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LANDING CHARACTERISTICS OF HIGH-SPEED WINGS

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The wings of aircraft designed to fly at transonic Mach numbers are usually characterized by thin airfoil sections and, in most cases, low aspect ratio and considerable sweep. The poor maximum lift characteristics of such wings and the difficulties associated with the prediction of their characteristics have greatly complicated the problem of designing high-speed aircraft to land at speeds within the capabilities even of highly skilled pilots. Considerable effort is therefore being directed toward the improvement of the maximum lift characteristics of wings suitable for high-speed applications. The present paper first reviews the development of high-lift devices in two dimensions; second, surveys the available large scale data of the characteristics of three-dimensional wings; and third, indicates briefly the correlation between the characteristics of swept and unswept wings.

The high-lift devices investigated are in the following two classes: those which are applied to the trailing edge of the airfoil and those which are applied to the leading edge of the airfoil. For airfoils which are only moderately thin, a section maximum lift sufficiently high often can be obtained by the use of a suitable trailing-edge device alone. For thin airfoils or for airfoils having sharp leading edges, however, the large peak negative pressures near the leading edge and the subsequent highly adverse pressure gradient cause laminar separation near the leading edge. Accordingly, it is necessary to use a leading-edge device designed to lower this peak and reduce the adverse pressure gradient in order to obtain large increases in the section maximum lift coefficient with these airfoil sections.

Double slotted flaps have long been known to provide about the largest gains in lift of all types of trailing-edge flaps. In figure 1 are shown results obtained with the NACA 65-210 airfoil equipped with such a flap and also with single slotted and with split flaps. (See reference 1.) The results herein shown and those for figures 2 to 4 have been obtained with a two-dimensional setup at a Reynolds number of 6×10^6 , which corresponds approximately to that for an airplane with a 6-foot-chord wing landing at 100 miles per hour. The relative merit of the types of flap is clearly shown. The highest maximum lift coefficient obtained was about 2.80 with the double slotted flap. The values shown for the two types of slotted flap are for the optimum locations of flap and vane and, if such flaps were applied to a three-dimensional swept wing, some further experimentation might be required to insure that the optimum location remains the same.

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The effects of section thickness ratio and the location of minimum pressure at the design lift coefficient have been investigated for a number of NACA 6-series airfoils with double slotted flaps (reference 2). In figure 2 the left side shows the variation of maximum lift coefficient with thickness ratio for airfoils with a design lift coefficient of 0.2. The variation is seen to be approximately linear for both smooth and rough airfoils over the test range. On the right side data indicating the effect of minimum pressure location at the design lift coefficient are shown for 10-percent-thick airfoils with a design lift coefficient of 0.2. The maximum lift coefficient is seen to decrease linearly as the position of minimum pressure moves rearward. (See curve for smooth airfoils in fig. 2.) For rough airfoils the minimum-pressure location is unimportant.

It should be pointed out herein that these high maximum lift coefficients are also accompanied by high negative pressure peaks at the leading edge. Inasmuch as high landing speeds are being considered for many high-speed aircraft, it is altogether possible that maximum lift coefficients different from those shown might be obtained because of Mach number effects (reference 3).

The effectiveness of leading-edge devices in increasing the maximum lift is shown in figure 3. These results were obtained with a NACA 641-012 airfoil section equipped with a split flap, with a nose flap of the type that is hinged out from the lower surface, and with a nose flap extending tangentially from the upper surface at the leading edge (reference 4). It is seen that the maximum effectiveness of the nose flaps is only realized when they are used in conjunction with the trailing-edge flap. Also, the tangential type of flap is seen to give somewhat better results than the lower surface type.

The leading-edge devices discussed herein are not the only ones that could be made effective. Any leading-edge device which tends to reduce the negative pressure peak and the adverse pressure gradient at the leading edge should be effective in increasing the maximum lift of a thin airfoil.

An indication of what can be accomplished on thin biconvex airfoils with another such device is shown in figure 4. A droop nose of 0.15c and a plain trailing-edge flap of 0.20c have been investigated on a biconvex airfoil 6-percent thick. (See reference 5.) The highest maximum lift coefficient of nearly 2.00 was obtained with the leading and trailing flaps at their optimum deflections of 30° and 60° , respectively. Substantially the same results were obtained with the 10-percent-thick biconvex section and with a 6-percent-thick NACA 64-series section between Reynolds numbers of 3×10^6 and 9×10^6 . Recent tests of an NACA 63-006 airfoil indicate a favorable scale effect between Reynolds numbers of 9×10^6 and 25×10^6 ; whereas over the same range the biconvex sections show no scale effect. These results indicate that at 6-percent thickness as well as at about 9-to

10-percent thickness the conventional section may have some slight advantage from a maximum lift standpoint.

The discussion has thus far dealt only with two-dimensional results. At present no adequate method has been developed for predicting the high-angle-of-attack characteristics of swept wings. Such studies as the ones by Sivells and Neely (reference 6) and Sivells (reference 7) in which nonlinear section data have been applied to the calculation of the characteristics of unswept wings and those described in references 8 and 9 in which lifting-line and lifting-surface theories have been applied to the calculation of swept-wing characteristics at low and moderate angles of attack together with the section data form a valuable background upon which to base conjectures as to the probable effect of various modifications to swept wings. It is necessary however to rely on large scale experiment for the final quantitative evaluation of the characteristics of wings having any considerable amount of sweep.

In answer to the need for an organization of the data pertaining to the maximum lift characteristics of swept wings Sweberg and Lange have summarized the existing data (reference 10). The principal emphasis in this report was on the effects of Reynolds number and the importance of obtaining swept-wing results at the highest possible scale was established. Since the investigation of reference 10 was made, a number of large Reynolds number investigations of the high-lift-range characteristics of wings for high-speed aircraft have been completed in the Langley 19-foot pressure tunnel, the Langley full-scale tunnel and in the Ames 40- by 80-foot tunnel. These investigations have been closely correlated but the configurations have not in general been sufficiently systematized to allow the isolation of the effects of sweep angle from those of aspect ratio and taper ratio. It is possible at this time, however, to draw a number of useful conclusions from these results.

The information of the characteristics of three-dimensional wings presented in figures 5 to 14 is only a very brief summary of the total of the information that is available. The detailed test results and analysis are contained in references 11 to 22 and a few other prospective reports.

The first effect to be discussed is that of Reynolds number. Figure 5 shows the maximum-lift-coefficient variation with Reynolds number obtained with four swept wings. Generally speaking the effects are small. The most significant result is a small increase in the maximum lift coefficient between Reynolds numbers of 4.2×10^6 and 5.5×10^6 for the wing having 42° sweep and NACA 64₁-112 airfoil sections. This increase is rather unimportant in itself but is accompanied by significant improvements in the longitudinal stability.

Adding standard roughness to the wing as shown by the dashed curve decreases the lift coefficient over the entire range and eliminates the favorable scale effect. The same wing with biconvex airfoil sections shows no scale effect within the test range just as was the case for the two-dimensional airfoil results.

The wing with 48° sweep had lower scale effect even than the 42° swept wing and the changes still occur below a Reynolds number of 5×10^6 . All of the results shown hereinafter were obtained above this critical range.

Inasmuch as the experimental information obtained herein has been obtained both with and without fuselage, it is desirable first to examine the effect of the fuselage on the maximum lift characteristics so that both types of results can be used later. Figure 6 shows the results of a series of tests made with a 42° swept wing of aspect ratio 4 with a fuselage in the high-wing, the midwing, and the low-wing locations. The fuselage had a relatively small effect on the maximum lift. The drag of the fuselage likewise is an unimportant factor in the high-lift-coefficient range. The vertical location of the wing on the fuselage made no difference for the plain-wing results and in the high-lift-coefficient range made no difference with the flapped wing. The same conclusions do not, however, apply to the longitudinal stability characteristics at the stall. In this connection a few stability effects, where they are of first-order importance, will be pointed out during the discussion of the results. However, the stability of swept wings in the low-speed ranges is the subject of a paper to be presented at this conference by Mr. Donlan entitled "Current Status of Longitudinal Stability."

The next variable discussed is that of airfoil section. Results are shown in figure 7 for three wings - one with 42° sweep, one with 48° sweep, and a 60° delta wing. Airfoils of conventional section and shape are represented by the NACA 641-112 airfoil sections (perpendicular to quarter-chord line) in the first two cases and by the NACA 0015-64 airfoil (root section) in the third case. The very thin sections are represented by biconvex sections 10-percent thick and in the case of the delta wing are also represented by adding a sharp leading edge to promote separation. For the 42° swept wing, representative of the moderate sweep case, it is seen that the airfoil section makes a large difference in the maximum lift characteristics. The decrease in maximum lift resulting from the use of the biconvex or thin sections is, likewise, accompanied by extremely undesirable changes in the longitudinal stability. In the higher sweep range represented by the 48° swept wing the effects of airfoil section are much less marked, and in the extremely high sweep range represented by the delta wing it would appear that sharp-leading-edge airfoil sections may have some slight advantages over the conventional sections although

it is suspected that more favorable results might have been obtained by the use of a thinner conventional section.

Throughout the investigations summarized herein, split flaps or plain flaps of about 20 percent chord have been used with the wings to give an index of the lift producing capacity of the wing with trailing-edge high-lift devices in general.

The results obtained by applying semispan split flaps to the 42° and the 48° swept wings with NACA 64-series airfoil sections are shown in figure 8. With the 42° swept wing a lift increment of 0.20 was obtained which was about two-thirds of the lift increment due to these flaps below the angle for maximum lift. The maximum lift increment for the 48° swept wing was considerably smaller although the increment in lift below the stall was about the same as for the 42° swept wing with due consideration taken of the differences in sweep of the two wings. It would appear from these results that the effectiveness of flaps in increasing the maximum lift falls off rapidly as the sweep increases. This is in accord with the data obtained by McCormack and Stevens in the Ames 40- by 80-foot tunnel (reference 11). These results indicate that at a sweep angle of about 60° flaps will be ineffective in increasing the maximum lift.

Also, shown in this figure are key letters designating the longitudinal stability characteristics at the stall for each configuration. These letters, G for good, M for marginal, and P for poor, will be used in figures 8 to 11. A curve of pitching-moment coefficient against lift coefficient which has no abrupt slope changes in a positive direction and which either breaks in a negative direction or does not change at the stall is considered to be good. A pitching-moment curve which has sharp changes in slope in an unstable (positive) direction below the stall or which breaks in a positive direction at the stall is considered poor. It must be realized, of course, that the tail geometry and location will also affect the stability of the final airplane. All of the wings shown in figure 8 had poor longitudinal stability at the stall, arising from tip stalling which caused unstable breaks.

The biconvex wing results are shown in figure 9. For the case of 0° sweep the increment obtained from the trailing-edge flap is very large. But as the sweep is increased the lift increment becomes progressively smaller even though reasonably large increments in lift coefficient are produced below the stall. The failure of the flaps to give substantial increases in maximum lift coefficient is a consequence of early tip stall, and it has become quite evident that in order to produce satisfactory lift characteristics on these wings it will be necessary to provide the wing tip with a leading-edge stall

control aid or high-lift device. An additional phenomenon shown herein is the beneficial effect of sweep on the maximum lift coefficient of these thin sections. For the unswept case the maximum lift coefficient of 0.58 measured for the basic wing is below the section value of about 0.7 by about the amount that would be calculated from standard methods of applying section data to three-dimensional wings. As the sweep increases, however, the maximum lift of the wing increases and exceeds the section value. This result is associated with a strong spanwise flow at the leading edge of the wing which enables the flow over the bubble of separation at the leading edge to reestablish itself at higher angles of attack than for the two-dimensional case (references 12 and 13).

The longitudinal stability characteristics of the unswept wing and of the delta wing are good. For the swept wings the pitching-moment curves have a highly unstable slope as maximum lift is approached and even though the eventual break is in a stable direction, the characteristics below the stall are sufficiently undesirable to warrant the poor classification.

The results obtained with leading-edge high-lift devices installed on these four wings are shown in figure 10. Two kinds of flap have been used - the droop nose and the extended type with a rounded leading edge (fig. 10). Drooping the nose of the rectangular wing increased the maximum lift coefficient by about 0.30; adding the extended type of nose flap gives an additional increment of almost 0.30 since, in this case, a rounded leading edge is provided for the airfoil as well as an increase in the forward camber. These improvements are additive to the increments that can be obtained by the use of trailing-edge flaps as shown by the top curve. A similar picture is presented for the 42° swept wing, and it appears that once the tip stalling is controlled by the use of the leading-edge device relatively large increases in the maximum lift can be obtained. The two flapped arrangements shown (fig. 10) are for partial-span leading-edge flaps. These arrangements are shown in preference to arrangements having a greater spanwise extent of the leading-edge flaps because they have favorable longitudinal stability characteristics, whereas some others which give slightly greater maximum lifts have unfavorable pitching-moment characteristics. On the 48° swept wing the leading-edge droop was also effective, but as noted in figure 9 with the plain trailing-edge flaps the greatest maximum lift coefficient attainable at this sweep was considerably smaller. On the delta wing a small increment in maximum lift was obtained by deflecting the small leading-edge droop indicated and an additional small increase in maximum lift coefficient was obtained by deflecting the trailing-edge flap. The increment in lift obtained below the stall for this arrangement may perhaps be useful for maintaining a more satisfactory attitude during the landing approach. For the 42° and 48° swept wings which had poor longitudinal stability at the stall

for the basic wing deflecting the nose flap had a distinctly beneficial effect. This is particularly true of the 42° swept-wing case in which the addition of the optimum configuration of nose flap provides excellent longitudinal characteristics.

The data from this figure show that the use of an optimum leading-edge high-lift device on any wing having a thin or sharp leading-edge airfoil section will improve significantly both its maximum lift characteristics and its longitudinal stability at the stall.

Similar results for the wings of NACA 64-series airfoil sections are shown in figure 11. The addition of the nose flap to the 42° swept wing increased the maximum lift coefficient about 0.20 and made the wing stable at the stall. (See fig. 11.) This lift increment is somewhat lower than that obtained with the biconvex wing principally because the maximum lift of the basic wing is much higher. The addition of split flaps gave a further increase in $C_{L_{max}}$ to 1.58, still maintaining stable longitudinal characteristics at the stall. This maximum lift value was only slightly higher than the one shown in figure 10 for the biconvex wing.

The addition of nose and split flaps to the 43° swept wing gave smaller increases than for the 42° swept wing as was noted earlier for split flaps and, moreover, the wing still remained unstable at the stall. On the extreme right in figure 11 are shown results that were obtained by the use of boundary-layer suction applied at the 0.20c, 0.40c, and 0.70c locations on the 48° swept wing with nose flaps and with both nose and split flaps. The lift increments obtained were relatively small but the stability was greatly improved. The maximum lift coefficient of almost 1.25 obtained for this configuration is the highest thus far obtained with this wing plan form.

This paper has, thus far, discussed only the changes in the maximum lift produced by these high-lift devices. If power-off landings are to be expected of the airplane or if the thrust available during the landing phase is limited, the drag near maximum lift is of great importance inasmuch as it determines the vertical speed during the landing approach. It has been found that a sinking speed in excess of about 25 to 30 feet per second will probably lead to erratic landings even on the part of highly skilled pilots (reference 23). This fact seems to be relatively independent of the forward speed at which the landing is made. In figure 12 some lift-drag polar curves for various configurations of the 42° swept wing have been shown. Superimposed upon these curves are contours of the forward speed and the vertical speed for a power-off glide at a wing loading of 40 pounds per square foot. In order to show the significance of these forward speed-sinking speed charts, a point is indicated that represents the forward speed and

sinking speed for a reference airplane for which flight test data were available (reference 23). This airplane was of the two-engine medium-bomber class and was only landed power off in emergency.

For the most favorable configurations the landing conditions appear to be no worse than those for the reference airplane. Certain changes from these conditions, however, such as increasing the wing loading, increasing the sweep, and increasing the roughness, make this picture appear less favorable. The effect of the high drag due to roughness on the basic wing, for example, is shown by the dashed curve. Not only is the maximum lift decreased but the sinking speed in the high-lift range is more than doubled. Split flaps, as pointed out earlier, give some increase in maximum lift, in this case enough to reduce the landing speed by 10 miles per hour. This is partially offset by an increase of about 5 feet per second in the sinking speed. Leading-edge flaps alone on account of their high drag at the higher lift do not appear to have any particular advantages. The combination of leading- and trailing-edge flaps, however, is quite effective in decreasing the landing speed provided that the increases in the rate of descent or alternately the amount of power required for landing can be tolerated.

The corresponding results for the biconvex wing (fig. 13) show that in general the higher drag of the biconvex sections will cause their rates of descent to be higher. In this case minor improvements only result from the deflection of split flaps alone; whereas deflecting the nose flaps greatly decreases the drag with some increase in the maximum lift. Deflecting the trailing-edge flaps in combination with the leading-edge flaps allows speeds almost as low as with conventional sections but with somewhat higher rates of descent. On account of the generally higher rates of descent shown for these sections, power-off landings will be distinctly more hazardous than for the NACA 64-series section wing in figure 12.

The problem of calculating the maximum lift of swept wings, as pointed out earlier, has thus far defied theoretical efforts. It is possible, however, to correlate some of the data that have been obtained on swept wings to get a guide in estimating the maximum lift. In figure 14 experimental values of maximum lift divided by the maximum lift of the wing rotated back to zero sweep have been plotted against sweep angle Λ . A plot of $\cos^2\Lambda$ is also shown for comparison. The data of McCormack and Stevens from the Ames 40- by 80-foot tunnel and of Anderson from some tests in the old Langley variable density tunnel (references 11 and 24) in which the sweep of the wing was varied systematically were particularly useful in forming this curve. Experimental values of $C_{L_{max}}$ for the 0° sweep conditions of the 42° swept

wing tested in the Langley 19-foot pressure tunnel and of the 48° swept wing tested in the Langley full-scale tunnel were not available, and hence were calculated by the method of Sivells and Neely (reference 6) which has been shown to give excellent agreement for unflapped unswept wings. The correlation curve shows a gradual decrease in maximum lift that is only about one-half that indicated by the simple $\cos^2\Lambda$ approximation.



In conclusion the results of the investigations of maximum lift characteristics discussed herein can be summarized as follows:

Maximum lift coefficients of the order of 1.3 to 1.6, depending upon the angle of sweep, have been obtained with the best combinations of split flaps and leading-edge devices investigated. The importance of the airfoil section has been shown to decrease as the sweep increases and as the thickness of the airfoil decreases, the characteristics of all sections tending to approach the characteristics of flat plates at high sweeps and low-aspect ratios. The drag is shown to be of great importance in determining the power-off rate of descent or alternately the amount of power required during the landing. Leading-edge high-lift devices of the types investigated are extremely effective in reducing the drag and improving the stability in the high-lift range for wings having biconvex or other thin airfoil sections and would thus be desirable for wings having these sections.

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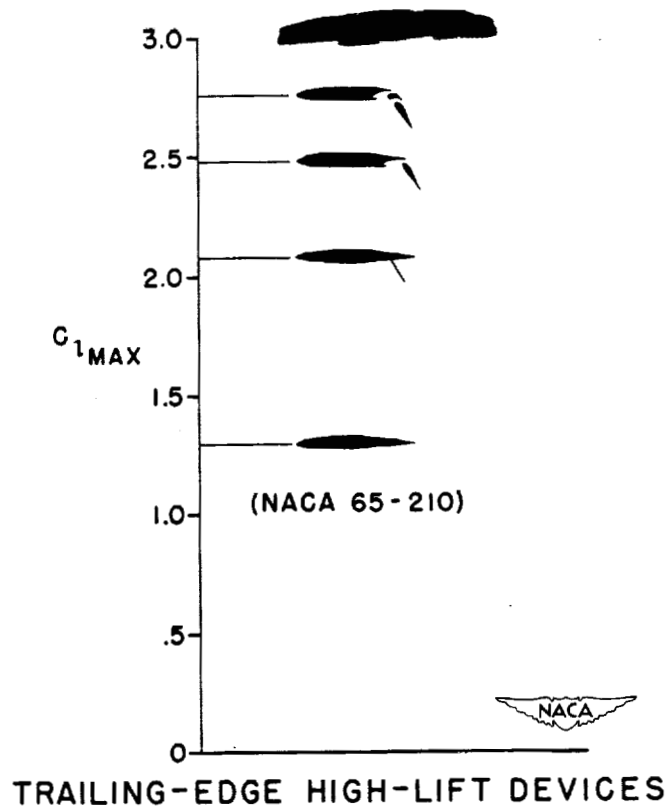
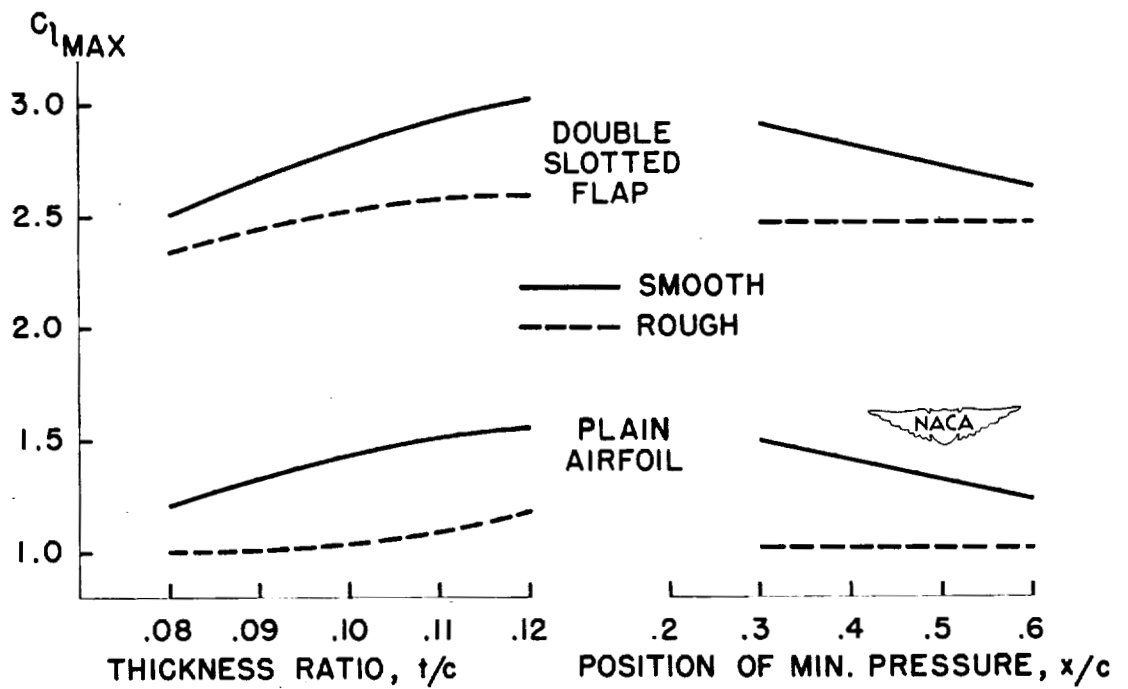


Figure 1.



EFFECTS OF AIRFOIL SHAPE ON MAXIMUM LIFT

Figure 2.

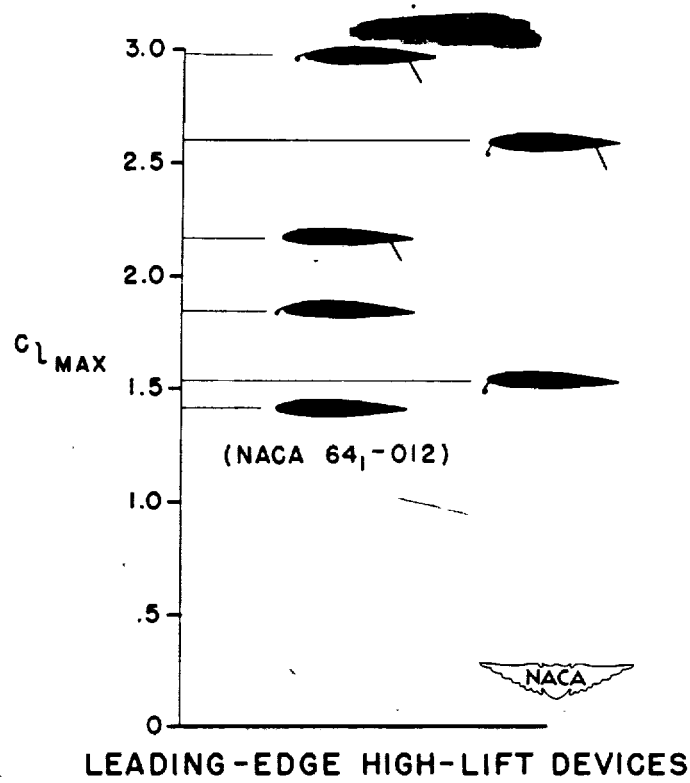
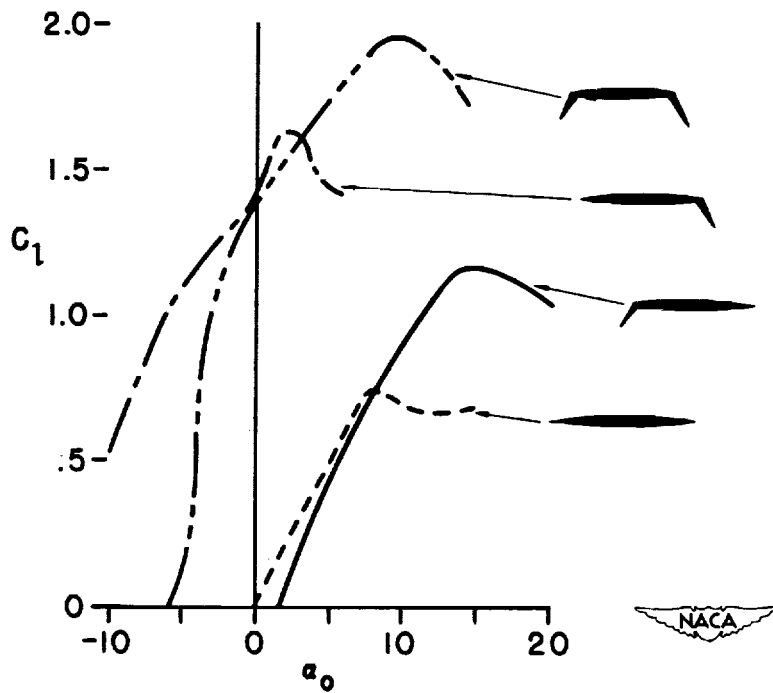


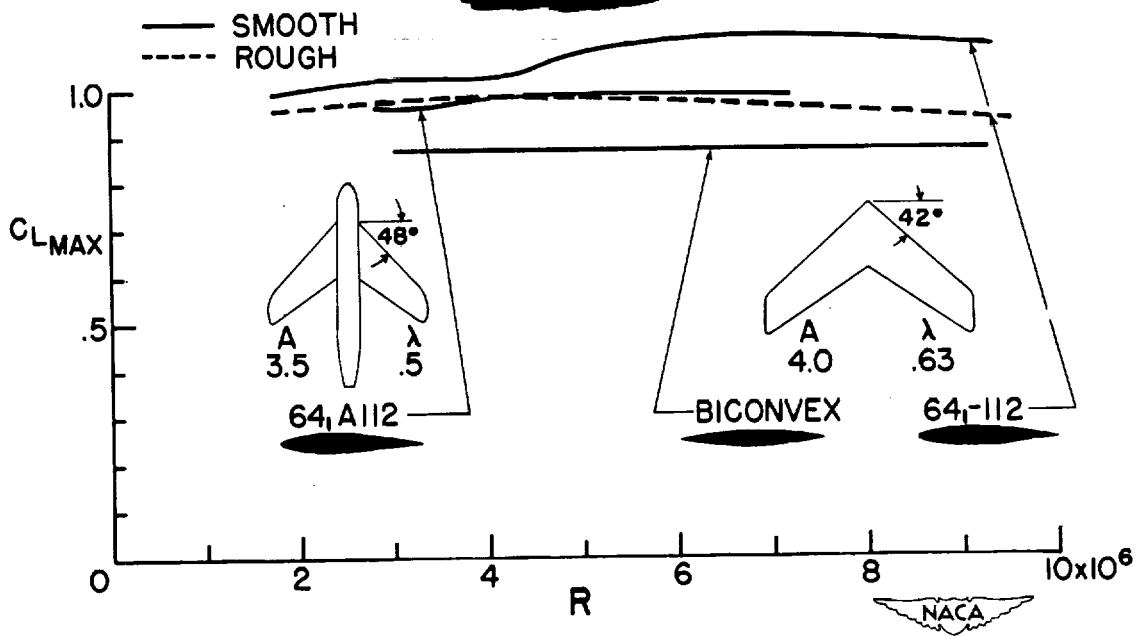
Figure 3.



HIGH-LIFT DEVICES ON A 6% THICK BICONVEX AIRFOIL

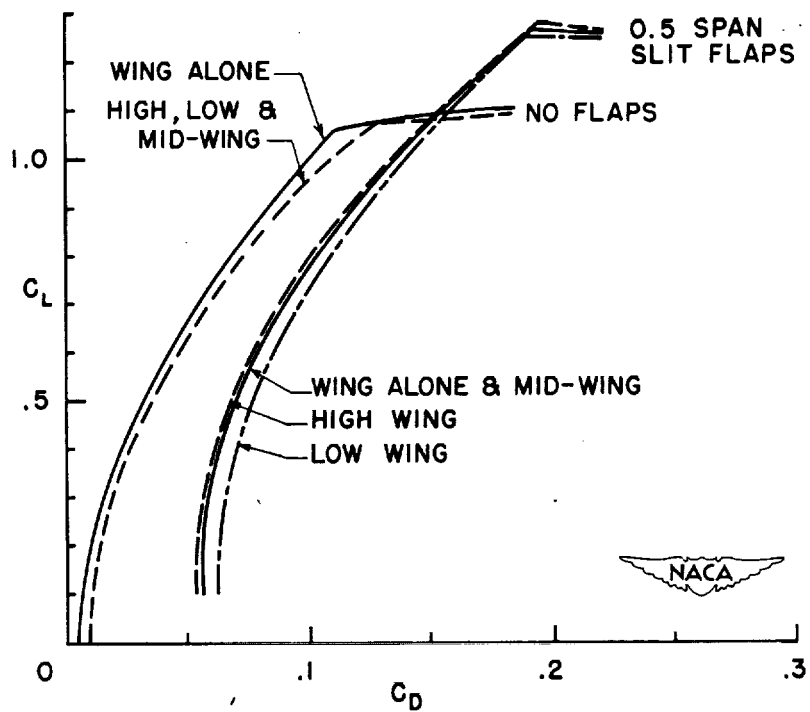
Figure 4.

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SCALE EFFECT ON MAXIMUM LIFT

Figure 5.



EFFECT OF FUSELAGE ON MAXIMUM LIFT

Figure 6.

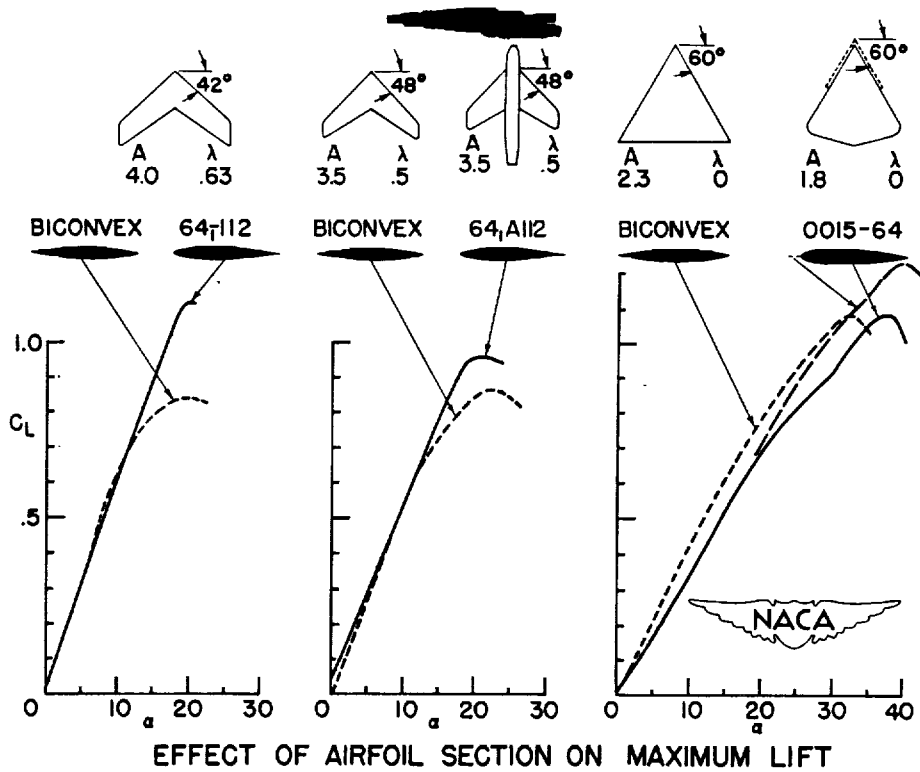


Figure 7.

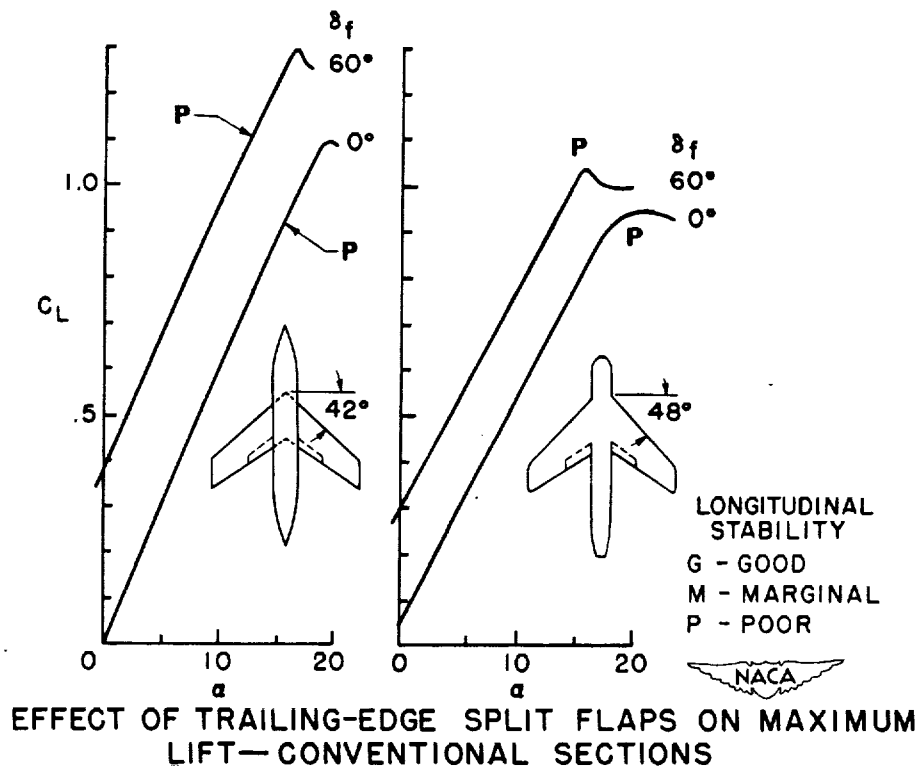


Figure 8.

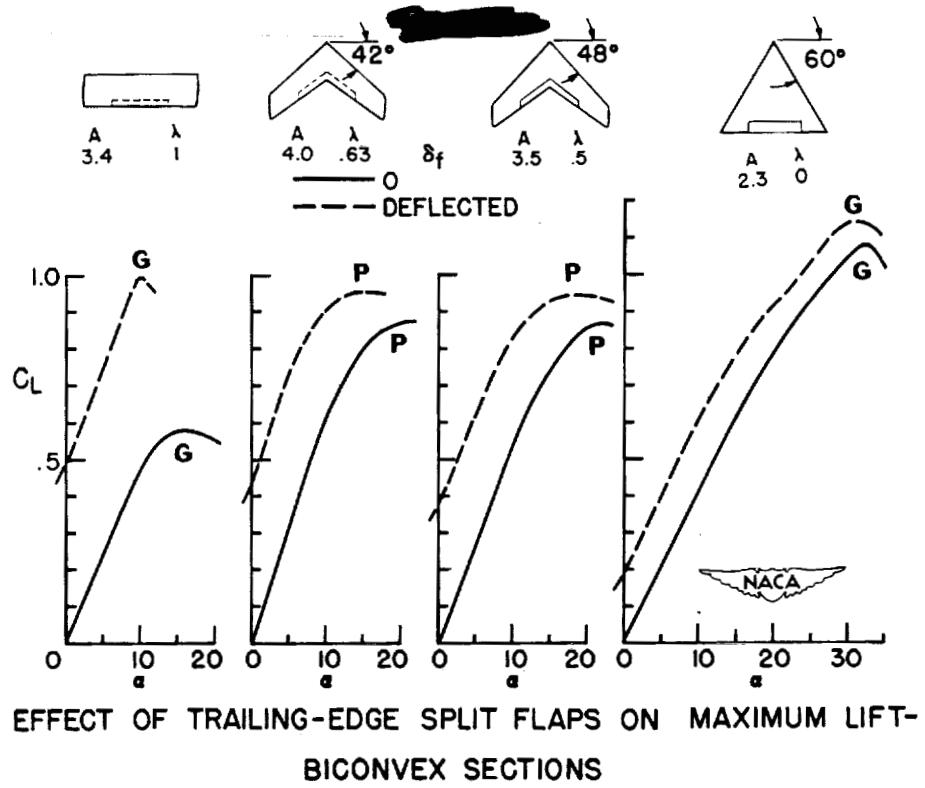


Figure 9.

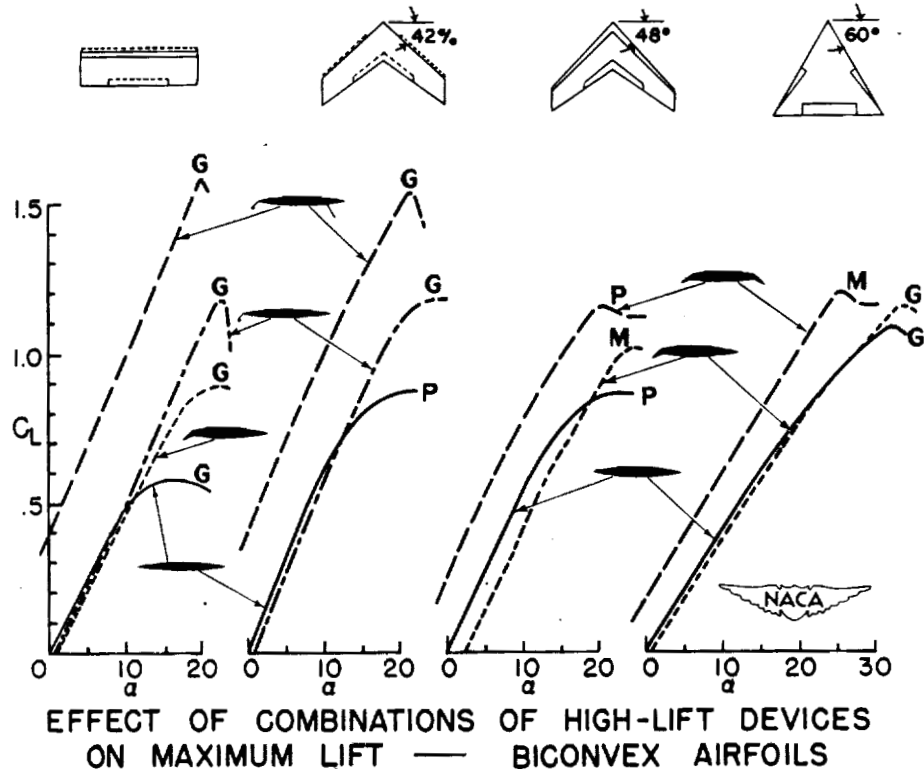


Figure 10.

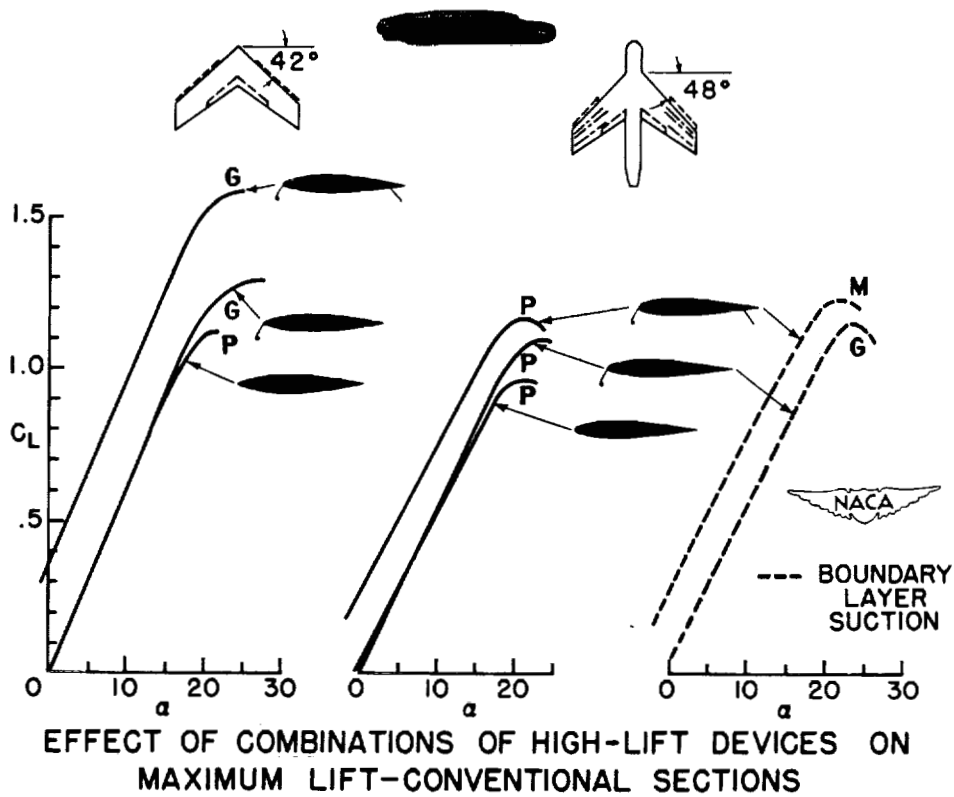
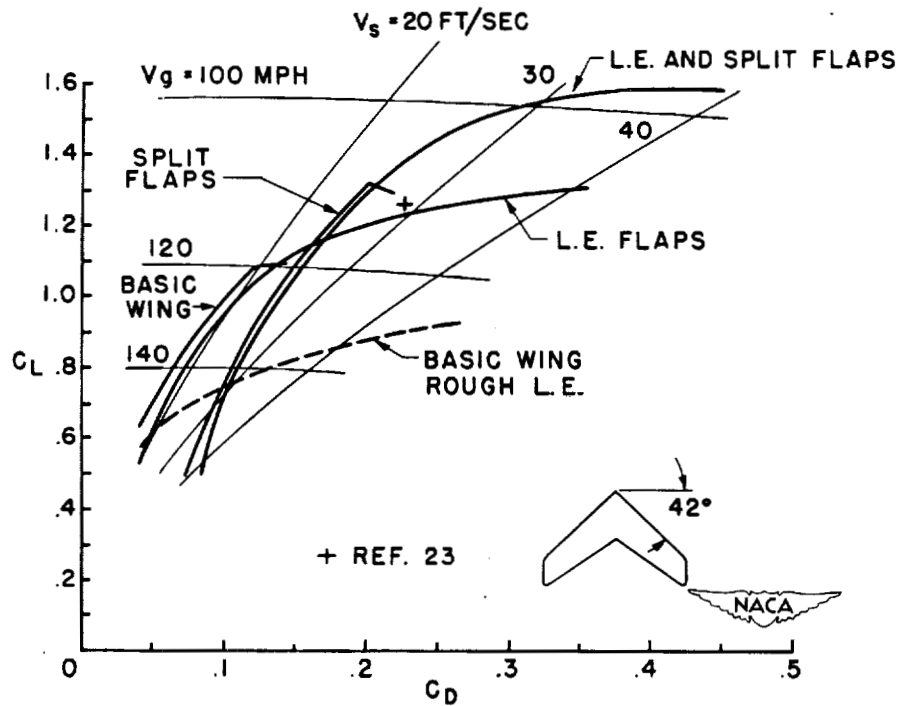


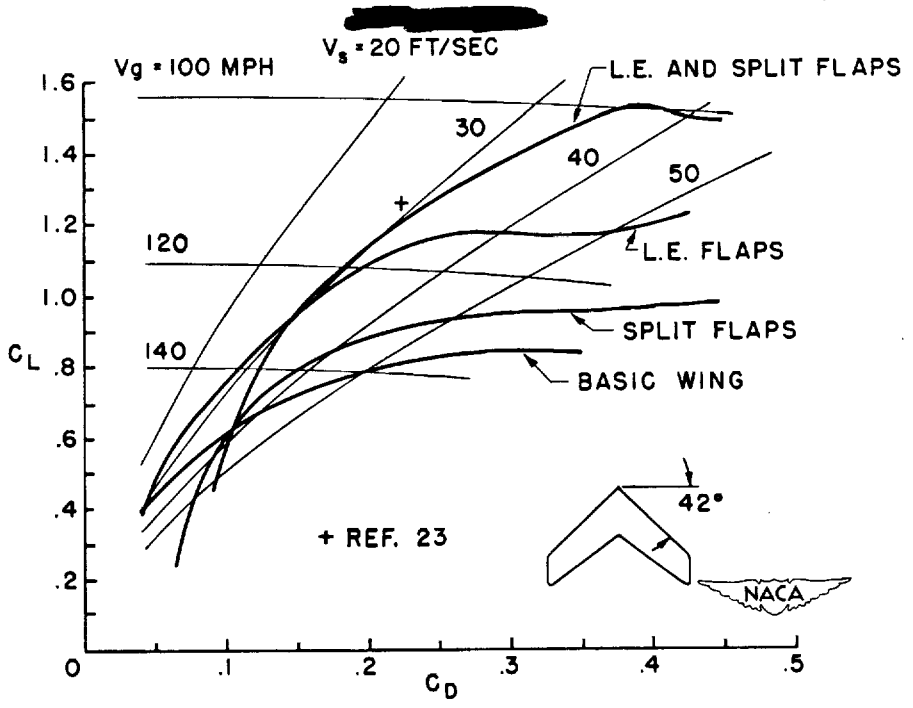
Figure 11.



EFFECT OF HIGH-LIFT DEVICES ON LIFT AND DRAG-64₁-112 AIRFOIL SECTIONS

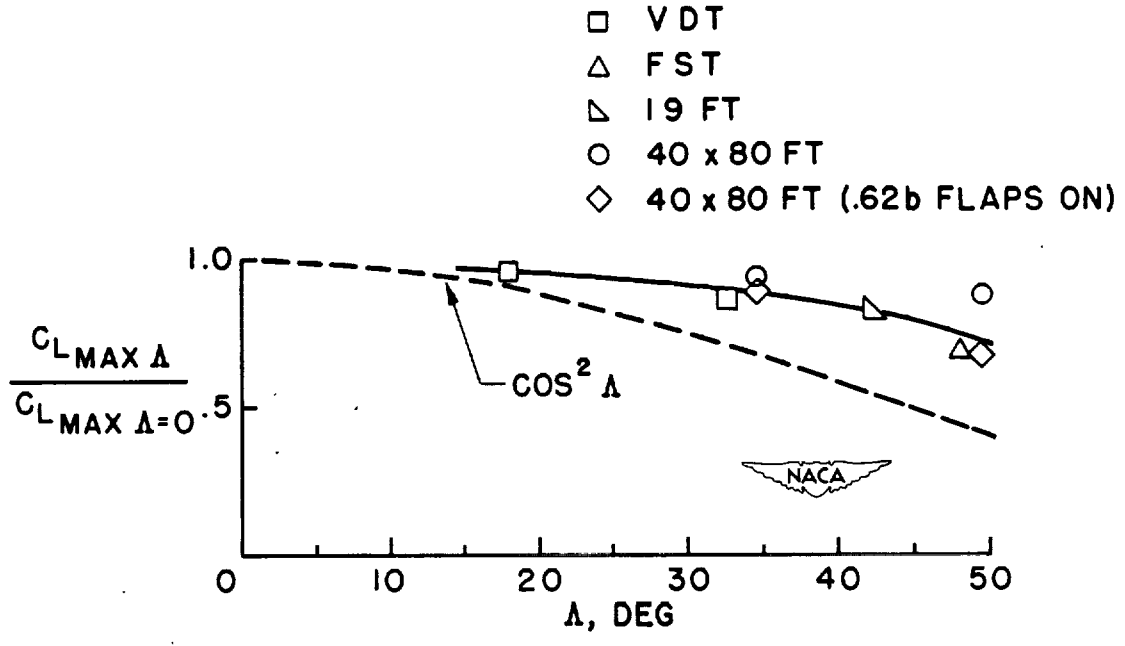
Figure 12.

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EFFECT OF HIGH-LIFT DEVICES ON LIFT AND DRAG - BICONVEX AIRFOIL SECTIONS

Figure 13.



EFFECT OF SWEEPBACK ON $C_{L \text{ MAX}}$

Figure 14.

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