REPORT No. 446

AIRFOIL SECTION CHARACTERISTICS AS AFFECTED BY PROTUBERANCES

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SUMMARY

The drag and interference caused by protuberance from the surface of an airfoil have been determined in the N. A. C. A. variable-density wind tunnel at a Reynolds Number of approximately 3,100,000. The effects of variations of the fore-and-aft position, height, and shape of the protuberance were measured by determining how the airfoil section characteristics were affected by the addition of the various protuberances extending along the entire span of the airfoil. The results provide fundamental data on which to base the prediction of the effects of actual short-span protuberances. The data may also be applied to the design of air brakes and spoilers.

INTRODUCTION

The ideal airplane, aerodynamically, may be considered as one having only the drag due to skin friction and the minimum induced drag associated with its lift. Prof. B. M. Jones in England has shown that actual airplanes fall far short of such an ideal. Interference effects, it seems, must be blamed for a considerable part of the energy wasted in producing the turbulence associated with the comparatively large drag of actual airplanes.

The National Advisory Committee for Aeronautics has planned a series of investigations dealing with the subject of aerodynamic interference. The investigations will, it is hoped, lead to the discovery of the cause of the serious adverse effects and will provide data that may be applied to the solution of practical problems of design. An examination of present-day airplanes, both military and commercial, has led to the belief that a considerable part of the adverse interference arises from small projecting objects, such as fittings, tubes, wires, rivet heads, lap joints, butt straps, filler caps, inspection plates, and many other projections from the main surfaces that may be considered together as protuberances. A systematic investigation of protuberances differently formed and variously located should indicate the relative magnitude of such effects and also show the effect of disturbing the flow in the boundary layer about otherwise streamline bodies.

Some early investigations of boundary-interference effects were originated by Prandtl at Göttingen in 1914 to study the effects of a small ring protruding from the surface of a sphere. Large negative, or favorable, interference effects were observed at certain values of the Reynolds Number because the turbulence produced by the protuberance changed the character of the boundary layer so as to delay the separation of the flow from the surface, thus producing a smaller turbulent wake and a smaller drag. Similar experiments have more recently been performed by Ower in England with streamline bodies. (Reference 1.) At low values of the Reynolds Number, when the flow in the boundary layer of the body is to a considerable extent laminar, protuberances from the forward portions of the body cause a transition from the laminar to the turbulent state of flow in the boundary layer with a resulting increase of drag. This effect is not of great practical significance, however, because the flow in the boundary layer of full-scale bodies is probably, in any event to a large extent, of the turbulent type. It is advisable, therefore, to make investigations involving boundary-interference effects at large values of the Reynolds Number if they are to be of the greatest practical value.

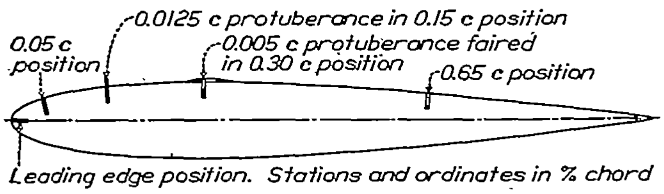
Tests have been made in the variable-density wind tunnel at large values of the Reynolds Number to determine the effects of protuberances from the surface of a streamlined body of revolution. The results have not yet been published. The present report deals with another phase of the investigation; that is, the effects on airfoil *section* characteristics of protuberances extending along the entire span from the airfoil surface. A succeeding report will consider the effects on *wing* characteristics of protuberances extending only over portions of the wing span. The tests with which the present report deals were made in the N. A. C. A. variable-density wind tunnel during March, 1932.

The N. A. C. A. 0012 airfoil section was employed throughout the investigation and the dynamic scale of the tests was maintained approximately the same throughout (Reynolds Number 3,100,000). The effects of variations of the position, size, and shape of the protuberance were measured by determining how the airfoil section characteristics were affected by the addition of the various protuberances.

TESTS

The N. A. C. A. variable-density tunnel and the methods employed for airfoil testing in the tunnel are described in detail in reference 2. These tests were made in the usual way, measuring the lift, drag, and pitching moments on a 5 by 30 inch duralumin airfoil mounted in the air stream so that the angle of attack could be varied. The model mounting differed in one respect from that described in reference 2. Instead of using a sting attached to the lower surface of the airfoil as part of the airfoil support, a special sting was employed that was attached near the trailing edge of the airfoil. As the airfoil has symmetrical sections, it was thus possible to make the airfoil and sting assembly symmetrical about the plane of the airfoil chords.

A section of the airfoil employed, the N. A. C. A. 0012 (reference 3), is shown in Figure 1. The protuberances were placed in the slots shown, the posi-



Station	Ordinate	Station	Ordinate	Station	Ordinate
0	0	15	5.345	70	3.664
1.25	1.894	20	5.738	80	2.623
2.5	2.615	30	6.002	90	1.448
5.0	3.555	40	5.803	95	0.807
7.5	4.200	50	5.294	100	(0.126)
10	4.683	60	4.563	L.E. Rad. = 1.576	

FIGURE 1.—N. A. C. A. 0012 airfoil showing protuberances

tions being: Directly at the leading edge; 5 per cent of the chord behind the leading edge; 15 per cent (approximately the front spar position); 30 per cent (maximum ordinate position); and 65 per cent (approximately the rear spar position). The protuberances were placed only on the upper side of the symmetrical airfoil, but the effect of each on the lower surface was determined by testing the airfoil through the negative angle-of-attack range.

The protuberance consisted of a strip of sheet duralumin having the desired height placed in one of the slots indicated in Figure 1 in such a way as to extend along the entire span of the model. The form that will be referred to as the faired protuberance was produced, as indicated in Figure 1, by forming over the protuberance a plaster-of-Paris fairing the cross section of which approximated a small half airfoil section on the surface of the main airfoil. The slots in the airfoil when not in use were filled with duralumin strips carefully filed to the surface and polished to present a continuous smooth surface. The protuberance was used in only one slot at a time, starting with the highest protuberance 0.0125c, and then reducing the height consecutively to 0.0050c, 0.0020c, and in some cases to 0.0010c and 0.0004c, by filing off the top of the projecting strip. The characteristics of the airfoil without protuberances—that is, with all slots filled—were measured twice during the progress of the investigation as a check on the consistency of the results.

For comparison with the results obtained at negative angles of attack, average curves for the negative-angle runs on the plain airfoil have been used. These differ slightly from the corresponding positive-angle curves because of asymmetrical support interference. When the protuberance was in the leading-edge position the tests were made at both positive and negative angles of attack, but average curves have been used to present the results. Thus the various curves presenting the results for the plain airfoil do not agree exactly. Furthermore, they should not be expected to agree with other tests of the same airfoil, because the tare-drag correction applied throughout this investigation did not allow for the lower drag of the special airfoil sting employed.

RESULTS AND DISCUSSION

The results are presented by means of curves of the lift coefficient C_L, profile-drag coefficient C_{D_0}, moment coefficient about a point one-quarter of the chord behind the leading edge $C_{m_{c/4}}$, and the angle of attack for infinite aspect ratio α_0. The results are thus presented as airfoil section characteristics. The most important results, those corresponding to the various heights and positions of the protuberance, are presented in Figures 2 to 10. Attention should be here called to the fact, however, that the characteristics thus presented should not be used with precise strip method calculations as though they were true infinite-aspect-ratio characteristics, but should be considered as average section characteristics deduced from the test data by the methods described in reference 2. Differences between these section characteristics and the true ones may probably be neglected as long as all the sections of the rectangular wing that was tested were operating at effective angles of attack within the range of approximately normal lift curve slope. Their use is also partly justified by the fact that approximately correct results for a full-span protuberance on a wing of normal aspect ratio are obtained from them when the simple aspect-ratio corrections (reference 2) are applied.

Proturberance position.—The results for the largest protuberance (0.0125c) in the various positions on the airfoil surface are shown in Figure 11. Considering first the effects of the protuberance on the lift at low angles of attack, it will be seen that the effect of the protuberance is to decrease the lift slightly for all upper-surface positions and to increase it slightly for all lower-surface positions. As regards the lift at higher angles of attack and the maximum value of the lift, the protuberances on the lower surface have little effect, whereas the adverse effect of those on the upper

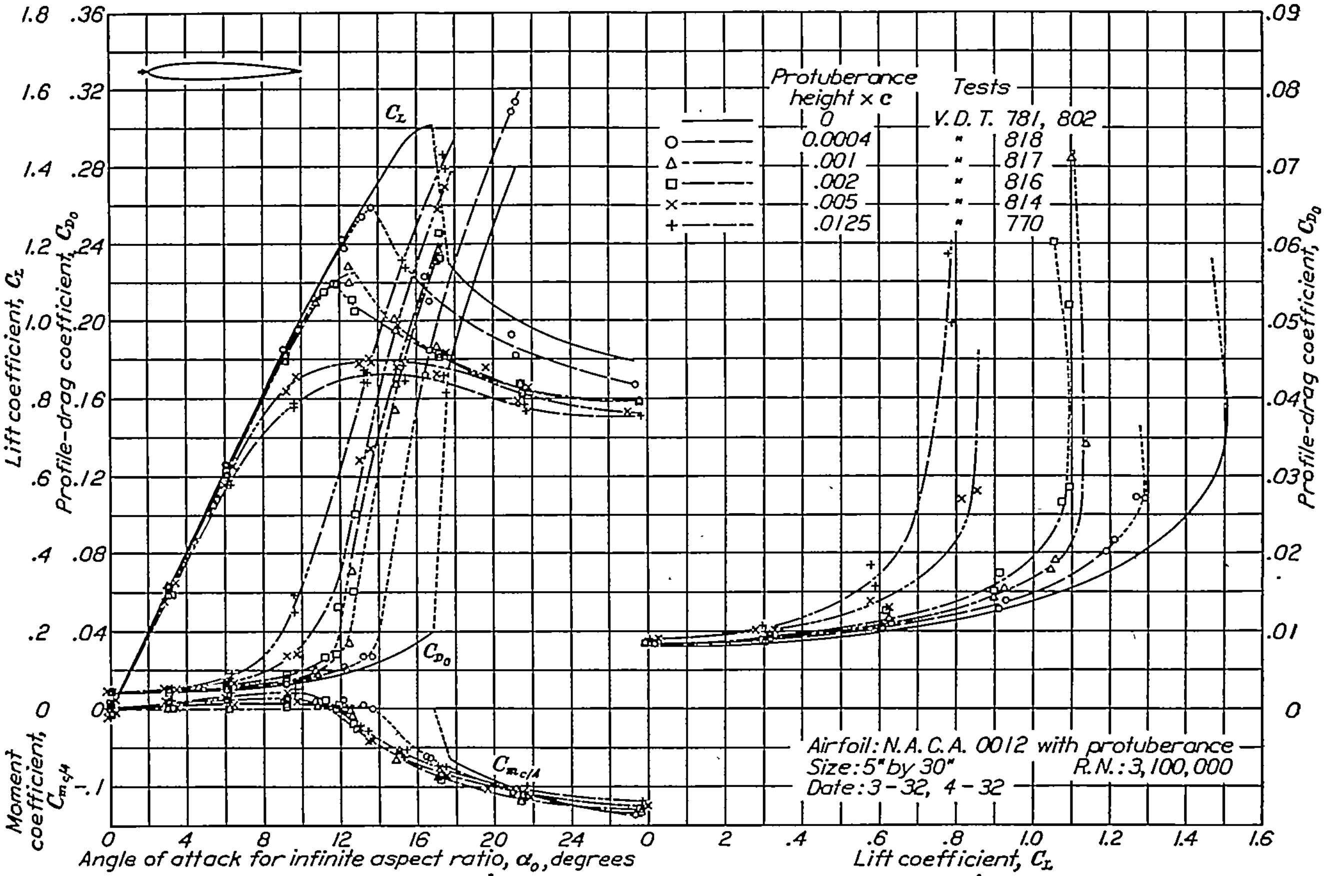


FIGURE 2.—Section characteristics for various protuberance heights. Protuberance on leading edge (position indicated by arrow)

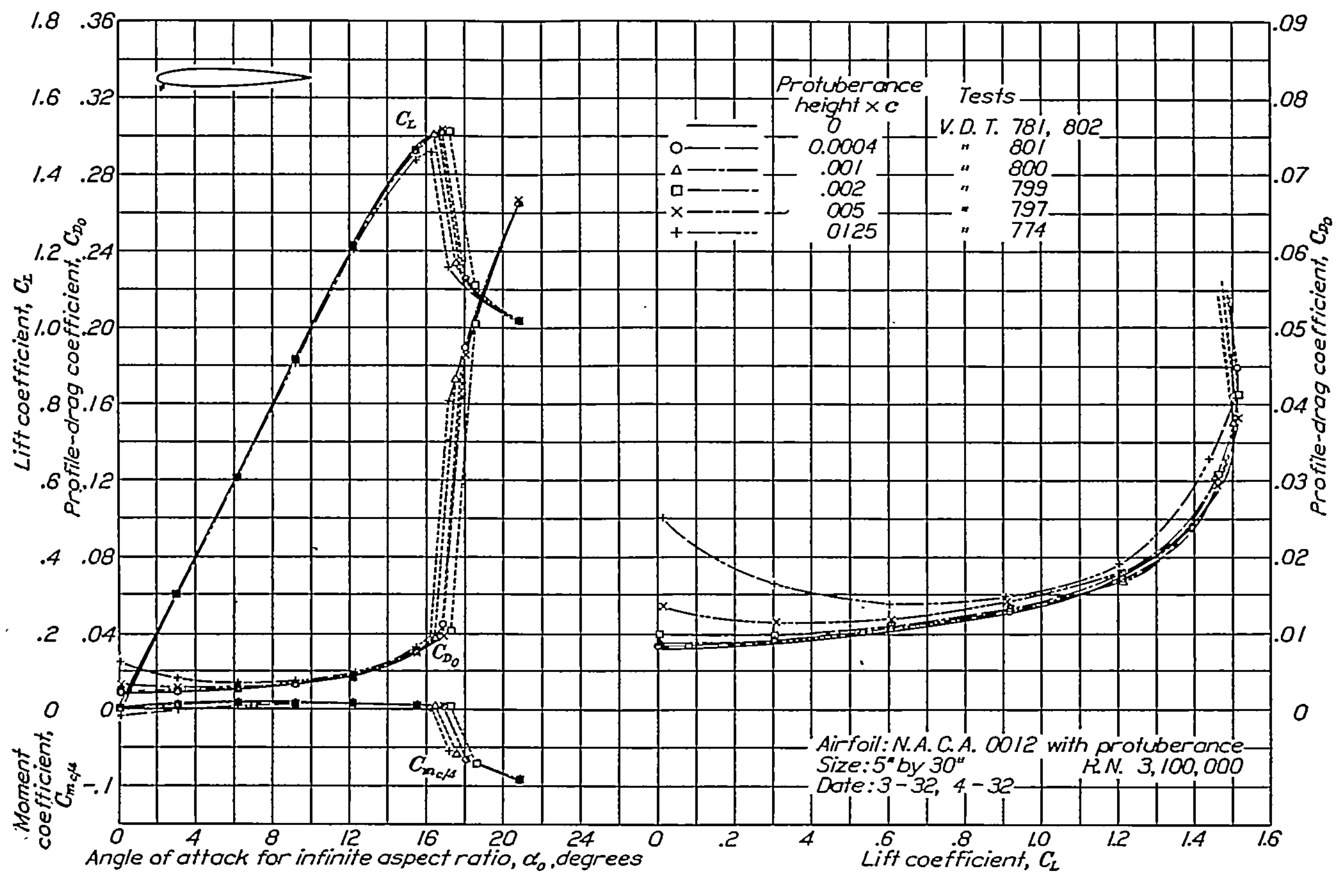


FIGURE 3.—Section characteristics for various protuberance heights. Protuberance on lower surface, 0.05c behind leading edge (position indicated by arrow)

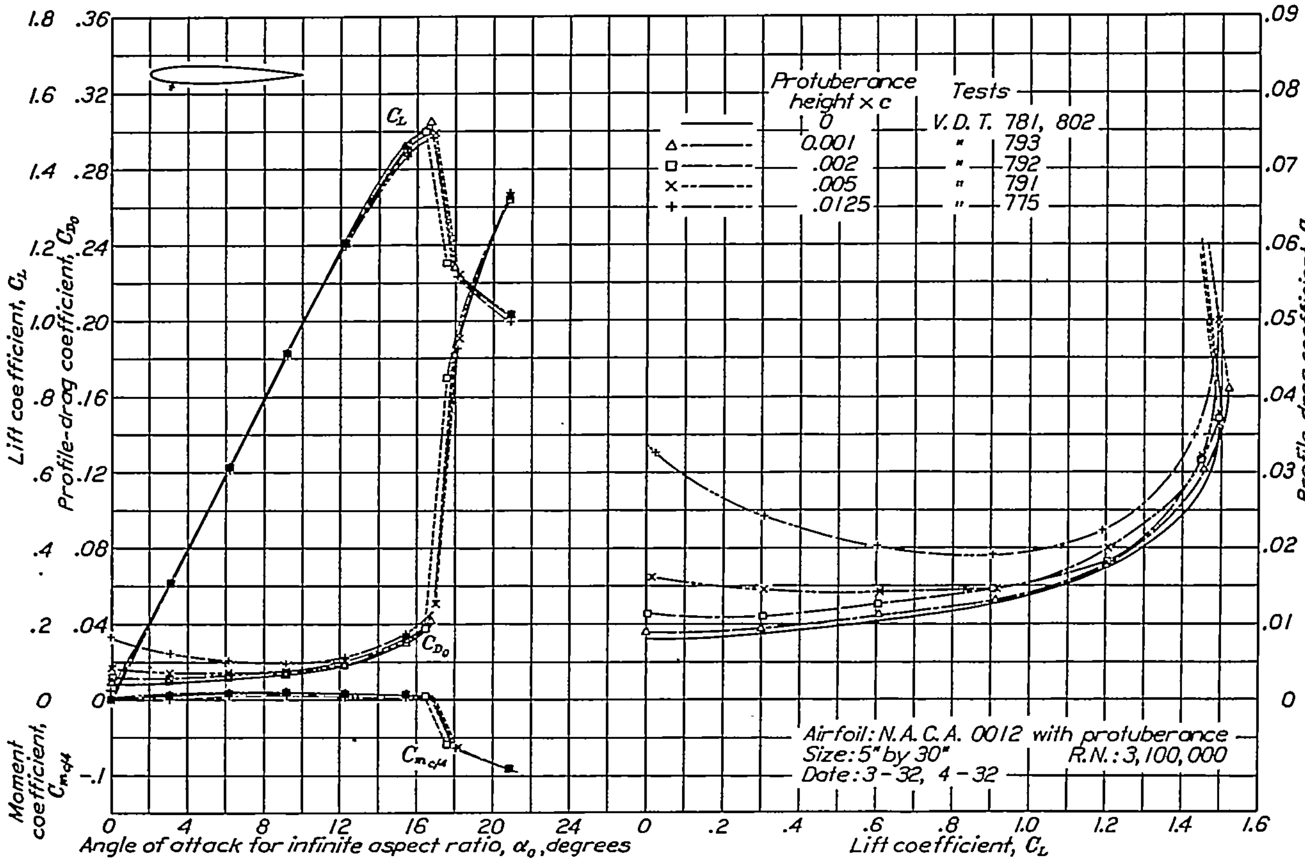


FIGURE 4.—Section characteristics for various protuberance heights. Protuberance on lower surface, 0.15c behind leading edge (position indicated by arrow)

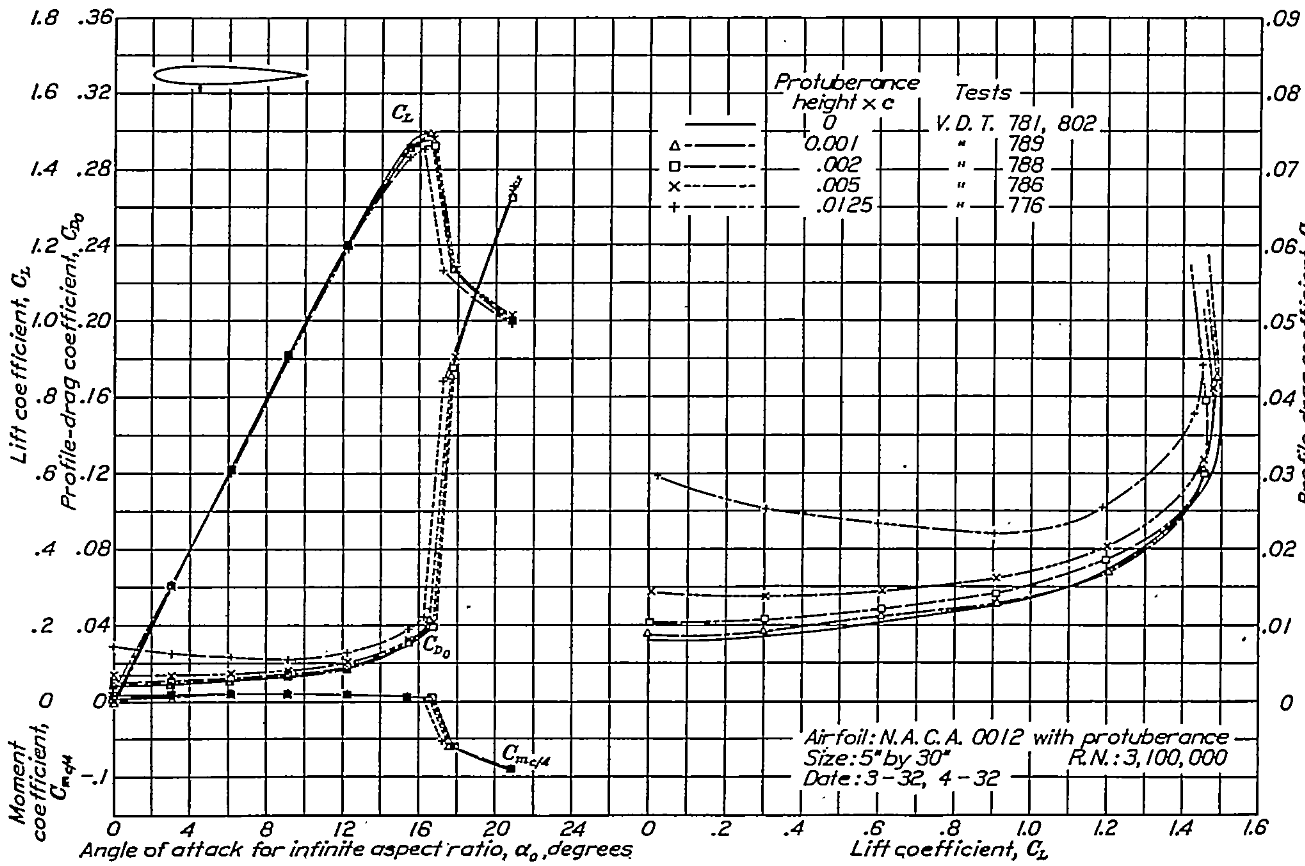


FIGURE 5.—Section characteristics for various protuberance heights. Protuberance on lower surface, 0.30c behind leading edge (position indicated by arrow)

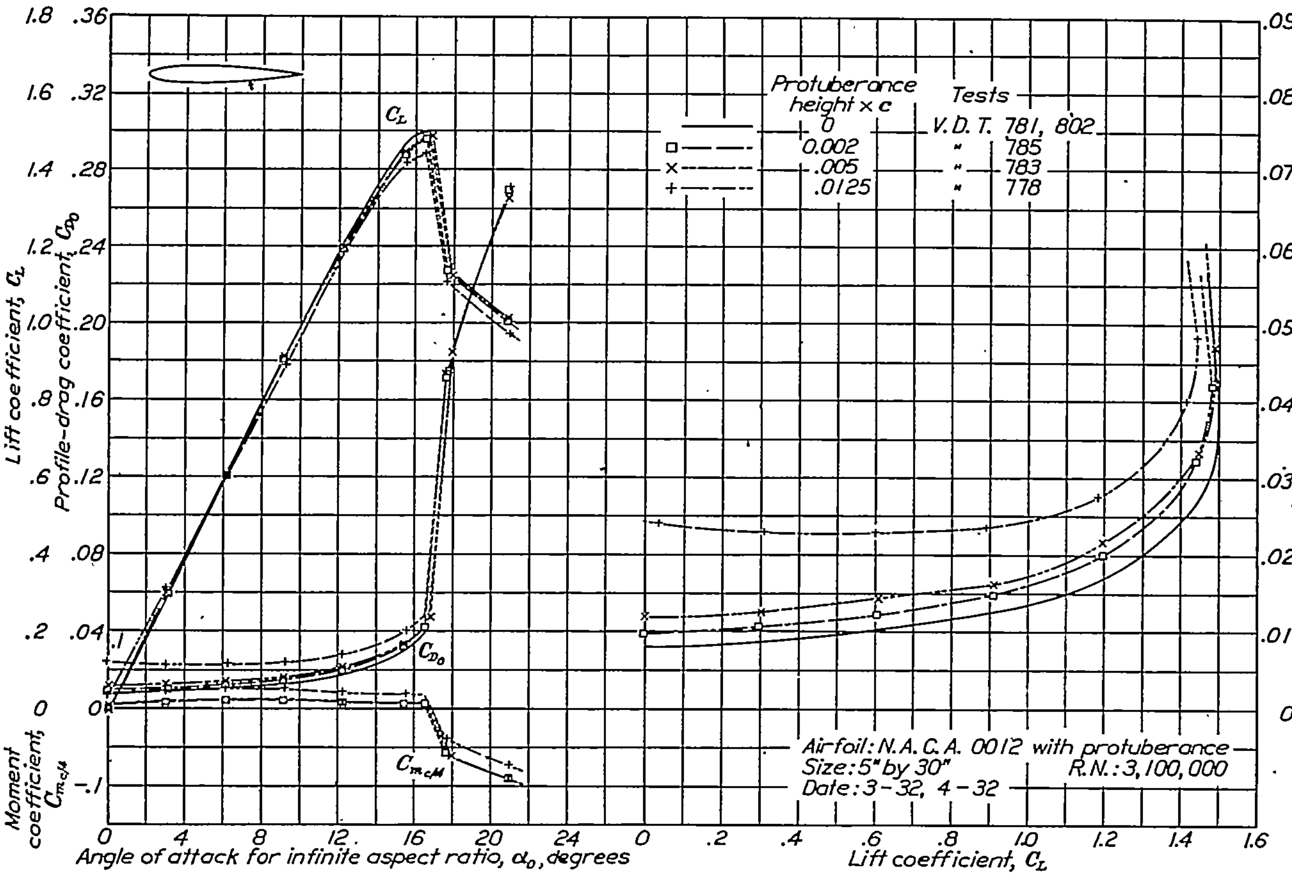


FIGURE 6.—Section characteristics for various protuberance heights. Protuberance on lower surface, 0.65c behind leading edge (position indicated by arrow)

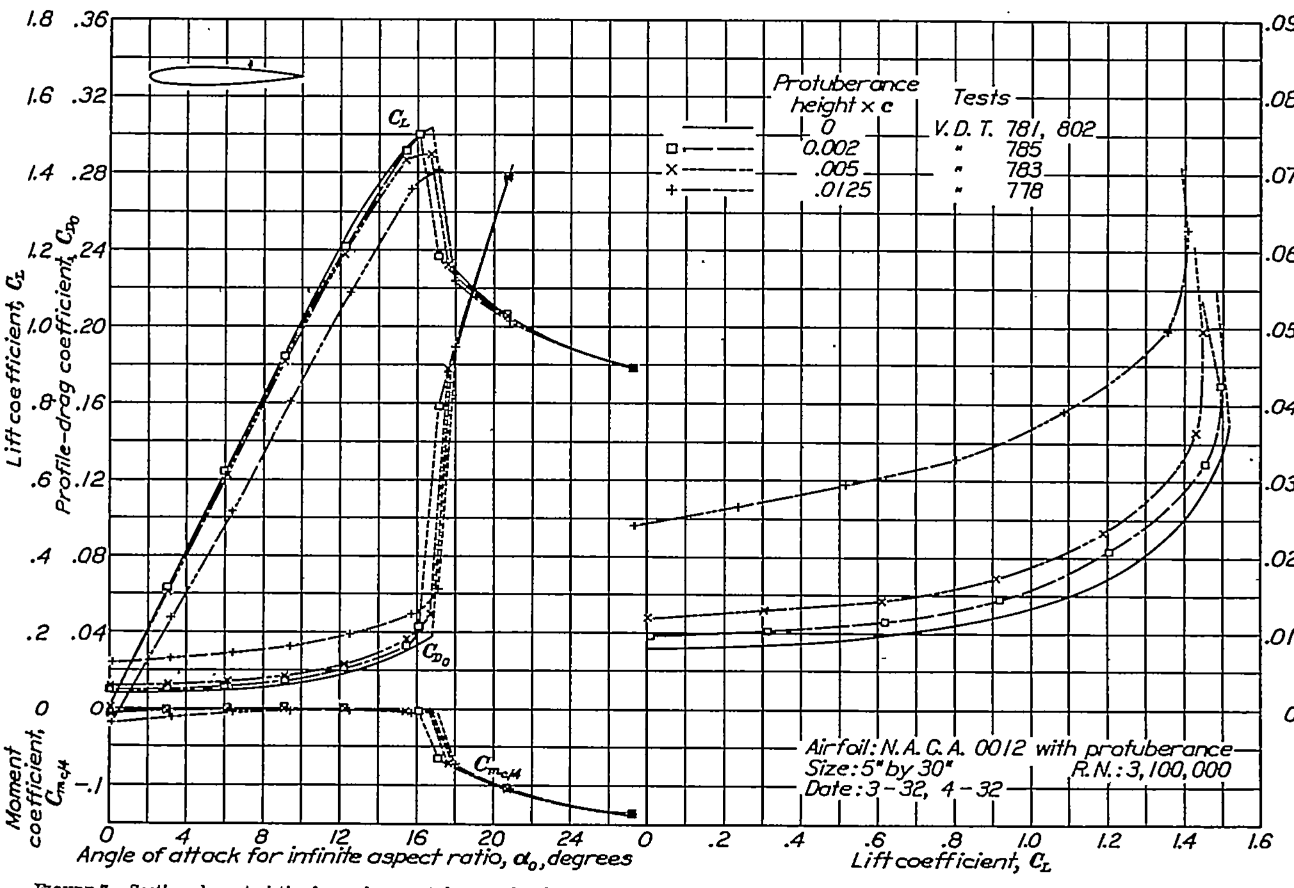


FIGURE 7.—Section characteristics for various protuberance heights. Protuberance on upper surface 0.65c behind leading edge (position indicated by arrow)

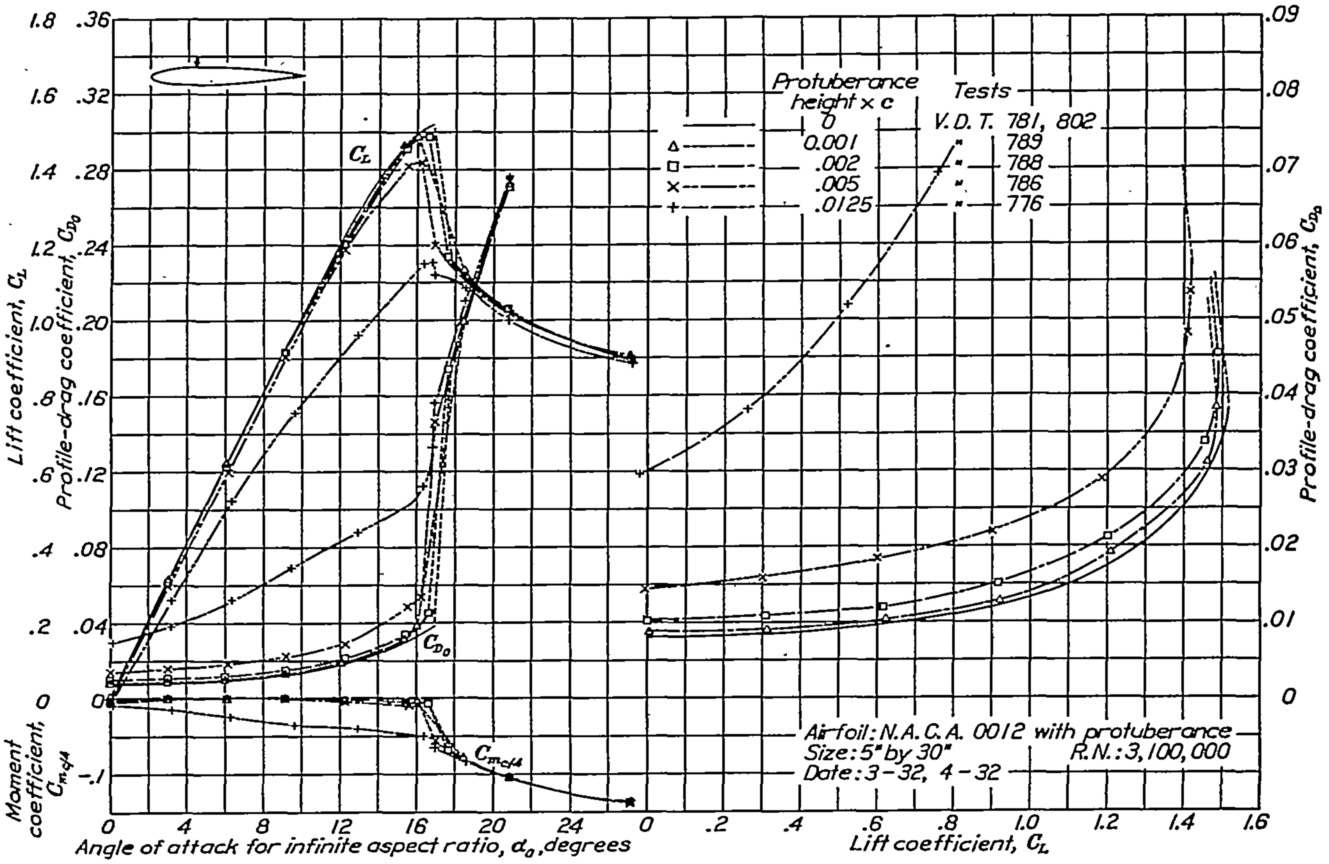


FIGURE 8.—Section characteristics for various protuberance heights. Protuberance on upper surface, 0.30c behind leading edge (position indicated by arrow)

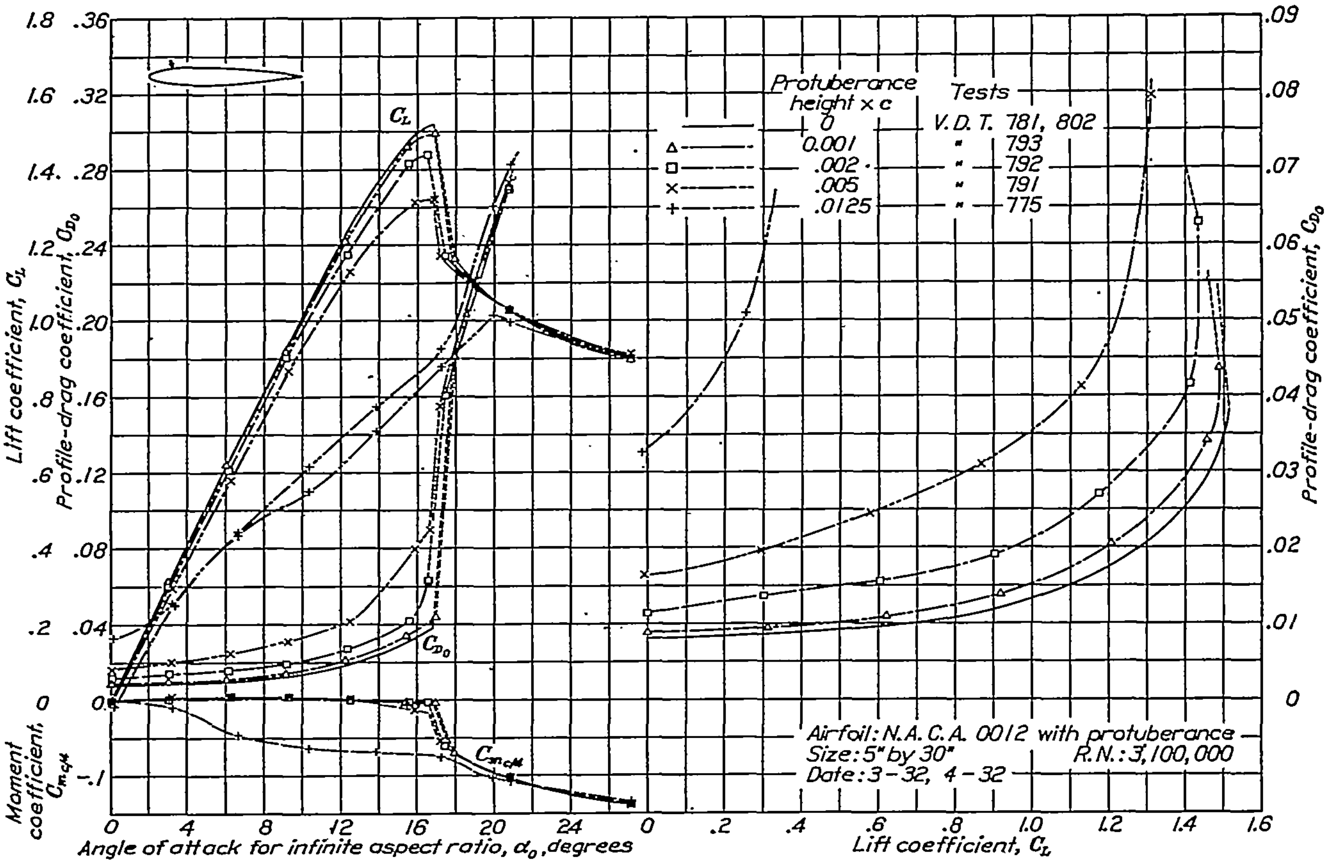


FIGURE 9.—Section characteristics for various protuberance heights. Protuberance on upper surface, 0.15c behind leading edge (position indicated by arrow)

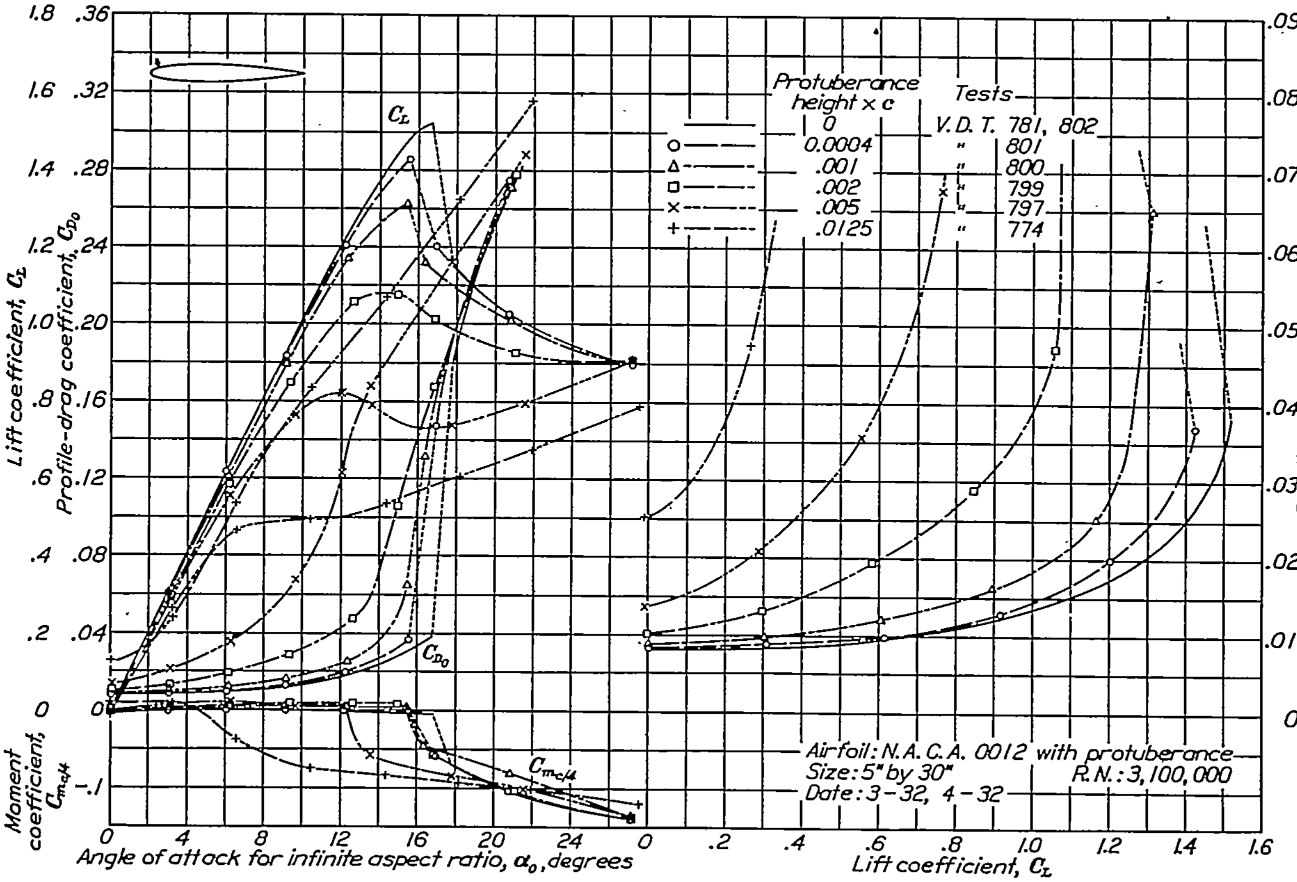


FIGURE 10.—Section characteristics for various protuberance heights. Protuberance on upper surface, 0.05c behind leading edge (position indicated by arrow)

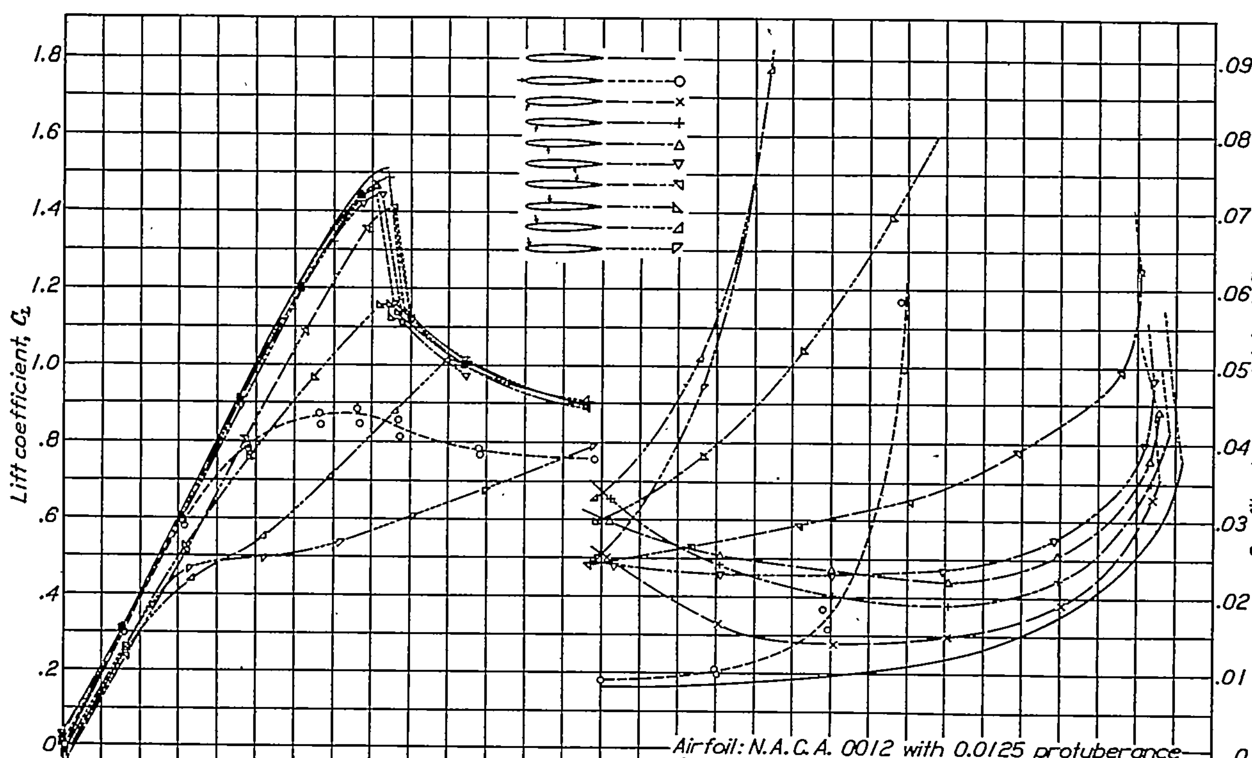


FIGURE 11.—Section characteristics for various protuberance positions. Height of protuberance: 0.0125c (positions indicated by arrows)

surface becomes increasingly serious as the protuberance approaches a point near the leading edge.

Considering now the effect of the protuberance on the drag, it will be seen from the plots of the profile-drag coefficient in Figure 11 that the effect is drastic for any position of the protuberance and attitude of the airfoil except for the nose position at low angles of attack and the lower-surface positions behind the nose at the higher angles of attack. The protuberances in the most critical positions, on the upper surface near the leading edge, produce very large increases of the profile drag even at comparatively low angles of attack.

Protuberance height.—The effect on the airfoil characteristics of varying the height of the protuberance is shown by the curves in Figures 2 to 10. These figures give complete test data for the various protuberance positions and heights. The effect on the drag of varying the height, however, is shown more advantageously in Figure 12, where the profile drag coefficients corresponding to $C_L=0$ and $C_L=0.5$ are plotted against protuberance height. Straight lines representing a calculated variation in drag with protuberance height are also included for comparison.

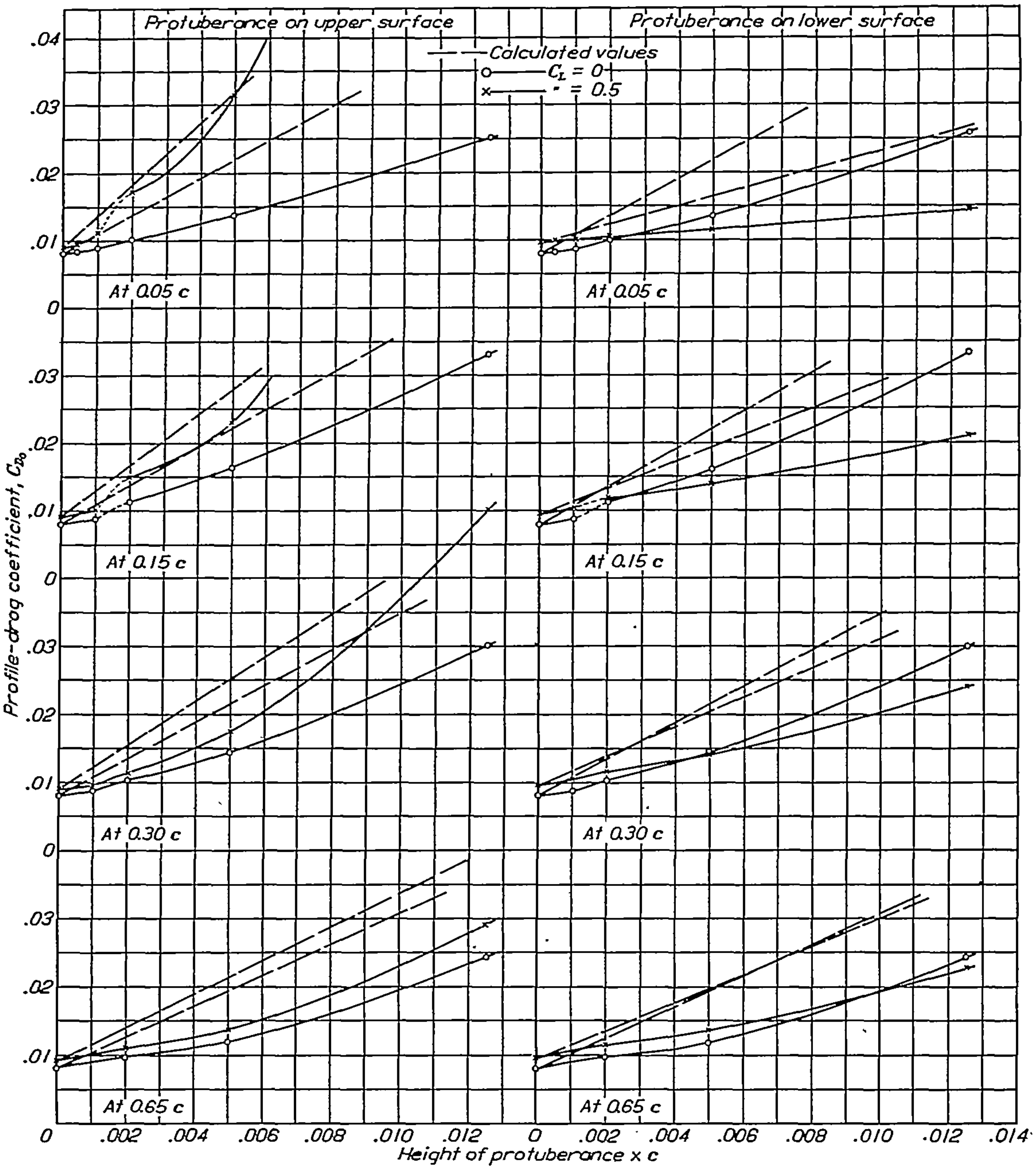


FIGURE 12.—Variation of drag with protuberance height

The calculated lines were obtained by computing the additional profile drag due to the protuberance from the formula

$$\Delta C_{D_0} = C_D\ (V'/V)^2\ h/c$$

C_D is the drag coefficient of the protuberance based on its frontal area. Weiselsberger (reference 4) gives the drag coefficient for flat plates of very large aspect ratio as approximately 2. The value 2 was therefore used for the calculations. The term $(V'/V)^2$ represents the square of the ratio of the local velocity at the airfoil surface at the position of the protuberance to the free-stream velocity. Values of this ratio claculated by the method of reference 5 are given in Table I for the positions on the surface corresponding to those of the protuberance. The ratio h/c is the ratio of the protuberance frontal area to the airfoil area. In other words, ΔC_{D_0} is the drag the plate would be expected to have expressed as a coefficient based on airfoil area neglecting the interference of the plate on the flow over the airfoil and the effects of the reduced velocity in the boundary layer of the airfoil on the drag of the plate. The lines plotted in Figure 12, obtained by adding ΔC_{D_0} to the profile drag of the wing without protuberance, are of value for comparison with the actual experimental curves.

TABLE I.—RESULTS OF CALCULATIONS OF VELOCITY AT SURFACE OF N. A. C. A. 0012 AIRFOIL

Station, per cent c	5	15	30	65
$\left(\frac{V \text{ at airfoil}}{V \text{ undisturbed stream}}\right)^2$ for $C_L=0$	1.38	1.41	1.36	1.14
$\left(\frac{V \text{ at airfoil}}{V \text{ undisturbed stream}}\right)^2$ on upper surface for $C_L=0.5$	2.29	1.89	1.61	1.24
$\left(\frac{V \text{ at airfoil}}{V \text{ undistrubed stream}}\right)^2$ on lower surface for $C_L=0.5$	.68	.98	1.06	1.03

A comparison of the lines with the experimental curves indicates that four regions may be considered as the protuberance height is increased.

The first is that region extending from $h=0$ to approximately $h=0.001c$, where the rate of increase of drag with protuberance height is low as compared with that indicated by the lines representing the calculated values. The relatively slow increase of drag with protuberance height in this region is probably due to the fact that the protuberance is in the low-velocity part of the wing boundary layer. Even in this region, however, the drag should not be considered as negligible, as shown by the fact that the drag increase due to the $0.001c$ protuberance expressed as a drag coefficient based on the free-stream dynamic pressure and the protuberance frontal area is in no case less than 0.7 at $C_L=0$.

The forward positions particularly show a second region extending from approximately $0.001c$ to $0.002c$ where the drag increases rapidly with protuberance height. In this region the protuberance is probably producing serious disturbing effects on the airfoil boundary layer. From a practical standpoint, it is therefore concluded that a special effort should be made to eliminate from a wing surface protuberances that exceed a height of $0.001c$. On a wing of 70-inch chord this height corresponds to 0.07 inch, or little more than one-sixteenth inch.

In the third region the curves tend to become parallel to the calculated lines. The actual drag influences, however, are much smaller than the calculated ones.

Some of the curves show a fourth region where the protuberance produces a marked interference with the flow over the airfoil. This region is not shown by any of the curves corresponding to $C_L=0$, and only by those corresponding to $C_L=0.5$ for the protuberance positions on the upper surface forward of the $0.65c$ position. Very rapid increases of drag with protuberance height are indicated in this region for protuberances higher than $0.005c$. The conclusion is that protuberances extending from the upper surface forward of the maximum-thickness position, having a height greater than $0.005c$, should be particularly avoided. These protuberances may, however, have a useful application as spoilers or air brakes.

For the estimation of the drag due to protuberances in connection with practical applications, a simpler method of calculating the drag due to protuberances based on the data given in the following table will probably be more satisfactory than the previous discussion. In the table are presented the important results at a lift coefficient of 0.2 corresponding to high-speed flight. The results are given as coefficients of drag due to the protuberance, the coefficients being based on the protuberance frontal area and the free-stream dynamic pressure, so that the drag due to a protuberance may be obtained simply as the product of the protuberance frontal area, dynamic pressure, and the coefficient from the following table:

COEFFICIENTS OF DRAG DUE TO PROTUBERANCE BASED ON PROTUBERANCE FRONTAL AREA ($C_L=0.2$)

per cent c behind leading edge \ Height in terms of chord	0.0004	0.001	0.002	0.005	0.0125
5 upper surface	1	1.1	1.8	1.9	2.4
15 upper surface		.8	2.3	2.0	2.9
30 upper surface		.7	1.2	1.5	2.2
65 upper surface			.9	.9	1.4
5 lower surface	1	.6	.7	.7	.8
15 lower surface		.8	1.2	1.3	1.5
30 lower surface		.7	1.1	1.1	1.5
65 lower surface			1.0	.8	1.2

As a rule, the drag due to most of the protuberances investigated could be roughly estimated as equal to or greater than the product of the protuberance frontal area and the free-stream dynamic pressure. A lower drag results from protuberances on the leading edge or near the leading edge on the lower surface, and from other small protuberances, but the rule may be found useful. The higher drags may be seen from the table to correspond to protuberances having a height of $0.002c$ or more, particularly when they are on the forward portion of the upper surface.

As a practical application, consider a $\frac{1}{32}$-inch thick butt strap at a position on the upper surface $0.05c$

behind the leading edge extending along the span of a wing having a 70-inch chord and a 35-foot span, the frontal area of the protuberance is then 0.091 square feet. If the velocity is 200 miles per hour, the dynamic pressure for standard air is 102.32 pounds per square foot. Applying the above rule, or taking the coefficient 1 from the preceding table, the drag is estimated as 102 times 0.091, or 9.3 pounds. The corresponding power consumption at the speed considered would be approximately 5 horsepower.

The effects on maximum lift of the protuberances of various heights are also shown in Figures 2 to 10. The effect can be seen more easily, however, from the curves of Figure 13 representing the variation of maximum lift with protuberance height for the various positions

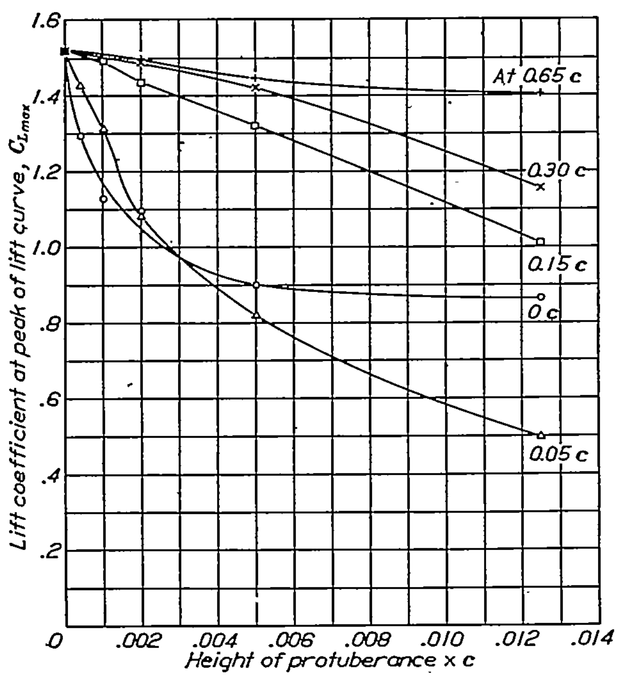


FIGURE 13.—Variation of maximum lift with protuberance height. Protuberance on upper surface

on the upper surface of the airfoil. It will be remembered that the protuberance on the lower surface produced only a slight change in the maximum lift coefficient. Figure 13 indicates that the loss of maximum lift due to the protuberance is nearly proportional to the protuberance height except for the positions near the leading edge on the upper surface. For these positions the small protuberances produce disproportionately large effects. In the nose position the protuberance having a height of only 0.0004c reduced the maximum lift by approximately 15 per cent. This protuberance was so small that it might rather be classed as a surface roughness. Because considerable difficulty was experienced in forming it, the shape of the protuberance was not maintained exactly as desired. Sections of the airfoil nose, including the protuberance, were measured after the protuberance had been reduced in height to 0.0004c. The results of these measurements for four sections are shown in Figure 14 to a scale corresponding approximately to full scale for medium-size airplanes. The general conclusion that may be drawn from this phase of the investigation is that the airfoil leading edge must be smooth and fair if high maximum lift coefficients are to be obtained.

Fairing.—The effects of fairing the 0.005c protuberance are shown in Figures 15 to 23. Each figure presents the airfoil section characteristics corresponding to one protuberance position for the plain airfoil, the airfoil with the normal 0.005c protuberance, and the airfoil with the faired protuberance.

The results showing the effects on drag of fairing the protuberances are shown by the profile-drag curves at the right of each figure. It is concluded from these results that the adverse drag effects of the protuberance may be greatly reduced but not entirely eliminated by employing a simple fairing over the protuberance as shown in Figure 1.

As regards the adverse effects of the protuberance on the maximum lift, it may be concluded that they can be practically eliminated by a simple fairing of the type employed except where the protuberance is near the leading edge. With the protuberance in the leading-edge position, it is obvious that a suitably formed fairing would eliminate the adverse effects. In this position, therefore, the fairing was applied to only one side of the protuberance. These results, which are presented in Figure 15, indicate that the fairing has little effect when it is employed on only one side of the protuberance. For the first position behind the leading edge on the upper surface the simple fairing employed apparently was not adequate, as the full value of maximum lift coefficient (fig. 23) was not regained after the fairing had been applied.

CONCLUSIONS

The following conclusions of immediate practical value may be drawn from the results in regard to the effects of full-span protuberances.

1. For most of the unfaired protuberances investigated except those very near the leading edge, the drag resulting from the addition of the protuberance could be roughly estimated as equal to or greater than the product of the free-stream dynamic pressure and the protuberance frontal area.

2. The greater drag increases may result from protuberances the height of which exceeds 0.001c, particularly when the protuberances are from points along either surface forward of the maximum-thickness position.

3. Very large increases of drag may result from the interference of a protuberance having a height exceeding 0.005c if it is on the forward portion of the upper surface of the profile.

4. A simple fairing over the protuberance greatly reduces but does not entirely eliminate the adverse effect.

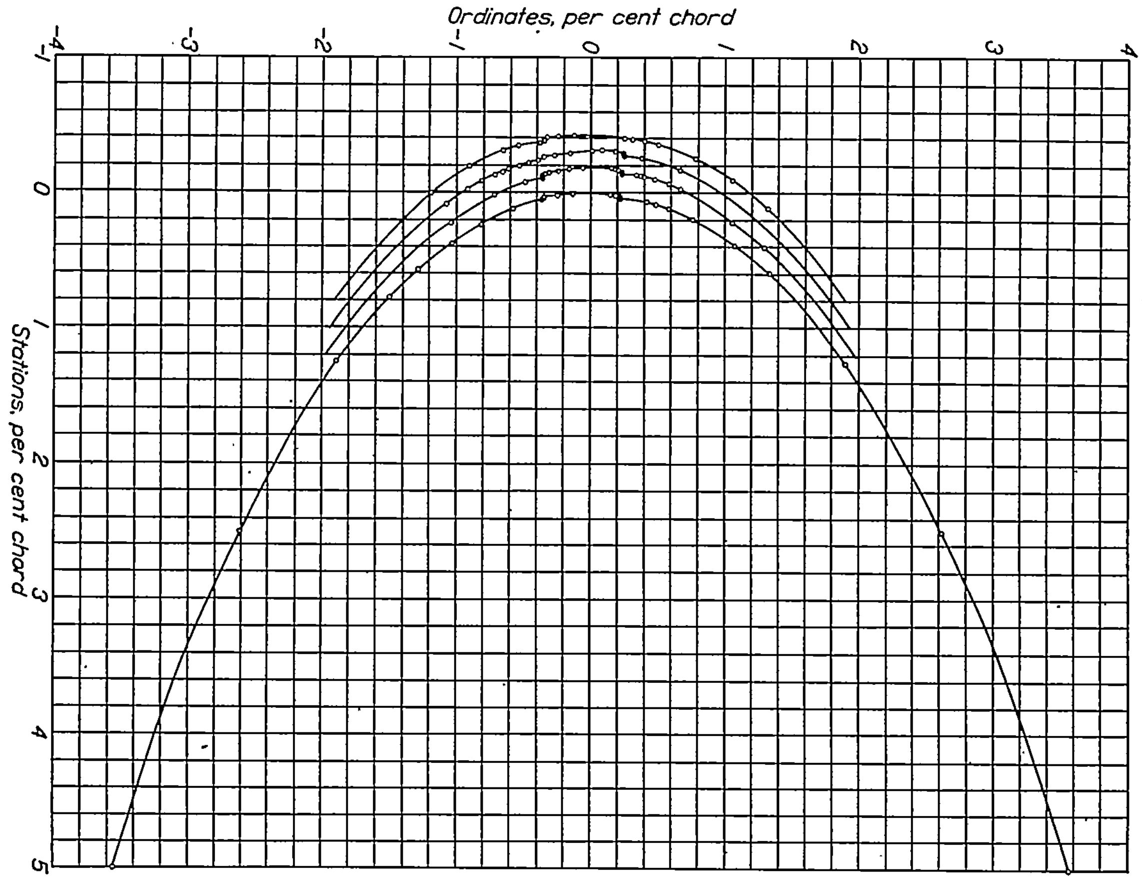


FIGURE 14.—Nose profile, measured at four representative stations along span, showing 0.0004c protuberance at leading edge

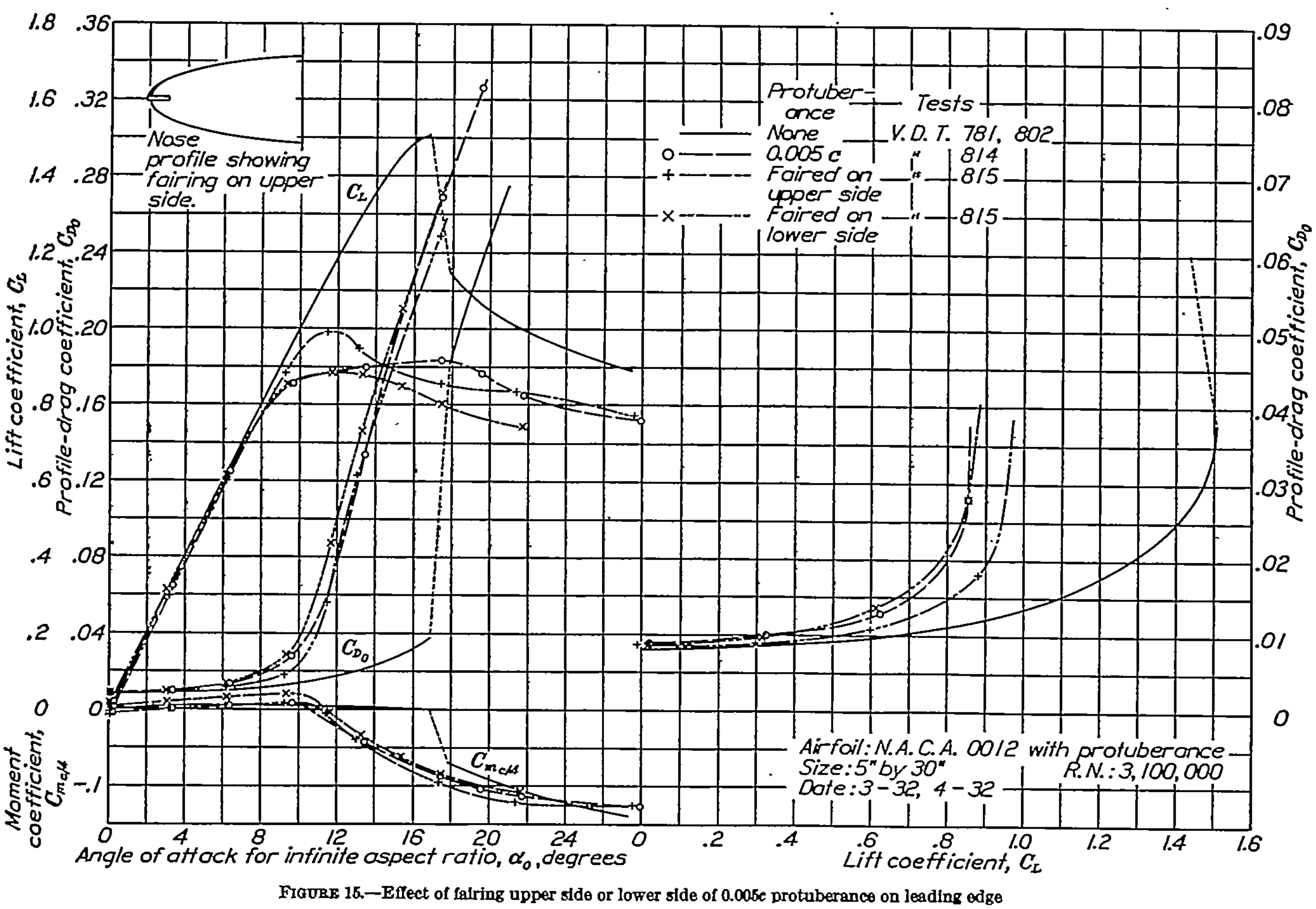


FIGURE 15.—Effect of fairing upper side or lower side of 0.005c protuberance on leading edge

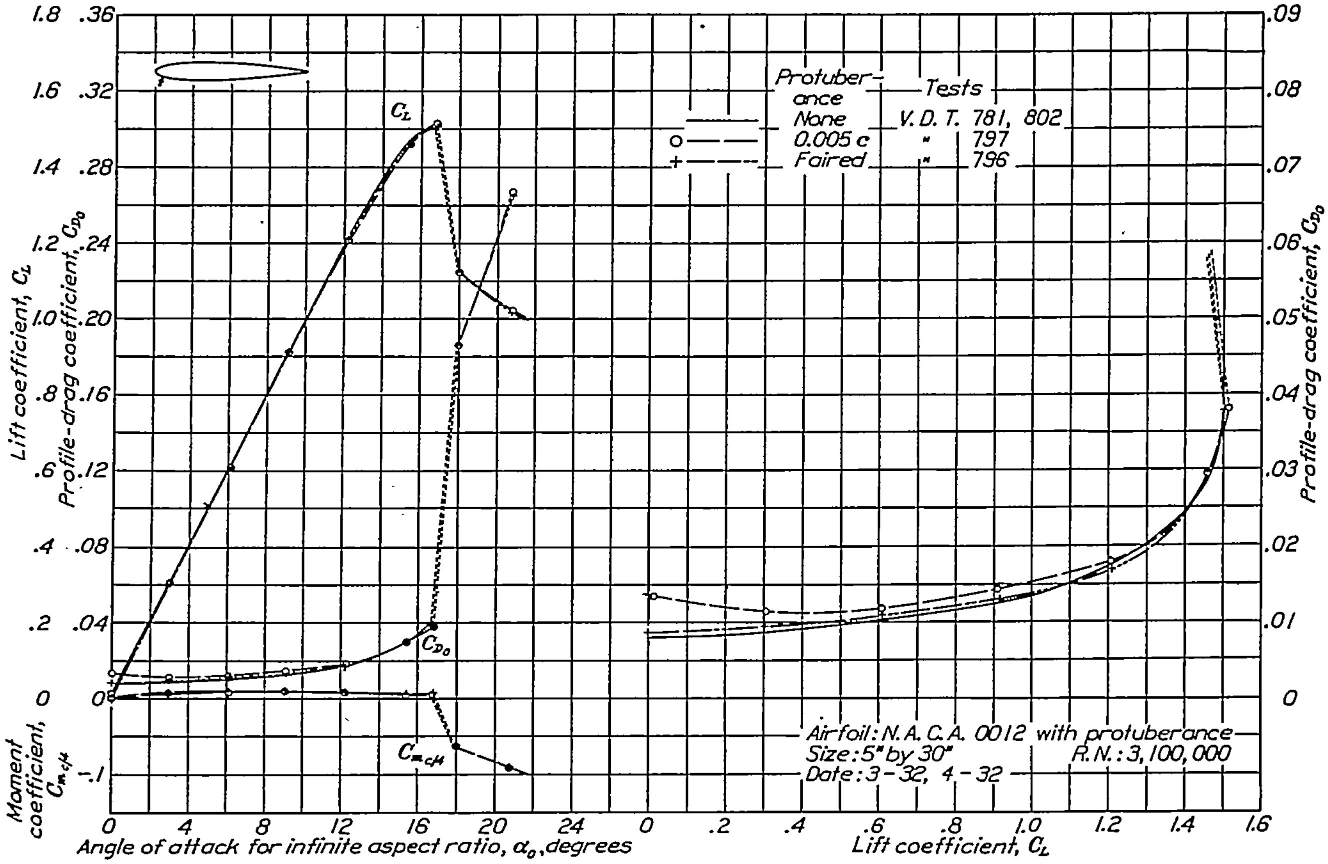


FIGURE 16.—Effect of fairing 0.005c protuberance on lower surface, 0.05c behind leading edge (position indicated by arrow)

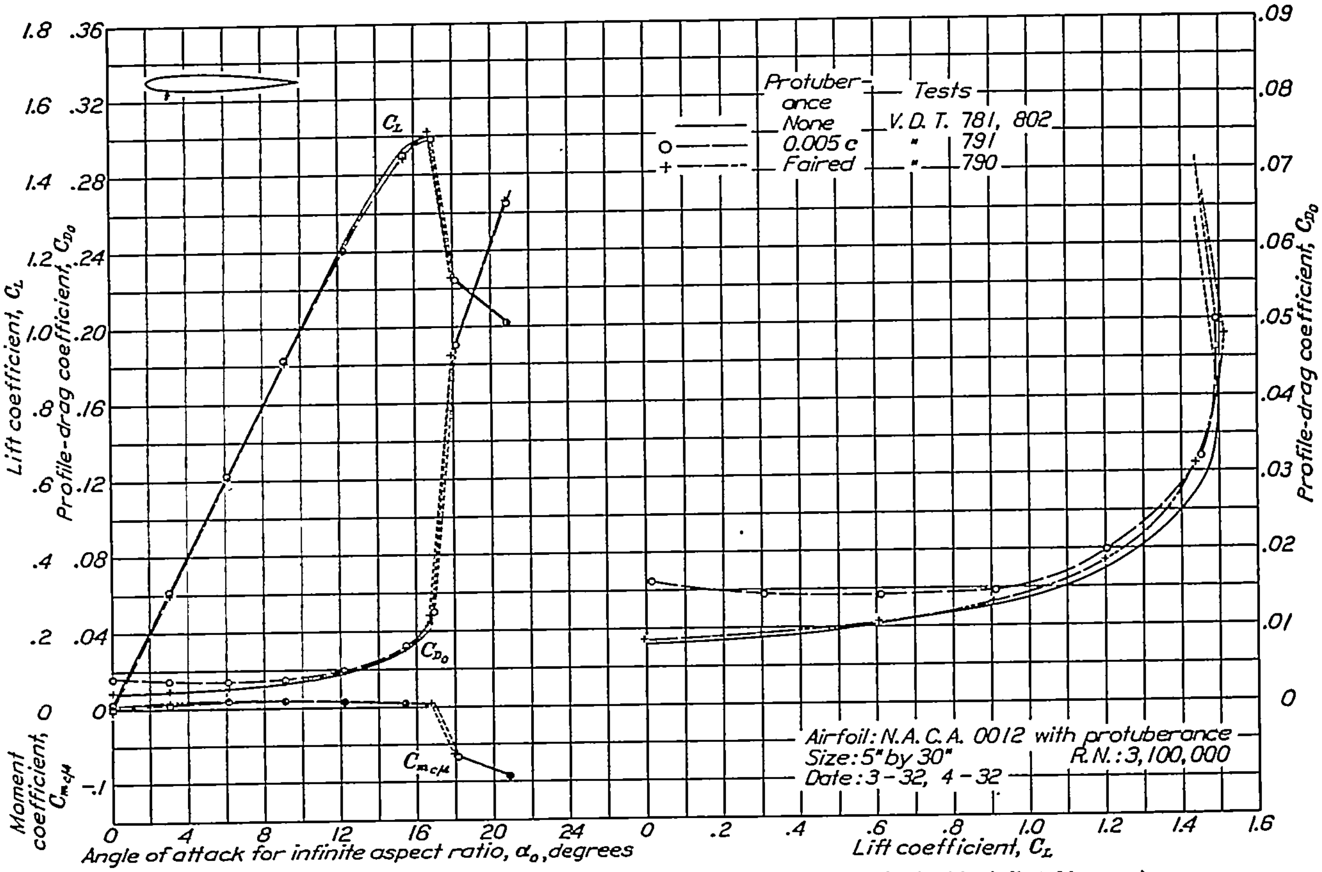


FIGURE 17.—Effect of fairing 0.005c protuberance on lower surface, 0.15c behind leading edge (position indicated by arrow)

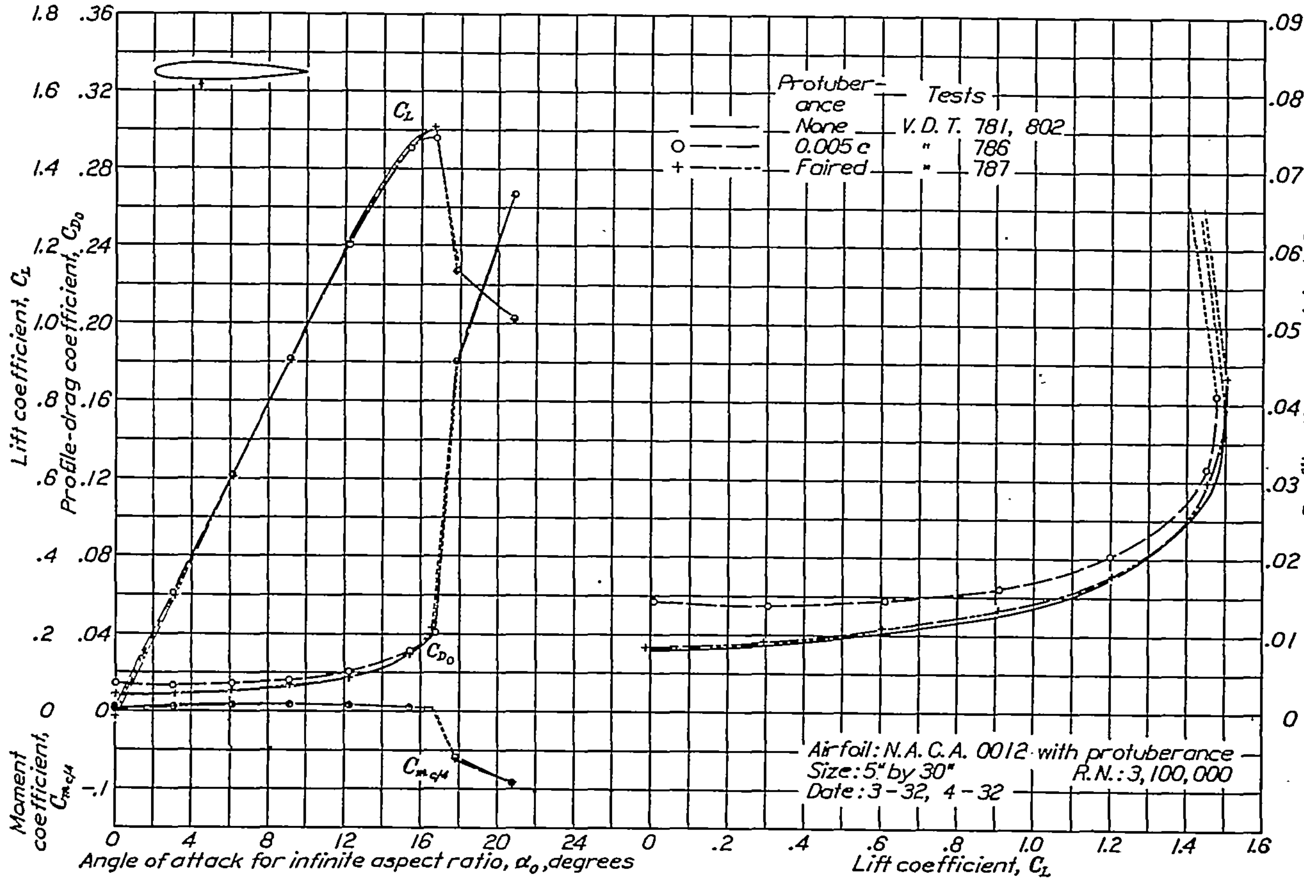


FIGURE 18.—Effect of fairing 0.005c protuberance on lower surface, 0.30c behind leading edge (position indicated by arrow)

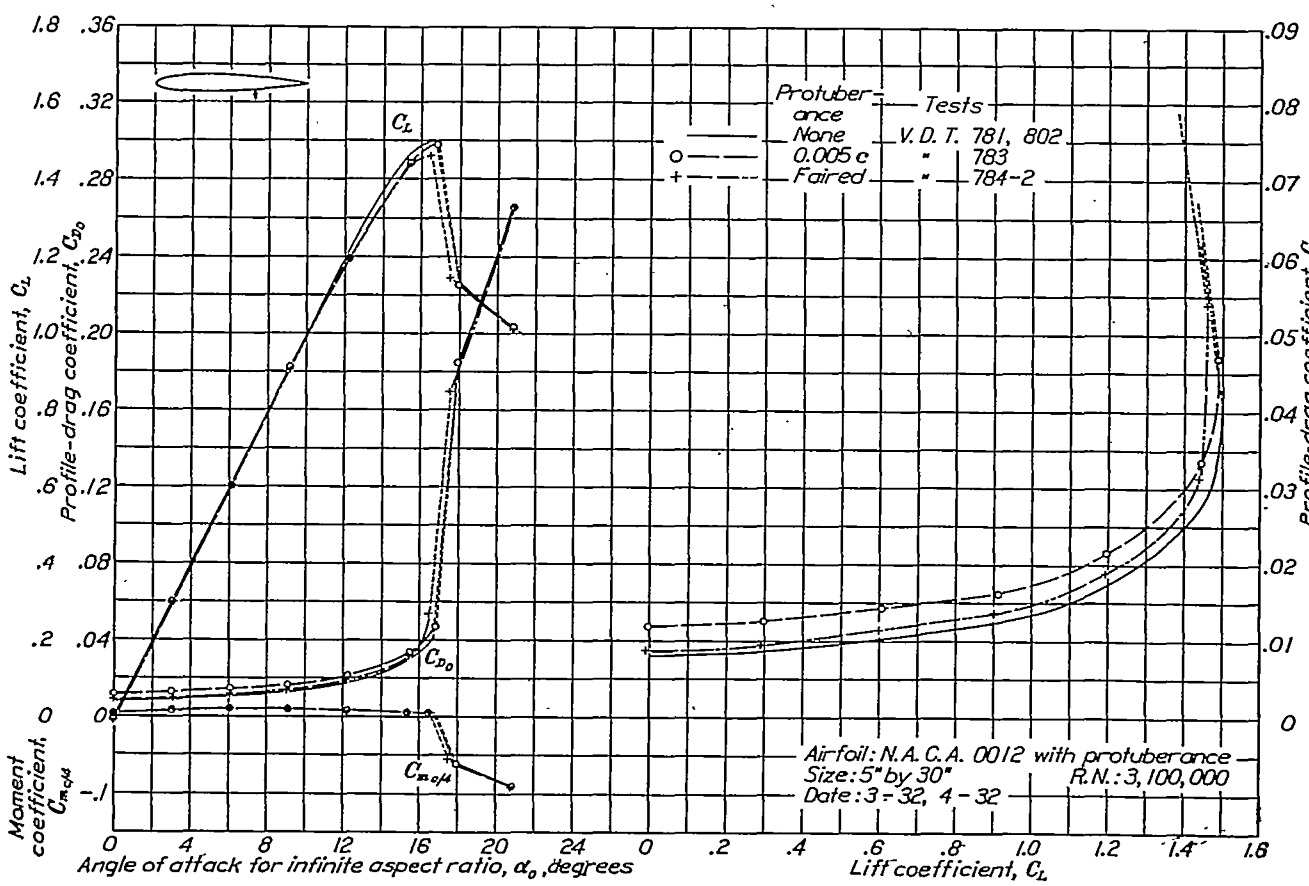


FIGURE 19.—Effect of fairing 0.005c protuberence on lower surface, 0.65c behind leading edge (position indicated by arrow)

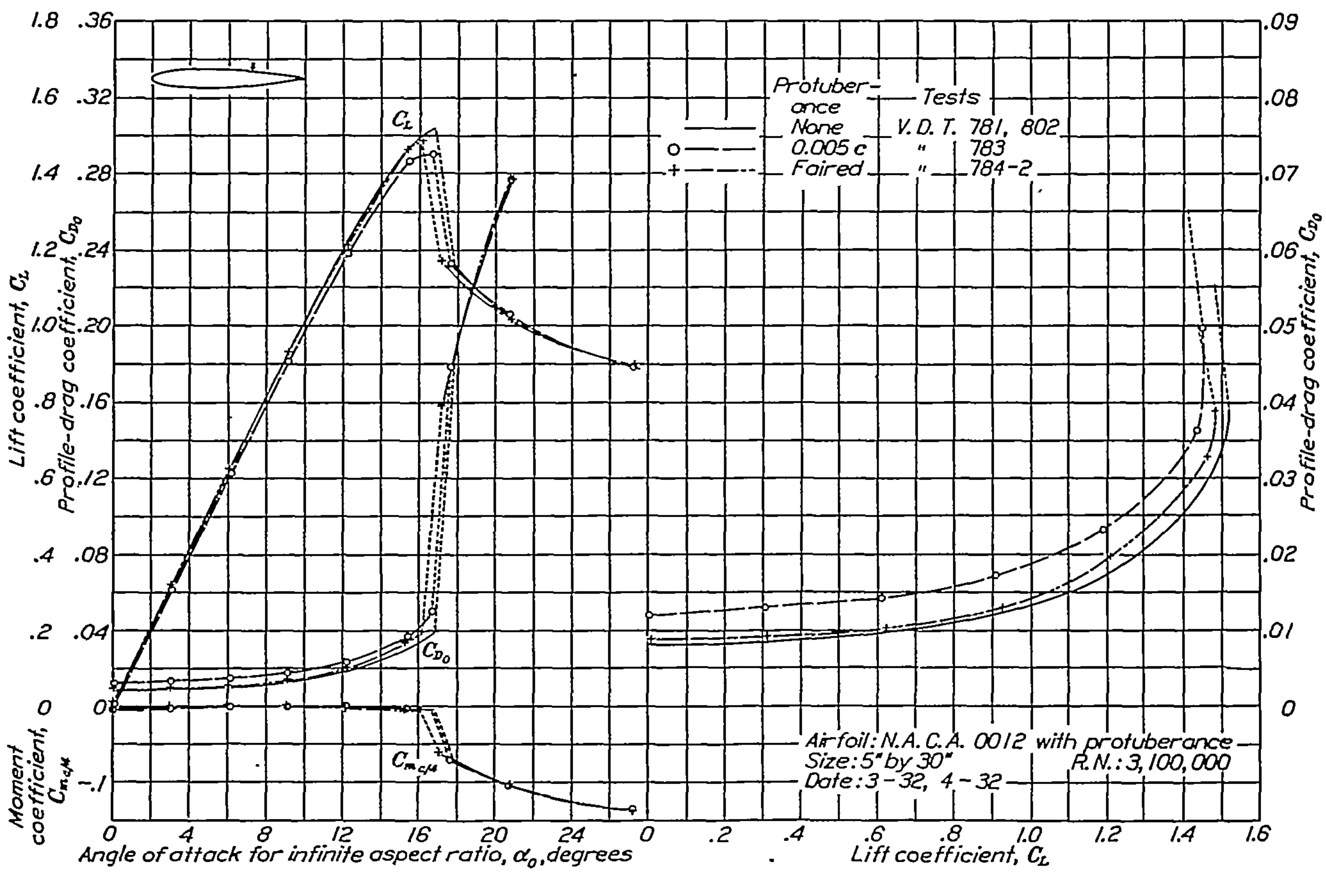


FIGURE 20.—Effect of fairing 0.005c protuberance on upper surface, 0.65c behind leading edge (position indicated by arrow)

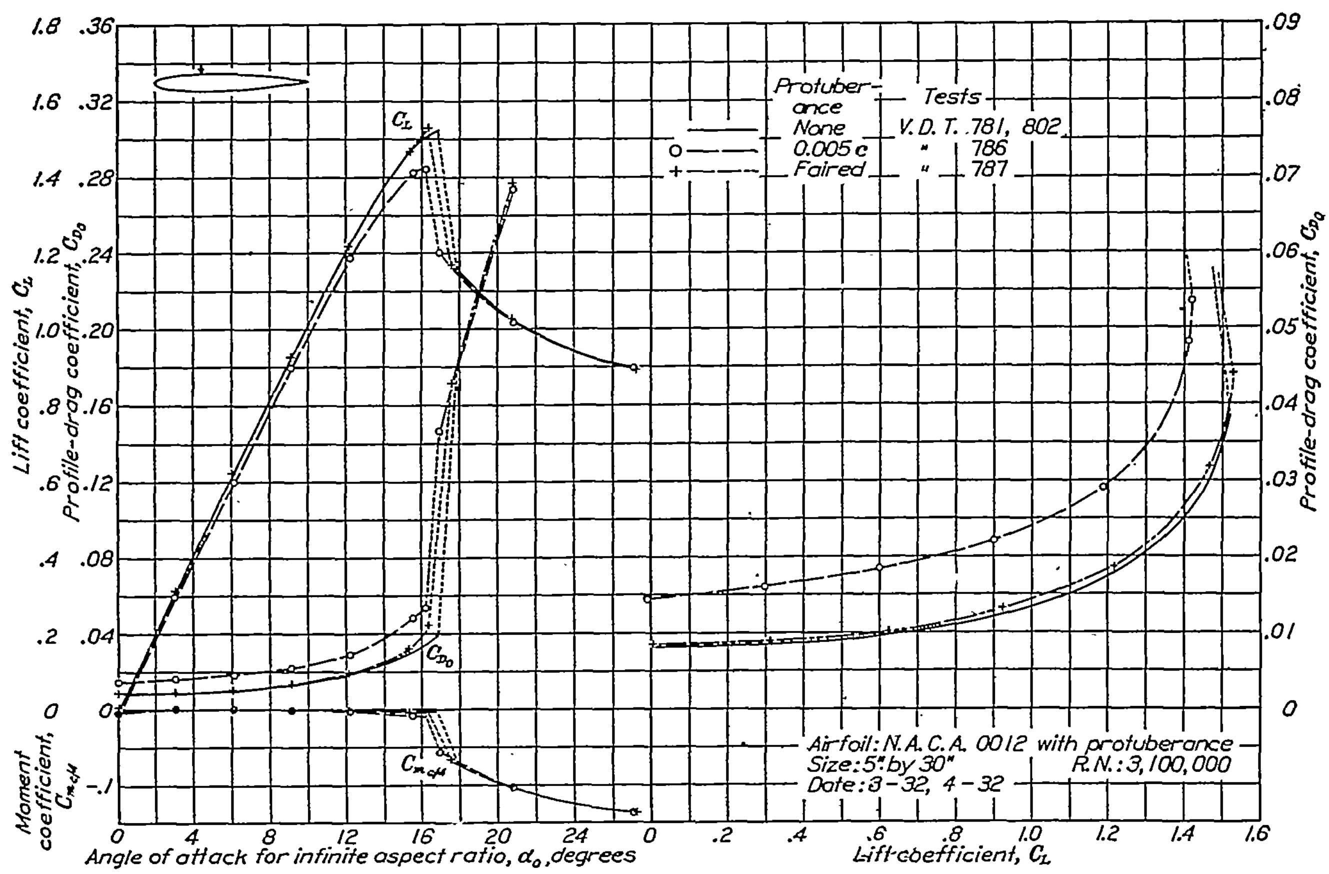


FIGURE 21.—Effect of fairing 0.005c protuberance on upper surface, 0.30c behind leading edge (position indicated by arrow)

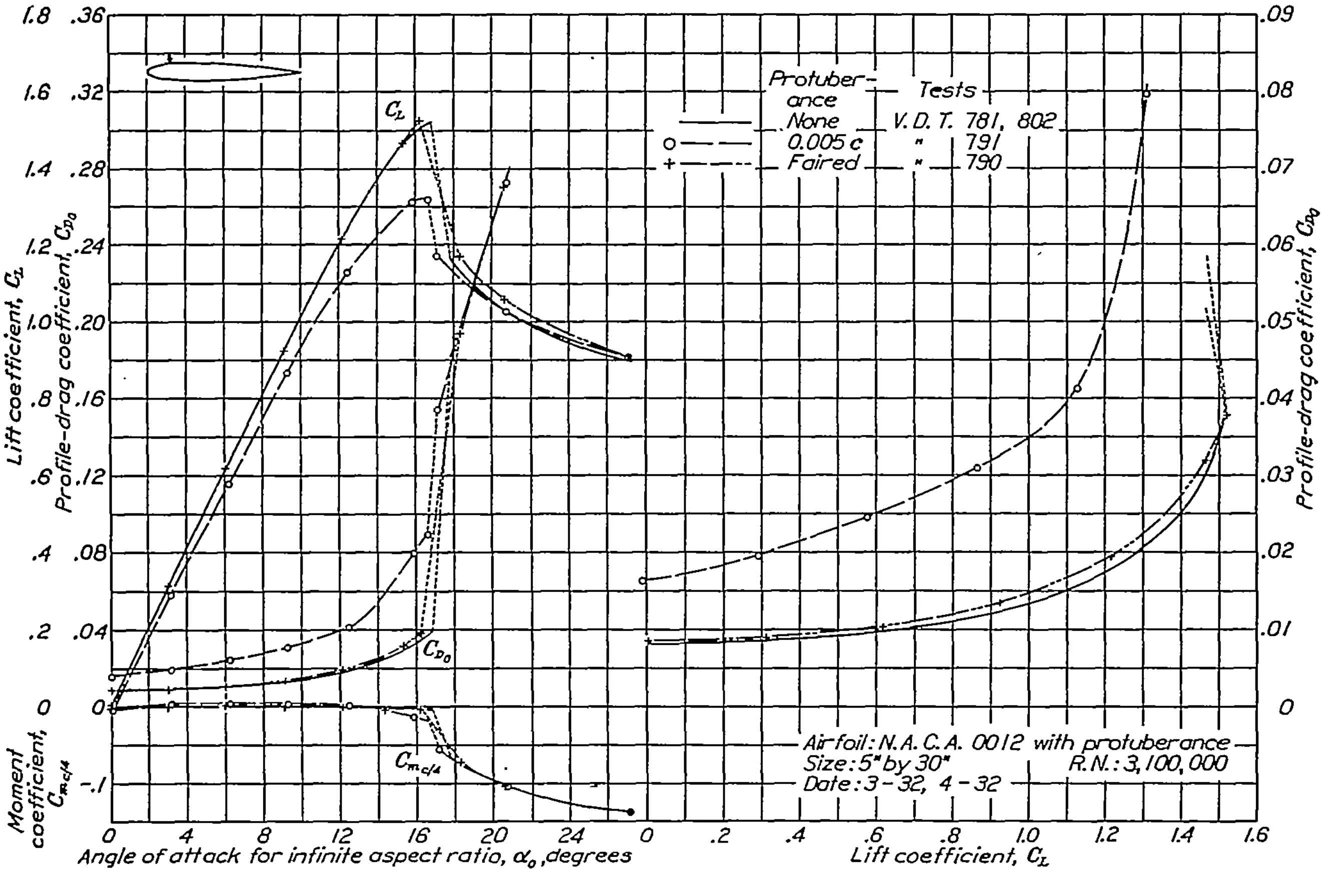


FIGURE 22.—Effect of fairing 0.005c protuberance on upper surface, 0.15c behind leading edge (position indicated by arrow)

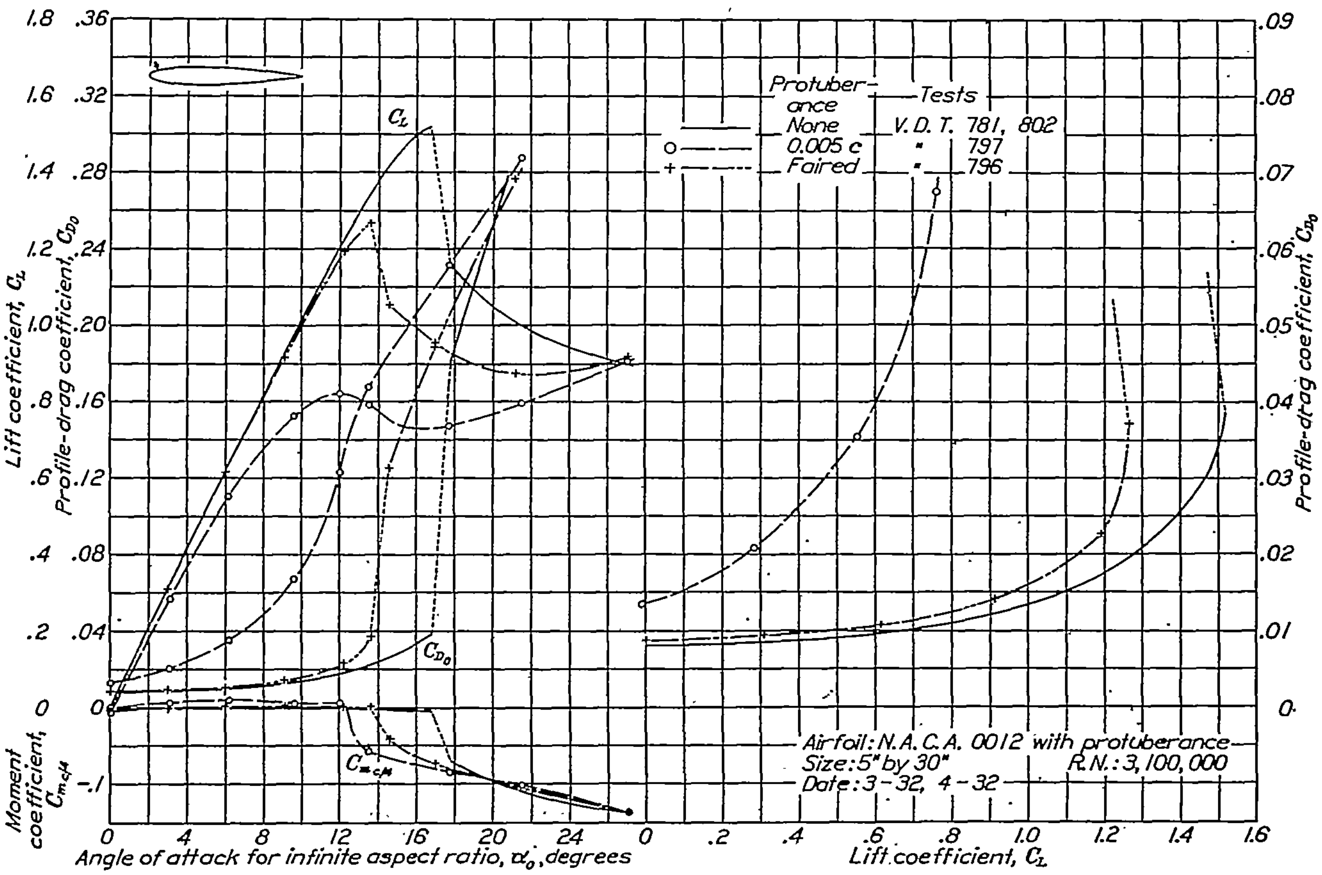


FIGURE 23.—Effect of fairing 0.005c protuberance on upper surface, 0.05c behind leading edge (position indicated by arrow)

5. The effect of a protuberance on the maximum lift is unimportant when the protuberance is on the lower surface, but becomes very important, even for a protuberance so small that it would ordinarily be classed as a surface roughness, as the position approaches the leading edge along the upper surface.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
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