NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4293

SPECIAL BODIES ADDED ON A WING TO REDUCE SHOCK-INDUCED BOUNDARY-LAYER SEPARATION AT HIGH SUBSONIC SPEEDS

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SUMMARY

The effects of special bodies added on the upper surface of a wing to reduce shock-induced boundary-layer separation for lifting conditions at high subsonic speeds have been investigated. The basic test configuration had a relatively thick 35° sweptback wing of aspect ratio 7.05 mounted on a contoured fuselage. Studies of the boundary-layer flow indicate that addition of the bodies resulted in a significant lessening of the separation on this configuration at high subsonic Mach numbers. Marked reductions in drag were associated with the improved flow. For a lift coefficient of 0.3, the added bodies reduced the drag coefficient by approximately 0.010 at a Mach number of 0.92 and increased the drag-rise Mach number by about 0.05. The additions also greatly reduced pitch-up at the lift coefficients and Mach numbers of the test. With an increase in sweep of the wing to 40°, the effectiveness of the added bodies in improving the drag and pitching-moment characteristics was increased.

INTRODUCTION

For the relatively thick cambered wings normally utilized with airplanes intended for flight at high subsonic speeds, the formation of the initial shock wave above the upper surface of the wing causes significant boundary-layer separation on that surface, particularly at lifting conditions. This separation is the primary cause of the initial drag rise, the losses in lift for a given angle of attack, and the severe changes of the pitching moment generally observed for such wings. The special fuselage addition on the forward part of the top of the fuselage described in reference 1 provides a practical means of obtaining a significant delay of this separation on the inboard sections of such a wing; however, this addition causes only secondary reductions of separation on the outboard sections. As a means of reducing the separation on these outer sections at lifting conditions, a series of special bodies added on the upper surface of the wing is proposed. The forward portions of these bodies decelerate the supersonic flow ahead of the shock wave above the wing with a resulting decrease of the strength of the shock and the associated separation. Furthermore, the local pressure fields produced by the bodies greatly reduce the adverse outward flow of separated boundary layer on sweptback wings.

Investigations have been made of the effect of adding a number of versions of the bodies to the thick-wing configuration of reference 1 at Mach numbers from 0.60 to 1.00; however, complete results and analysis are presented herein only for the most promising configuration. Results obtained from tests of a configuration with and without the forward fuselage addition of reference 1, with a rearward fuselage addition, and with two angles of sweep of the wing are included. In order to provide an indication of the nature of the effect of the added bodies, photographs are presented of the boundary-layer flow on the wing with and without the bodies. Data for one other configuration are included, and results for other configurations are discussed briefly.

SYMBOLS

C_D	drag coefficient
ΔC_D	incremental drag coefficient
C_L	lift coefficient
C_m	pitching-moment coefficient based on mean aerodynamic chord
M	Mach number
ΔM	increment in Mach number
r	body radius
x	longitudinal body coordinate
α	angle of attack

CONFIGURATIONS

Description

Wings.- The basic wing utilized, as shown in figures 1(a) and 1(b), has 35° sweepback of the quarter-chord line, an aspect ratio of 7.05, and a taper ratio of 0.38. The airfoil sections of the wing vary linearly from an NACA 65A213, a = 0.5 section at the wing-fuselage juncture to an NACA 65A209, a = 0.5 section at the 0.38-semispan station with NACA 65A209, a = 0.5 sections from that station to the tip. For the tests with the bodies added to the wing, the forward corner of the tip was rounded as shown. The wing has no built-in twist or dihedral; however, because of the relatively low stiffness of the fiber-glass and plastic construction of the outer 25 percent of the wings, the tip region had considerable twist and dihedral while the wing was being tested. Measurements made during a test indicate that with the bodies added to the wing the aeroelastic deflection resulted in approximately 1.5° of washout of the tip at an angle of attack of 3° and a Mach number of 0.92. The airfoil sections of this wing differ slightly from those of the configuration of reference 1. The results obtained from the two investigations should not, therefore, be compared directly. Tests were also made with the basic wing rotated rearward 5° about the point C, as shown in figure 1(c). This modified wing has a sweep angle of 40°, an aspect ratio of approximately 6.3, and wing thicknesses of 12.2 percent at the juncture station and 8.5 percent from the 0.38-semispan station to the tip.

Fuselage shapes.- The basic fuselage of the present investigation is the basic fuselage of reference 1, and the forward fuselage addition is the primary addition discussed in that reference. The extended fuselage, shown in figure 1(c), incorporates a one-diameter extension of the cylindrical section of the basic fuselage. The rearward fuselage addition, placed on the top of the rearward part of the fuselage (fig. 1(c)), provides improvements of the total area development for the configurations incorporating the wing additions with wing sweep angles of 35° and 40°.

Added bodied.- The bodies which were added to the wings in the present investigation are shown in figures 1(a) and 2. Five bodies were placed on each wing with the body center lines near the 27-, 45-, 60-, 72-, and 83-percent-semispan stations. The noses of the various bodies were at the 15-, 18-, 21-, 23-, and 25-percent-chord stations; the rear ends were downstream of the trailing edge 45, 42, 39, 37, and 35 percent chord. The tops of the bodies were essentially one-half bodies of revolution with the maximum radii at the 95-, 92-, 89-, 87-, and 85-percent-chord stations. The maximum radii were 8 percent of the local chords. Radii forward and rearward of the maximum are listed in the table of figure 1(a). Roughly, the forward 40 percent of the forebodies was conical, the curvature of the longitudinal contour increasing gradually from the conical region to maximum diameter; the fineness ratios of the afterbodies were roughly 3. Rearward of the maximum diameters the axes were approximately parallel to the chord plane and displaced from the plane a distance approximately equal to the maximum thickness of the upper surface of the wing. Forward of the maximum diameters the axes sloped downward so that the noses of the bodies were on the surface of the wing. The contours of the bodies were faired into the wing surface with fillets having radii approximately equal to the body radii. Rearward of the wing trailing edge the lines of the lower parts of the bodies were faired to the fillets and the lower surface of the wing. The fairing for the central body is defined by the cross section of figure 1(a). On the wing with 40° of sweepback these added bodies are inclined at an angle of 5° to the vertical plane of symmetry as shown in figure 1(c) as a result of rotating the basic wing.

The bodies tested in one preliminary investigation are shown in figure 1(b). Four bodies placed on each wing with center lines near the 27-, 45-, 63-, and 80-percent-semispan stations extended from the 40- to the 140-percent-chord stations. These bodies were partial bodies of revolution with straight axes approximately parallel to the chord plane of the wing. The maximum radii, at the 90-percent-chord stations, were approximately 7.5 percent of the local chord. Other radii are listed in the table of figure 1(b). No fillets were used. Rearward of the wing trailing edge, the lower part of the body of revolution was removed so that no part of the bodies extended below the wing plane.

Design of Bodies

Spanwise distribution.- Results not reported herein indicate that the spanwise extent of the favorable effects of the added bodies on the flow field above the wing is relatively limited near the drag-rise Mach number; therefore, a number of such bodies must be utilized to obtain a satisfactory reduction of separation across the span. For configurations with fuselage additions similar to those utilized in the present investigation, no bodies need be placed on the wing near the fuselage. The surface flow surveys presented herein indicate that with such additions the shock-induced boundary-layer separation is effectively eliminated near the fuselage at the conditions under consideration. For the present configuration, the inboard body has arbitrarily been placed approximately one-half the wing-fuselage-juncture chord length outboard of the surface of the fuselage. The outboard body was placed one tip chord length inboard of the tip since surveys indicate that flow around the tip reduces separation in this region. The bodies on the middle region of the span were placed roughly one-half the local chord length apart.

Longitudinal shapes.- One of several methods might logically have been utilized to arrive at approximately the most satisfactory longitudinal shape of the added bodies. In the present analysis a special extension of the area rule has been used. At Mach numbers near drag rise, the local supersonic flow field, while not so broad as at Mach numbers near 1.0, does have considerable vertical extent. (See ref. 2.) An indication of the general influence of the added bodies on this moderately extensive field should be provided by an analysis of the effects of the cross-sectional areas of the bodies on the area developments for localized chordwise segments along the span of the wing. The analysis should be most indicative with a wing of high aspect ratio and the added bodies relatively closely spaced, such as the configuration of the present investigation. The most readily interpreted results are obtained by considering segments which include single bodies. The segments shown in figure 1(a) with widths approximately proportional to the local chords and centered on the included bodies have been utilized as a basis for the design of the configuration of the present investigation.

For the present configuration with the special fuselage shaping, a significant proportion of the cross-sectional areas for the wing near the fuselage (segment A, fig. 1(a)) has not been included in the design analysis of the shape of the inboard added body since a large part of the disturbances produced by the longitudinal variations of such areas are offset by the influence of the fuselage shape. Also, the cross-sectional areas for the tip region of the wing (segment B, fig. 1(a)) are not included in the analysis for the outboard body. Because the flow field above the wing at low lift coefficients is associated primarily with the shape of the upper surface, only the cross-sectional areas above the chord plane have been considered.

For a high-aspect-ratio swept wing and a contoured fuselage, the flow about the midpanel region approximates that for a swept section of infinite span (ref. 3). Since the flow about such a section is primarily dependent on the shape of the section perpendicular to the swept elements (ref. 4), it would seem reasonable that the flow about the segments would be most closely defined by chordwise developments of the cross-sectional areas intercepted by cutting planes along the swept elements. Such a development for the basic wing has essentially the same shape as the mean section of the segment. (See fig. 3.)

In determining the most satisfactory shape of the total area development to be obtained by the addition of the bodies, it is assumed that the general flow above a wing segment and body is similar to that above a two-dimensional wing section with a similar upper-surface area development. A correlation of drag rise with airfoil shape for most usual airfoils (ref. 2) indicates that the primary factor leading to a delay and reduction of the initial drag rise at moderate lift coefficients is a reduction of curvature of the upper surface near the maximum ordinate of that surface. Therefore, the total area developments shown in figure 3 have been designed primarily to have such a reduced curvature. For the middle segment the curvature over a 40-percent-chord region centered on the maximum total area has been made approximately one-half that for a corresponding region of the area development for the basic wing segment. The general shape is similar to that of an NACA 16-series airfoil. In order to obtain the desired reduction in curvature considerably ahead of the peak area, cross-sectional area has been added well ahead of the station of maximum thickness for the wing and the maximum cross-sectional area has been made greater than that for the wing. Further, to reduce secondary disturbances and to obtain the most desirable change of curvature of the total area development, the added areas have been increased very gradually initially.

As for an NACA 16-series airfoil section, the total area developments for the various segments have considerably greater curvatures in the rearward regions than near the maximum cross sections. The large curvatures in these regions should result in no severe adverse effects at Mach numbers near or just above that for initial drag rise. The added cross-sectional areas near the trailing edge are approximately 60 percent of the maximum areas for the wing segments.

Results obtained by A. B. Haines of the Aircraft Research Association, Ltd. (England), indicate that the drag rise of a sweptback wing may be delayed somewhat by providing spanwise differences in the shapes of the sections so that the sweep of the line of maximum induced velocities is increased. The differences in the total area developments shown in figure 3 are the result of an attempt to provide a similar effect for the configuration of the present investigation.

The cross-sectional areas of the added bodies shown in figure 1(a) and described previously provide the differences between the basic and modified area developments shown in figure 3. The cross-sectional areas of the bodies downstream of the wing trailing edge are not included in the analysis since the aerodynamic effects of these sections of the bodies are relatively complex and unknown. These effects are probably secondary to those of the sections of the bodies above the wing surface.

Detailed shapes of bodies and wing.- Flow surveys obtained for configurations with added bodies without fillets indicated small local regions of separation at the junctures of the bodies with the wing along the rearward parts of the bodies. Fillets were added in an attempt to alleviate this separation.

Obviously, because of practical considerations, the extension of the bodies downstream of the wing trailing edge should be as small as aerodynamic considerations will allow. The extensions for the test configuration, while relatively short, provide contours sufficiently gradual to prevent significant separation on the afterbodies at Mach numbers somewhat higher than the drag-rise values for these tests.

Flow surveys obtained with configurations with the original wing tip essentially parallel to the stream indicate a local region of separation near the tip associated with the intersection of positive pressure disturbances from the forward corner of the tip and the nose of the outboard body. This separation is reduced somewhat by the rounding of the forward corner, shown in figure 1(a). Preliminary results indicate that with the rounding the disturbances originating at the corner spread and thus reduce the adverse effect on the boundary layer. A similar change has been proposed as a means for improving the shapes of the isobars near the tip (ref. 5).

TESTS

The tests were made in the Langley 8-foot transonic tunnel over a Mach number range from 0.60 to 1.00. The model was supported on a sting-mounted internal strain-gage balance. The tests were conducted at a Reynolds number of approximately 4×10^6 per foot. All configurations were tested with transition fixed by roughness strips at the 10-percent-chord stations on the upper and lower surfaces of the wing. The strips were 0.1 inch wide and consisted of No. 120 carborundum grains with approximately 20 grains per inch.

Observations of the surface boundary-layer flow were made by using a fluorescent oil-film method recently developed at the Langley Laboratory. Preceding a test, petroleum-base lubrication oil is smeared on the model. During the test, the oil film moves in the direction of surface shear. The thin film of oil is barely detectable in natural light; however, under the ultraviolet radiation provided, the oil fluoresces and is observable.

RESULTS AND DISCUSSION

Photographs of the fluorescent surface oil film for several configurations are shown in figure 4. Comparisons of variations of drag coefficient, angle of attack, and pitching-moment coefficient with lift coefficient and Mach number for the several configurations of the present investigation are presented in figures 5 to 7. The pitching-moment coefficients for the wing with 35° of sweep have been determined about the 18-percent mean-aerodynamic-chord station as shown in figure 1. In order to facilitate comparisons, the pitching-moment coefficients for the wing with 40° of sweep have been determined by using the same chord and axis with reference to the fuselage. The axis crosses the 8-percent-chord station of the mean aerodynamic chord of this configuration. The results have been corrected to the condition of free-stream static pressure at the base of the fuselage.

Basic Effects

Since the wing additions were designed to be utilized in conjunction with the forward fuselage addition shown in figure 1(a), basic comparisons are made for the configuration with that addition present.

Flow phenomena.- The development of shock-induced boundary-layer separation on the upper surface of the configuration with 35° of sweep and the forward fuselage addition for a representative angle of attack of approximately 3.7° at Mach numbers of 0.88, 0.90, and 0.92 is indicated by the oil-film study of figure 4(a). The origination of separation on the wing is indicated by the light line resulting from accumulated oil. The separation downstream of this region is indicated by the forward flow of oil with respect to the swept elements. The oil film indicates a significant amount of separation on the rearward part of the middle region of the wing. The pronounced outward flow of the low-energy boundary-layer air in the region of separation usually present on swept wings is apparent.

Addition of the bodies shown in figure 1(a) to the wing of the configuration having 35° of sweep and a forward fuselage addition for an angle of attack of approximately 3.7° essentially eliminated the separated flow at Mach numbers up to 0.90 and greatly reduced it at higher values (fig. 4(b)). This reduction in separation results primarily from the effect of the pressure fields for the bodies on the general flow about the wing, this effect being broadly defined by the changes of the localized area developments shown in figure 3. Physically, the forward parts of these bodies decelerate the supersonic flow more gradually ahead of the shock wave above the wing with a resulting decrease of the strength of the shock and the associated boundary-layer separation.

Incipient separation occurs at a Mach number of 0.90 just inboard of the third and fourth bodies. At a Mach number of 0.92 significant separation occurs along the entire span outboard of the second body, the most severe separation occurring inboard of the third and fourth bodies. At a Mach number of 0.95 the shock and induced separation on the outboard region of the wing move close to the wing trailing edge except outboard of the fifth body where separation is initiated near the midchord. It is probable that the severe separation on this region could be reduced somewhat by placing the outboard body closer to the tip.

Relatively little separation is present on the wing inboard of the second body or on the fuselage at all the test Mach numbers. The near elimination of separation in this region results in part from the same factors which cause the less pronounced reductions of separation on the same region of the wing without the added bodies (fig. 4(a)). The favorable influence of the fuselage addition on the flow is probably one of the most important of these factors. The pressure fields of the first and second bodies considerably augment these favorable effects for the basic configuration. As for the configuration without the added bodies, the aerodynamic characteristics could probably be improved by providing washout twist to reduce the lift on the critical outboard region while increasing it on the less critical inboard region. Because of the influence of the bodies on the inboard flow field, the favorable effect of twist would probably be improved by the addition of the bodies.

At a Mach number of 0.92, no separation originates on the tops and outboard sides of the bodies even in the most critical region just outboard of the midpanel. (The accumulation of oil on the top of the third body results from the slight outward flow of low-energy air from the region of separation just inboard of this body.) This effect results from a thinning and stabilization of the boundary layer on the bodies, as indicated by the sparseness of the oil film on these components. These local improvements of the boundary layer are associated with favorable changes of the pressure gradients on the bodies in the vicinity of the shock wave produced by lateral and vertical cross flows over the bodies and the longitudinal contours of the bodies. At a Mach number of 0.95, severe separation is present on the four outboard bodies as well as on the wing. This separation could possibly be reduced by the use of afterbodies with higher fineness ratios for the additions.

The outward flow of low-energy boundary-layer air on the configuration with the added bodies is considerably less severe than that on the wing without the added bodies (fig. 1(a)). For Mach numbers of 0.92 and 0.95, local regions of significant spanwise flow of the boundary layer occur between the bodies; however, the outward-moving low-energy air is swept downstream on the inner parts of the bodies. The phenomenon is most apparent on the third body at a Mach number of 0.92. This action greatly reduces the accumulation of low-energy air on the outer regions of the wing and the resulting aggravation of the separation in this region usually present on swept wings (fig. 1(a)). The bodies act effectively as aerodynamic fences. This effect is associated with the pressure gradients on the three-dimensional bodies that lead to the delay of separation on these regions as just described and not to the mere presence of vertical obstacles to the flow. Preliminary experiments of this investigation indicate that simple thin fences at the same positions as the bodies provide relatively little effective deterrent to the spanwise flow. At a Mach number of 0.95 some low-energy air moves completely over the three outboard bodies and increases the severity of separation just outboard of these bodies. However, because of the localized nature of separation at this Mach number, this action should have only secondary effects on the overall aerodynamic characteristics.

Drag characteristics.- The lessening of separation associated with adding the bodies to the configuration with a fuselage addition resulted in substantial reductions in drag at lifting conditions for Mach numbers greater than approximately 0.86 (fig. 5(a)). For a lift coefficient of 0.3 at a Mach number of 0.92, the drag coefficient was reduced by approximately 0.010 (fig. 5(d)). Also, the drag-rise Mach number, at which $\frac{\Delta C_D}{\Delta M} = 0.1$, is increased by approximately 0.05 at a lift coefficient of 0.3 (from 0.85 to 0.90). The added bodies increased the drag coefficient at a Mach number of 0.80 for moderate lift coefficients by 0.0018. This increment is significantly greater than that for the turbulent skin friction of the added wetted area. The exact cause of this difference is not apparent. The drag coefficient for moderate lift coefficients increases slightly from a Mach number of 0.80 to that for the abrupt drag rise.

Lift characteristics.- The added bodies increase the angle of zero lift at all test Mach numbers, as would be expected (fig. 5(b)). At Mach numbers up to 0.90, the increase is roughly 0.8°. However, the bodies result in significant lessening or elimination of the reductions of lift-curve slope at Mach numbers greater than roughly 0.86.

Pitching-moment characteristics.- Adding the bodies resulted in an essential elimination of the severe variations of pitching moment with lift in the pitch-up direction for the test lift coefficients at Mach numbers of 0.80 and greater (fig. 5(c)). Instead, the configuration with added bodies experienced significant "pitch-down" at several of the test Mach numbers. The pitch-up of the basic swept wing is, as usual, caused by more severe separation on the outboard region than on the inboard region, which results in a greater loss of lift on the outer sections. At the test Mach numbers of 0.80 and greater, this separation is associated with a shock wave. The favorable effect of the bodies on the pitching-moment characteristics may be attributed in part to reductions in the separation on the outboard region which result from the lessening of the strength of the local shock and the retardation of the outflow of the boundary layer into this region. However, even with these improvements, the most severe separation still occurs on the outboard sections for the configuration with the added bodies. The elimination of pitch-up in spite of this adverse distribution of separation could be associated with several effects. It may result from the anticipated rearward movement of the region of separation on the outboard sections (figs. 4(a) and 4(b)). Two-dimensional airfoil data (ref. 2) indicate that such a change usually results in a lessening of the loss of lift associated with separation. This elimination may also be caused in part by lift forces on the bodies or by alterations of the induced flow fields associated with separation.

The pitch-up for the configuration without the bodies at a Mach number of 0.60 is more severe than that at a Mach number of 0.80. The difference probably results primarily from the considerably smaller aeroelastic twist at a Mach number of 0.60. The severity of the initial pitch-up at a Mach number of 0.60 is little affected by the bodies inasmuch as the bodies have only slight influence on the leading-edge separation which causes the initial change for this Mach number (ref. 6). However, the bodies significantly reduce the unstable slope at somewhat higher lift coefficients. At these higher lift coefficients the leading-edge-separation vortex on the critical region just outboard of the midsemispan spreads considerably farther downstream (ref. 6). The pressure gradients and aerodynamic-fence action produced by the bodies should provide a retardation of the development of this more rearwardly located vortex.

The configuration without the wing additions experiences variable shifts of the aerodynamic-center position with Mach number at moderate lift coefficients. For the configuration with the additions, the aerodynamic center shifts rearward roughly 12 percent of the mean aerodynamic chord between Mach numbers of 0.86 and 0.92 for a lift coefficient of 0.3.

Variations of Additions

Refinements.- Comparison of the results for the preliminary added bodies shown in figure 1(b) with those for the bodies shown in figure 1(a) provides an indication of the combined effects of certain design refinements: closer placement of the bodies on the outboard region, more gradual forebodies, spanwise variations of the bodies, somewhat greater cross-sectional area, fillets, and a rounding of the forward corner of the tip of the wing. An indication of the improved flow associated with the refinements is provided by a comparison of figures 4(b) and 4(c). The drag rise is reduced significantly by the changes, especially at the higher lift coefficients (fig. 5(a)). Of particular importance, the gradual increase in drag with Mach number below the abrupt drag rise is considerably less for the configuration shown in figure 1(a) than for the preliminary configuration (see fig. 5(d)). Investigations of intermediate configurations indicate that the reductions in the severe drag rise at the higher Mach numbers result principally from the added body on the outboard region. The reduction in the drag increase below the drag rise is provided primarily by the more gradual forebodies and the fillets. The refinements also improve the variations of pitching moment with lift at the test conditions (fig. 5(c)). Each of the changes contributes to these favorable effects. As shown in figure 5(c), the pitching-moment coefficient for zero lift for the configuration shown in figure 1(a) is roughly 0.01 more positive than that for the preliminary configuration shown in figure 1(b). This difference results from the reduction of lift on the outboard region of the wing associated with the addition of the fifth body on the configuration shown in figure 1(a).

Distribution and size.- Tests for which results are not included herein indicate that increasing the lateral displacements of the bodies from one-half the local chord, as shown in figure 1(a), to roughly two-thirds the local chord results in a small loss of effectiveness of the bodies in reducing separation; however, distribution of the bodies one chord length apart causes a significant decrease of effectiveness. Closer placement of the bodies than that shown in figure 1(a) results in an increase in skin-friction losses with little further reduction of separation. Other preliminary results indicate that bodies with cross-sectional areas approximately 20 percent smaller than those for which results are presented provide somewhat less effectiveness in reducing separation at the higher lift coefficients, while the use of bodies roughly 50 percent smaller results in marked reductions of effectiveness at most conditions. Use of larger bodies results in some increase in effectiveness at the higher lift coefficients. However, this improvement is probably less important than the associated adverse increase in skin-friction drag.

Special variations.- Several special variations of the added bodies have been investigated. In one variation, the cross-sectional area for the forward portions of the bodies was spread laterally along swept elements to provide oblique-wedge shaped noses. This variation resulted in no appreciable improvement of the characteristics. For another special variation, the axes of the bodies were bent to be more nearly alined with local flow over the wing at each of the chordwise stations. This variation also resulted in no appreciable improvement.

Effects of Fuselage Shape

Forward fuselage addition.- Adding the bodies to the configuration with 35° of sweep without a forward fuselage addition resulted in reductions in the drag coefficients similar to those obtained for the configuration with the addition at the Mach numbers above the abrupt drag rise (fig. 6(a)). However, removal of the forward fuselage addition caused pronounced increases in the drag coefficients from a Mach number of approximately 0.86 to that for the abrupt rise (fig. 6(d)). The variations of pitching moment with lift for the configuration without the forward fuselage addition (fig. 6(c)) are approximately the same as those obtained with this addition present.

The wing additions, in combination with the forward fuselage addition, provided a total increase in drag-rise Mach number of 0.07 (from 0.83 to 0.90) for a lift coefficient of 0.3 (fig. 6(d)).

Rearward fuselage addition.- Results not included herein indicate that extension of the fuselage one diameter produced no measurable variations in the aerodynamic characteristics at Mach numbers to the highest test value, 0.95, for the configuration with 35° of sweep, the forward fuselage addition, and the bodies added to the wing. The rearward addition illustrated in figure 1(c) on the top of the extended fuselage of the same configuration resulted in no changes in the characteristics at Mach numbers up to 0.97 but reduced the drag coefficient approximately 0.0025 at a Mach number of 1.00 for lift coefficients to 0.4.

Wing Sweep

Because of the pronounced reductions of pitch-up caused by the added bodies, incorporation of the additions should significantly relax the limitations on wing sweep usually imposed by this effect. In many cases, considerably greater sweep may be practical. An indication of the influence of a moderate increase in sweep, from 35° to 40°, on the combined effects of the wing and fuselage additions, is provided by a comparison of results presented in figures 6 and 7.

For the basic configuration, increasing the sweep increased the drag-rise Mach number by approximately 0.03, from 0.83 to 0.86. The pitch-up for the basic configuration at a Mach number of 0.60 is little affected by the increased sweep; however, the variations of pitch with lift are improved at Mach numbers from 0.86 to 0.92. The increased sweep moves the aerodynamic center rearward 8 percent of the mean aerodynamic chord for a lift coefficient of 0.3 at a Mach number of 0.80.

The boundary-layer flow on the configuration having 40° of sweep with the bodies added to the wing for an angle of attack of 3° at Mach numbers of 0.92 (fig. 4(d)) is generally similar to that on the configuration with 35° of sweep at a Mach number of 0.88 (fig. 4(b)). The flow for the configuration with 40° of sweep at a Mach number of 0.95 is between that for the configuration with 35° of sweep at Mach numbers of 0.90 and 0.92. The surveys of figure 4(d) and others, not presented, indicate that for the configuration with 40° of sweep no significant separation occurs inboard of the middle added body.

The reductions in drag rise and increases of drag-rise Mach number resulting from adding the bodies to the configuration with 40° of sweep (figs. 7(a) and 7(d)) are approximately the same as those for the configuration with 35° of sweep. However, the increment in drag at a Mach number of 0.80 associated with adding the bodies and the gradual increase in drag at Mach numbers below that for abrupt drag rise are significantly lessened by the increase in sweep. These reductions may result in part from improvements of the local flows about the bodies associated with the 5° lateral inclination of these additions for the configuration with the increased sweep. With such inclinations, the bodies are more nearly alined with the mean direction of the flow over the upper surface of the wing in the region of the additions.

For the configuration with 40° of sweep, the addition of the bodies essentially eliminated pitch-up at all test Mach numbers, including a Mach number of 0.60 (fig. 7(c)). The pronounced improvement of the effectiveness of the added bodies in reducing pitch-up at a Mach number of 0.60 associated with the increased sweep may result from an expansion of the leading-edge separation vortex (ref. 6) in an action similar to that at higher lift coefficients for the configuration with 35° of sweep. For this configuration, the aerodynamic center at a lift coefficient of 0.3 shifts rearward 9 percent of the mean aerodynamic chord between Mach numbers of 0.86 and 0.92.

For this and other configurations on which shock-induced separation occurs at higher Mach numbers than for the configuration with 35° of sweep of figure 1(a), it is probable that the most satisfactory spanwise distances from the fuselage to the first body and between the bodies should be somewhat greater than those arrived at for that configuration, since at the higher Mach numbers the spanwise extents of the favorable effects of the bodies are increased.

CONCLUDING REMARKS

An experimental study has been conducted of the effects on aerodynamic characteristics of special bodies on the upper surface of a sweptback wing at high subsonic Mach numbers. This study indicates that the presence of the bodies caused significant reductions of the shock-induced boundary-layer separation at lifting conditions and, therefore, marked reductions of the drag at high subsonic Mach numbers and increases of the drag-rise Mach number of approximately 0.05 for a lift coefficient of 0.3. These additions also significantly reduced pitch-up at the test lift coefficients and Mach numbers. The effects of the added bodies on the aerodynamic characteristics were improved by an increase in sweep from 35° to 40°.

Langley Aeronautical Laboratory,
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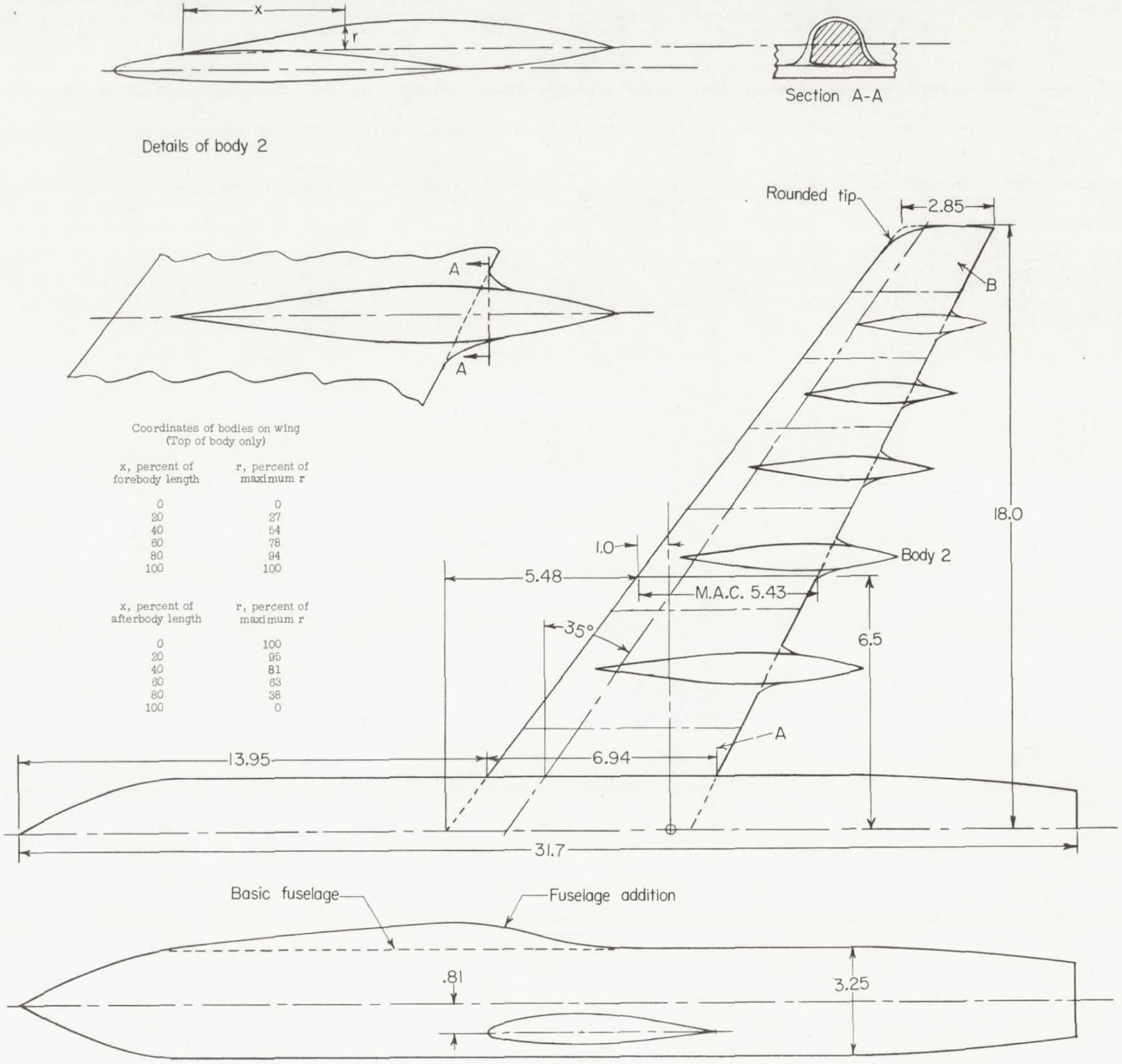


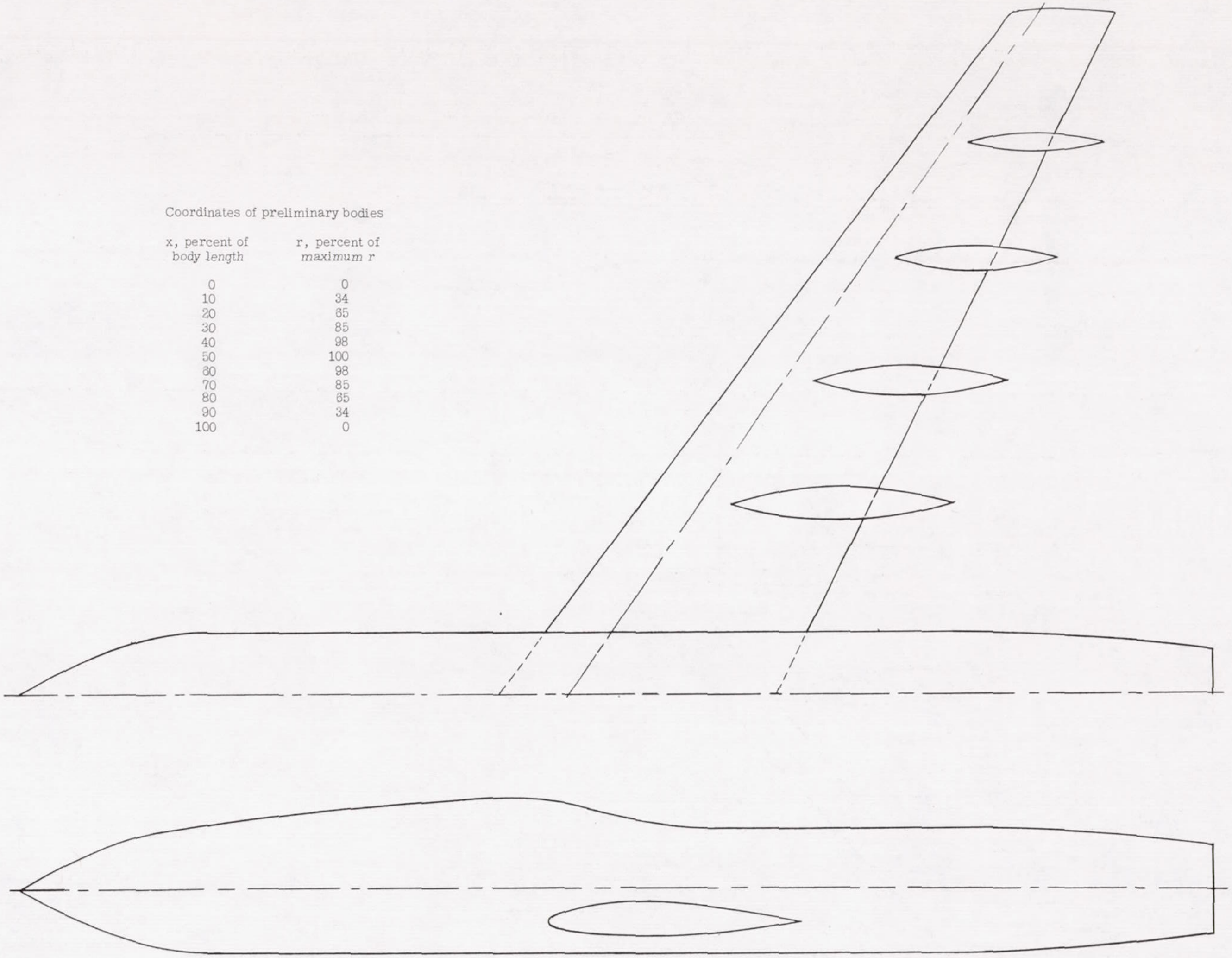
Coordinates of bodies on wing
(Top of body only)

x, percent of forebody length	r, percent of maximum r
0	0
20	27
40	54
60	78
80	94
100	100

x, percent of afterbody length	r, percent of maximum r
0	100
20	95
40	81
60	63
80	38
100	0

(a) Configuration with 35° of sweep, forward fuselage addition, and bodies on wing.

Figure 1.- Dimensions of experimental configurations. All dimensions are in inches.

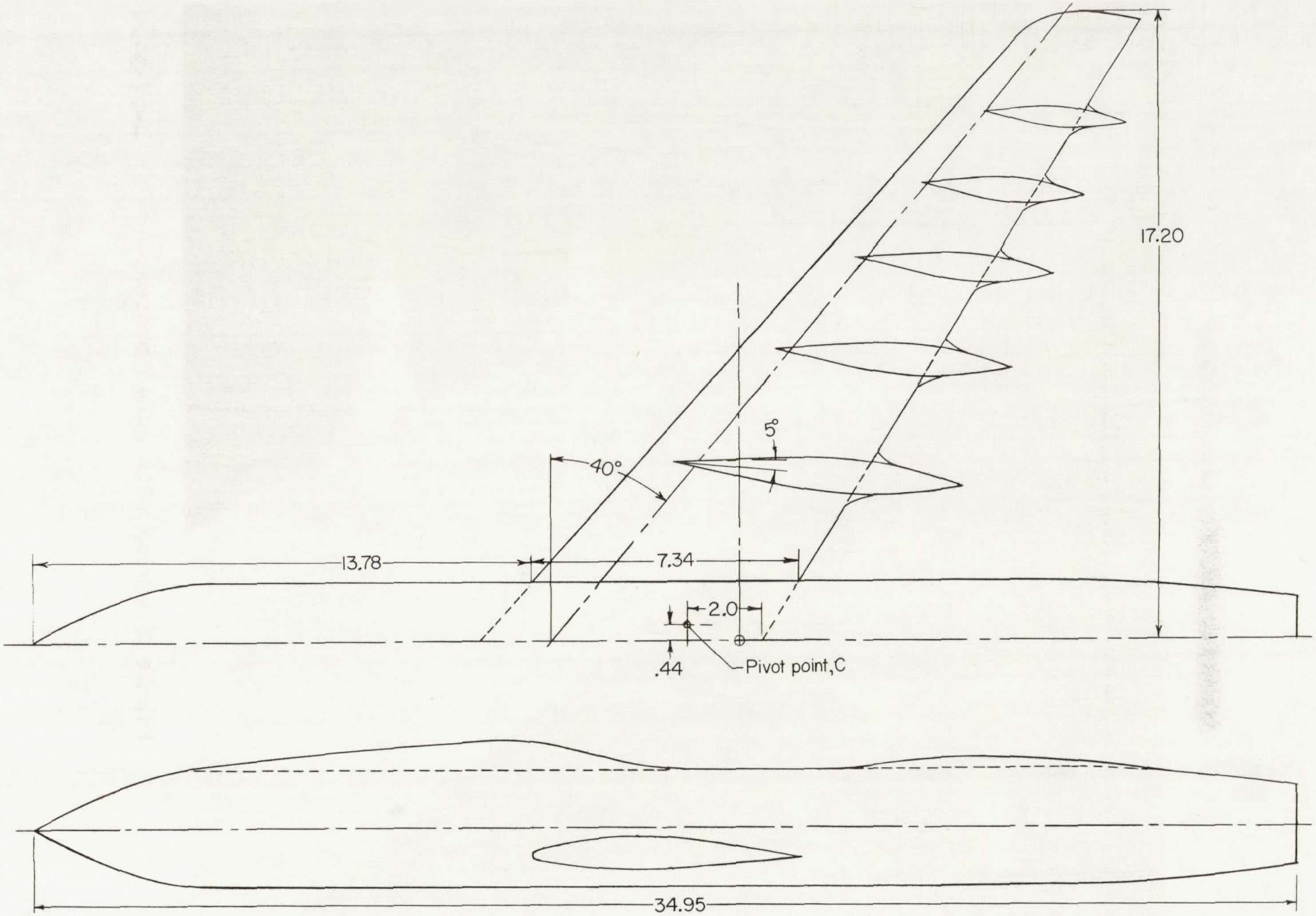


Coordinates of preliminary bodies

x, percent of body length	r, percent of maximum r
0	0
10	34
20	65
30	85
40	98
50	100
60	98
70	85
80	65
90	34
100	0

(b) Configuration with 35° of sweep, forward fuselage addition, and preliminary bodies on wing.

Figure 1.- Continued.



(c) Configuration with 40° of sweep, forward and rearward fuselage additions, and bodies on wing.

Figure 1.- Concluded.

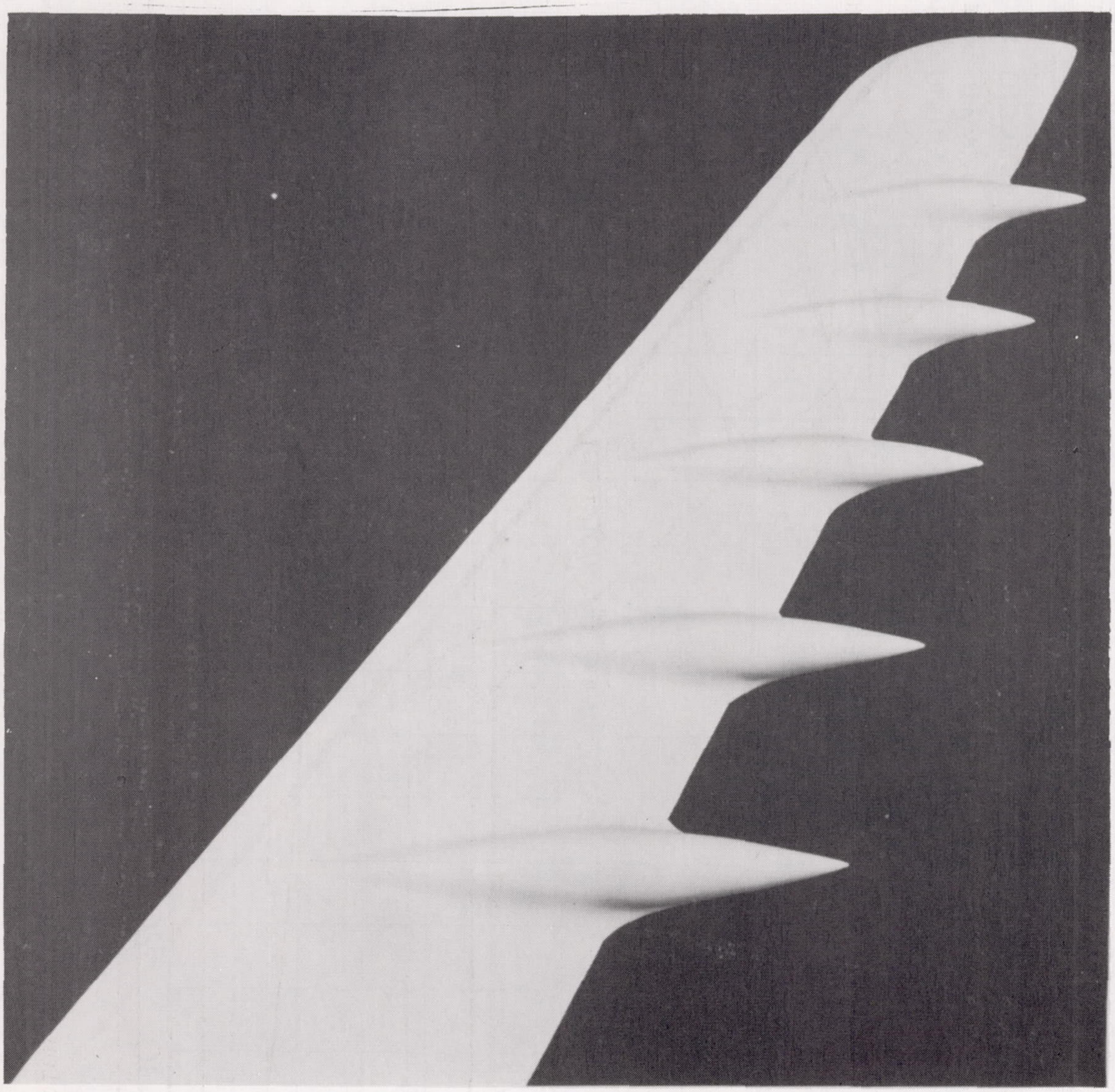


Figure 2.- Wing with added bodies.

L-57-5414

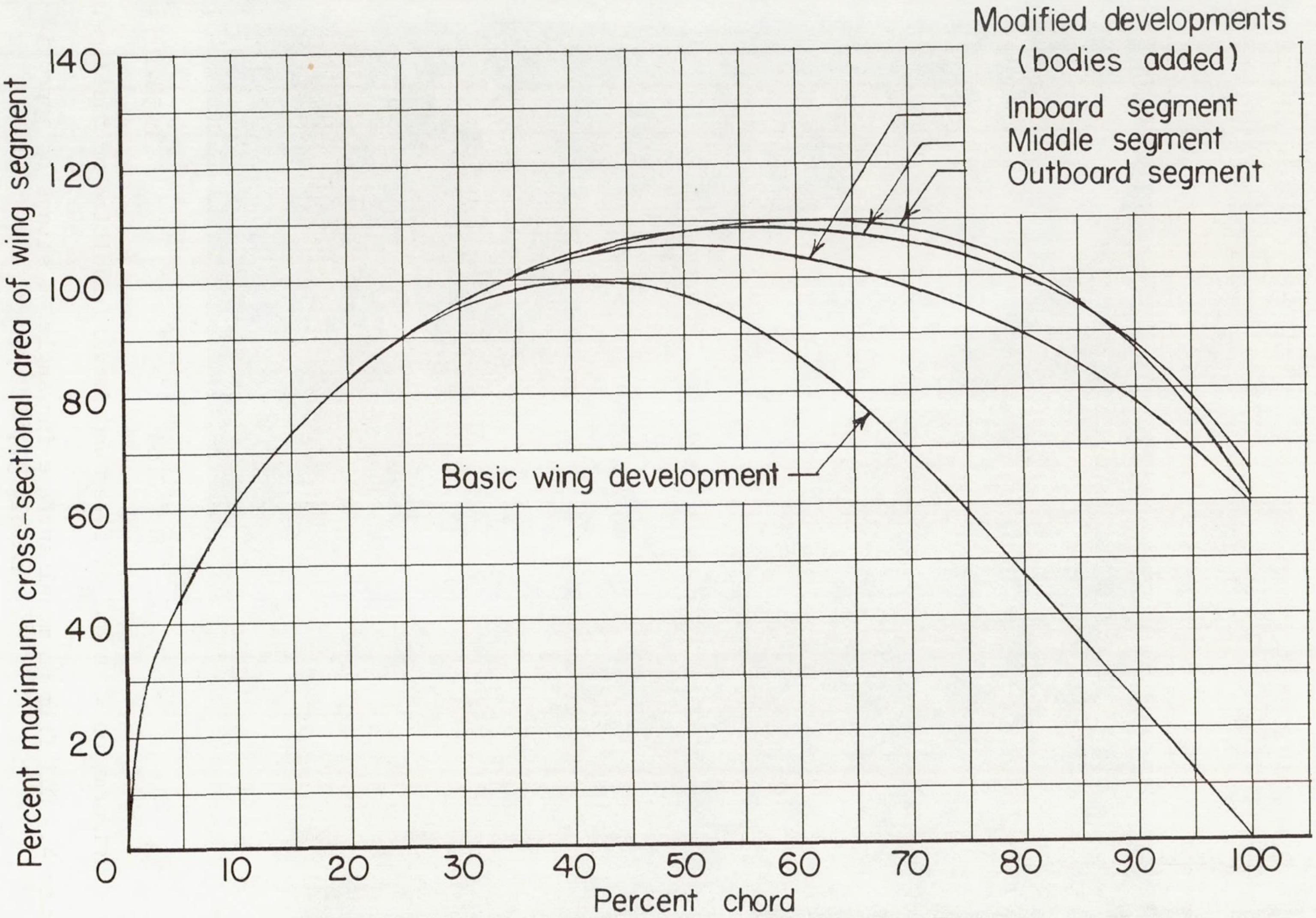
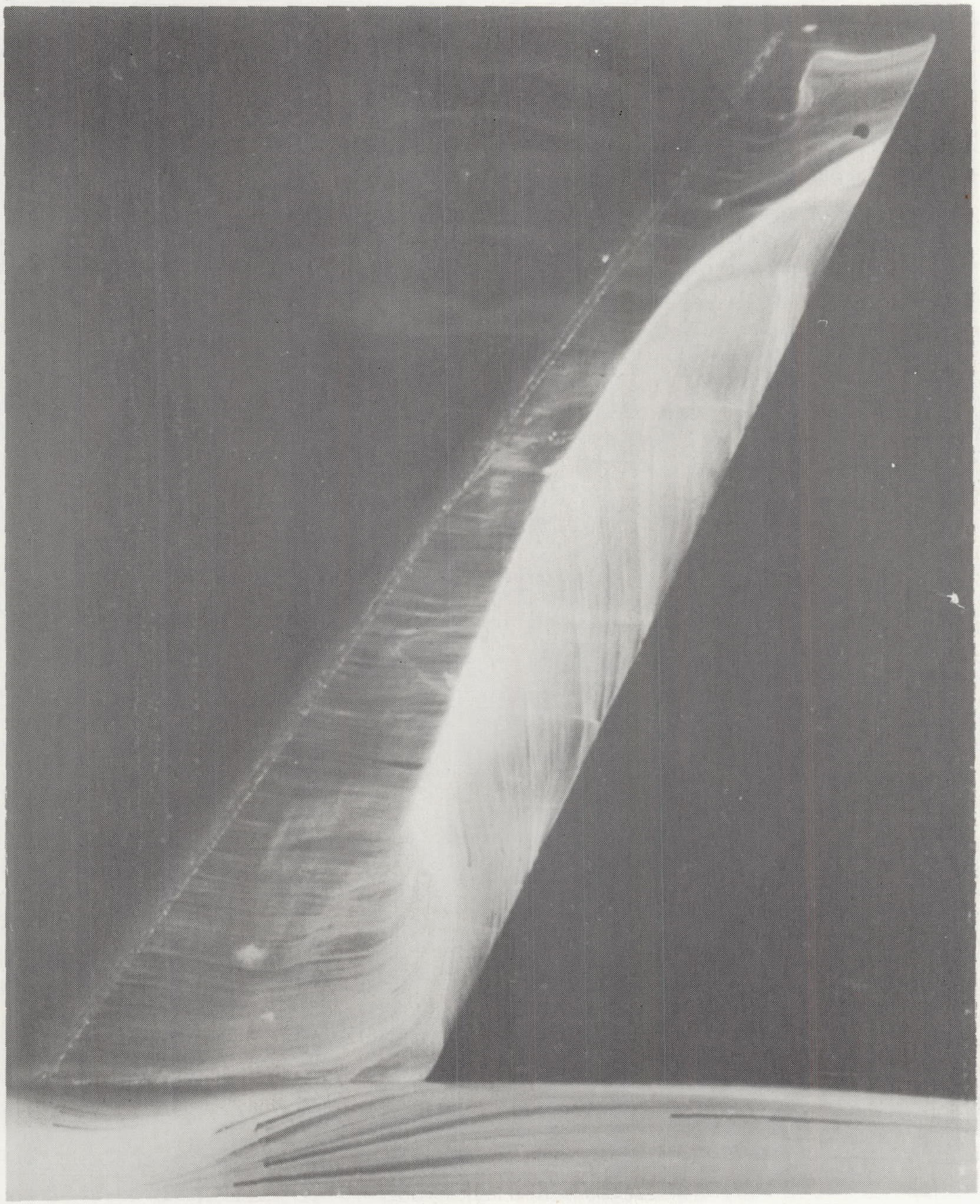


Figure 3.- Basic and modified segment area developments for configuration with 35° of sweep. (Areas taken above chord plane of wing.)

M = 0.88 L-58-165

(a) Configuration with 35° of sweep and forward addition on fuselage.

Figure 4.- Oil film on model surface for angle of attack of approximately 3.7°.



M = 0.90 L-58-166

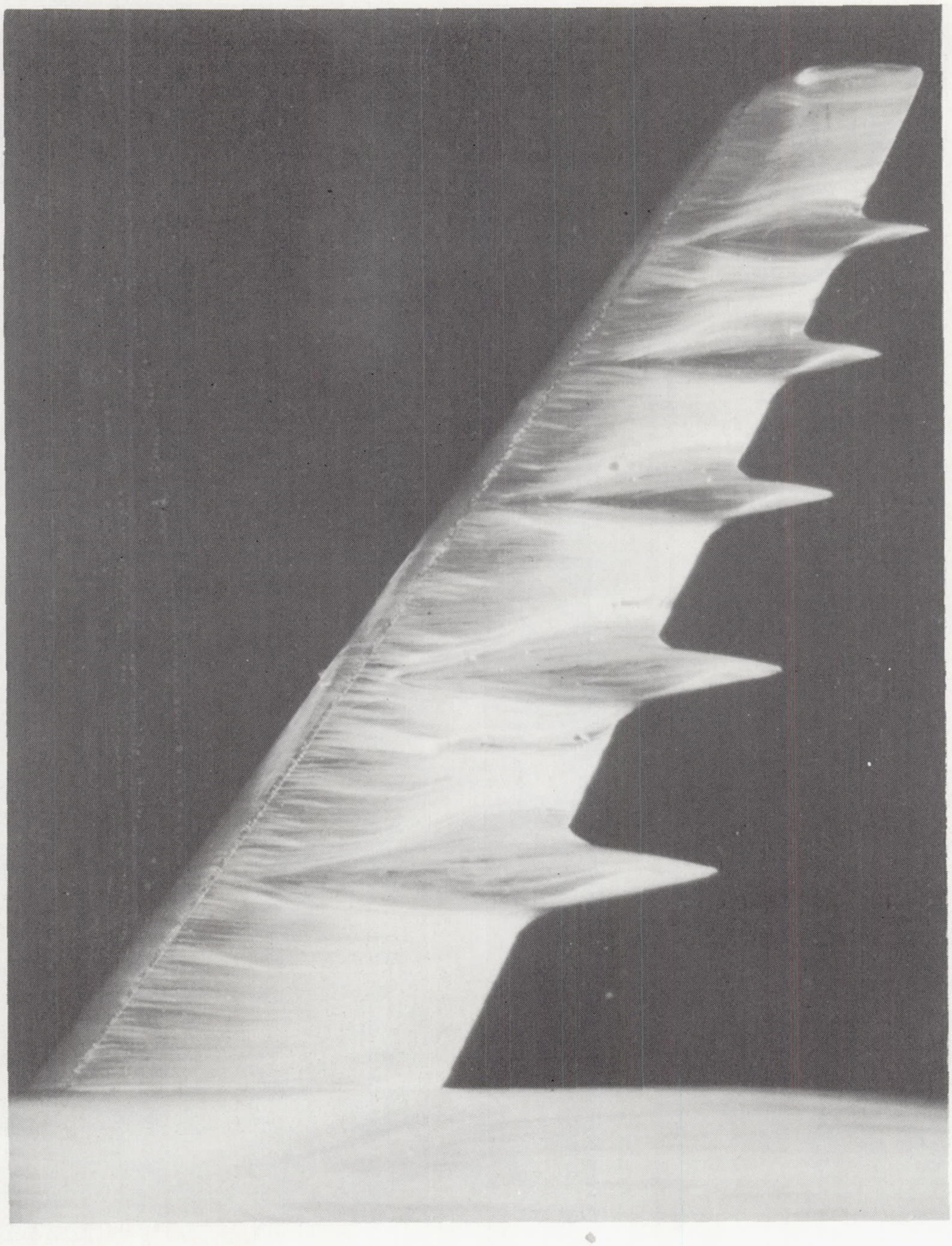
(a) Continued.

Figure 4.- Continued.

M = 0.92 L-58-167

(a) Concluded.

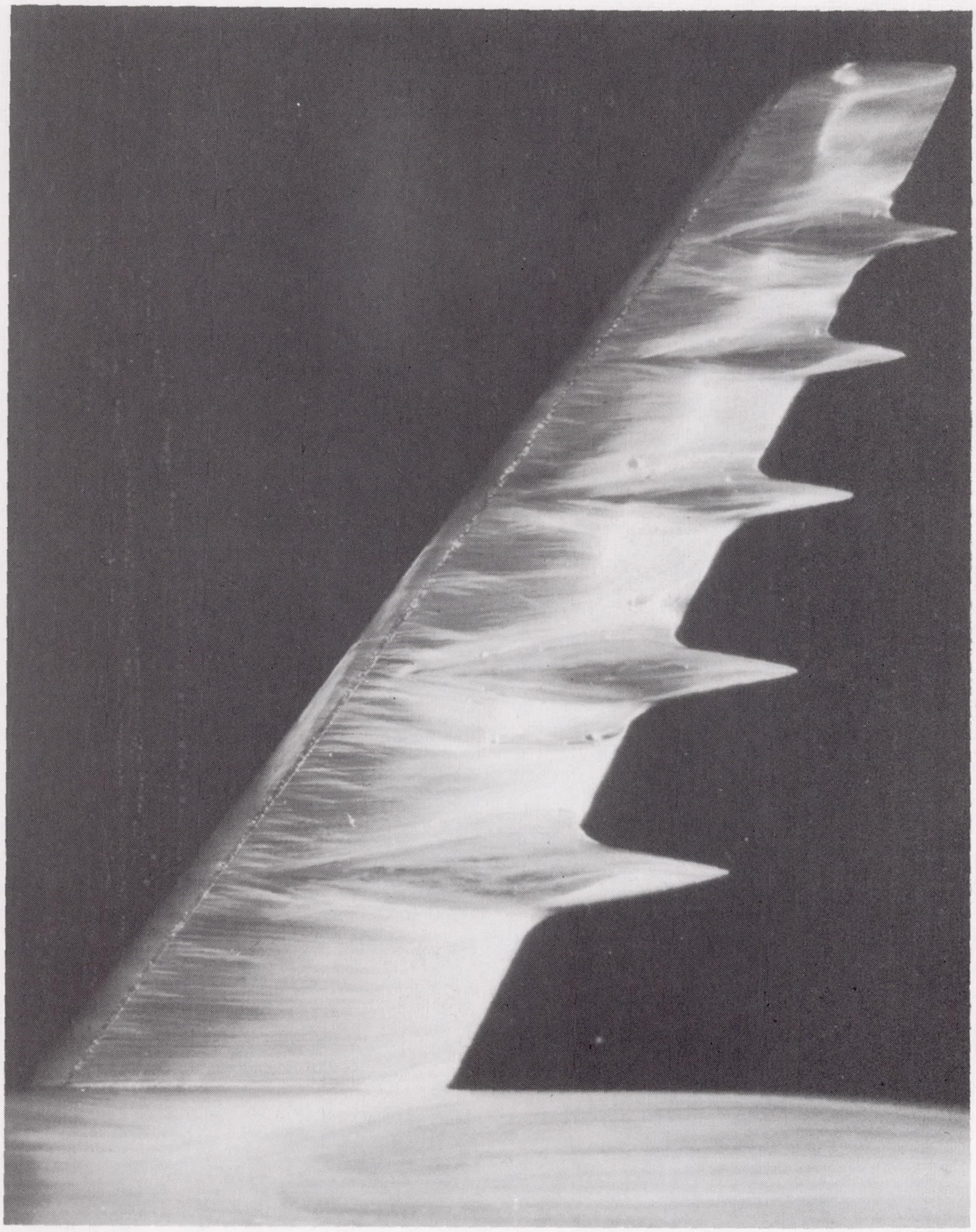
Figure 4.- Continued.



M = 0.88 L-58-168

(b) Configuration with 35° of sweep, forward addition on fuselage, and bodies on wing.

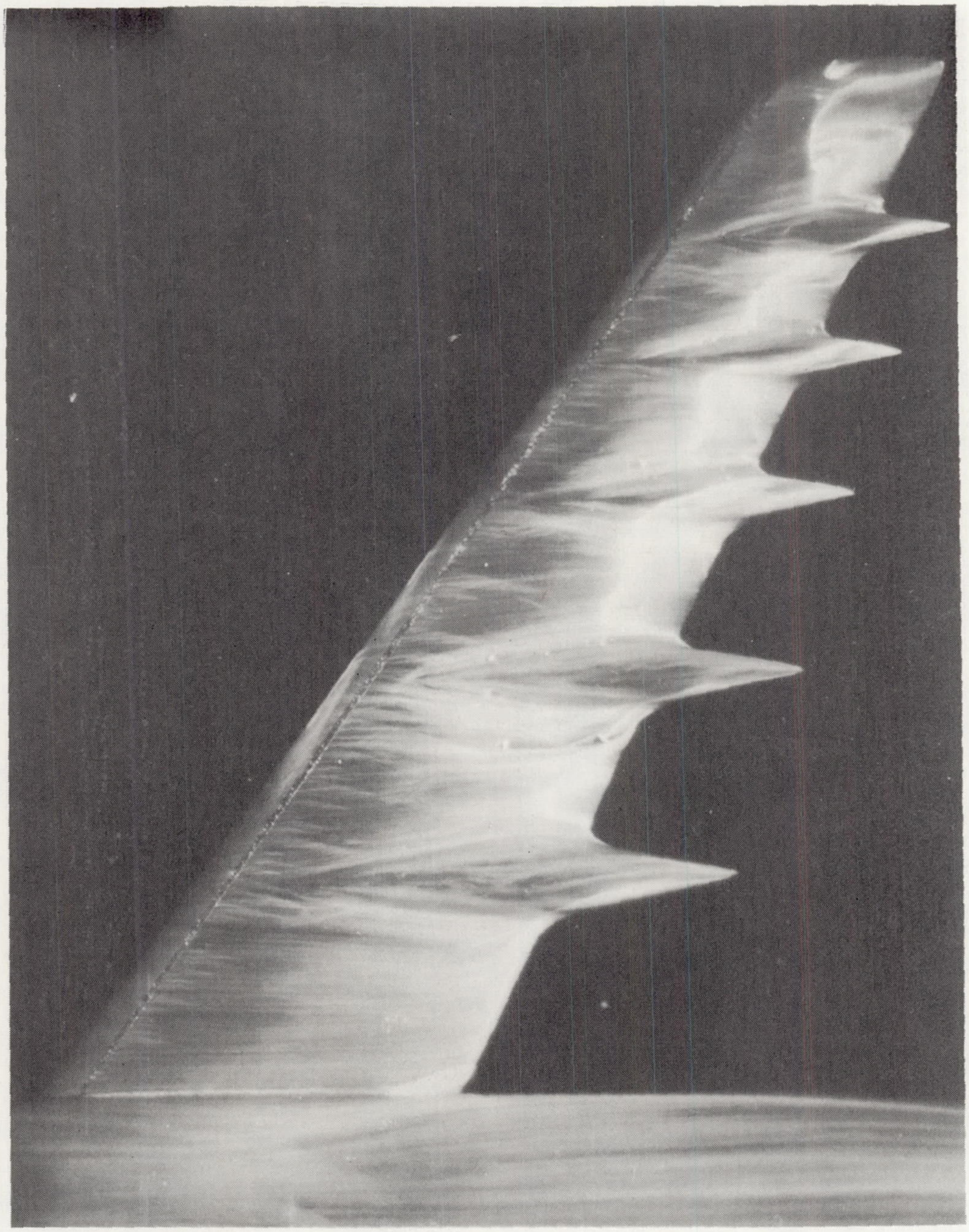
Figure 4.- Continued.



M = 0.90 L-58-169

(b) Continued.

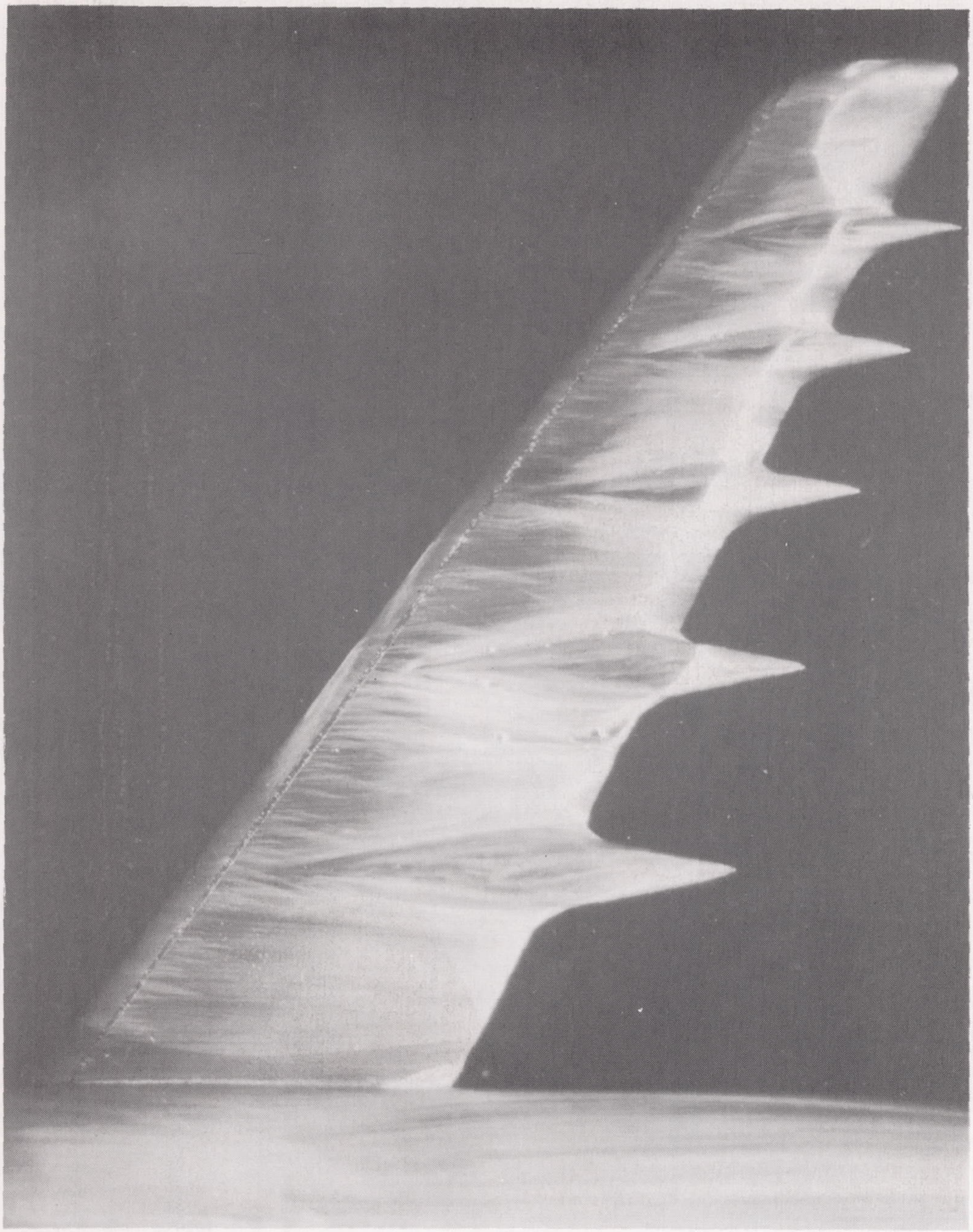
Figure 4.- Continued.



M = 0.92 L-58-170

(b) Continued.

Figure 4.- Continued.

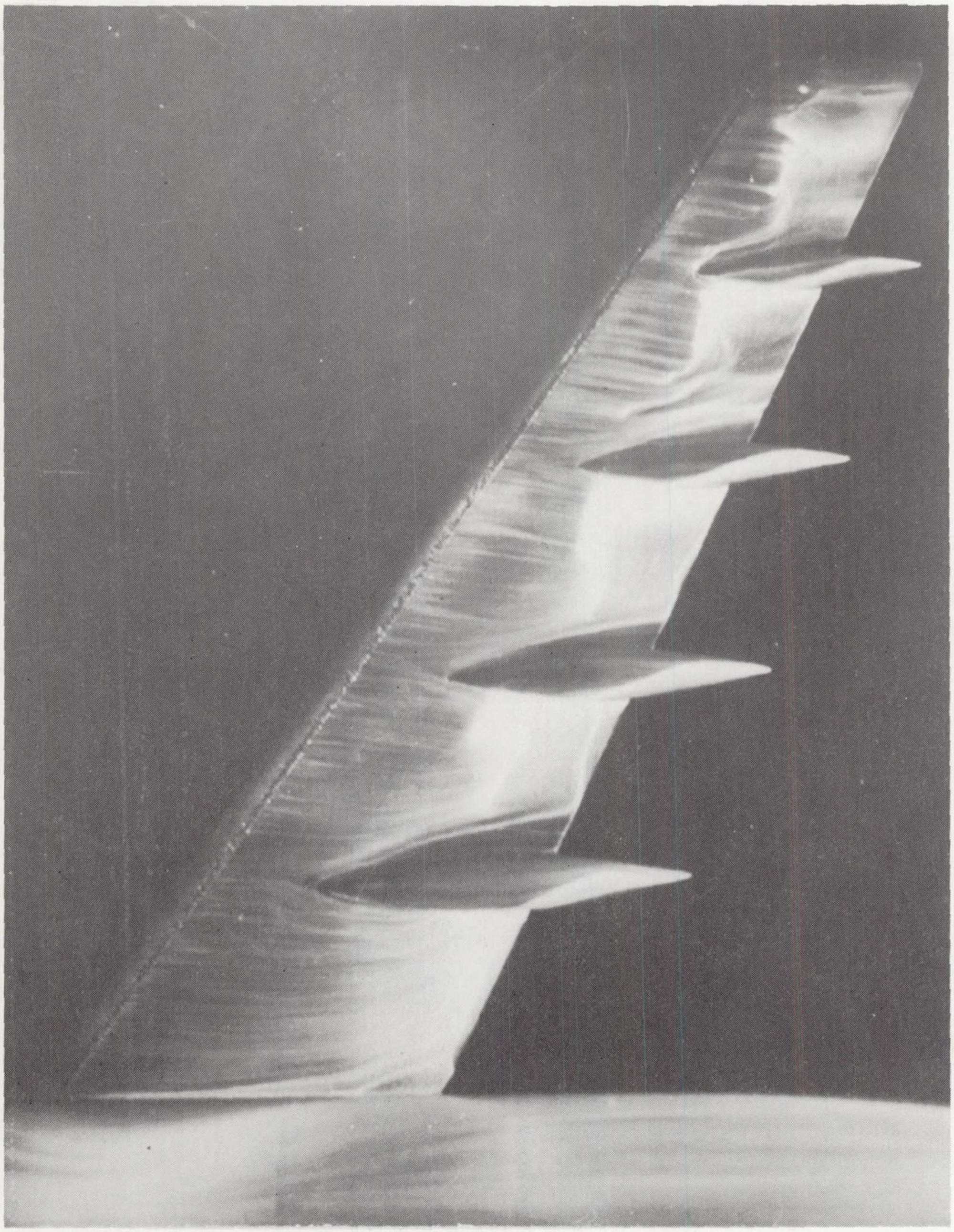


M = 0.95

L-58-171

(b) Concluded.

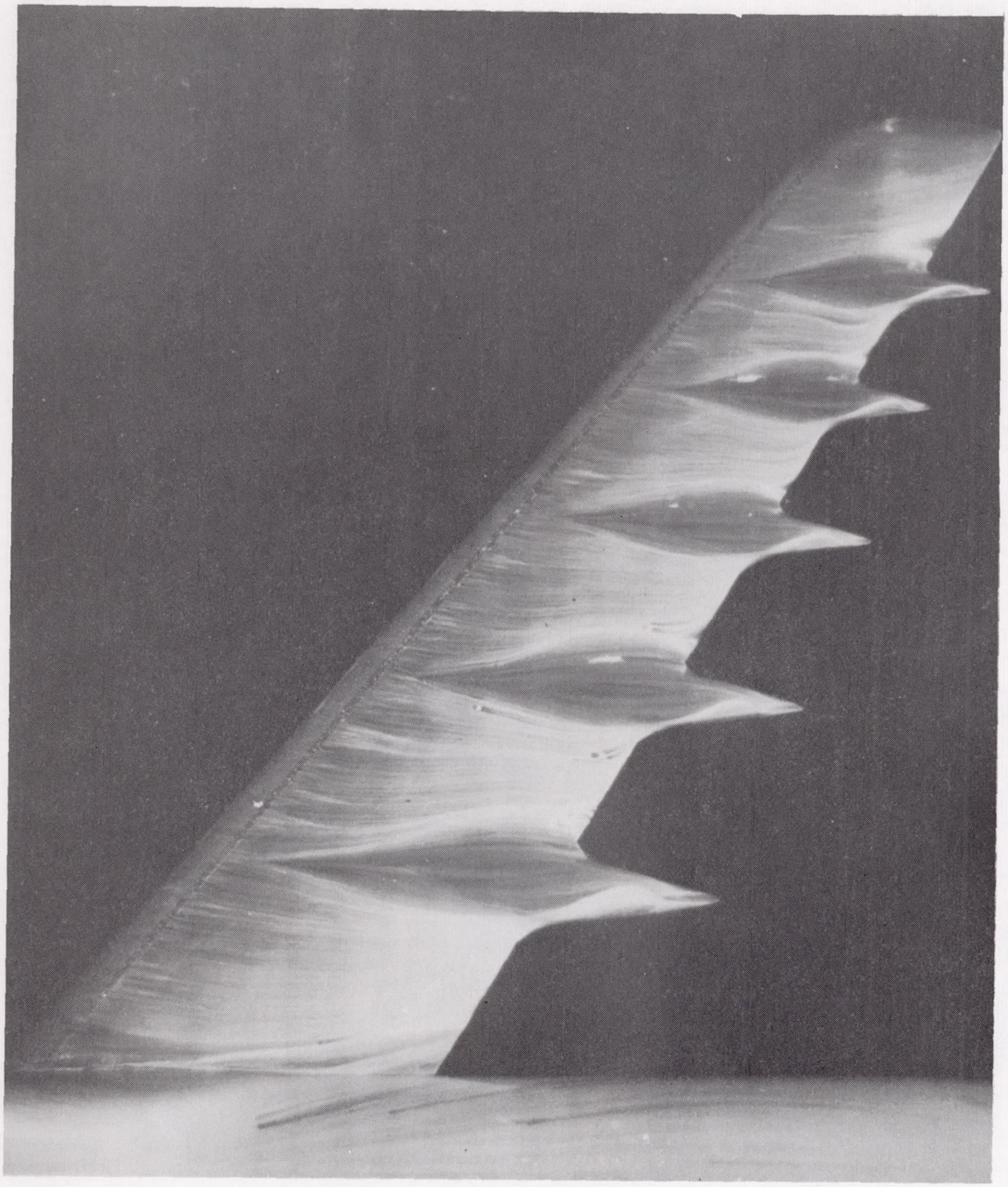
Figure 4.- Continued.



M = 0.90 L-58-172

(c) Configuration with 35° of sweep, forward addition on fuselage, and preliminary bodies on wing.

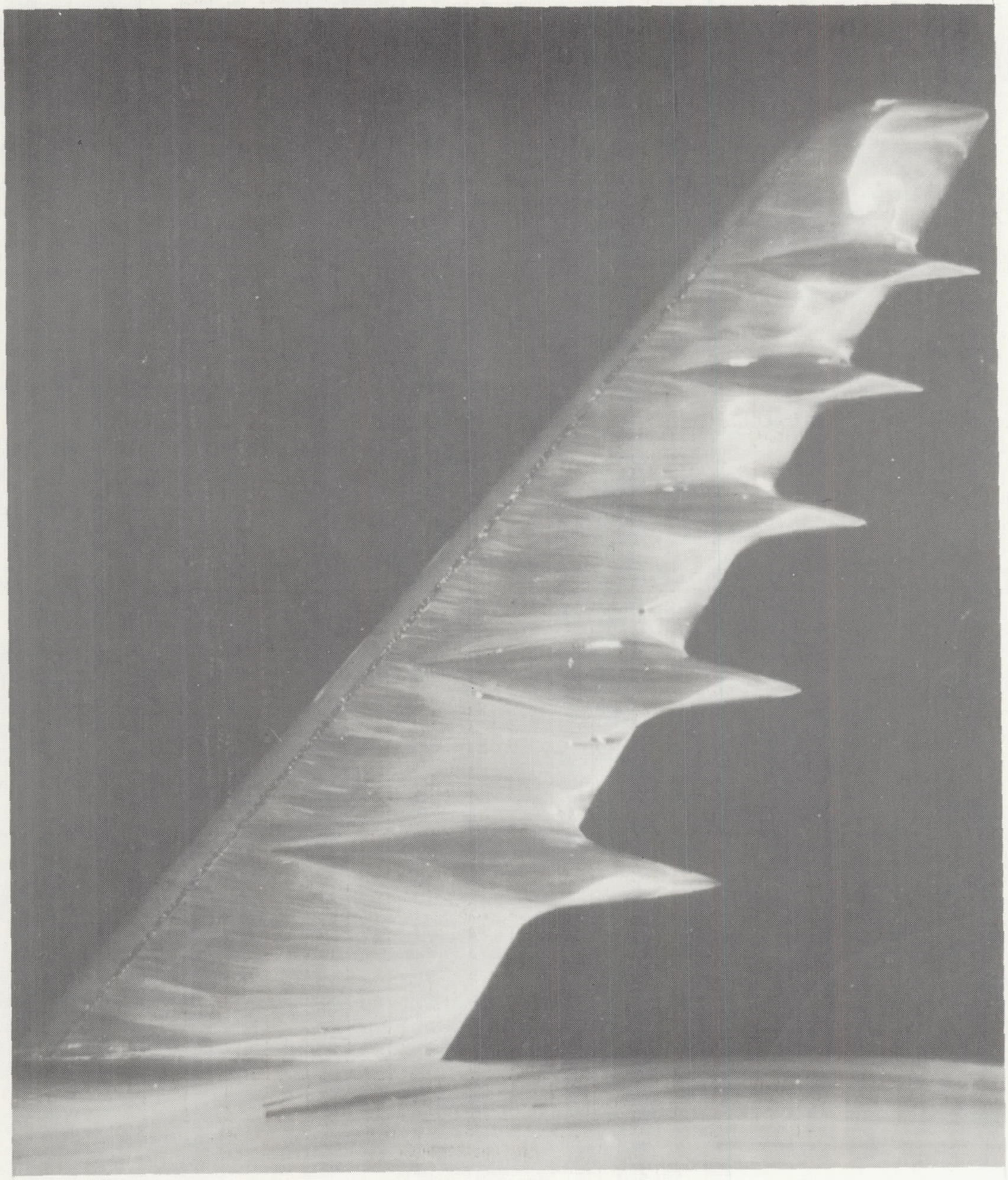
Figure 4.- Continued.



M = 0.92 L-58-173

(d) Configuration with 40° of sweep, forward and rearward additions on fuselage, and added bodies on wing.

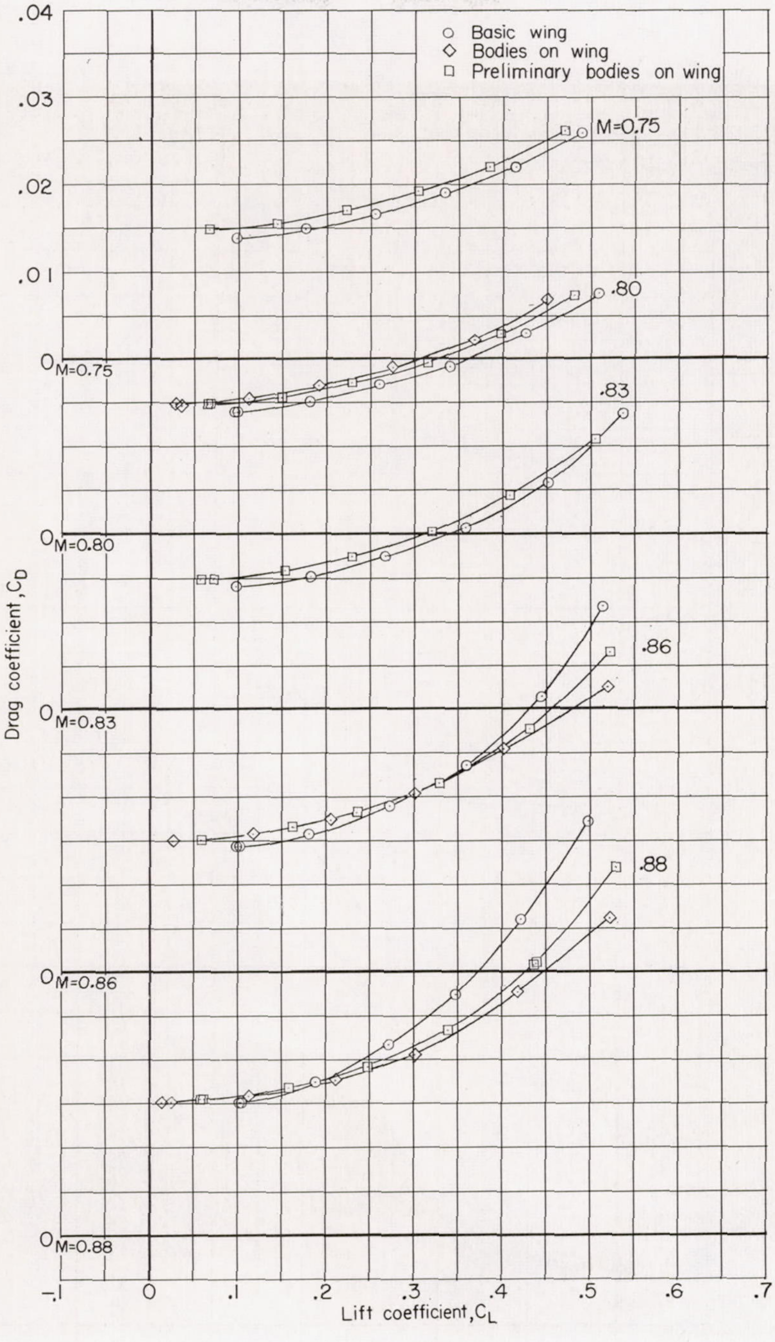
Figure 4.- Continued.



M = 0.95 L-58-174

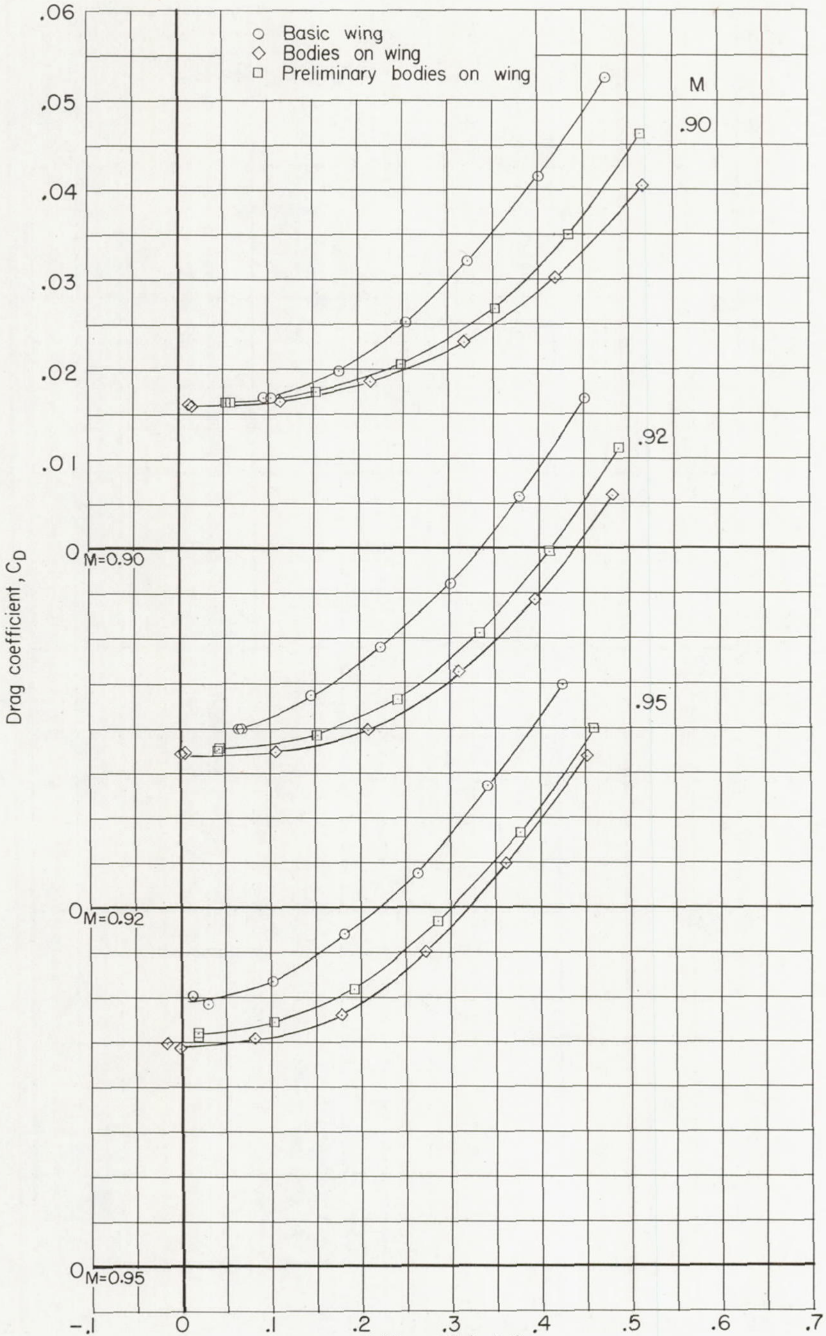
(d) Concluded.

Figure 4.- Concluded.



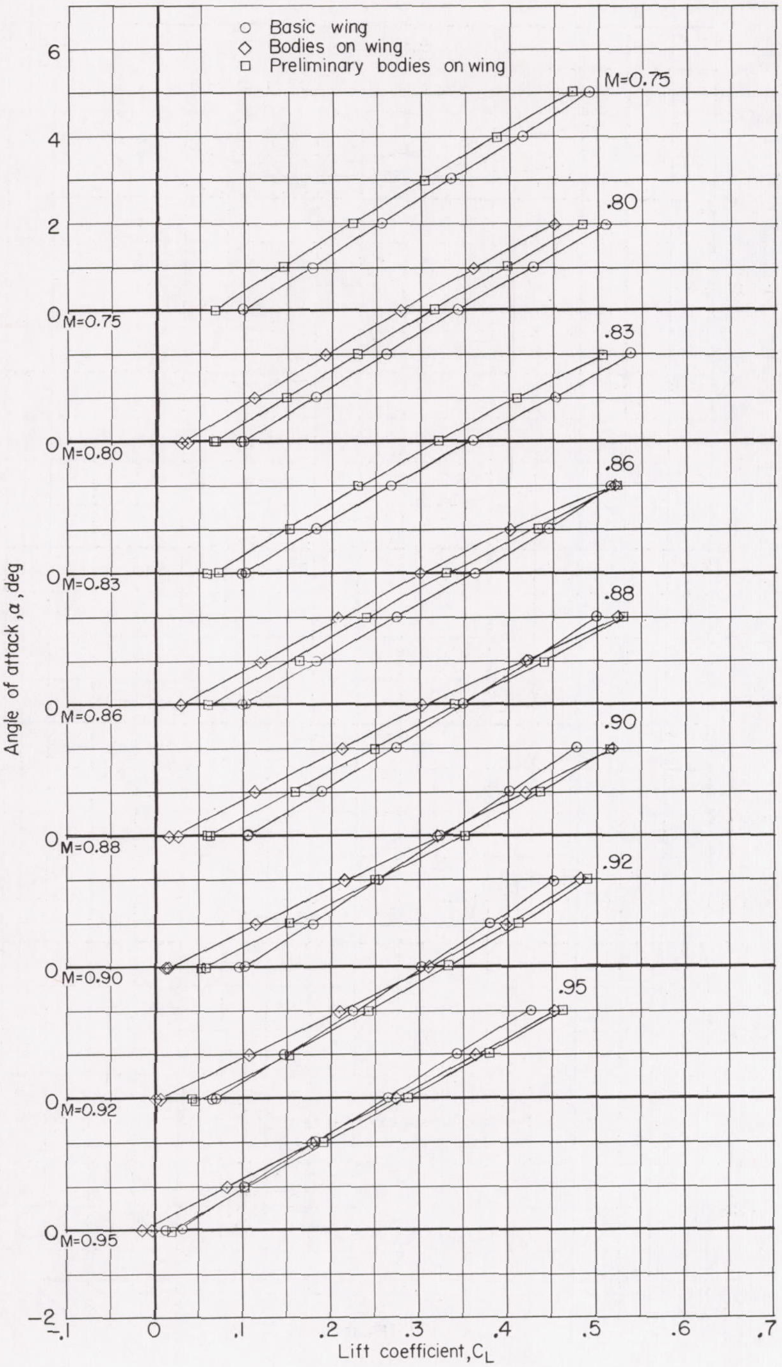
(a) Variation of drag coefficient with lift coefficient for various Mach numbers.

Figure 5.- Effect of added bodies on aerodynamic characteristics of configuration with 35° of sweep and forward addition on fuselage.



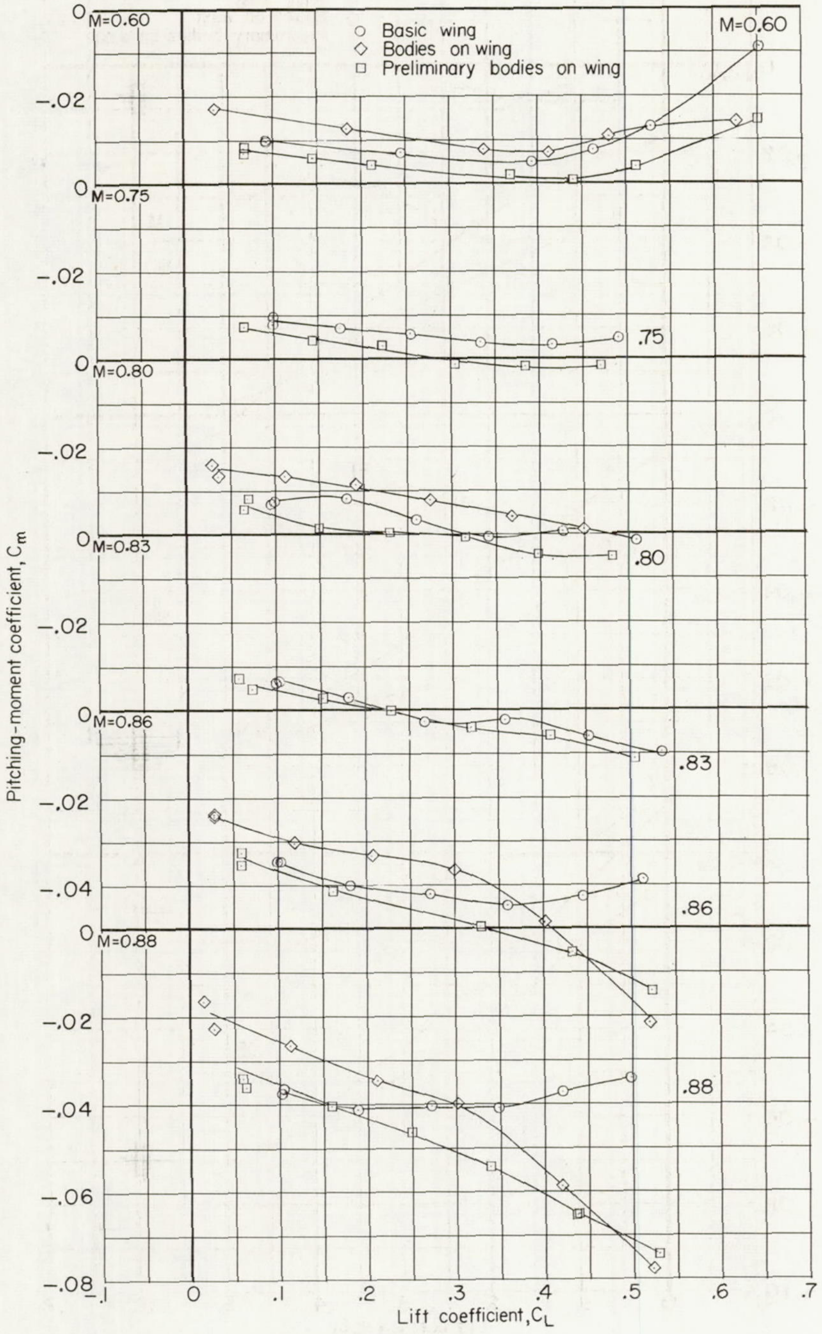
(a) Concluded.

Figure 5.- Continued.



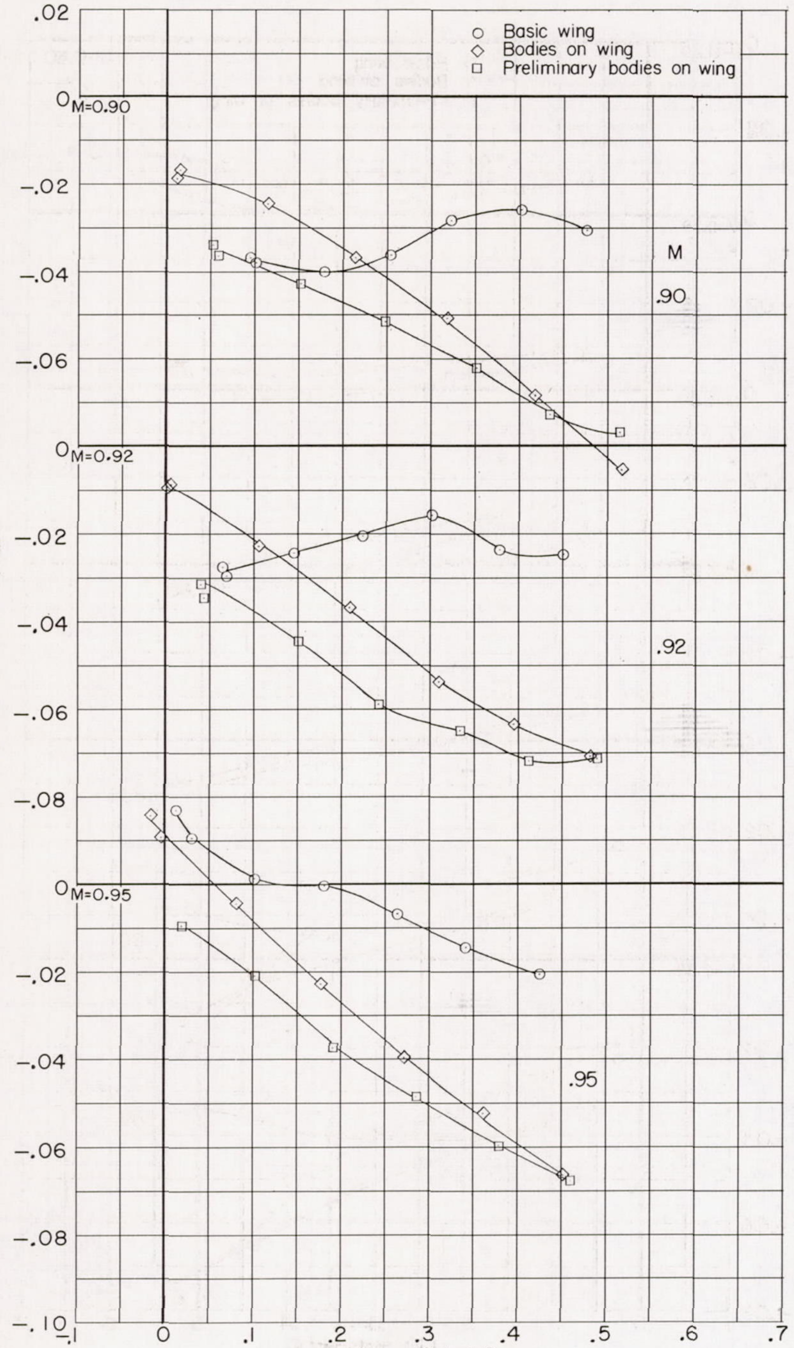
(b) Variation of angle of attack with lift coefficient for various Mach numbers.

Figure 5.- Continued.



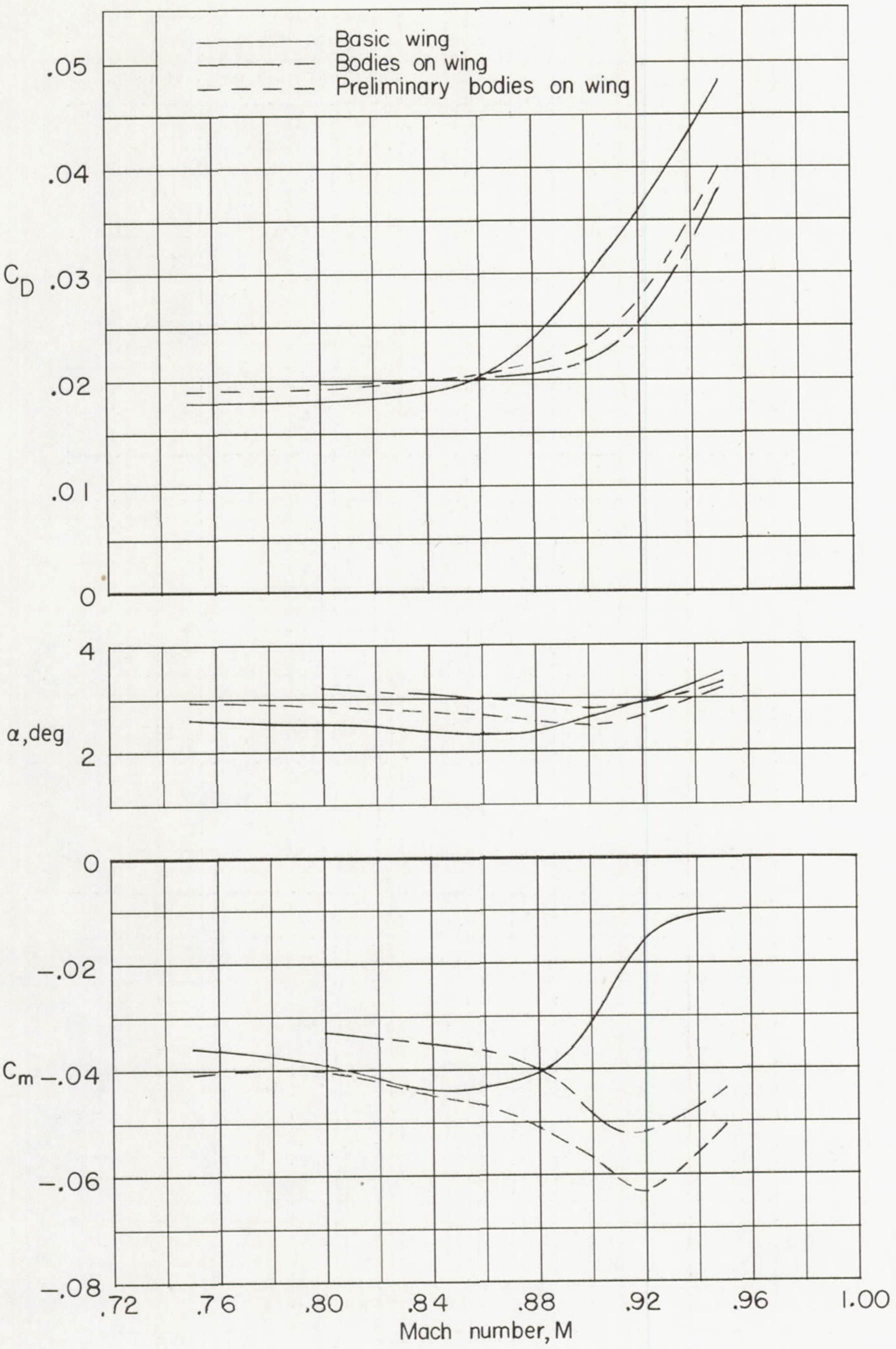
(c) Variation of pitching-moment coefficient with lift coefficient for various Mach numbers.

Figure 5.- Continued.



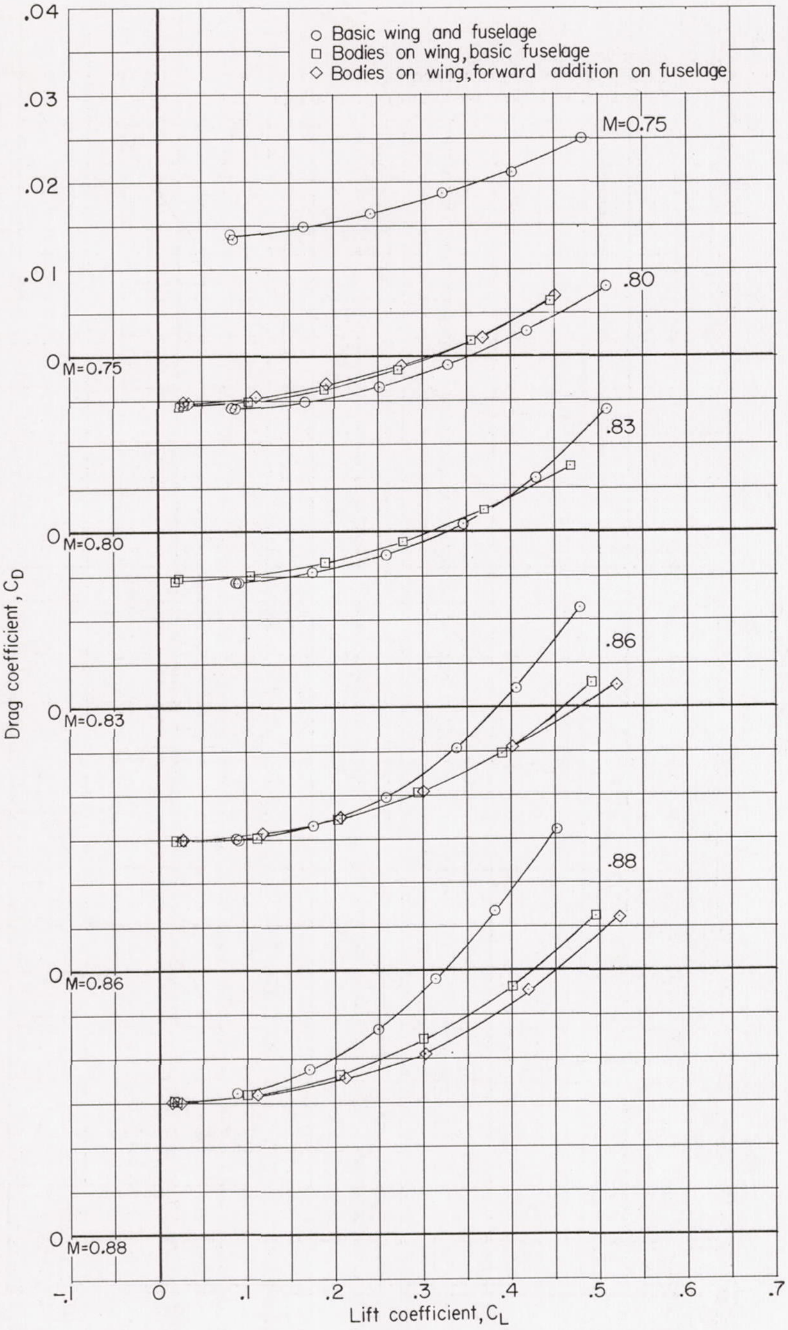
(c) Concluded.

Figure 5.- Continued.



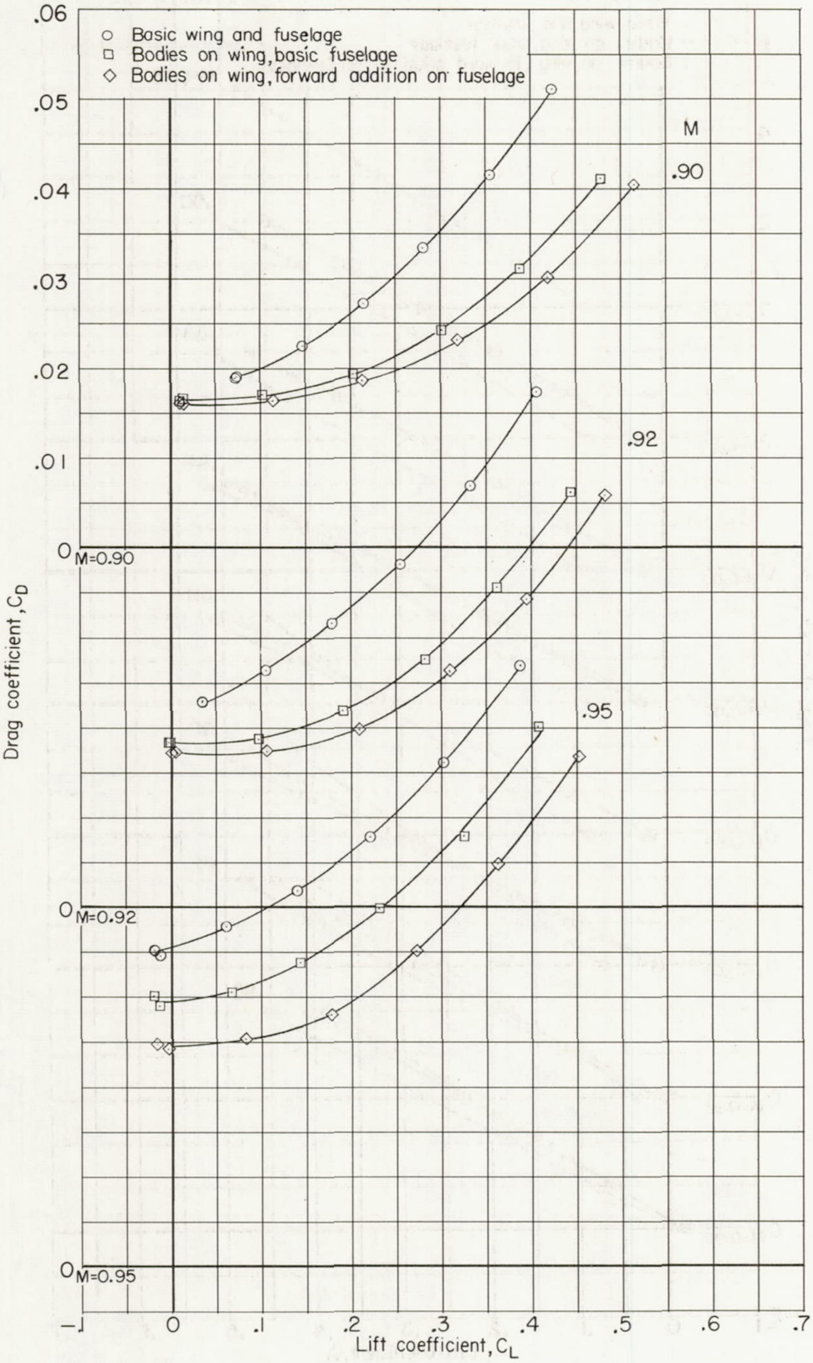
(d) Variation of drag coefficient, angle of attack, and pitching-moment coefficient with Mach number for lift coefficient of 0.3.

Figure 5.- Concluded.



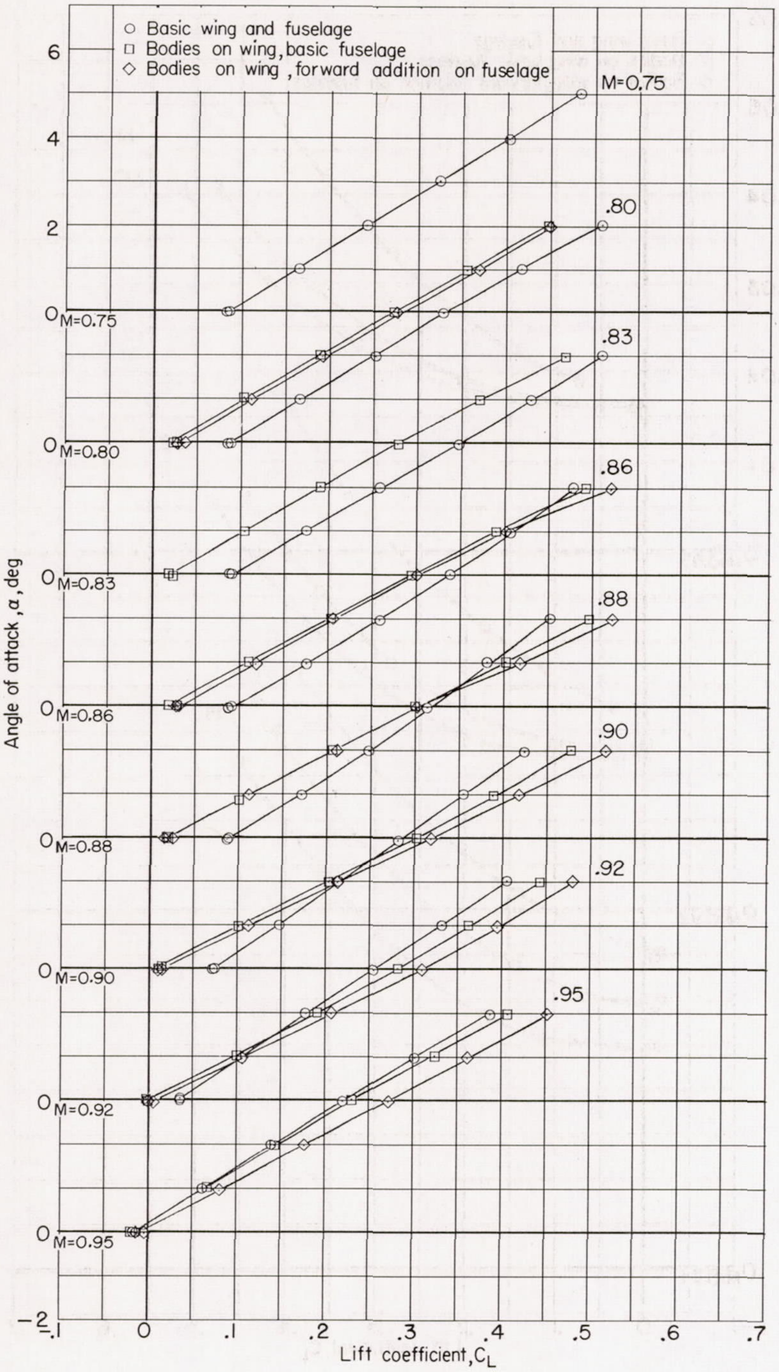
(a) Variation of drag coefficient with lift coefficient for various Mach numbers.

Figure 6.- Effect of added bodies and forward fuselage addition on aerodynamic characteristics of basic configuration with 35° of sweep.



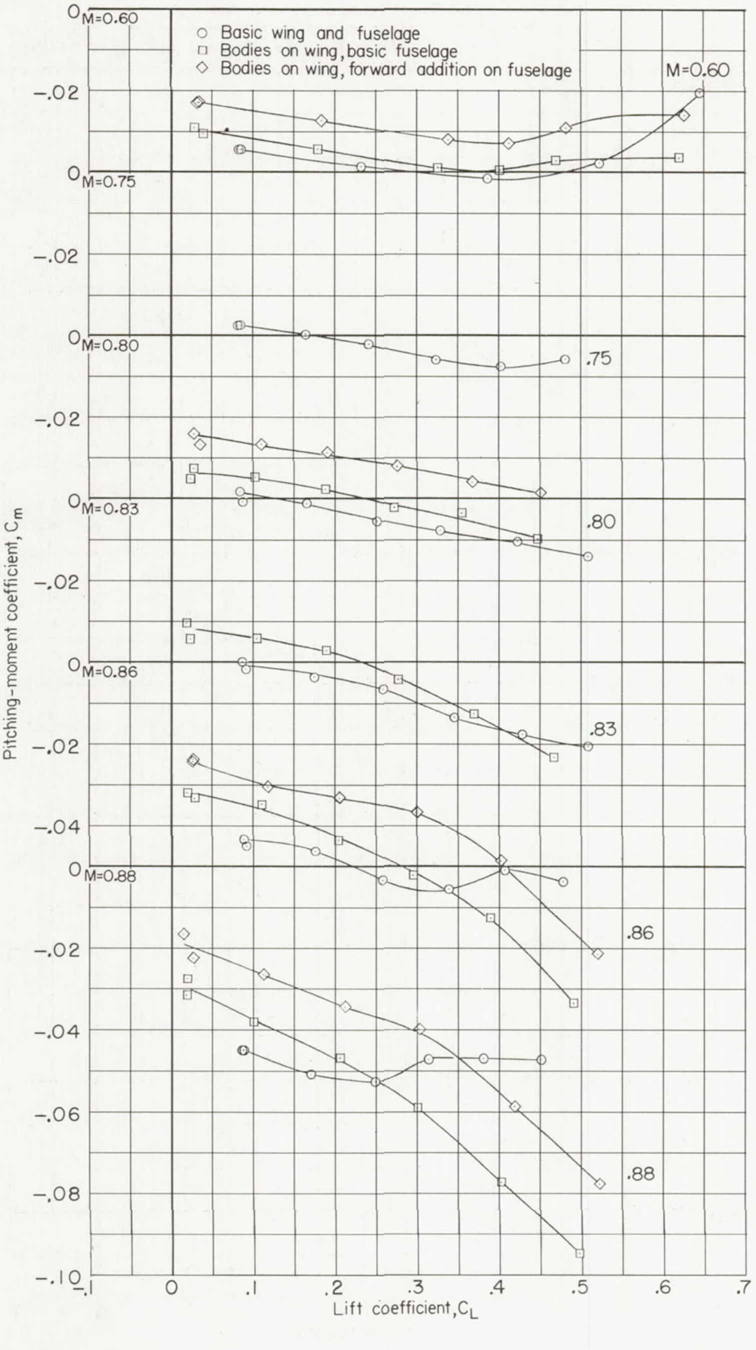
(a) Concluded.

Figure 6.- Continued.



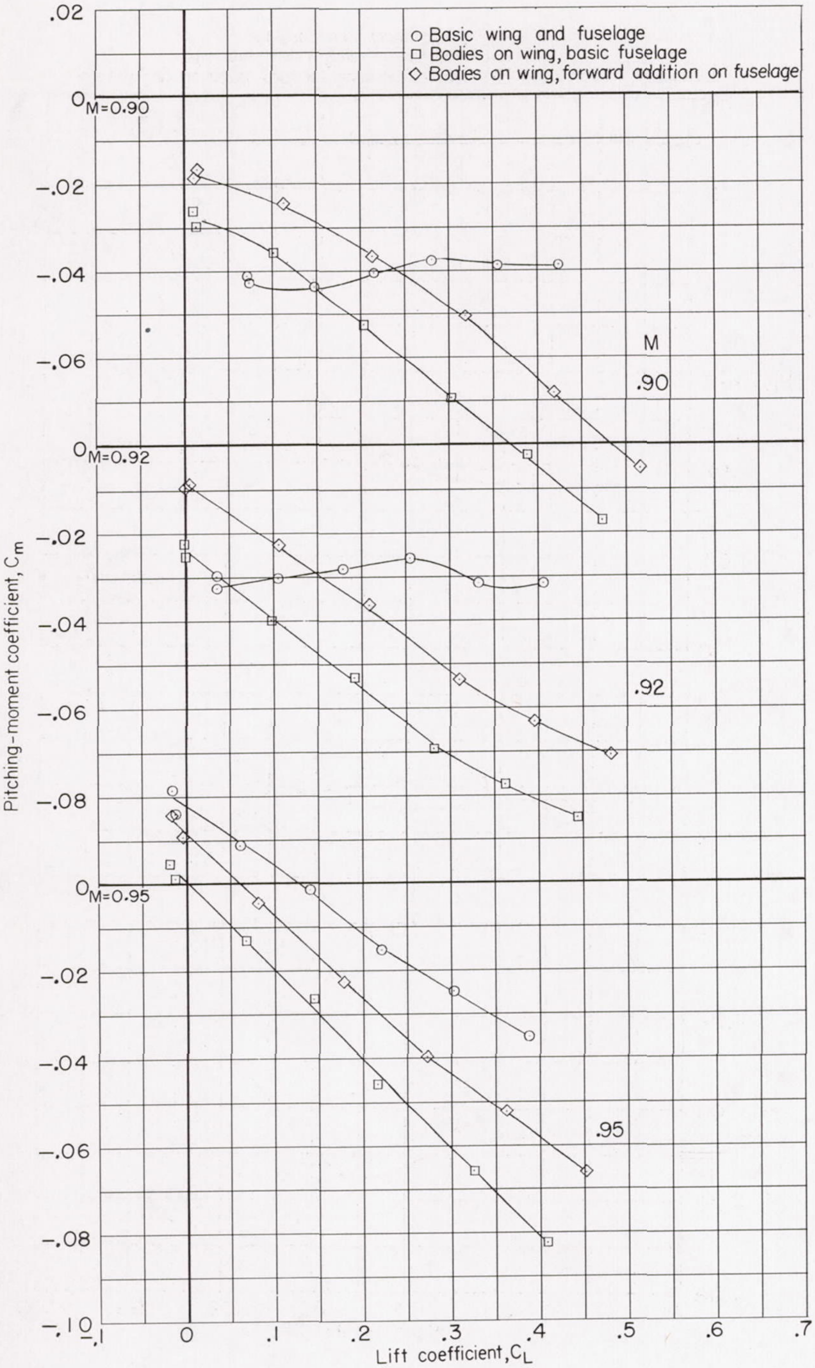
(b) Variation of angle of attack with lift coefficient for various Mach numbers.

Figure 6.- Continued.



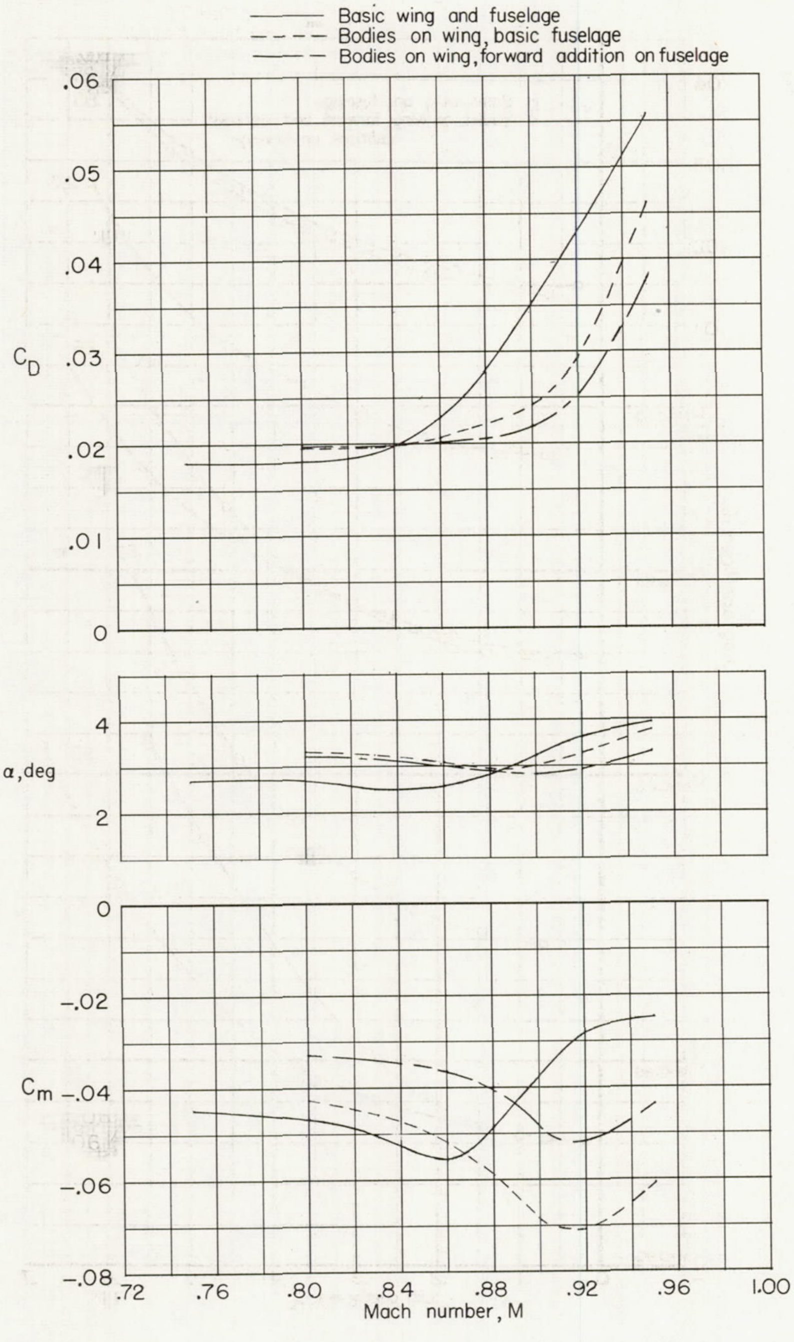
(c) Variation of pitching-moment coefficient with lift coefficient for various Mach numbers.

Figure 6.- Continued.



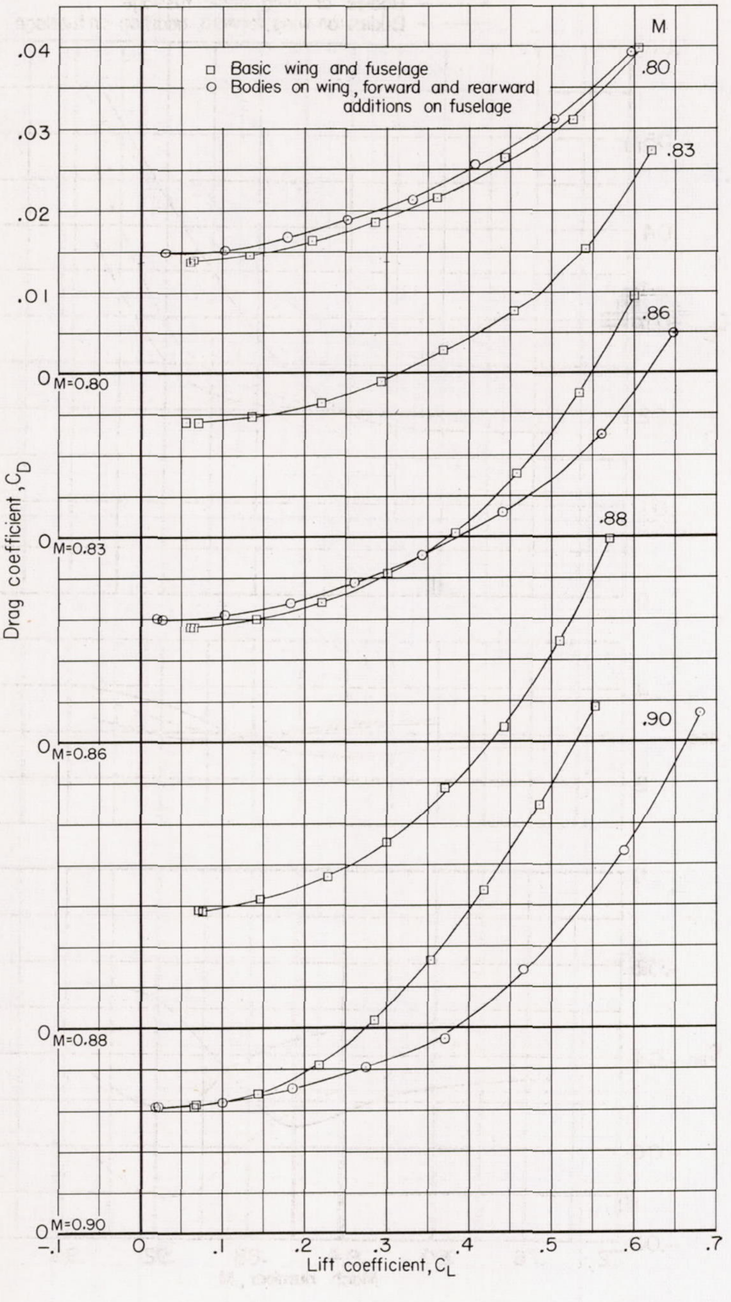
(c) Concluded.

Figure 6.- Continued.



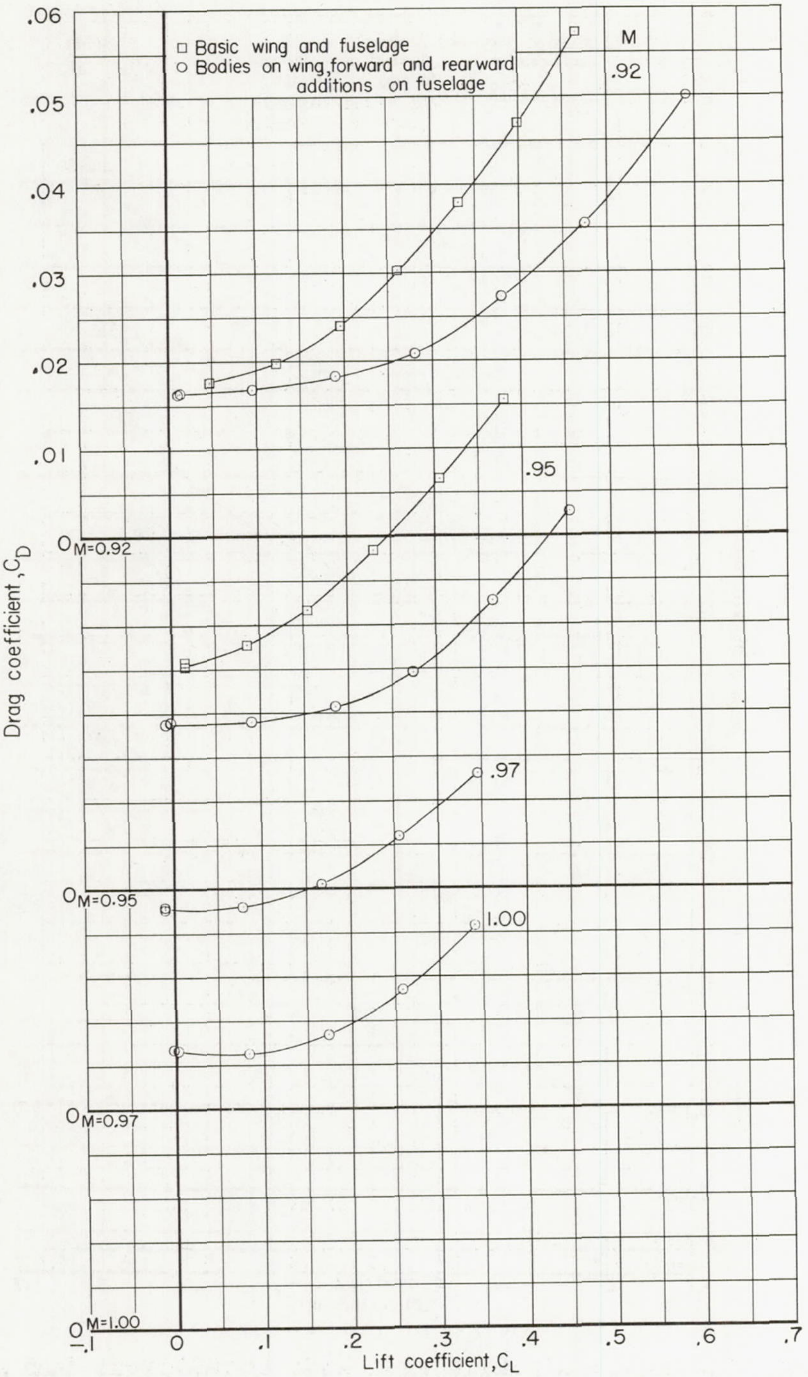
(d) Variation of drag coefficient, angle of attack, and pitching-moment coefficient with Mach number for lift coefficient of 0.3.

Figure 6.- Concluded.



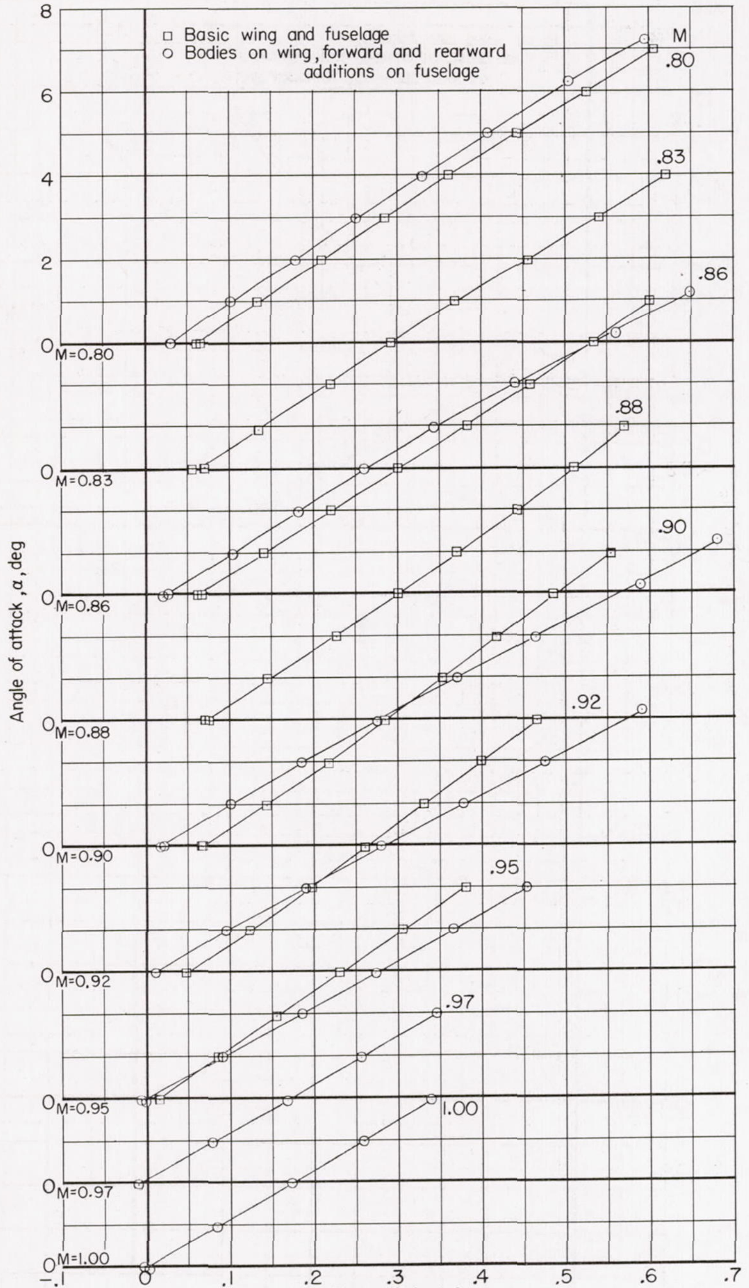
(a) Variation of drag coefficient with lift coefficient for various Mach numbers.

Figure 7.- Combined effect of added bodies and forward and rearward fuselage additions on aerodynamic characteristics of basic configuration with 40° of sweep.



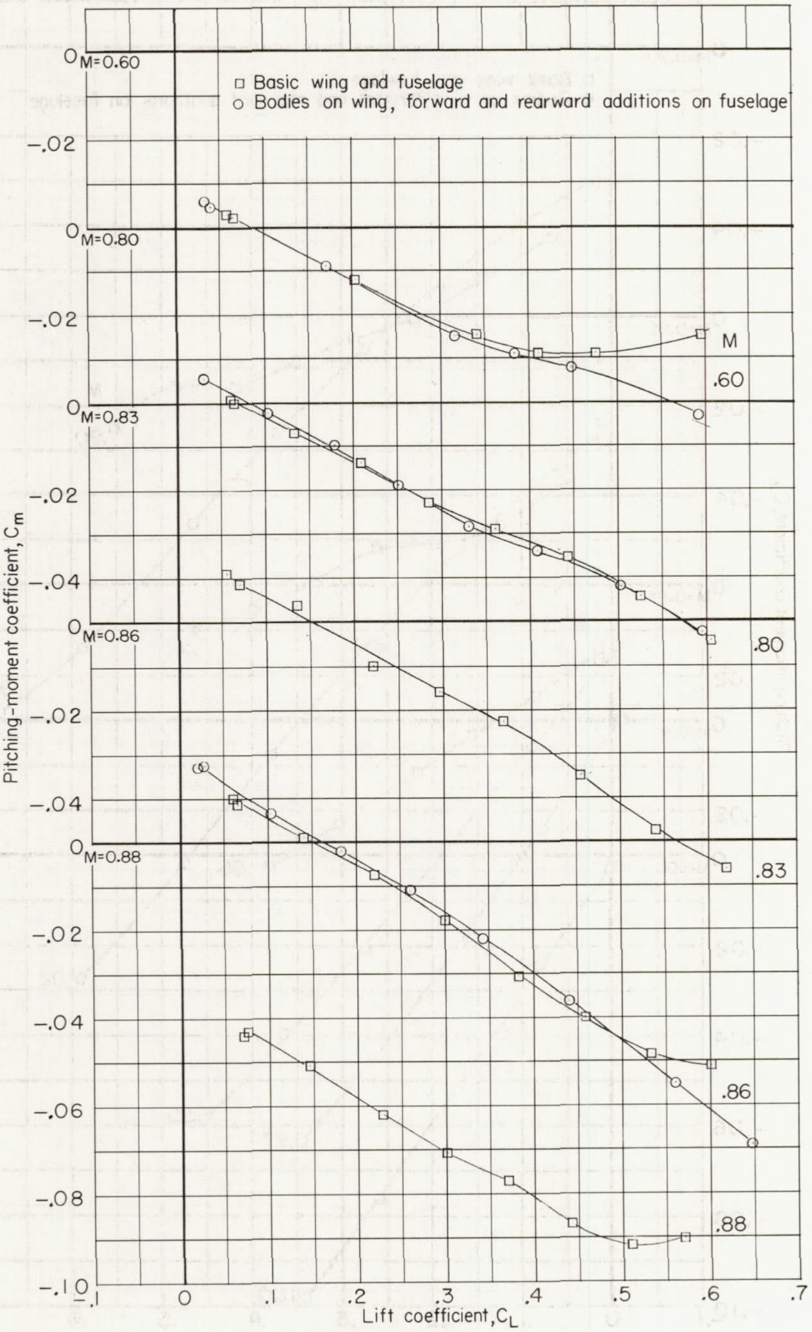
(a) Concluded.

Figure 7.- Continued.



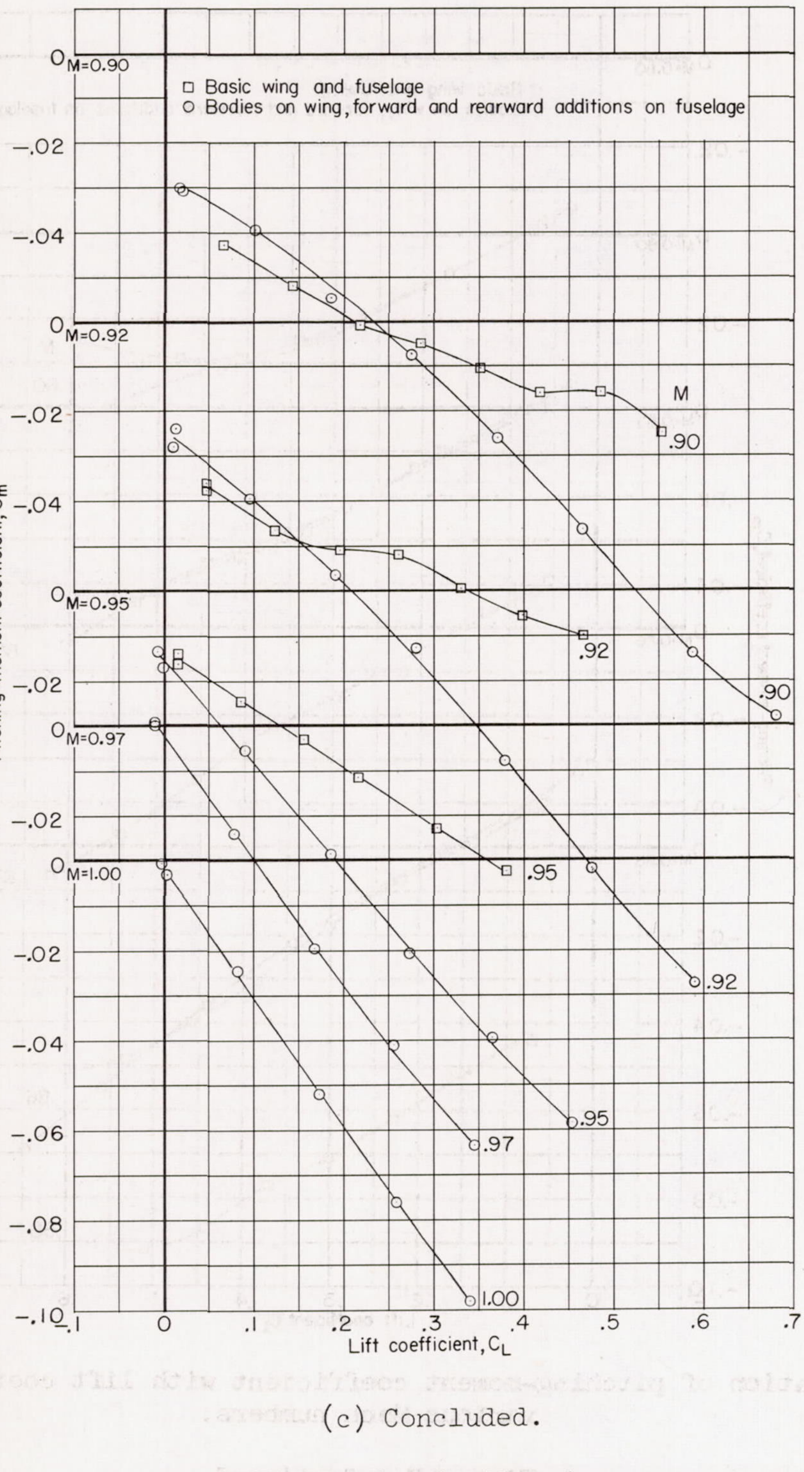
(b) Variation of angle of attack with lift coefficient for various Mach numbers.

Figure 7.- Continued.



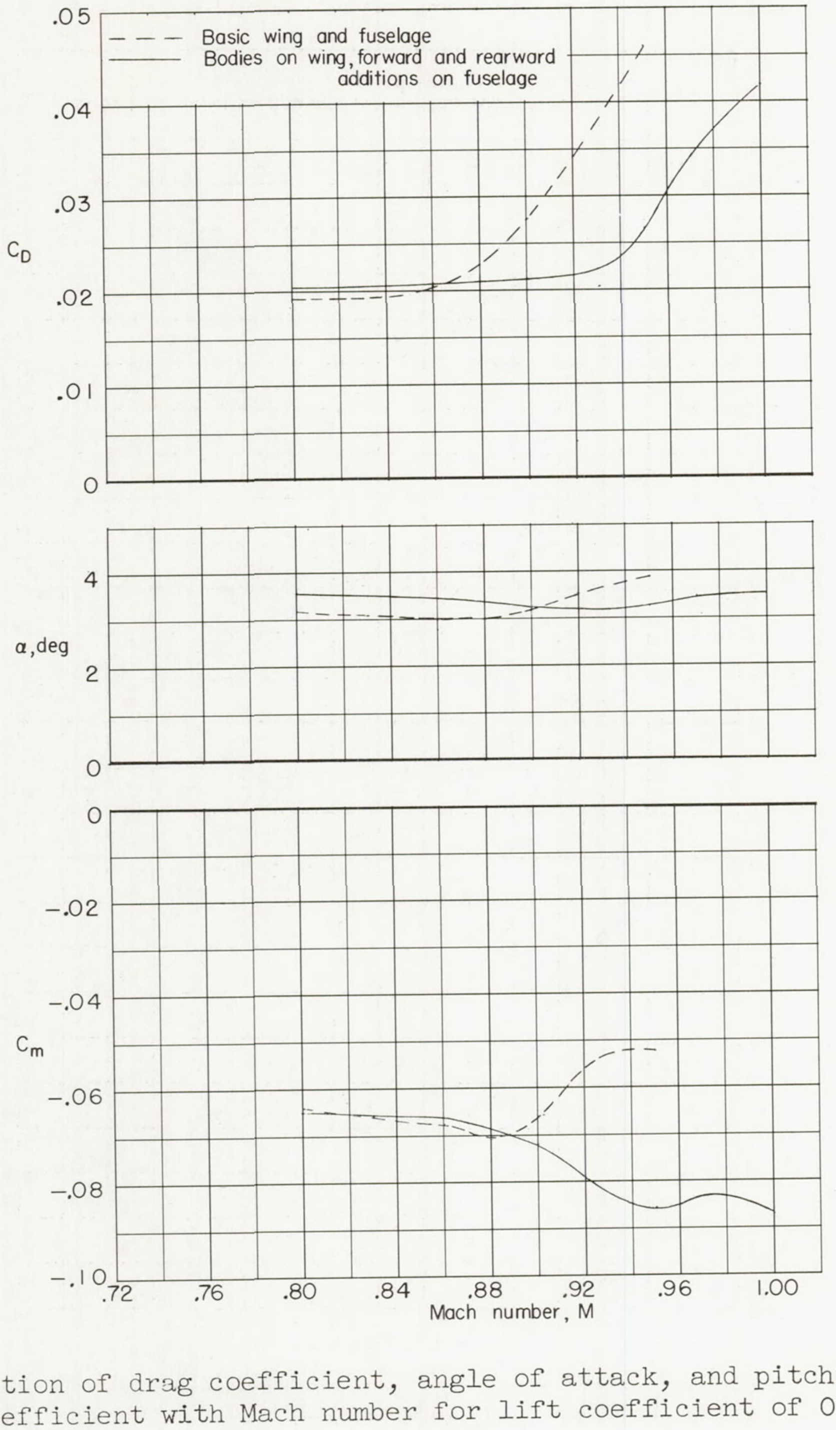
(c) Variation of pitching-moment coefficient with lift coefficient for various Mach numbers.

Figure 7.- Continued.



(c) Concluded.

Figure 7.- Continued.



(d) Variation of drag coefficient, angle of attack, and pitching-moment coefficient with Mach number for lift coefficient of 0.3.

Figure 7.- Concluded.

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