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5 KWE REACTOR TE REFLECTOR SECTOR DRIVE ACTUATOR DESIGN SUMMARY

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06531	22510	REL. DATE 10.11.72k

PREPARED BY/DATE	DEPT	MAIL ADDR
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APPROVALS		DATE
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O. P. Steele, III		10/5/72
T. Nakae		10/5/72

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UNCL	☒	☐
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ABSTRACT

The results of the 5 KWe Reactor TE System actuator parametric study, and subsequent load and performance calculations, are presented, together with the results of the stress analysis.

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FIGURES

I. INTRODUCTION

The 5 Kwe Reactor TE System reactor is controlled by the axial movement of two control sectors in the reflector assembly. An actuator, mounted near the shield, supplies the rotational energy required to position each control sector. Environmental and performance requirements, and space allocation for the actuator are specified in Reference 1 through 11, and are summarized in Section IV.

This report describes the approach used in arriving at an optimized actuator design, and describes the prototype actuator design.

II. OPTIMIZATION APPROACH - STEPPER MOTOR

The approach to optimization was to perform the following steps iteratively, improving the design with each evolution, making such compromises as necessary to interface the various requirements.

A. Conceptual Layout

The arrangement of parts with the various parts sized on very preliminary calculations were shown on a preliminary layout drawing.

B. Calculation of Stepper Performance

The performance of various stepper motors that would fit within the conceptual layout was calculated by use of a computer analysis model.

C. Determination of Performance Requirement

The torque requirements for slow speed stepping and rapid scram were determined as a function of actuator step size because of the system requirement of approximately 5 mils of axial control sector movement per actuator step. The actuator speed to meet scram requirement varies with step size.

D. Evaluation

The calculated actuator performance was plotted on a common basis as the requirements and the overall evaluations were made.

E. Selection

The final design of the prototype actuator was selected on the basis of performance vs. requirement evaluation.

III. OPTIMIZATION STUDY - STEPPER MOTOR

The static torque of a reluctance stepper motor, since it is a permeance machine, is described by:

$$T = K\,NI^2\,\frac{dP}{d\theta}$$

where (Reference 12)

T = Static torque in oz-in.
K = Constant to accommodate units used
NI = Magnetomotive force in ampere turns
$\frac{dP}{d\theta}$ = Differential permeance with angular motion

This formula is the basis of the torque formula used in the computer program in the form

$$T = K\,L\,N\,R\,(B_1^2\,G_1 - B_2^2\,G_2)$$

where

T = Static torque in oz-in.
K = Constant to accommodate units used
L = Length of teeth in inches
N = Number of working teeth
R = Radius of rotor teeth at gap in inches
B_1 = Flux density, forward torque in KL/in^2
G_1 = Air gap (rotor to stator) at forward flux density in inches
B_2 = Flux density, reverse torque in KL/in^2
G_2 = Air gap (rotor to stator) at reverse flux density in inches

Because the value $B_2^2 \times G_2$ is very difficult to calculate analytically, experimentally adjusted data were used.

Calculations were initially made to arrive at stepper motor design with a fixed length, shell diameters, and magnetic gap. The rotor diameter and the rotor and stator teeth configurations were then calculated, in accordance with the following matrix.

STEP SIZE	TOOTH SIZE	ROTOR DIA.
3.462° (3 teeth/pole)	.140	2.317
	.150	2.483
	.160	2.648
	.170	2.814
	.180	2.979
2.647° (4 teeth/pole)	.115	2.489
	.120	2.597
	.125	2.706
	.130	2.814
	.135	2.922
2.143° (5 teeth/pole)	.090	2.406
	.095	2.540
	.100	2.674
	.105	2.807
	.110	2.941

(cont.)

STEP SIZE	TOOTH SIZE	ROTOR DIA.
1.800° (6 teeth/pole)	.075	2.387
	.080	2.546
	.085	2.706
	.090	2.865
	.095	3.024
1.368° (8 teeth/pole)	.055	2.311
	.060	2.521
	.065	2.731
	.070	2.941
1.000° (11 teeth/pole)	.045	2.578
	.050	2.865
0.738° (15 teeth/pole)	.035	2.718

The inputs to the computer model used for the calculations are:

Trial rotor dia.
Magnetic gap
Core length
Shell ID
Shell OD
Tooth size
Slot Depth
Pole width
Pole thickness
Wire diameter
Conductor resistivity

and the outputs are:

Final rotor dia.
Teeth/pole

Coil current
Coil voltage
Current density
Static torque
Stepping torque
Turns/coil
Inductance
Flux densities in all parts
Ampere turns in all parts

A typical computed torque output, for 5 teeth/pole, 2.143° step, is shown in Figure 1.

A replot of this curve, Figure 2, shows how, for a specific current density, the output varies with the tooth size.

The maximum stepping scram torque requirements for various actuator speed (step size) are shown in Figure 3. The scram rating curve shown is the equivalent stepping torque to compensate for torque reduction associated with output speed. The rating curve was determined on the basis of experimental data generated on the S8DR design actuators as a function of actuator speed. However, unless the scram speed is greater than 8 RPM, it is the low speed requirements that are the controlling value for optimizing the actuator design. The torque requirements are tabulated:

ACTUATOR STEP SIZE VS. TORQUE REQUIREMENTS

Teeth/Pole	8	6	5	4	3
Step-degrees	1.37	1.8	2.14	2.65	3.46
4 step sequence-degrees	5.48	7.2	8.65	10.60	13.84
Ref. movement-inch	.0054	.0054	.0054	.0054	.0054
Scram RPM	4.57	6.00	7.12	8.84	11.50

(cont.)

Step torque max oz-in.	103	76	62	49	37
Scram torque max	70	50	42	39	27

Figure 4 shows how the required torques and actuator developed torque vary with actuator speed. It appears that the largest design margins exist in the range of speed between 6 to 9 RPM. The following factors tend to favor a slower speed.

1. Lower bearing surface speed.
2. Lower gear ratio, easier to integrate into the space available.
3. Larger drive pinion to reduce rotor shaft stresses.
4. Less bearing surface travel.

On the basis of the above evaluation, the 6 teeth/pole which results in 6 RPM scram speed was selected. The other parameters were then also fixed.

IV. ACTUATOR OPERATIONAL AND DESIGN REQUIREMENTS

A. Expected Operational Torques

With the selection of the actuator design parameters resulting in a 1.8° step (6 RPM scram), the expected operational torque requirements at the actuator rotor to drive and brake the control sector under the various operational modes were determined as the function of the friction coefficient of the drive system and actuator bearings. Analyses had shown the variation of the friction coefficient to be the dominant factor in the torque requirements for a given design. The expected friction coefficient is .35 over the operational conditions, with the upper and lower limits of .60 and .10. The calculated torque requirements are shown below:

Ground test (reactor down)

Acceleration		+ 1.0g	
Friction coefficient	.1	.35	.6
Stepping torque	16.4	42.2	74.4
Scram torque	9.4	27.2	50.6
Brake holding torque	3.6	0	0

Flight

Acceleration		+ 0.1g	
Friction coefficient	.1	.35	.6
Stepping torque	3.9	9.9	17.3
Scram torque	0.1	1.8	6.5
Brake holding torque	1.1	0.0	0.0

Flight

Acceleration		- 0.1g	
Friction coefficient	.1	.35	.6
Stepping torque	9.9	24.9	43.9
Scram torque	0.0	3.7	15.2
Brake holding torque	3.2	0.0	0.0

Launch (reactor down)

Acceleration		+ 16.25g	
Friction coefficient	.1	.35	.6
Brake holding torque	138.9	0	0

Launch (reactor up)

Acceleration		-16.25g	
Friction coefficient	.1	.35	.6
Brake holding torque*	170.8	0	0

---

* Control Sector held by mechanical "full out" stop.

B. Actuator Design Requirements

The expected ground test, launch and flight operational environments and torque requirements were evaluated to select the design requirements listed below. The torques listed include approximately 30% design margin above the maximum expected values.

Environmental

Non operating (Launch)

Temperature	50°F - 130°F
Pressure	Sea level to 10^{-8} Torr

Acceleration:

Axial	Lateral	
7.5	2.0	any combination
1.0	1.25	
16.25	.625	

Shock	None
Vibration	To be determined (effects expected to be less than acceleration)

Operational

Temperature	50°F - 800°F
Thermal Cycles	~15F/minute
Pressure	1×10^{-5} Torr max
IRRADIATION (TOTAL)	1×10^{19} NVT (.1 Mev) 5×10^{11} RAD

Performance

Output step size	7.2° (4 pulses of 1.8° each)
Stepping torque (step/sec)	100 oz-in. minimum
Scram torque (6 RPM)	70 oz-in. minimum
Brake torque (holding)	180 oz-in. minimum
Lifetime	
Hours	44,000 minimum
Thermal cycles	50 over the temp range
Operational cycles (step or scram rate)	50,000 steps in each direction

Interface

Envelope	Approx 5.0 dia by 4.0 long
Electrical	Adaptable to hard cales
Mechanical	Integral 2.78 reduction gear

V. PROTOTYPE ACTUATOR DESIGN

The design of the prototype actuator to meet the design requirements is shown on Figure 5. The design torque values are as follows:

Stepping torque	107 oz-in.
Scram torque	80 oz-in. (at 6 RPM)
Brake torque	225 oz-in.

VI. DESIGN ANALYSIS

A. Mechanical Calculations

Mechanical loads for stress analysis were based upon the combination of the maximum axial load of 16.25g, and the maximum lateral load of 2.0g, while the brake is loaded to 180 oz-in. torsional load.

Maximum stress and design factor

	Stress PSI	Design Factor
Rotor pinion	10.680	2.75
Rotor shaft	2,134	17.74
Mounting end bell	728	53.95
Brake teeth	1,512	25.45
Brake discs	73	547
Bellows (Torsion)	26,500	5.23
Bearings	17,000	.47*

Design factor is $\frac{\text{Yield Stress}}{\text{Load Stress}} - 1$

---

*Identical to S8DR - all other values better than S8DR

Material capabilities for design factor calculations are as follows:

	Yield Stress Ambient	Yield Stress 800F
Hiperco 27	40,000	30,000
Inconel 718	165,000	155,000
Carbon Bearings		
Compressive	25,000	25,000

The only exception to the above stresses as worst case under the assumed g-loading is the bellows. When the bellows is compressed during the stepping sequence, the bending stresses exceed the torsional stresses occurring during launch as follows:

	Stress PSI	Design Factor
Bellows (flexing)	40,000	3.13

B. Electromagnetic Calculations

All values of electromagnetic calculations are similar to the S8DR values. The final selected current densities are identical to the S8DR current densities.

1. Stepper Motor

Equivalent static torque to meet rating

Stepping 160 oz-in. $\left[\frac{100}{.63} = 160\right]$

Scram 148 oz-in. $\left[\frac{70}{.63\text{x}.75} = \qquad\right]$
(6 RPM Derating = .75)

Ampere Turns (NI)

Gap	412
Pole	37
Shell	64

Teeth	7
Rotor	8
Total	528

Saturation Factor 1.28

Coil and Connections calculations

Turns/Coil	96
Wire size	No. 24 AWG oxalloy

Input phase current 5.5 amperes

Connection	2 parallel coils/phase
Conductor current density	8,666 amperes/in^2

Resultant calculated torque

Static torque	170 oz-in.
Low speed stepping	107 oz-in.
Scram (6 RPM)	80 oz-in

Flux densities

Gap	82.2 KL/in^2
Pole	81.7 KL/in^2
Rotor	46.4 KL/in^2
Shell	65.0 KL/in^2

2. Actuator Brake

Magnetic Pull	5.0 lb/min
Spring load	2.5 lbs (225 oz-in at $\mu = 0.1$)
Spring rate	75 lbs/inch
Magnetic gap	0.070 inch

Ampere turns (NI)

Inner gap	136.0

Inner pole	1.8
Core	12.7
Back plate	6.3
Shell	7.1
Outer pole	1.3
Outer gap	118.0
Armature	3.6
Total	286.8
Saturation factor	1.13

Coil and Connection Calculations

Turns/Coil	330
Wire size	No. 24 AWG oxalloy
Brake Input current	.869 amperes
Connection	single coil
Conductor current density	2743 amperes/in^2
Resultant magnetic pull	See Figure 6

Flux densities

Inner gap	6.2 KL/in
Inner pole	35.8 KL/in
Core	26.5 KL/in
Back plate	46.8 KL/in
Shell	9.6 KL/in
Outer pole	20.8 KL/in
Outer gap	5.4 KL/in
Armature	24.2 KL/in

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2. Telephone conversation, R. Thexton to L. Donelan, "Torque Load Requirements", 4-7-72

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5. IL, T. Nakae to E. Matlin, "Design of the Modified Actuator for the Sliding Reflector Drive", 5-24-72

6. Hand data from E. Matlin to L. Donelan, 6-13-72

7. Design Review, 8-7-72

   IL, R. Thexton to Those Listed, "Action Items on Informal Design Review", 8-9-72

8. IL, T. Nakae to E. Matlin, "Design Criteria for the Prototype Actuator", 8-15-72

9. Design Review, 8-22-72

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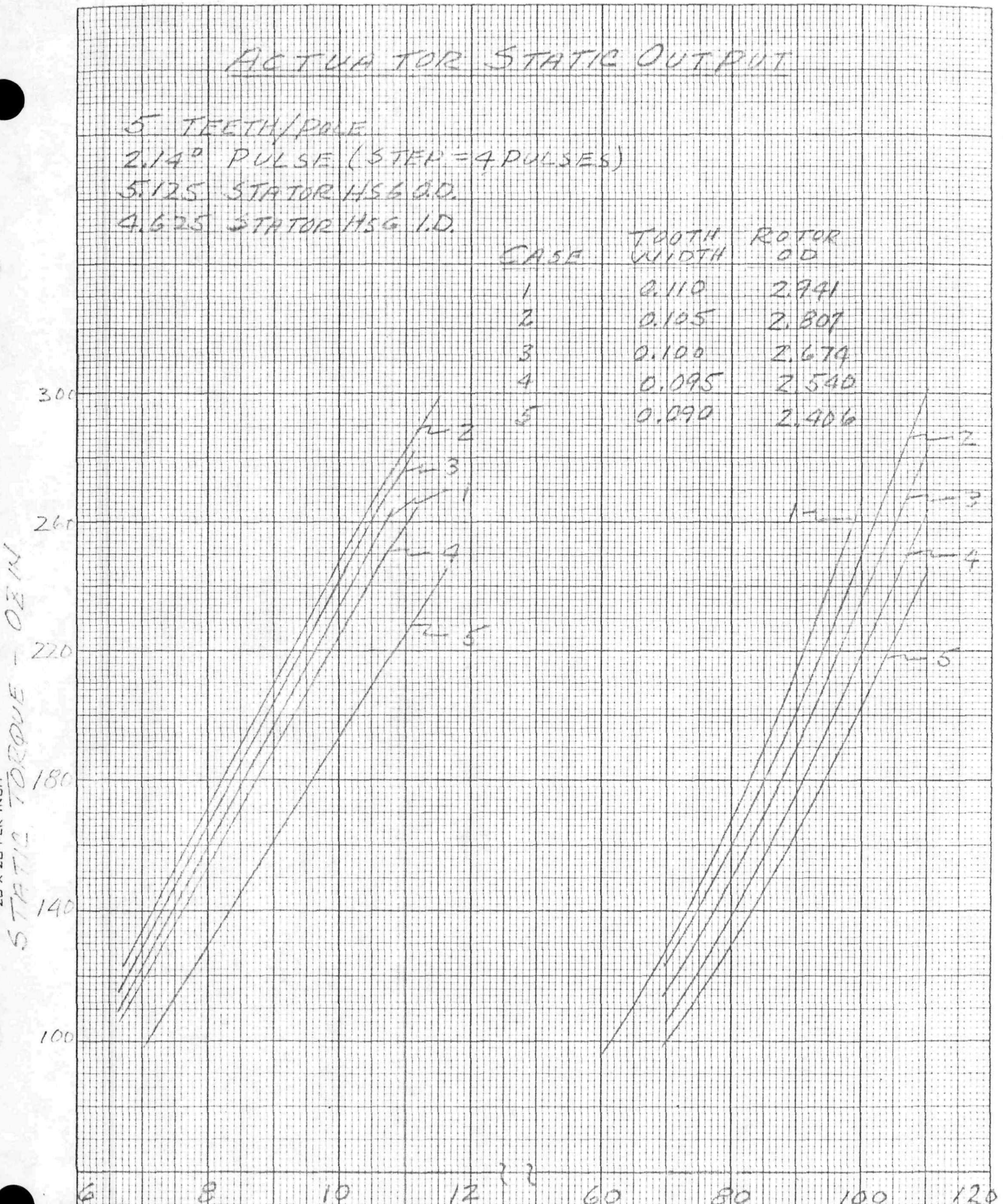
10. Design Review, 8-28-72
    DRR-652-220-002, 8-29-72

11. IL, L. Donelan to E. Matlin, "Weight Reduction", 9-4-72

12. <u>Electromagnetic Devices</u> by Herbert C. Roters, John Wiley & Sons Inc. 1941

FIGURE 1



ACTUATOR STATIC OUTPUT

5 TEETH/POLE
2.14° PULSE (STEP = 4 PULSES)
5.125 STATOR HSG O.D.
4.525 STATOR HSG I.D.

CASE	TOOTH WIDTH	ROTOR OD
1	0.110	2.941
2	0.105	2.807
3	0.100	2.674
4	0.095	2.540
5	0.090	2.406

FIGURE 2

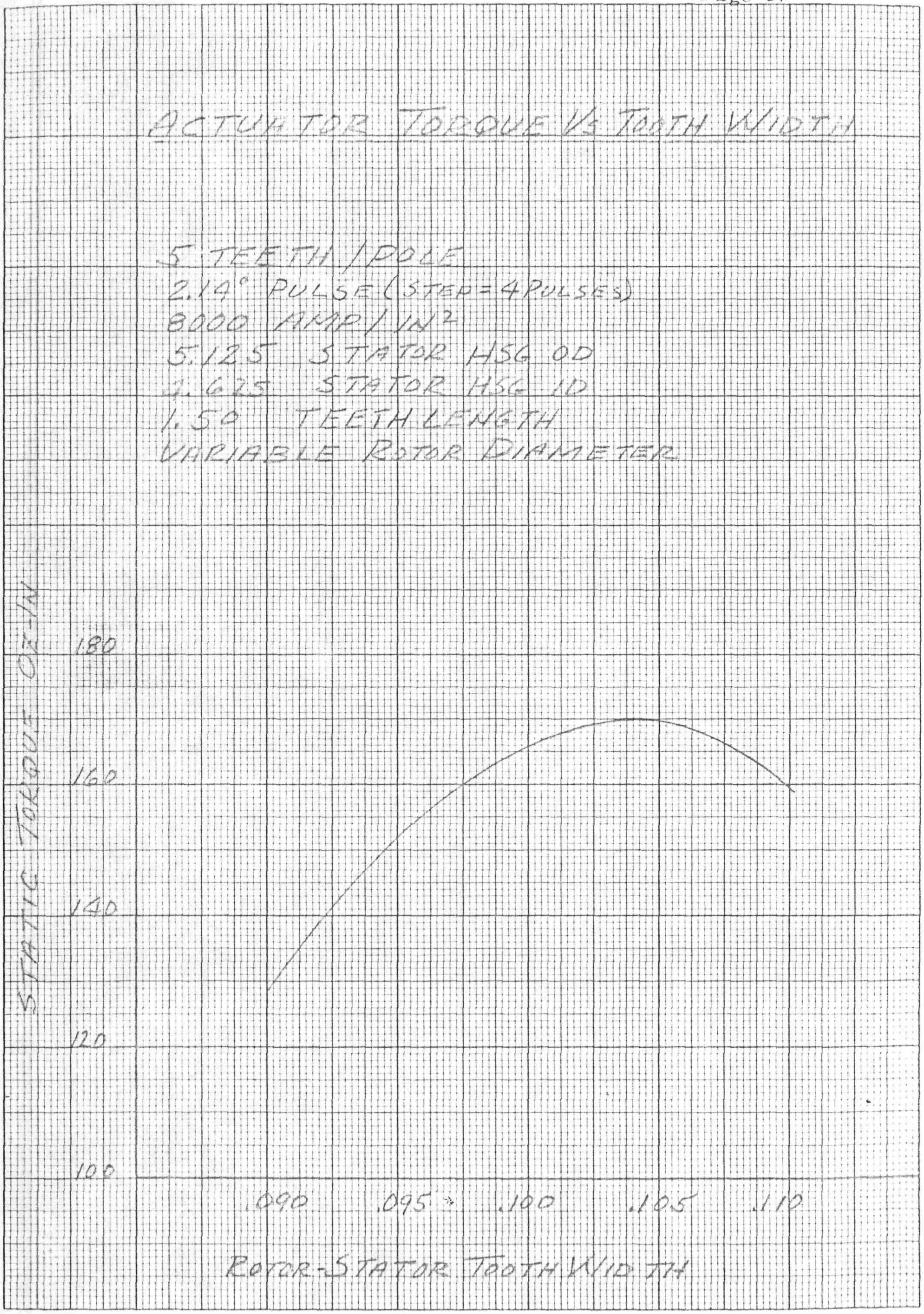

ACTUATOR TORQUE VS TOOTH WIDTH
5 TEETH / POLE
2.14° PULSE (STEP = 4 PULSES)
8000 AMP / IN²
5.125 STATOR HSG OD
4.625 STATOR HSG ID
1.50 TEETH LENGTH
VARIABLE ROTOR DIAMETER
STATIC TORQUE OZ-IN
180
160
140
120
100
.090
.095
.100
.105
.110
ROTOR-STATOR TOOTH WIDTH

FIGURE 3

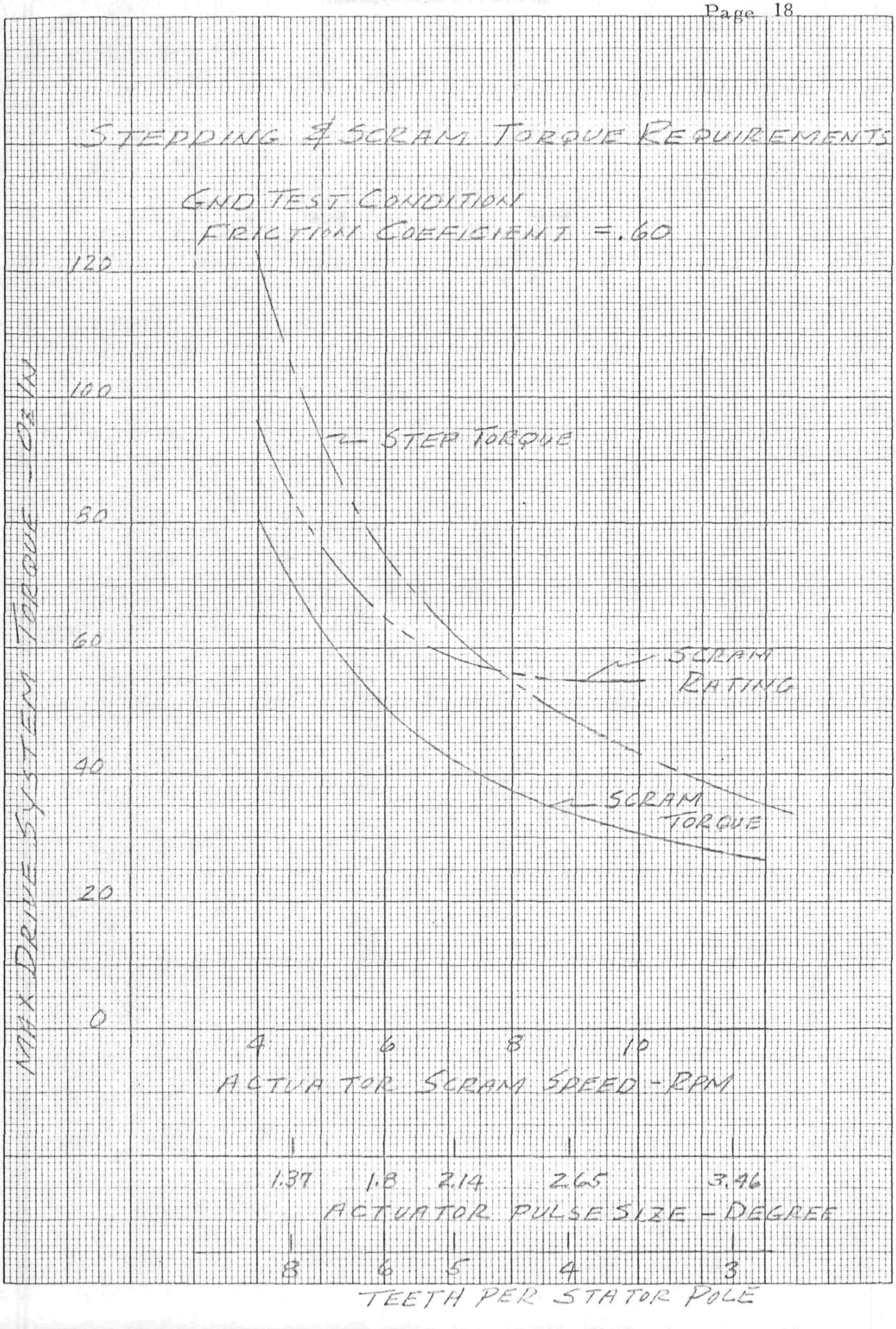
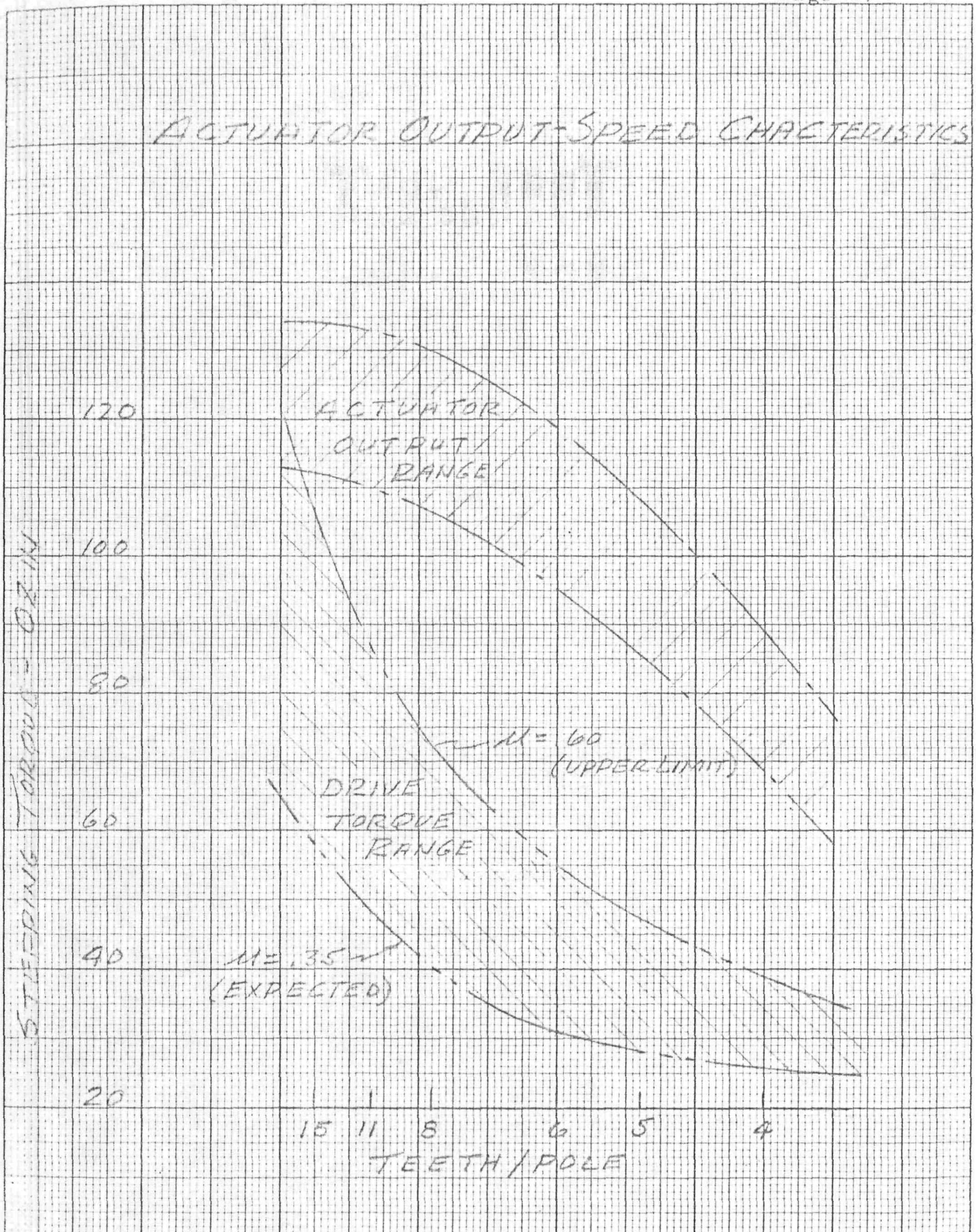

STEPPING & SCRAM TORQUE REQUIREMENTS
GND TEST CONDITION
FRICTION COEFICIENT = .60
MAX DRIVE SYSTEM TORQUE - OZ IN
120
100
80
60
40
20
0
STEP TORQUE
SCRAM RATING
SCRAM TORQUE
4
6
8
10
ACTUATOR SCRAM SPEED - RPM
1.37
1.8
2.14
2.65
3.46
ACTUATOR PULSE SIZE - DEGREE
8
6
5
4
3
TEETH PER STATOR POLE

FIGURE 4


ACTUATOR OUTPUT-SPEED CHACTERISTICS
STEPPING TORQUE - OZ IN
120
100
80
60
40
20
ACTUATOR OUTPUT RANGE
μ = .60 (UPPER LIMIT)
DRIVE TORQUE RANGE
μ = .35 (EXPECTED)
15
11
8
6
5
4
TEETH / POLE
4
6
8
10
12
ACTUATOR SCRAM SPEED - RPM

OSTI ID 040102618
TI-652-220-007

NOTES: UNLESS OTHERWISE SPECIFIED ON THIS DRAWING

1. MATERIAL: 27% CO-IRON PER ST0160NB0001 EXCEPT AS MARKED.
2. REFERENCE SBDR ACTUATOR DWG NO. SHOWN AFTER N652--- DWG NO. FOR REF ONLY.

NOTES: CONTINUED

① 3. ROTATE BOLT LOCATIONS 5° CLOCKWISE (FROM PINION END) ON DETAIL & ASSY DRAWINGS.
4. ALL 8-32 UNC-3B HOLES ARE USED FOR DIS-ASSY. LOCATION AND NUMBER ABOVE 2 ARE OPTIONAL
5. ROTOR (N652220036) 50 TEETH GAP BETWEEN TEETH .085 WIDTH
6. POLE (N652220070) 6 TEETH, GAP BETWEEN TEETH .085
7. GEAR DATA:
PINION - 18 TEETH 32 PITCH
GEAR - 50 TEETH 32 PITCH
℄ DISTANCE - 1.0625

REFER TO ECP 652-220-002

DR BY	R.T. THORTON	8-21-72
CHK BY		9-9-72

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LAYOUT - REFLECTOR DRIVE ACTUATOR, EXNETE SYSTEM (PRELIMINARY)

SIZE	CODE IDENT NO.	DRAWING NO.
J	09974	R-N652220095

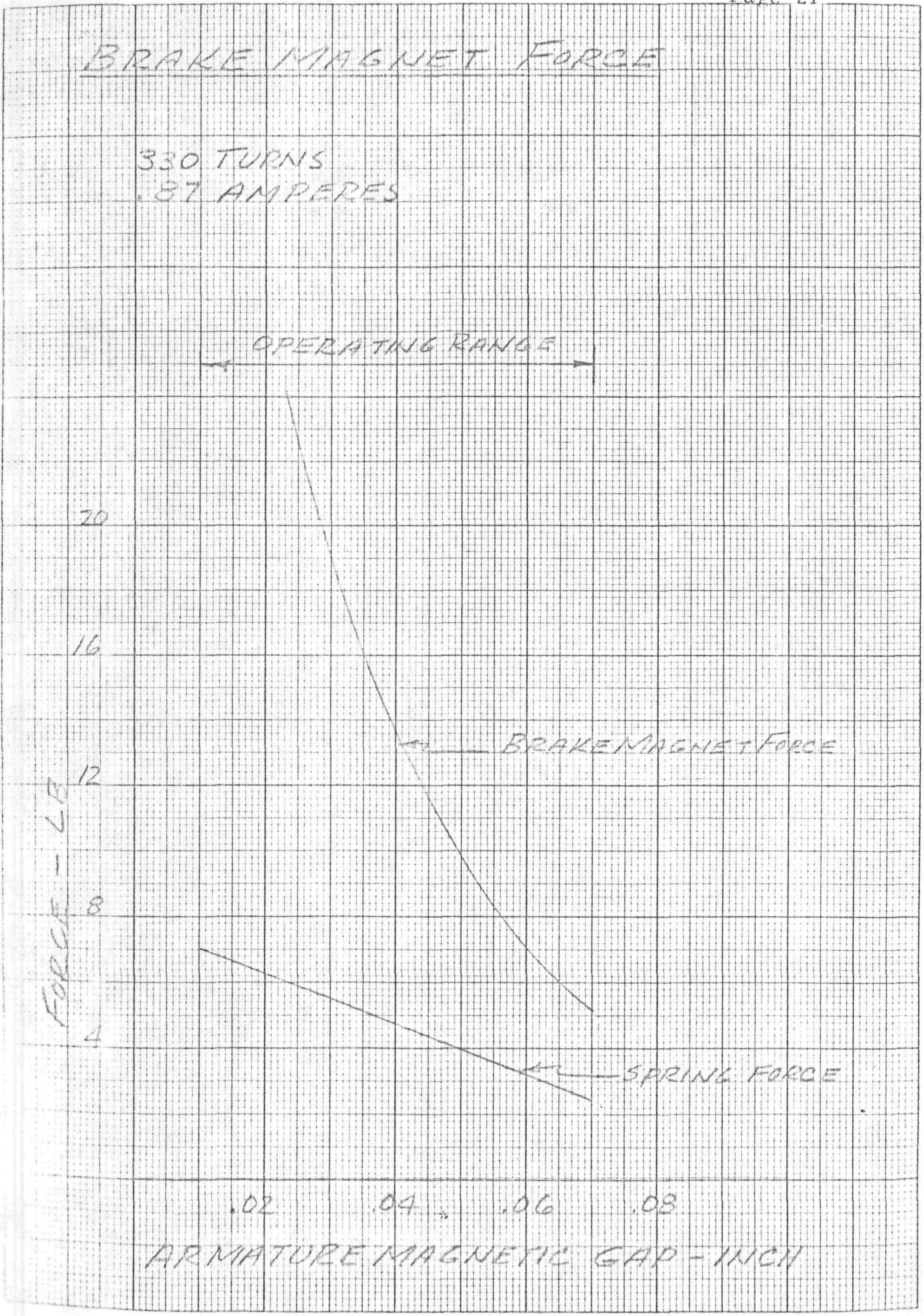
SCALE 2/1 SHEET

SECURITY CLASSIFICATION

DRAWING NO. R-N652220095

Figure 5

FIGURE 6


BRAKE MAGNET FORCE
330 TURNS
.37 AMPERES
OPERATING RANGE
BRAKE MAGNET FORCE
SPRING FORCE
20
16
12
8
4
FORCE - LB
.02
.04
.06
.08
ARMATURE MAGNETIC GAP - INCH