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RESEARCH MEMORANDUM

AERODYNAMIC CHARACTERISTICS AT SUBCRITICAL AND SUPERCRITICAL MACH NUMBERS OF TWO AIRFOIL SECTIONS HAVING SHARP LEADING EDGES AND EXTREME REARWARD POSITIONS OF MAXIMUM THICKNESS

By A. J. Eggers, Jr.

Ames Aeronautical Laboratory
Moffett Field, Calif.

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NATIONAL ADVISORY COMMITTEE
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WASHINGTON

November 6, 1947

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RESEARCH MEMORANDUM

AERODYNAMIC CHARACTERISTICS AT SUBCRITICAL AND SUPERCRITICAL MACH NUMBERS OF TWO AIRFOIL SECTIONS HAVING SHARP LEADING EDGES AND EXTREME REARWARD POSITIONS OF MAXIMUM THICKNESS

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By A.E. Newlan
Date NOV 8 1950

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SUMMARY

A high-speed wind-tunnel investigation has been conducted to determine the subsonic aerodynamic properties of a 12-percent-chord-thick, single-wedge airfoil section and a reversed NACA 0012 profile. Lift, drag, and quarter-chord pitching-moment coefficients of these sections are presented for small angles of attack and for Mach numbers ranging from 0.3 to approximately 0.9. From a comparison of these characteristics with the corresponding properties of the NACA 0012 profile, an evaluation is made of the relative merits at transonic velocities of the two unconventional airfoil sections and the conventional profile.

At small constant angles of attack the lift coefficient of the wedge section increases continuously with Mach number to the highest Mach number of the tests; whereas the corresponding property of the reversed NACA 0012 airfoil does not markedly increase or decrease at Mach numbers above the critical. The normal NACA 0012 section displays the familiar loss of lift at supercritical speeds. In all cases the drag coefficient of the wedge section is higher than the drag coefficient of either the reversed or normal NACA 0012 profiles; however the supercritical drag rise of this section is less than that of either of the latter airfoils. At higher lift coefficients in the supercritical Mach number range, the drag characteristics of the reversed NACA 0012 section are superior to those of the normal NACA 0012 section. Of the three sections, the reversed NACA 0012 section has the most favorable variation of pitching moment with Mach number in the transonic speed range.

INTRODUCTION

It is well established that the subsonic aerodynamic characteristics of conventional airfoil sections undergo radical changes when Mach numbers appreciably in excess of the airfoil critical Mach number are attained. These changes are manifested in rapid increases in drag coefficient, decreases in lift coefficient, and erratic variations in pitching-moment coefficient with Mach number, often so severe as to render the flight of aircraft employing such profiles as wing sections extremely hazardous at transonic velocities.

Several wind-tunnel investigations have been conducted at subsonic velocities to determine the causes for the marked differences between section characteristics at subcritical and supercritical Mach numbers. In one of the first of these studies (reference 1) it was found that the Mach numbers associated with unfavorable changes in section properties corresponded closely to the Mach number at which shock waves first became evident. A more detailed investigation of this phenomenon in reference 2 indicated that one of the principal effects of a shock wave is to promote serious thickening, if not separation, of the boundary layer on an airfoil surface by virtue of the adverse pressure gradient existing across the wave. Consequently, the profile in the region of and behind the shock may be thought of as effectively altered, with the result that the section characteristics are materially different from what they would have been, had the shock not influenced the boundary layer. For this reason it might be expected that an airfoil section for which shock-imposed distortions of the effective profile are minimized would display less severe changes in aerodynamic properties at supercritical speeds than those evidenced by conventional sections. A type of section which should at least partially satisfy this condition is one on which shock waves form at extreme rearward chordwise positions, for in this case only the small portion of the profile in the region of and behind the waves should be effectively altered by their presence. Since it has been observed that shock waves form near the maximum thickness or minimum pressure position of a section, it is probable, then, that shock-imposed changes of the aerodynamic characteristics of an airfoil will be smaller for sections having extreme rearward maximum thickness locations. It is to be expected, of course, that at least the subcritical drag characteristics of an airfoil will be adversely affected by an extreme rearward shift of the minimum pressure point.

To investigate the validity of the foregoing reasoning, high-speed wind-tunnel tests have been made of two unconventional airfoil sections having extreme rearward positions of maximum thickness and provided with sharp leading edges for supersonic speed applications. A 12-percent-chord-thick wedge section and a reversed NACA 0012 section were chosen for these tests as they are representative of sections having no boat tailing and appreciable boat tailing (i.e., blunt and rounded trailing edges, respectively), and the results of this investigation are compared with those obtained from a previous investigation of the NACA 0012 section. Conclusions are drawn regarding the relative merits of the two unconventional sections and the conventional section in the transonic speed range.

APPARATUS AND TESTS

The investigation was conducted in the Ames 1- by 3-1/2-foot, closed-throat, high-speed wind tunnel which obtains a two-dimensional flow of low turbulence in the test section. The power supplied by two 1000-horsepower motors is sufficient to choke the tunnel in the manner described in reference 3.

Sketches of the normal and reversed NACA 0012 section and the 12-percent-chord-thick wedge section are shown in figure 1. Ordinates for the former section are given in table I. The wedge airfoil was of 3-inch chord and constructed of steel; whereas the NACA 0012 airfoil had a 6-inch chord and was of duralumin construction. Both airfoils spanned the 1-foot width of the tunnel test section as shown in figure 2, and two-dimensional flow was insured by the use of rubber gaskets compressed between the model ends and the tunnel sidewalls, thus preventing end leakage around the model.

Section lift, drag, and quarter-chord pitching moment were measured at Mach numbers ranging from 0.3 to approximately 0.9 and for 0°, 2°, and 4° angles of attack. The corresponding Reynolds numbers varied from about 0.50×10^6 to 1×10^6 for the wedge section, and from approximately 1×10^6 to 2×10^6 for the NACA 0012 section. The drag was determined from wake surveys with a movable rake of total-head tubes, and lift and pitching moment were found from reactions on the tunnel walls of the forces experienced by the airfoil.

TEST RESULTS

In figures 3, 4, and 5 are shown the variations with Mach number of the section lift, drag, and quarter-chord pitching-moment coefficients, respectively, for three angles of attack of the 12-percent-chord-thick wedge section and the NACA 0012 profile in its normal and reversed attitude. These characteristics have been corrected for the presence of the tunnel walls by the methods of reference 3. It is noted that in the region of the choking Mach number of the wind tunnel all curves on these figures are represented by a short dashed line. This practice has been adopted to indicate that data obtained in this speed range are not considered reliable. Likewise it is observed that none of the three sections display zero lift or pitching moment at 0° angle of attack. This is ascribed to three conditions: (1) the airfoils were not exactly symmetrical about their chord lines, (2) angle-of-attack settings were subject to some error, and (3) at small angles of attack the order of magnitude of the tare corrections was the same as that of the indicated forces. In the case of the pitching-moment coefficients for the wedge airfoil at approximately 0.30 Mach number, the error from this last source was considered sufficiently pronounced to warrant neglecting the experimental points and establishing the curves in this speed range by extrapolation from the higher Mach number data.

The variation with Mach number of lift-curve slope $dc_l/d\alpha$ at zero lift is given in figure 6 for the three sections investigated. Figure 7 shows one of the longitudinal-stability parameters, $\dfrac{dc_{m_{c/4}}}{dc_l}$ at zero lift, as a function of Mach number for the same airfoils. Figure 8, in which the variation of c_d with c_l is shown for the normal and reversed NACA 0012 sections at several Mach numbers, was obtained by cross-plotting figures 3 and 4. It should be pointed out, however, that the accuracy of the curves of figures 6, 7, and 8 is limited as sufficient experimental points were not available to establish the curves at intermediate lift and drag coefficients.

DISCUSSION

Lift Characteristics

It was pointed out in the Introduction that if the marked changes occurring in the aerodynamic characteristics of an airfoil section with the formation of shock waves are due in large part to a distortion of the effective profile in the region of and behind the waves, then the severity of these changes should be appreciably reduced by causing the shocks to occur at more rearward chordwise stations. Accordingly, it was reasoned that sections having extreme rearward peak negative pressure points might display certain properties at supercritical velocities superior to those evidenced by conventional sections. The soundness of this argument in the case of lift characteristics is substantiated in part by the data presented in figure 3. Here it is seen that for 2° angle of attack the normal NACA 0012 section suffers the familiar loss of lift at supercritical Mach numbers; whereas the reversed profile sustains relatively small decreases in lift, and the wedge section none at all. Essentially the same behavior is exhibited at 4° angle of attack; however, the wedge section now displays an abrupt increase in lift coefficient at about 0.775 Mach number. Since the half-wedge angle is slightly exceeded by the angle of incidence, this phenomenon may be the consequence of a Prandtl-Meyer expansion around the leading edge of the airfoil followed by a local supersonic region of high negative pressures over the upper surface. In support of this explanation are the findings of reference 4 which show that under similar conditions some such expansion does occur around the leading edge of an airfoil causing a marked increase in lift.

Because of its important influence on the stability and control characteristics of an airplane, a factor of particular interest to the aircraft designer is the lift-curve slope $dc_l/d\alpha$ of an airfoil section. The variation of this parameter at zero lift with Mach number is shown in figure 6 for the three sections. It is clear that both unconventional sections are superior to the NACA 0012 section in this respect at supercritical Mach numbers; however, as is pointed out in reference 5, marked increases in the lift-curve slope of the wing of an airplane may cause a pronounced decrease in the stability of the airplane. For this reason the reversed NACA 0012 has a more desirable variation of $dc_l/d\alpha$ with Mach number than the wedge section. The unusually high lift-curve slope of the reversed NACA 0012 section at the lower Mach numbers is apparently characteristic of such boat-tailed or bluntly rounded trailing-edge sections in the Reynolds number range of these tests. For example in reference 6, it was found that the lift-curve slope at zero lift of an elliptic cylinder is roughly doubled as the Reynolds number is reduced from 1.5×10^6 to 0.5×10^6.

Drag Characteristics

From figure 4 it is apparent that, as would be expected, the drag of the wedge section is excessively large relative to other types of airfoils, particularly at subcritical velocities. This is the case for all attitudes of the airfoil; however, the variation of drag coefficient with Mach number at 4° angle of attack is worthy of special attention for it is observed to deviate markedly from the corresponding variation at the lower angles of attack. In particular, the section drag coefficients of the wedge airfoil at 4° angle of attack are lower throughout the entire subcritical speed range than those at either 0° or 2° angle of attack; whereas at supercritical speeds the reverse is true, the drag coefficient at the larger angle of attack increasing precipitously with Mach number to values well above those for the smaller angles of attack. Since this drag rise ensues at a Mach number somewhat below that at which the previously observed abrupt increase in lift takes place, it is possibly associated with the formation of intense shock waves near the trailing edge of the section. On the other hand, no unusual variation takes place in the lift at subcritical speeds which would suggest that the relatively low subcritical drag is associated with an increased base pressure.

The reversed NACA 0012 section displays drag characteristics at supercritical Mach numbers which in certain instances are superior to those of the airfoil in its normal attitude. This is most apparent in figure 8 where it is observed that at high lift coefficients the polar curves of drag coefficient as a function of lift coefficient for the reversed section become superior to those for the normal sections at about 0.75 Mach number. At progressively higher Mach numbers this condition becomes manifest at lower lift coefficients. Thus it is evident that by employing boat tailing on a section having a sharp leading edge and an extreme rearward maximum thickness position, supercritical lift characteristics which are superior to those of a conventional section may be obtained at no over-all expense in supercritical drag, and without prohibitive sacrifice in subcritical drag characteristics. This is contrasted to the wedge section which, by virtue of its relatively poor drag characteristics at both subcritical and supercritical velocities, would require some method of reducing the wing drag (e.g., exhausting a jet from the trailing edge) if it were utilized as a wing section on a transonic aircraft or missile.

Pitching-Moment Characteristics

It is clear in figure 5 that the variation of pitching-moment coefficient with Mach number for the reversed NACA 0012 section is smaller than that for either the conventional or wedge profile. Likewise it is observed in figure 7 that the reversed NACA 0012 profile develops the smallest negative values of $\frac{dc_{m_{c/4}}}{dc_l}$ at high Mach numbers. From the standpoint of the effect of this parameter and the pitching-moment coefficient on the stability and control requirements of an airplane employing one of these sections at high subsonic velocities, it would then appear that the NACA 0012 profile in reversed attitude has the most favorable pitching-moment characteristics. It should be emphasized, however, that the stability and control characteristics (note reference 5) of an airplane operating at high subsonic speeds are determined primarily by the effects of compressibility on the lift developed by the wing, and that changes in the pitching-moment characteristics of the wing are generally of secondary importance.

CONCLUSIONS

Two airfoil sections with sharp leading edges and extreme rearward maximum thickness positions have been found from experiment to have the following subsonic aerodynamic properties at moderate angles of attack:

1. A 12-percent-chord-thick wedge section at fixed angles of attack less than the half-wedge angle displays a smooth variation of lift coefficient with Mach number to Mach numbers well above the critical, the lift coefficient increasing continuously throughout the entire Mach number range. The drag coefficient of this section is excessively large relative to conventional airfoils, particularly at subcritical Mach numbers.

2. A reversed NACA 0012 section, representing an airfoil with boat tailing aft of the extreme rearward maximum thickness position, displays lift and pitching-moment characteristics at supercritical Mach numbers which are generally superior to those evidenced by the section in its normal attitude. The drag of the reversed section is well below that of the wedge section at both subcritical and supercritical Mach numbers, and is the same order of magnitude as the drag of the normal NACA 0012 section at supercritical Mach numbers.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif.

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x (Percent C)	y (Percent C)
0	0
.5	----
1.25	1.894
2.5	2.615
5.0	3.555
7.5	4.200
10	4.683
15	5.345
20	5.737
25	5.941
30	6.002
40	5.803
50	5.294
60	4.563
70	3.664
80	2.623
90	1.448
95	.807
100	.126
L.E. RADIUS: 1.58 PERCENT C	

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TABLE I.- ORDINATES IN PERCENT CHORD FOR THE NACA 0012 AIRFOIL SECTION.

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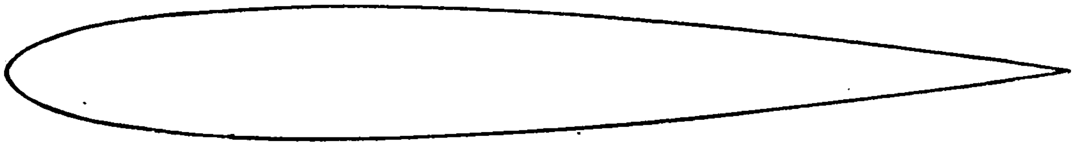
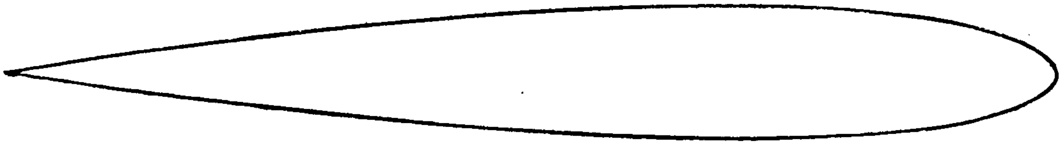
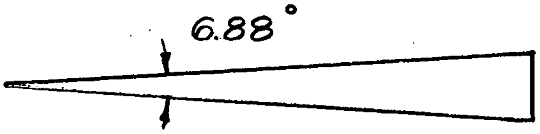


NACA 0012, NORMAL



NACA 0012, REVERSED



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12-PERCENT-CHORD-THICK WEDGE

FIGURE 1. COMPARISON OF AIRFOIL PROFILES

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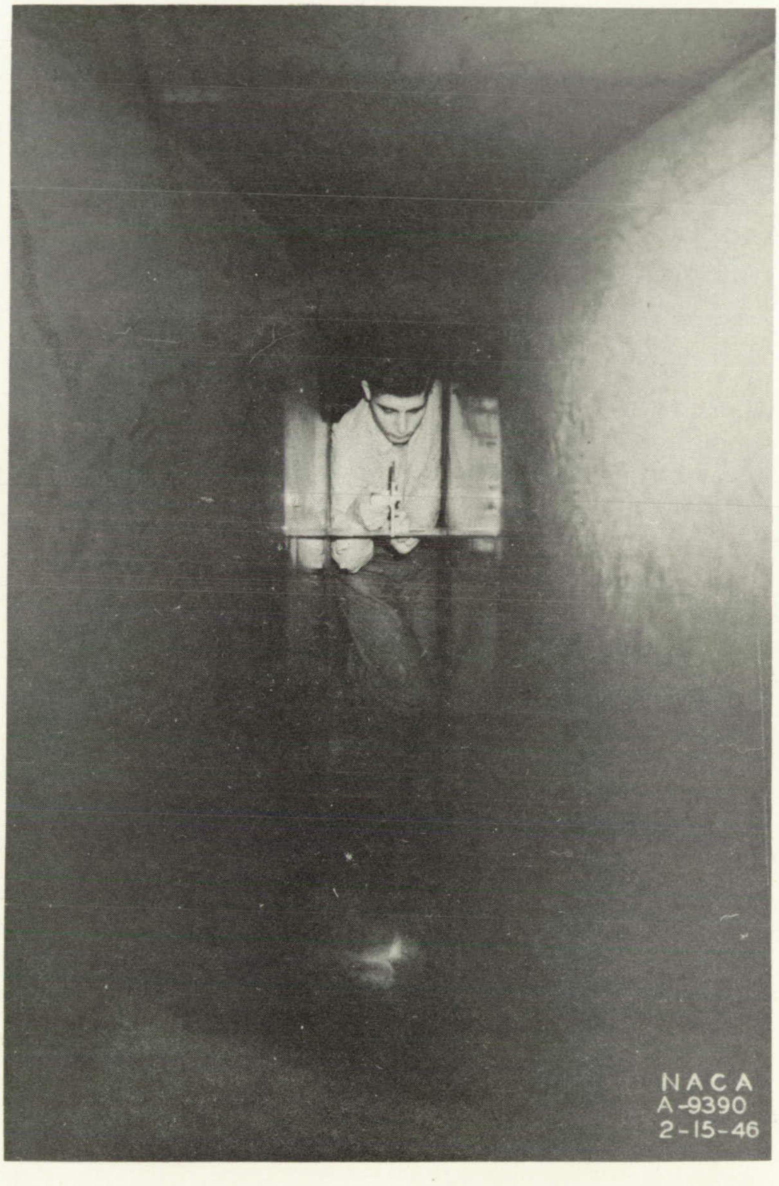

Figure 2.- Airfoil mounted in test section of the 1- by $3\frac{1}{2}$-foot high-speed wind tunnel.

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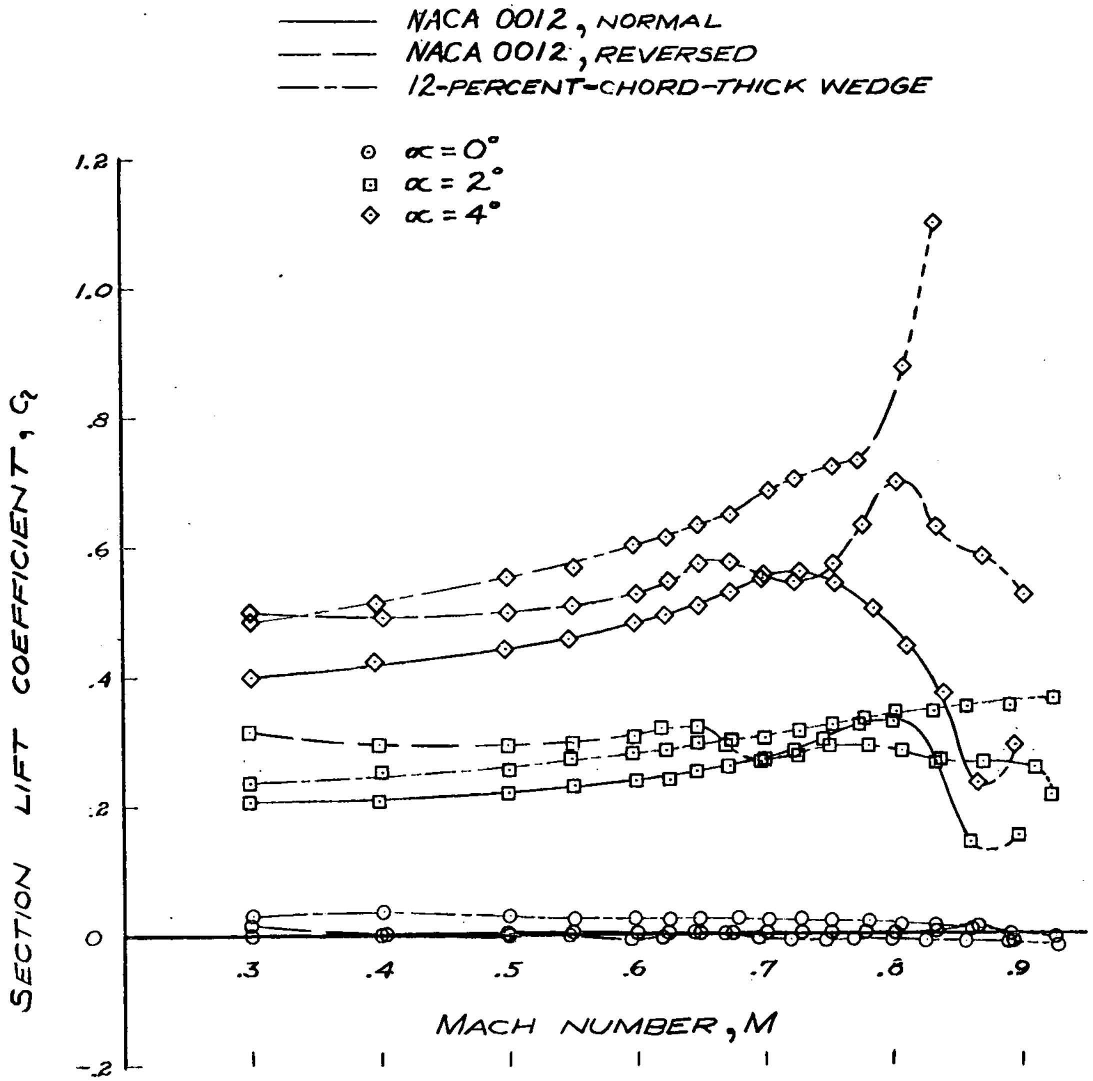

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FIGURE 3: VARIATION OF SECTION LIFT COEFFICIENT WITH MACH NUMBER FOR THREE ANGLES OF ATTACK OF THE REVERSED AND NORMAL NACA 0012 AIRFOILS AND THE 12-PERCENT-CHORD-THICK WEDGE AIRFOIL.

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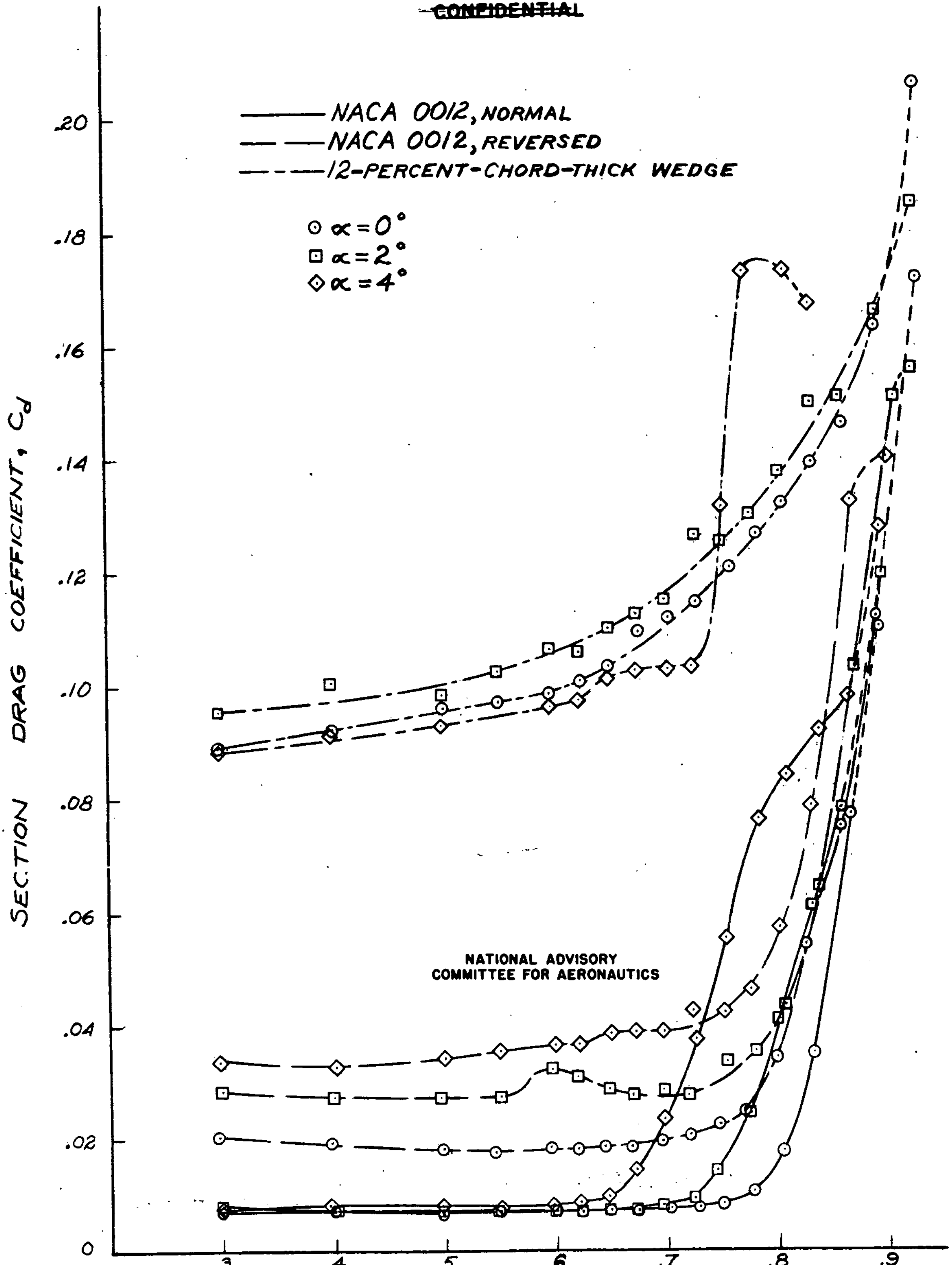

FIGURE 4.-VARIATION OF SECTION DRAG COEFFICIENT WITH MACH NUMBER FOR THREE ANGLES OF ATTACK OF THE REVERSED AND NORMAL NACA 0012 AND THE 12-PERCENT-CHORD-THICK WEDGE AIRFOILS.

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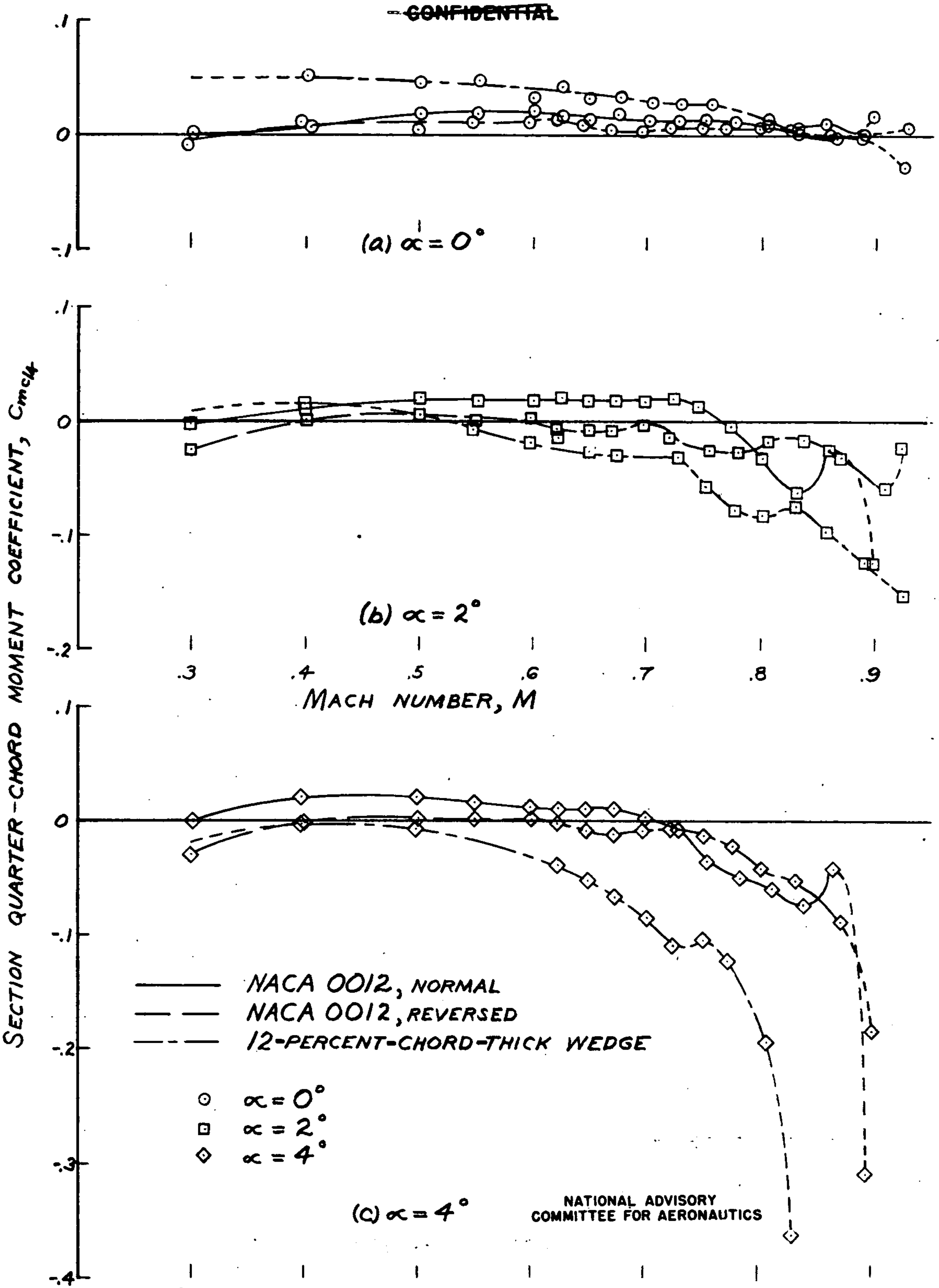

Figure 5.- Variation of section quarter-chord moment coefficient with Mach number for three angles of attack of the reversed and normal NACA 0012 airfoils and the 12-percent-chord-thick wedge airfoil.

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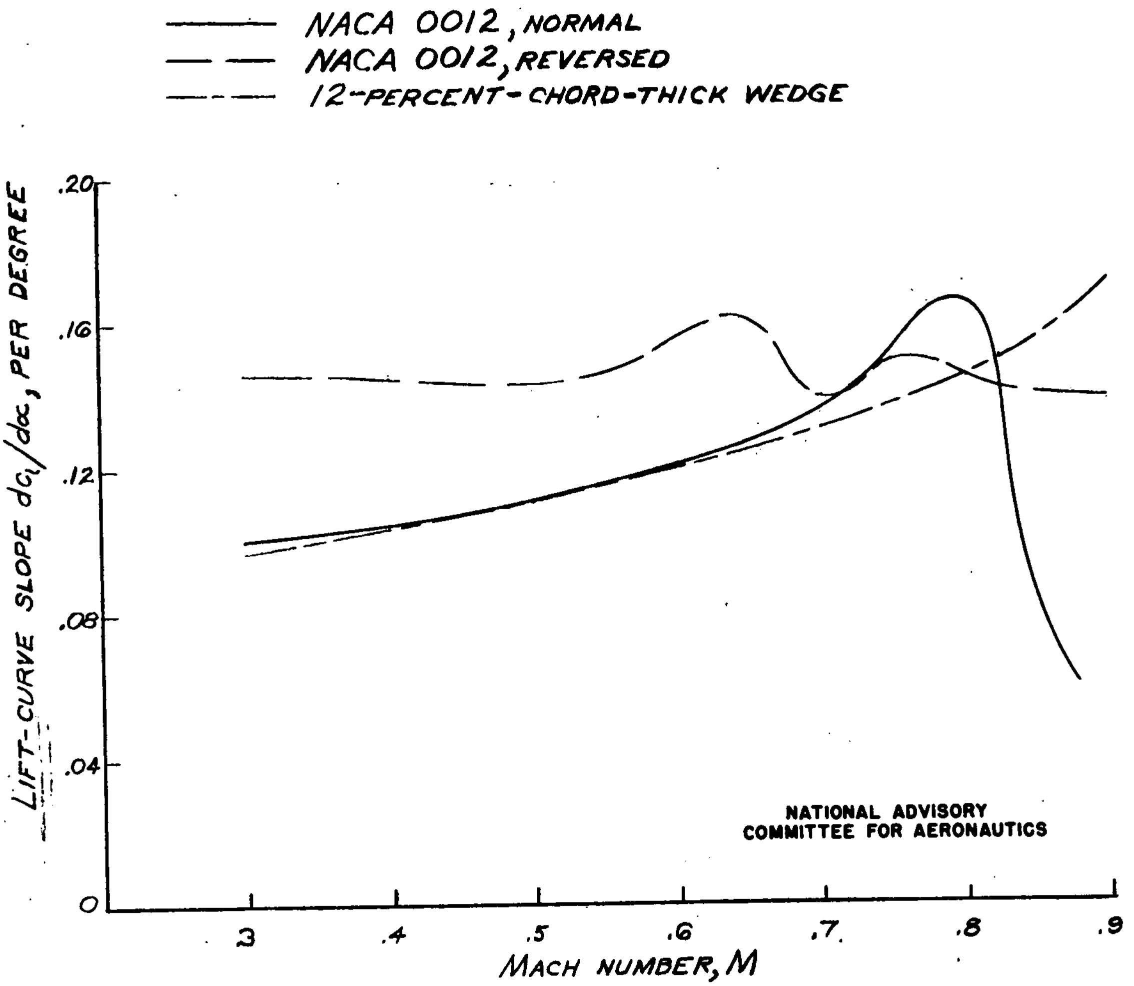

FIGURE 6.- VARIATION OF LIFT-CURVE SLOPE WITH MACH NUMBER AT ZERO SECTION LIFT COEFFICIENT FOR THE REVERSED AND NORMAL NACA 0012 AIRFOILS, AND THE 12-PERCENT-CHORD-THICK WEDGE AIRFOIL.

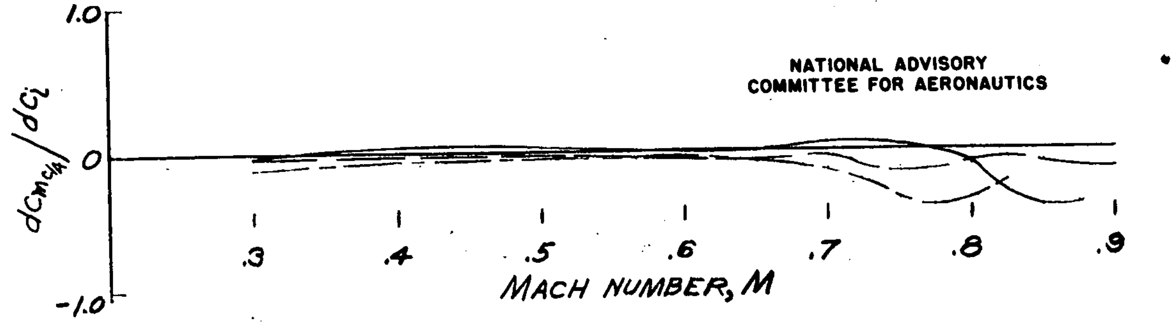

FIGURE 7.- VARIATION OF $dc_{m_{c/4}}/dc_l$ WITH MACH NUMBER AT ZERO SECTION LIFT COEFFICIENT FOR THE REVERSED AND NORMAL NACA 0012 AIRFOILS, AND THE 12-PERCENT-CHORD-THICK WEDGE AIRFOIL

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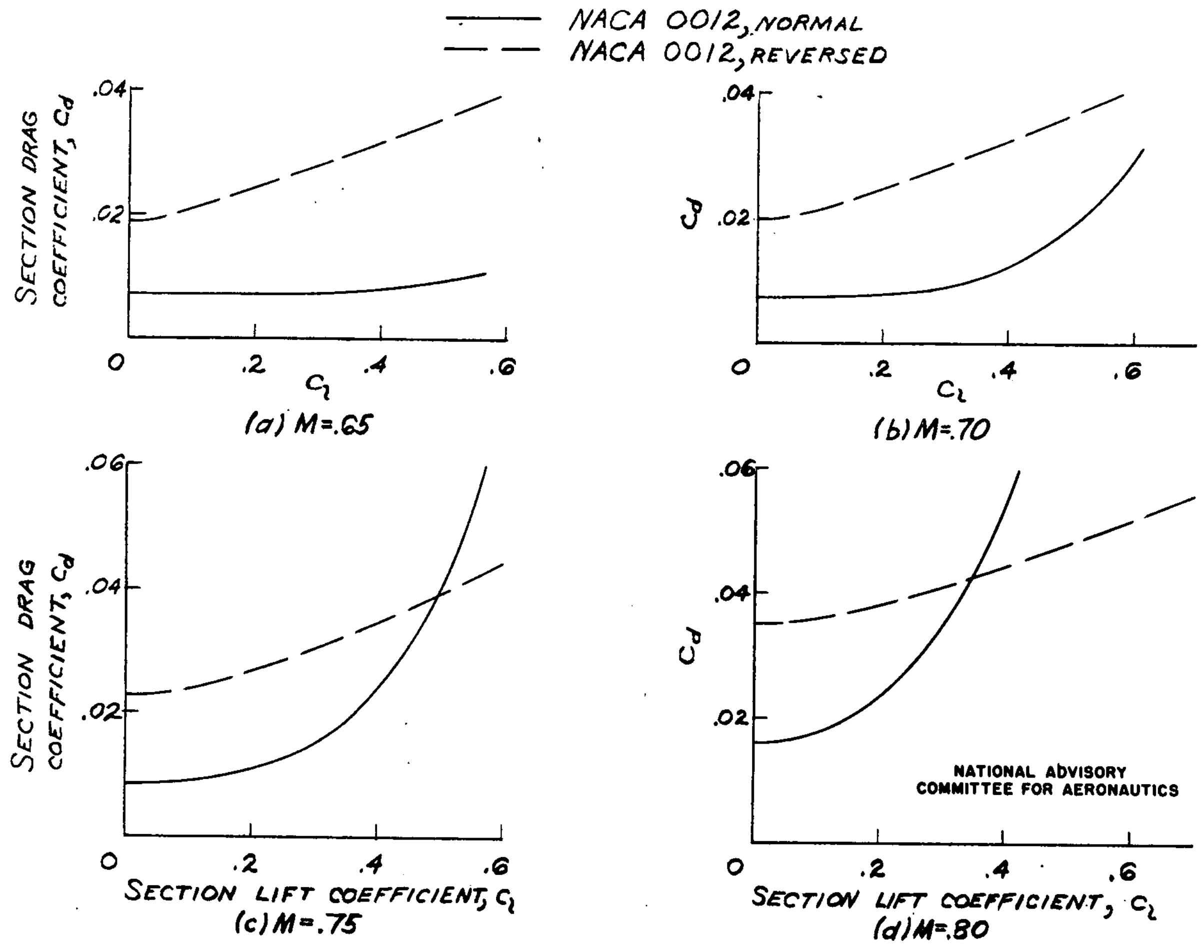

(a) M=.65

(b) M=.70

(c) M=.75

(d) M=.80

FIGURE 8.- COMPARISON AT SEVERAL MACH NUMBERS OF THE VARIATION IN SECTION DRAG COEFFICIENT WITH SECTION LIFT COEFFICIENT FOR THE REVERSED AND NORMAL NACA 0012 AIRFOILS.

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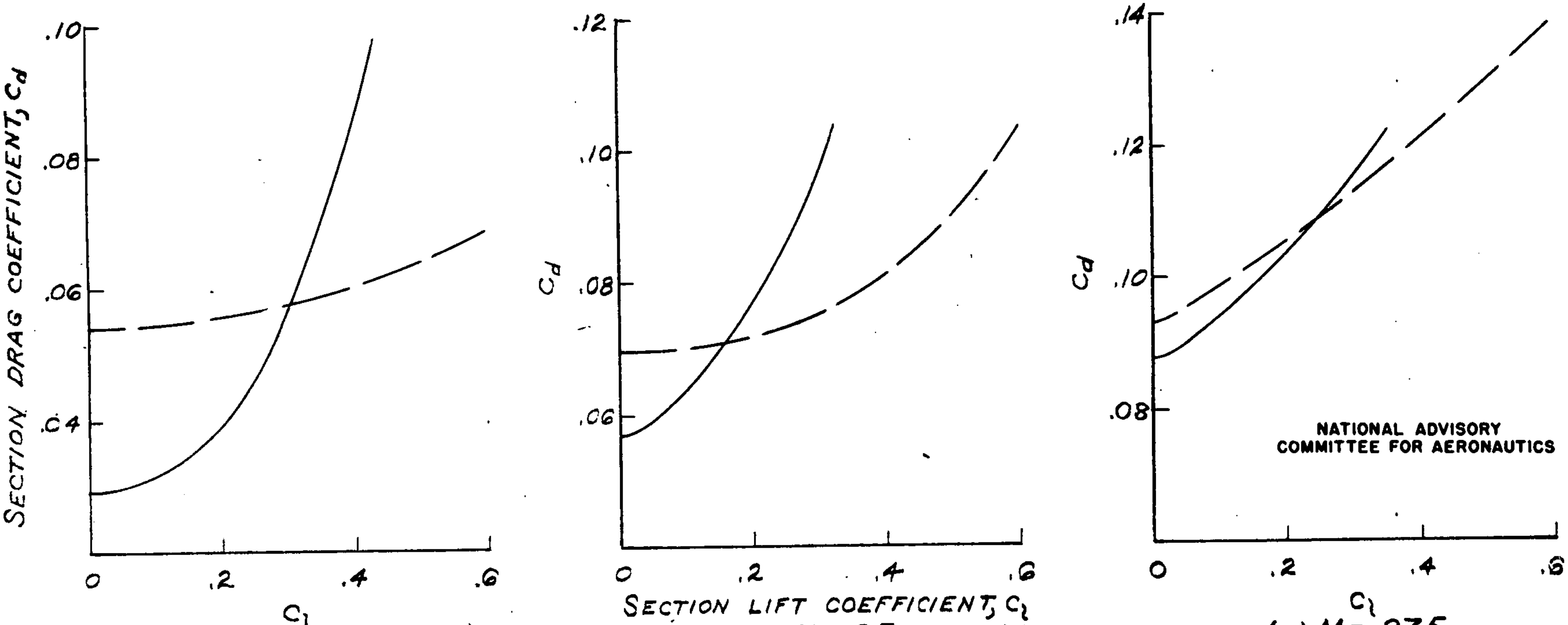

(e) $M = .825$

(f) $M = .85$

(g) $M = .875$

FIGURE 8.- CONCLUDED.

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