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RESEARCH MEMORANDUM

PRESENT STATUS OF RESEARCH ON BOUNDARY-LAYER CONTROL

By

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SUMMARY

A survey has been made of the present status of research on boundary-layer control and its possible applications in aeronautics. The applications of boundary-layer control considered are:

(1) Reduction of profile drag by the elimination of turbulent separation and by increasing the relative extent of laminar flow.

(2) Increase of the maximum lift coefficient through control of laminar and turbulent separation.

(3) The use of suction and blowing slots near the trailing edge of an airfoil as a means of lateral control.

(4) The use of boundary-layer control as a means of increasing the efficiency of diffusers and bends.

(5) The use of boundary-layer control to influence shock-boundary-layer interaction at high speed.

The possible improvements in airplane characteristics resulting from these applications of boundary-layer control are discussed and the general lines of future research are indicated.

INTRODUCTION

Since Prandtl's first paper on boundary layers, removal of a portion of the boundary layer or the injection of high energy air under the boundary layer has been considered as possible means for avoiding boundary-layer separation. More recently, removal of a portion of the laminar boundary layer either through discrete slots or through a permeable surface has been proposed as a means of increasing the stability, and thereby the relative extent of the laminar layer at high

Reynolds numbers, so that the skin friction drag is reduced. It has been suggested that the effects on the potential flow field of withdrawing or ejecting small quantities of air near the trailing edge be used as a means of varying the lift of an airfoil.

A great deal of research has been conducted on various phases of boundary-layer control but very few results of this vast quantity of research have found practical application. The purposes of the present paper are to state briefly the present status of information regarding various types of boundary-layer control, to discuss the possibility of improving the characteristics of aircraft by boundary-layer control, and to indicate the general lines of future research on this subject that appear to offer the greatest promise of producing useful results.

The possibility of using boundary-layer control exists each time that the avoidance of separation or the maintenance of extensive laminar flow becomes a problem. Because of the large number of ways in which boundary-layer control can conceivably be applied, no general conclusions regarding the applicability of boundary-layer control can be drawn. The scope of the present paper is, therefore, limited to the consideration of proposed methods of boundary-layer control as they affect the individual aerodynamic characteristics of an aircraft. The applications considered are:

(1) Reduction of profile drag by the elimination of turbulent separation and by increasing the relative extent of laminar flow.

(2) Increase of the maximum lift coefficient through control of laminar and turbulent separation.

(3) The use of suction and blowing slots near the rear portion of the airfoil as a means of lateral control.

(4) The use of boundary-layer control as a means of increasing the efficiency and the range of efficient operating conditions of diffusers and bends.

(5) The use of boundary-layer control to influence shock boundary-layer interaction at high speeds, and in particular, to eliminate boundary-layer separation following the shock.

The use of slots represents in all cases one method of applying boundary-layer control and in such cases the gains resulting from the use of boundary-layer control may depend in large measure on the design of the slots. For this reason, a short discussion of the status of research on the development of efficient slots is included at the end of the paper.

The possible use of jet engines as boundary-layer control pumps is also discussed briefly.

SYMBOLS

A	aspect ratio (b^2/S)
b	wing span
c	chord
x	distance along chord
t	airfoil maximum thickness
S	wing area
W	airplane weight
V	free-stream velocity
Q	volume flow per unit span
v/V	ratio of local velocity to free-stream velocity
W/S	wing loading, pounds per square foot
L/D	lift-drag ratio
c_d	section drag coefficient
c_l	section lift coefficient
C_L	wing lift coefficient
c_Q	section flow coefficient (Q/cV)
R	Reynolds number
α_o	section angle of attack

Subscript:

max	maximum

DRAG

As mentioned in the introduction, reductions in the profile drag can be achieved by boundary-layer control through control of the turbulent layer and through extending the length of the laminar layer. Numerous design calculations have indicated the comparatively large improvements in airplane performance to be expected from reductions in the profile drag. The improvement in performance that can be expected from reductions in the profile drag through the maintenance of extensive laminar layers is shown to be even more marked for jet than for propeller-driven aircraft (reference 1). The effectiveness of control of the turbulent boundary layer as a means of reducing the profile drag is considered first.

Control of the Turbulent Layer

In the absence of separation, theoretically, some reduction in the net drag can be obtained by sucking the boundary layer into the interior of the airfoil at the trailing edge and discharging the air thus withdrawn at free-stream total pressure. It seems unlikely that any net gain could result from such a process because of the necessary losses associated with the internal flow. If, however, fairly extensive regions of separated flow exist, controlling the turbulent boundary layer in such a way as to eliminate separation results in substantial reduction of the profile drag even when the necessary pumping power is included in the drag coefficient (references 2 and 3). Such separation occurs on airfoils of moderate thickness at lift coefficients approaching the maximum and on extremely thick airfoil sections throughout the entire range of operating lift coefficients. The reduction in drag observed at the higher lift coefficients for the thin sections usually comes about as a by-product of attempts to improve the maximum lift by boundary-layer control. For wings having aspect ratios less than 10 or 12 and airfoil sections of less than 20-percent thickness, such savings in drag are particularly marked only for lift coefficients above those for maximum L/D, and hence are of relatively minor importance.

The use of aspect ratios of the order of 15 to 25 has always appeared attractive from the point of view of lower induced drag but has not been practical because, for structural reasons, the root sections of such wings are quite thick so that flow separation occurs at all useful lift coefficients and the associated increase in profile drag equals or exceeds the saving in induced drag. Under such circumstances the prevention of separation by boundary-layer control would seem to offer the possibility of realizing net drag savings and increased values of L/D on wings of high aspect ratio. With this thought in mind an experimental investigation has recently been made at the NACA of the characteristics of three NACA 6-series airfoils of 24-, 32-, and 40-percent thickness ratio employing boundary-layer control by suction to prevent separation of the turbulent boundary layer. The airfoils were cambered to have theoretical design lift coefficients of 0.4. The suction was applied through a single slot at or slightly behind the midchord position of the airfoil sections. In order that the results should correspond approximately to the very limited extent of laminar flow that is usually obtained on airplane wings under practical operating conditions, the tests were made with the leading edges of the models roughened sufficiently to cause immediate transition. Lift and drag data are now available for the 24-percent-thick section (reference 2) and are being prepared for publication for the 32- and 40-percent thick sections. The data for the three thick sections together with those for airfoils of 12- to 21-percent thickness employing boundary-layer control (references 4, 5, and 6) are sufficient to enable designers to determine the desirability of employing boundary-layer control for the purpose of improving the characteristics of high-aspect-ratio wings. In order to supply detailed design information, however, further research will be necessary to determine optimum slot shapes, pitching-moment characteristics, and the behavior of three-dimensional wings employing boundary-layer control.

In order to give some indication of the possible improvement in wing characteristics which can be realized by employing boundary-layer control on wings of high aspect ratio, a comparison is made in figure 1 of a group of wings having a taper ratio of 0.4 and a varying aspect ratio with and without boundary-layer control. The wings are composed of NACA 6-series airfoils with leading edges roughened sufficiently to cause immediate transition. The root section thickness ratios were based on the structural design criterion that the ratio of the span to root thickness should be 35 to 1, but in no case was the root section thickness ratio made less than 12 percent. In all cases the tip had a 12-percent thickness ratio. A linear spanwise distribution of thickness ratio was assumed. The drag values used in computing the values of L/D included the wake drag plus the drag equivalent of the suction power.

A comparison of the data for the wings shown in figure 1 indicates that the optimum aspect ratio for maximum L/D is increased from approximately 11 to 20 by the use of boundary-layer control with an accompanying increase in L/D of approximately 19 percent. The suction power considered in the calculations is that required to remove the necessary quantity of air from the surface of the wing through the slot but does not include any estimate of the losses which would occur in the ducting and pumping equipment of an airplane. The results for the two sets of wings given in figure 1 are, however, strictly comparable if the net efficiency of the pumping system from the boundary-layer control slot to the discharge outlet is equal to the propulsive efficiency of the main driving unit.

Despite the fact that the L/D of the wing with boundary-layer control is higher than that of the wing without boundary-layer control, the value of the profile-drag coefficient at $(L/D)_{max}$ is greater for the wing with boundary-layer control. Consequently, the addition of a given increment of parasite drag coefficient will make the comparison more favorable for the wing with boundary-layer control. Figure 1(b) gives a comparison between the two sets of wings when an arbitrary increment of parasite drag coefficient of 0.0100 has been added to each. Inspection of the data of figure 1(b) indicates that the optimum aspect ratio is now slightly higher than 20 for the wings with boundary-layer control and that the use of boundary-layer control gives an increase in $(L/D)_{max}$ of approximately 30 percent.

It should be noted that the maximum lift coefficients of the thick sections are quite high, and as is shown subsequently, it is on wings of high aspect ratio that high maximum lift coefficients can be most effectively employed.

This application of boundary-layer control would be of primary interest for relatively low-speed airplanes where range is of the greatest importance. For example, the critical Mach number obtained from low-speed pressure-distribution diagrams for the 40-percent-thick airfoil section at conditions corresponding to maximum L/D of the wing is 0.450. In spite of a number of obvious difficulties, it is thought that the possibility of increasing this limiting speed somewhat by the use of a moderate amount of sweep should be investigated.

Control of the Laminar Layer

The first attempts to obtain reductions in the profile drag by increasing the relative extent of laminar flow consisted of the design of new airfoil shapes having the position of minimum pressure far back along the surface. The rearward practical limit of the position of minimum pressure was dictated by the avoidance of turbulent separation over the rear portion of the airfoil, particularly for lift coefficients outside the low-drag range. Three general types of boundary-layer control have been proposed to increase the possible relative extent of laminar flow: first, multiple slots to limit the growth of the boundary-layer thickness and eliminate laminar separation; second, special airfoil sections having the position of minimum pressure extremely far back, together with a single suction slot to eliminate separation at a pressure discontinuity; and third, continuous boundary-layer suction through a porous surface.

The use of multiple slots.- Multiple slots have two distinct and interrelated effects on the boundary layer; they decrease the value of the boundary-layer Reynolds number and delay or prevent laminar separation. Work on this problem has been carried out by Holstein (references 7 and 8) in Germany, by Pfenninger (reference 9), and Ackeret, Ras, and Pfenninger (reference 10) in Switzerland, and by the NACA in the United States. These investigations showed in general that it was possible to extend the laminar layer in a region of adverse pressure gradient practically to the trailing edge with a small expenditure of power such that very large net drag savings were realized. The most favorable results were obtained at a fairly low value of the Reynolds number. For example, Pfenninger's best results, which showed a net drag saving of 50 percent, were obtained at a Reynolds number of 2.0×10^6. In both Pfenninger's and Holstein's experiments, however, the saving in drag disappeared when an attempt was made to repeat the tests at higher Reynolds numbers. Pfenninger attributed this adverse scale effect to increasing turbulence in the tunnel as the speed was increased. Holstein (reference 8) was able to maintain extensive laminar flow up to Reynolds numbers of 3.2×10^6. He found however that if the slot spacing was not decreased as the Reynolds number was increased the power required to limit the growth of the laminar boundary layer would become excessive. He gave no explanation of his failure to achieve extensive laminar flow at Reynolds numbers above 3.2×10^6.

An investigation is currently being carried out by the NACA on a symmetrical NACA 64A010 airfoil section of 3-foot chord designed to maintain laminar flow to the trailing edge by means of suction slots up to Reynolds numbers of the order of 25.0×10^6. The model is being tested at zero lift in the Langley two-dimensional low-turbulence pressure tunnel.

The following considerations dictated the slot spacing and slot size: First, the boundary-layer Reynolds number should not be allowed to exceed a definite value. Boundary-layer Reynolds numbers corresponding to transition (based on displacement thickness) of 6000 to 7500 have been measured in flight (reference 11) and values of 5000 to 6000 have been measured on another wing section in the Langley two-dimensional low-turbulence pressure tunnel (reference 12). In order to be reasonably conservative, the design value of the maximum boundary-layer Reynolds number for the slotted wing section was chosen to be approximately 2600 at a wing Reynolds number of 25×10^6. Second, the spacing between the slots was determined from suction-power considerations. Although the suction power required to maintain the boundary-layer Reynolds number decreases continuously with decreasing slot spacing, it was found that the savings of power corresponding to a slot spacing smaller than 3/4 of an inch on the present model (a Reynolds number run of 0.5×10^6) were relatively small. Furthermore, a smaller slot spacing would increase considerably the mechanical difficulties of constructing the model. Previous investigations in the Langley low-turbulence tunnel indicated that the slot width should not be greater than the boundary-layer thickness. For the model under consideration, this slot width was approximately 0.005 inch.

Three parameters, namely, the maximum value of the boundary-layer Reynolds number, the ratio of the slot width to the boundary-layer thickness, and the Reynolds number run between slots, are sufficient to determine the design of a slot installation. If the values of these three parameters are held constant, the slot spacing and slot width expressed as fractions of the chord will be functions of the design Reynolds number. For example, the slot spacing and slot width on the NACA 64A010 airfoil model would be 5 inches and 0.034 inch, respectively, at a Reynolds number of 25×10^6 if the chord of the airfoil were increased to 20 feet. If, however, with the 20-foot chord the design Reynolds number were increased to 83×10^6, the slot spacing and slot width would be $1\frac{1}{2}$ inches and 0.010 inch respectively, and the number of slots would increase in proportion to the Reynolds number.

The theoretical pressure distribution together with the slot locations are given in figure 2 for the 3-foot-chord NACA 64A010 airfoil model designed for a Reynolds number of 25.0×10^6. Great pains were taken in the construction of the model to maintain the machined aluminum surfaces in a smooth and fair condition. A photograph of the model partially disassembled is shown in figure 3. Preliminary test results indicated that not much difficulty was encountered in obtaining laminar flow over substantially the entire surface of the model up to a Reynolds number of about 3.0×10^6. As the Reynolds number was increased, however, the laminar flow in the boundary layer became exceedingly sensitive to minute changes in the shape of the slot entry and flow quantity removed. It was found that honing the edges of the slot slightly with a lead pencil produced sufficient changes in the slot contour to affect markedly the maximum Reynolds number at which laminar flow could be obtained over the slot. The maximum Reynolds number at which laminar flow could be obtained over substantially the entire upper surface was 10.0×10^6 whereas the corresponding maximum Reynolds number for the lower surface was 5.5×10^6. These Reynolds numbers, although not as high as expected flight values, are considerably higher than those for which complete laminar flow was obtained in the investigations of Holstein (reference 8) and Pfenninger (reference 9) and were obtained only after a great deal of effort had been expended in trying to eliminate minute irregularities from the slot contours. Since the airfoil was symmetrical, the differences in results between the upper and lower surfaces are attributed to small variations in the contours of individual slots. These variations were so slight that they could be observed only with the aid of a powerful magnifying glass. It was also observed that once transition had occurred, no amount of suction applied downstream of the transition point restored the boundary layer to the laminar state. The conclusion drawn from this investigation is that, although the possible region of laminar flow may be extended to the trailing edge of an airfoil through a region of adverse pressure gradient at fairly high Reynolds numbers, the laminar layer becomes increasingly sensitive to surface irregularities as the Reynolds number is increased. This result is entirely consistent with those of a previous flight investigation (reference 13) in which no decrease in sensitivity of the laminar boundary layer to surface irregularities was observed to result from the installation of a number of suction slots on a wing panel. In view of the observed increasing sensitivity of the laminar layer to surface irregularities with increasing Reynolds numbers and the difficulties that have been experienced in the past in obtaining the design extent of laminar flow on low-drag airfoils on operational airplanes, the use of suction slots to increase the possible extent of laminar flow does not appear to be very attractive. The practicability seems especially limited when consideration is given to the extreme difficulty of manufacturing and maintaining sufficiently accurate slot contours.

Airfoils designed especially for boundary-layer control.- The second method of overcoming the limitations on the design extent of laminar flow imposed by the consideration of turbulent separation at the rear of the airfoil was suggested by Griffith and discussed in some detail by Goldstein in his Wright Brothers lecture (reference 14). The original basic idea of this method of approach was to design an airfoil that had favorable pressure gradients over the entire region from leading edge to trailing edge. In order to obtain a closed shape consistent with this condition, it was necessary that the pressure increase discontinuously at some point along the airfoil surface. Suction was to be introduced at this singular point in order to enable the flow to follow the contour without separation. A typical velocity distribution and corresponding airfoil profile (taken from reference 14) are shown in figure 4. Because of the necessarily concave nature of the surface downstream of the pressure discontinuity and the corresponding Goertler type of instability, it was not possible to obtain laminar flow downstream of the suction slot except at very low Reynolds numbers. Consequently, in spite of the favorable pressure gradient over the rear portion of the airfoil, laminar flow could be expected only in the region upstream of the slot. Later airfoils of this type were, therefore, designed with the pressure discontinuity and associated suction slot at a more rearward position than shown in figure 4. More rearward positions of minimum pressure and correspondingly lower drag coefficients would be feasible with this type of airfoil section than, for example, with NACA 6-series sections without boundary-layer control, provided laminar flow were obtained up to the slot. If, however, laminar flow were not obtained up to the slot it seems very unlikely that the suction airfoil would show an appreciably lower drag coefficient than that of a plain airfoil section designed to have minimum pressure at the assumed forward position of transition. Practical airfoils can be designed with the position of minimum pressure as far back as 60 percent of the chord. Experience with operational airplanes having low-drag wings, however, indicates that laminar flow usually extends over a distance of no more than 15 to 20 percent of the chord back from the leading edge (reference 15). The difficulty appears to be not only the presence of inaccuracies in construction but also the accumulation of insects and dirt associated with the necessarily exposed nature of the wing surfaces. There is no reason to expect that the laminar boundary layer over the forward portion of suction airfoils of the Griffith type would be noticeably less sensitive to small surface irregularities than the corresponding region for NACA 6-series airfoils without suction. Unless the certainty of obtaining extensive laminar flow over more than the first 60 percent of the airfoil chord can be made considerably greater than it is at present, it is not likely that an airplane designer would feel inclined to compromise the design of his airplane to the extent of using this type of suction airfoil. Since the advantages of extensive laminar flow are well known and the drag corresponding to various extents of laminar flow can be calculated theoretically, further research on the design of Griffith type airfoils and on their experimental characteristics under ideal conditions is much less urgent than is research on methods of insuring the realization of extensive laminar flow.

Area suction.- A basic difficulty of obtaining laminar flow on airplanes is the sensitivity of the laminar boundary layer at high Reynolds numbers to surface defects that are sufficiently small as to be almost unavoidable. The only method of boundary-layer control that offers even any theoretical hope of reducing the sensitivity of the laminar layer to such small disturbances consists of continuous suction through a porous surface. The theory of the stability of laminar boundary layers to small two-dimensional disturbances was developed by Tollmien (references 16 and 17) and Schlichting (reference 18) and checked experimentally for the Blasius velocity distribution by Schubauer and Skramstad (reference 19). The theory was extended by Schlichting and others (references 20, 21, 22, 23, 24, and 25) to include the effects of variations in pressure gradients and the effects of blowing or sucking through a porous surface on the stability of the laminar layer. One of the most important conclusions of this theoretical work (dealing only with small two-dimensional disturbances) is that continuous suction through a porous surface markedly stabilizes the laminar layer with respect to small disturbances and that the quantity of air that has to be removed to achieve this marked stabilizing effect is extremely small. For example, the theory indicates that the lower critical boundary-layer Reynolds number based on the displacement thickness for the flow over a flat plate with zero pressure gradient is increased from a value of approximately 420 without suction (reference 26) to an asymptotic value of 55,000 (reference 23) to 70,000 (reference 22) with an amount of suction corresponding to a component of velocity normal to the plate of the order of 0.01 of 1.0 percent of the free-stream velocity.

An experimental investigation to determine the effects of continuous suction on the drag of an NACA 64A010 airfoil of 3-foot chord is now being carried out by the NACA in the Langley two-dimensional low-turbulence tunnels. The skin of the model is a $\frac{3}{32}$-inch-thick sheet of porous bronze which is made up of powder consisting of approximately spherical particles of such size that all the particles will pass through a 200-mesh screen but none through a 400-mesh screen. The sheet is wrapped in one continuous piece from the trailing edge on the upper surface around the leading edge to the trailing edge on the lower surface. The porous region has a span of one foot situated in the center of the 3-foot span model. A photograph of the model is shown in figure 5. Although some waviness was present in the model, the chordwise waves were actually much less severe than seems to be indicated in this photograph.

Typical results in the form of drag coefficient against flow coefficient are shown in figure 6 for a Reynolds number of 6.0×10^6. Boundary-layer surveys taken near the trailing edge indicated that laminar flow was obtained over virtually the entire porous surface of the model for flow rates corresponding to the lowest drags obtained. These data show that substantial net savings in drag can be obtained and that completely laminar flow can be maintained even when the model is not quite aerodynamically smooth and fair. The fact that the model was not quite aerodynamically smooth and fair is shown by the comparison of the drag coefficient for the boundary-layer control model with sealed surface and the corresponding drag coefficient of the solid, fair, and smooth model of the same airfoil section. In sealing the porous model the surface texture was not altered. At Reynolds numbers substantially higher than 6.0×10^6, it was not possible to obtain any net reduction of drag. This adverse scale effect appears to be associated with the particular sample of material used in the investigation. The pressure drop across the porous material is directly proportional to the flow velocity through it, so that the chordwise distribution of inflow velocity becomes increasingly nonuniform not only with decreasing flow coefficient but also with increasing Reynolds number. The flow coefficient corresponding to $c_{d_{min}}$ at a Reynolds number of 6.0×10^6 is somewhat greater than that indicated as theoretically necessary with a uniform inflow velocity to obtain the desired stability. Relative to free-stream velocity, the minimum inflow velocity necessary to avoid local regions of outflow increased with increasing Reynolds number. At high values of the flow coefficient, it was rather difficult to judge whether the boundary layer was laminar or turbulent. In general, however, the results seem to indicate that complete laminar flow was obtained provided there were no local regions of outflow over the surface. At Reynolds numbers much above 6.0×10^6, the flow coefficient necessary to satisfy this condition was so large that no net saving in drag was obtained in spite of the fact that the internal structure of the model was divided into a number of compartments with separately adjustable suction pressures. It is planned to continue the investigation using a much more dense porous material. It should be pointed out that the pressure drop through the porous surface itself is sufficiently small compared with the free-stream dynamic pressure for the flow rates of interest that the pressure drop can be increased several fold without materially affecting the suction power requirements.

In addition to the stabilizing effect indicated in the discussion of the data of figure 6, a further indication of the stabilizing action was obtained by spanwise drag surveys in the neighborhood of the juncture between the porous and solid portions of the surface of the model. This juncture was not completely smooth. As a result, transition spread inward from the juncture over the porous region and decreased the spanwise extent of the low-drag region behind the model. It was noticed that the spanwise extent of the low-drag region increased with increasing inflow velocity which indicates that continuous suction decreases the angle of spread of turbulence.

Before any recommendations can be made regarding the use of continuous suction on airplane wings, not only must the feasibility of obtaining substantial reductions in drag be determined at higher Reynolds number but, more importantly, the effects of surface irregularities such as are likely to be present under practical operating conditions must be found.

MAXIMUM LIFT

Usable maximum lift coefficient.- One of the earliest applications of boundary-layer control to receive attention is that of increasing the maximum lift coefficient. The gains in performance associated with such an improvement in wing characteristics were thought to be obvious. It is not at all certain, however, that such is the case. For example, a recent analytical investigation of a conventional, low-speed airplane having a pay load of 5000 pounds (reference 27) has indicated that the gains in take-off performance resulting from increasing the available maximum lift coefficient from values of the order of 3.0, which can be obtained without boundary-layer control, up to a value of approximately 5.0, which can be obtained only with boundary-layer control, did not result in a proportionate decrease in the total take-off distance. The improvement in take-off performance appeared to be relatively unimportant for aspect ratios much less than 15. The results of the analysis are consistent with results of German flight tests of two airplanes incorporating boundary-layer control to increase maximum lift coefficient (reference 28). It should be pointed out that the take-off distance considered to be of primary importance in these investigations was the distance required to clear a 50-foot obstacle. In nearly all cases, increases in the maximum lift coefficient resulted in decreases in the ground run, which might be of considerable importance in special problems such as those encountered in the design of aircraft for carrier operation.

These investigations served to clarify considerably current concepts regarding the usefulness of high maximum lift coefficients for the particular take-off problem studied. Similar studies of both take-off and landing performance are badly needed for other types of aircraft, particularly those designed primarily for high-speed performance and having extremely thin wings or wings of unusual plan form. Although the usable maximum lift coefficients for most of the proposed high-speed wing configurations are probably lower than those of wings of more conventional plan form because of the associated high induced drags and low take-off thrusts, there does seem to be a possibility of improving the landing and take-off characteristics of such high-speed configurations by increasing the maximum lift coefficients above the present extremely low values. There appear then to be two possible fields of application for boundary-layer control to increase the maximum lift coefficient: first, to relatively low-speed airplanes having wings of extremely high aspect ratio; and second, to high-speed airplanes with wings that have extremely low maximum lift coefficients.

Low-speed configurations.- For conventional wings of high aspect ratio, methods exist for predicting the wing characteristics from airfoil section data. The discussion of methods of improving the maximum lift of conventional wings is, therefore, concerned with results which have been obtained from two-dimensional investigations of airfoils with boundary-layer control and other high-lift devices.

For smooth airfoils at all reasonably high angles of attack, laminar separation occurs near the leading edge, but below the maximum lift coefficient the flow reattaches itself to the surface forming a turbulent boundary layer. The amount of pressure recovery that can occur before the turbulent boundary layer separates depends markedly on the details of the flow conditions associated with the initial forming of the turbulent boundary layer. Turbulent separation near the trailing edge and the laminar separation near the leading edge have a regenerative effect upon each other (reference 29). Maximum lift finally occurs either as a result of a progressive forward movement of separation from the trailing edge or permanent separation of the laminar boundary layer near the leading edge. Because of the regenerative effect, increases of maximum lift coefficient on almost any given airfoil can be obtained by delaying either form of separation. The larger effect, however, is generally obtained by delaying the type of separation that finally results in complete flow breakdown. For example, the thicker airfoils with blunter leading edges which have round-top lift curves generally can be improved most by delaying separation of the turbulent boundary layer; whereas the largest increases in maximum lift of the thinner sections can be obtained by controlling separation near the leading edge. In any case, if boundary-layer control is used to prevent one type of separation, maximum lift will then be limited by the other type.

The type of boundary-layer control that has received the most attention has been that which delays turbulent separation over the rear portions of airfoils of 12-percent thickness and greater. Turbulent separation can be delayed either by removing a portion of the low-energy air in the boundary layer or by injecting high-energy air under the boundary layer. Boundary-layer control is effective in increasing the maximum lift coefficient either with or without other high-lift devices. Their use in connection with boundary-layer control, however, generally has two advantages: first, the values of the maximum lift which can be obtained are greatly increased; and second, the angles of attack for maximum lift are not excessive when trailing-edge high-lift devices are employed. A comparison of the most common methods of controlling the turbulent boundary layer is given in figure 7. The figure shows a plot of maximum lift coefficient as a function of blower power for a given wing loading. The data were obtained from references 5, 30, and 31. The choice of the most effective method of boundary-layer control is seen to depend upon the power expenditure per unit wing area. The data are seen to indicate that for the lowest power expenditures the midchord suction slot in combination with a trailing-edge double-slotted flap is most effective. Extremely high maximum lift coefficients can be obtained with an arrangement whereby air is blown over the flap, but only with relatively large expenditure of power. The arrangement whereby air is withdrawn in the neighborhood of the flap hinge may be slightly better than the other two arrangements for intermediate power expenditures.

Some of the results of a systematic investigation of boundary-layer control on smooth airfoils of various thickness ratios are given in figure 8 (references 2, 4, 5, and 6). In each case boundary-layer control was applied through a single suction slot located at the approximate midchord position. The increment of maximum lift coefficient due to boundary-layer control increased progressively with airfoil thickness ratio. The reason for the relatively small increments in maximum lift observed for the thinner sections is that for these airfoils maximum lift was originally limited by permanent laminar separation near the leading edge. In all cases with suction applied, maximum lift finally occurred as a result of permanent laminar separation near the leading edge.

An obvious method of further increasing the maximum lift coefficient is to delay or eliminate leading-edge separation. This can be done by the use of leading-edge slats or flaps or by the use of boundary-layer control. The effect of the addition of a leading-edge slat to the 12-percent-thick airfoil with boundary-layer control and double-slotted flap (reference 4) can be seen in figure 9. It is seen that substantial increments in maximum lift are gained by the use of the leading-edge slat such that maximum lift coefficients of the order of 4.0 are possible for all of the airfoils of 12- to 24-percent thickness.

In the hope that some form of boundary-layer control might be more effective or convenient in controlling leading-edge separation than slats or flaps, several investigations have been made. The types of boundary-layer control investigated include the location of slots near the leading edge and the use of a porous leading edge (references 32, 33, and 34 and the work of the British investigators Cheers, Douglas, and Raymer discussed in reference 14). All data that are available from these investigations are for airfoils employing leading-edge boundary-layer control alone without means for controlling separation over the rear of the airfoil. As might have been expected, the boundary-layer control eliminated leading-edge separation but turbulent separation over the rear of the airfoil limited the maximum lift to values of the order of those obtainable with a slat. Further research is needed in order to determine whether boundary-layer control applied to the leading edge of the thinner sections will prove more effective than leading-edge slats when used in conjunction with other types of boundary-layer control and high-lift devices. Boundary-layer control by continuous suction near the leading edge may have some advantages over discrete slots or leading-edge slats in that, presumably, detailed investigation of individual sections would not be necessary to obtain optimum configurations.

High-speed configurations.- Wing configurations which have been designed primarily to obtain good aerodynamic characteristics at high Mach numbers generally have airfoil section thickness ratios of less than 12 percent and may have considerable amounts of sweep. Both of these characteristics lead to low values of the maximum lift coefficient. The low maximum lift of the thin sections is caused by relatively early separation of the flow from the leading edge. The largest improvements in the maximum lift would, therefore, be expected to occur as a result of control of the flow separation near the leading edge. Investigations have shown that the use of a plain, drooped leading-edge flap in conjunction with a plain trailing-edge flap increased the maximum lift of a 6-percent-thick airfoil section from 0.78 to 1.89 (reference 35). At least equally large increments in the section maximum lift coefficient could probably be obtained by substituting boundary-layer control for the flap at the leading edge but the pressure difference through which the boundary-layer-control blower would have to operate would be very large. This pressure difference would probably be a substantial fraction of the absolute pressure with normal landing speeds for airfoils of the order of 6-percent thickness. It is questionable whether this application of boundary-layer control would be sufficiently more effective than the simple leading-edge flap to warrant its use. No final conclusion can be reached, however, until data are obtained on the pressure and flow-quantity requirements.

The maximum lift coefficients of the swept-type wings now being used for high-speed aircraft are generally extremely low. The flow phenomena believed to result in the occurrence of maximum lift on swept wings is briefly discussed in order to indicate by what means the maximum lift of such wings might be improved. According to the concepts of simple sweep theory, the characteristics of individual sections of an infinite yawed wing depend upon the component of velocity normal to the leading edge. The characteristics of finite sweptback wings are, however, rather strongly influenced by three-dimensional effects not present in the case of the infinite yawed wing.

The distribution of shed vorticity has two important adverse effects upon the characteristics of the sweptback wing: first, the induced vertical velocity field shifts the spanwise center of pressure outboard as the sweepback is increased; and second, an effective negative camber is induced in the sections near the tip. The resultant effect upon the flow is that pressure peaks near the leading edge of the outboard sections tend to be accentuated. As a result, the tip sections of sweptback wings usually stall sooner than do those near the root, and the stall originates with separation near the leading edge. Early tip stalling is further provoked by the fact that the spanwise pressure gradient exercises a measure of boundary-layer control on the sections near the root, and by the fact that the distribution of shed vorticity induces an effective positive camber in these root sections. Consequently, the first step in attempting to improve the low-speed characteristics of such wings should be the delay of leading-edge separation on the outboard portions of the wing.

A preliminary investigation has been made in the Langley full-scale tunnel of a 45° sweptback wing having boundary-layer suction slots to control turbulent separation over the rear of approximately the outer half of the wing (reference 36). As might have been expected from the preceding qualitative discussion of the maximum lift of swept wings, the increases in maximum lift coefficient resulting from this type of boundary-layer control were relatively small. The use of a leading-edge flap to control leading-edge separation together with the boundary-layer control slots over the rear delayed the stall of the outboard sections such that the undesirable longitudinal stability characteristics associated with tip stalling were eliminated. The associated increases in maximum lift, however, were relatively small because stalling of the inboard sections occurred at a lift coefficient only slightly higher than that at which the tip sections previously stalled. A more extensive British investigation (reference 37) of boundary-layer control on a sweptback wing gave generally similar results, as did a short German investigation (reference 38).

The ultimate desirability of using boundary-layer control to improve the low-speed characteristics of sweptback wings has not yet been demonstrated because, for example, stable stalling characteristics were obtained in the Langley 19-foot pressure tunnel for several sweptback wings by the use of leading-edge devices of proper design (for example, reference 39).

At the present time, some further investigations of sweptback and sweptforward wings with boundary-layer control are being planned for the Langley full-scale and Ames 40- by 80-foot tunnels, respectively. Descriptions are also available (reference 40) of a British tailless airplane having swept wings with boundary-layer control applied through a single suction slot located near the midchord position just ahead of the outboard control surface. There do not appear, however, to be available any experimental data on this airplane at the present time.

LATERAL CONTROL

The effectiveness of boundary-layer control as a lateral-control device depends upon the sensitivity of the lift of an airfoil section to details of the flow conditions at the trailing edge. Various investigations have been made in Germany (reference 38) of the effect upon the direction of the streamline leaving the trailing edge, and consequently the lift, of discharging and withdrawing air through different arrangements of slots located at or near the trailing edge. Several of these devices proved quite effective in changing the lift coefficient at a given angle of attack in much the same way as an aileron acts. A device having a similar effect has been proposed by Thwaites (references 41 and 42). This device consists of forming the trailing edge of a small cylinder of porous material with a short tab attached to control the direction of flow leaving the trailing edge. Suction is applied through the porous material in order to make the flow follow the contour. Although there is little reason to doubt the effectiveness of these devices, at least at subcritical speeds, or the fact that they might lead to extremely light control forces, it is not evident that they would prove to be simpler or more reliable than conventional lateral-control devices with boosters where necessary.

DIFFUSERS AND BENDS

Efficient diffusers are even more important on jet-type airplanes than on airplanes with conventional power plants because any losses in the diffuser would not only represent an increment of drag but would also greatly decrease the efficiency and output of the jet engine itself. It is extremely difficult to determine any general rules or design criterions for the use of boundary-layer control on diffusers because of the marked effect of the initial conditions of the boundary layer at the entrance of the diffuser on the pressure-recovery characteristics and the rapidity with which the diffusion can be accomplished without encountering serious losses. In many cases the entrance to the duct is situated fairly well back on a body as for example a scoop inlet on a fuselage. In these cases, improvements in the efficiency of the diffuser can be obtained by removing a portion of the boundary-layer air ahead of the duct as well as within the duct itself. The removal of boundary-layer air through a suction slot situated immediately ahead of the entrance to a duct is now being investigated at the Ames and Langley Aeronautical Laboratories in connection with scoop-type inlets for transonic and supersonic speeds. The by-passing of low-energy boundary-layer air from the duct entrance is now general practice for nearly all scoop-type air inlets. The use of suction to avoid separation within a diffuser is not a new principle. Unfortunately, however, generalized data giving the quantity and pressure requirements are not available. Such data for several specific configurations, however, are given in reference 43. In gereral it appears that high-efficiency diffusion can be obtained with the use of a single suction slot withdrawing a quantity of air of the order of 5 percent of the total quantity of air passing through the duct. In many cases, the improvement in airplane performance gained as a result of the improved efficiency of diffusion might more than counterbalance the losses associated with withdrawing the required boundary-layer air. Because in general the static pressure within the diffuser is higher than free-stream static pressure, no auxiliary pumping equipment is necessary. This application of boundary-layer control appears quite attractive and should be considered whenever the problem of efficient diffusion in a short distance arises. Because of the varied nature of individual applications, however, it is difficult to outline a systematic research program that would provide adequate data. Future research would probably most profitably deal with proposed specific installations.

The application of suction to prevent separation in bends does not appear as attractive as that just discussed because the local pressure at the point where boundary-layer control is required is generally fairly low as compared with free-stream static pressure. Furthermore, considerable improvement in the efficiency of bends can be obtained by the proper use of guide vanes.

Little detailed information is available on the use of blowing slots to improve the flow in diffusers and bends. One such installation has been made, however, in the exit cone of the Langley high-speed 7- by 10-foot wind tunnel, where a comparatively small amount of air, having a total pressure equal to that in the center of the tunnel, is introduced under the boundary layer in the exit cone. It was found that these blowing slots had little effect on the energy ratio of the tunnel, but they eliminated the unsteadiness of the flow in the tunnel. It is possible that a corresponding arrangement in the entrance diffuser of a jet-engine installation might have a beneficial influence on the steadiness of the flow entering the compressor.

BOUNDARY-LAYER CONTROL AT HIGH MACH NUMBERS

Another possible application of boundary-layer control is the control of separation following a shock at high Mach numbers. It is fairly well agreed that one of the principal reasons for the rapid increase in drag above the critical Mach number is the separation of the flow from the surface that accompanies shock formation rather than the losses in the shock itself, at least at low supercritical Mach numbers. It also seems likely that the position of the shock is strongly affected by boundary-layer conditions. Boundary-layer control as a method for preventing separation following a shock has been investigated in Germany and England (references 44 and 45) and at present is being investigated in flight on an F-80 airplane at the Ames Aeronautical Laboratory. These tests indicate that the external drag can be reduced at some Mach numbers, but in many cases the power requirements were about equivalent to the saving in wake drag. These investigations however are not necessarily conclusive. In each case boundary-layer control was applied through a single suction slot. If the primary purpose of the boundary-layer control is to eliminate the flow separation associated with shock formation, there is some doubt as to the effectiveness of any single slot configuration because of the large variation of the shock position with Mach number and angle of attack. The possible reductions in drag coefficient and elimination of buffeting, and the fact that boundary-layer control may tend to reduce or at least postpone to higher Mach numbers the large erratic changes in lift and pitching moment makes further investigations of boundary-layer control at high Mach numbers seem very important. These investigations should include not only the effects of individual suction and blowing slots but also the effects of suction through a porous surface. The purpose of the porous surface in this case would not be so much to maintain extensive laminar flow as to insure that suction would always be applied in the vicinity of the shock.

The application of boundary-layer control at supersonic speeds is not very clear. On the one hand, analysis indicates that for bodies of optimum fineness ratio the skin friction accounts for one-half to two-thirds of the total drag. The data of reference 46 indicate that the laws for turbulent-boundary-layer skin friction are not greatly different at supersonic speeds than at subsonic speeds. Reductions of the skin-friction drag must, therefore, as at subsonic speeds, come about through an increase in the relative extent of laminar flow. On the other hand, the details of the shock formation at the trailing edge of a supersonic airfoil section appear to have a large effect on the drag. In general, thickening of the boundary layer near the trailing edge appears to increase the trailing-edge pressure and thereby results in a decrease of the pressure drag (reference 47). Boundary-layer control or any other effect that would tend to increase the extent of laminar flow and decrease the skin friction drag would appear therefore to have a tendency to increase the pressure drag. Hence, boundary-layer control at supersonic speeds presents a much more complex problem than at subsonic speeds and is badly in need of thorough investigation.

SUCTION-SLOT DESIGN

The requirements for a good suction slot depend upon whether the slot is to be used for removing a portion of the laminar or turbulent boundary layer. The primary requirement for slots designed to extend laminar flow is that the slots themselves shall not introduce any disturbance which will cause transition. Slots have been designed that satisfy this condition in the investigations of references 7, 8, 9, and 13. Further work on the design of suction slots for laminar layers is discussed in references 48 and 49. Losses in slots designed to control the laminar boundary layer are usually not of critical importance because the amount of air withdrawn at a single slot is small in a correctly designed installation. Furthermore, the velocity with which the air is withdrawn cannot be very large without disturbing the laminar layer and causing transition. It is necessary of course that the flow into the slot be stable and this question has been investigated in reference 1.

The conditions affecting the design of slots to operate in a turbulent boundary layer are quite different. In this case the external flow is relatively insensitive to detailed changes in the slot design and is affected primarily only by the quantity of air withdrawn. Changes in the design of the suction slot do however have a marked effect on the internal losses. These losses are more important than for laminar layers because of the relatively large quantities of air withdrawn in each slot. Investigations to develop efficient slot configurations for turbulent boundary layers are given in references 50 and 51. The problem of reducing the losses following entry of the air into the slot is primarily that of designing efficient diffusers and bends. This problem is considered in some detail in reference 52.

JET ENGINES AS PUMPS

The suggestion has been made repeatedly that jet-type power plants be used as a pump for boundary-layer control. An investigation carried out by Wilsted and Stemples (reference 53) indicates that the loss of considerable ram such as is associated with any means of boundary-layer control by suction causes serious losses in the performance of jet engines. Final conclusions regarding the use of jet engines as a pump cannot be drawn, however, because of the lack of detailed information regarding the quantity and pressure requirements for boundary-layer control. The question must finally be decided by comparing the decrease in performance of the jet engine with the aerodynamic gains. Up to the present time, no marked gains in the aerodynamic performance of typical high-speed configurations that would require jet engines have been demonstrated to result from the use of boundary-layer control. More detailed research on the use of a jet engine as a pump would therefore seem to be premature.

CONCLUSIONS

Consideration of the present status of the application of various methods of boundary-layer control indicates the following conclusions:

1. For relatively low-speed, long-range aircraft, boundary-layer control may be effectively employed to eliminate turbulent separation on thick root-section airfoils such that wings of higher aspect ratio may be employed to give improved values of the lift-to-drag ratio. The data on which the analysis was based were obtained for airfoils having completely turbulent boundary layers extending back from the leading edge.

2. In order to obtain extensive regions of laminar flow and correspondingly low profile-drag coefficients such as might be obtainable with NACA 6-series airfoils or airfoils of the Griffith type, some means must be found for decreasing the sensitivity of the laminar boundary layer to surface imperfections that are apt to occur under practical operating conditions. The use of multiple slots does not appear to decrease the sensitivity of the laminar boundary layer. Although information regarding the effects of area suction is not sufficiently complete to be conclusive, such data as are available indicate that area suction does have some stabilizing action and that the suction power requirements are small. Further research should be carried out on boundary-layer control by area suction.

3. By the appropriate use of boundary-layer control maximum lift coefficients of the order of 4.0 can be obtained for airfoil sections of 12-percent thickness and above without the expenditure of excessive amounts of power. Maximum lift coefficients of the order of 3.0 or 4.0 are effective in decreasing the take-off distance only for airplanes having wings of extremely high aspect ratio. The use of boundary-layer control on thin sweptback wings has to date resulted only in relatively small increments of the maximum lift coefficient although considerable improvement in the longitudinal stability characteristics at the stall has been obtained. Because of the relatively low aspect ratio and take-off thrust which usually characterize high-speed configurations, an analytical investigation should be made of the effectiveness of increasing the maximum lift, above the values now obtainable, as a means of improving the take-off and landing characteristics of typical configurations of high-speed aircraft.

4. The use of boundary-layer control as a means of increasing or decreasing the lift of an airfoil independently of the angle of attack has been the subject of several investigations. These methods proved to be quite effective. It is not clear, however, that they would be any simpler or more effective than conventional control surfaces.

5. The use of suction to control separation appears to be a particularly convenient method of increasing the efficiency of short diffusers because the pressure at the suction slot usually is sufficiently high to eliminate the need for auxiliary pumping equipment. Because of the varied nature of individual applications, however, future research on this problem would probably most profitably deal with proposed specific installations.

6. Several short investigations have been made of the effect of boundary-layer control on the drag at supercritical Mach numbers. These tests showed little net decrease in the drag. The method employed for applying the boundary-layer control, however, did not appear to be the optimum. Further research on boundary-layer control at supercritical speeds is necessary in order to explore more completely the possibilities of the application of boundary-layer control not only for reducing the drag but also for improving the lift and moment characteristics. In particular, it is felt that the use of continuous or area suction should be investigated at high Mach numbers.

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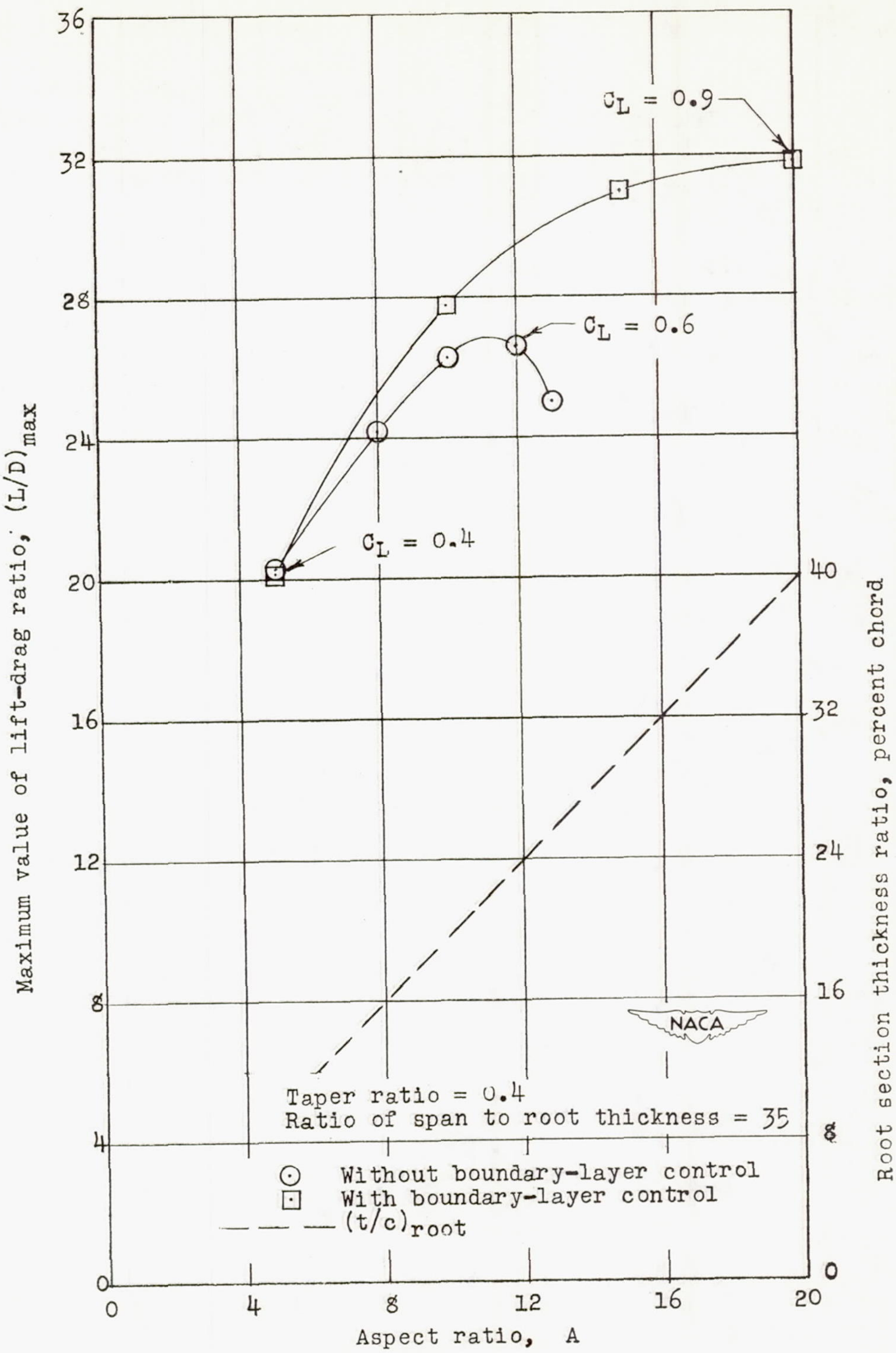
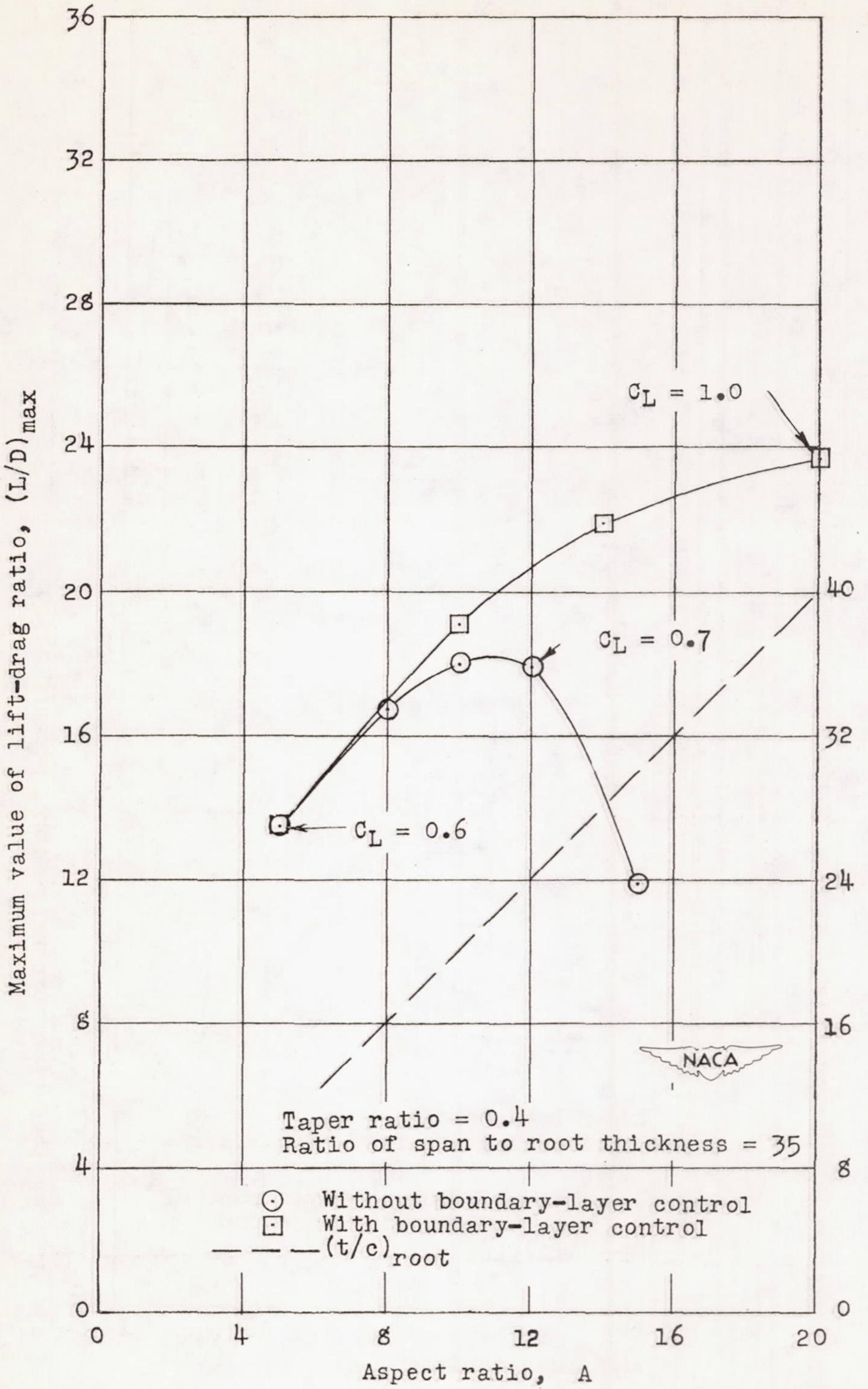


(a) Wings alone.

Figure 1.- Effect upon $(L/D)_{max}$ of controlling turbulent separation on the thick root sections of high-aspect-ratio wings with leading-edge roughness.



(b) 0.01 parasite-drag coefficient added.

Figure 1.- Concluded.

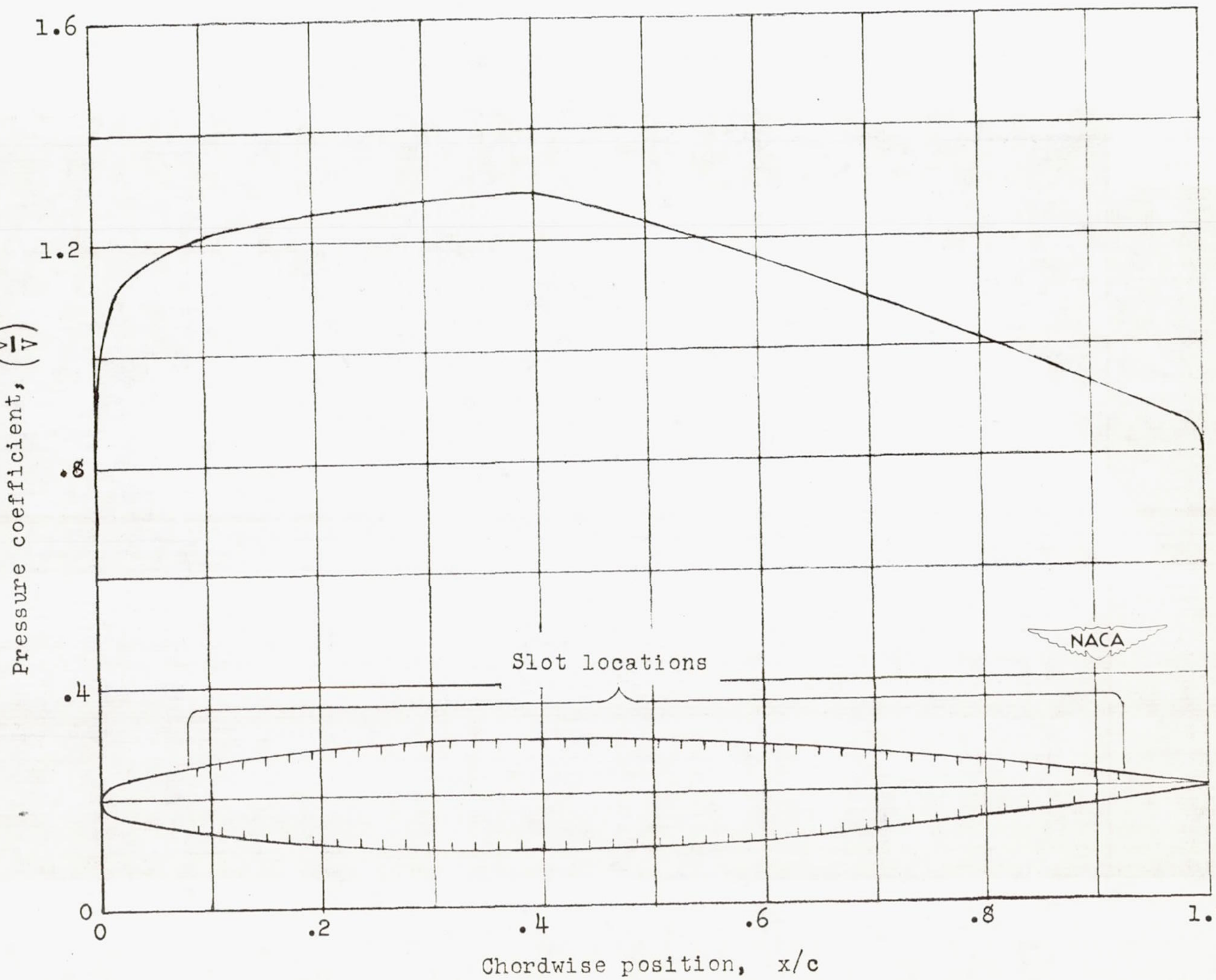


Figure 2.- Pressure distribution and suction-slot locations for an NACA 64A010 airfoil section.

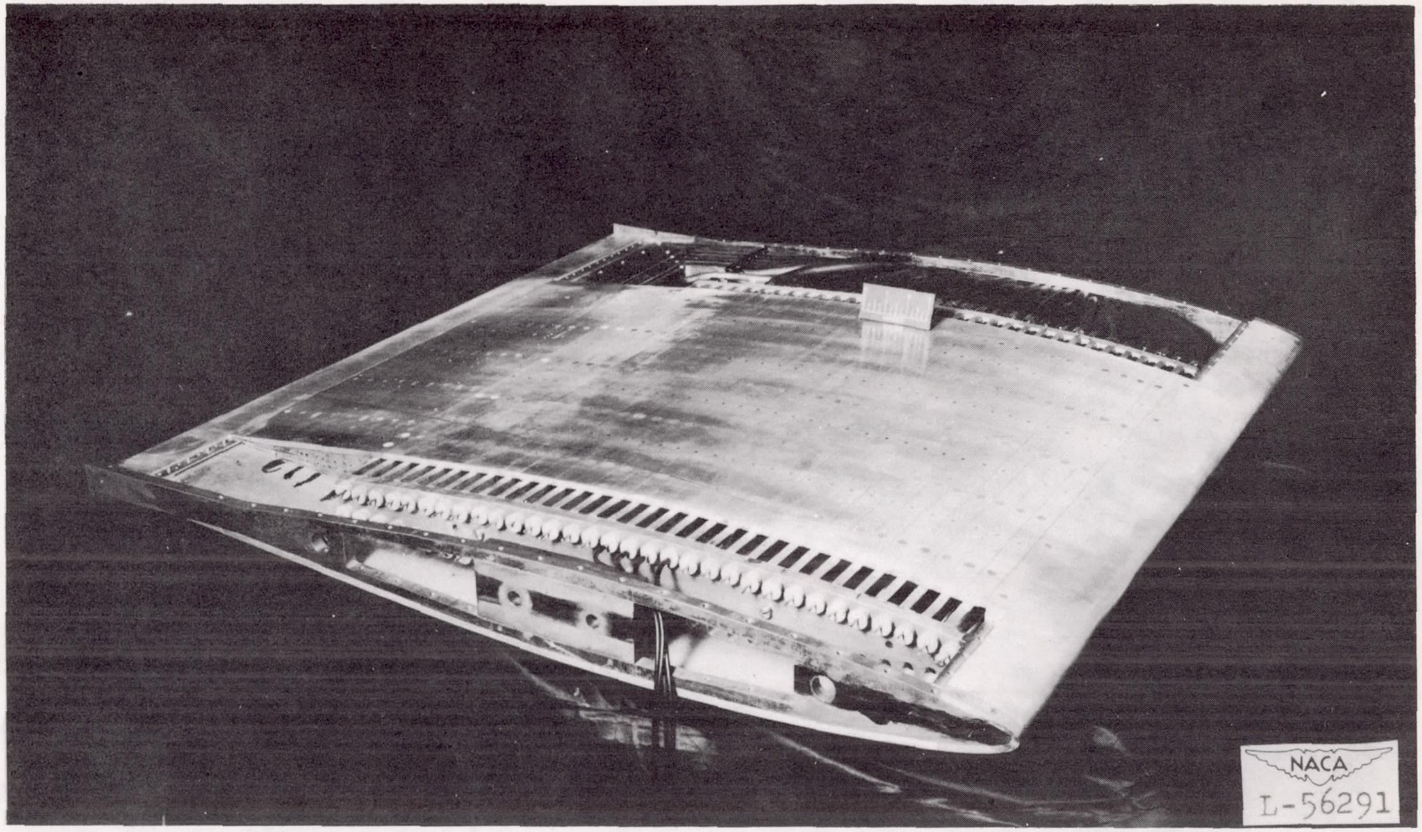


Figure 3.- Model of the NACA 64A010 airfoil section equipped with 41 suction slots on upper and lower surfaces.

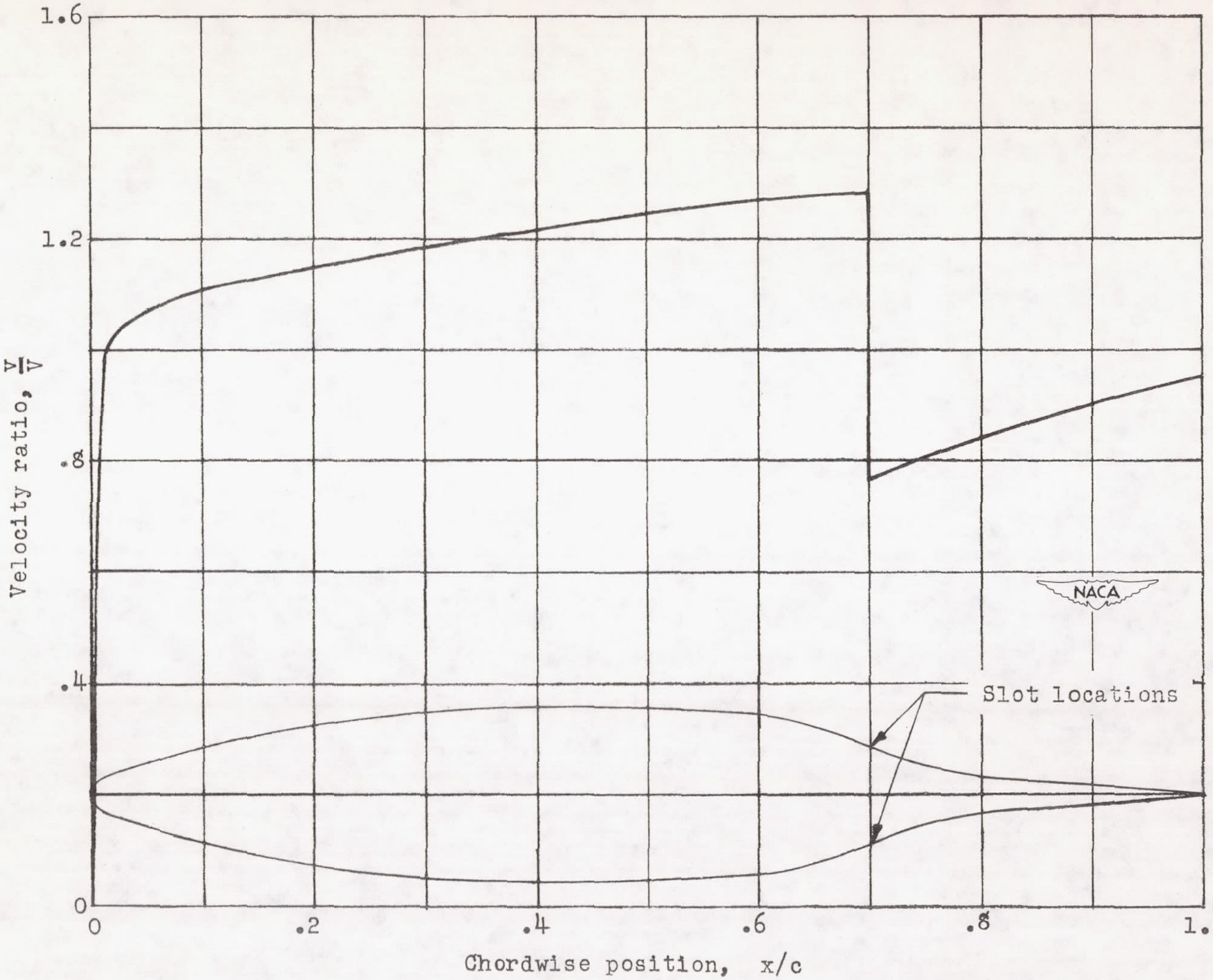


Figure 4.- Profile shape and velocity distribution of a symmetrical suction airfoil section of approximately 16-percent thickness (reference 14).

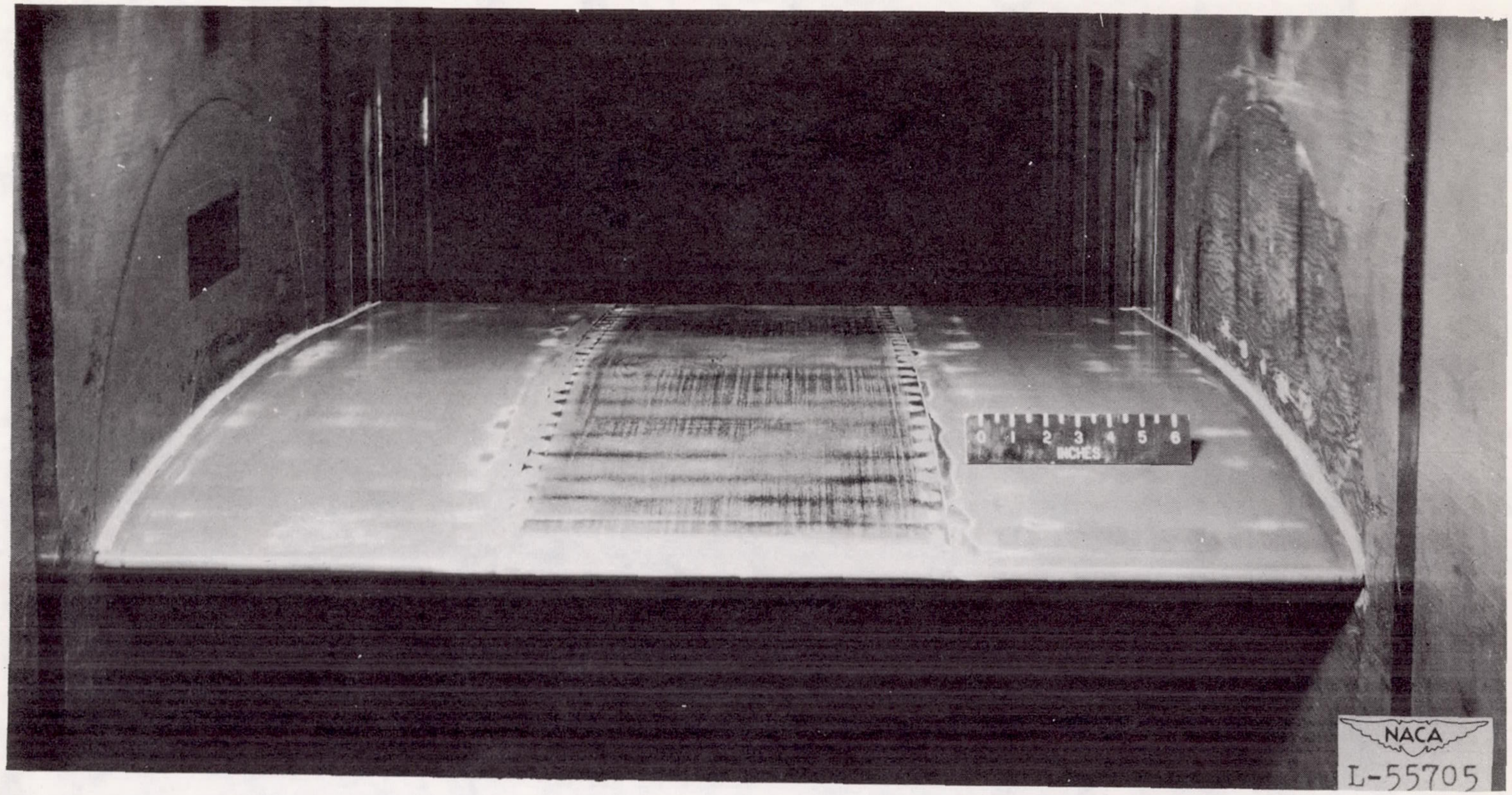


Figure 5.- Model of the NACA 64A010 airfoil section having the center section covered with sintered bronze.

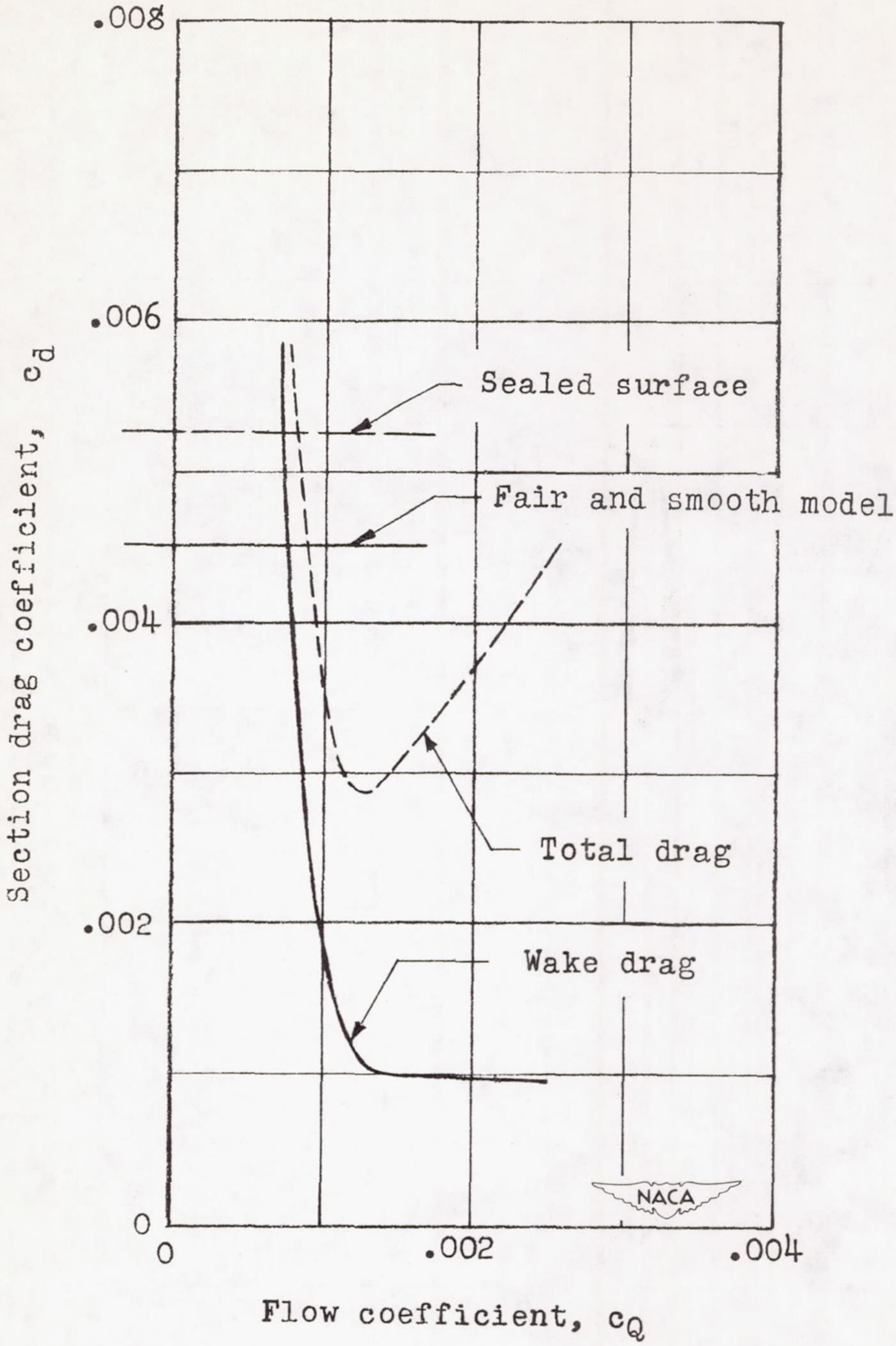


Figure 6.- Drag results obtained for the NACA 64A010 airfoil section with and without suction through the surface of sintered bronze. $R = 6.0 \times 10^6$.

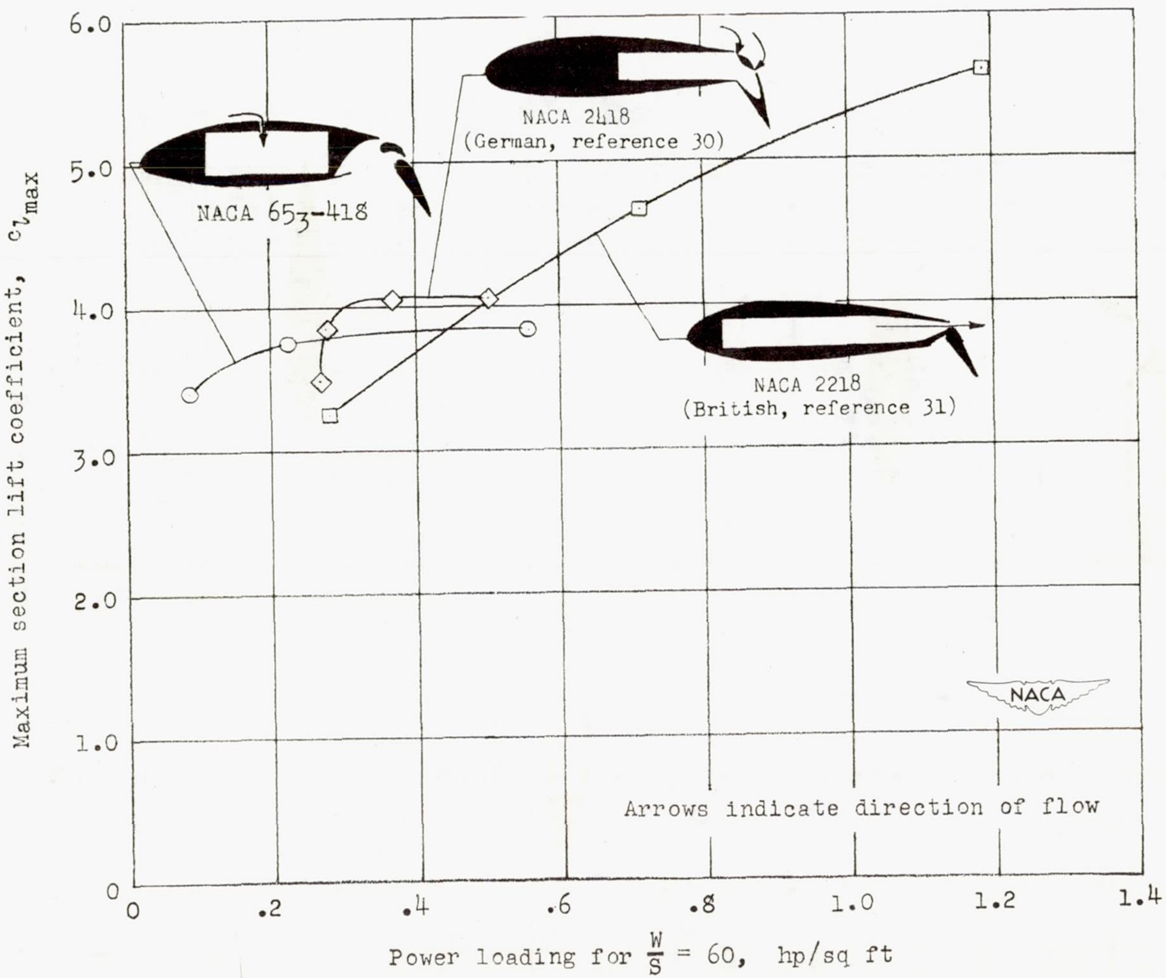


Figure 7.- Effect upon the maximum lift coefficient of boundary-layer control by suction and blowing.

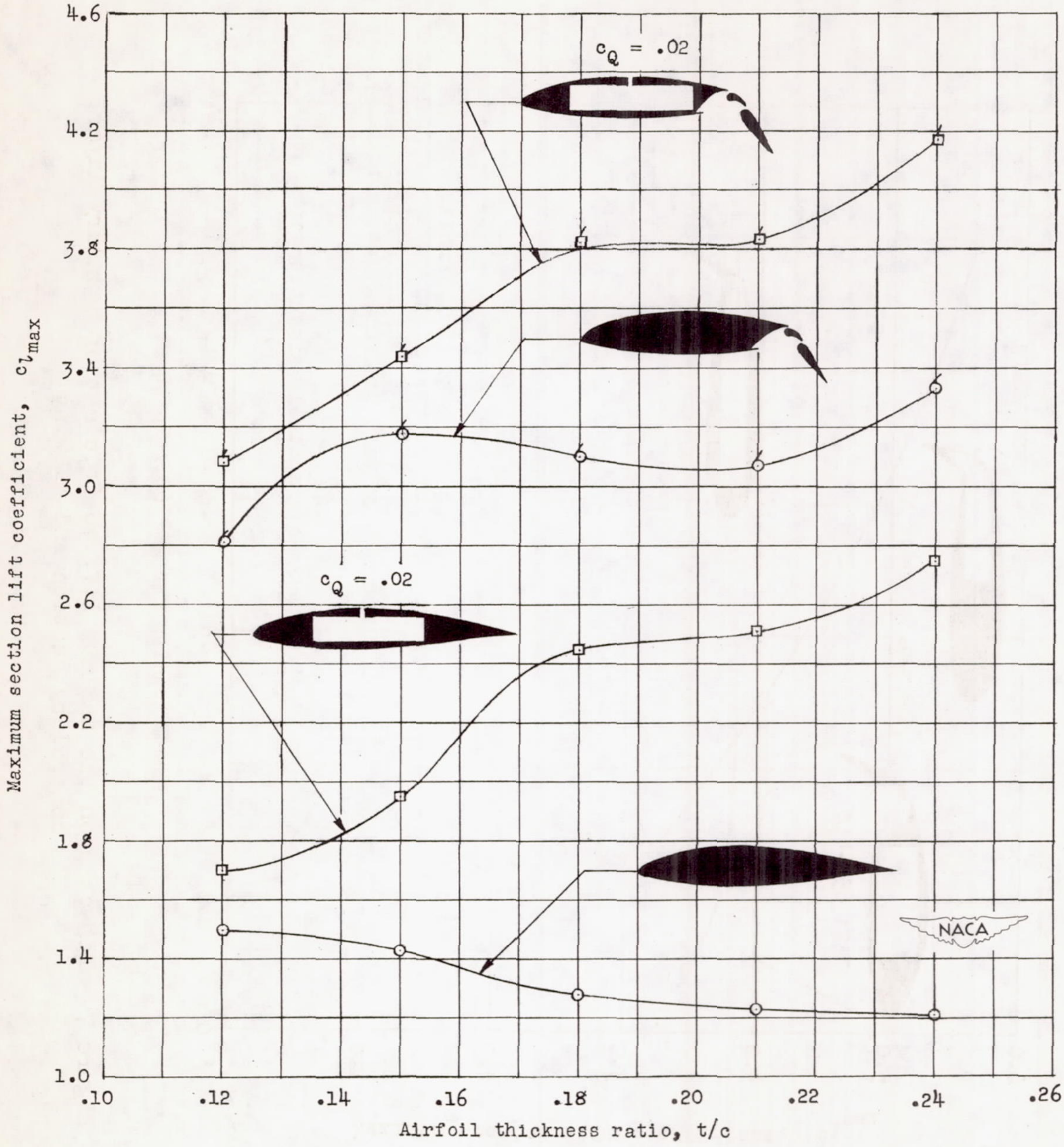
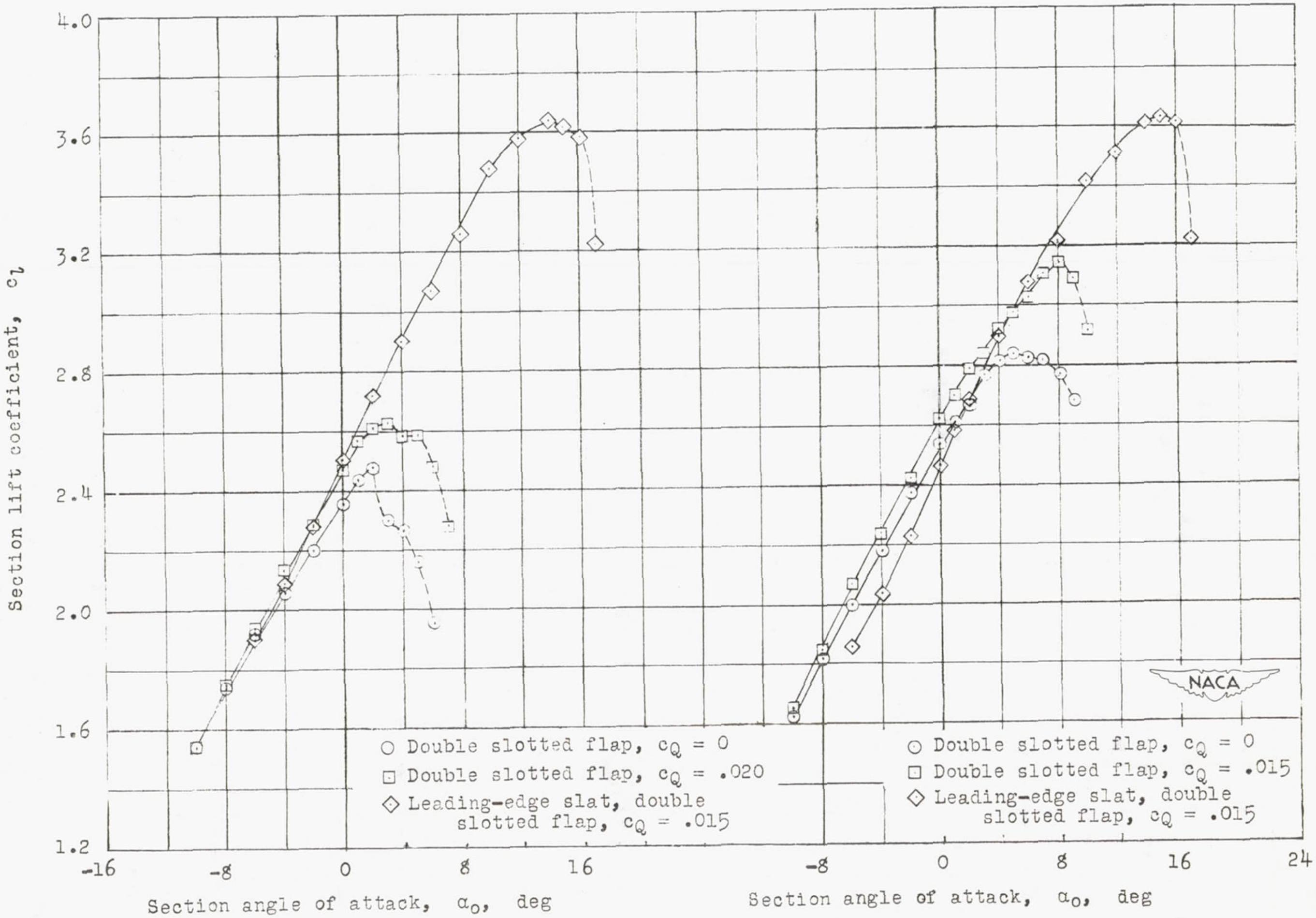


Figure 8.- Effect upon the maximum lift coefficient of airfoil thickness ratio for NACA 65-series airfoils with and without boundary-layer control by suction and double slotted flaps. $R = 2.2 \times 10^6$.



(a) $R = 1.5 \times 10^6$.

(b) $R = 6.0 \times 10^6$.

Figure 9.- Influence of a leading-edge slat upon the maximum lift obtained for a 12-percent-thick airfoil equipped with a double slotted flap and boundary-layer control by suction at the midchord position.