An

INVESTIGATION

of the

AERODYNAMIC CHARACTERISTICS

of

ROTATING WIND-DRIVEN AIRFOILS

Submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Aeronautical Engineering from the

MASSACHUSETTS INSTITUTE of TECHNOLOGY

June 1925

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ACKNOWLEDGEMENT

Appreciation is hereby expressed for the advice and assistance given by Professor Edward P. Warner, and for the encouragement and interest of Mr. C. P. Burgess and Mr. Heraclio Alfaro.

INTRODUCTION

At the outset it should be understood that this investigation was not an attempt to obtain results from the innumerable combinations of airfoils, angles of yaw, angles of attack, aspect ratios or other conditions possible to obtain in " Auto-rotors "; but rather to lay the foundation for further study of the possibilities of rotating airfoils, and the phenomena of auto-rotation. The authors have attempted to obtain data on a sufficient variety of operating conditions to allow some logical mathematical development of the results along numerous diversions.

It has been assumed that the reader is familiar with the characteristics of airfoils functioning under normal conditions and also acquainted with the manner of testing in a wind tunnel. On that basis much of the preparation, minor details and methods of obtaining results have been omitted except where inclusion of these has direct bearing on the understanding of the results.

For the explanation of results, in several instances, conclusions have been drawn, assumptions made and explanations offered, but these are in no way final. Where phenomena of unusal nature was observed it has been explained in detail allowing the reader to make his own explanation and draw similar conclusions.

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THEORY

Consider a set of airfoils arranged to rotate as a windmill. An element along the blade will have a velocity of rotation which may be transposed to corresponding lineal velocity and represented by the vector $OA = V_R$ (Fig. 1). This is equivalent to the wind striking the element with the same velocity in the reverse direction and represented by the vector AO. If the velocity of the wind perpendicular to the plane of rotation of the blades is represented by the vector $BO = V_W$, then the resultant direction and velocity of the wind with respect to the blade is $CO = V$.

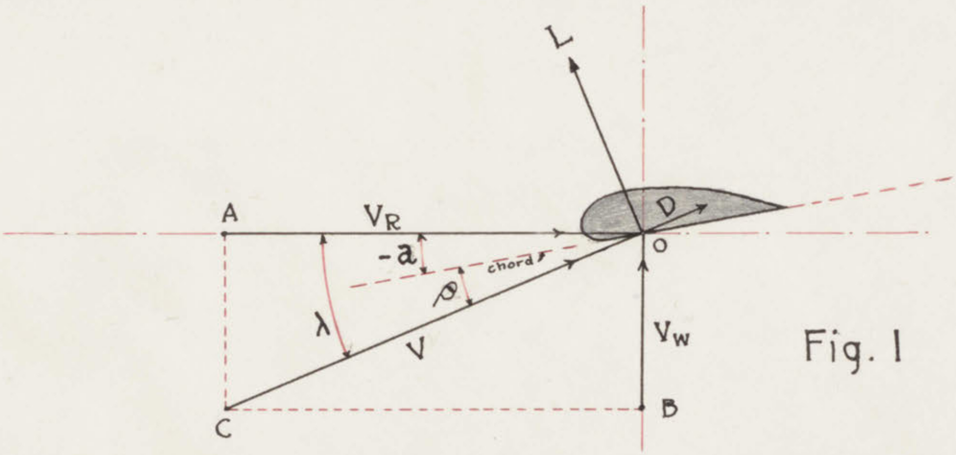


Fig. 1

Consider the blade initially set in its holders so that its chord is inclined at an angle $-a$ to the plane of rotation. The angle the resultant wind makes with the plane of rotation of the blades is $\lambda = -a + \beta$. Therefore, the resultant angle angle of attack of the element is $\beta = \lambda - a$. As determined from the characteristics of airfoil sections, at this angle of attack the element will have a drag(parallel to the wind) equal to D and a lift (perpendicular to the wind) equal to L . Then the pressure along the axis equals L cos $(a+\beta)$ + D sin $(a+\beta) = P$.

Also, $\tan(a+\beta) = \frac{V_W}{V_R} = \frac{D}{L}$

As the rotational velocity is so great with respect to the wind velocity, V_R may be considered equal to V without appreciable error. Therefore,

$$\frac{D}{L} = \frac{V_W}{V} \qquad \text{or,} \qquad V = V_W\left[\frac{L}{D}\right]$$

Substituting in the standard formula

$$L = L_c\, S\, V^2 \quad ,$$

this becomes

$$L = L_c\, S\, V_W^2 \left[\frac{L}{D}\right]^2$$

When S and V each equal unity,

$$L = L_c\left[\frac{L}{D}\right]^2$$

which shows that the lift and consequently the pressure along the axis is a function of $L_c\left[\frac{L}{D}\right]^2$. As shown further on β at the tip of the blade is small and increases toward the axis due to the decrease of radius and hence decrease of V_R. Thus, for best results, it is essential to use a wing section having high values of this coefficient $L_c\left[\frac{L}{D}\right]^2$. In graph A, values of this coefficient have been plotted for a number of popular sections and it will be seen that the USA-35 B gives a wide range of high values endorsing its use.

In Fig. 2, it will seen that the resultant for a particular example slopes forward of the axis of rotation at an angle μ. The pressure parallel to the axis will be R cos μ, and that parallel to the plane of rotation R sin μ. This latter component will obviously tend to accelerate the rotational speed. In turn, as the Vr increases and the Vw stays constant, V will increase and β and λ will decrease. As β decreases, the lift (@ 9o° to V) decreases its angle to the axis and decreases the angle μ, and this will decrease the component R sin μ or the accelerating force. This process will continue until the line of action of R is parallel to the axis of rotation.

Should the speed increase slightly beyond this point, R will lie on the opposite side of the axis and the component $-R \sin\mu$ will decelerate the speed; hence, at some speed where the resultant force lies parallel to the axis there will be no acceleration nor deceleration and rotation will remain in equilibrium under the steadying influence of these two forces.

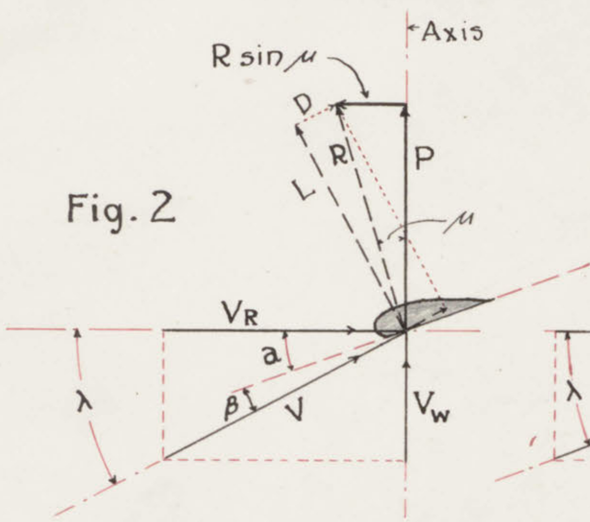


Fig. 2

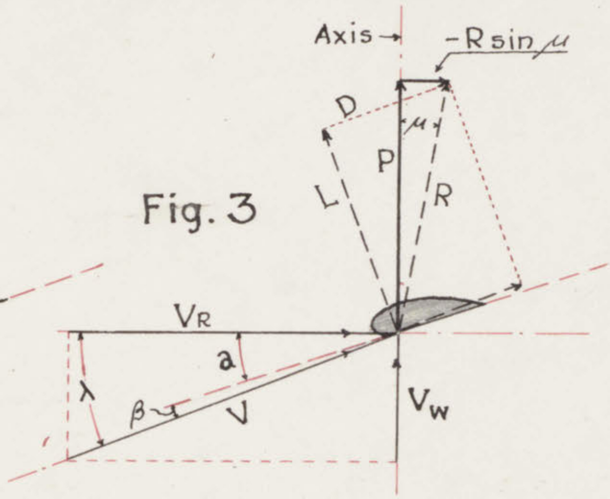


Fig. 3

At low rotational speeds, the angle of attack β will be great with consequent small lift and large drag and the resultant will lie on the trailing side of the axis. The component $-R \sin\mu$ (Fig. 3.) will decelerate the r. p. m. which in turn increases the angle of attack , increasing the drag in greater proportion than the lift. This will increase $-R \sin\mu$ and slow down the speed until the blades rotate as an ordinary windmill.

Thus, it is necessary to initially get the speed of rotational velocity above the first value at which the component R sin μ is positive. Once above this point, the mill will accelerate itself until it reaches it steady speed as explained above.

This effect of the accelerating component of the resultant of the lift and drag has been called herein the " Auto-rotational Effect " and the mill in which it acts, an " Auto-rotor ".

APPARATUS

All tests were made in the four foot wind tunnel at the MASSACHUSETTS INSTITUTE of TECHNOLOGY, using a wind velocity of twenty miles an hour (20mph).

The blades tested were mounted on thin wide phosphor bronze plates as shown in Fig. 4, and this arrangement was mounted on a ball bearing held on a horizontal shaft which in turn was mounted in the spindle of the wind tunnel balance. The bronze plates were flexible to some extent allowing the blades to spring slightly in a direction parallel to the shaft without changing their angle of attack. It was found that this feature damped out most of the vibration of the rotating mill giving steadier balance readings and preserving the pivot point of the balance better than in former tests where stiff connections between the blades and bearings were used. The use of an accurate ball bearing with no thrust play and negligible wobbling play further enhanced the accuracy. For all practical purposes, the initial braking torque due to friction of the bearing may be considered nil so that the mills are assumed to operate freely rotating.

In all tests, the blade section remained the same from root to tip and no tapered sections were used. The blades used were, with the exception of the segment section, accurately cut to coordinates on a model-wing cutting machine. The symmetrical and Pomilio sections were correspondingly accurate.

The blades used and their dimensions were as follows:

Section	Length (each blade)	chord	A. R.
U. S. A. 35 B	7.75"	1.5"	5.17
Pomilio (Large)	7.75"	1.75"	4.43
Pomilio (Small)	7.75"	1.15"	6.73
Segment (3" diameter)	7.75"	1.5"	5.17
Symmetrical	7.75"	1.5"	5.17

Flat plate of diameter = 18.25".

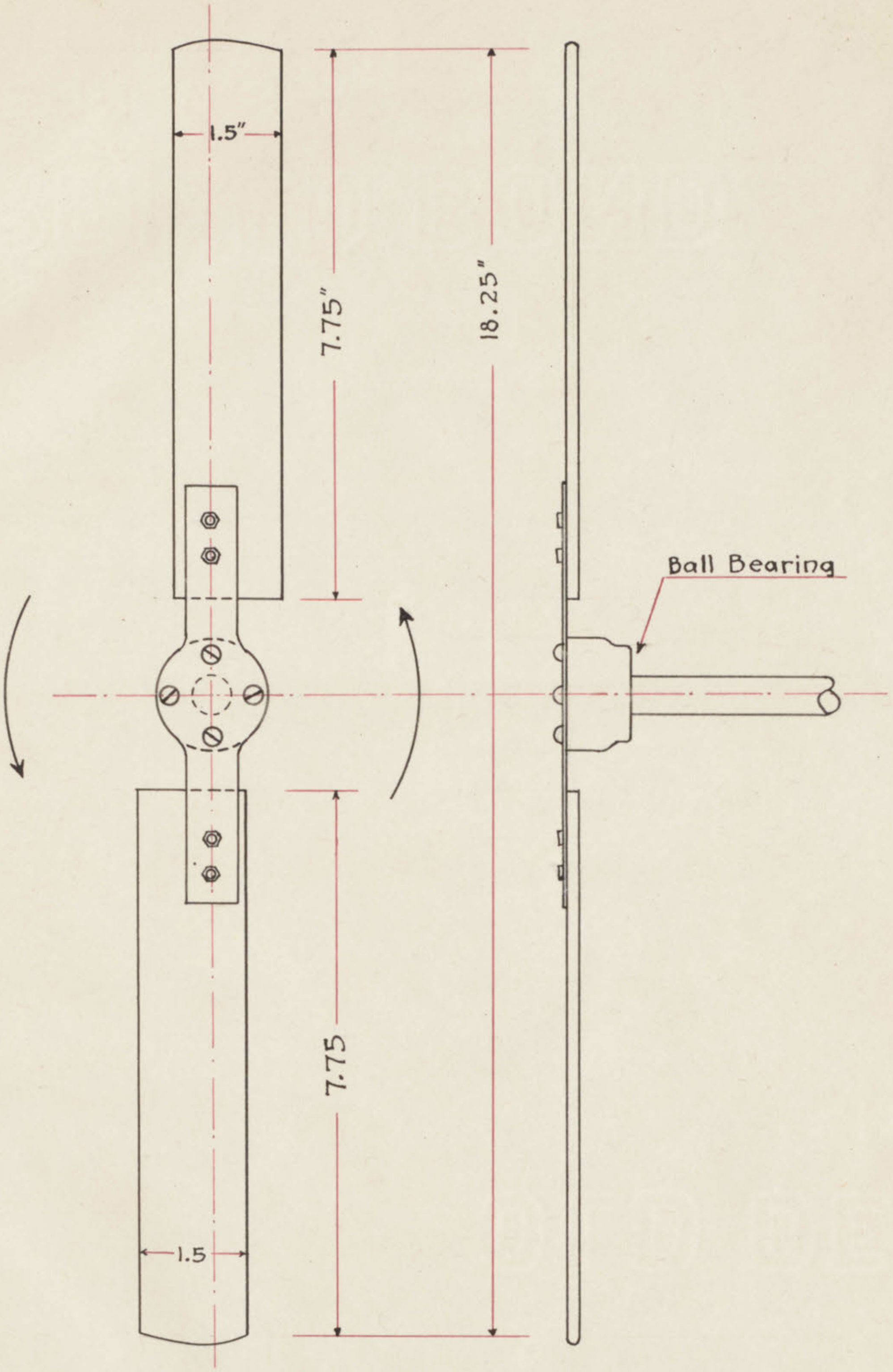


Fig. 4.

PROCEEDURE

"Zero" drags and lifts were first measured on the spindle, shaft and bearing with a wind velocity of twenty miles per hour (20 m.p.h.) for angles of yaw between 0° and 90°. These were then corrected at each station angle for the error introduced by the intereference of the rotating mill. The actual velocity of the air that flowed through the mill was determined by placing a Pitot tube in the plane of the spindle above it and taking readings from the shaft radially outward, at intervals as shown in graph B . This corrected reading was again corrected at each station angle of yaw for the effect that the weight of the blades (not rotating and with no wind) made on the readings. Thus, correct zero readings for the drag and lift at each station angle of yaw due to the wind on the spindle, etc., and due to the moment of the weight of the apparatus resulted.

When the blades were initially set at negative angles of attack, the wind rotated them forward as a windmill. The rotational speed increased gradually till the auto-rotor effect or the accelerating component of the resultant came into play at which instant there was a sudden and sharp increase of speed and rapid acceleration to the equilibrium speed.

With the plane of the blades at right angles to the wind stream, the force parallel was called drag of the mill and the force 90° to the wind stream was called the lift of the mill. These were symbolized as " D_m" and as " L_m" respectively. Readings on the drag and lift arms of the balance and the r. p. m. (by mechanical stroboscope) were taken at each station angle of yaw. Likewise, the actual mean velocity of the air flow in the tunnel was taken by Pitot tube placed far enough ahead of the mill that the effect of the distortion of the outflow was not included. (It is here that the difference between free air conditions and confined flow must be noted, for, in the wind tunnel the path of the outflow is confined while in free air different conditions exist. The area of the disk covered by the rotating blades at an angle of yaw of 90 degrees constitutes 14.45% of the cross-sectional area of the tunnel. The result of the blocking effect and the nozzling of the outflow around the disk is shown by graph B .)

In order that a fair comparison with properties of a flat plate may be made under the same conditions, a circular flat plate of the same diameter was tested in the same manner as the mills for the same angles of yaw. The ratio of the mill results to the flat plate results as measured in the tunnel should give a fairly good approximation to corresponding ratios in free air.

With constant setting of the wind tunnel power motor resistance, it was found that the mean velocity of the wind in front of the mill varied as the angle of yaw of the mill was changed, increasing as θ decreased and caused the mill to present less projected area to the cross-section of the tunnel. Therefore, to bring the results to a comparable basis of a 20 mph. wind, the difference between the measured readings and the zero readings was multiplied by the " square-of-the-velocity" ratio at each station angle.

While the r. p. m., for a constant speed of the wind tunnel propeller, stayed constant from values of $\theta = 90°$ to $\theta = 45°$ in most cases in the actual test of the mills, the variation of the wind, as explained above, and the correction ratio just mentioned causes the r. p. m. to be shown varying over this range in the tables of results. In most tests, the rotational speed stayed constant to some angle of yaw near 45,° then suddenly "broke" and stayed at an equilibrium speed for each station angle. (See Graph C for variation of wind velocity with angle of yaw.) (Graph D shows corrected r. p. m. for $V_w = 20$ miles per hour.)

Readings were taken at intervals of angle of yaw as recorded in the results, down to the angle of yaw at which the mill ceased to rotate. Above this angle, it was found that there was an angle at which it was visible that the the auto-rotor effect either decreased rapidly or ceased to function, but the mill continued to rotate as a wind mill. An inspection of the curve of speeds (Graph D) will show this to some extent while sudden breaks of speed are noted in the tables of results.

In each case, the $D_{c_{mill}}$ and $L_{c_{mill}}$ were obtained by dividing the corrected drag and lift in pounds by the product of the swept area of the mill in square feet and the square of the velocity in miles per hour, thus giving the coefficients in standard pounds per square foot per mile per hour units. In the same manner the coefficients for a flat plate under the same conditions were computed for comparison.

The vector sum of resultant of the D and L were computed and in the case of the flat plate and

U.S.A. 35 B section at an angle of attack equal 0°
the angle that this resultant made with the perpendicular to the plane of rotation of the mill is tabulated. The forces perpendicular and parallel to the plane of the blades were also computed in this case to give a general idea of the behavior of these forces. With other blades and angles of attack these latter figures (Δ, R cos Δ, and R sin Δ) (Fig. 5) have been omitted except where wide deviation from the example mentioned justifies including them.

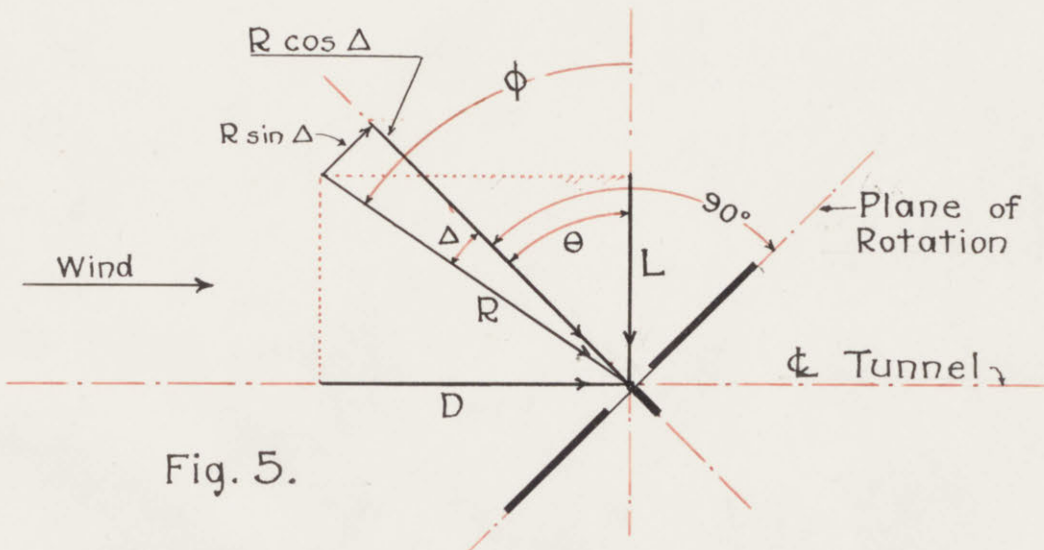


Fig. 5.

To show the effect of chord and aspect ratio, two runs were made using a Pomilio section, the blades having the same length but different chords. The results are shown in the tables of results and in Graph E.

A symmetrical section was tried with $a = 0°$ and with $\theta = 90°$ but with the means at hand, it was impossible to get this to rotate above the speed shown in Graph D .

In like manner, tests were made on four-bladed mills using U.S.A. 35 B sections. Results were obtained to show the effect of increasing the number of blades. A run was made with $a = 0°$ for several angles of yaw in order that comparison through a range might be made with the two-bladed mill at $a = 0°$ using the same sections.

A crude section was tested using blades whose section was the segment of a 3 inch circle having a chord of 1.5". This gave a set of results which are interesting inasmuch as the section was quickly turned out of a lath by rough whittling and sand papering down to smooth contour.

A very important fact is to be noted in that when the blades were set at 0° angle of attack and the plane of rotation at 90° to the wind, there was no initial tendency to rotate. When given a slight rotational velocity hy hand, the mill slowed down and refused to run. This initial velocity was increased until the speed of the mill got above its " hump speed" or speed at which the auto-rotational effect became active at which point the mill " caught " and accelerated itself up to its equilibrium speed. With $a = +3^{\circ}$, the mill initially tended to rotate backward and would have reached a hump speed in that direction had it not been stopped and accelerated above its hump speed rotating forward. Although not measured, this hump speed forward is thought to lie between the range of 500 to 800 r. p. m. Once above this, the mills raced to their first steady speed as shown in Graph D for the steady speeds at each angle of yaw. This hump speed changed for the same blade when set at different angles of attack. However, this value of hump speed will not be the same for larger mills at the same angle of attack as a clear understanding of the theory will show.

No effort was made to obtain readings with torque applied as a brake to the speed nor with mills in tandem. Neither was the scale effect investigated.

DISCUSSION OF RESULTS

DRAG.

The highest drag was found with the four-bladed U.S.A. 35 B mill at $\theta = 90^\circ$ with all blades at $\alpha = 0^\circ$. The value found was 0.00495 for D_c . This is 83.4% of a flat plate D_c which was found to be 0.00593 when determined under similar conditions. (See Graphs F and G). Comparison of the D_c 's at $\theta = 90^\circ$ is shown in Graph G .

INCREASING CHORD.

Increasing the chord by 52.2% (and thereby decreasing the aspect ratio and increasing the blade area by the same percentage) increased the D_c at $\theta = 90^\circ$ by 33.7% and increased the max. L_c at $\theta = 45^\circ$ from 0.00117 to 0.00193 or an increase of 44.7% . The $\frac{L}{D}$ increased by 10.6% at $\theta = 30^\circ$. (See Graph E) How far this increase in blade area will continue to give better results was not determined in these tests.

INCREASING NUMBER OF BLADES.

The tables and graphs show that by using four instead of two blades when $\alpha = 0^\circ$ the drag at $\theta = 90^\circ$

was increased by 5.5% ; the maximum L_c was decreased by 13.9% . The decrease in $\frac{L}{D}$ amounted to 30.7% . The speed of the two-bladed mill was 3470 r.p.m., that of the four-bladed mill 2370 r.p.m. or a decrease of 31.7% . Similarly, when $\alpha = +3°$ the D_c at $\theta = 90°$ for the four-bladed mill was 7.3% highar than for the two-bladed mill, and the r.p.m. 32.8% lower. Graph H shows the results obtained by a four-bladed mill with two blades set at $\alpha = +1°$ and the opposite two blades set at $\alpha = -5°$.

LIFTS .

Graph J shows the max, L_c for each run and the angle of yaw at which it occurred.

ROTATIONAL SPEED.

Graph D shows the plots of r.p.m. vs. angle of yaw for each of the conditions tested.

GENERAL.

The curves of D_c , L_c , and $\frac{L}{D}$ have been plotted separately for all the two-bladed USA 35 B mills in Graphs K, L, M and N .

The results of the segment test are shown in Graph O and those of the flat plate in Graph P.

CONCLUSIONS

Again it must be stressed that the coefficients determined are accurately applicable only to the size mills used in these experiments and operating under the conditions explained in the proceedure, unless scale factors for these mills are used. It is believed that much larger mills will give better results inasmuch as the rotational velocity will be decreased, the curve of variation of angle of attack along the mill radius will flatten out giving a wider range of efficient angles of attack and hence, a more efficient mill.

Tests conducted in actual free air conditions would be of relatively more practical use although an attempt has been made in this paper to simulate such conditions.

Other conclusions may be drawn from the facts noted in the " DISCUSSION OF RESULTS ". Many other conclusions are of a nature too complex to be included within the scope of this paper.

U.S.A. 35 B Section
2 Bladed Mill
$\alpha = 0°$
Wind velocity 20 miles per hour

θ	Actual wind speed	Measured drag	Measured lift	Zero drag	Zero lift	Actual drag	Actual lift
90°	19.1	3.1000	0.3000	0.0635	0.2955	3.0365	0.0045
85°	19.2	3.0800	0.5600	0.0690	0.2812	3.0110	0.2788
80°	19.3	3.0625	0.8150	0.0729	0.2775	2.9896	0.5375
75°	19.5	2.9735	1.3100	0.0756	0.2740	2.8919	1.0360
70°	19.9	2.6740	1.7400	0.0786	0.2705	2.5954	1.4695
60°	20.6	2.3310	2.1000	0.0839	0.2645	2.2471	1.8355
45°	22.4	1.9530	2.3800	0.0944	0.2554	1.8586	2.1246
30°	23.9	1.4230	2.4200	0.1058	0.2498	1.3172	2.1712
20°	24.4	0.7900	1.8300	0.1136	0.2481	0.6764	1.5819
15°	24.7	0.4755	1.2700	0.1200	0.2472	0.3555	1.0228
10°	24.9	0.2080	0.4700	0.1205	0.2463	0.0875	0.2237

Wind speed given in miles per hour

Lifts and Drags given in pounds.

U.S.A. 35 B Section
2 Bladed Mill
$\alpha = 0°$
Wind velocity 20 miles per hour

Resultant	$\phi = \tan^{-1} D/L$	$\phi - \theta = \Delta$	R cos Δ	R sin Δ	Corrected R.P.M.	Corrected resultant	θ
3.0365	90	0.0	3.0365	0.0000	3470	3.3250	90°
3.0243	84.7	0.3	3.0243	0.0151	3430	3.2850	85°
3.0170	79.9	0.1	3.0170	0.0061	3390	3.2350	80°
3.0700	70.3	4.7	3.0600	0.2520	3330	3.2350	75°
2.9850	60.5	9.5	2.9410	0.4920	3190	3.1500	70°
2.9000	50.7	9.3	2.8800	0.4680	2980	2.7300	60°
2.7100	36.7	8.3	3.0800	0.4480	2520	2.4800	45°
2.5350	31.2	1.2	2.5345	0.0530	2210	1.7750	30°
1.7200	23.1	3.1	1.7190	0.0930	1750	1.1550	20°
1.0820	19.1	4.1	1.0770	0.0772	1390	0.7160	15°
0.2405	21.4	7.4	0.2355	0.0477	516	0.1550	10°

Corrected values are the observed values multiplied by the "Velocity Ratio" or the ratio of (the observed wind speed to 20 m.p.h.) squared.

U.S.A. 35 B Section
2 Bladed Mill
$a = 0°$
Wind velocity 20 miles per hour (concluded)

θ	Corrected Drag	Corrected Lift	Dc (mill)	Lc (mill)	Lc (mill) / Dc (mill)
90°	3.3250	0.0000	.004580	.000000	.00000
85°	3.2720	0.3035	.004510	.000417	.0947
80°	3.1850	0.5670	.004380	.000780	.1780
75°	3.0450	1.0900	.004180	.001500	.3580
70°	2.7420	1.5500	.003780	.002130	.5630
60°	2.1120	1.7300	.002910	.002380	.8180
45°	1.4823	1.9900	.002040	.002740	1.3430
30°	0.9190	1.5150	.001264	.002080	1.645
20°	0.4530	1.0610	.000624	.001460	2.340
15°	0.2340	0.6760	.000322	.000930	2.890
10°	0.0567	0.1448	.000078	.000512	6.430

Corrected Drag and Lift is obtained by multiplying the actual Drags and Lifts by the "Velocity Ratio" as noted on the preceeding page.

Pomilio Section
2 Bladed Mill
$a = 0°$
Wind velocity 20 miles per hour

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	Lc (mill) / Dc (mill)
90°	2440	0.00393	0.00	0.00
85°	2420	0.00393	0.000342	0.087
80°	2390	0.00388	0.000670	0.173
75°	2350	0.00380	0.001000	0.263
70°	2250	0.00366	0.001300	0.355
60°	2100	0.00316	0.001770	0.560
45°	1780	0.00203	0.001930	0.955
30°	1120	0.00087	0.001350	1.560

Pomilio Section
2 Bladed Mill
a = 0°
Wind velocity 20 miles per hour

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	Lc (mill) / Dc (mill)
90°	2440	0.00294	0.00	0.00
85°	2420	0.00287	0.000239	0.0834
80°	2390	0.00278	0.000487	0.1750
75°	2350	0.00270	0.000740	0.2740
70°	2250	0,00251	0.000970	0.3860
60°	2100	0.002145	0.001170	0.5450
45°	1610	0.00122	0.001170	0.9600
30°	720	0.000367	0.000520	1.4100

U.S.A. 35 B Section
4 Bladed Mill
(4 @ a = 0°)
Wind speed 20 miles per hour

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	$\frac{Lc\ (mill)}{Dc\ (mill)}$
90°	2370	0.00495	0.00	0.00
75°	2280	0.00480	0.00125	0.26
60°	2035	0.00361	0.00203	0.563
45°	1720	0.00254	0.00236	0.930

....

4 Bladed Mill
(4 @ - 3°)

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	$\frac{Lc\ (mill)}{Dc\ (mill)}$
90°	2990	0.00477	0.00	0.00

....

4 Bladed Mill
(4 @ + 3°)

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	$\frac{Lc\ (mill)}{Dc\ (mill)}$
90°	1970	0.00468	0.00	0.00

....

4 Bladed Mill
(2 @ + 3°)(2 @ - 3°)

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	$\frac{Lc\ (mill)}{Dc\ (mill)}$
90°	2370	0.00447	0.00	0.00

....

U.S.A. 35 B Section
4 Bladed Mill
(2 @+1°) (2 @-5°)
Wind velocity 20 miles per hour

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	Lc (mill) / Dc (mill)
90°	3000	0.00467	0.000374	0.00
85°	2970	0.00463	0.000775	0.0808
80°	2930	0.00458	0.001150	0.1690
75°	2880	0.00451	0.001440	0.2550
70°	2760	0.00417	0.001860	0.3450
60°	2575	0.00337	0.002120	0.5530
45°	2180	0.00234	0.002030	0.9470
30°	1715	0.00120	0.001520	1.5850
20°	1353	0.000668	0.00370	2.2800
10°	192	0.000127	0.00110	2.9200

U.S.A. 35 B Section
2 Bladed Mill
$a = +3^\circ$
Wind Speed 20 Miles per Hour

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	$\frac{\text{Lc (mill)}}{\text{Dc (mill)}}$
90°	2930	0.00436	0.00	0.00
85°	2900	0.00453	0.00040	0.0882
80°	2860	0.00445	0.00077	0.173
75°	2810	0.00433	0.00114	0.263
60°	2510	0.00349	0.00196	0.562
45°	2130	0.00234	0.00224	0.956
30°	1870	0.00131	0.00210	1.600
20°	1400	0.00058	0.00076	1.31

U.S.A. 35 B Section
2 Bladed Mill
$a = +1°$
Wind velocity 20 miles per hour

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	Lc (mill) / Dc (mill)
90°	3630	0.00454	0.000068	0.015
85°	3600	0.00452	0.000334	0.074
80°	3550	0.00445	0.000802	0.180
75°	3490	0.00443	0.00118	0.266
60°	3120	0.00354	0.00201	0.570
45°	2640	0.00272	0.00228	0.838
30°	2320	0.00130	0.00213	1.640
20°	2230	0.00066	0.00109	1.650
10°	2140	0.00008	0.00034	4.250

U.S.A. 35 B Section
2 Bladed Mill
$a = -5°$
Wind speed 20 miles per hour

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	$\frac{Lc\ (mill)}{Dc\ (mill)}$
90°	4340	0.00406	0.00	0.00
85°	4300	0.00402	0.00037	0.092
80°	4250	0.00400	0.00070	0.175
75°	4180	0.00396	0.00090	0.250
60°	3730	0.00356	0.00174	0.490
45°	3160	0.00289	0.00195-	0.695
30°	2520	0.00192	0.00162	0.845

Symmetrical Section
2 Bladed Mill
$a = 0°$
Wind speed 20 miles per hour

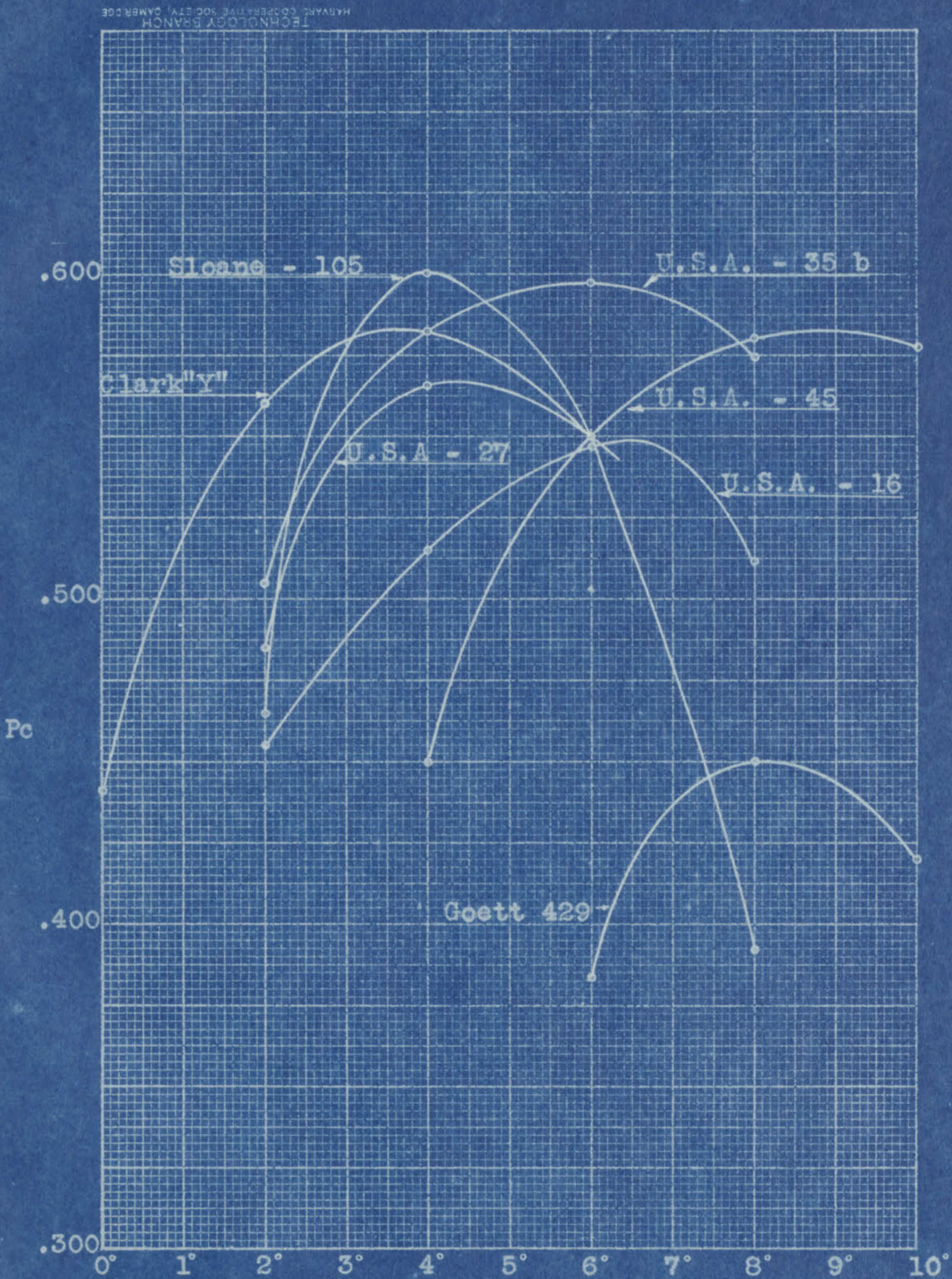
θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	$\frac{Lc\ (mill)}{Dc\ (mill)}$
90°	532	0.000500	0.000	0.000
60°	-	0.000274	0.000130	0.474

Crude Sector Section
2 Bladed Mill
$a = 0°$

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	$\frac{Lc\ (mill)}{Dc\ (mill)}$
90°	2850	0.00377	0.00	0.00
85°	2875	0.00376	0.000326	0.0866
80°	2790	0.00361	0.000622	0.1720
75°	2790	0.00344	0.0004015	0.2660
60°	2310	0.00274	0.001575	0.5740
45°	1605	0.001755	0.001650	0.9390
30°	1210	0.000640	0.000975	1.5230
20°	483	0.000182	0.000326	1.7900

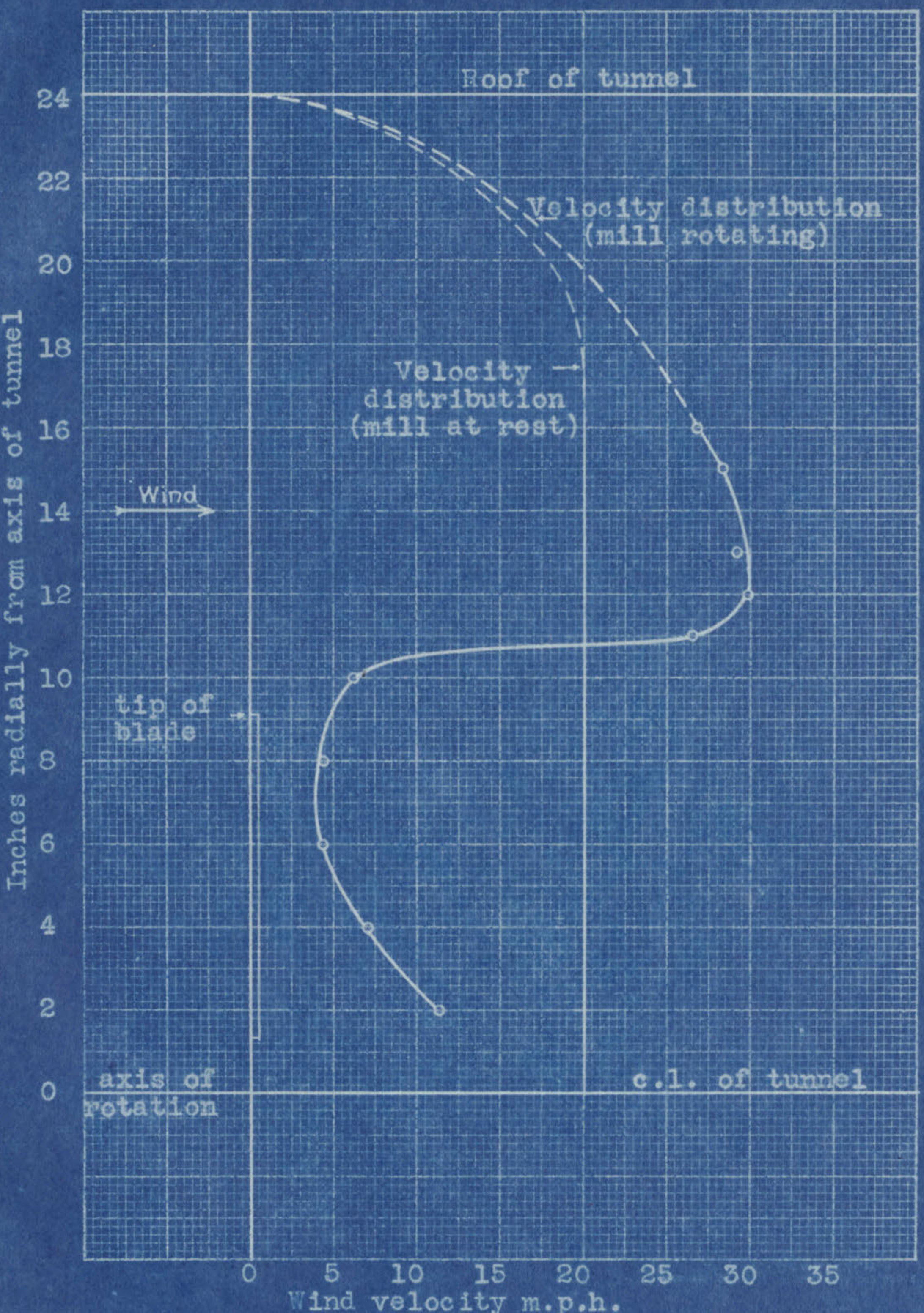
U.S.A. 35 B section
2 Bladed Mill
$a = -2°$
Wind velocity 20 miles per hour

θ	Corrected R.P.M.	Dc (mill)	Lc (mill)	$\frac{Lc\ (mill)}{Dc\ (mill)}$
90°	3950	0.00449	0.00	0.00
85°	3910	0.00447	0.000394	0.0882
80°	3860	0.00447	0.000755	0.1690
75°	3790	0.00448	0.001130	0.2520
70°	3640	0.00437	0.001450	0.3320
60°	3390	0.00402	0.001920	0.4780
45°	2870	0.00318	0.002210	0.6950
30°	2320	0.00245	0.002080	0.8480
20°	1750	0.00149	0.001370	0.9200
15°	1420	0.00085	0.000850	1.0000

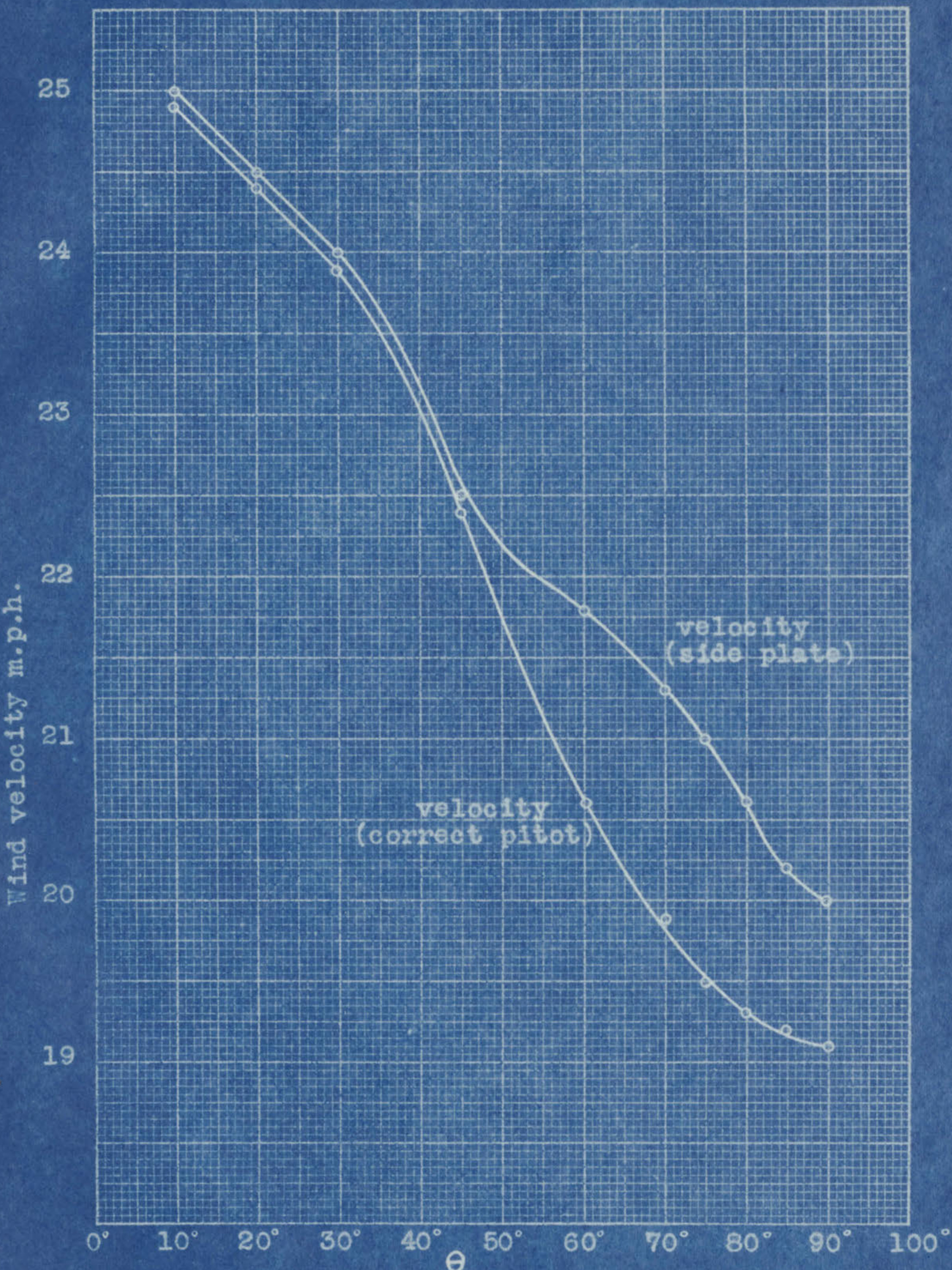


Comparison of Pc vs. angle of attack of wing
for various airfoil sections

(A.)

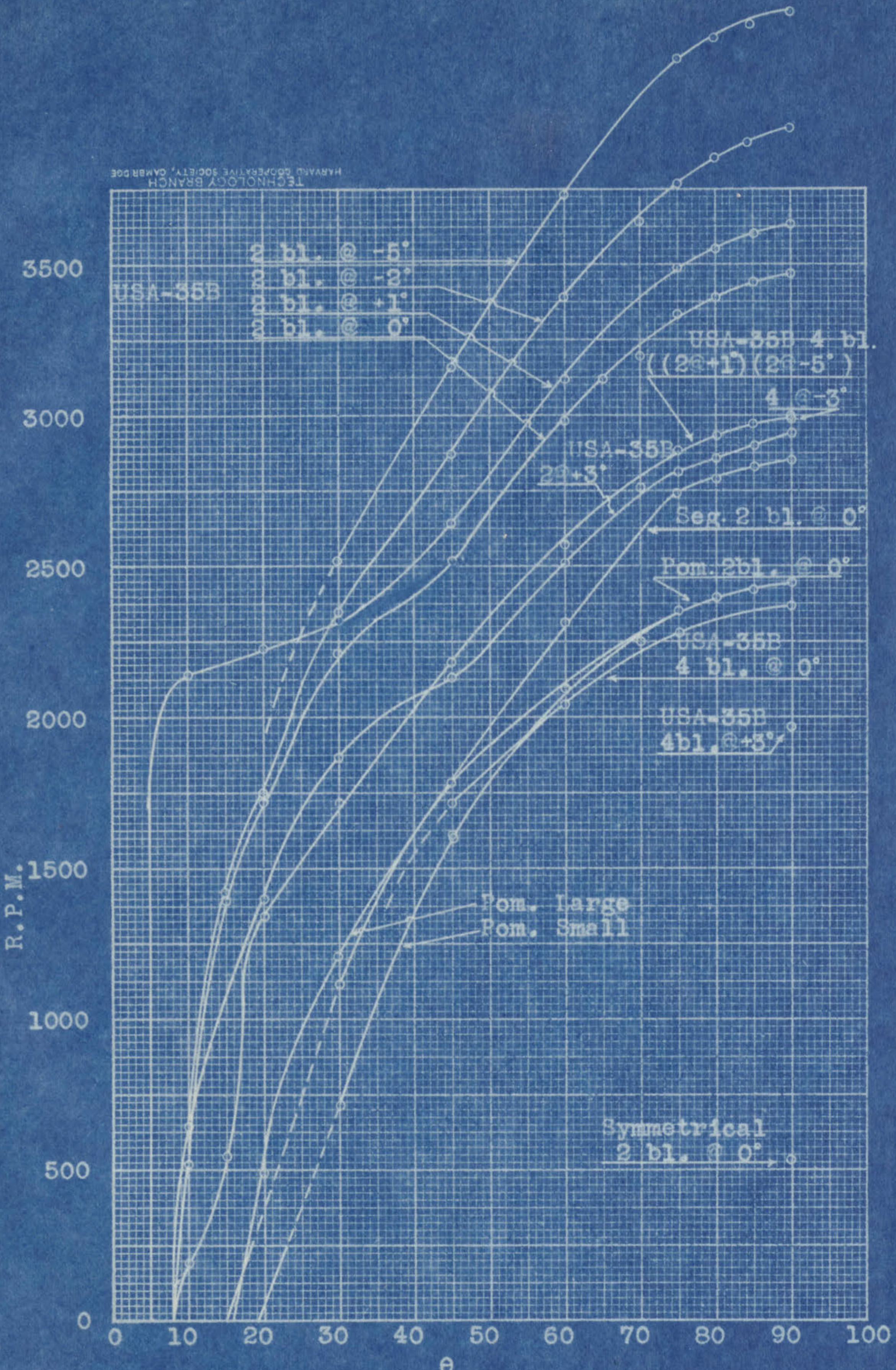

Roof of tunnel
Velocity distribution
(mill rotating)
Velocity
distribution
(mill at rest)
Wind
tip of
blade
axis of
rotation
c.l. of tunnel
Inches radially from axis of tunnel
24
22
20
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
Wind velocity m.p.h.

B.

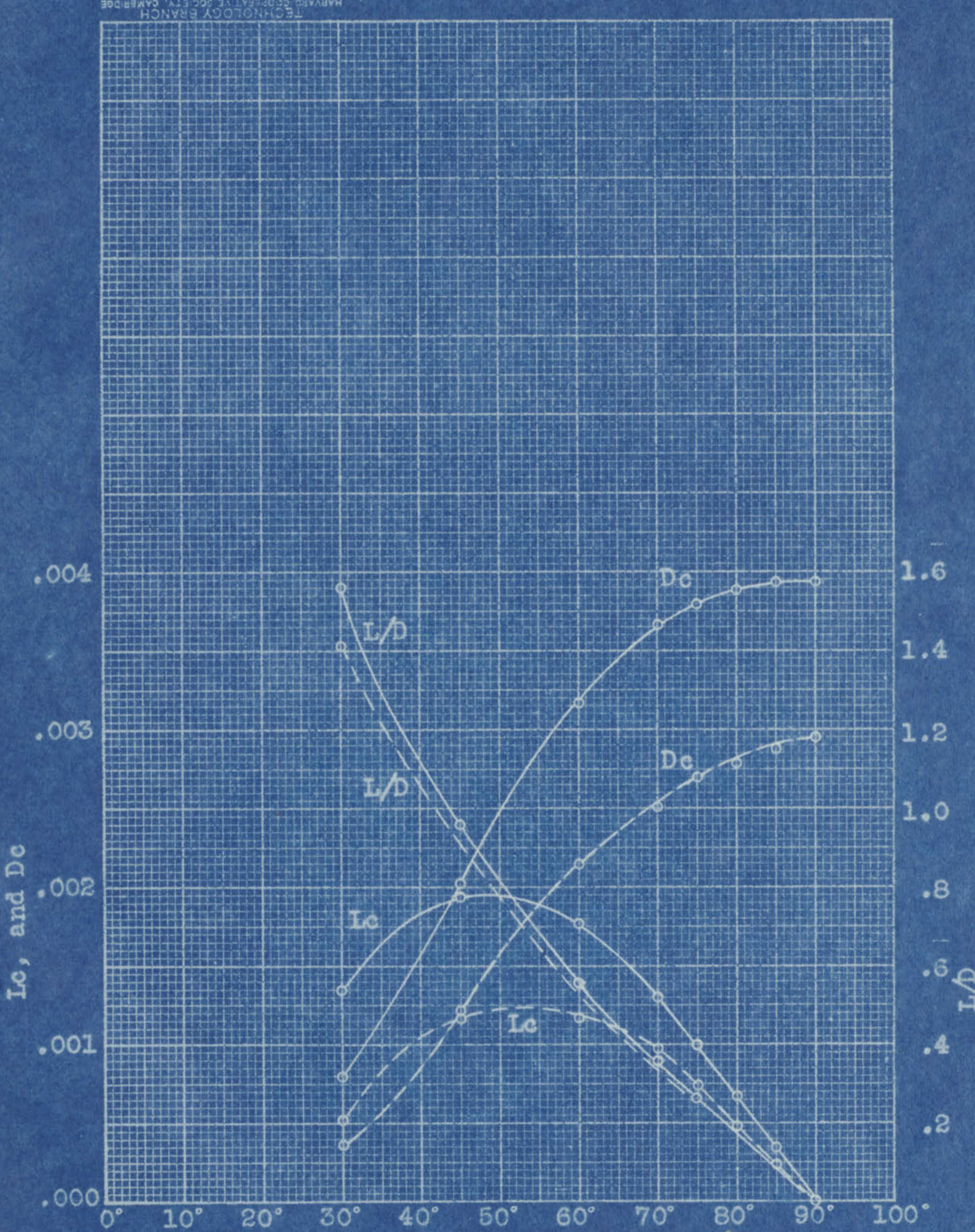


Wind velocity in tunnel vs angle of yaw(θ)

C.



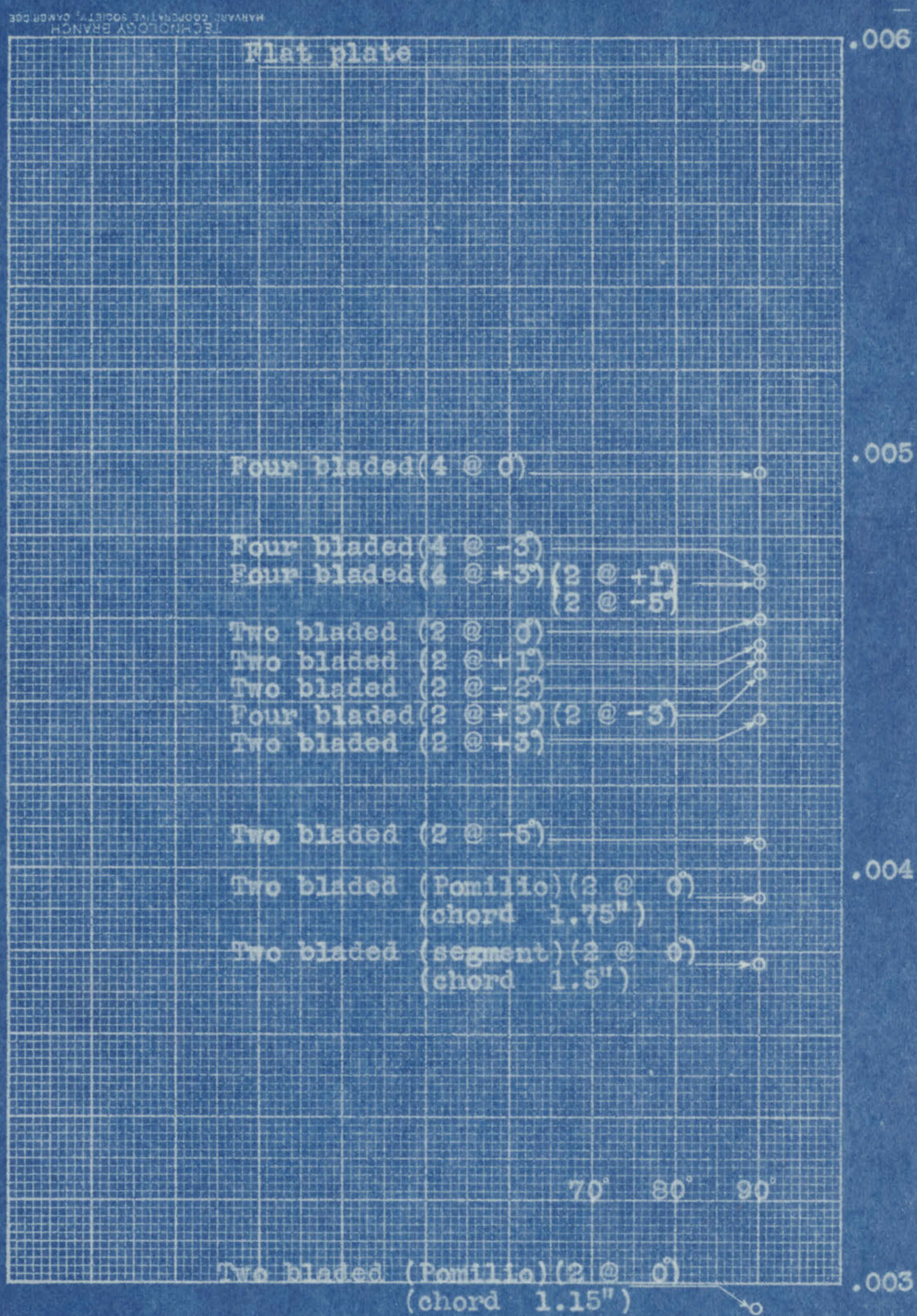
R.P.M. vs. Angle of Yaw



Lc, Dc, and L/D vs. angle of yaw

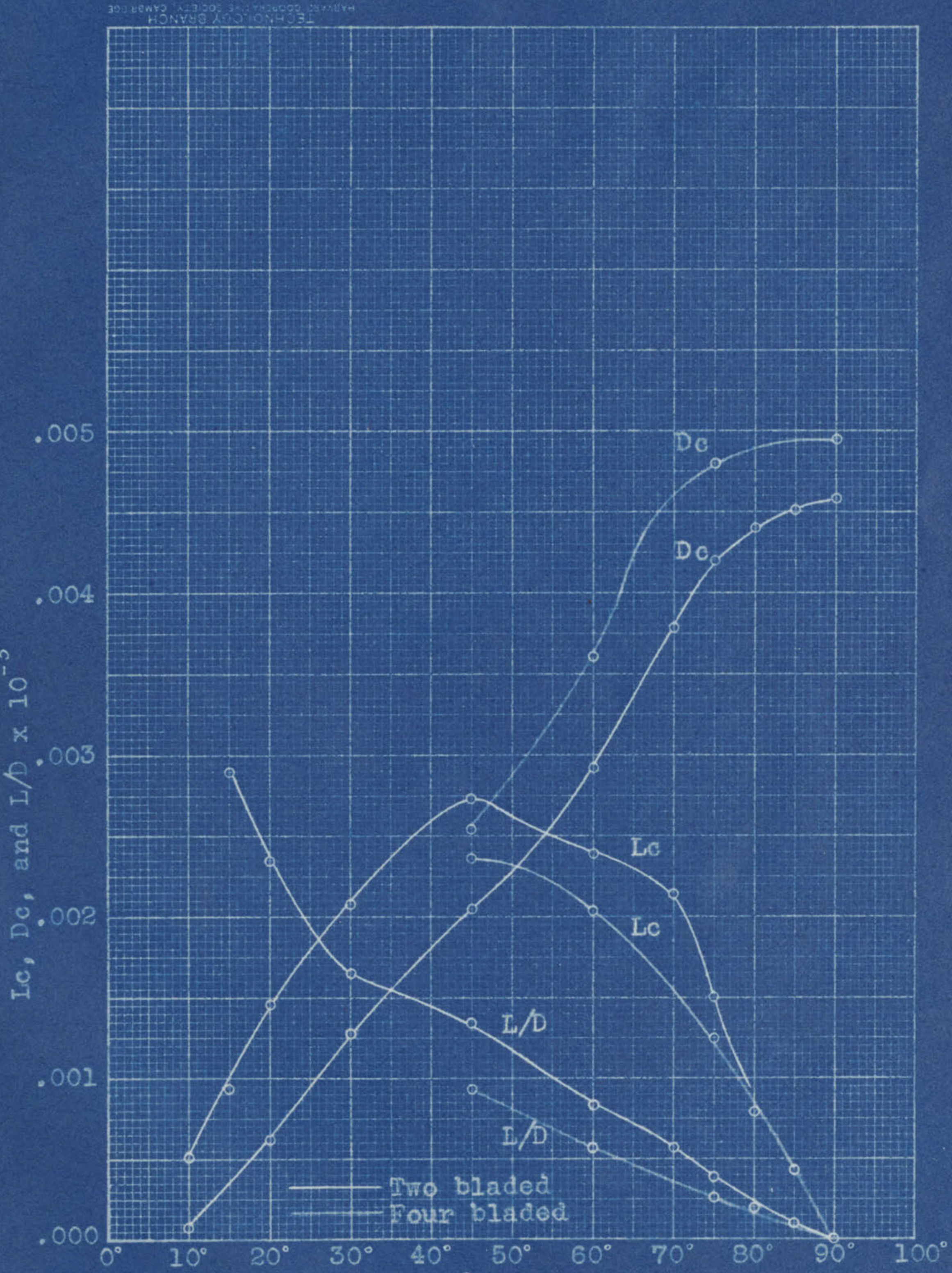
———— , Pomilio (large) chord = 1.75"
- - - - - , Pomilio (small) chord = 1.15"
Angle of attack = 0°

(E.)



Comparison of Dc for all sections at $\theta = 90°$

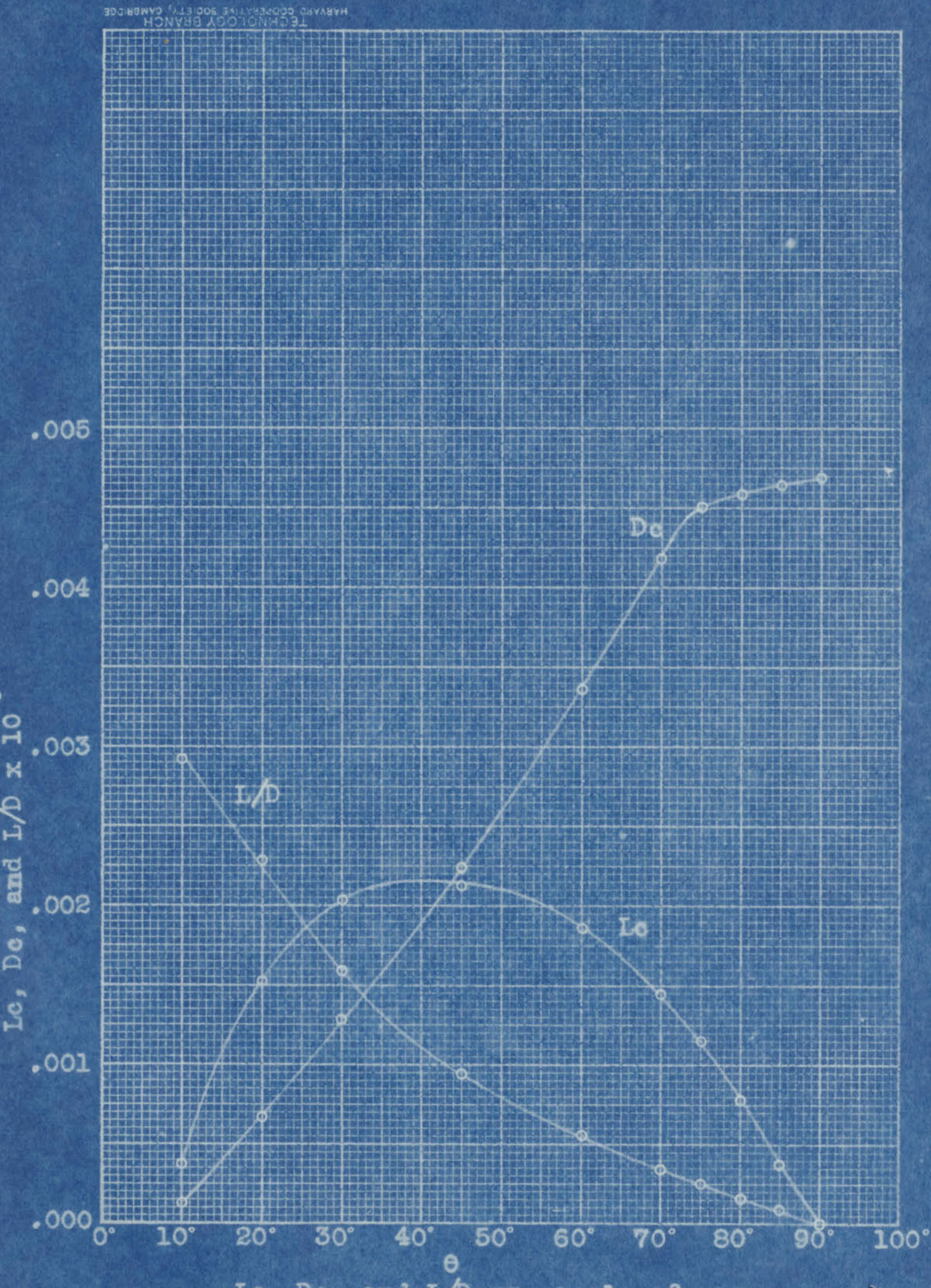
(F.)



Lc, Dc, and L/D vs angle of yaw
U.S.A. 35 B sections at a = 0°

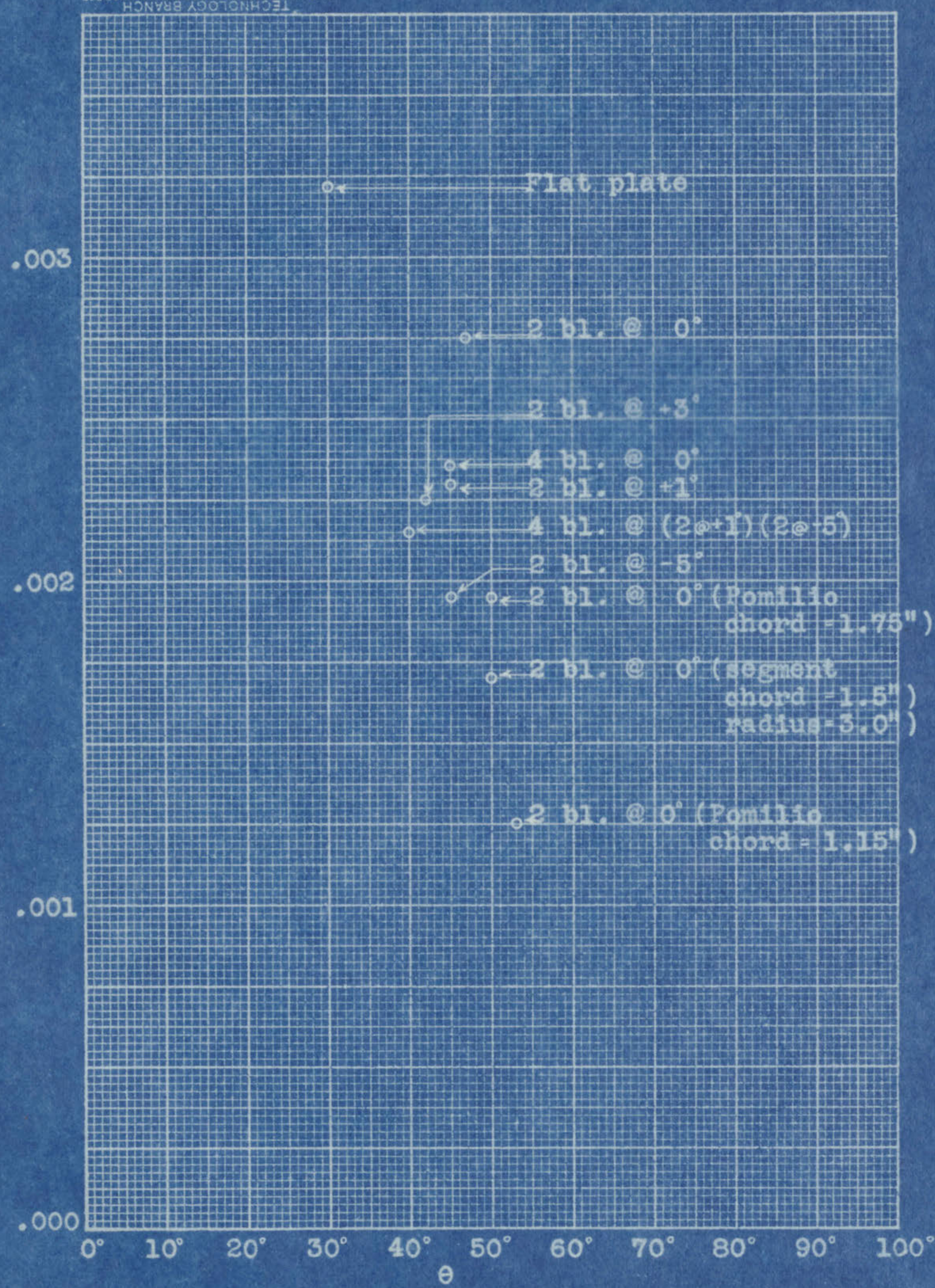
Comparison of two bladed and four bladed mills

G.



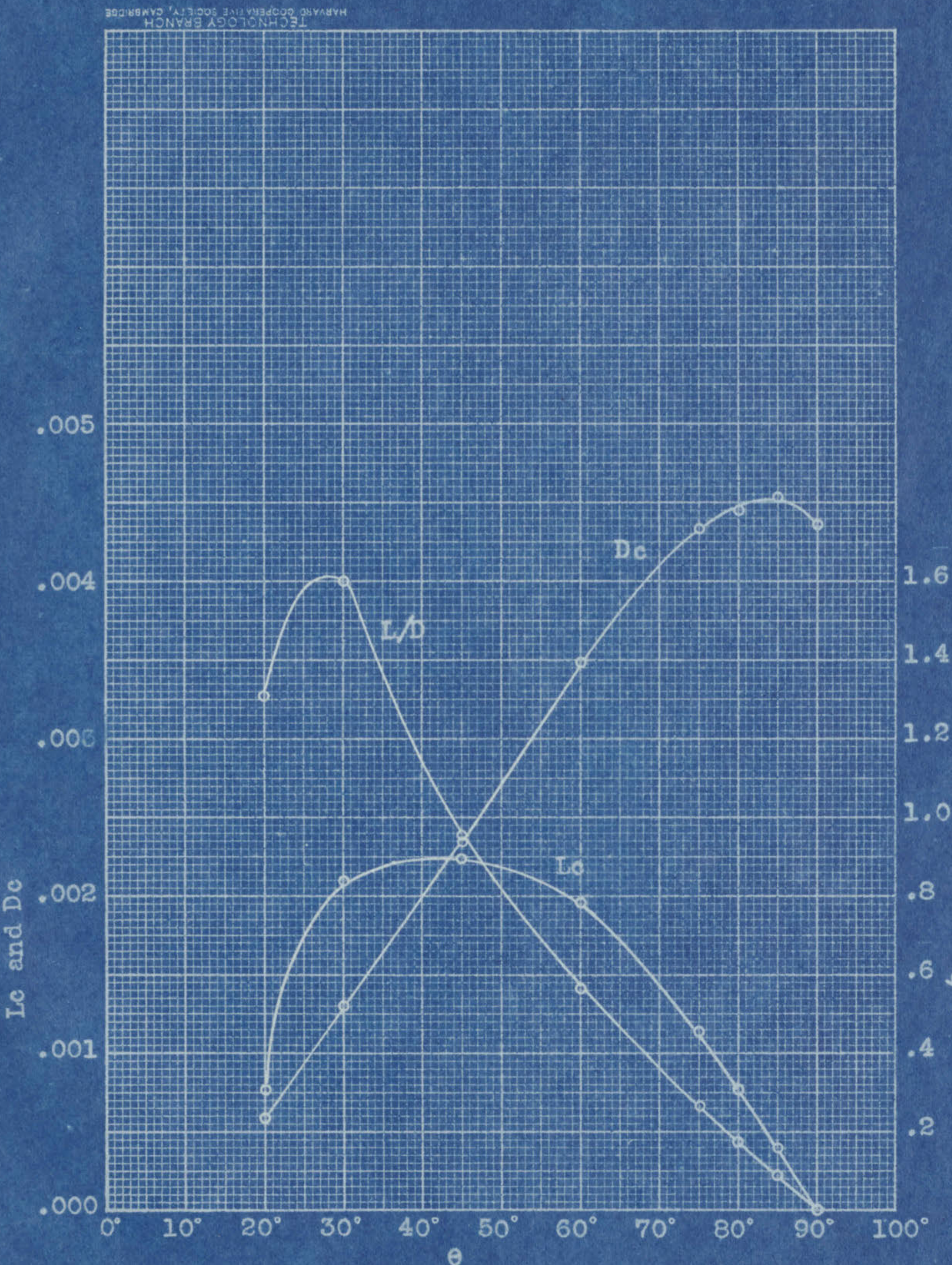
Lc, Dc, and L/D vs. angle of yaw
Four bladed mill U.S.A. 35 B sections
Two blades at a = + 1°
Two blades at a = − 5°

(H.)



Maximum Lc and angle at which it occurs, for all sections tested

J.

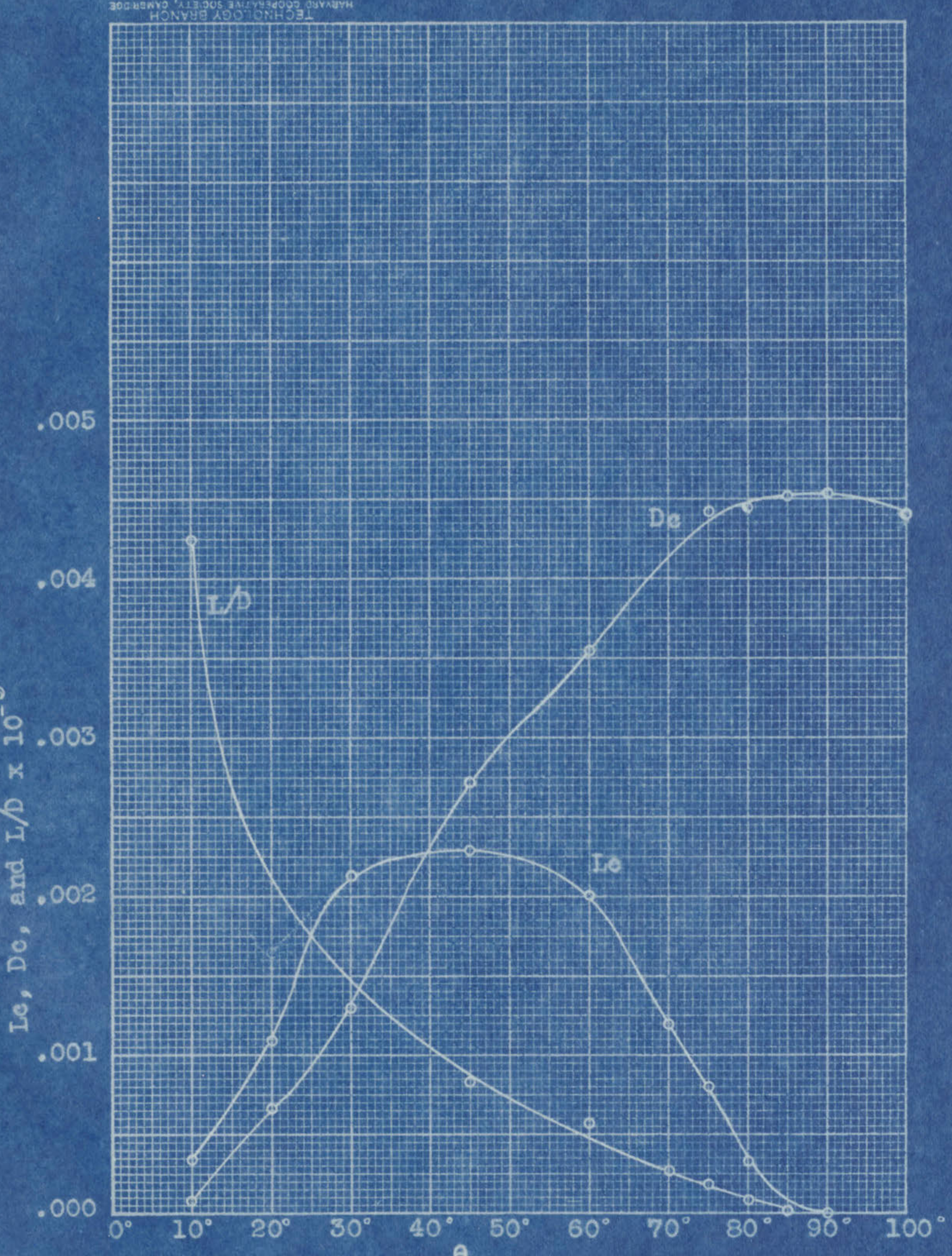


Lc, Dc, and L/D vs. angle of yaw

Two bladed mill U.S.A. 35 B sections

Angle of attack of +3°

(K.)

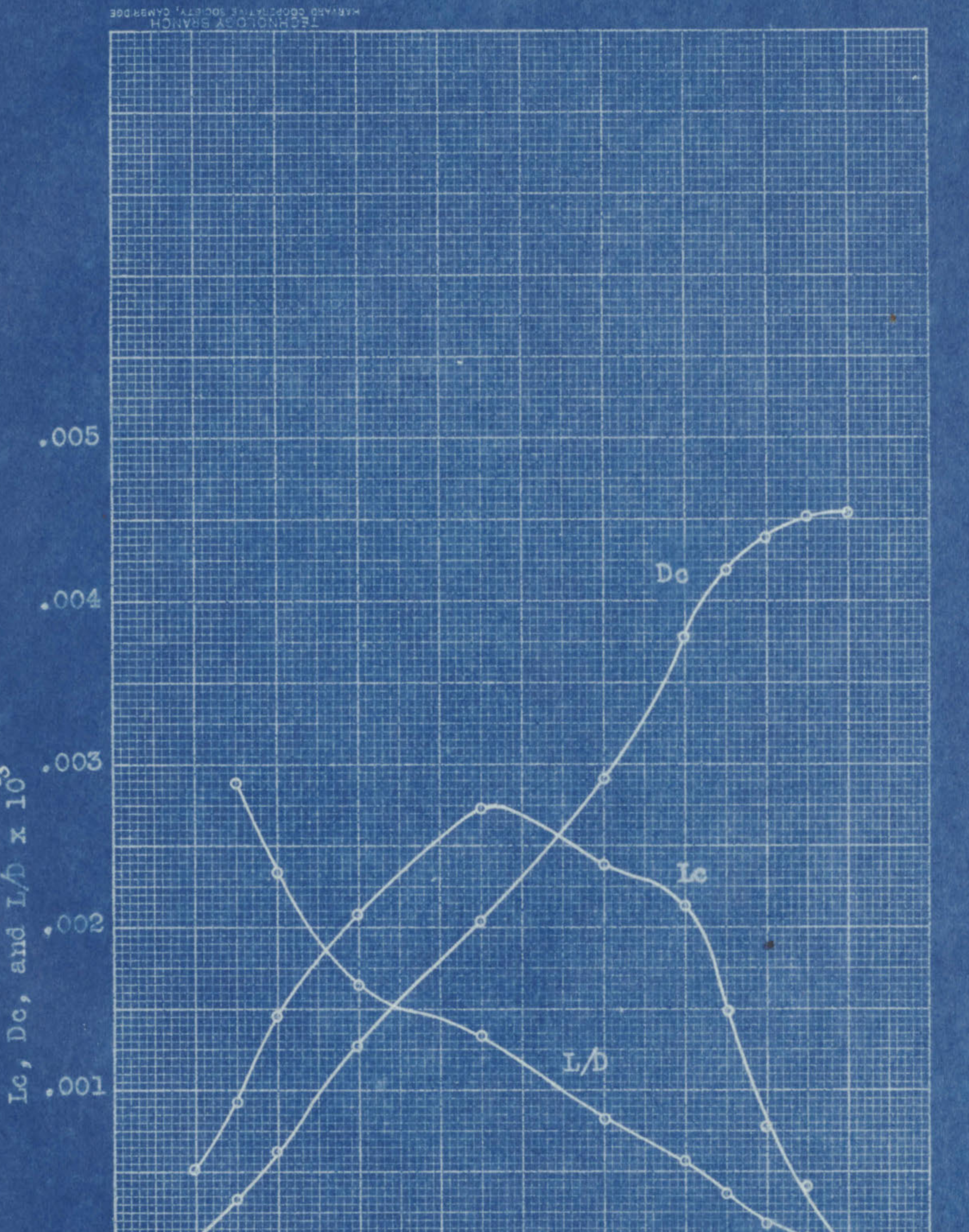


Lc, Dc, and L/D vs. angle of yaw

Two bladed mill, U.S.A. 35 B sections

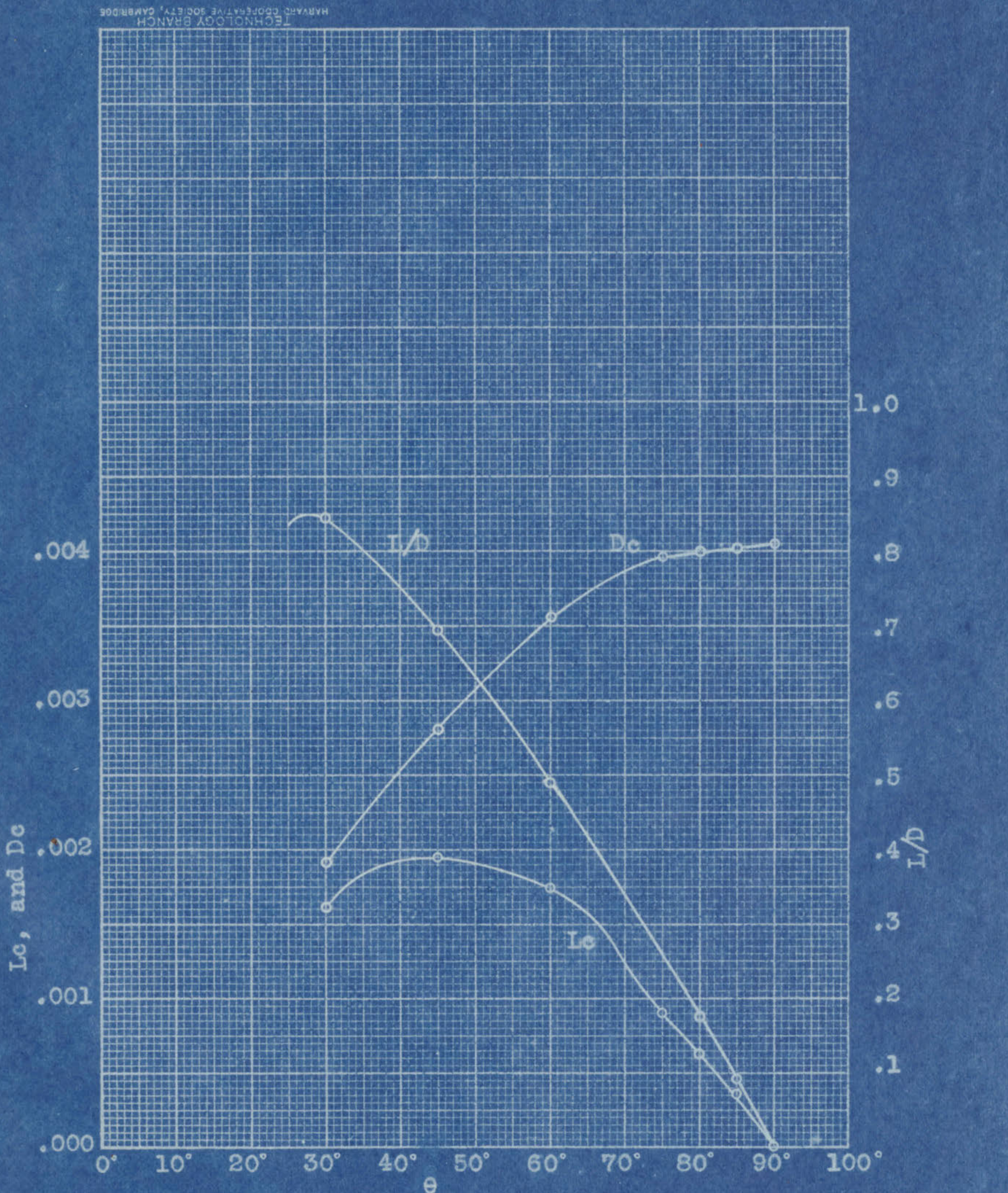
Angle of attack of + 1°

(L.)



Lc, Dc, and L/D of Mill vs. angle of yaw

Two bladed mill U.S.A. 35 B sections
at angle of attack of 0°

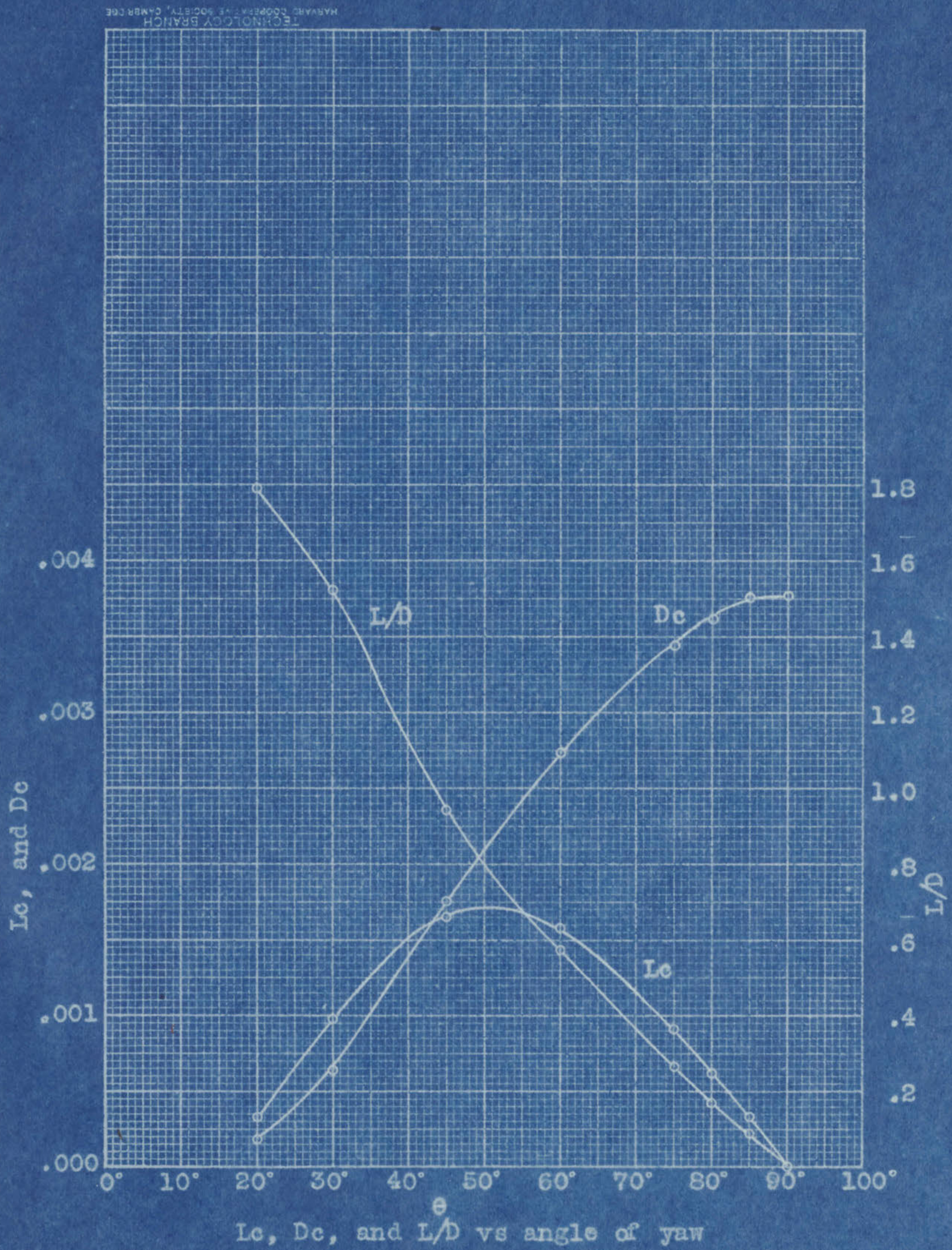


Lc, Dc, and L/D vs. angle of yaw

Two bladed mill U.S.A. 35 B sections

Angle of attack of −5°

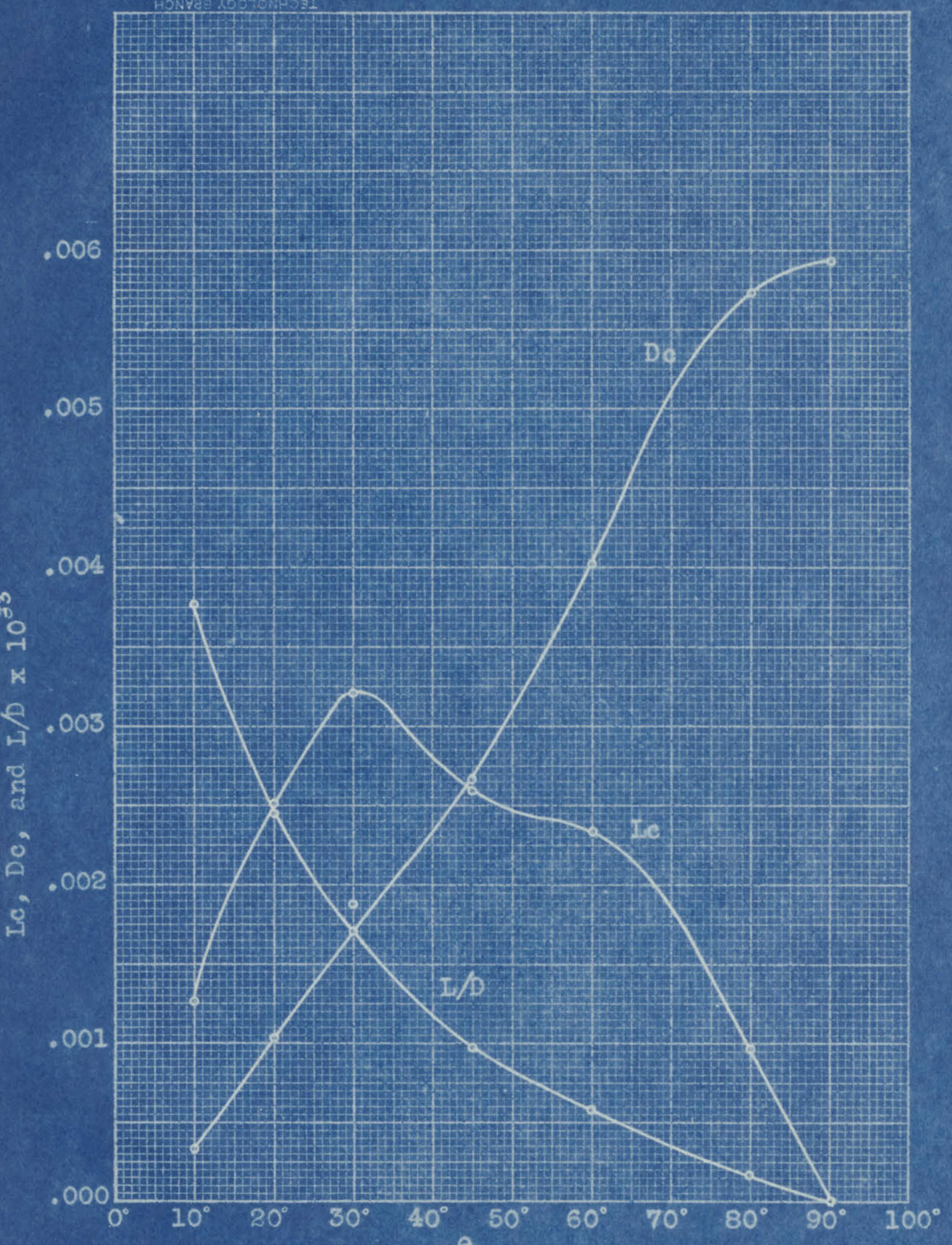
(N.)



Lc, Dc, and L/D vs angle of yaw

Section;- Segment of radius = 3"
chord = 1.5"
Angle of attack = 0.0°

(O.)



Lc, Dc, and L/D of flat plate vs. angle of yaw

Circular plate of diameter 18.25"

Ⓟ