REPORT No. 391

THE AERODYNAMIC CHARACTERISTICS OF EIGHT VERY THICK AIRFOILS FROM TESTS IN THE VARIABLE DENSITY WIND TUNNEL

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SUMMARY

A group of eight very thick airfoils having sections of the same thickness as those used near the roots of tapered airfoils were tested in the Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics. The tests were made to study certain discontinuities in the characteristic curves that have been obtained from previous tests of these airfoils, and to compare the characteristics of the different sections at values of the Reynolds Number comparable with those attained in flight. The discontinuities were found to disappear as the Reynolds Number was increased. The results obtained from the large-scale tests in this series indicate that the N. A. C. A. 0021 airfoil, a symmetrical airfoil having a thickness ratio of 21 per cent, has the best general characteristics.

INTRODUCTION

Very thick airfoil sections are used near the hubs of wooden propellers, near the roots of tapered wings, and elsewhere on airplanes when the structural advantages resulting from their use compensate for the aerodynamic disadvantages. It is therefore necessary to know the aerodynamic characteristics of very thick airfoils in order to arrive at the most desirable balance between the conflicting structural and aerodynamic requirements.

Previous to this investigation, practically no large-scale data were available on the characteristics of very thick airfoils. Two exceptions to this statement may be mentioned. In reference 1 are given the characteristics of a thick propeller section as determined from both low-scale and high-scale tests in the Variable Density Wind Tunnel, and in reference 2 are given data on the minimum drag of several thick symmetrical airfoils or strut sections. However, the first-mentioned reference gives only the characteristics of one airfoil of poor form aerodynamically, and the second only minimum drag values. Nevertheless these data are sufficient to indicate that the characteristics as determined from small-scale model tests of very thick airfoils may be subject to important scale-effect corrections. The results of the relatively large number of small-scale tests of airfoils give an indication of the changes that may be expected in their characteristics with increasing thickness. It appears from the low-scale results that airfoil sections having a thickness much greater than 20 per cent of the chord are so poor aerodynamically that their use will seldom be justified by other considerations. It also appears that these airfoils may exhibit serious discontinuities in their aerodynamic characteristics as the angle of attack is increased in the region of maximum lift. Some airfoils suddenly lose as much as one-half of their lift, while the angle of attack remains unchanged.

The present investigation was undertaken with three objects in view.

1. To obtain and compare the characteristics of several types of very thick airfoils.
2. To study the discontinuities in the aerodynamic characteristics that some thick airfoils exhibit when tested at low values of the Reynolds Number.
3. To study scale effect on very thick airfoils, particularly the maximum lift changes with the Reynolds Number.

The investigation was carried out in the Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics. The first tests, dealing with the discontinuities, were made during June and July, 1929, and the remainder of the tests during August, 1930.

MODELS

The following airfoils were chosen for the investigation:

N. A. C. A. 100
N. A. C. A. 101
N. A. C. A. 102
N. A. C. A. 103
N. A. C. A. 104
U. S. N. P. S. 6
N. A. C. A. 0021
N. A. C. A. 6321

Drawings of the profiles and tables of their ordinates are given in Figures 4 to 11. The N. A. C. A. 100 is a symmetrical airfoil of 21 per cent maximum thickness derived by thickening the R. A. F. 30 profile. The

N. A. C. A. 101 is a Joukowski airfoil slightly modified to thicken the trailing edge. The maximum upper surface ordinate is approximately 22 per cent of the chord, but because of the concavity of the lower surface the maximum thickness is approximately 20 per cent of the chord. The N. A. C. A. 102 airfoil was derived by increasing the ordinates of the C–62 airfoil and refairing the nose and tail slightly. The N. A. C. A. 103 was derived from the Clark Y by increasing the ordinates to produce a maximum thickness of 21 per cent of the chord. The N. A. C. A. 104 airfoil was derived from the Göttingen 398 in a different manner:

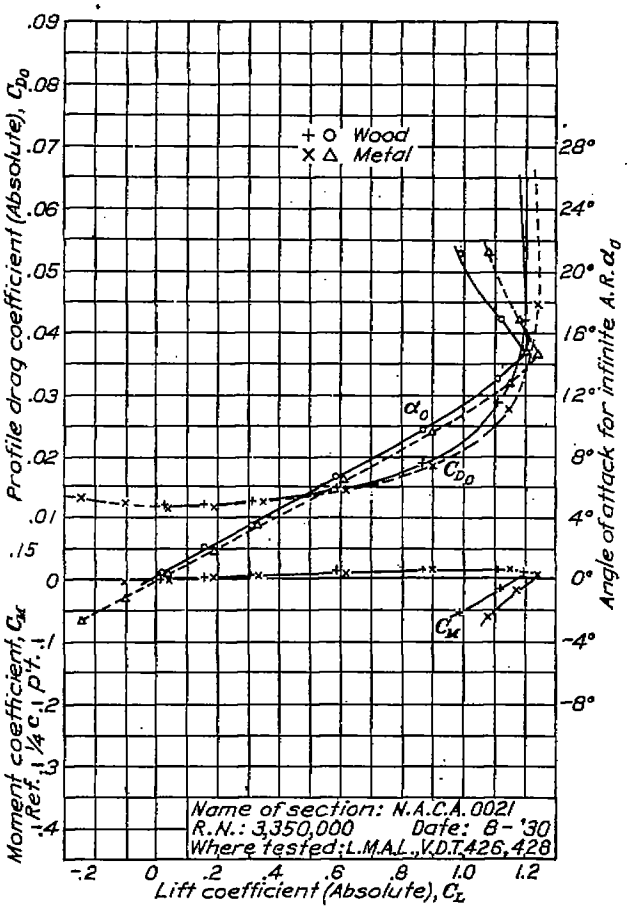


FIGURE 1.—Comparison of wood and metal airfoils

The vertical distance above and below the original mean line of the section was increased by applying a constant ratio so determined that the maximum thickness became 21 per cent of the chord. In this way the airfoil was thickened without increasing its effective camber. The U. S. N. P. S. 6 is a standard Navy propeller section (Reference 1) having a flat lower surface and a maximum thickness of 20 per cent of the chord.

The remaining two airfoils, the N. A. C. A. 0021 and the N. A. C. A. 6321, are members of a large family of airfoils, the other members of which are to be investigated in the Variable Density Wind Tunnel. The derivation of the airfoils will not be given here. It is sufficient to state that their forms are given by empirical equations and each airfoil is designated by a number of four digits, the first giving the maximum mean camber in per cent of the chord; the second, the position of the maximum mean camber in tenths of the chord from the leading edge; and the last two, the thickness in per cent of the chord.

It will be noted that all the profiles have a thickness of 20 or 21 per cent of the chord. This thickness was chosen because it was believed to be the greatest for which a practical application might be found. All the airfoils chosen were of approximately the same thickness in order to eliminate this variable.

ACCURACY

Because the airfoils were made of wood and more than a year elapsed between the time that they were finished and the time that the first tests were made, their profiles were not very accurate. For that reason both the specified ordinates and those from measurements made after all tests had been completed have been given. Furthermore, the surface of a wooden airfoil will not remain smooth under the conditions of testing in the Variable Density Wind Tunnel. Therefore, in order to form an estimate of the errors arising from these sources, a highly polished metal 0021 airfoil was tested for comparison with the tests of the wooden airfoil. The results of these tests, which are presented for comparison in Figure 1, will enable the reader to form an estimate of the accuracy of the other results, which, with the exception of those for the U. S. N. P. S. 6, are from tests of wooden models. It is estimated that the minimum profile drag and the maximum lift are in error by less than 5 per cent.

TESTS

The tests were divided into three groups, as follows:

1. Tests to study the discontinuity in the characteristic curves at various values of the Reynolds Number.
2. Tests to determine the characteristics of the airfoils at a large dymanic scale or Reynolds Number.
3. Tests to study scale effect and the effects of variations of the tubulence of the air stream.

An interval of more than a year elapsed between Groups 1 and 2 of the tests, during which time several major changes were made in the tunnel. The investigation was not completed at the time the first tests were made because the tunnel was then operated with an open throat, and extraneous air currents on the balance prevented the securing of reliable drag values. Before the second part of the investigation was started the tunnel was changed in several respects. A closed test section was installed, radial vanes were substituted for the honeycomb, and the shape of the entrance cone

was changed. A comparison of Figures 2 and 3 will indicate the nature of these changes. The changes improved the velocity distribution in the test section, reduced the vibration of the tunnel, and eliminated the extraneous air currents on the balance.

Characteristic discontinuities.—The tests of the first group were made by measuring the lift of each airfoil and the angle of attack in the usual manner (reference 3), with the exception that the maximum-lift range was investigated more carefully. Near the angles of maximum lift the angle of attack was increased slowly, while the lift-balance beam was maintained in equilibrium. The discontinuity of flow was indicated by a sudden drop of the beam. The reading was then recorded, and without changing the angle of attack the beam was again balanced and the reading again recorded. The region in which the discontinuity occurred was investigated also for decreasing angles of attack of the airfoils. The abrupt change observed when the angle of attack was reduced tended to appear at a lower angle, but, because the results were difficult to reproduce and because they were considered to be of little practical importance, they have not been presented in most instances.

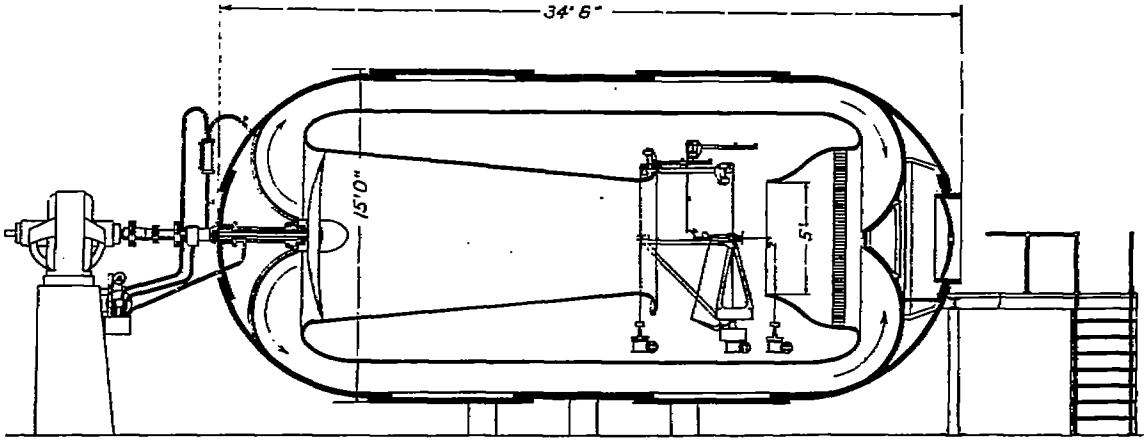


FIGURE 2.—The open-throat Variable Density Wind Tunnel

Large-scale characteristics.—As previously stated, these tests were made after the tunnel had been altered. The models were carefully refinished and tested in the usual manner with an air pressure in the tunnel of 20 atmospheres, corresponding to the highest Reynolds Number at which tests are usually made. Lift, drag, pitching moment, dynamic pressure, air pressure, and air temperature were measured in the usual manner. (Reference 3.)

Tests to study scale effect.—Additional tests of one of the airfoils, the N. A. C. A. 0021, were made to study the scale effects in greater detail, to determine how the results are influenced by a change of the airstream turbulence, and to compare the results that were obtained from the open-throat and from the closed-throat tunnels. A metal model with a polished surface was constructed for the additional tests in the closed-throat tunnel in order to eliminate possible effects from variations of the surface condition.

The additional tests, which were made under the same conditions and immediately following those that were made to compare the airfoils, consisted of lift and drag measurements over a wide range of values of the Reynolds Number, and additional measurements made

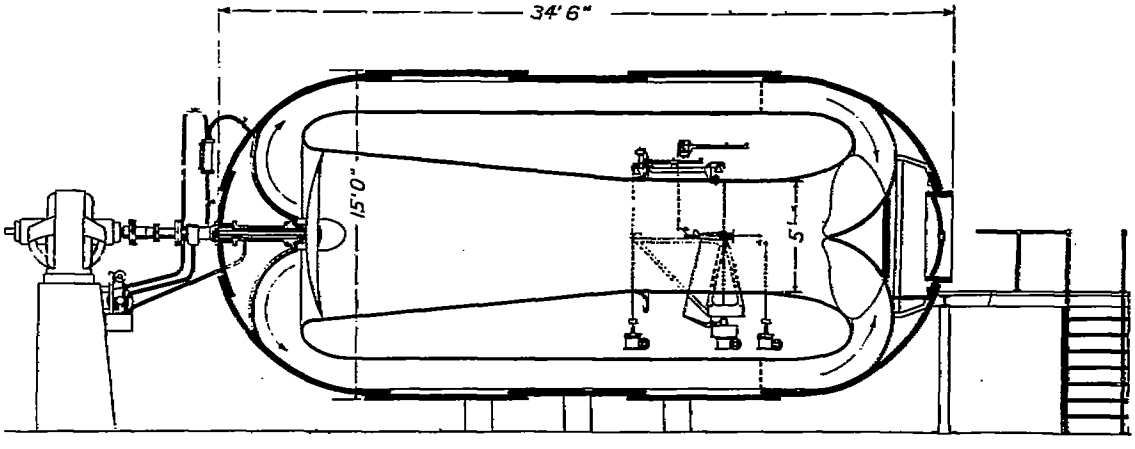


FIGURE 3.—The modified closed-throat Variable Density Wind Tunnel

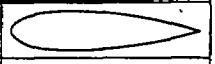
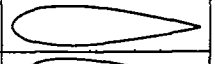
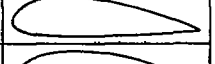
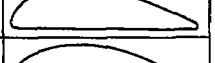
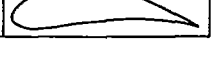
after the turbulence of the air stream had been increased. To extend the Reynolds Number range to lower values, the air pressures in the tunnel were reduced to subatmospheric pressures.

The turbulence of the air stream was increased by the introduction of a screen across the test section 17 inches ahead of the model. The screen was constructed of round-edge flat strip five-sixteenths inch wide, woven on 1½-inch centers to form a square mesh lattice having 1¾₁₆-inch openings.

DISCUSSION

Comparison of the airfoils.—In order that the aerodynamic characteristics of the various sections may be compared at a large value of the Reynolds Number, the characteristics from tests at a Reynolds Number of approximately 3,400,000 are given in a form that has been adopted as standard at the laboratory. In Figures 4 to 11 an outline of the profile, a table of ordinates, and the complete aerodynamic characteristics are given for each section. Two plots are given for each airfoil. First, the characteristics corrected to aspect ratio 6 (reference 4) are plotted against angle of attack. Second, in order to compare the section characteristics, the results have been corrected by the method given in reference 4 to infinite aspect ratio and plotted against the lift coefficient as the independent variable. To facilitate a comparison of the airfoils, their most important properties are tabulated in Tables I and II.

TABLE I

Airfoil	$C_{L_{max.}}$	Profile drag, C_{D_0}				C_{M_0}	Profile
		$C_L=0$	$C_L=.3$	$C_L=.6$	$C_L=.9$	$C_L=0$	
100	1.09	.0121	.0128	.0163	.0228	+.002	
0021	1.20	.0120	.0125	.0150	.0195	−.001	
102	1.17	.0138	.0140	.0160	.0222	−.068	
104	1.22	.0125	.0128	.0151	.0215	−.071	
6321	1.21	.0140	.0142	.0163	.0232	−.085	
103	1.22	.0150	.0153	.0183	.0284	−.097	
P.S.6	1.29	.0520	.0222	.0227	.0315	−.092	
101	1.48	.0355	.0208	.0192	.0254	−.195	

The relative desirability of the various profiles when used as wing sections may be compared by referring to Table I, where the airfoils are arranged in the order of decreasing moment coefficients. It will be noted that the N. A. C. A. 100 is inferior to the N. A. C. A. 0021, the other symmetrical airfoil. Excluding the U. S. N. P. S. 6 because of its excessive drag, and, for the time being, the 101 because of its extreme camber, the remaining airfoils may be compared with the 0021. It will be noted that the maximum lift coefficients of the remaining five airfoils all lie between 1.17 and 1.22, a variation of less than ±2½ per cent from that of the 0021. The other airfoils have higher profile drag coefficients than the 0021 airfoil at any given value of the lift coefficient between 0 and 0.9. The 104, which was derived from the Göttingen 398 by increasing its thickness equally on either side of the original mean camber line, is nearly as efficient as the 0021. The others are decidedly inferior. The highly cambered 101 airfoil is of interest because it shows a maximum lift coefficient of 1.48, 23 per cent higher than that of the 0021. Referring to Figure 11, the profile drag is seen to have only a small range of low values near a lift coefficient of 0.45, and at this lift coefficient the profile drag is 32 per cent higher than that of the 0021. The above discussion indicates that camber is of questionable value in thick airfoils.

Air flow discontinuities.—Wind-tunnel tests have frequently indicated that the air forces on certain thick airfoils do not vary continuously with the angle of attack. A sudden loss of more than half the total lift would be a serious matter if it occurred in flight. It is important, therefore, to consider such discontinuities.

Lift curves for all the airfoils from tests in the open-throat tunnel at several values of the Reynolds Number between 150,000 and 1,500,000 are presented in Figures 12 to 19. The curves indicate that five of the eight airfoils exhibit discontinuities at a value of the Reynolds Number corresponding to the tests made with atmospheric pressure in the tunnel. As the Reynolds Number is increased the sudden loss of lift becomes less pronounced and all the airfoils cease to show discontinuities when the value of the Reynolds Number reaches 750,000, a value well below the full-scale range for airplane wings.

The abrupt loss of lift is undoubtedly due to an abrupt change in the character of the flow over the airfoil. In general, as the angle of attack of an airfoil is increased, the rate at which the lift increases falls off because of a thickening of the boundary layer on the upper surface or because separation of the flow from the surface may take place at a point forward of the trailing edge, as a result of reversed flow in the boundary layer. Either effect tends to decrease the angle through which the air is directed downward by the wing, and therefore tends to reduce the lift. An abrupt loss of lift, such as that shown by some of the airfoils, must correspond to an abrupt change in the position of the separation point and might be explained by the assumption that the return flow in the boundary

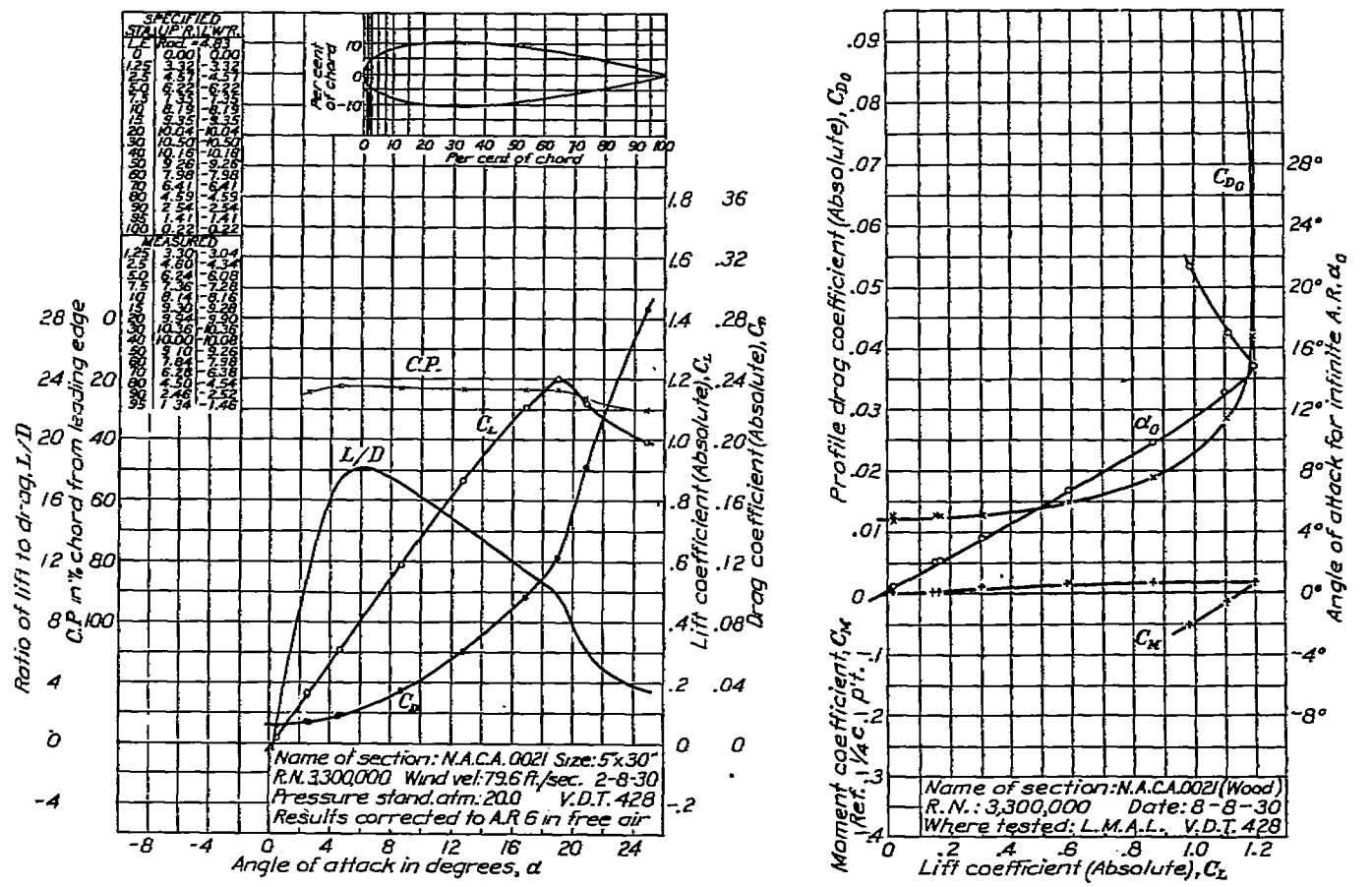


FIGURE 4.—N. A. C. A. 0021 airfoil. (Modified closed-throat tunnel)

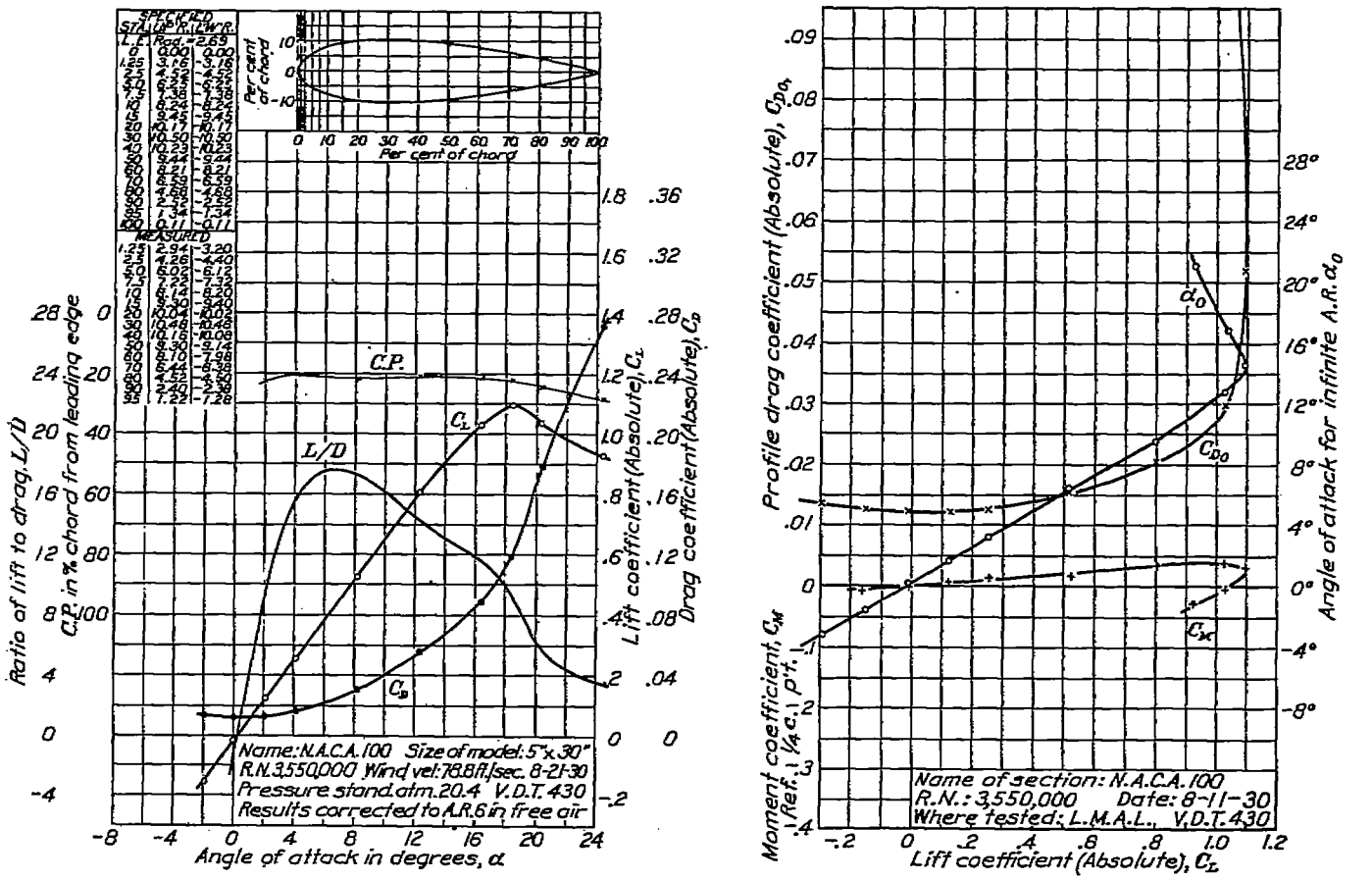


FIGURE 5.—N. A. C. A. 100 airfoil. (Modified closed-throat tunnel)

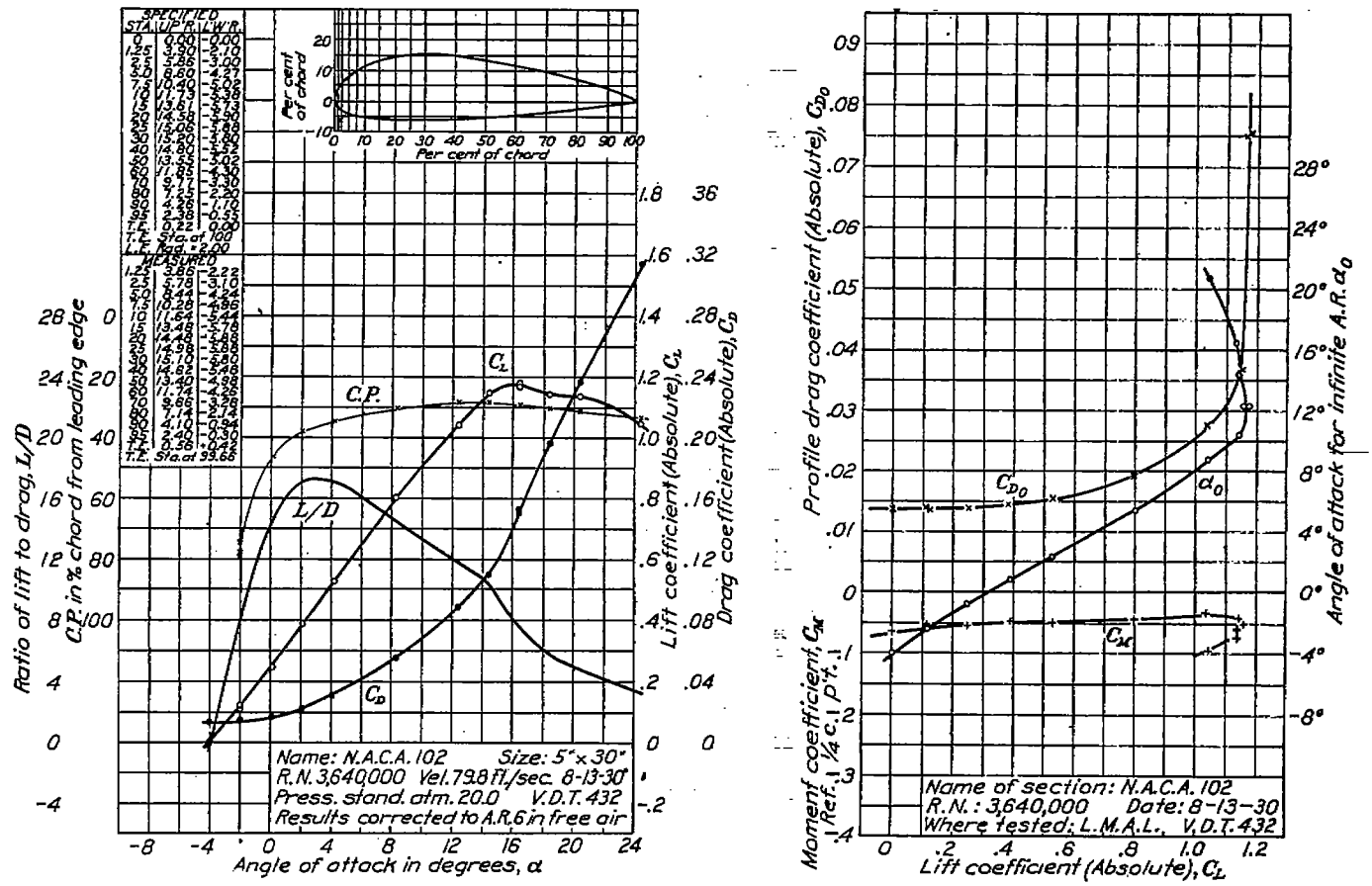


FIGURE 6.—N. A. C. A. 102 airfoil. (Modified closed-throat tunnel)

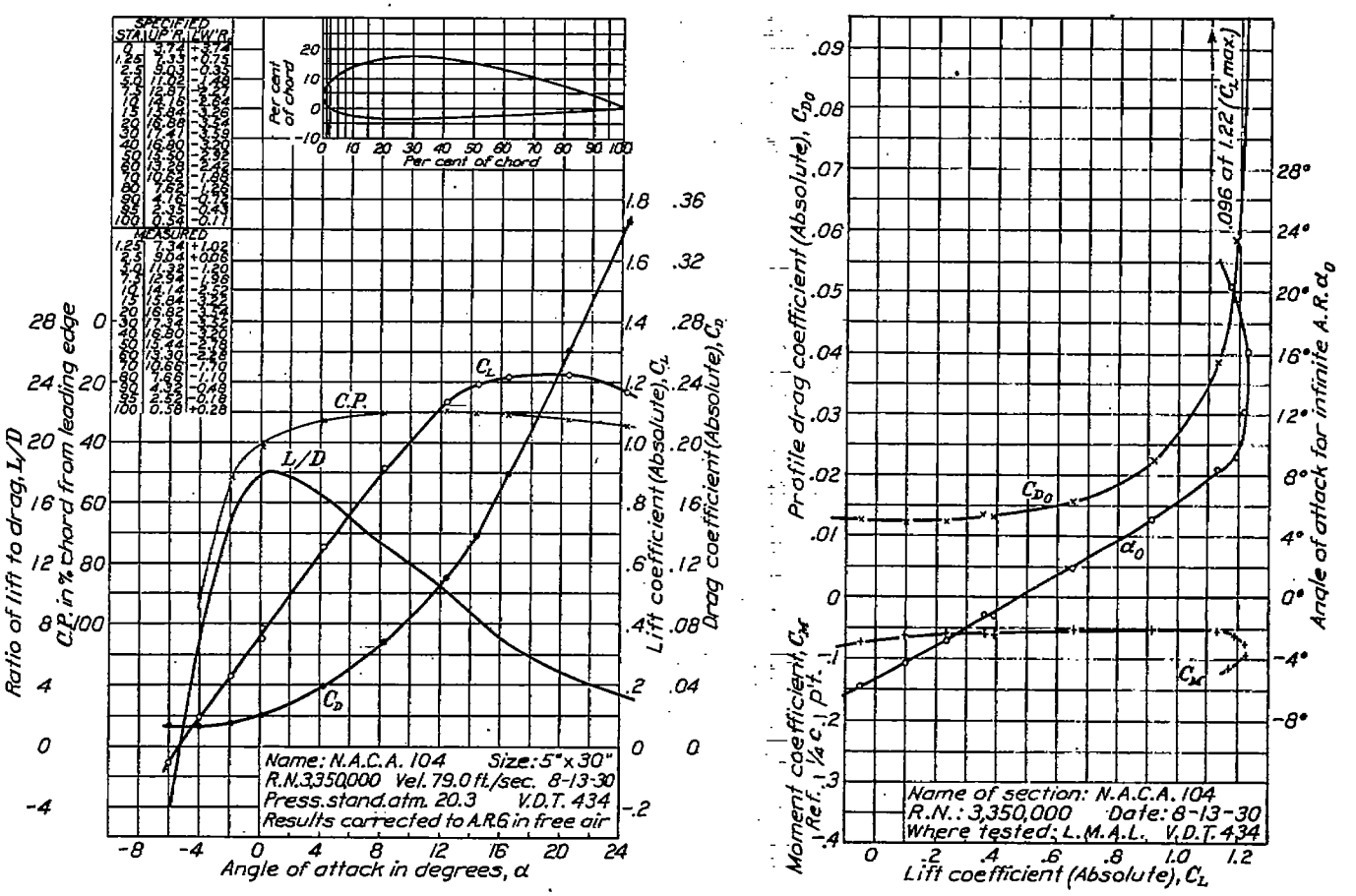


FIGURE 7.—N. A. C. A. 104 airfoil. (Modified closed-throat tunnel)

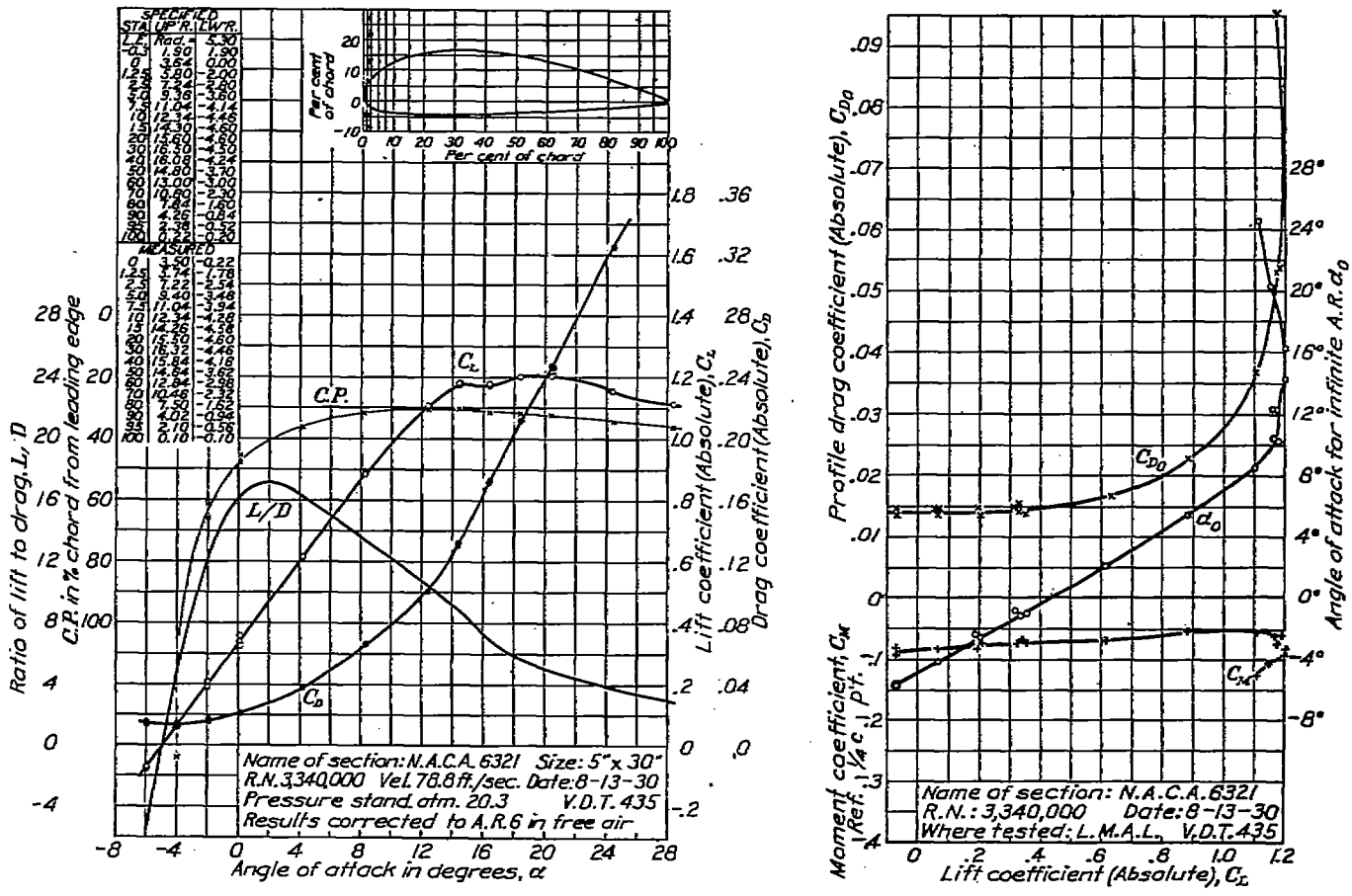


FIGURE 8.—N. A. C. A. 6321 airfoil. (Modified closed-throat tunnel)

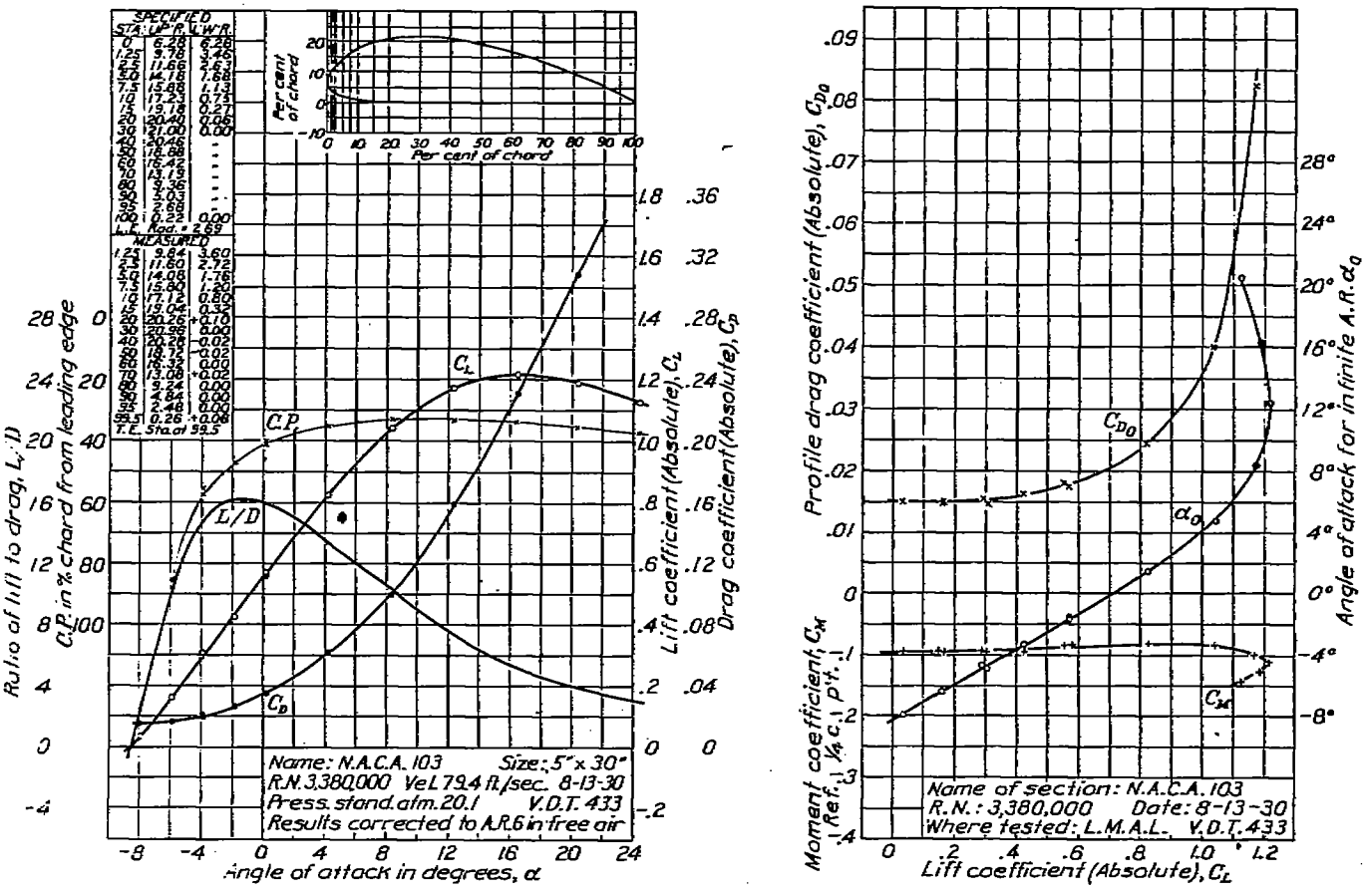


FIGURE 9.—N. A. C. A. 103 airfoil. (Modified closed-throat tunnel)

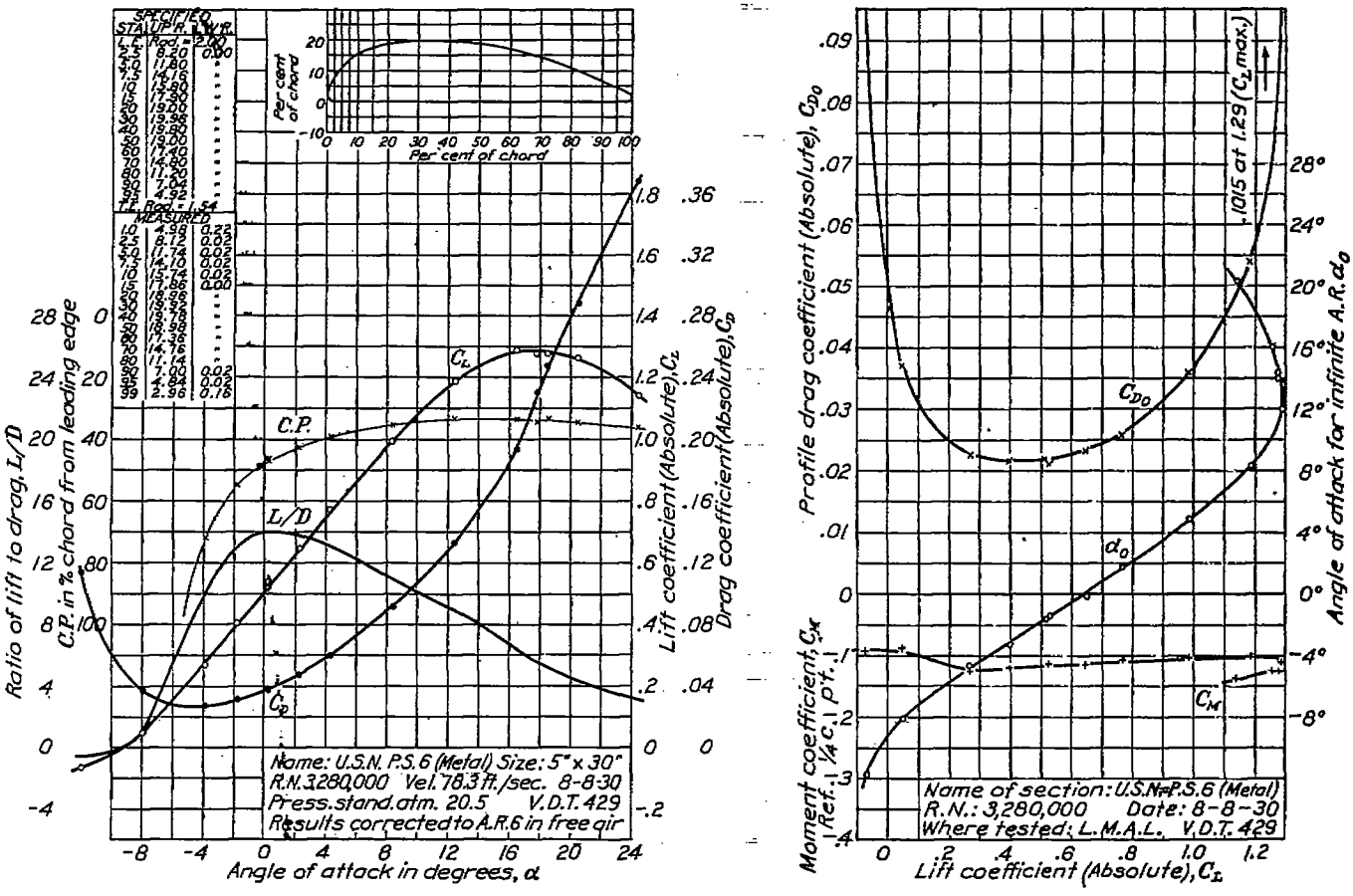


FIGURE 10.—U. S. N. P. S. 6 airfoil. (Modified closed-throat tunnel)

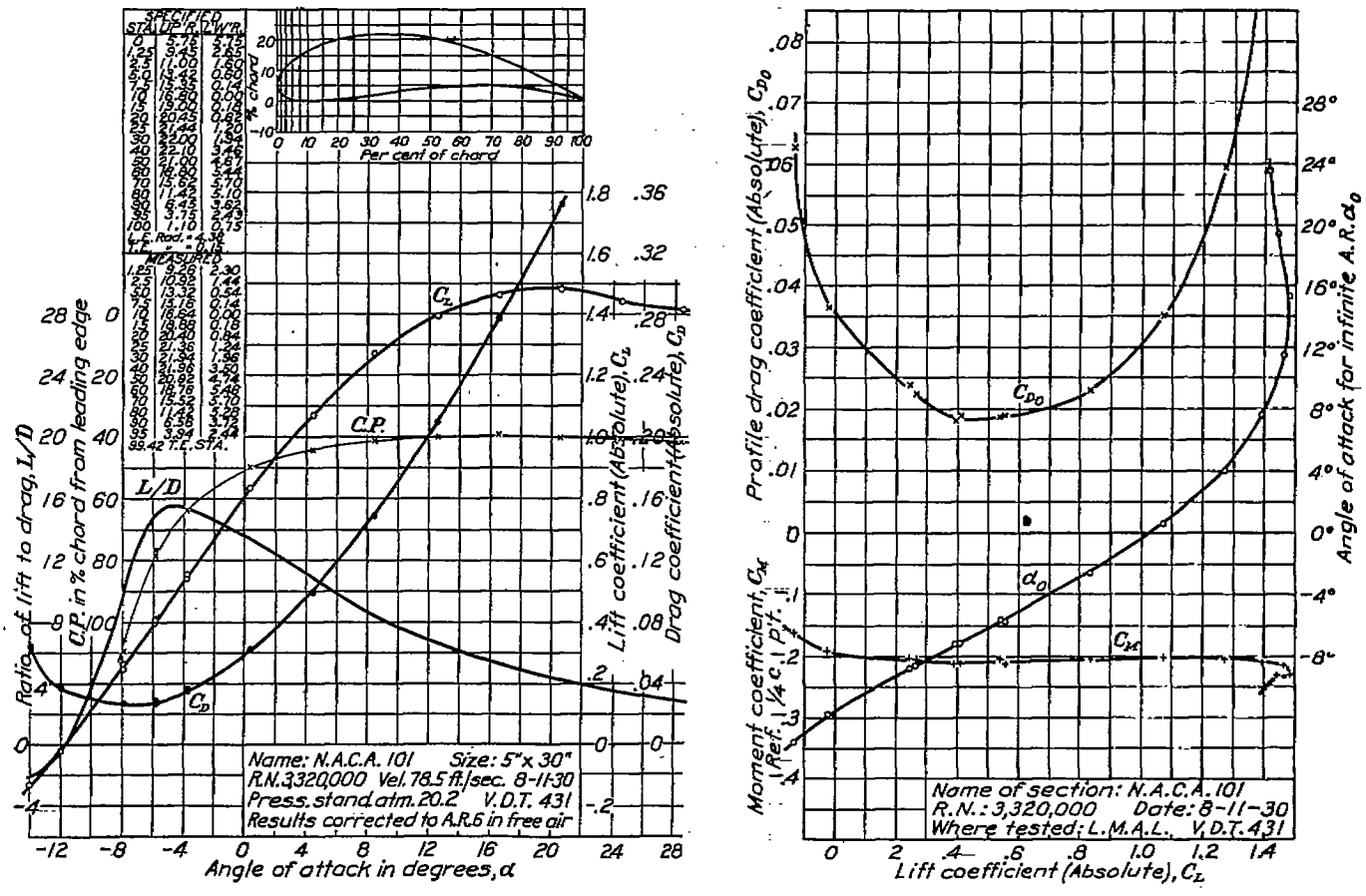


FIGURE 11.—N. A. C. A. 101 airfoil. (Modified closed-throat tunnel)

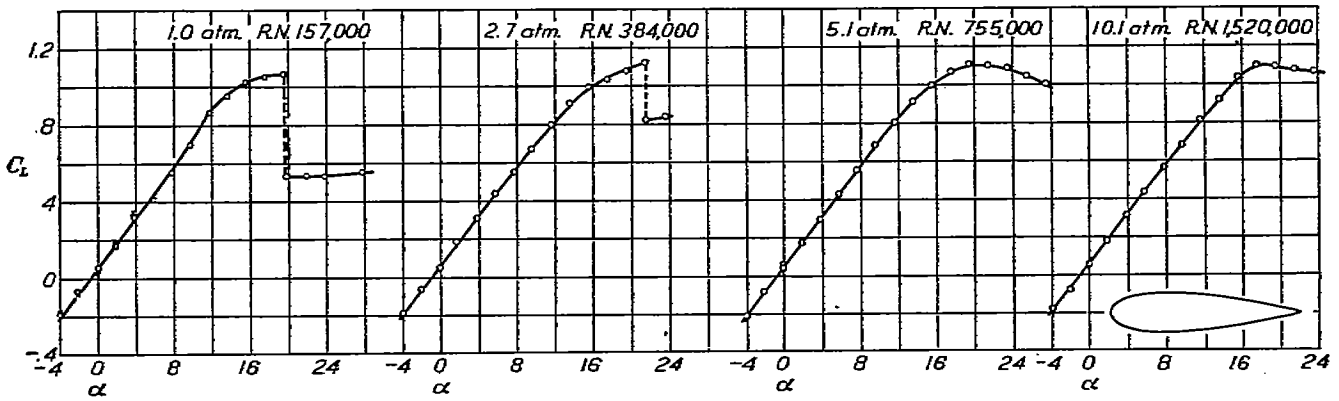


FIGURE 12.—N. A. C. A. 0021 airfoil (wood). From tests in open-throat tunnel

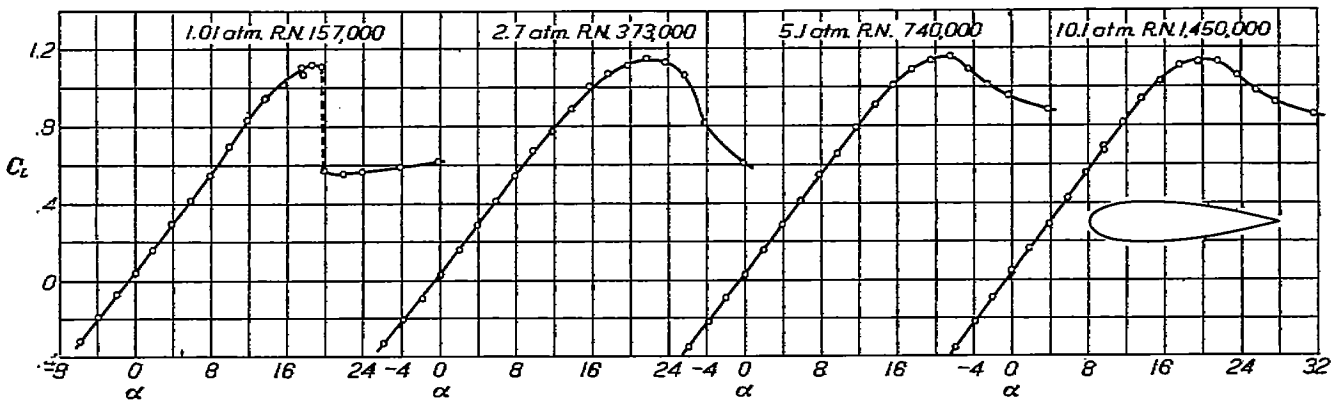


FIGURE 13.—N. A. C. A. 100 airfoil. From tests in open-throat tunnel

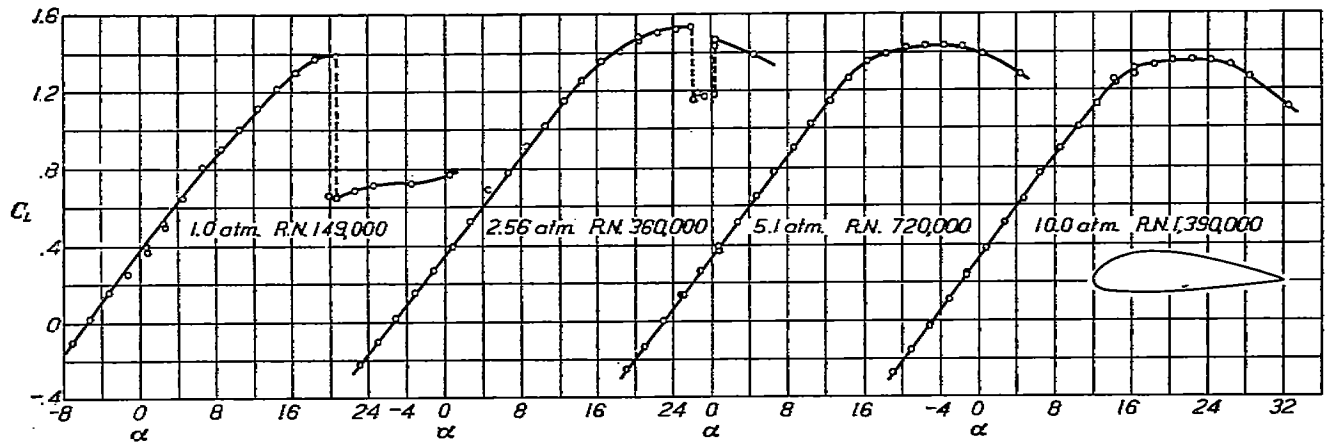


FIGURE 14.—N. A. C. A. 102 airfoil. From tests in open-throat tunnel

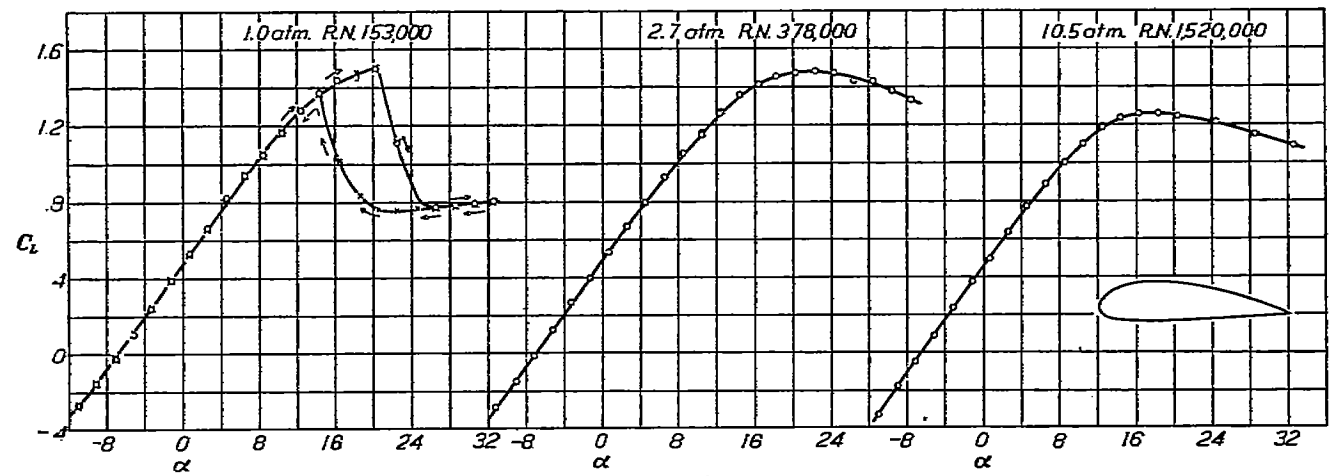


FIGURE 15.—N. A. C. A. 104 airfoil. From tests in open-throat tunnel

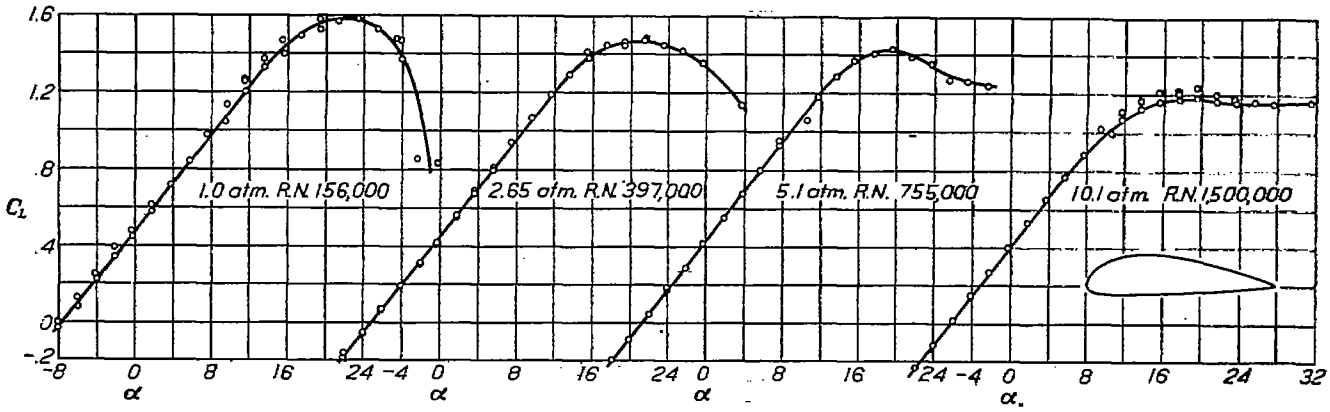


FIGURE 16.—N. A. C. A. 6321 airfoil. From tests in open-throat tunnel

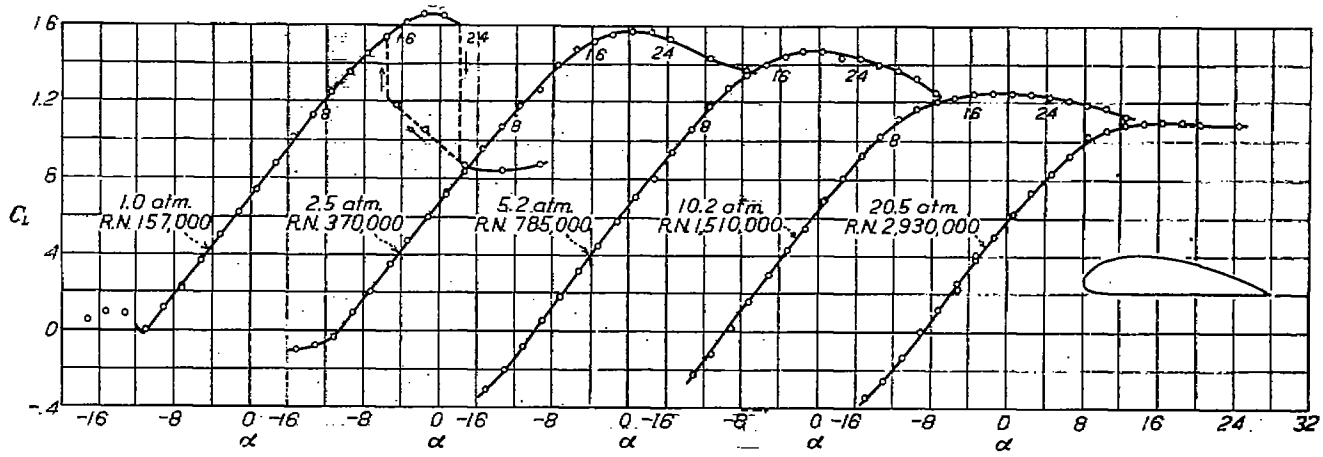


FIGURE 17.—N. A. C. A. 103 airfoil. From tests in open-throat tunnel

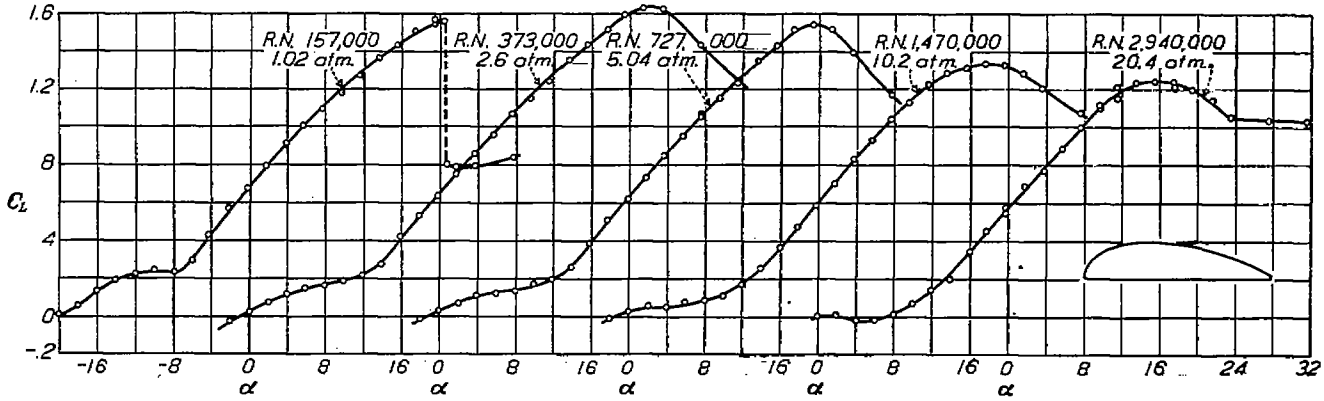


FIGURE 18.—U. S. N. P. S. 6 airfoil. From tests in open-throat tunnel

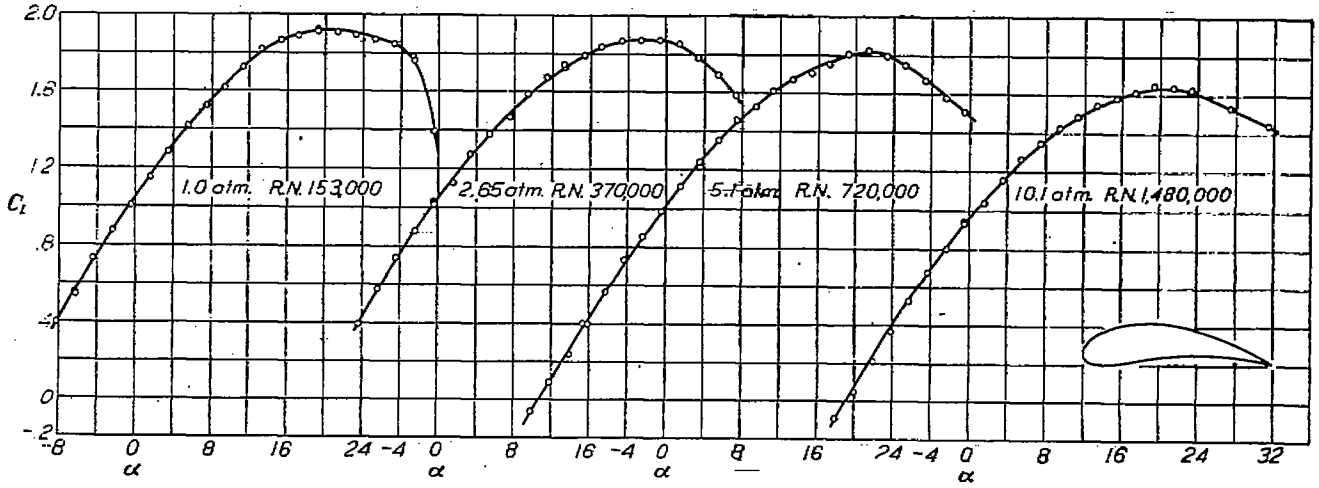


FIGURE 19.—N. A. C. A. 101 airfoil. From tests in open-throat tunnel

layer either starts well forward, where the adverse pressure gradient along the surface of the airfoil is very large, or continues forward until the separation point is displaced to a position near the leading edge. It is also probable that at the higher values of the Reynolds Number the increased turbulence in the boundary layer, through the scouring action of the turbulent air, tends to prevent the accumulation of dead air and the resulting complete separation. (A similar phenomenon in relation to the drag of spheres is discussed in reference 6.) The character of the discontinuity exhibited by the N. A. C. A. 102 airfoil at a Reynolds Number of 360,000 is noteworthy because it gives some indication of how the type of flow corresponding to the low-lift region beyond the discontinuity disappears at the higher values of the Reynolds Number.

Scale effect.—The scale effect on the maximum lift may best be studied by referring to Figures 11 to 19, where lift curves from tests in the open-throat tunnel at various values of the Reynolds Number are plotted together, and to Figure 20, where the lift data for the N. A. C. A. 0021 airfoil from tests in the closed-throat tunnel are presented. The maximum lift coefficients of all the cambered airfoils decrease with increasing values of the Reynolds Number; the moderately cambered airfoils, which give high maximum lift coefficients in the usual range of model tests, suffer the greatest loss. The scale effect on the symmetrical airfoils, however, may be favorable, but is not large and is somewhat dependent on the degree of air-stream turbulence.

It is unnecessary to consider in detail here the effects produced by changes of the air-stream turbulence, as more complete data and a discussion of the subject may be found in reference 5. The change in the maximum lift coefficient produced by a change of the air-stream turbulence may be observed in Figure 20. It will be noted that the lift-curve discontinuities disappeared when the turbulence was increased and that the maximum lift coefficients obtained at the higher values of the Reynolds Number were increased.

Comparison of the scale effect in the different tunnels.—The differences between the results from the open-throat and from the closed-throat tunnels may now be considered. In order to provide a basis for an estimate of the degree of the tunnel air-stream turbulence under the different conditions, sphere drag tests similar to those described in reference 6 were conducted. The results of these tests are presented in Figure 21 as plots of the drag coefficient against the Reynolds Number. It is known (reference 7) that increased turbulence produces a shift of the steep part of the drag curves toward lower values of the Reynolds Number. An estimate of the degree of turbulence from these results is, of course, only qualitative, and the degree of turbulence indicated is that in the center of the air stream at comparatively low values of the Reynolds Number. Laying aside such considerations, however, the results of the sphere tests indicate that the air flow in the test section of the closed-throat tunnel is more turbulent than the flow in the open-throat tunnel, and that the flow behind the screen is, of course, the most turbulent. It is not surprising, there-

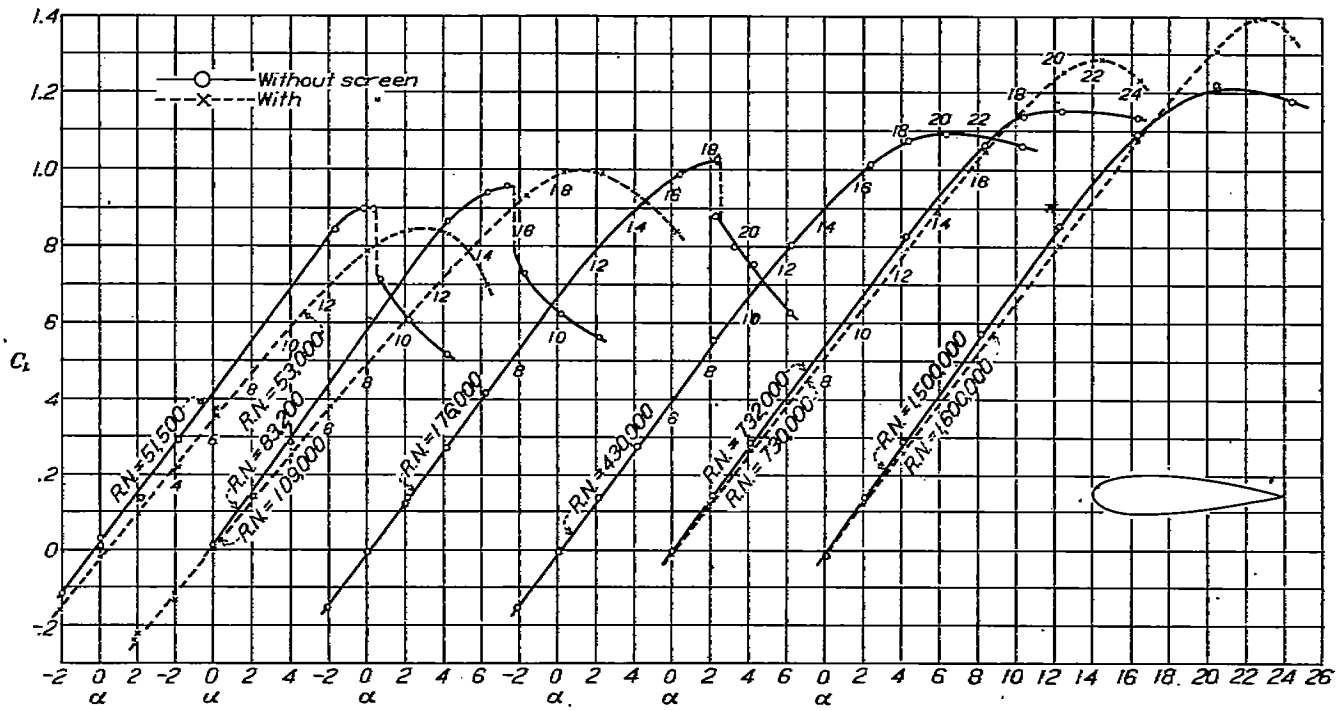


FIGURE 20.—N. A. C. A. 0021 airfoil. Results from closed-throat tunnel showing effect of increased turbulence

fore, that certain differences may be observed between the results of tests of the N. A. C. A. 0021 airfoil in the open-throat tunnel (fig. 12) and in the closed-throat tunnel (fig. 20). In the more turbulent air stream of the closed-throat tunnel the lift discontinuity is less pronounced. Comparing the lift curves corresponding to a Reynolds Number of approximately 1,600,000, it will be noted that the maximum lift

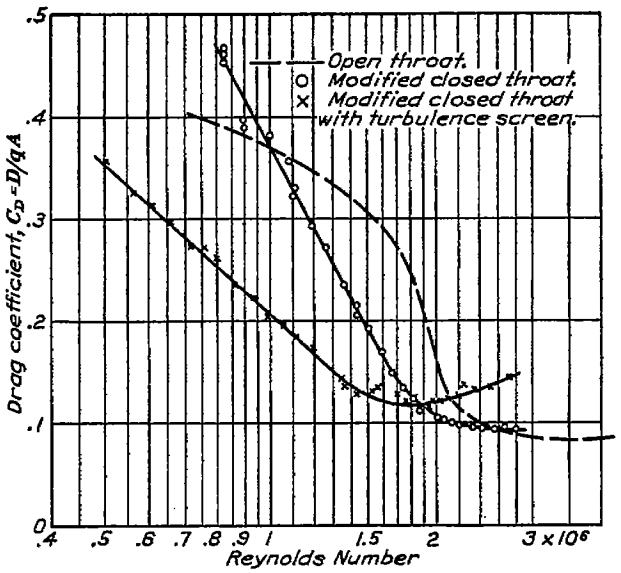


FIGURE 21.—Drag of 20-cm. sphere

coefficient from the tests in the closed tunnel is 10 per cent higher than that from the tests in the open-throat tunnel. The results in Figure 1 indicate that a difference of approximately 4 per cent may be attributed to the fact that a highly polished metal model was used in the later tests. The remainder, 6 per cent, is not very important as compared with the changes resulting from true scale effect on some of the airfoils, and is of the same order as the difference that would be expected to result from the change in the degree of turbulence.

CONCLUSIONS

1. Discontinuities of the type that have been observed in the testing of thick airfoils disappear as the Reynolds Number is increased, and therefore will not be encountered in flight if wing sections of this type are used.

2. For airfoils having a thickness ratio of approximately 20 per cent of the chord, camber is of questionable value.

3. Very thick, moderately cambered airfoils that give high maximum lift coefficients in the usual Reynolds Number range of model tests will be found to give lower maximum lift coefficients in flight.

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TABLE II.—IMPORTANT CHARACTERISTICS AT HIGH REYNOLDS NUMBER (3,400,000)

Airfoil	C_L maximum	C_{D_0} minimum	C_L max. / C_{D_0} mim.	C_{M_0} at zero lift	A. R. 6 C_D minimum	A. R. 6 L/D maximum	Thickness at— 0.15 chord	Thickness at— 0.65 chord	C. P. at— C_L maximum	C. P. at— ¼ C_L maximum
							Per cent chord		Per cent chord	
N. A. C. A. 0021	1.20	0.012	100	−0.001	0.012	18.2	18.7	14.4	24	22
N. A. C. A. 100	1.09	.012	91	+.002	.012	17.6	18.9	14.9	23	21
N. A. C. A. 101	1.48	.018	82	−.165	.026	15.5	18.8	11.7	40	82
N. A. C. A. 102	1.17	.014	82	−.063	.014	17.2	19.3	14.7	29	43
N. A. C. A. 103	1.22	.015	81	−.097	.015	16.2	17.9	14.9	34	56
N. A. C. A. 104	1.22	.012	102	−.071	.013	18.1	19.1	14.2	32	44
N. A. C. A. 6321	1.21	.014	86	−.085	.014	17.1	18.9	14.4	32	50
U. S. N. P. S. 6	1.29	.022	59	−.092	.026	14.1	17.9	16.2	34	65