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**AN INVESTIGATION OF THE AERODYNAMIC CHARACTERISTICS  
OF ROTATING CIRCULAR AND TRIANGULAR CYLINDERS**

By R. H. Heald and L. M. Sargent

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To  
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**AN INVESTIGATION OF THE AERODYNAMIC CHARACTERISTICS  
OF ROTATING CIRCULAR AND TRIANGULAR CYLINDERS**

By R. H. Heald and L. M. Sargent

Fluid Mechanics Section  
Mechanics Division

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To  
Army Chemical Center  
Maryland  
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AN INVESTIGATION OF THE AERODYNAMIC CHARACTERISTICS  
OF ROTATING CIRCULAR AND TRIANGULAR CYLINDERS

By R. H. Heald and L. M. Sargent

1. INTRODUCTION

This investigation, conducted on request of representatives of the Chemical Warfare Laboratories, Army Chemical Center, Maryland, concerned the question of lift, drag, and spin magnitudes developed by rotating missiles having circular and triangular cross sections. The models used in the experiments were free to rotate on ball-bearing spindles, and were driven by air impingement on narrow blades extending lengthwise along their surfaces. The models are shown in figure 1, and their principal dimensions are given in the headings of tables 1-4. In the cases of the large cylindrical rotor and the two triangular rotors, the lift and drag forces were sufficiently large to permit measurements on the flexure-plate balance as well as the NPL balance. The original bearing and spindle arrangement which supported each model was used in each set of measurements. All force measurements were made during steady rotation of the models.

The experiments were conducted in the National Bureau of Standards 6-foot wind tunnel at air speeds ranging between 53 and 275 feet per second. The corresponding range of Reynolds Numbers was from  $0.4 \times 10^5$  to  $3.3 \times 10^5$ , where  $RN = \frac{Vd}{\nu}$  and  $V$  = air speed, fps,  $d$  = basic diameter in the case of the circular shapes or face width in the case of the triangular shapes, feet, and  $\nu$  = coefficient of kinematic viscosity for air at 15°C and 760 mm Hg = 0.000157 ft<sup>2</sup>/sec..

2. EXPERIMENTAL PROCEDURES

The measurements for the small cylinders were all made using the NPL-type of spindle aerodynamic balance which has maximum lift and drag force capacities of about 3 pounds each and is graduated to 0.001 pound. As previously indicated the forces acting on the other three models were measured on both the NPL balance and the high-capacity flexure-plate balance. On the latter, measurements can be obtained with an accuracy of about 0.2 pound.

Each of the models was supported by a 5/16-inch ball-bearing spindle attached to the model as shown in figure 1. Lift and drag measurements were made

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on each model at a number of air speeds during steady state rotation. The rotational speeds were determined by stroboscopes at the time the force measurements were made.

The acceleration time of the triangular models was determined at an air speed slightly above 70 miles per hour. For these measurements the model was held stationary from outside the wind tunnel while the air speed in the tunnel was adjusted to the desired steady value. When this was obtained the model was released and rotation began. The time required for the model to reach steady state rotation from rest was determined using a timer reading to 0.01 second.

### 3. RESULTS

The results of this investigation are given in tables 1 - 4 and the summary table 5 which is based on mean values. They are shown plotted in figures 2 - 5. The curves shown in the figures were faired through the plotted values of rotational speed, lift coefficient  $C_L$ , drag coefficient  $C_D$ , and the ratio  $\frac{C_L}{C_D}$  given in the tables. For clarity individual points are not shown on the figures.

#### 3.1 Rotational Characteristics

As shown in figure 2, the rotational speed of the small rotor varied linearly with air speed within experimental limits, the values ranging from 1690 rpm at a wind speed of 36.3 mph to 10750 rpm at 156.8 mph. For the test range the mean value of the ratio of rotational speed in rpm to wind speed in mph was 60.1 (table 5). The mean value of the ratio of tip speed in fps to air speed in fps for this rotor was 0.208.

The rotational speeds of the large cylindrical rotor and the two triangular rotors departed appreciably from a linear relationship with air speed in the higher speed regions, possibly as a result of model and shaft distortion with consequent increased bearing friction. The speed ratios for these rotors are also given in table 5. Acceleration times were 7.87 seconds at a wind speed of 71.1 mph for the triangular rotor equipped with 30° fins, and 4.57 seconds at 72.7 mph for the rotor with 120° fins.

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### 3.2 Lift and Drag Characteristics

The results of the force measurements are given in tables 1 - 4 and are summarized in table 5. In general the data for the large cylinder and those for the two triangular shapes which were obtained using the two different balance systems are in fair agreement. As previously indicated, the flexure-plate balance is not well adapted to the measurement of small forces, i. e., those amounting to less than about 5 pounds. Although there is considerable range in the values of drag coefficient with Reynolds Number, the mean values of  $C_D$  for the two circular cylinders do not differ greatly in the range of Reynolds Numbers of the experiments,  $0.4 \times 10^5$  to  $1.6 \times 10^5$  for the small cylinder, and  $0.7 \times 10^5$  to  $3.3 \times 10^5$  for the large cylinder. For these ranges of Reynolds Numbers and including the data taken on both balances, the mean value of drag coefficient for the large cylinder is 1.031 as against a mean value of 1.010 for the small cylinder. Correspondingly, the mean values of the lift coefficient were 0.461 for the large cylinder and 0.610 for the small one. However, the values of lift coefficient for the small cylinder obtained on the spindle balance indicate the presence of substantial Reynolds Number effects,  $C_L$  ranging downward from 0.661 at R. N. =  $0.405 \times 10^5$  to 0.45 at R. N. =  $1.678 \times 10^5$ . The measurements of lift of the large cylinder which were made on both balances indicate rather small scale effects in the lower range of Reynolds Numbers, i. e., between  $0.7 \times 10^5$  and about  $1.6 \times 10^5$ . The data for the large cylinder, obtained using the flexure-plate balance, indicate an increase in  $C_L$  of about 25 percent between R. N. =  $1.7 \times 10^5$  and  $2.8 \times 10^5$ . In the vicinity of the latter value of R. N. the indications are that  $C_L$  has reached a maximum and is tending to decrease at R. N. =  $3.33 \times 10^5$ . The variation of  $\frac{C_L}{C_D}$  with Reynolds Number for both circular cylinders shows about the same pattern as  $C_L$  versus R. N., since  $C_D$  varies relatively slightly with R. N.

On the basis of mean values the triangular rotors show lower values of both lift and drag coefficient in the test range than do the cylindrical rotors. As shown in table 5, the mean value of  $C_L$  for the triangular rotor with  $90^\circ$  fins is 0.728, the individual values ranging from 0.624 to 0.839. The mean value of  $C_L$  for the triangular rotor equipped with  $120^\circ$  fins is 0.626, individual values ranging from 0.715 to 0.745. The mean values of

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$C_D$  for the 90° fin rotor is 1.392 compared with 1.577 for the rotor equipped with 120° fins. In the former case, individual values of  $C_L$  range from 1.348 to 1.471; in the latter case, the range is from 1.418 to 1.706. The mean value of  $\frac{C_L}{C_D}$  for the triangular rotor equipped with 90° fins is 17 per cent greater than that for the rotor with 120° fins.

## 4. CONCLUSION

The lift and drag characteristics of the four rotors included in these experiments show considerable variation with Reynolds Number in the test range. The values of lift and drag coefficient and  $\frac{C_L}{C_D}$  decrease continuously as the Reynolds Number is increased. On the other hand values of  $C_L$ ,  $C_D$ , and  $\frac{C_L}{C_D}$  for the large cylindrical rotor show less consistency with increased Reynolds Number. Referring to figure 3,  $C_L$  for this cylinder shows a decrease of the order of 10 per cent from about 0.48 between R.N. -  $0.7 \times 10^5$  and  $1.7 \times 10^5$ , followed by an increase above the minimum value (of about 0.43) amounting to about 40 per cent at the maximum. Two points above R.N. -  $2.8 \times 10^5$  indicate the rate of increase in this region to be lessening. The values of  $C_D$  for this rotor show considerably less variation with R.N. than the values of  $C_L$ . The range of  $C_D$  is of the order of 15 per cent, generally upward, and then downward as R.N. is increased from  $0.7 \times 10^5$  to  $3.3 \times 10^5$ . The value of  $C_D = 1.00$  at  $3.3 \times 10^5$  is close to that at R.N. -  $0.7 \times 10^5$ . Variations in the value of  $\frac{C_L}{C_D}$  with R.N. for this model follow somewhat the same pattern as of  $C_L$ .

The values of lift coefficient for the two triangular rotors, excluding three divergent points, and their means differ by only a few per cent. In both cases a downward trend in  $C_L$  is shown for values of R.N. above  $1.8 \times 10^5$ . The shapes of the  $C_D$  vs. R.N. curves differ quite appreciably, the values of  $C_D$  for the triangular rotor equipped with 120° fins averaging about 14 per cent greater than for the rotor with 90° fins.

For the Director,

*G. E. Schuber*

G. E. Schuber, Chief  
Fluid Mechanics Section

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Table 1  
 Cylindrical Rotor (Small)  
 $(C_{L1}, C_{D1}, L, H, A, B, \beta)$   
 Length 4.60 inches, Diameter 1.50 inches  
 Fin Angle 30 degrees, Fin Width 0.187 inches  
 Lift, Drag, and Rotational Speed

Air Speed fps	Air Speed mph	Lift lb	Drag lb	Rotation rpm	Coefficients		$\frac{C_L}{C_D}$	Reynold's Number	Tip Speed, fps Air Speed, fps	Rotational Speed, rpm Air Speed, mph
					Drag ( $C_D$ )	Lift ( $C_L$ )				
Spindle (NPL) Balance										
51.3	36.3	0.139	0.169	1690	1.046	0.861	0.822	$0.405 \times 10^5$	0.208	46.6
72.7	49.7	.244	.322	2600	1.061	.804	.758	.553	.233	52.3
87.2	59.4	.327	.460	3250	1.062	.755	.711	.659	.244	54.7
100.8	68.7	.391	.606	3950	1.044	.674	.645	.757	.257	57.5
117.5	80.1	.509	.832	4550	1.055	.646	.612	.883	.254	56.8
133.2	90.8	.621	1.063	5550	1.046	.613	.584	.999	.273	61.1
143.8	95.0	.684	1.233	6000	1.046	.580	.555	1.077	.273	61.2
166.8	111.7	.858	1.659	7150	1.045	.541	.517	1.250	.281	62.9
181.5	123.7	.913	1.938	7950	1.031	.486	.471	1.351	.289	64.3
192.9	131.5	.970	2.126	8700	1.001	.457	.456	1.420	.295	66.2
208.9	142.4	1.095	2.481	9750	.996	.448	.441	1.531	.306	68.5
230.0	156.8	1.359	3.144	10750	1.041	.450	.432	1.678	.306	68.5
averages					1.040	0.610	0.584		0.268	60.1

$$C_L = \frac{L}{\frac{1}{2}\rho A V^2}$$

$$C_D = \frac{D}{\frac{1}{2}\rho A V^2}$$

$$1/2\rho A = 0.0000571$$

Area computed on basis of basic diameter (1.50 inches)  
 Tip speed computed on basis of basic diameter (1.50 inches)  
 Reynold's Number computed on basis of basic diameter (1.50 inches)

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Table 2  
 Cylindrical Rotor (Large)  
 ( $C_{L_1} - D_2 L_2 H_6 A_3 B_2$ )  
 Length 7.62 inches; Diameter 2.50 inches  
 Fin Angle 30 degrees, Fin Width 0.230 inches  
 Lift, Drag, and Rotational Speed

Air Speed		Lift	Drag	Rotation	Coefficients		$\frac{C_L}{C_D}$	Reynold's	Tip Speed, fps	Rotational Speed, rpm
fps	mph	lb	lb	rpm	Drag ( $C_D$ )	Lift ( $C_L$ )	$\frac{C_L}{C_D}$	Number	Air Speed, fps	Air Speed, mph
Spindle (WT) Balance										
56.8	38.7	0.240	0.507	1650	1.002	0.474	0.473	$0.718 \times 10^5$	0.317	42.6
80.3	54.7	.487	1.039	2410	1.030	.483	.469	1.012	.328	44.0
104.6	71.3	.763	1.710	3180	.996	.444	.446	1.318	.332	44.6
128.8	87.8	1.149	2.605	4010	1.001	.442	.441	1.619	.339	45.7
158.0	107.7	1.719	3.904	5100	.997	.439	.440	1.979	.352	47.3
182.2	124.2	2.635	5.169	6700	.970	.494	.510	2.275	.389	52.3
averages					0.999	0.463	0.463		0.363	49.1

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Table 2 (continued)

Air Speed fps	Air Speed mph	Lift lb	Drag lb	Rotation rpm	Coefficients			Reynold's Number	Tip Speed, fps Air Speed, fps	Rotational Speed, rpm Air Speed, mph
					Drag (C <sub>D</sub> )	Lift (C <sub>L</sub> )	$\frac{C_L}{C_D}$			
Flexure Plate Balance										
59.6	40.6	-	0.6	1820	1.020	-	-	0.75 $\times 10^5$	0.332	44.8
80.1	54.7	0.5	1.1	2560	1.090	.496	0.455	1.009	.347	46.8
106.4	72.5	.8	2.0	3520	1.129	.451	.400	1.336	.361	48.5
134.2	91.5	1.2	3.2	4650	1.132	.425	.375	1.681	.378	50.8
157.1	107.1	1.9	4.2	5600	1.085	.491	.452	1.962	.388	52.3
182.1	124.1	2.4	5.5	6000	1.058	.462	.436	2.262	.359	48.3
208.2	141.9	3.8	6.9	6380	1.015	.559	.551	2.508	.334	44.9
234.1	159.6	5.1	8.7	7420	1.012	.593	.586	2.863	.346	46.5
274.5	187.1	6.8	11.8	7360	<u>0.999</u>	<u>.576</u>	<u>.576</u>	3.327	<u>.292</u>	<u>39.6</u>
averages					1.060	0.459	0.479		0.350	46.9

$$C_L = \frac{L}{1/2\rho AV^2}$$

$$C_D = \frac{D}{1/2\rho AV^2}$$

$$1/2\rho A = 0.0001569$$

Area computed on basis of basic diameter (2.50 inches)  
 Tip speed computed on basis of basic diameter (2.50 inches)  
 Reynold's Number computed on basis of basic diameter (2.50 inches)

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Table 3  
 Triangular Rotor (90° Fins)  
 Length 10.00 inches, Width of Face 3.25 inches  
 Fin Angle 90 degrees, Fin Height 0.43 inches  
 Lift, Drag, and Rotational Speed

Air Speed		Lift	Drag	Rotation	Coefficients			Reynold's	Tip Speed, fps	Rotational Speed, rpm
fps	mph	lb	lb	rpm	Drag (C <sub>D</sub> )	Lift (C <sub>L</sub> )	$\frac{C_L}{C_D}$	Number	Air Speed, fps	Air Speed, mph
Spindle (NPL) Balance										
57.1	38.9	0.731	1.181	2190	1.348	0.835	0.619	0.904x10 <sup>5</sup>	0.629	56.3
72.8	49.6	1.199	1.959	2850	<u>1.380</u>	<u>.624</u>	<u>.612</u>	2.149	<u>.641</u>	<u>57.4</u>
averages					1.364	0.730	0.616		0.635	56.9
Flange Plate Balance										
55.2	37.6	-	1.2	2080	1.471	-	-	0.892	0.618	55.3
61.4	55.5	1.5	2.5	3150	1.404	0.843	0.600	1.313	.635	56.8
104.2	71.0	2.5	4.1	4050	1.408	.859	.610	1.680	.637	57.1
125.7	85.7	3.6	5.9	4800	1.390	.848	.610	2.022	.626	56.0
157.3	107.2	5.3	9.5	5350	<u>1.431</u>	<u>.798</u>	<u>.558</u>	2.522	<u>.558</u>	<u>49.9</u>
averages					1.421	0.839	0.595		0.615	55.0

acceleration time - 7.67 sec at an air speed of 71.1 mph

$$C_L = \frac{L}{1/2\rho AV^2} \quad C_D = \frac{D}{1/2\rho AV^2} \quad 1/2\rho A = 0.0002687$$

Area computed on basis of one face (3.25 inches)

Tip speed computed on basis of circumference of circumscribed circle (radius equal 1.88 inches)

Reynold's Number computed on basis of one face (3.25 inches)

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Table 4  
 Triangular Meter (120° Fins)  
 Length 10.00 inches, Width of Face 3.25 inches  
 Fin Angle 120 degrees, Fin Height 0.43 inches  
 Lift, Drag, and Rotational Speed

Air Speed		Lift	Drag	Rotation	Coefficients			Reynold's	Tip Speed, f/s	Rotational Speed, rpm
f/s	mph	lb	lb	rpm	Drag (C <sub>D</sub> )	Lift (C <sub>L</sub> )	C <sub>L</sub> /C <sub>D</sub>	Number	Air Speed, f/s	Air Speed, mph
<u>Spindle (NPL) Balance</u>										
54.0	36.8	0.637	1.161	1760	1.418	0.813	0.549	0.856x10 <sup>5</sup>	0.535	47.8
72.7	49.7	1.321	2.431	2610	1.702	.925	.510	1.152	.453	52.5
97.9	66.7	2.134	3.911	3310	<u>1.522</u>	<u>.830</u>	<u>.546</u>	1.541	<u>.555</u>	<u>49.6</u>
averages					1.547	0.856	0.545		0.514	50.0
<u>Flexure Plate Balance</u>										
60.9	41.5	0.8	1.7	2030	1.706	0.803	0.471	0.984	0.547	48.9
81.6	57.0	1.4	3.0	2830	1.590	.745	.467	1.349	.555	49.6
107.2	73.1	2.6	4.9	3610	1.583	.842	.531	1.730	.552	49.4
132.8	90.5	4.0	5.4	4150	1.141*	.845	.741*	2.139	.550	49.2
161.5	110.1	5.6	11.0	5300	1.570	.799	.509	2.589	.538	48.1
181.6	123.8	6.8	14.1	5550	<u>1.580</u>	<u>.767</u>	<u>.482</u>	2.905	<u>.501</u>	<u>44.8</u>
averages					1.606	0.800	0.492		0.541	48.3

Acceleration time - 4.57 sec at an air speed of 72.7 mph.  
 \* Omitted from mean and range data in table 5.

$$C_L = \frac{L}{\frac{1}{2}\rho AV^2} \quad C_D = \frac{D}{\frac{1}{2}\rho AV^2} \quad 1/2\rho A = 0.0002687$$

Area computed on basis of one face (3.25 inches)  
 Tip Speed computed on basis of circumference of circumscribed circle, (radius equal 1.88 inches)  
 Reynold's Number computed on basis of one face (3.25 inches)

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Table 5  
Summary

Range of Mach	Air Speed Range		R. M. Range		$C_L$		$C_D$		$\frac{C_L}{C_D}$		Speed Ratios		
	Min	Max	Min	Max	Range	Mean	Range	Mean	Range	Mean	Rotational Speed, rpm to Air Speed, mph	Tip Speed, fps to Air Speed, fps	
0.10 to 0.15	53.3	36.3	0.105x10 <sup>5</sup>	0.140x10 <sup>5</sup>	0.450	0.996	0.432	0.584	0.432	0.584	46.6 to 66.5	60.1	0.208 to 0.306
	130.0	156.8	1.670x10 <sup>5</sup>	1.670x10 <sup>5</sup>	0.861	1.062	0.822						
0.15 to 0.20	54.8	38.7	0.710x10 <sup>5</sup>	0.710x10 <sup>5</sup>	0.439	0.970	0.375	0.472	0.375	0.472	39.6 to 52.3	48.0	0.292 to 0.389
	137.5	137.1	3.327x10 <sup>5</sup>	3.327x10 <sup>5</sup>	0.593	1.132	0.586						
0.20 to 0.25	57.1	38.9	0.904x10 <sup>5</sup>	0.904x10 <sup>5</sup>	0.624	1.348	0.558	0.606	0.558	0.606	49.9 to 57.4	55.9	0.558 to 0.641
	137.3	137.2	2.522x10 <sup>5</sup>	2.522x10 <sup>5</sup>	0.859	1.471	0.619						
0.25 to 0.30	58.0	36.8	0.856x10 <sup>5</sup>	0.715	0.715	1.418	0.467	0.519	0.467	0.519	44.8 to 52.5	49.2	0.453 to 0.528
	131.6	133.8	2.905x10 <sup>5</sup>	0.925	0.925	1.706	0.549						

Note: The maximum and minimum values of  $C_L$ ,  $C_D$  and  $\frac{C_L}{C_D}$  given in the "Range" columns do not always correspond to the maximum and minimum values of Air Speed and R.M. See detailed data given in Tables 1 - 4. Mean values of  $C_L$ ,  $C_D$  and  $\frac{C_L}{C_D}$  and the speed ratios are based on data obtained on both the spinball balance and the clearance-plate balance.

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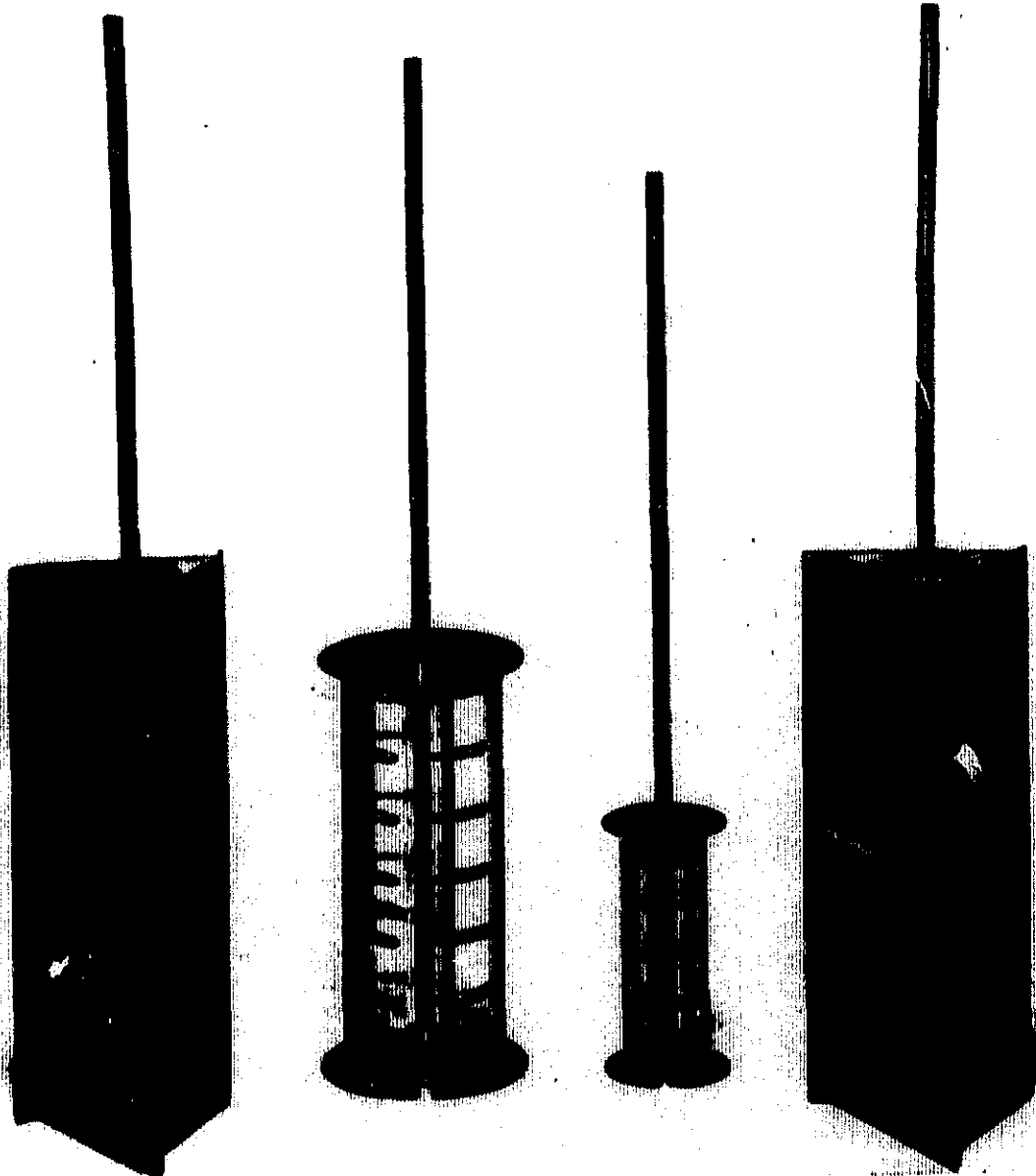


Figure 1

View of the four models. Reading from left to right: Triangular Rotor, 90 degree fins; Large Cylindrical Rotor ( $C_4-D_4-L_4-N_4-A_4-B_4$ ); Small Cylindrical Rotor ( $C_4-D_4-L_4-N_4-A_4-B_4$ ); Triangular Rotor, 120 degree fins.

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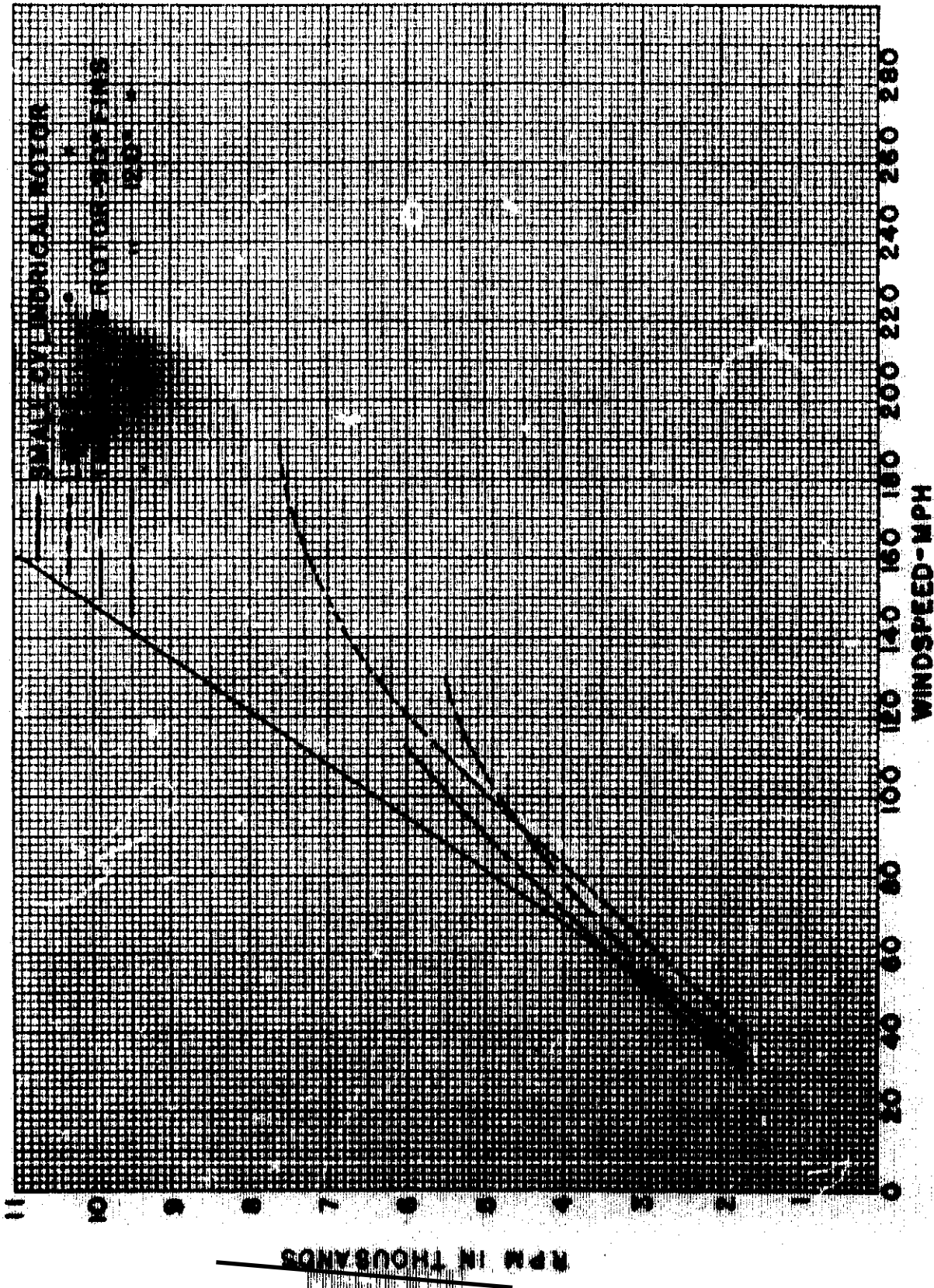


FIGURE 2

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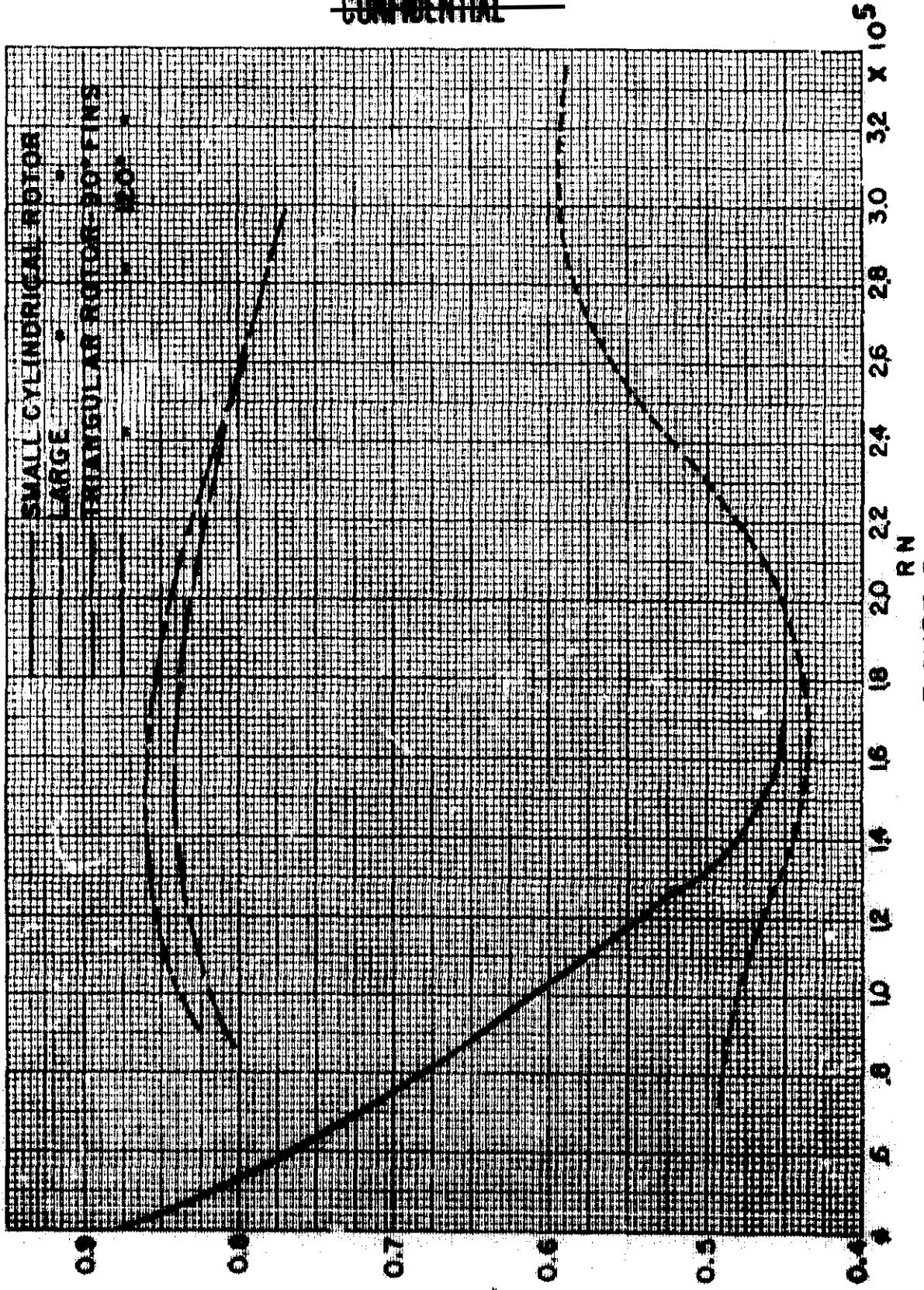


FIGURE 3

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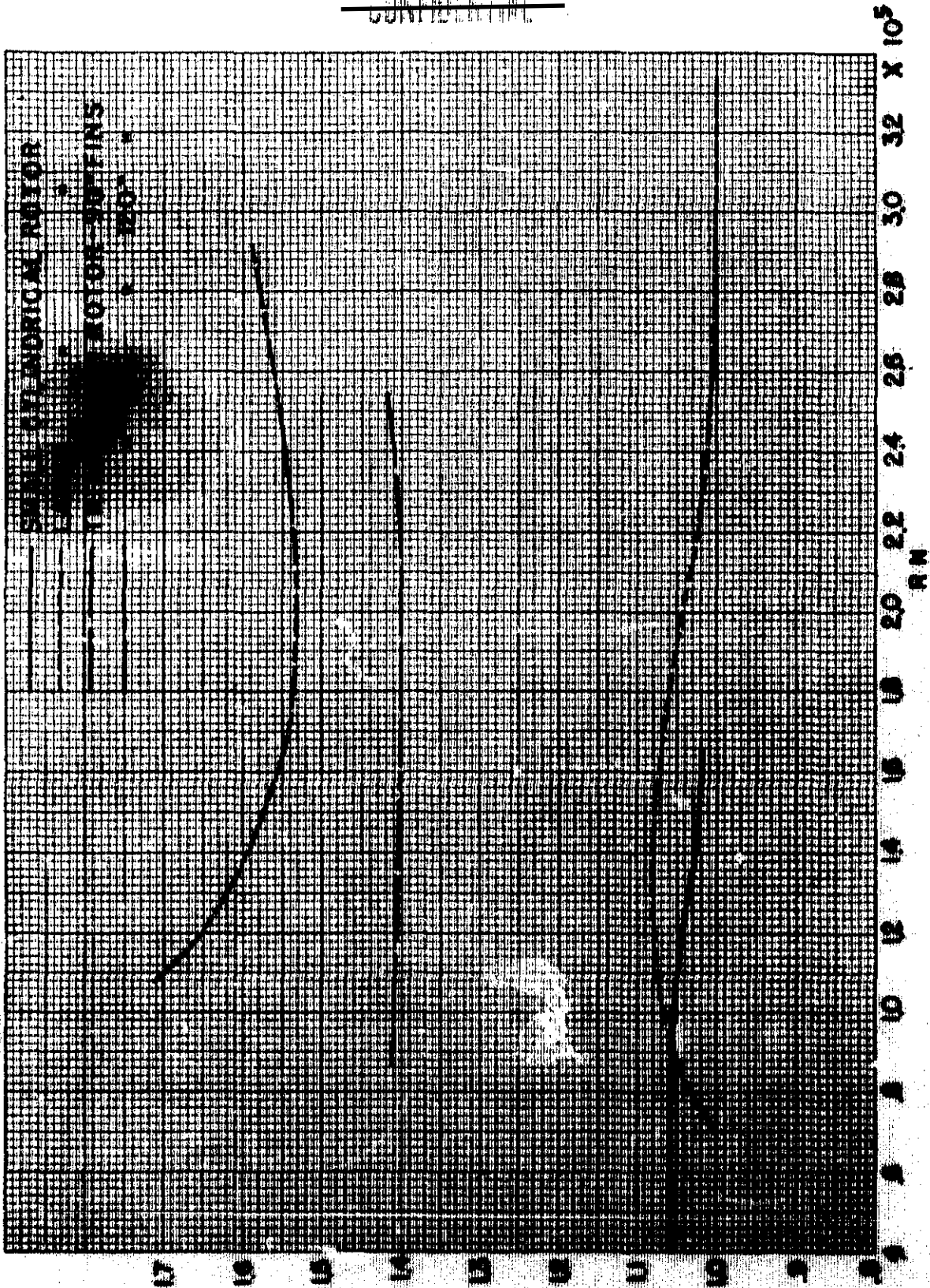


FIGURE 4

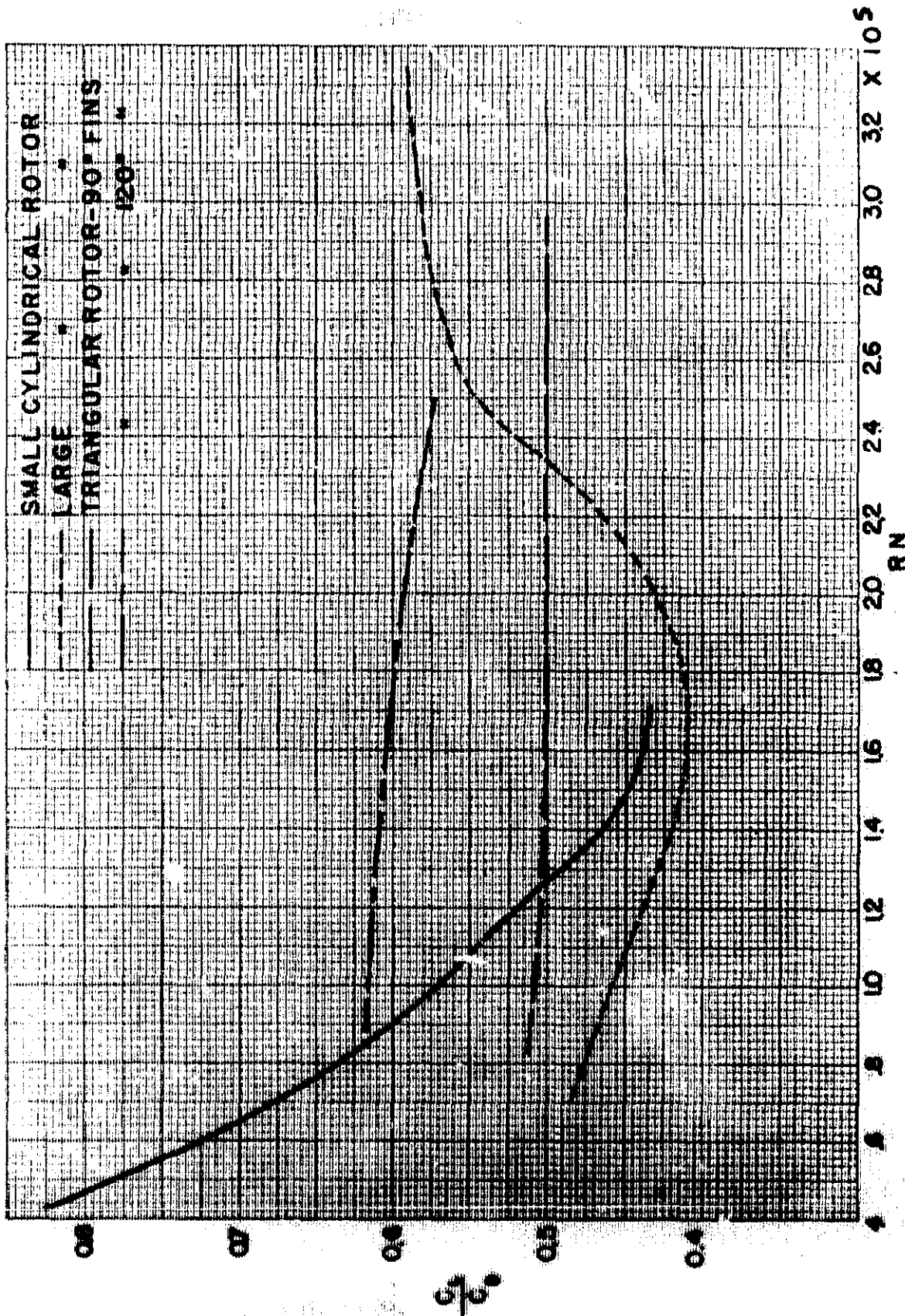


FIGURE 5