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EXPERIMENTAL WINDAGE LOSSES FOR CLOSE CLEARANCE ROTATING CYLINDERS IN THE TURBULENT FLOW REGIME

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Lewis Research Center
Cleveland, Ohio
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ABSTRACT

Viscous torque (windage) of a 12-inch diameter, 5.9-inch long cylinder rotating within a stationary concentric housing was measured at speeds up to 24,000 rpm. Three housings were used to produce gap distances of 0.0565, 0.116, and 0.236 inch. The housings were mounted on a reaction torque measuring device which eliminated any disc type end effects. Reynolds numbers (Re) in excess of 100,000 were produced using the gap thickness as the characteristic dimension. It was found that above a Re of 15,000 the curves of drag coefficient vs Re for all three gaps coincided within five percent.

E-5786

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SUMMARY

Viscous torque (windage) of a 12-inch diameter, 5.9-inch long cylinder rotating within a stationary concentric housing was measured at speeds up to 24,000 rpm. Three housings were used to produce gap distances of 0.0565, 0.116, and 0.236 inch. The housings were mounted on a reaction torque measuring device which eliminated any disc type end effects. Reynolds numbers (Re) in excess of 100,000 were produced using the gap thickness as the characteristic dimension. It was found that above a Re of 15,000 the curves of drag coefficient vs Re for all three gaps coincided within five percent.

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INTRODUCTION

Present high speed generators proposed for use in space power systems develop turbulent velocity profiles in the rotor-stator gap well above the levels previously investigated. The exact velocity distribution in this regime has not yet been defined, but flow between coaxial rotating cylinders is a basic problem in the study of windage.

The laminar case of flow between concentric rotating cylinders has been studied by Couette (ref. 1). Taylor (refs. 2 and 3), Vohr (ref. 4), and DiPrima (ref. 5) also studied the vortex flow regime. The turbulent flow case (Re above 7,000) was investigated by Taylor, Vohr, Wendt, and Pai (refs. 2, 4, 6, and 7) with Re as high as 40,000. For the most part, however, the high Re were based on large gap widths, e.g., gap-to-radius ratios of 0.1 to 0.23 (refs. 2 and 4). Proposed designs for space power system alternators use gap-to-radius ratios of 0.01 to 0.04 with Re as high as 100,000. Data for this range could only be extrapolated. Experimental data were necessary to permit accurate calculation of the windage power loss.

The present test program was undertaken to extend the existing information and provide design data needed for future electrical generators. A rotor with a 12-inch diameter, 5.9-inch long cylindrical section was rotated at speeds from 0 to 24,000 rpm. The gap-to-radius ratio was varied from approximately 0.01 to 0.04 by changing the housing (stator) enclosure. The housing was mounted on a reaction torque device so that only viscous drag from cylindrical section of rotor would be measured. Tests were run in ambient air to obtain Re of 100,000.

APPARATUS AND PROCEDURE

The windage test unit (fig. 1) consisted of a rotor mounted on air-oil mist-lubricated ball bearings and a housing (stator) attached to a "floating" support table. Strain gages mounted in four flexure arms held the housing and support table assembly so that it would pivot about the rotor axis. Reaction torque (viscous drag) between the rotor and housing was measured by a Wheatstone bridge circuit connecting the strain gages. A variable speed dynamometer consisting of a dc motor and two tandem gear units was used to drive the rotor. A splined coupling connected the test unit to the drive system.

The cylindrical section of the rotor was 12.005 inches in diameter and 5.900 inches long. It was made from a heat-treated forging of a low alloy vanadium steel and had a 28 rms surface finish. The aluminum housings were made in two halves (fig. 2) so that they could be removed without changing the rotor alignment. All parts were doweled or keyed so that the machined matching of the parts could be reproduced. Three rotor-housing configurations (fig. 3) were tested. All the housings had a length of 5.900 inches. The radial gaps for the three housings were 0.0565, 0.116, and 0.236 inch.

The rotor was run at speeds up to 24,000 rpm for the two larger gap sizes, and 22,000 rpm for the small gap. Several runs were made for each housing to insure reproducibility of the data. The acceleration rate for all the tests was approximately 10 rpm/sec.

INSTRUMENTATION

Instrumentation for the tests consisted of speed, torque, temperature, and vibration sensors. Much of the instrumentation was protection for the test rig. Only speed, torque, and gap temperature were used for the data analysis.

Speed was measured by a magnetic pickup and a 60-tooth gear arrangement on the shaft of the dynamometer. The signal generated was sent to a counter and recorded. Rotational speed could be controlled within 5 rpm.

Torque measurements were made using a reaction torque device (fig. 1). Strain gages are located in four flexure arms so that they can sense torque about only one axis. This axis was made to coincide with the axis of the rotor and its housing. Any torque developed about this sensing axis will produce a strain proportional to the torque. All static torques or loads remain constant and are "calibrated out". The torque unit was calibrated by hanging accurately-known weights from the calibration arm to produce known torques. Measurements were accurate within 0.05 in-lb, although measurements could be taken at 0.01 in-lb increments. Linearity was found to be within 0.1 percent of full scale. The strain gage output from the

Wheatstone bridge circuit was measured on an integrating digital voltmeter. Vibration transmitted to the reaction torque instrument caused approximately 1 to 2 percent variation in the signal output. Torque measurements taken at speeds above 5,000 rpm are approximately 5 percent accurate.

All temperatures were measured using Iron-Constantan type J thermocouples. The housings had one thermocouple at each end, and one thermocouple in the center, each extending halfway into the gap, as well as one thermocouple on the outer skin. In addition, the 0.0565-inch gap housing had a thermocouple installed in the gap, 1-1/2 inch from one end, while the 0.236-inch gap housing had a thermocouple 3/4 inch from the end. Thermocouples were also placed in the oil mist system and on the bearing outer race to monitor the conditions of the bearings.

Accelerometers were mounted on both bearing supports and the dynamometer gear box to measure vibration in three directions. These were used to identify critical speeds of the rotor-dynamometer combination, as well as to check for bearing fatigue. The unit was not allowed to remain at any of the various critical speeds encountered, and no problems were encountered with the bearings for the length of the test.

DISCUSSION OF RESULTS

The test section of the apparatus consisted of a smooth cylinder rotating within an open-ended stationary concentric cylindrical housing. Windage power loss due to viscous drag on a rotating cylinder of radius R and rotational speed ω is given by

$$W = \omega R F \qquad (1)$$

where F is the frictional force on the cylinder. The effect of pressure forces is assumed negligible (ref. 7). By definition

$$F \equiv \lambda A K \qquad (2)$$

where λ is the friction factor or drag coefficient, A is a characteristic area and K is the kinetic energy/unit volume. Expanding Equation (2),

$$F = \lambda (2\pi R L)(1/2 \varrho U^2) \qquad (2a)$$

where $U = \omega R$. Combining terms

$$F = \lambda \varrho \pi \omega^2 R^3 L \qquad (3)$$

Substituting into Equation (1)

$$W = \lambda \rho \pi \omega^3 R^4 L \tag{4}$$

Since the primary measured parameters in this test were torque and speed, Equation (1) can be rewritten

$$W = T\omega \tag{1a}$$

where $T = FR$. Solving Equation (4) for the drag coefficient in terms of the measured parameters

$$\lambda = \frac{T}{\rho \pi \omega^2 R^4 L} \tag{5}$$

A non-dimensional curve was plotted in figure 4 of drag coefficient vs Re for each of the gap sizes. Here Re is defined as

$$Re = \frac{UD}{\nu} \tag{6}$$

where the characteristic dimension D is the radial gap thickness. Two assumptions were made. The first was that the pressure in the gap remained ambient since the housing was not enclosed. The second was that the average gap temperature was equal to the gap temperature in the center of the housing; this is the temperature shown in Tables I to III, typical test runs for each gap thickness.

Thermocouple instrumentation on the housings indicated that the temperature profile was symmetric. Table IV shows the difference between the center and the end housing temperatures for the three gaps at various speeds. The effect of using the center gap temperature is negligible since using a lower temperature would increase the Re and lower the drag coefficient without actually changing the curve presented in figure 4.

The non-dimensional curve in figure 4 shows that above a Re of 15,000, the deviation between the drag coefficients for the different gaps is less than 5 percent. This result is supported by Taylor in reference 2. Below a Re of 10,000, the 0.116-inch gap had a higher drag coefficient than the 0.0565-inch gap. It would be expected based on previous works (e.g., Wendt, ref. 6), that the 0.236-inch gap would be still higher. However, the torque values in this range for the 0.236-inch gap were extremely low and subject to large errors. The slope of the drag coefficient vs Re curve changes at an approximate Re of 5,000 to 7,000. This is caused by the change from vortex to turbulent flow as shown in reference 4.

The value of the slope changes from approximately -0.5, which correlates with references 4 and 6, to approximately -0.22 to -0.25 in the turbulent range for the large gap.

The speed and windage data presented in Tables I, II, and III were plotted in figure 5. The windage viscous power loss, W , was calculated from the product of speed and torque. The curve for each gap shows that the windage is proportional to speed to approximately 2.75 power. The windage is seen to be an inverse function of the gap size.

SUMMARY OF RESULTS

A 12-inch diameter cylinder was rotated in air at speeds up to 24,000 rpm inside a stationary concentric housing. The gap thickness was varied by changing the inside diameter of the housing. Results of the test were:

(1) Reynolds numbers over 100,000 were produced. Above Reynolds numbers of 15,000 the drag coefficients for the different gaps coincided within five percent.

(2) The curves of drag coefficient vs Reynolds number changed slope at approximately 5,000 to 7,000 Reynolds number, corresponding to the change from vortex to turbulent flow.

(3) Power losses decreased as the gap size was increased.

SYMBOL LIST

A	Characteristic area (wetted area)
D	Characteristic dimension (rotor to stator, radial gap thickness)
F	Frictional force
K	Kinetic energy/unit volume
L	Length
R	Radius
Re	Reynolds number
T	Torque
U	Velocity
W	Windage viscous power loss
λ	Drag coefficient (friction factor)
ν	Kinematic viscosity
ρ	Density
ω	Rotational speed

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TABLE I. RUN NO. 10 - GAP=.0565 in. - BAROMETRIC PRESSURE=29.37 in. Hg

SPEED (rpm)	TORQUE (in-lb)	REYNOLDS NUMBER	DRAG COEFFICIENT (λ)	TEMPERATURE (°F)	WINDAGE (watts)
241	.01534	351	9.209×10^{-3}	76	.043738
483	.03835	703	5.732	76	0.2191
735	.07670	1070	4.950	76	0.66697
975	.1227	1419	4.500	76	1.415
1220	.1687	1775	3.952	76	2.554
1457	.2301	2120	3.779	76	3.9718
1714	.2761	2494	3.277	76	5.5988
1954	.3528	2843	3.222	76	8.1559
2194	.4295	3193	3.111	76	11.148
2462	.5139	3583	2.956	76	14.9688
2710	.6059	3943	2.877	76	19.426
2964	.6980	4313	2.770	76	24.477
3214	.8054	4661	2.724	77	30.625
3456	.9127	5012	2.669	77	37.318
3700	1.0201	5365	2.603	77	44.655
3939	1.1352	5712	2.556	77	52.903
4229	1.289	6113	2.522	78	64.493
4475	1.427	6469	2.494	78	75.55
4800	1.611	6938	2.447	78	91.487
5109	1.818	7374	2.445	78	109.716
5406	2.010	7788	2.412	79	128.556
5709	2.224	8224	2.393	79	150.216
6006	2.447	8623	2.383	80	173.876
6410	2.800	9203	2.394	80	212.34

TABLE I. (Continued)

SPEED (rpm)	TORQUE (in-lb)	REYNOLDS NUMBER	DRAG COEFFICIENT (λ)	TEMPERATURE (°F)	WINDAGE (watts)
6809	3.129	9742	2.375×10^{-3}	81	251.73
7201	3.490	10271	2.373	82	297.33
7605	3.866	10810	2.361	83	347.84
7964	4.180	11247	2.337	85	393.85
8650	4.893	12096	2.331	88	500.74
9028	5.323	12546	2.337	90	568.55
9519	5.845	13100	2.321	93	658.26
9994	6.404	13668	2.315	95	757.20
10569	7.041	14268	2.292	99	880.42
11154	7.762	14868	2.285	103	1024.3
11725	8.491	15437	2.278	107	1177.86
12440	9.410	16131	2.261	112	1385.5
13175	10.378	16768	2.248	118	1617.65
13898	11.405	17370	2.243	124	1875.3
14617	12.487	17886	2.247	131	2159.4
15337	13.553	18328	2.245	139	2459.2
16268	14.795	18989	2.207	147	2847.5
17242	15.931	19613	2.147	156	3249.8
18432	17.679	20149	2.133	170	3853.3
19657	19.313	20672	2.094	184	4491.5
20852	21.108	21006	2.084	200	5207.5
22070	22.719	21208	2.052	218	5932.0

TABLE II. RUN NO. 6 - GAP=.116 in. - BAROMETRIC PRESSURE=29.05 in. Hg

SPEED (rpm)	TORQUE (in-lb)	REYNOLDS NUMBER	DRAG COEFFICIENT (λ)	TEMPERATURE (°F)	WINDAGE (watts)
270	.0153	802	7.377×10^{-3}	74	.04888
515	.03825	1531	5.069	74	.233
760	.06885	2257	4.189	74	.6191
1000	.1071	2972	3.764	74	1.267
1245	.1530	3700	3.469	74	2.2538
1480	.1925	4398	3.068	74	3.349
1729	.25245	5138	2.968	74	5.164
1975	.31365	5870	2.735	74	7.329
2220	.3825	6598	2.727	74	10.05
2450	.45135	7281	2.642	74	13.08
2705	.5202	8039	2.499	74	16.65
2955	.60435	8782	2.433	74	21.13
3345	.7497	9940	2.355	74	29.67
3830	.90095	11345	2.259	75	42.6397
4247	1.13985	12581	2.225	75	57.28
4604	1.3158	13596	2.190	76	71.68
4845	1.446	14307	2.173	76	82.89
5254	1.644	15516	2.101	76	102.198
5651	1.890	16629	2.092	77	126.37
6070	2.134	17862	2.047	77	153.26
6456	2.410	18998	2.043	77	184.09
6851	2.670	20097	2.014	78	216.43
7256	2.953	21213	1.989	79	253.52
7653	3.251	22221	1.976	81	294.37

TABLE II. (Continued)

SPEED (rpm)	TORQUE (in-lb)	REYNOLDS NUMBER	DRAG COEFFICIENT (λ)	TEMPERATURE (°F)	WINDAGE (watts)
7952	3.473	22939	1.963×10^{-3}	83	326.76
8541	3.955	24395	1.948	86	399.67
9032	4.391	25471	1.948	90	469.24
9485	4.758	26489	1.925	93	533.96
9998	5.210	27572	1.911	97	616.31
10485	5.669	28629	1.901	100	703.27
10960	6.128	29649	1.890	103	794.65
11448	6.602	30680	1.876	106	894.24
11920	7.084	31553	1.870	110	999.08
12635	7.857	33034	1.859	114	1174.6
13380	8.652	34142	1.851	122	1369.7
14100	9.463	35438	1.839	127	1578.7
15047	10.565	36924	1.827	135	1880.9
15762	11.383	38116	1.809	140	2122.8
16482	12.133	39042	1.784	147	2366.07
17451	13.395	40284	1.783	156	2765.7
18672	14.925	41661	1.769	168	3297.3
19620	16.149	42461	1.764	179	3748.8
20566	17.297	43309	1.747	189	4208.9
21752	18.980	43659	1.761	207	4884.8
22990	20.586	44251	1.751	223	5599.6
24020	21.963	44530	1.749	238	6241.8

TABLE III. RUN NO. 3 - GAP=.236 in. - BAROMETRIC PRESSURE=29.22 in. Hg

SPEED (rpm)	TORQUE (in-lb)	REYNOLDS NUMBER	DRAG COEFFICIENT (λ)	TEMPERATURE (°F)	WINDAGE (watts)
1203	.1076	7373	2.586×10^{-3}	72	1.531
1496	.1460	9180	2.263	72	2.584
1786	.1844	10945	2.011	72	3.896
2075	.2535	12713	2.048	72	6.223
2378	.330	14573	2.030	72	9.285
2676	.415	16400	2.016	72	13.13
2976	.507	18237	1.991	72	17.86
3262	.599	19917	1.962	73	23.12
3565	.707	21768	1.938	73	29.82
3855	.830	23539	1.946	73	37.86
4152	.945	25352	1.910	73	46.42
4436	1.060	27000	1.881	74	55.63
4483	1.099	27287	1.909	74	58.29
4826	1.245	29374	1.866	74	71.09
5002	1.314	30444	1.833	74	77.77
5204	1.429	31675	1.842	74	87.99
5486	1.537	33391	1.783	74	99.77
5711	1.652	34760	1.768	74	111.62
5911	1.775	35978	1.774	74	124.14
6108	1.882	37177	1.761	74	136.00
6305	1.944	38133	1.714	76	145.02
6502	2.113	39325	1.751	76	162.55
6705	2.213	40552	1.725	76	175.56
6905	2.297	41763	1.688	76	187.66

TABLE III. (Continued)

SPEED (rpm)	TORQUE (in-lb)	REYNOLDS NUMBER	DRAG COEFFICIENT (λ)	TEMPERATURE (°F)	WINDAGE (watts)
7108	2.451	42840	1.703×10^{-3}	77	206.13
7227	2.520	43557	1.694	77	215.48
7402	2.581	44472	1.657	78	226.04
7601	2.720	45667	1.656	78	244.62
7727	2.804	46103	1.658	80	256.35
7968	2.996	47228	1.672	82	282.49
8277	3.181	48894	1.649	83	311.52
8769	3.457	51638	1.599	84	358.67
9257	3.842	54143	1.601	86	420.80
9725	4.187	56514	1.586	88	481.77
10200	4.533	58904	1.567	90	547.06
10674	4.879	61247	1.546	92	616.18
11172	5.301	63495	1.541	95	700.71
11635	5.610	65708	1.509	97	772.28
12365	6.185	68721	1.487	102	904.86
13044	6.800	71584	1.479	106	1049.47
13751	7.45	74539	1.468	110	1212.1
14785	8.41	78682	1.449	116	1471.18
15747	9.3	82528	1.425	121	1732.7
16608	10.1	85478	1.405	127	1984.67
17768	11.29	89028	1.394	136	2373.4
18234	11.91	90813	1.401	138	2569.5
18560	12.14	91365	1.387	142	2665.9

TABLE IV.

GAP TEMPERATURE DIFFERENCES BETWEEN CENTER AND END AT VARIOUS SPEEDS

GAP (inch)	SPEED (rpm)	ΔT (°F)
0.0565	17,000	30
	22,000	60
0.116	18,000	30
	24,000	60
0.236	20,000	20
	24,000	40

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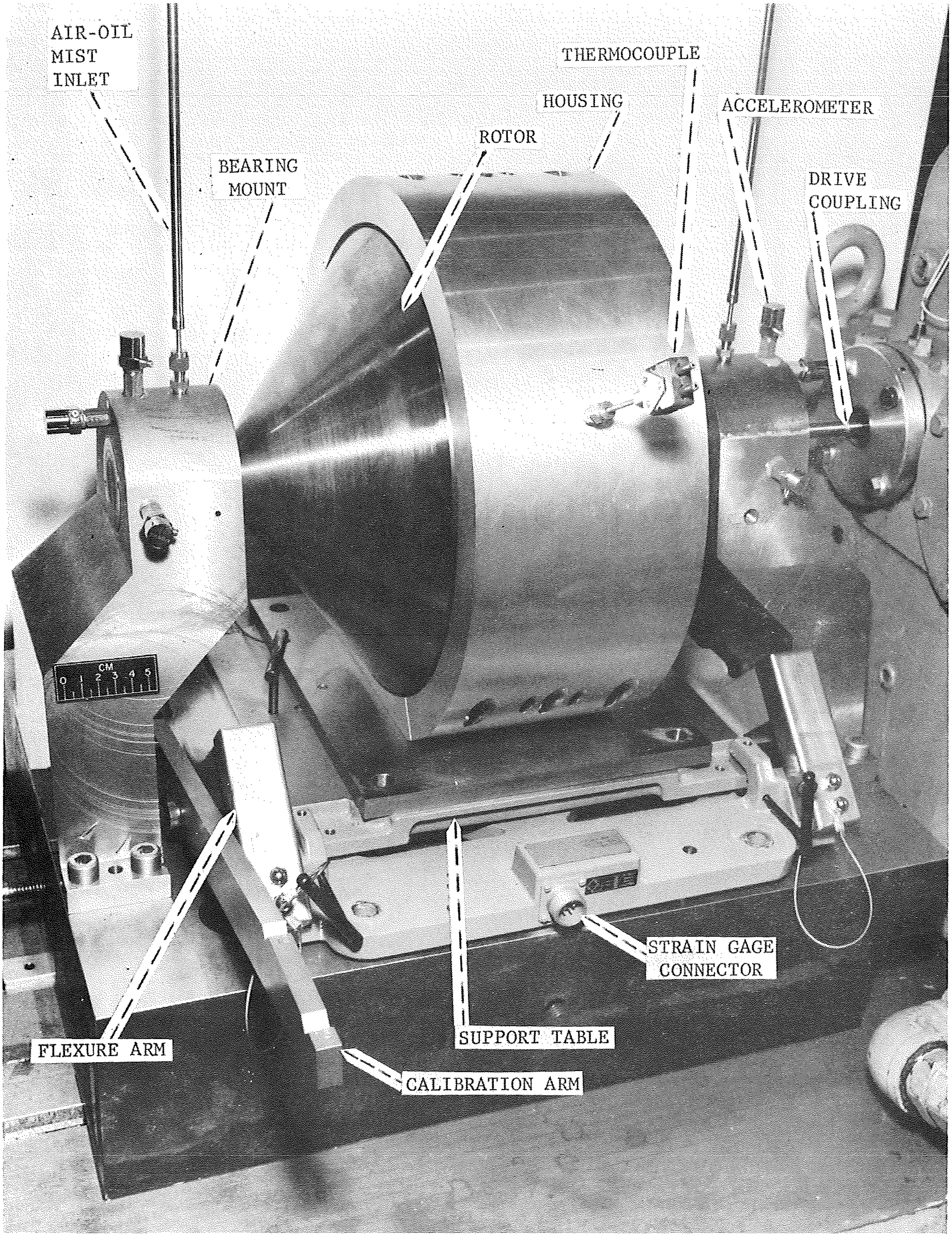


FIGURE 1. WINDAGE TEST UNIT

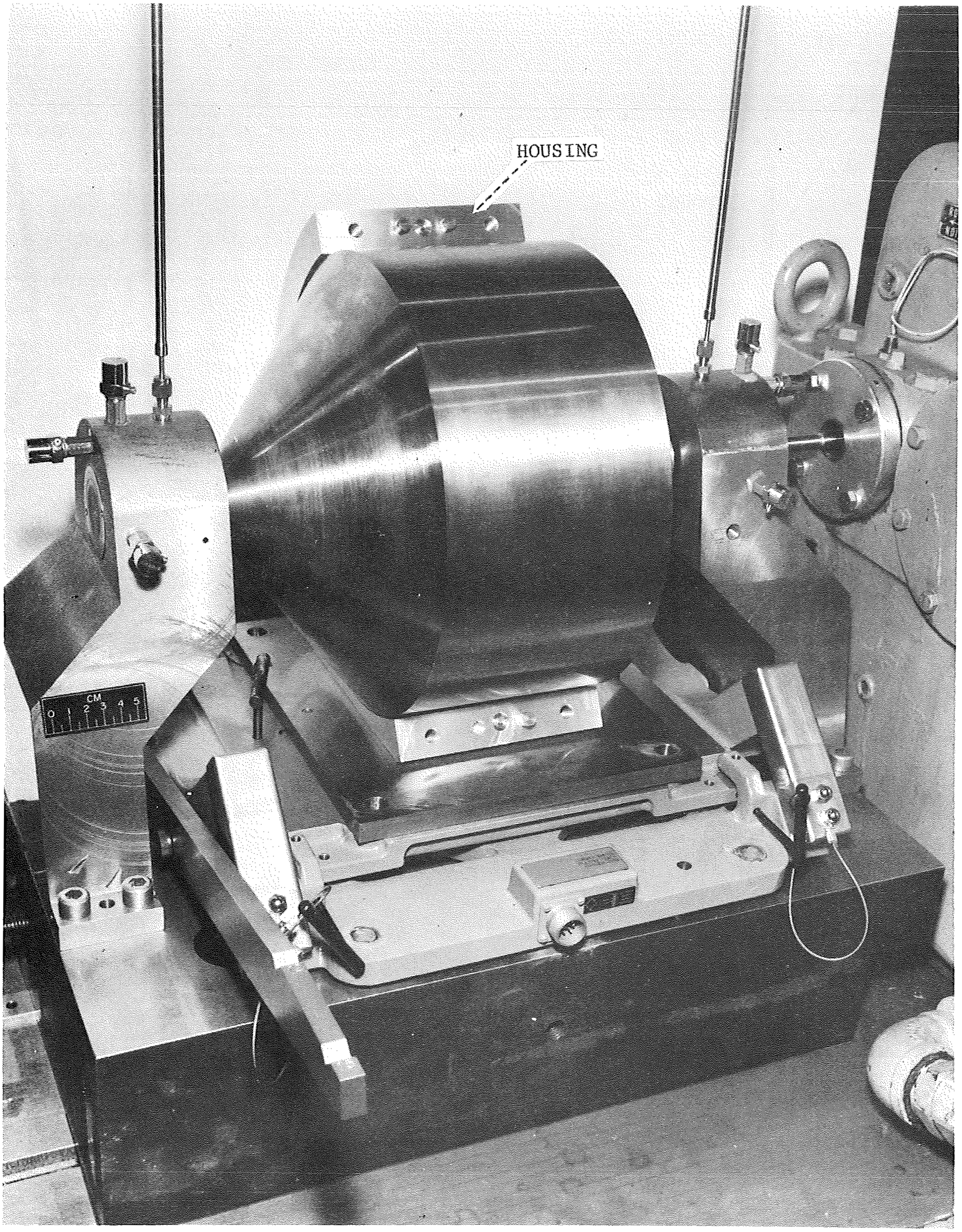
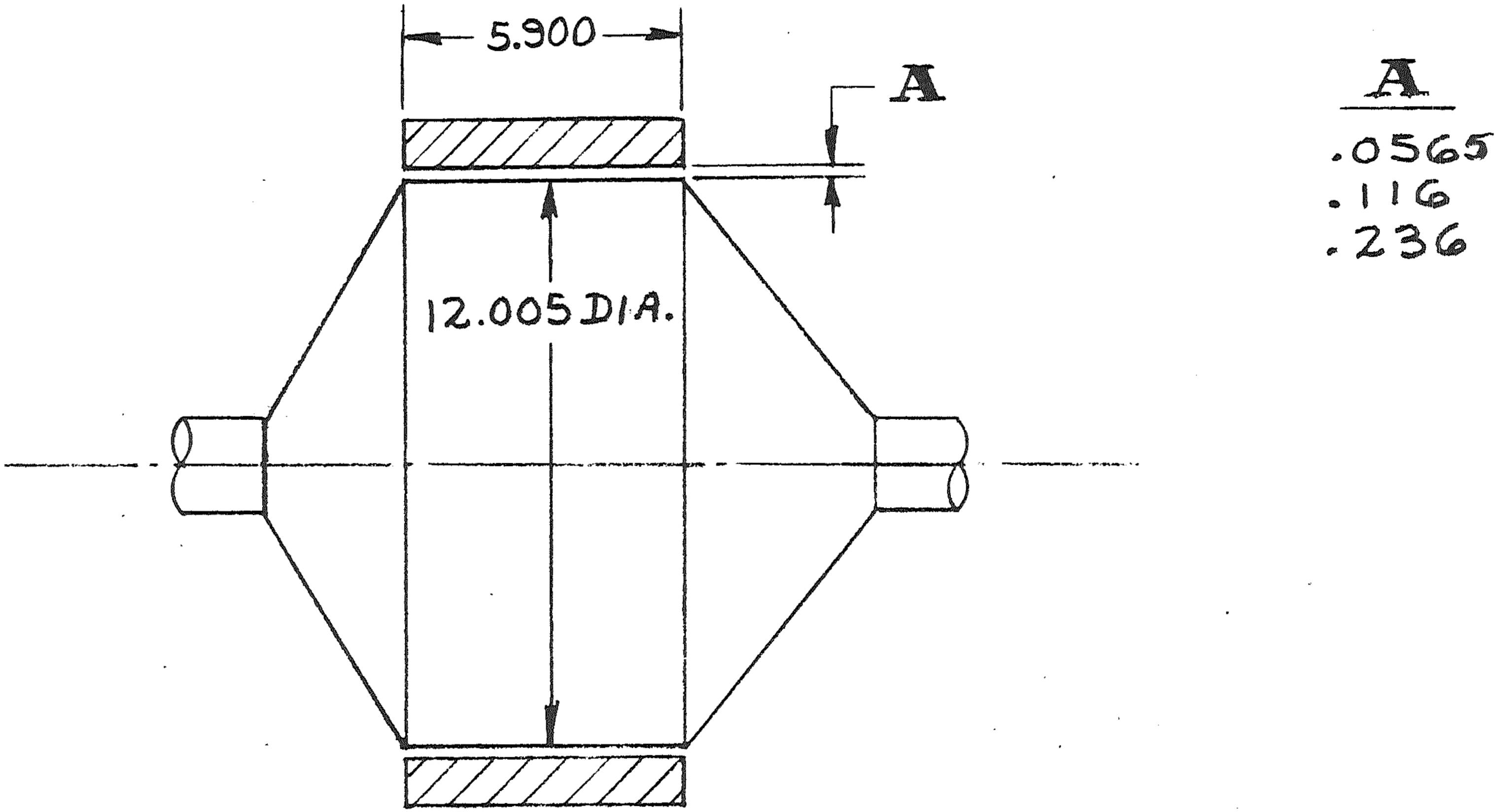


FIGURE 2. WINDAGE TEST UNIT WITH HALF THE HOUSING REMOVED



ALL DIMENSIONS IN INCHES

ROTOR - HOUSING CONFIGURATION

FIGURE 3

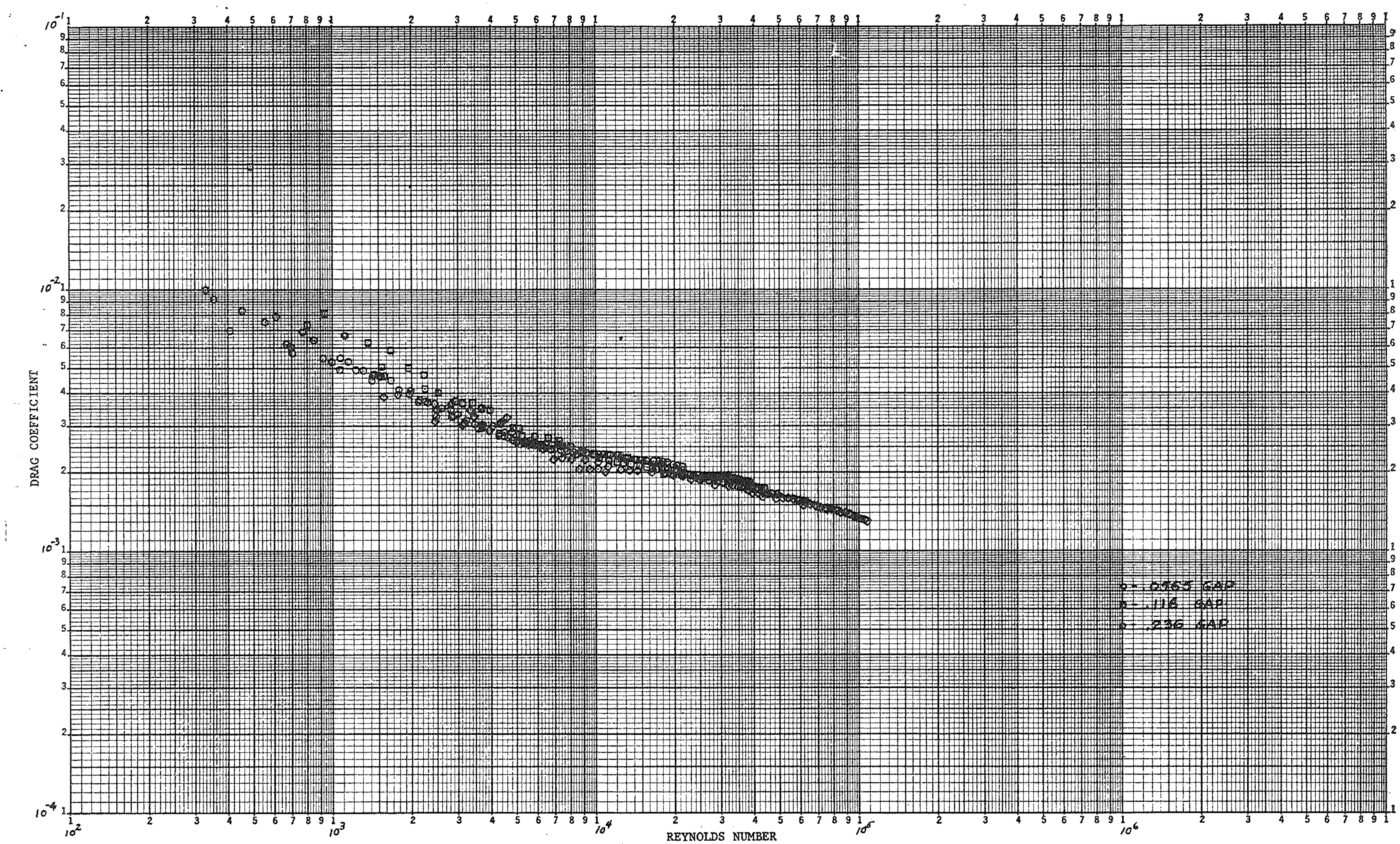


FIGURE 4. DRAG COEFFICIENT VS REYNOLDS NUMBER FOR A ROTATING CYLINDER IN A STATIONARY CYLINDRICAL HOUSING.

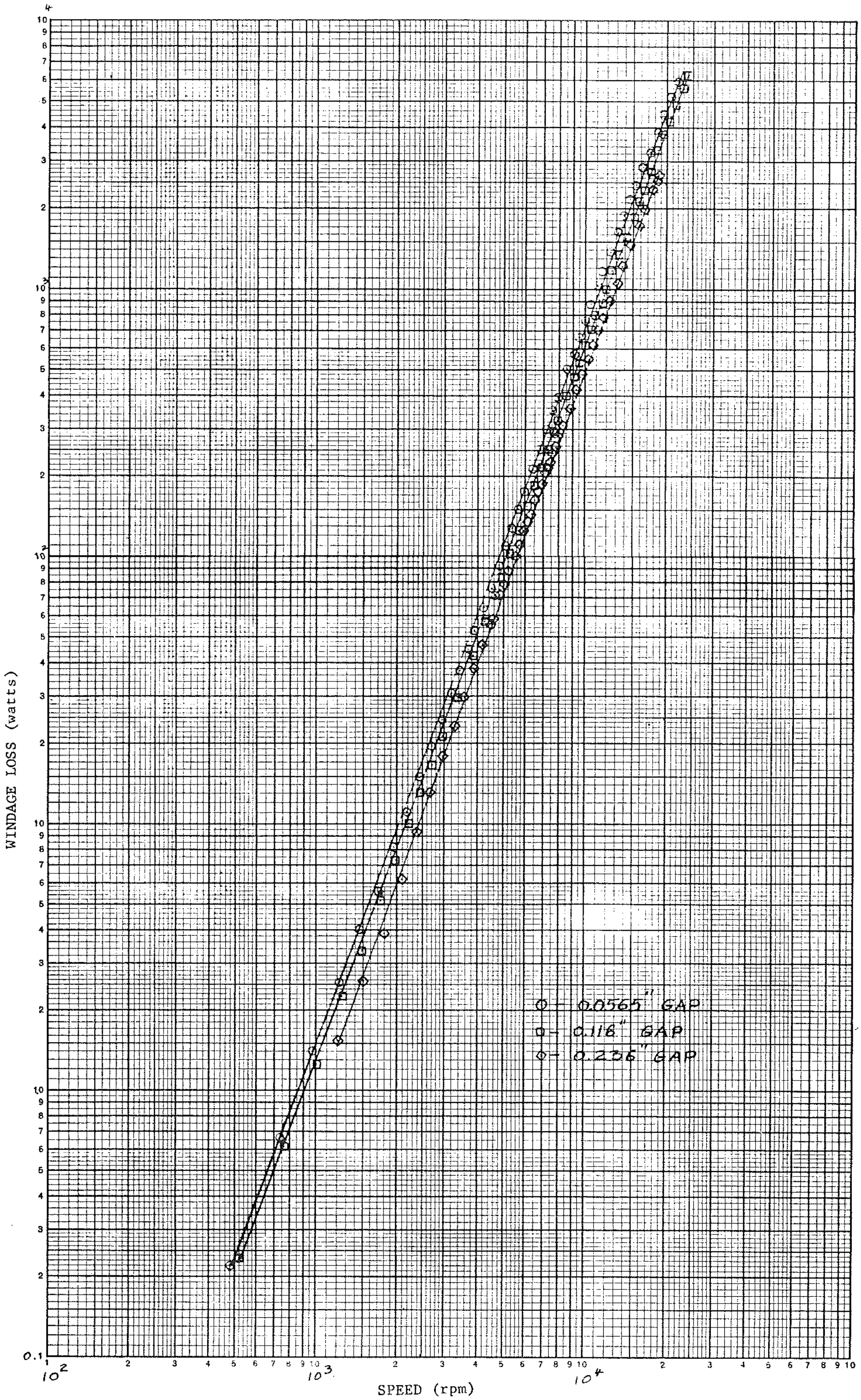


FIGURE 5. WINDAGE POWER LOSS FOR A 12-INCH DIAMETER, 5.9-INCH LONG CYLINDER ROTATING WITHIN A STATIONARY CONCENTRIC HOUSING AT VARIOUS GAPS.