTS EQUAL DECADPOT READING X3 / 1000)
UNIT UNFILLED
MASS MOTION
AWAY FROM HEADER
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
APPLIED ACCELERATION G'S

FIGURE 13

LINEARITY CALCULATION (UNFILLED)

x Input g's	y Output V	xy	y^1 V	$y-y^1$	Error % F.S.
.75	4.044	3.0330	4.057	-.013	-.32
.70	3.784	2.6488	3.786	-.002	-.05
.60	3.238	1.9428	3.244	-.006	-.15
.50	2.700	1.3500	2.702	-.002	-.05
.40	2.158	.8632	2.161	-.003	-.07
.30	1.618	.4854	1.619	-.001	-.02
.20	1.090	.2180	1.077	+.013	+.32
.10	.526	.0526	.536	+.010	+.25
0					
-.10	-.536	.0536	-.548	+.012	+.30
-.20	-1.074	.2148	-1.089	+.015	+.37
-.30	-1.618	.4854	-1.631	+.013	+.32
-.40	-2.162	..8648	-2.173	+.011	+.27
-.50	-2.712	1.3560	-2.715	+.003	+.07
-.60	-3.250	1.9500	-3.256	+.006	+.15
-.70	-3.800	2.6600	-3.798	-.002	-.05
-.75	-4.104	3.0780	-4.069	-.035	-.86

$$y^1 = -.006125 + 5.417x$$

CHART 2

LINEAR ACCELEROMETER

OUTPUT AND FORCE BALANCE
(Mass Motion Away From Header)

10/25/65

INPUT		OUTPUT		
°/sec	g's	Potentiometer Setting	Quadrature - MV	Force Balance Current - MA
0	0	5	20	0
100	.079	192	82	4.2
120	.1138	270	140	6.5
140	.155	356	194	
160	.202	454	256	11.4
180	.2565	560	330	
200	.316	675	400	17.4
220	.382	808	483	
240	.455	949	576	22.9
260	.534	1100	680	
280	.618	1253	780	34.2
300	.711	1422	844	
320	.810	1601	1000	44.9
340	.912	1794	1130	
360	1.022	1988	1240	57.6

CHART 3

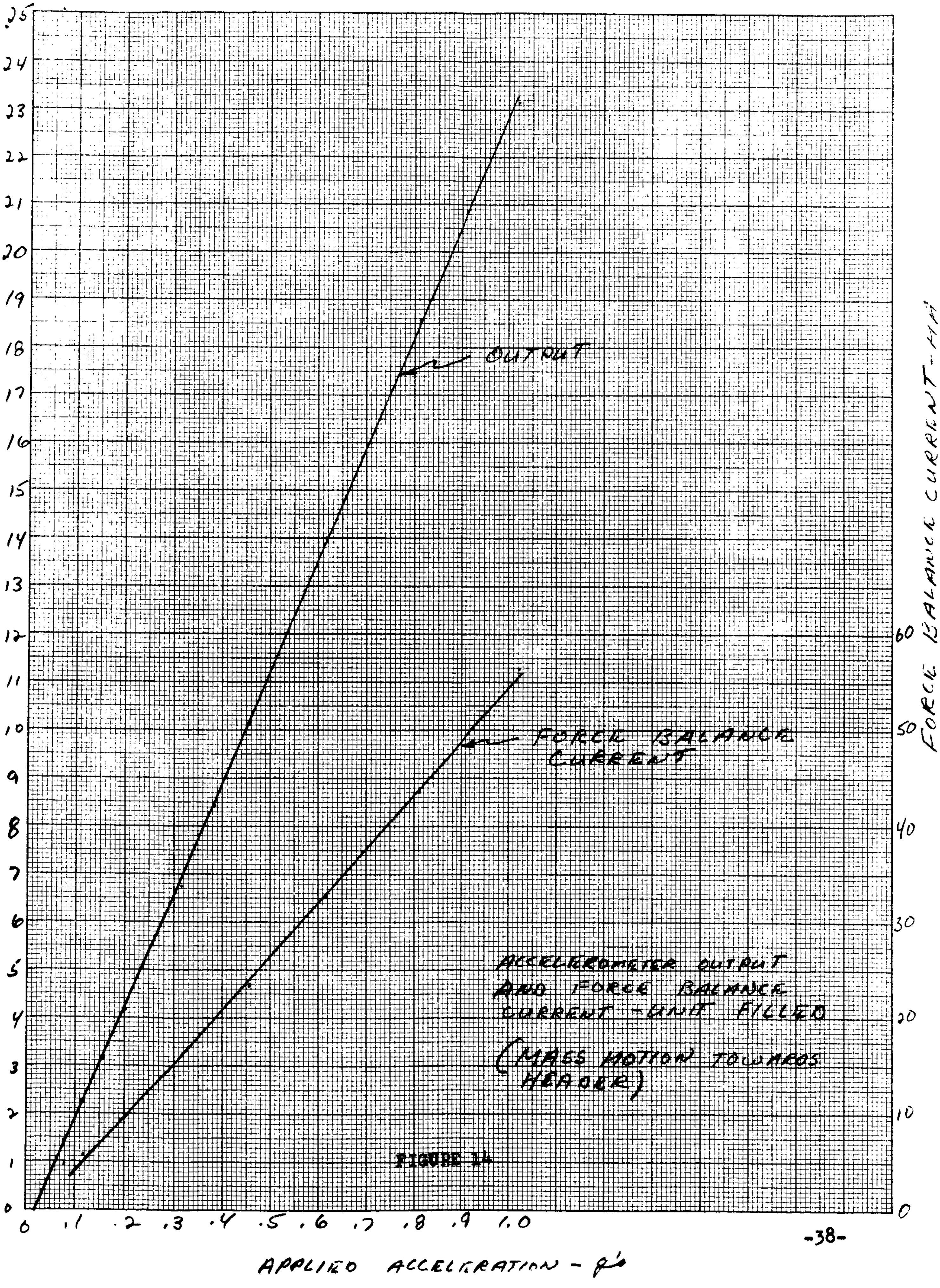
LINEAR ACCELEROMETER

OUTPUT AND FORCE BALANCE
(Mass Motion Towards Header)

10/25/65

INPUT		OUTPUT		Force Balance Current - MA
°/sec	g's	Potentiometer Setting	Quadrature - MV	
0	0	+5	22.0	0
100	.079	-146		4.8
120	.1138	-223	206	5.6
140	.155	-312	260	
160	.202	-418	340	9.9
180	.2565	-551	420	
200	.316	-673	510	16.3
220	.382	-846	610	
240	.455	-1016	720	23.5
260	.534	-1202	824	
280	.618	-1399	1000	32.7
300	.711	-1616	1130	
320	.810	-1856	1260	43.7
340	.912	-2086	1420	
360	1.022	-2316	1600	56.4

CHART 4



25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
APPLIED ACCELERATION - g's
60
50
40
30
20
10
0
FORCE BALANCE CURRENT - MA
OUTPUT
FORCE BALANCE CURRENT
ACCELEROMETER OUTPUT AND FORCE BALANCE CURRENT - UNIT FILLED
(MASS MOTION TOWARDS HEADER)

FIGURE 14

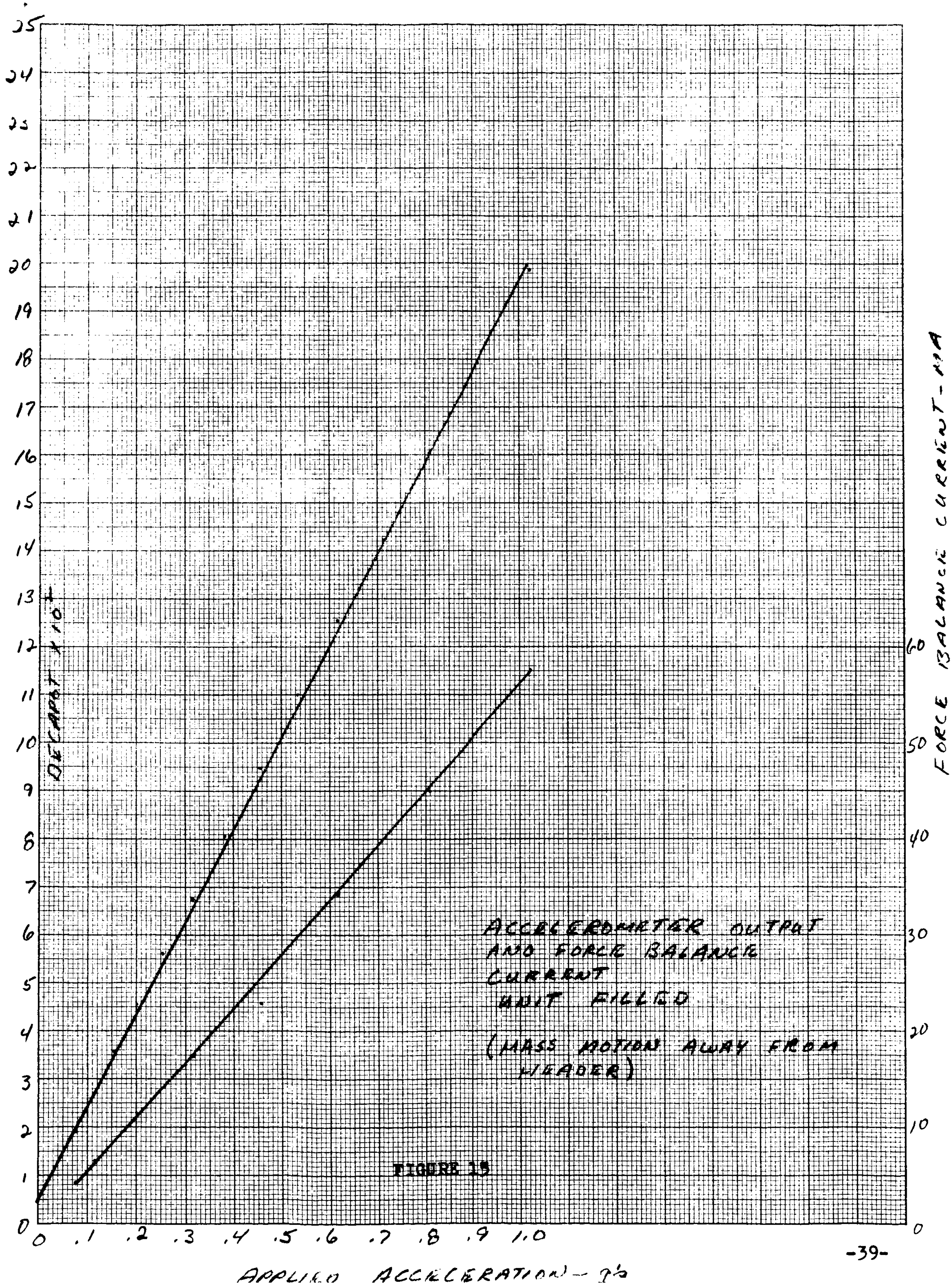

ACCELEROMETER OUTPUT
AND FORCE BALANCE
CURRENT
UNIT FILLED
(MASS MOTION AWAY FROM
HEADER)
FORCE BALANCE CURRENT - MA
APPLIED ACCELERATION - G's
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
0
10
20
30
40
50
60

FIGURE 15

LINEARITY FILLED

x Input g's	y Output V	xy	y^1	$\frac{y-y^1}{4.522 - y^1}$	Error % F.S.
1.022	3.976	4.063	4.622	-.646	-14.3
.912	3.588	3.272	4.124	-.536	-11.8
.810	3.202	2.593	3.662	-.460	-10.2
.711	2.844	2.022	3.215	-.371	-8.2
.618	2.506	1.549	2.794	-.288	-6.4
.534	2.200	1.175	2.414	-.214	-4.7
.455	1.898	.864	2.057	-.159	-3.5
.382	1.616	.617	1.727	-.111	-2.5
.316	1.350	.427	1.429	-.079	-1.7
.2565	1.120	.287	1.160	-.040	-.88
.202	.980	.183	.913	+.067	+1.48
.155	.712	.110	.701	+.011	+.24
.1138	.540	.0615	.515	+.025	+.55
.079	.384	.0303	.357	+.027	+.60
-.079	-.292	.0231	-.357	+.065	+1.44
-.1138	-.446	.0507	-.515	+.069	+1.53
-.155	-.624	.0967	-.701	+.077	+1.70
-.202	-.836	.169	-.913	+.077	+1.70
-.2565	-1.102	.283	-1.160	+.058	+1.28
-.316	-1.346	.425	-1.429	+.083	+1.84
-.382	-1.692	.646	-1.727	+.035	+.77
-.455	-2.036	.926	-2.057	+.021	+.46
-.534	-2.404	1.284	-2.414	+.010	+.22
-.618	-2.798	1.729	-2.794	-.004	-.09
-.711	-3.232	2.298	-3.215	-.017	-.38
-.810	-3.712	3.007	-3.662	-.060	-1.33
-.912	-4.172	3.805	-4.124	-.048	-1.06
-1.022	-4.632	4.734	-4.622	-.010	-.22

$y^1 = 4.522x$

CHART 5

LINEARITY FILLED

x Input g's	y Output V	xy	y^1	$y-y^1$ $4.356 - y^1$	Error % F.S.
1.022	3.976	4.063	4.268	-.292	-6.7
.912	3.588	3.272	3.799	-.211	-4.84
.810	3.202	2.593	3.364	-.164	-3.76
.711	2.844	2.022	2.942	-.098	-2.25
.618	2.506	1.549	2.546	-.040	- .92
.534	2.200	1.175	2.188	+.012	+.27
.455	1.898	.864	1.851	+.047	+1.08
.382	1.616	.617	1.540	+.076	+1.74
.316	1.350	.427	1.259	+.091	+2.09
.2565	1.120	.287	1.005	+.115	+2.64
.202	.908	.183	.773	+.135	+3.10
.155	.712	.110	.572	+.140	+3.21
.1138	.540	.0615	.397	+.143	+3.28
.079	.384	.0303	.248	+.136	+3.12
-.079	-.292	.0231	-.425	+.133	+3.05
-.1138	-.446	.0507	-.574	+.128	+2.94
-.155	-.624	.0967	-.749	+.125	+2.87
-.202	-.836	.169	-.950	+.114	+2.62
-.2565	-1.102	.283	-1.182	+.080	+1.84
-.316	-1.346	.425	-1.436	+.090	+2.07
-.382	-1.692	.646	-1.717	+.025	+.57
-.455	-2.036	.926	-2.028	-.008	-.18
-.534	-2.404	1.284	-2.365	-.039	-.90
-.618	-2.798	1.729	-2.723	-.075	-1.72
-.711	-3.232	2.298	-3.120	-.112	-2.57
-.810	-3.712	3.007	-3.542	-.170	-3.90
-.912	-4.172	3.805	-3.976	-.196	-4.50
-1.022	-4.632	4.734	-4.445	-.187	-4.29
Σx^2 8.615	$\Sigma \frac{y}{n}$ .0886	Σxy 36.7303	$y^1 = -.0886 + 4.263x$		CHART 6

ACCELEROMETER OUTPUT

Mass Motion Towards Header

Input		Output	
°/sec	g's	Potentiometer Setting	Quad. Voltage - MV
120	.1138	223	129
160	.202	395	248
200	.316	603	380
240	.455	858	560
280	.618	1161	760
320	.810	1508	970
360	1.022	1904	1240

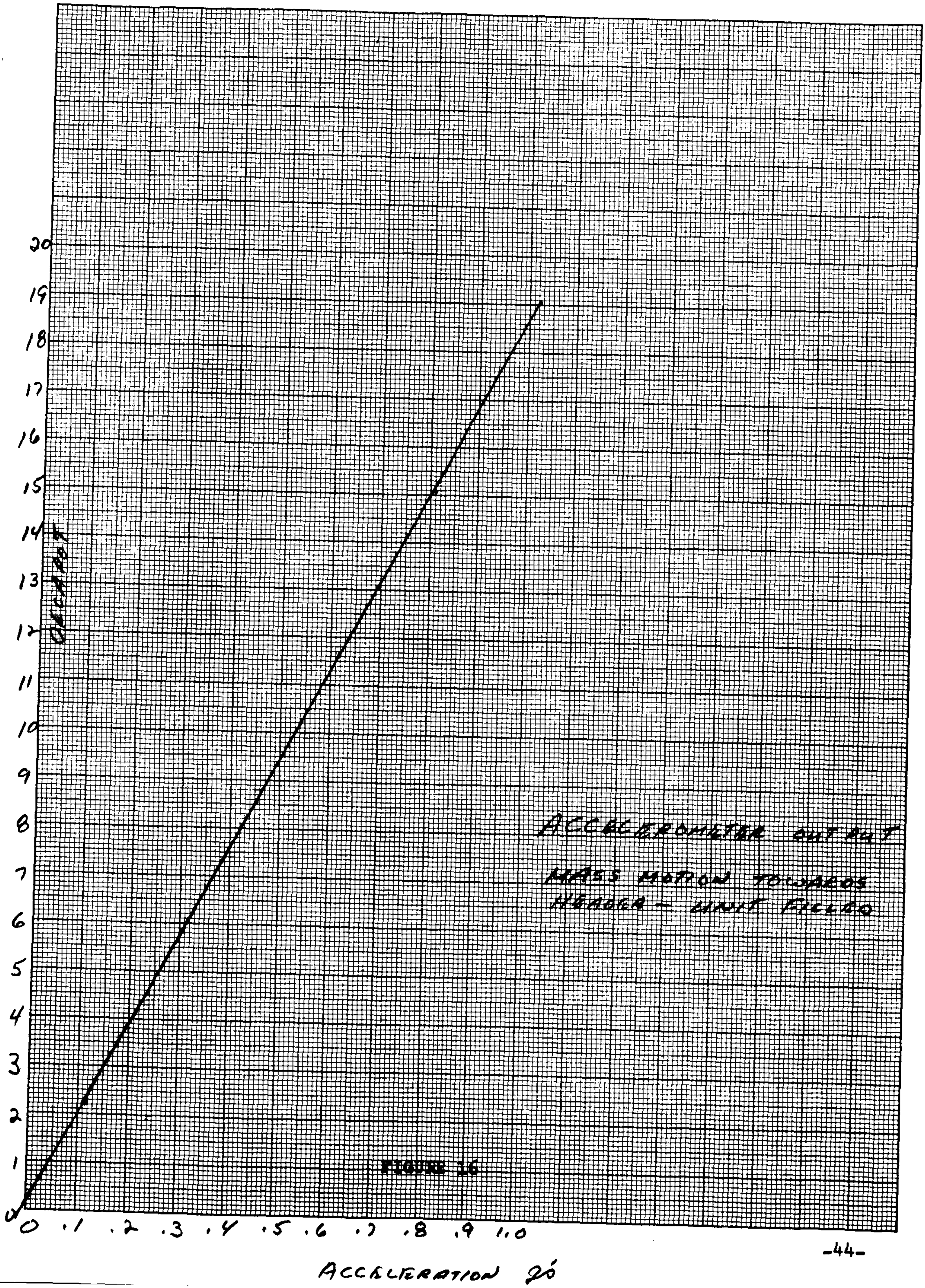
CHART 7

ACCELEROMETER OUTPUT

Mass Motion Away From Header

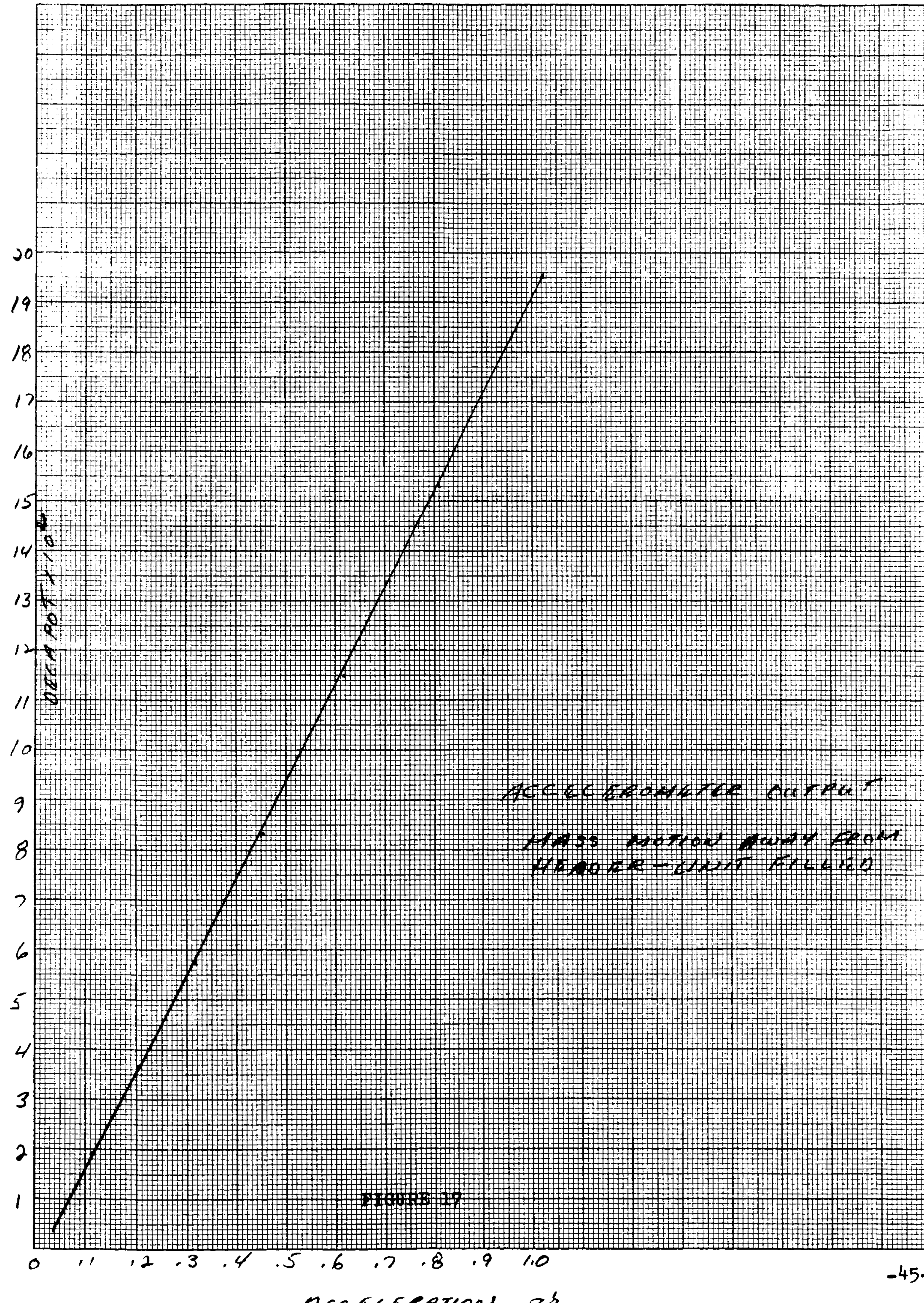
Input		Output	
°/sec	g's	Potentiometer Setting	Quad. Voltage - MV
120	.1138	191	150
160	.202	364	260
200	.316	575	400
240	.455	834	570
280	.618	1149	790
320	.810	1530	1040
360	1.022	1953	1320

CHART 8



20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
ACCELERATION g's
ACCELEROMETER OUTPUT
MASS MOTION TOWARDS HEADER - UNIT FILLED

FIGURE 16



ACCELEROMETER OUTPUT
MASS MOTION AWAY FROM HEADER-UNIT FILLED
DECAPOT × 10²
ACCELERATION g's

FIGURE 17

LINEARITY CALCULATION FILLED

x Input g's	y Output V	xy	y^1	$y-y^1$	Error % F. S.
1.022	3.906	3.992	3.829	+.077	+1.95
.810	3.060	2.479	3.033	+.027	+.68
.618	2.298	1.420	2.312	-.014	-.35
.455	1.668	.759	1.700	-.032	-.81
.316	1.150	.363	1.178	-.028	-.71
.202	.728	.147	.750	-.022	-.56
.1138	.382	.043	.419	-.037	-.94
0	.004				
-.1138	-.446	0.051	-.435	-.011	-.28
-.202	-.790	.160	-.766	-.024	-.61
-.316	-1.206	.381	1.194	-.010	-.25
-.455	-1.716	.781	1.716	-000	0
-.618	-2.322	1.435	2.328	+.008	+.20
-.810	-3.016	2.443	3.041	+.025	+.63
-1.022	-3.808	3.892	3.845	+.037	+.94

$\Sigma y = -.113 \qquad \frac{\Sigma y}{n} = \frac{-.113}{14} = -.008 = a$

$\Sigma xy = 18.346 \qquad \frac{\Sigma xy}{\Sigma x^2} = 3.755 = b$

$\Sigma x^2 = 4.886$

$y^1 = a + bx = -.008 + (3.755)x$

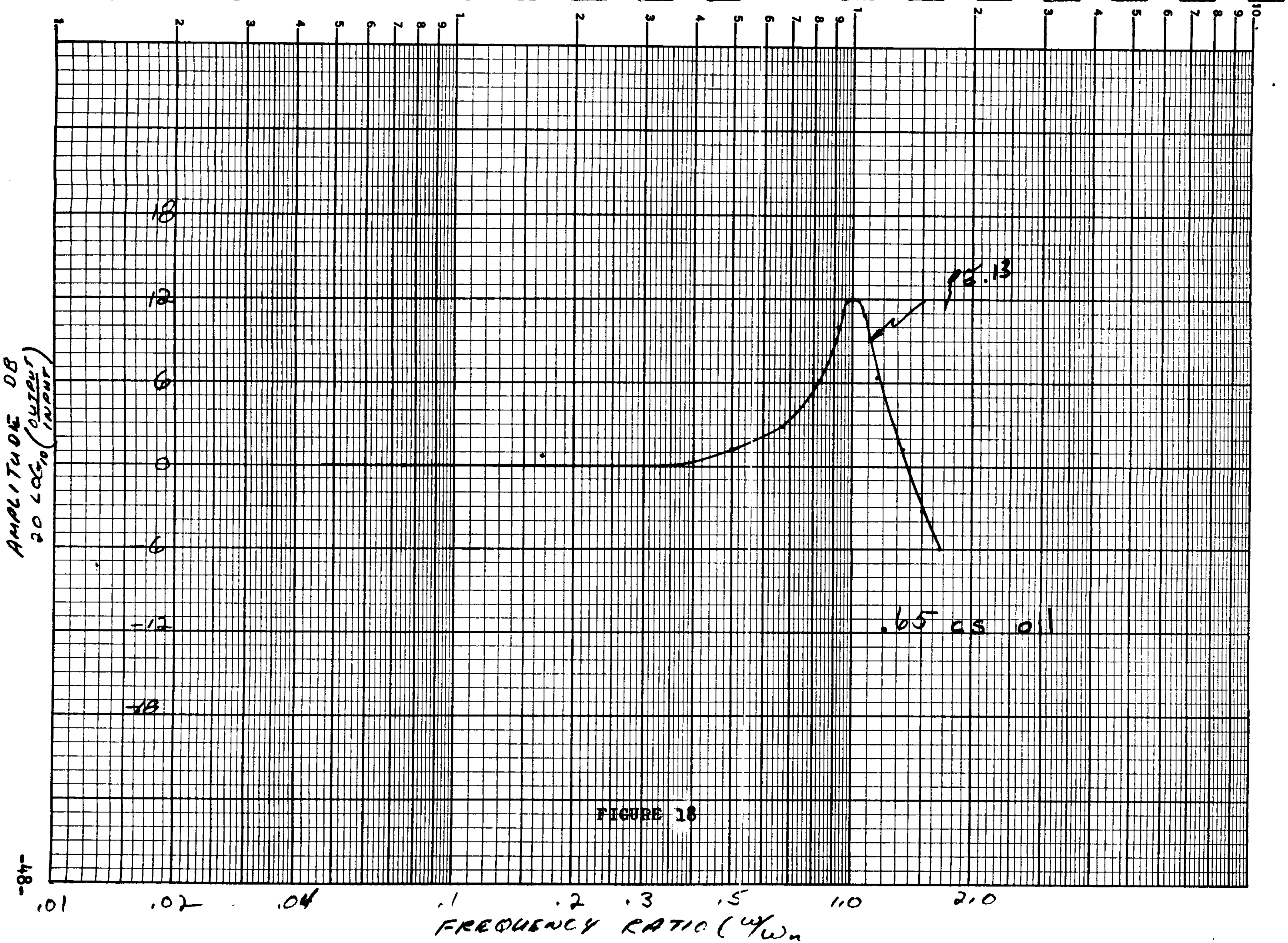
CHART 9

10/26/65

FREQUENCY RESPONSE

FREQ.	FREQ. RATIO $(\frac{\omega}{\omega_n})$	INPUT AMPLITUDE	OUTPUT AMPLITUDE	RATIO $\left(\frac{\text{Output}}{\text{Input}}\right)$	db $20 \log_{10}\left(\frac{\text{Output}}{\text{Input}}\right)$
.45	.075	10	10	1	0
1.0	.166	10	11	1.1	.84
2.0	.333	10	10	1	0
3.0	.50	10	11.5	1.15	1.2
4.0	.666	10	14	1.4	2.92
5.0	.833	10	20	2.0	6.0
5.5	.915	10	32.5	3.25	10.0
6.0	1.00	10	40	4.0	12.0
6.5	1.08	10	35.0	3.5	10.9
7.0	1.166	10	21	2.5	6.44
8.0	1.33	10	11.6	1.15	1.2
9.0	1.5	10	7.0	.7	-3.10
10.0	1.66	10	5.0	.5	-6.0

CHART 10



AMPLITUDE DB
20 LOG10 (OUTPUT / INPUT)
18
12
6
0
-6
-12
-18
.01
.02
.04
.1
.2
.3
.5
1.0
2.0
FREQUENCY RATIO (ω/ωn
.13
.65 cs oil

FIGURE 18

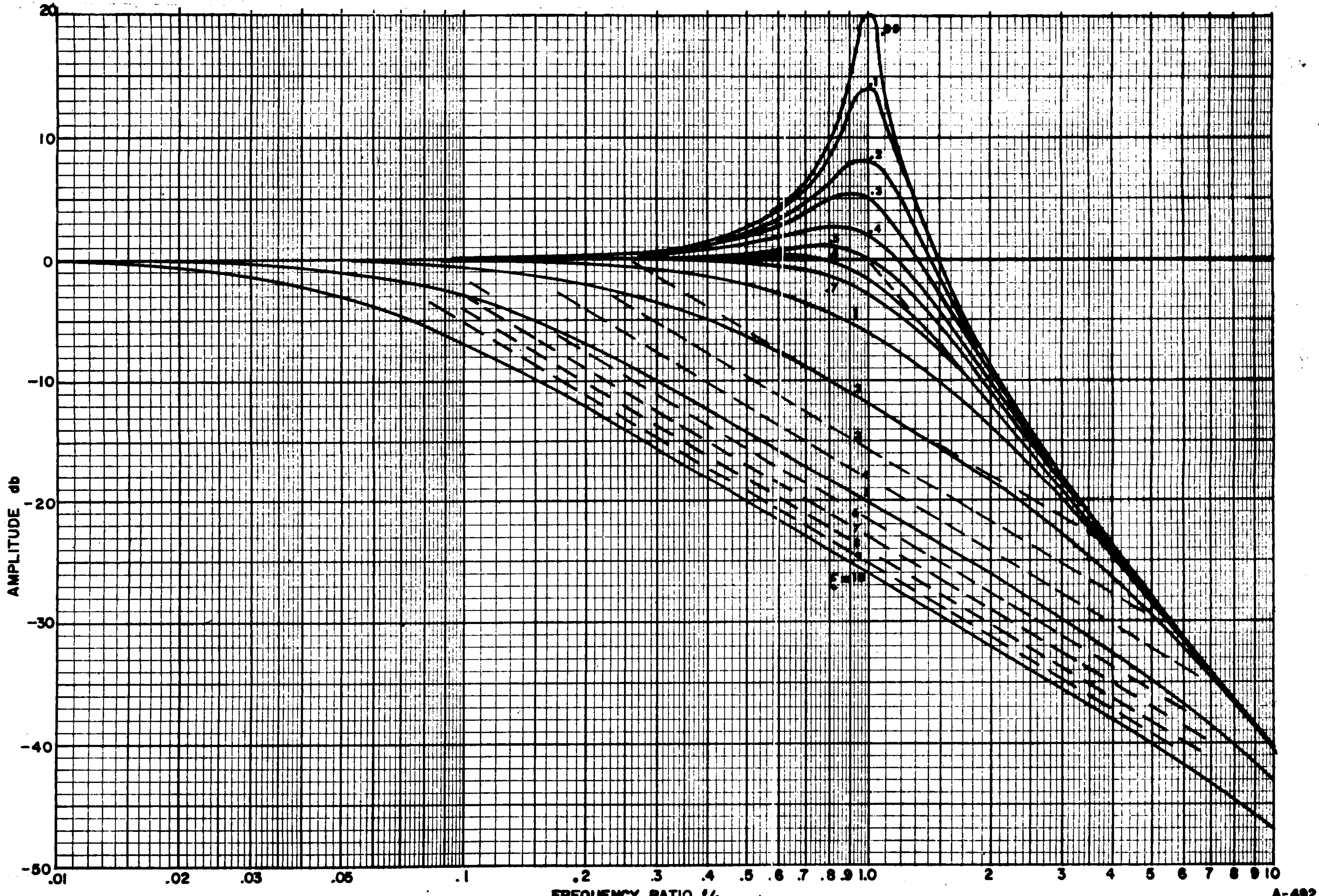


FIGURE 19

FREQUENCY RESPONSE

$f_n = 5$ cps 10 cs silicone oil

FREQ.	FREQ. RATIO $\left(\frac{\omega}{\omega_n}\right)$	Input Amplitude	Output Amplitude	Ratio $\left(\frac{\text{Output}}{\text{Input}}\right)$	db 20 $\log_{10}\left(\frac{\text{Output}}{\text{Input}}\right)$
.5	.1	10	10	1	0
1	.2	10	10	1	0
2	.4	10	11	1.1	.8
3	.6	10	11	1.1	.8
4	.8	10	10.5	1.05	.4
5	1.0	10	9.0	.9	-.920
6	1.2	10	7.0	.7	-3.10
7	1.4	10	5.5	.55	-5.20

CHART 11

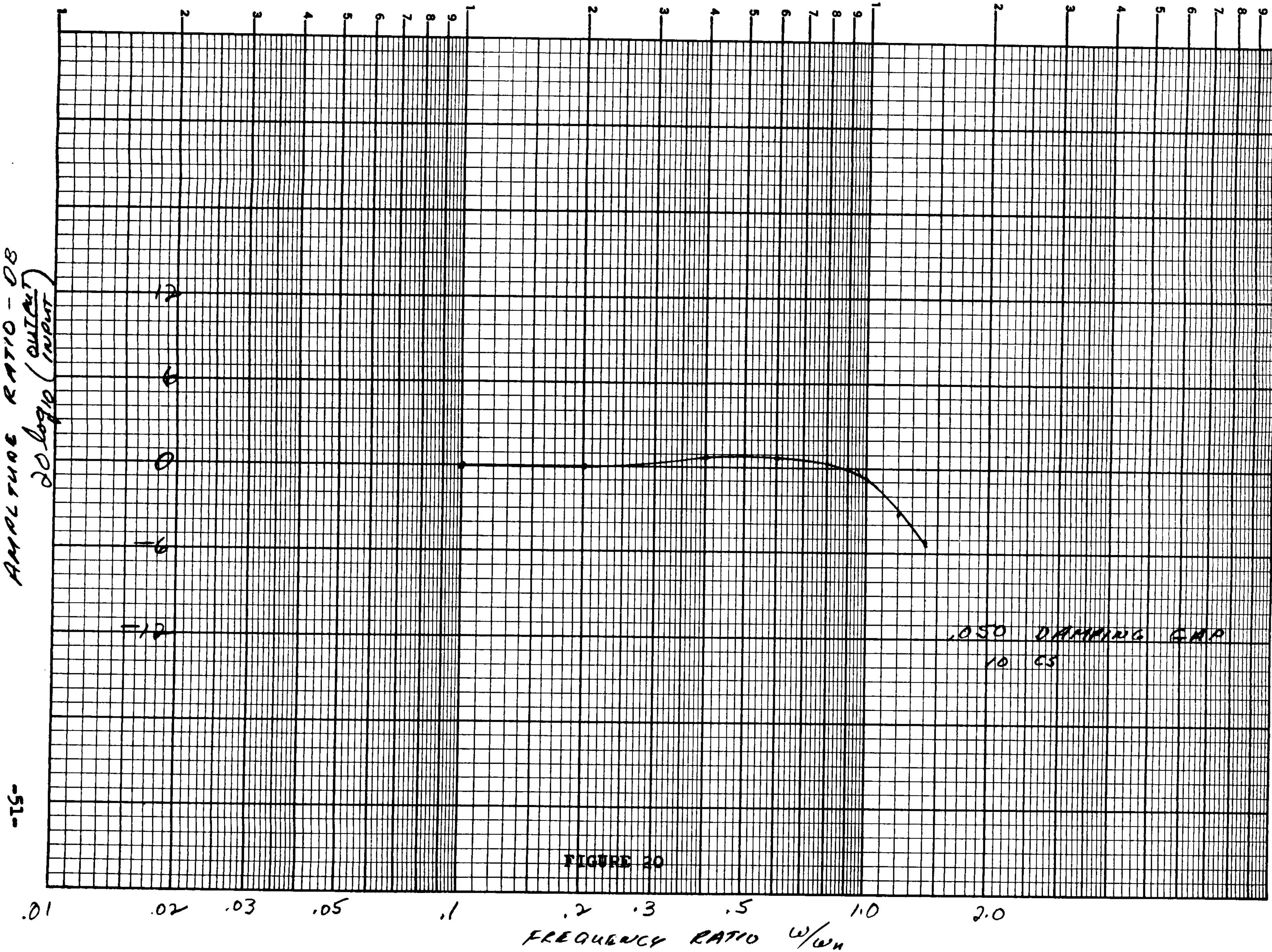

AMPLITUDE RATIO - DB
20 log10 (OUTPUT / INPUT)
12
6
0
-6
-12
.050 DAMPING GAP
10 CS
.01
.02
.03
.05
.1
.2
.3
.5
1.0
2.0
FREQUENCY RATIO ω/ωn

FIGURE 20

VII. CONCLUSIONS AND RECOMMENDATIONS

By examining the evaluation prototype test data, it is evident that a high degree of success in attaining the design goals has been achieved. The modifications required to achieve the design goals are of a nature that improve the instrument integrity. Changes in the evaluation prototype would include:

1. Strengthening of the suspension members to increase the natural frequency.

2. Incorporation of the Sanborn, LVDT, to reduce phase shift and increase the excitation frequency.

3. Tighter control on "S" spring positioning to reduce static accuracy errors.

4. Changing the damping gap and damping fluid viscosity which will provide for better temperature compensation.

All of the above changes can be incorporated into the evaluation prototype.

Information obtained from the above changes will be directly applicable to the future design, which will be smaller in size and lighter in weight. The reduction in size and weight is possible by incorporation of the Sanborn LVDT and a smaller self-test forcer. The next logical step in the program would be the fabrication of units incorporating these improvements and extensive testing and evaluation to establish design integrity.

APPENDIX A

LVDT AND AMPLIFIER EVALUATION

LVDT AND AMPLIFIER EVALUATION

In October, further work was done on the combination of Sanborn 595DT-050 Linear Differential Transformer and Amplifier to reduce the overall change of sensitivity with temperature.

For this purpose, the collector resistor of the output stage of the amplifier was replaced by a combination of resistor and thermistor. Figure 1 shows the results of several trials: (1) Line XX represents the full scale output of the differential transformer alone, multiplied by 5 to bring it into the range of the other curves; (2) Line YY represents the output of the transformer and uncorrected amplifier; (3) Line OO represents the results of the first trial in which the collector load was an 1800 ohm resistor in series with a 300 ohm thermistor; (4) Line AA represents the results of the 2nd trial in which the collector load was an 1800 ohm resistor in series with a 100 ohm thermistor; (5) Line BB represents the results of the 3rd trial in which the collector load was a 2000 ohm resistor in series with the parallel combination of a 100 ohm thermistor and 100 ohm resistor; (6) Line CC represents the results of the 4th trial in which the resistor shunting the thermistor was raised to 300 ohms; and (7) Line DD represents the results of the 5th trial in which the shunt resistor was further increased to 510 ohms. Data for lines XX and YY are taken from the September report, Tables V and VII. Data for the remaining curves are tabulated in Table I.

Curve DD in Figure 1, compared to curve XX, seemed to indicate that satisfactory operation would be obtained from this arrangement of collector load. A complete set of data was taken therefore, which is given in Table II. Compared to Table VII in the September report, considerable improvement is indicated; but at room temperature and at 100°F, there are too many points out of tolerance.

At this time, the technician taking the data, stated that he sometimes was not sure "which null to use" on the oscilloscope. A simple 12 point harmonic analysis was run therefore on the null pattern displayed on the oscilloscope with the results of Table III.

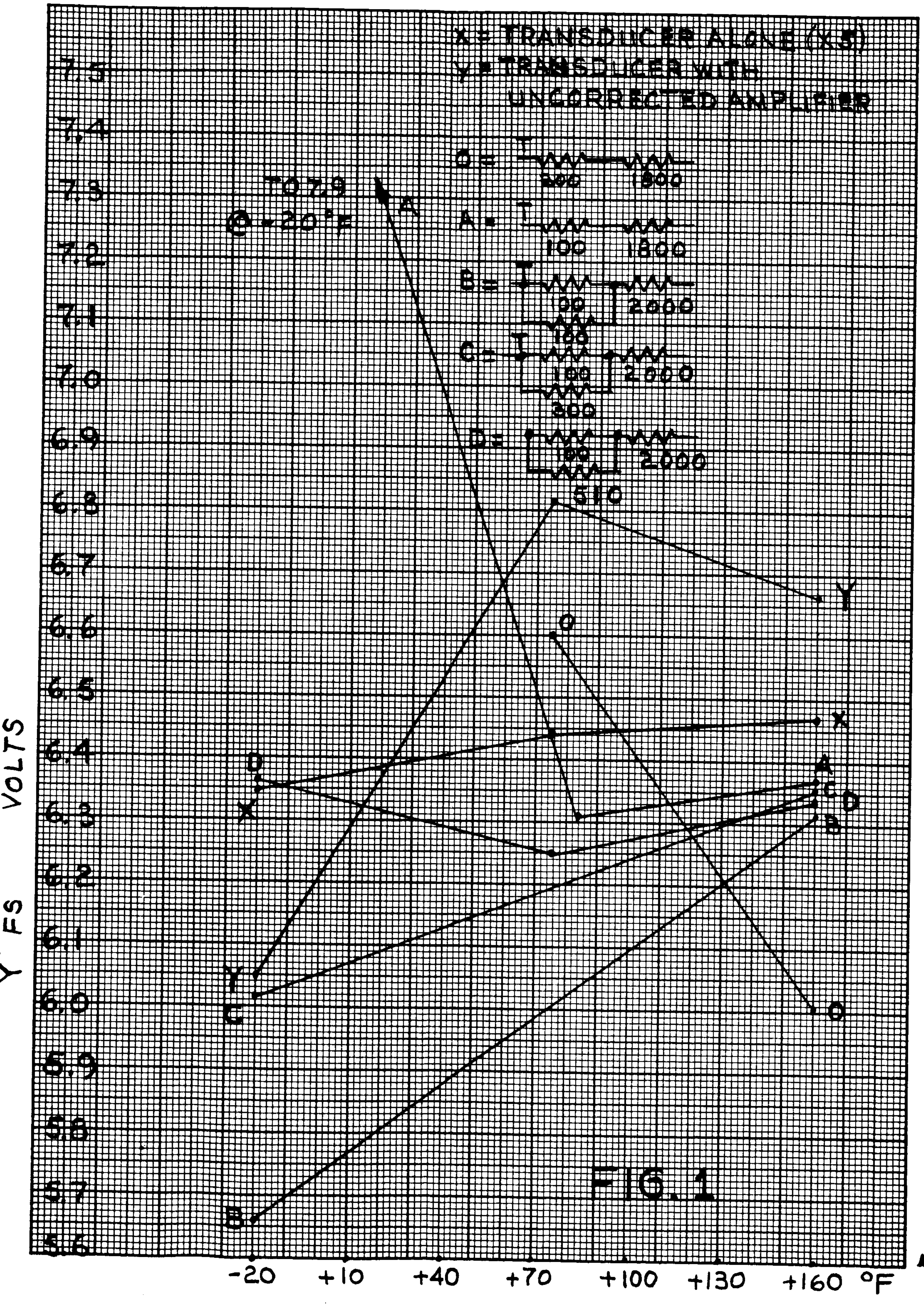

X = TRANSDUCER ALONE (X5)
Y = TRANSDUCER WITH UNCORRECTED AMPLIFIER
O = T 200 1800
A = T 100 1800
B = T 100 2000 180
C = T 100 2000 300
D = 100 2000 510
TO 7.9 @ -20°F
Y' FS VOLTS
7.5
7.4
7.3
7.2
7.1
7.0
6.9
6.8
6.7
6.6
6.5
6.4
6.3
6.2
6.1
6.0
5.9
5.8
5.7
5.6
-20
+10
+40
+70
+100
+130
+160
°F

FIG. 1

A-2

Although the residual fundamental in the null pattern (2 mv) is tolerable (representing about .05% uncertainty in readings), nevertheless, for the remainder of the work on the Sanborn Transformer a Wave Analyzer was used for final null balance settings. The test arrangement was then as given in Figure 2.

To see if our previous data were in error, a rerun of Table II was made using the wave analyzer for null setting. The results are given in Table IV. In view of these results, the collector load was changed to a 2000 ohm resistor in series with the parallel combination of a 100 ohm thermistor and a 390 ohm resistor and the data of Table V were then taken.

The results show no improvement and led to a recapitulation of our temperature-gain data tabulated in Table VI and plotted in Figure 3. From Figure 3, it appears that we overshot the mark and should return to a shunt resistor of 470 ohms, which certainly would have a gain spread no greater than that of the transformer alone.

TABLE I

Curve 00

DISP. X IN.	Y DEKAPOT READING 75°F	160°F	XY IN. VOLTS 75°F	160°F
.05	3327	2959	.33270	.29590
.04	2664	2348	.21312	.18784
.03	2007	1738	.12042	.10428
.02	1345	1128	.05380	.04512
.01	681	524	.01362	.01048
.00	15	-70	--	--
-.01	-641	-674	.01282	.01348
-.02	-1294	-1271	.05176	.05084
-.03	-1953	-1886	.11718	.11316
-.04	-2610	-2509	.20880	.20072
-.05	-3282	-3123	.32820	.31230
Σxy			1.45242	1.33412
y^1_{FS}			6.602	6.064 ($= \frac{5 \ \Sigma xy}{.011}$) volts

TABLE I (Cont'd)

Curve AA

DISP X IN.	Y DEKAPOT READING -20°F	84°F	160°F	XY INCH - VOLTS -20°F	84°F	160°F
.05	3713	3177	3111	.37130	.31770	.31110
.04	3269	2547	2476	.26152	.20376	.19808
.03	2779	1909	1838	.16674	.11454	.11028
.02	1929	1278	1200	.07716	.05112	.04800
.01	1064	641	560	.02128	.01282	.01120
.00	156	12	-74	---	---	----
-.01	-724	-614	-708	.01448	.01228	.01416
-.02	-1591	-1242	-1336	.06364	.04968	.05344
-.03	-2450	-1873	-1977	.14700	.11238	.11862
-.04	-3160	-2515	-2628	.25280	.20120	.21024
-.05	-3638	-3142	-3262	.36380	.31420	.32620
	Σ xy			1.73972	1.38968	1.40132
	y^1_{FS}			7.908	6.317	6.370

TABLE I (Cont'd)

Curve BB

DISP X IN.	Y DECAPOT READING -20°F	Y DECAPOT READING 160°F	XY INCH - VOLTS -20°F	XY INCH - VOLTS 160°F
.05	2954	3109	.29540	.31090
.04	2369	2467	.18952	.19736
.03	1812	1824	.10872	.10944
.02	1239	1192	.04956	.04768
.01	672	562	.01344	.01124
.00	106	-63	--	--
-.01	-453	-679	.00906	.01358
-.02	-1006	-1304	.04024	.05216
-.03	-1574	-1941	.09444	.11646
-.04	-2153	-2586	.17224	.20688
-.05	-2730	-3231	.27300	.32310
	Σxy		1.24562	1.38880
	y^{1}_{FS}		5.662	6.313

TABLE I (Cont'd)

Curve CC

DISP X IN.	Y DEKAPOT READING -20°F	Y DEKAPOT READING 160°F	XY INCH - VOLTS -20°F	XY INCH - VOLTS 160°F
.05	3132	3124	.31320	.31240
.04	2514	2476	.20112	.19808
.03	1910	1827	.11460	.10962
.02	1210	1245	.04840	.04980
.01	705	565	.01410	.01130
.00	109	-53	---	---
-.01	-490	-676	.00980	.01352
-.02	-1088	-1322	.04352	.05288
-.03	-1694	-1957	.10164	.11742
-.04	-2312	-2614	.18496	.20912
-.05	-2929	-3249	.29290	.32490
	Σ xy		1.32424	1.39904
	y^1_{FS}		6.019	6.359

TABLE I (Cont'd)

Curve DD

DISP. X IN.	X CORRECTED VOLTS -20°F	85°F	160°F	XY INCH - VOLTS -20°F	85°F	160°F
.05	6.276	6.274	6.362	.31380	.31370	.31810
.04	5.116	5.004	5.074	.20464	.20016	.20296
.03	3.836	3.738	3.794	.11508	.11214	.11382
.02	2.500	2.496	2.520	.05000	.04992	.05040
.01	1.272	1.246	1.260	.01272	.01246	.01260
.00	.000	.000	.000	--	--	--
-.01	-1.288	-1.232	-1.254	.01288	.01232	.01254
-.02	-2.546	-2.460	-2.506	.05092	.04920	.05012
-.03	-3.838	-3.714	-3.774	.11514	.11142	.11322
-.04	-5.126	-4.988	-5.064	.20504	.19952	.20256
-.05	-6.384	-6.262	-6.344	.31920	.31310	.31720
Σxy				1.39942	1.37394	1.39352
y^1_{FS}				6.361	6.245	6.334

TABLE II

Sanborn 595DT-050 with amplifier collector load of 100 Ω thermistor// with 570 Ω R in series with 2 KR.

DISP. X IN.	Excitation = 10 V, 7KHz ← y, volts → -20°F	10°F	40°F	85°F	100°F	130°F	160°F
.05	6.508	6.528	6.436	6.298	6.248	6.230	6.218
.04	5.348	5.294	5.170	5.028	4.980	4.962	4.930
.03	4.068	3.998	3.898	3.762	3.714	3.694	3.650
.02	2.732	2.714	2.624	2.520	2.468	2.426	2.376
.01	1.504	1.440	1.364	1.270	1.222	1.186	1.116
.00	.232	.158	.098	.024	-.008	-.084	-.144
-.01	-1.056	-1.112	-1.154	-1.208	-1.230	-1.316	-1.398
-.02	-2.314	-2.368	-2.390	-2.436	-2.462	-2.564	-2.650
-.03	-3.606	-3.644	-3.662	-3.690	-3.710	-3.824	-3.918
-.04	-4.894	-4.936	-4.946	-4.964	-4.978	-5.120	-5.208
-.05	-6.152	-6.200	-6.230	-6.238	-6.250	-6.392	-6.488

TABLE II (Cont'd)

DISP. X IN.	y, corrected for null, volts -20°F	10°F	40°F	85°F	100°F	130°F	160°F
.05	6.276	6.370	6.338	6.274	6.256	6.314	6.362
.04	5.116	5.136	5.072	5.004	4.988	5.046	5.074
.03	3.836	3.840	3.800	3.738	3.722	3.778	3.794
.02	2.500	2.556	2.526	2.496	2.476	2.510	2.520
.01	1.272	1.282	1.266	1.246	1.230	1.270	1.260
.00	.000	.000	.000	.000	.000	.000	.000
-.01	-1.288	-1.270	-1.252	-1.232	-1.222	-1.232	-1.254
-.02	-2.546	-2.526	-2.488	-2.460	-2.454	-2.480	-2.506
-.03	-3.838	-3.802	-3.760	-3.714	-3.702	-3.740	-3.774
-.04	-5.126	-5.094	-5.044	-4.988	-4.970	-5.036	-5.064
-.05	-6.384	-6.358	-6.328	-6.262	-6.242	-6.308	-6.344

TABLE II (Cont'd)

DISP. X IN.	xy in volts -20°F	10°F	40°F	85°F	100°F	130°F	160°F
.05	.31380	.31850	.31690	.31370	.31280	.31570	.31810
.04	.20464	.20544	.20288	.20016	.19952	.20184	.20296
.03	.11508	.11520	.11400	.11214	.11166	.11334	.11382
.02	.05000	.05112	.05052	.04992	.04952	.05020	.05040
.01	.01272	.01282	.01266	.01246	.01230	.01270	.01260
.00							
-.01	.01288	.01270	.01252	.01232	.01222	.01232	.01254
-.02	.05092	.05052	.04976	.04920	.04908	.04960	.05012
-.03	.11514	.11406	.11280	.11142	.11106	.11220	.11322
-.04	.20504	.20376	.20176	.19952	.19880	.20144	.20256
-.05	.31920	.31790	.31640	.31310	.31210	.31540	.31720

$\Sigma y = .456$ $\Sigma xy = 9.71290$

$y^1 = .007 + 126.14$ $y^1_{FS} = 6.307$

TABLE II (Cont'd)

DISP. X IN.	y^1 volts	$y-y^1$, volts -20°F	10°F	40°F	85°F	100°F	130°F	160°F
.05	6.307	-.031	.063	.031	-.033	-.051	.007	.055
.04	5.053	.063	.083	.019	-.049	-.065	-.007	.021
.03	3.791	.045	.049	.009	-.053	-.069	-.013	.003
.02	2.530	-.030	.026	-.004	-.034	-.054	-.020	-.010
.01	1.268	.004	.014	-.002	-.022	-.038	+.002	-.008
-.00								
-.01	-1.254	-.034	-.016	.002	.022	.032	.022	.000
-.02	-2.516	-.030	-.010	.028	.056	.062	.036	.010
-.03	-3.777	-.061	-.025	.017	.063	.075	.037	.003
-.04	-5.039	-.087	-.055	-.005	.051	.069	.003	-.025
-.05	-6.300	-.084	-.058	-.028	.038	.058	-.008	-.044

TABLE II (Cont'd)

DISP. X IN.	Error, $\%y^1_{FS}$ -20°F	10°F	40°F	85°F	100°F	130°F	160°F
.05	-.49	1.00	.49	-.52	-.81	.11	.87
.04	1.00	1.32	.30	-.78	-1.03	-.11	.33
.03	.71	.78	.14	-.84	-1.09	-.21	.05
.02	-.48	.41	-.06	-.54	-.86	-.32	-.16
.01	.06	.22	-.03	-.35	-.60	.03	-.13
.00							
-.01	-.54	-.25	.03	.35	.51	.35	.00
-.02	-.48	-.16	.44	.89	.98	.57	.16
-.03	-.97	-.40	.27	1.00	1.19	.59	.05
-.04	-1.38	-.87	-.08	.81	1.09	.05	-.40
-.05	-1.33	-.92	-.44	.60	.92	-.13	-.70

Solid: ±1/2%

Dash: ±1%

Dot Dash: ±1-1/2%

Open: ±2-1/2%

TABLE III

12 Point Harmonic Analysis of Null Pattern

Y_0	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8	Y_9	Y_{10}	Y_{11}	
.8	-.4	-.6	.2	.7	0	-.8	0	.6	.1	0	.2	cm

Y_0	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6		.8	-.4	-.6	.2	.7	0	-.8
	Y_{11}	Y_{10}	Y_9	Y_8	Y_7				.2	0	.1	.6	0	
S_0	S_1	S_2	S_3	S_4	S_5	S_6		.8	-.2	-.6	.3	1.3	0	-.8
	d_1	d_2	d_3	d_4	d_5				-.6	-.6	.1	.1	0	

S_0	S_1	S_2	S_3		.8	-.2	-.6	.3
S_6	S_5	S_4			-.8	0	1.3	
$\bar{S}_0$	$\bar{S}_1$	$\bar{S}_2$	$\bar{S}_3$		0	-.2	.7	.3
D_0	D_1	D_2			1.6	-.2	-1.9	

$\bar{S}_0$	$\bar{S}_1$		0	-.2
$\bar{S}_2$	$\bar{S}_3$		.7	.3
$\bar{S}_7$	$\bar{S}_8$		.7	.1

d_1	d_2	d_3		-.6	-.6	.1
d_5	d_4			0	.1	
$\bar{S}_4$	$\bar{S}_5$	$\bar{S}_6$		-.6	-.5	.1
D_3	D_4			-.6	-.7	

TABLE III (Cont'd)

$\overline{S}_4$	D_0	-.6	1.6
$\overline{S}_6$	D_2	.1	-1.9
D_5	D_6	-.7	3.5

$$B_1 = \frac{D_0 + .866\,D_1 + .5\,D_2}{6} = \frac{1.6 + (.866)(-.2) + (0.5)(-1.9)}{6}$$

$$= \frac{1.6 - .1732 - .95}{6} = \frac{1.6 - 1.12}{6} = \frac{.48}{6} = .08$$

$$A_1 = \frac{.5\overline{S}_4 + .866\overline{S}_5 + \overline{S}_6}{6} = \frac{(.5)(-.6) + (.866)(-.5) + .1}{6}$$

$$= \frac{-.3 - .433 + .1}{6} = \frac{-.733 + .1}{6} = \frac{-.633}{6} = -.106$$

$$A_2 = \frac{.866\,(D_3 + D_4)}{6} = \frac{(.866)(-.6 - .7)}{6} = \frac{(.866)(-1.3)}{6}$$

$$= \frac{-1.1258}{6} = -.1876$$

$$B_2 = \frac{\overline{S}_0 + .5\overline{S}_1 - .5\overline{S}_2 - \overline{S}_3}{6} = \frac{0 + (.5)(-.2) - (.5)(.7) - .3}{6}$$

$$= \frac{-.1 - .35 - .3}{6} = \frac{-.75}{6} = -.125$$

TABLE III (Cont'd)

$$B_3 = \frac{D_6}{6} = \frac{3.5}{6} = .6$$

$$A_3 = \frac{D_5}{6} = \frac{-.7}{6} = -.12$$

$$C_1 = \sqrt{A_1^{\,2} + B_1^{\,2}} = .133$$

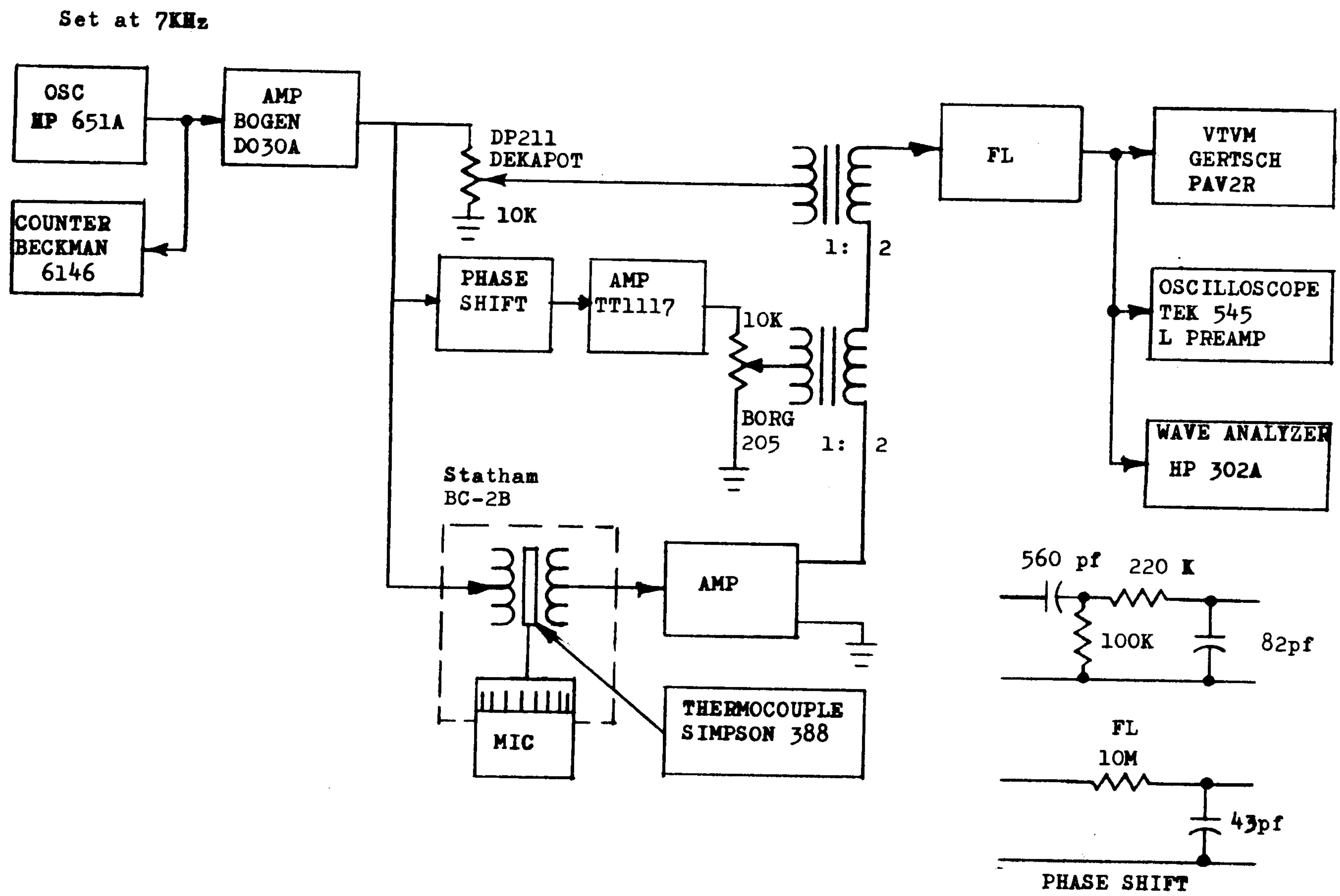
$$C_2 = \sqrt{A_2^{\,2} + B_2^{\,2}} = .225$$

$$C_3 = \sqrt{A_3^{\,2} + B_3^{\,2}} = .61$$

Oscilloscope Calibration: 1.3 cm = 20 mv

$\therefore C_1 = 2$ mv

$C_3 = 10$ mv



LVDT TEST

FIGURE 2

TABLE IV

Sanborn 595DT-050 with amplifier collector load of 100 Ω thermistor// 510 Ω R in series with 2KR.

Excitation 10 V, 7 KHz. Nulled with H.P. 302A Wave Analyzer.

DISP. X IN.	y, volts						
	-20°F	10°F	40°F	82°F	100°F	130°F	160°F
.05	6.482	6.422	6.338	6.236	6.204	6.138	6.128
.04	5.312	5.240	5.130	4.984	4.956	4.914	4.886
.03	4.030	3.964	3.854	3.730	3.692	3.646	3.606
.02	2.748	2.688	2.588	2.478	2.452	2.350	2.340
.01	1.474	1.418	1.334	1.236	1.218	1.144	1.098
.00	.224	.158	.104	.016	.000	-.056	-.136
-.01	-1.026	-1.080	-1.120	-1.200	-1.220	-1.292	-1.376
-.02	-2.288	-2.334	-2.358	-2.428	-2.456	-2.540	-2.614
-.03	-3.572	-3.614	-3.626	-3.692	-3.714	-3.800	-3.888
-.04	-4.862	-4.918	-4.892	-4.968	-4.984	-5.064	-5.176
-.05	-6.132	-6.166	-6.134	-6.218	-6.250	-6.324	-6.434

TABLE IV (Cont'd)

DISP. X IN.	y, corrected for null shift, volts						
	-20°F	10°F	40°F	82°F	100°F	130°F	160°F
.05	6.258	6.264	6.234	6.220	6.204	6.194	6.264
.04	5.088	5.082	5.026	4.968	4.956	4.970	5.022
.03	3.806	3.806	3.750	3.714	3.692	3.702	3.742
.02	2.524	2.530	2.484	2.462	2.452	2.406	2.476
.01	1.250	1.260	1.230	1.220	1.218	1.200	1.234
.00	.000	.000	.000	.000	.000	.000	.000
-.01	-1.250	-1.238	-1.224	-1.216	-1.220	-1.236	-1.240
-.02	-2.512	-2.492	-2.462	-2.444	-2.456	-2.484	-2.478
-.03	-3.796	-3.772	-3.730	-3.708	-3.714	-3.744	-3.752
-.04	-5.086	-5.076	-4.996	-4.984	-4.984	-5.008	-5.040
-.05	-6.356	-6.324	-6.238	-6.234	-6.250	-6.268	-6.298

$\Sigma y = -.402$

TABLE IV (Cont'd)

DISP. X IN.	xy -20°F	10°F	40°F	82°F	100°F	130°F	160°F
.05	.31490	.31320	.31170	.31100	.31020	.30970	.31320
.04	.20352	.20328	.20104	.19872	.19824	.19880	.20088
.03	.11418	.11418	.11250	.11142	.11076	.11106	.11226
.02	.05048	.05060	.04968	.04924	.04904	.04812	.04952
.01	.01250	.01260	.01230	.01220	.01218	.01200	.01234
.00							
-.01	.01250	.01238	.01224	.01216	.01220	.01236	.01240
-.02	.05024	.04984	.04924	.04888	.04912	.04968	.04956
-.03	.11388	.11316	.11190	.11124	.11142	.11232	.11256
-.04	.20344	.20304	.19984	.19936	.19936	.20032	.20160
-.05	.31780	.31610	.31160	.31170	.31250	.31340	.31490

$\Sigma xy = 9.63178$

$y^1 = -.006 + 125.09X$ $\quad$ $y^1_{FS} = 6.255$

TABLE IV (Cont'd)

DISP. X IN.	y^1 V	Error, $y-y^1$, mv -20°F	10°F	40°F	82°F	100°F	130°F	160°F
.05	6.249	9	15	-15	-29	-45	-55	15
.04	4.998	90	84	28	-30	-58	-28	24
.03	3.747	59	59	3	-33	-56	-45	-5
.02	2.496	28	34	-12	-34	-44	-90	-20
.01	1.245	5	15	-15	-25	-27	-45	-11
.00								
-.01	-1.257	7	19	33	41	37	21	17
-.02	-2.508	-4	16	46	64	52	24	+30
-.03	-3.759	-37	-13	29	51	45	15	+7
-.04	-5.010	-76	-66	14	26	26	2	-30
-.05	-6.261	-95	-63	23	27	11	-7	-37

TABLE IV (Cont'd)

DISP. X IN.	Error, % y^{1}_{FS} -20°F	10°F	40°F	82°F	100°F	130°F	160°F
.05	.14	.24	-.24	-.46	-.72	-.88	.24
.04	1.44	1.34	.45	-.48	-.93	-.45	.38
.03	.94	.94	.05	-.53	-.89	-.72	-.08
.02	.45	.54	-.19	-.54	-.70	-1.44	-.32
.01	.08	.24	-.24	-.40	-.43	-.72	-.18
.00							
-.01	.11	.30	.53	.66	.59	.34	.27
-.02	-.06	.26	.74	1.02	.83	.38	.48
-.03	-.59	-.21	.46	.82	.72	.24	.11
-.04	-1.22	-1.06	.22	.42	.42	.03	-.48
-.05	-1.52	-1.01	.37	.43	.18	-.11	-.59

Solid: ±1/2%

Dash: ±1%

Dot dash: ±1-1/2%

Open: ±2-1/2%

TABLE V

Sanborn 595DT-050 with amplifier collector load of 100 Ω Thermistor //390 Ω R in series with 2KR.

Excitation 10V, 7 KHz

DISP. X IN.	y volts -20°F	10°F	40°F	75°F	100°F	130°F	160°F
.05	6.374	6.380	6.292	6.214	6.158	6.142	6.138
.04	5.168	5.152	5.054	4.964	4.912	4.892	4.878
.03	3.906	3.890	3.794	3.710	3.666	3.628	3.608
.02	2.686	2.636	2.568	2.432	2.434	2.372	2.348
.01	1.440	1.400	1.300	1.250	1.200	1.148	1.098
.00	.224	.168	+.100	.036	.000	-.068	-.108
-.01	-.950	-1.050	-1.096	-1.154	-1.200	-1.278	-1.372
-.02	-2.196	-2.276	-2.310	-2.400	-2.424	-2.530	-2.616
-.03	-3.440	-3.528	-3.562	-3.640	-3.600	-3.776	-3.882
-.04	-4.676	-4.770	-4.820	-4.874	-4.900	-5.040	-5.176
-.05	-5.920	-6.040	-6.074	-6.096	-6.190	-6.288	-6.402

TABLE V (Cont'd)

DISP. X IN.	y, corrected for null volts -20°F	10°F	40°F	75°F	100°F	130°F	160°F
.05	6.150	6.212	6.192	6.178	6.158	6.210	6.246
.04	4.944	4.984	4.954	4.928	4.912	4.960	4.986
.03	3.682	3.722	3.694	3.674	3.666	3.696	3.716
.02	2.462	2.468	2.468	2.396	2.434	2.440	2.456
.01	1.216	1.232	1.200	1.214	1.200	1.216	1.206
.00	.000	.000	.000	.000	.000	.000	.000
-.01	-1.174	-1.218	-1.196	-1.190	-1.200	-1.210	-1.264
-.02	-2.420	-2.444	-2.410	-2.436	-2.424	-2.462	-2.508
-.03	-3.664	-3.696	-3.662	-3.676	-3.600	-3.708	-3.774
-.04	-4.900	-4.938	-4.920	-4.910	-4.900	-4.972	-5.068
-.05	-6.144	-6.208	-6.174	-6.132	-6.190	-6.220	-6.294

$\Sigma y = .166$

TABLE V (Cont'd)

DISP. X IN.	xy, volt - in. .20°F	10°F	40°F	75°F	100°F	130°F	160°F
.05	.30750	.31060	.30960	.30890	.30790	.31050	.31230
.04	.19776	.19936	.19816	.19712	.19648	.19840	.19944
.03	.11046	.11166	.11082	.11022	.10998	.11088	.11148
.02	.04924	.04936	.04936	.04792	.04868	.04880	.04912
.01	.01216	.01232	.01200	.01214	.01200	.01216	.01206
.00	--	--	--	--	--	--	--
-.01	.01174	.01218	.01196	.01190	.01200	.01210	.01264
-.02	.04840	.04888	.04820	.04872	.04848	.04924	.05016
-.03	.10992	.11088	.10986	.11028	.10800	.11124	.11322
-.04	.19600	.19752	.19680	.19640	.19600	.19888	.20272
-.05	.30720	.31040	.30870	.30660	.30950	.31100	.31470

$\Sigma xy = 500$

$y^1 = .002 + 123.50X$ $\qquad$ $y^1_{FS} = 6.175$

TABLE V (Cont'd)

DISP. X IN.	y^1 V	Error, $y - y^1$, mv -20°F	10°F	40°F	75°F	100°F	130°F	160°F
.05	6.177	-27	35	15	1	-19	33	69
.04	4.942	2	42	+12	-14	-30	18	44
.03	3.707	-25	15	-13	-33	-41	-11	9
.02	2.472	-10	-4	-4	-76	-38	-32	-16
.01	1.237	-21	-5	-37	-23	-37	-21	-31
.00	.000	--	--	--	--	---	--	--
-.01	-1.233	59	15	37	43	33	23	-31
-.02	-2.468	48	24	58	32	44	6	-40
-.03	-3.703	39	7	41	27	103	-5	-71
-.04	-4.938	38	0	18	28	38	-34	-130
-.05	-6.173	29	-35	-1	41	-17	-47	-121

TABLE V (Cont'd)

DISP. X IN.	-20°F	10°F	40°F	75°F	100°F	130°F	160°F
	Error % y^1_{FS}						
.05	-.44	.57	.24	.02	-.31	.54	1.12
.04	.03	.68	.19	-.23	-.49	.29	.71
.03	-.40	.24	-.21	-.53	-.67	-.18	.15
.02	-.16	-.06	-.06	-1.23	-.62	-.52	-.26
.01	-.34	-.08	-.60	-.37	-.60	-.34	-.50
.00	---	--	--	--	---	--	--
-.01	.96	.24	.60	.70	.54	.37	-.50
-.02	.78	.39	.94	.52	.71	.10	-.65
-.03	.63	.11	.67	.44	1.67	-.08	-1.15
-.04	.62	0	.29	.45	.62	-.55	-2.11
-.05	.47	-.57	-.02	.67	-.28	-.76	-1.96

Solid: ±1/2%

Dash: ±1%

Dot dash: ± 1-1/2%

Open: ±2-1/2%

TABLE VI

	-20°F	10°F	40°F	RT	100°F	130°F	160°F
X5 =	6.350	6.365	6.390	6.440	6.450	6.450	6.465
LVDT alone	1.270	1.273	1.278	1.288	1.290	1.290	1.293
LVDT + AMP (1)	6.044	6.401	6.617	6.812	6.752	6.756	6.663
LVDT + AMP (2)	6.361	6.373	6.319	6.245	6.223	6.294	6.334
LVDT + AMP (3)	6.334	6.311	6.237	6.209	6.205	6.217	6.269
LVDT + AMP (4)	6.138	6.196	6.161	6.137	6.132	6.196	6.263

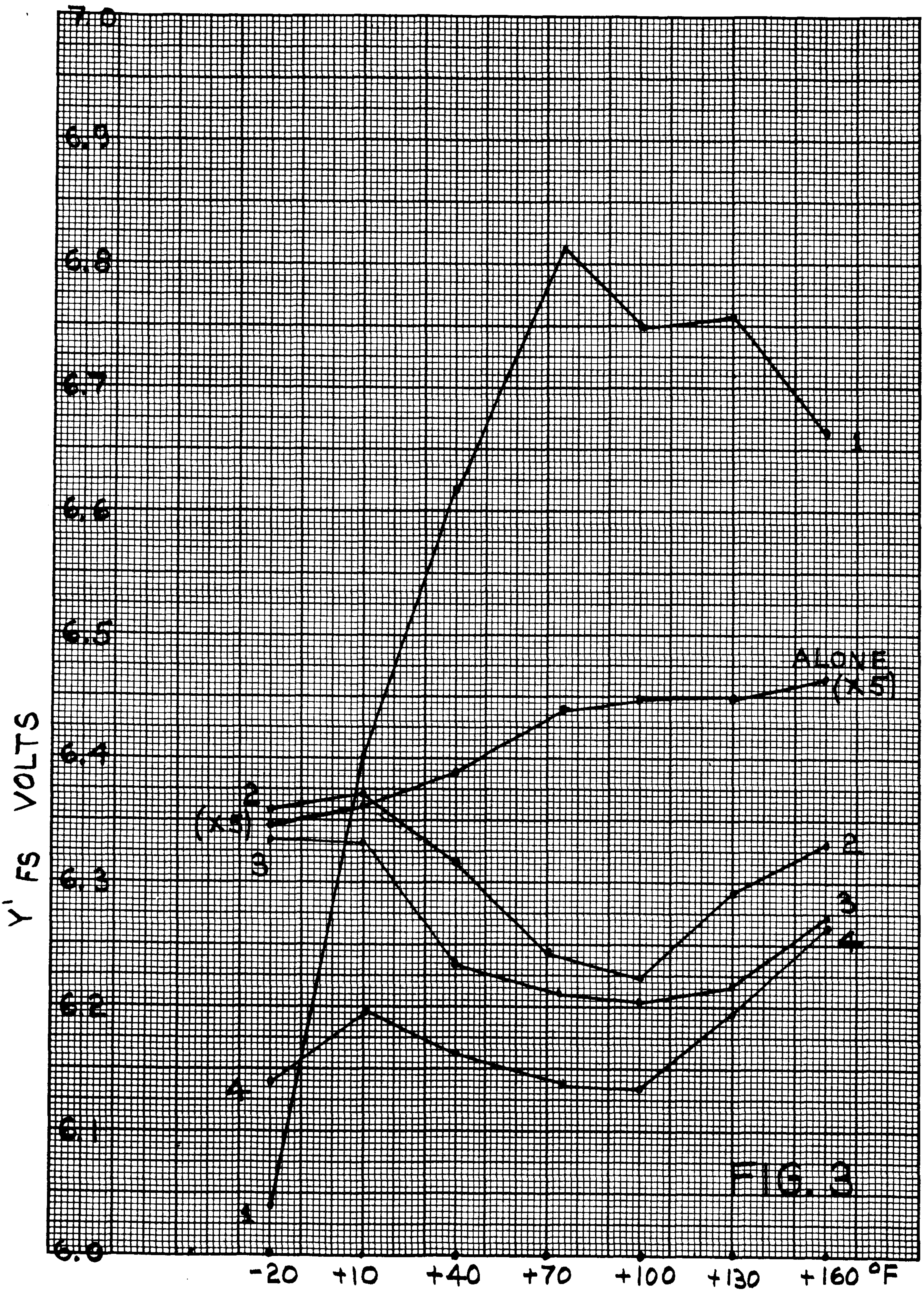
(4) 100 Ω th//390 Ω R + 2K (Wave Meter)

(3) Same as (2) but nulled with wave meter

(2) 100 Ω th//510 Ω R + 2K

(1) Unmodified amp. (Sept. Table VII)

LVDT alone (Sept. Table V)



Y' FS VOLTS
7.0
6.9
6.8
6.7
6.6
6.5
6.4
6.3
6.2
6.1
6.0
-20
+10
+40
+70
+100
+130
+160 °F
1
ALONE (x5)
(x5) 2
3
2
3
4
4
1

FIG. 3

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