TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 367

THE AERODYNAMIC CHARACTERISTICS OF THREE TAPERED AIRFOILS TESTED IN THE VARIABLE DENSITY WIND TUNNEL

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Summary

This report contains the lift, drag, and moment characteristics of tapered Clark Y, Göttingen 398, and U.S.A. 45 airfoils as obtained from tests made in the Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics. The results are given at both low and high Reynolds Numbers to show scale effect and to provide data for use in airplane design.

Introduction

In the last few years tapered wings have been used in increasing numbers. There has, however, been no corresponding increase in the study of their aerodynamic characteristics. Some early tests to determine the characteristics of thick and tapered airfoils are reported in References 1, 2, and 3, and the results of additional tests are given in the series of N.A.C.A. reports entitled "Aerodynamic Characteristics of Airfoils." These tests, however, were comparatively few, and were made at low Reynolds Numbers, with the exception of one on the N.A.C.A. 81-J airfoil made in the Variable Density Wind Tunnel.

Because of this lack of data, and in response to requests from airplane manufacturers, tests of three tapered airfoils were made in the Variable Density Wind Tunnel. The airfoils chosen were the U.S.A. 45, a model of which had been previously tested at Massachusetts Institute of Technology, and two others having as their basic profiles the Clark Y and Göttingen 398 sections. The airfoils were tested at high values of the Reynolds Number to provide data for use in airplane design, and also at comparatively low values of the Reynolds Number to make possible the determination of the scale effect. The data on scale effect will be useful in estimating the high Reynolds Number characteristics of other tapered airfoils tested in other wind tunnels.

Description of Airfoils

The general dimensions of the airfoils are given on Figure 1. It will be noted that all the models are of aspect ratio 6. For the Clark Y and Göttingen 398, the ratios of the tip chord to the center chord and the tip thickness to the center thickness are 0.5 and 0.25, respectively. The corresponding values for the U.S.A. 45 are 0.6 and 0.36.

In the design of the wings geometric twist was eliminated by placing the chords of all sections along the semispan in a plane. The profiles of the Clark Y and Göttingen 398 were derived by thickening and thinning from the mean camber line of the standard sections. The resulting profiles vary along the span, as indicated by the end views of Figures 3 and 4. The mean camber line of each section along the span is geometrically similar to that of the standard section, and as the shape of the mean camber line determines the moment coefficient about the quarter chord point and the angle of zero lift, these values will be approximately the same for the tapered wing as for a rectangular wing having the same basic profile. As there is no geometric twist and the mean camber lines of all sections are similar, aerodynamic twist is eliminated; that is, all sections along the span begin to lift at the same time. For the U.S.A. 45 airfoil, however, the tip ordinates were found by multiplying the ordinates of the center section in per cent of chord by 0.6. Therefore, the mean camber lines of the center and tip sections are not similar, and the wing has aerodynamic twist.

All the airfoils have the maximum upper surface ordinates in a plane parallel to the chords, which results in an effective dihedral (elevation view of Fig. 1). As shown in the plan view of Figure 1 and the end views of Figures 3, 4, and 5, the quarter chord points of all sections (sometimes referred to as the aerodynamic centers) lie in a plane perpendicular to the plane of symmetry.

In the construction of the airfoils, templates were placed at the center and tips. The surface was then cut to a straight edge set between corresponding stations of the templates. The airfoils were made of mahogany and finished with varnish. After completion of the tests, the ordinates of the airfoils were measured at sections $\frac{1}{2}$ inch from the root and tip, and the root and tip ordinates were then determined by extrapolation. Both specified and measured ordinates are given in Table I. The deviations between the specified and measured ordinates were too small to affect the aerodynamic characteristics.

Apparatus and Tests

A description of the tunnel and of the method of operation is given in Reference 5. The tunnel described there has since been changed in many respects. The arrangement at the time of these tests is shown on Figure 2. Lift, drag, and moment were measured for angles of attack from -6 degrees to +24 degrees at Reynolds Numbers of approximately 200,000 and 4,000,000.

Results

The data, corrected for the influence of the tunnel walls, are given in two forms. Plots of the high Reynolds Number data against angle of attack are given on Figures 3, 4, and 5. The center of pressure plotted on these curves is measured from the leading edge of the mean chord and in per cent of the mean chord. Both low and high Reynolds Number data are given in the form of polars on Figures 6, 7, and 8. The moment coefficient is based upon the mean chord and is referred to the quarter mean chord point. The location of the moment axis is shown on Figures 3, 4, and 5. In the calculation of the induced drag parabola plotted on Figures 6, 7, and 8, a factor has been included to allow for the increase in drag due to the variation of span loading from the elliptical (Reference 6). A summary of high Reynolds Number characteristics is given in Table II to facilitate the comparison of the airfoils.

Discussion

Before comparing the aerodynamic characteristics of the three airfoils the differences in their shapes should be noted. The difference in plan form taper and thickness taper is small, but the U.S.A. 45 is thinner than the Clark Y and Göttingen 398. A comparison of the aerodynamic characteristics from Table II shows the following: the order of increasing $C_{L\,max}$ and $C_{D_0 min}$ is U.S.A. 45, Clark Y, and Göttingen 398. Center of pressure travel and maximum L/D improve in reverse order. The U.S.A. 45 airfoil has 4 degrees less angular range from zero to maximum lift than the Clark Y and the Göttingen 398 airfoils.

It is of interest to compare these data with those on the only other tapered airfoil tested in the Variable Density Tunnel, the N.A.C.A. 81-J. The N.A.C.A. 81-J airfoil had the same plan form taper as the Clark Y and Göttingen 398 airfoils, but the thickness taper was much greater - from 22.99 per cent to 5.74 per cent, and the airfoil was given a geometric twist of 5 degrees to approximately eliminate aerodynamic twist. The tests were made in the original Variable Density Tunnel at a Reynolds Number of 3,440,000 and gave the following values: $C_{L\ max}$ = 1.30, $C_{D_0 min}$ = 0.010, and C_M at zero lift = -0.10. Although somewhat different characteristics might result from tests of the N.A.C.A. 81-J airfoil under conditions similar to those under which the three tapered airfoils were tested, the difference is sufficiently large to justify the conclusion that the N.A.C.A. 81-J airfoil is inferior.

The effect of increase of Reynolds Number on the characteristics of the three tapered airfoils is favorable, and larger on the minimum profile drag coefficient than on the maximum lift coefficient. The high scale maximum lift coefficients, as compared with the low scale maximum lift coefficients, show an increase of 5.8 per cent, 8.3 per cent, and 12.3 per cent for the U.S.A. 45, Göttingen 398, and Clark Y, respectively. The minimum profile drag coefficients show a decrease of 46.7 per cent, 37.7 per cent, and 40.0 per cent, respectively. The low Reynolds Number data on the Clark Y have also been used for comparison with data from a test of the same model in the Atmospheric Wind Tunnel. The tests were made at approximately the same Reynolds Number and agree closely, as shown on Figure 6.

The effect of plan form on the characteristics of airfoils may be predicted by aerodynamic theory. According to the theory an elliptical span loading, which may be obtained by elliptical plan form, results in the minimum induced drag and the minimum induced angle of attack. These values are lowest for tapered wings when the tip chord is from one-third to one-half the central chord. For aspect ratio 6, the induced drag of a rectangular wing is 5 per cent more than that of an elliptical wing, whereas the induced drag of an airfoil with 2 to 1 taper is only 1 per cent higher than that of an elliptical wing.

In order to illustrate the difference between the aerodynamic characteristics of the tapered airfoils and a standard rectangular airfoil, the characteristics of a rectangular duralumin Clark Y airfoil, obtained under the same tunnel conditions as those of the tapered airfoils, are compared with the tapered airfoil characteristics on Figure 9. It will be seen that the minimum drag of the rectangular wing is approximately 20 per cent less than that of the tapered wing. Inasmuch as the profile of the rectangular wing is thinner than the mean section of the tapered wing (Fig. 10), the rectangular wing would be expected to have a lower minimum drag. The drag of the tapered wing, however, approaches that of the rectangular wing as the lift coefficient is increased, probably because the induced drag of the tapered wing is smaller.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 10, 1931.

References

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2. Norton, F. H. and Bacon, D. L. : Pressure Distribution Over Thick Airfoils - Model Tests. N.A.C.A. Technical Report No. 150, 1922.

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4. National Advisory Committee for Aeronautics : Aerodynamic Characteristics of Airfoils - V. N.A.C.A. Technical Report No. 286, 1928.

5. Munk, Max M. and Miller, Elton W. : The Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics. N.A.C.A. Technical Report No. 227, 1926.

6. Glauert, H. : The Elements of Airfoil and Airscrew Theory. Cambridge University Press, 1926.

TABLE I

Ordinates of Airfoils

	Tapered Clark Y							
	Center Per cent of Chord				Tip Per cent of Chord			
	Specified		Measured		Specified		Measured	
Station	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
0	3.50	+3.50			3.50	3.50		
1-1/4	6.40	+0.98	6.55	+0.97	5.04	2.34	5.06	1.74
2-1/2	7.85	+0.11	7.83	+0.09	5.92	2.06	6.00	1.62
5	9.78	-0.94	9.74	-0.94	7.10	1.74	7.18	1.42
7-1/2	11.06	-1.58	11.10	-1.61	7.90	1.58	7.92	1.34
10	12.07	-2.05	12.11	-2.08	8.54	1.48	8.55	1.30
15	13.53	-2.69	13.54	-2.71	9.47	1.37	9.50	1.24
20	14.42	-3.02	14.38	-3.08	10.06	1.33	10.06	1.24
30	14.85	-3.15	14.85	-3.23	10.35	1.35	10.44	1.30
40	14.47	-3.07	14.41	-3.12	10.08	1.32	10.11	1.27
50	13.35	-2.83	13.31	-2.90	9.30	1.22	9.32	1.22
60	11.62	-2.46	11.62	-2.53	8.10	1.06	8.10	1.05
70	9.33	-1.98	9.34	-2.07	6.50	0.85	6.53	0.87
80	6.63	-1.41	6.57	-1.46	4.62	0.60	4.68	0.57
90	3.56	-0.76	3.53	-0.75	2.48	0.32	2.57	0.25
95	1.89	-0.40	1.87	-0.35	1.32	0.17	1.42	0.10
100	0.15	-0.03			0.11	0.01		

TABLE I (Cont'd)

Ordinates of Airfoils

	Tapered Göttingen 398							
	Center Per cent of Chord				Tip Per cent of Chord			
	Specified		Measured		Specified		Measured	
Station	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
0	3.74	+3.74			3.74	3.74		
1-1/4	6.86	+1.22	6.94	+1.30	5.45	2.63	5.70	2.58
2-1/2	8.35	+0.33	8.38	+0.41	6.35	2.33	6.58	2.33
5	*	-0.58	10.43	-0.60	*	2.10	7.80	2.13
7-1/2	*	-1.20	11.90	-1.15	*	2.05	8.70	2.13
10	12.96	-1.44	13.04	-1.51	9.36	2.16	9.43	2.13
15	14.49	-1.90	14.57	-1.86	10.40	2.20	10.38	2.18
20	15,42	-2,08	15.40	-2.05	11.04	2.29	11.03	2.20
30	15.91	-2.09	15.93	-2.06	11.41	2.41	11.40	2.35
40	15.38	-1.79	15.44	-1.89	11.09	2.50	11.10	2.35
50	14.20	-1.61	14.16	-1.65	10.25	2.34	10.20	2.20
60	12.16	-1.31	12.16	-1.34	8.80	2.06	8.82	1.95
70	9.72	-1.00	9.71	-1.03	7.04	1.69	7.03	1.58
80	6.98	-0.64	6.98	-0.73	5.08	1.27	5.05	1.20
90	3.82	-0.37	3.85	-0.41	2.77	0.68	2.83	0.75
95	2.15	-0.23	2.18	-0.28	1.56	0.36	1.62	0.50
100	0.50	-0.07			0.36	0.07		

*These ordinates were omitted because they did not fair with the others.

TABLE I (Cont'd)

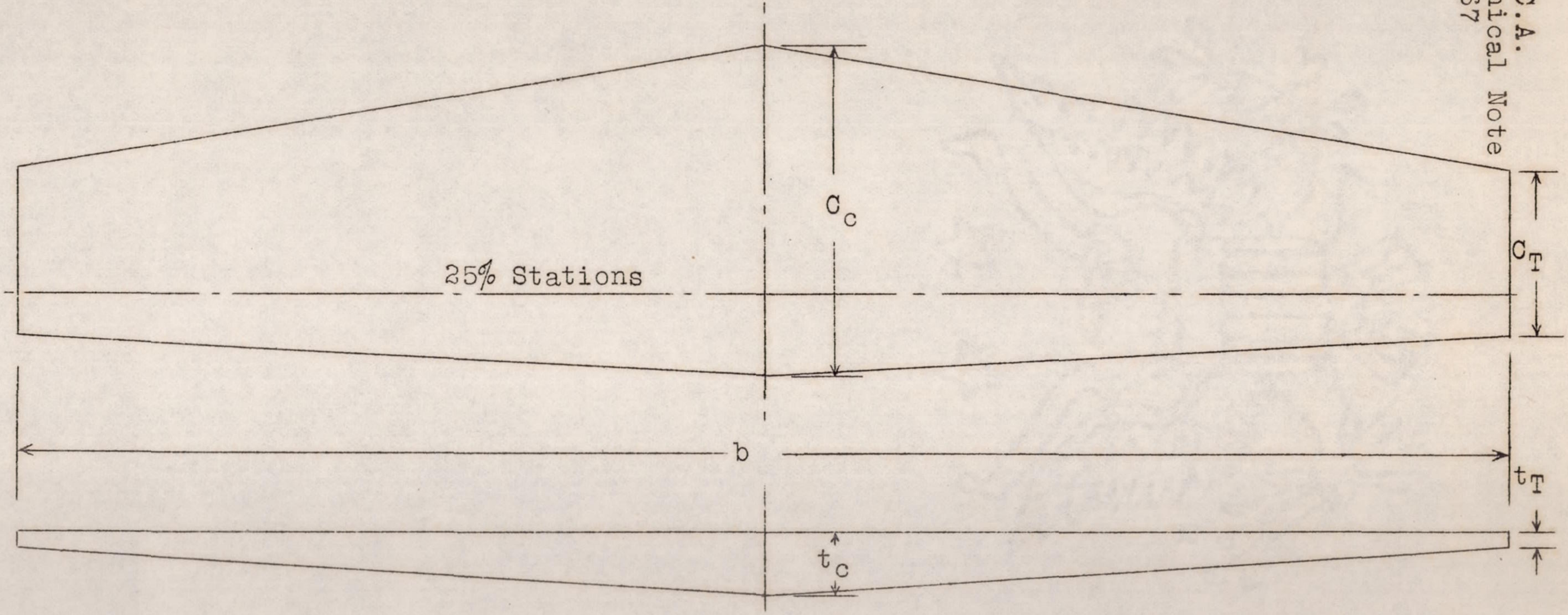
Ordinates of Airfoils

	Tapered U.S.A. 45							
	Center Per cent of Chord				Tip Per cent of Chord			
	Specified		Measured		Specified		Measured	
Station	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
0	1.63	+1.63			0.98	+0.98		
1-1/4	4.00	+0.25	4.09	+0.25	2.40	+0.15	2.50	+0.04
2-1/2	5.31	-0.20	5.46	-0.20	3.19	-0.12	3.26	-0.20
5	7.49	-0.74	7.61	-0.74	4.49	-0.44	4.45	-0.46
7-1/2	9.09	-1.06	9.14	-1.08	5.45	-0.64	5.40	-0.69
10	10.20	-1.30	10.22	-1.32	6.12	-0.78	6.14	-0.82
15	11.69	-1.63	11.66	-1.62	7.01	-0.98	7.16	-1.02
20	12.49	-1.79	12.45	-1.81	7.49	-1.07	7.66	-1.13
30	12.56	-1.96	12.55	-2.01	7.54	-1.18	7.56	-1.22
40	11.54	-2.00	11.51	-2.05	6.92	-1.20	6.94	-1.24
50	10.13	-1.96	10.06	-2.00	6.08	-1.18	6.07	-1.22
60	8.44	-1.79	8.36	-1.81	5.06	-1.07	5.10	-1.13
70	6.54	-1.50	6.50	-1.49	3.92	-0.90	3.97	-0.91
80	4.48	-1.09	4.44	-1.08	2.69	-0.65	2.79	-0.64
90	2.29	-0.60	2.29	-0.57	1.37	-0.36	1.57	-0.26
95	1.15	-0.30	1.14	-0.29	0.69	-0.18	0.91	-0.13
100	0.00	0.00			0.00	0.00		

TABLE II

Characteristics for Reynolds Number = 4,000,000

	Clark Y	Göttingen 398	U.S.A. 45
Maximum lift coefficient	1.54	1.61	1.43
Minimum profile drag coefficient	.0093	.0101	.0080
L/D maximum	21.9	20.9	23.2
C.P. at $C_{L\,max}$ (%)	28	30	26
C.P. at 1/4 $C_{L\,max}$ (%)	40	44	33
Angle from zero to maximum lift	23.3°	24.2°	19.8°



Tip and center chords are parallel

Airfoil	Span	Mean chord	Center chord	Tip chord	C_T/C_c	t_c/C_c, (%)	t_T/C_T, (%)	t_T/t_c
Clark Y, Gött. 398	36"	6"	8"	4"	0.5	18.00	9.00	0.25
U.S.A. 45	36"	6"	7.5"	4.5"	0.6	14.52	8.71	0.36

Fig.1 Dimensions of airfoils.

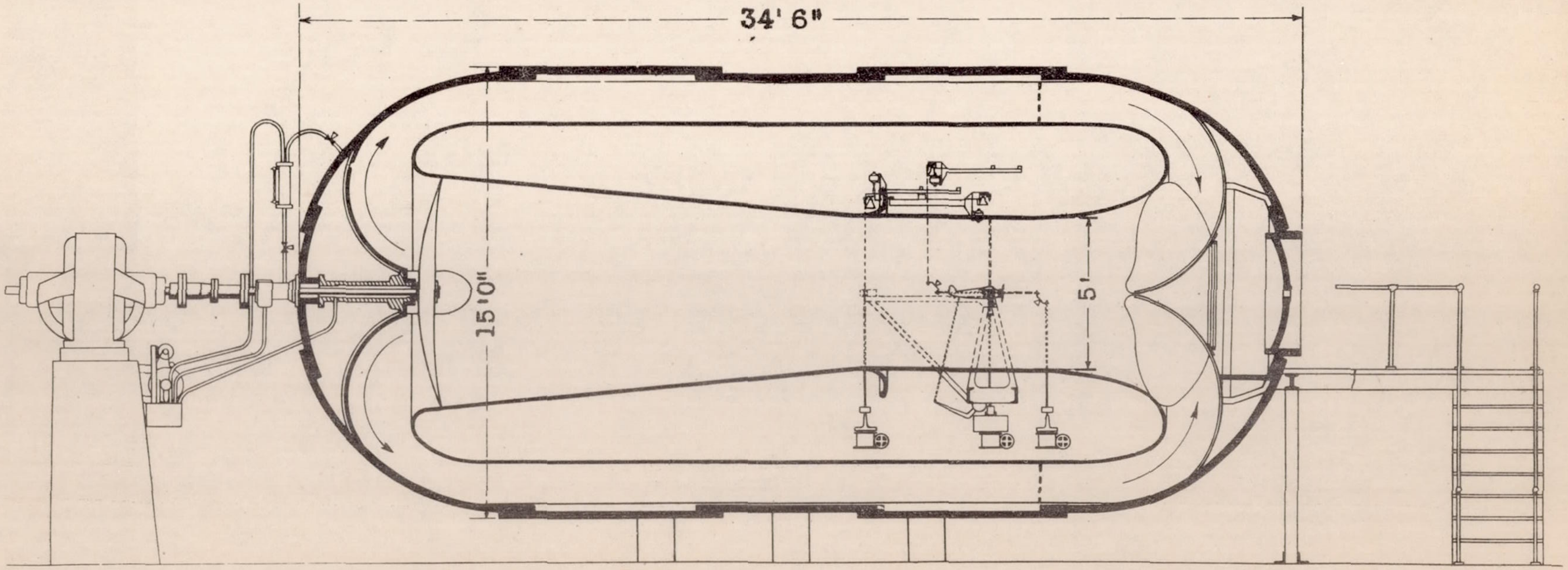
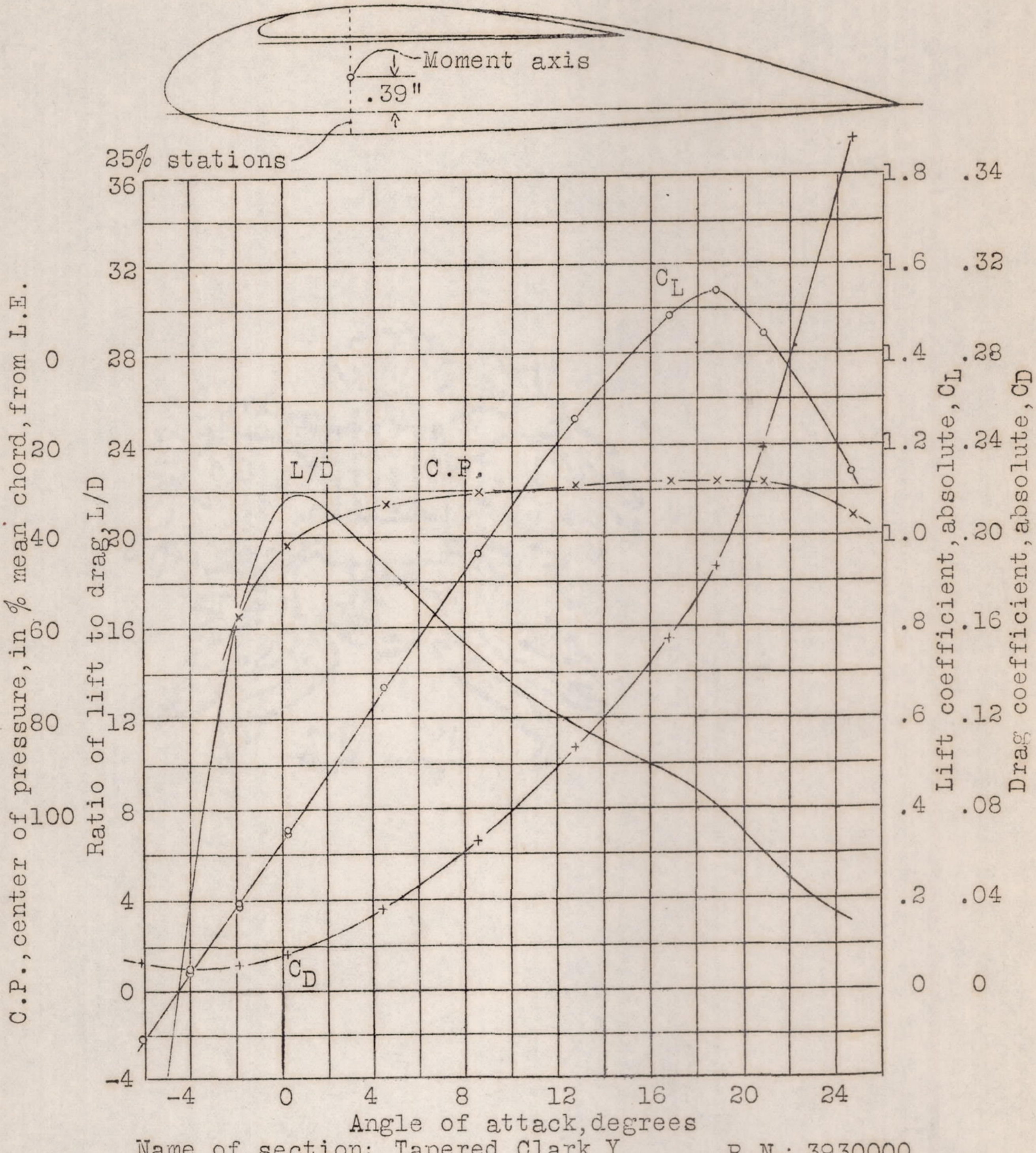


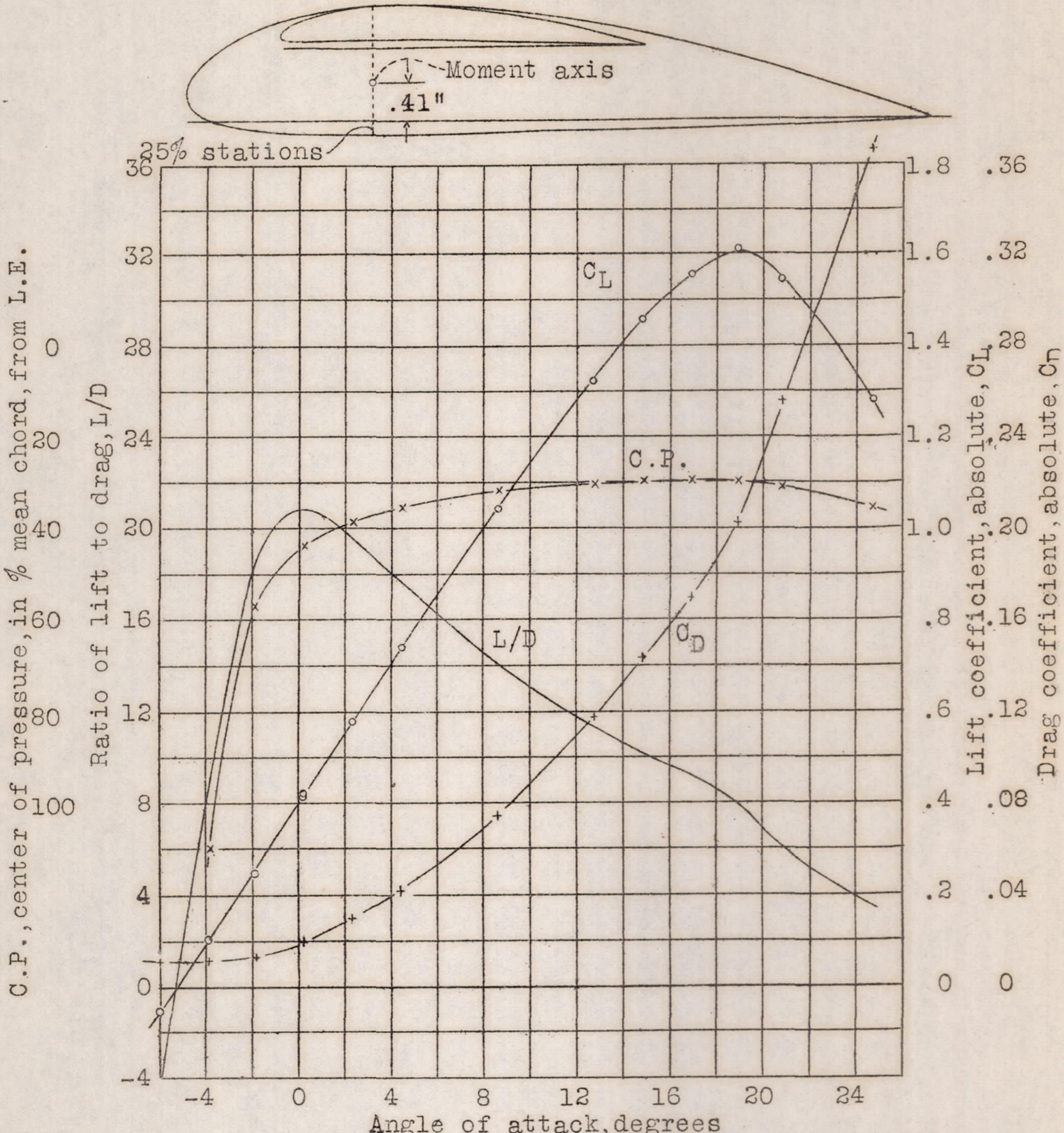
Fig. 2 The modified closed throat variable density wind tunnel.



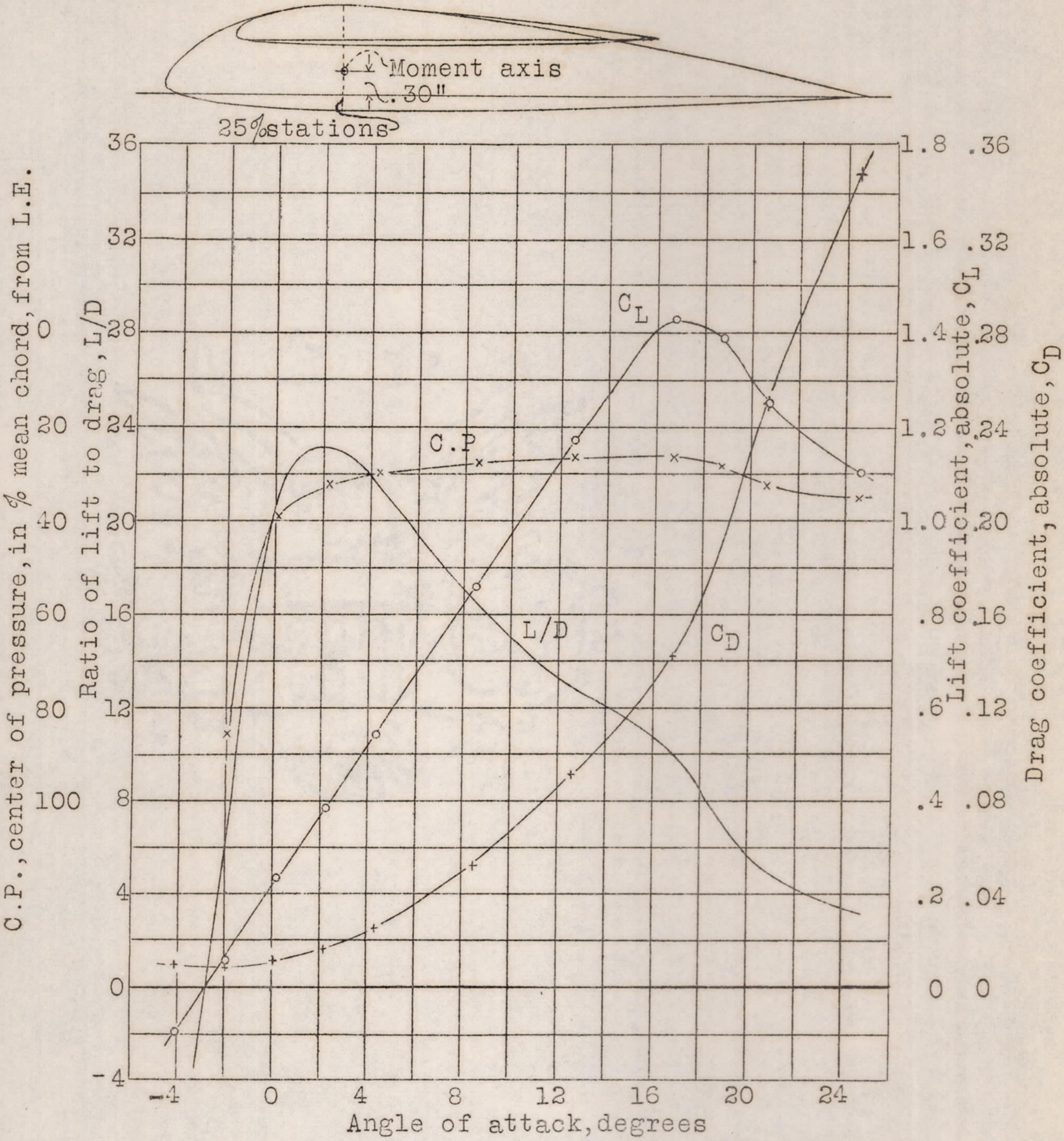
Name of section: Tapered Clark Y
Size of model: 4"×8"×36"
Pressure in standard atmospheres: 20.6
Wind velocity in ft. per sec.: 77.0
Results corrected to aspect ratio 6 in free air

R.N.: 3,930,000
Tests: V.D.T.464-2

Fig.3



Name of section: Tapered Göttingen 398 R.N.: 4,050,000
Size of model: 4"×8"×36" Tests: V.D.T.463-2
Pressure in standard atmospheres: 20.8
Wind velocity in ft. per sec.: 77.8
Results corrected to aspect ratio 6 in free air.
Fig.4



Name of section:-U.S.A. 45 R.N.: 3,980,000

Size of model:-4.5"×7.5"×36" Tests: V.D.T.465-2

Pressure in standard atmospheres: 20.3

Wind velocity in ft.per sec.: 77.4

Results corrected to aspect ratio 6 in free air

Fig.5

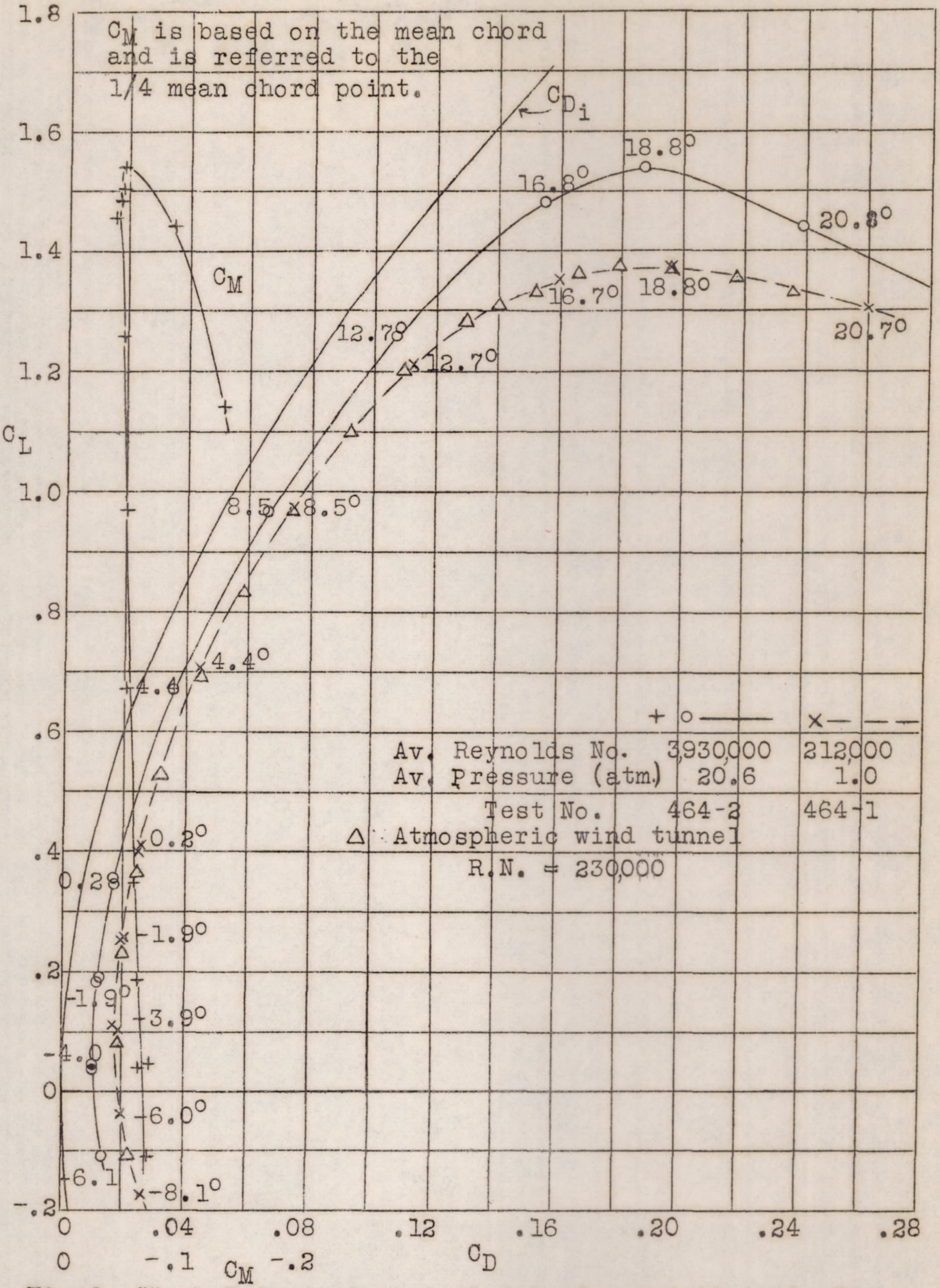


Fig.6 Clark Y tapered airfoil data for aspect ratio 6, free air.

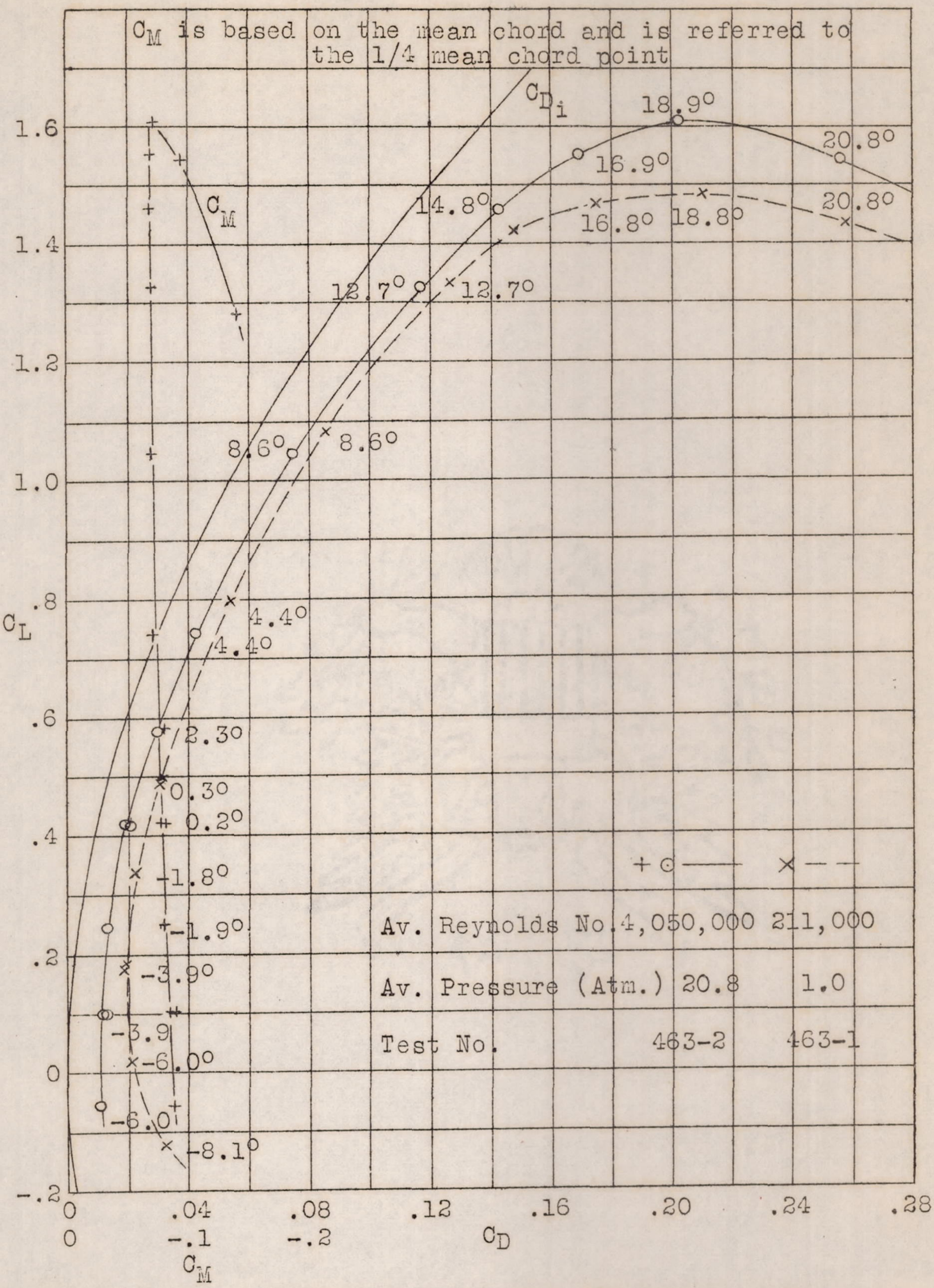


Fig. 7 Tapered Göttingen 398 airfoil. Data for aspect ratio 6 , free air.

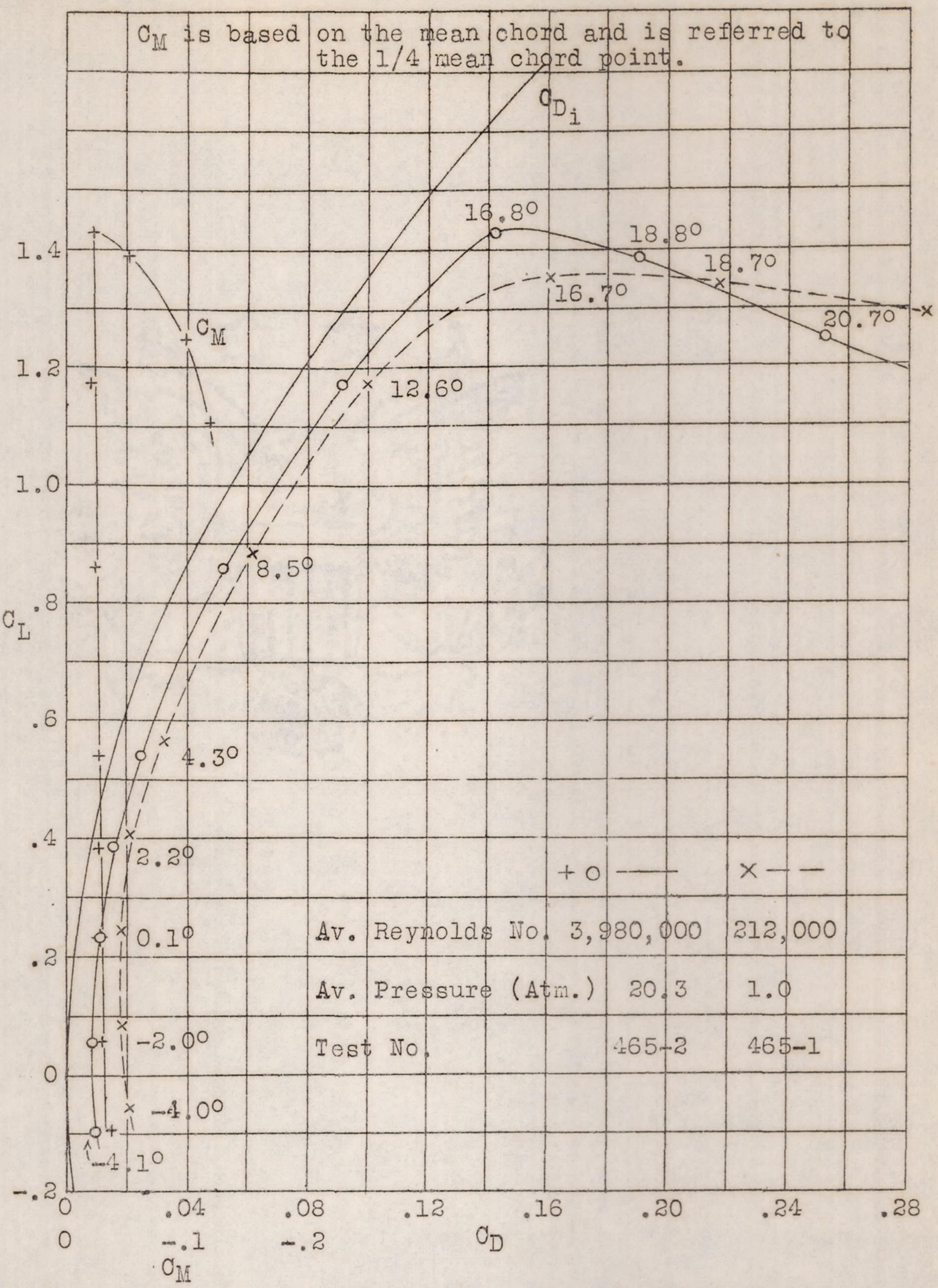


Fig. 8 U.S.A. 45 airfoil. Data for aspect ratio 6, free air

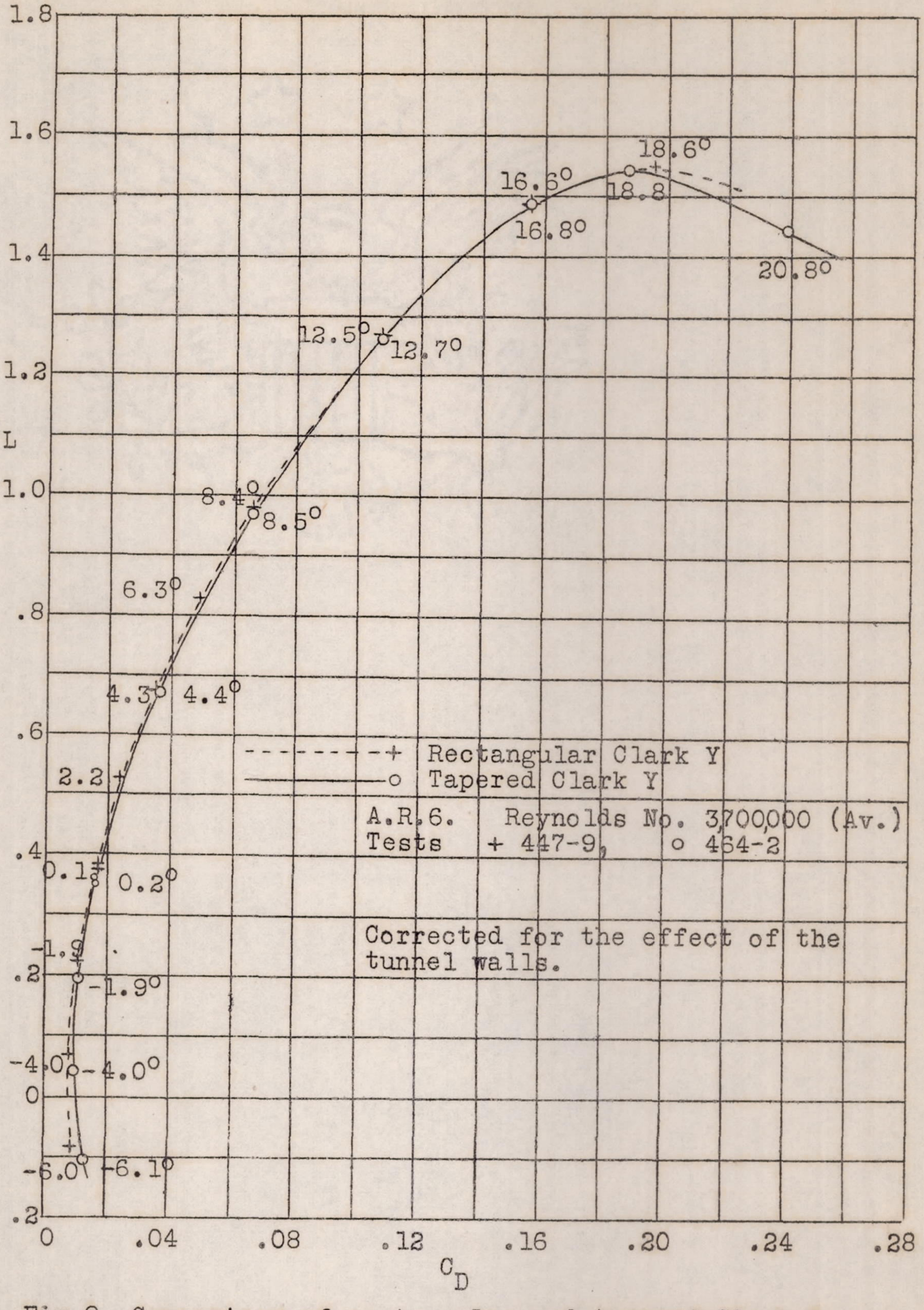


Fig.9 Comparison of rectangular and tapered Clark Y airfoils.

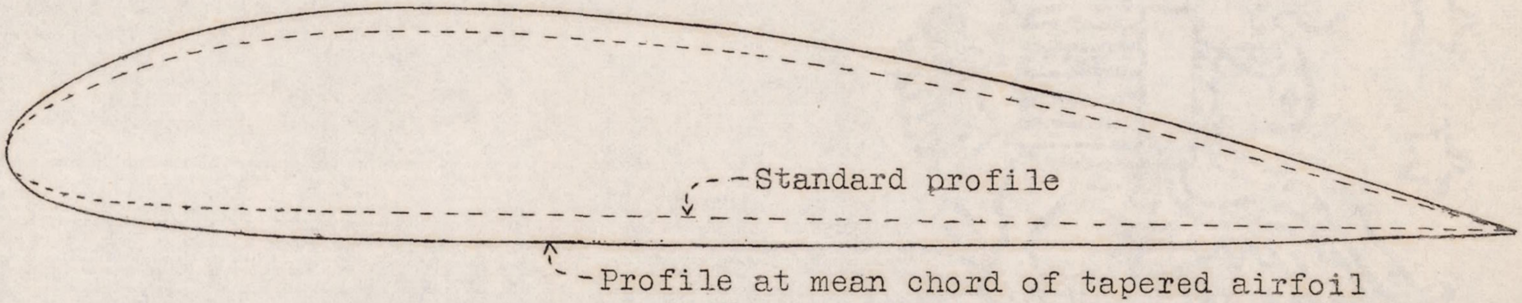


Fig.10 Comparison of profiles of standard and tapered Clark Y airfoils.