NACA

RESEARCH MEMORANDUM

PRELIMINARY STUDY OF AIRPLANE CONFIGURATIONS HAVING TAIL SURFACES OUTBOARD OF THE WING TIPS

By William C. Sleeman, Jr.

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON

March 24, 1958
Declassified May 29, 1961

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PRELIMINARY STUDY OF AIRPLANE CONFIGURATIONS HAVING TAIL SURFACES OUTBOARD OF THE WING TIPS

By William C. Sleeman, Jr.

SUMMARY

This report is concerned primarily with the concepts and applications underlying the basic arrangement of airplane configurations having tail surfaces outboard of the wing tips. This type of arrangement was conceived to be consistent with good supersonic performance characteristics and, also, to avoid some of the stability and trim-drag problems encountered on other supersonic configurations. The arrangements considered both experimentally and analytically in the present study had outboard horizontal tails and twin vertical tails mounted on slender bodies attached to the tips of a low-aspect-ratio swept wing.

Experimental results indicated that location of the horizontal-tail surfaces in the upwash field of the wing-tip vortices would be expected to be favorable from the standpoint of drag due to lift and trimmed lift-drag ratios at subsonic and supersonic speeds. Indications are that outboard tail configurations would also be expected to have satisfactory directional stability characteristics at both subsonic and supersonic speeds. Pitching-moment curves for an outboard tail model showed gradually increasing stability with lift up to a lift coefficient of approximately 1.0 at a Mach number of 0.60, above which a pitch-up tendency was indicated. These and other data indicate a possible longitudinal stability problem for outboard tail configurations, which is believed to be associated with instability caused by loss of upwash when the wing-tip vortex becomes displaced at high angles of attack.

An analytical study at Mach number 3.0 of effects of design variables has indicated that values of trimmed maximum lift-drag ratios were relatively insensitive to the amount of stability for static margins between 0 and 10 percent mean aerodynamic chord and the trends indicated in these estimates were verified experimentally at $M = 2.01$. Introduction of a small amount of pitching moment at zero lift may be used to compensate for losses in lift-drag ratio occurring as a result of somewhat higher stability. This analysis also indicated a gradual increase in trimmed maximum lift-drag ratio with both tail length and tail size; however, increases with tail length were generally quite small for lengths in excess of about one wing mean chord.

INTRODUCTION

Problems of maintaining adequate longitudinal and lateral stability and control over the range of angles of attack and sideslip and Mach number expected for current and projected airplane configurations are becoming increasingly severe as a result of certain design trends for high-speed airplanes. The relatively large high-fineness-ratio fuselages and relatively small thin wings have given rise to stability problems associated with large effects on tail surfaces of vortices emanating from both the long fuselage nose and from the tips of low-aspect-ratio wings. In addition to problems of avoiding regions of adverse flow for location of stabilizing surfaces, problems of airplane balance are becoming more acute with the design trend toward more rearward engine placement and accompanying rearward center-of-gravity position. With the weight far rearward, the wing must be placed far back and the tail length then becomes short. In fact, when a large airplane requiring perhaps four or six engines is considered, the condition is reached for which there is little point in attempting to install a horizontal tail behind the wing. In addition to the stability problems of conventional airplane configurations, performance penalties often result from the negative tail lift increments at supersonic speeds and associated high drag in trimmed flight. A more efficient configuration for supersonic cruise would, on the other hand, have the various components placed so that bad interference effects between components would be avoided and the trimming surfaces placed to provide favorable lift increments for trim. Also, arrangement of the airplane components would be such that all possible favorable interference effects could be exploited. The more obvious possible solutions to problems of balance and excessive supersonic stability would be to abandon the rearward horizontal tail and select a tailless configuration or to adopt a canard arrangement. These possibilities, particularly with respect to canard configurations, are discussed in references 1 and 2. Both the tailless and canard configurations may be subject to problems of obtaining adequate vertical-tail moment arm and of maintaining sufficient longitudinal control at high lift.

The present report presents some of the concepts and some supporting experimental evidence relative to airplane configurations having the horizontal stabilizing surfaces outboard and rearward of the wing tips. The configurations studied both experimentally and analytically had horizontal tails and twin vertical tails mounted on bodies attached to the tips of a low-aspect-ratio swept wing. This type of arrangement would not be expected to have a large drag penalty due to trimming at supersonic speeds as has been found for some other configurations. The location of the horizontal tail in an outboard position would be expected to be favorable from the standpoint of drag due to lift inasmuch as the tail, operating in the upwash from the wing-tip vortex, would recover part of the vortex energy as positive lift provided an upload on the tail is required for trimmed flight.

Interest in outboard tail configurations from stability considerations arises from past experience with a wide range of conventional and some unusual airplane arrangements. Results of many studies directed toward elimination of pitch-up at moderate and high angles of attack have indicated in general where horizontal tails may be favorably located behind certain wing plan forms. Other studies, however, (for example, see ref. 3) have not been as fruitful in defining placement and shape of the vertical tail to maintain adequate directional stability over a substantial angle-of-attack range. Past experience from the standpoint of directional stability therefore may be summarized with the observation that finding a favorable location and configuration for tail surfaces behind a wing on a large body can be extremely difficult. The results of reference 4 have shown, however, that significant directional stability benefits could be obtained by going to a three-body arrangement in which the volume of a large central body was distributed into a smaller forward central body and two rearward bodies placed outboard on the wing. These results and other results to be discussed later led to the present outboard tail concept which places the tail surfaces away from regions of large dynamic-pressure losses due to wing wake effects and away from extensive body vortices.

An analytical study has been made to investigate the effects of several basic geometric and aerodynamic parameters on the lift-drag ratios of a generalized arrangement having outboard tails. The assumed aerodynamic characteristics were selected to represent a flight Mach number of approximately 3.0.

SYMBOLS

Lateral stability results of this investigation are referred to the body axes which are shown in figure 1 together with an indication of positive directions of forces, moments, and angular deflections of the model. The lift and drag characteristics presented are, respectively, normal and parallel to the relative wind as shown in the side view in figure 1.

C_L lift coefficient, $\frac{\text{Lift}}{qS}$

C_D drag coefficient, $\frac{\text{Drag}}{qS}$

ΔC_D	drag due to lift
C_m	pitching-moment coefficient, $\frac{\text{Pitching moment}}{qS\bar{c}}$
C_{m_o}	pitching-moment coefficient at zero lift
C_l	rolling-moment coefficient, $\frac{\text{Rolling moment}}{qSb}$
C_n	yawing-moment coefficient, $\frac{\text{Yawing moment}}{qSb}$
C_Y	lateral-force coefficient, $\frac{\text{Lateral force}}{qS}$
L/D	lift-drag ratio, C_L/C_D
q	dynamic pressure, lb/sq ft
A	wing aspect ratio, $\frac{b^2}{S}$
M	Mach number
S	wing area (including area inside fuselage), sq ft
S_t	horizontal-tail area (total of both outboard panels), sq ft
S_v	vertical-tail area (total of both tails), sq ft
b	wing span
$\bar{c}$	wing mean aerodynamic chord, ft
l	tail length from moment reference, ft
x'	distance from wing-body aerodynamic center to airplane center of gravity, ft
y	spanwise distance from plane of symmetry in terms of wing semispan

$C_{V,v}$	vertical-tail volume coefficient, $\frac{S_v l_v}{(Sb)_{A=3}}$
α	angle of attack of fuselage center line, deg
β	angle of sideslip, deg
ϵ	downwash angle (with negative sign, upwash), deg
i_t	incidence of horizontal tail, deg

Subscripts:

β	partial derivative of a coefficient with respect to sideslip; for example, $C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$
t	horizontal tail
v	vertical tail
L	left
R	right

Configuration designation:

W	wing
F	fuselage
N	outer bodies
V	twin vertical tails
H_0	horizontal tails at 0.25° setting
H_{14}	horizontal tails at -14.69° setting
E	ventral fins

DISCUSSION

Some of the problems which confront the designers of high-speed aircraft have been discussed in the introduction of this report with regard to different types of airplane configurations. The magnitude of the difficulties expected for some of these configurations has stimulated interest in other arrangements and the outboard tail configuration is a possible design which may avoid some of the major problems of other airplane arrangements. The discussion of outboard tail configurations is concerned primarily with the salient concepts basic to this airplane arrangement and only a brief reference is made to experimental results from several different studies of configurations having wings of low aspect ratio and swept or modified delta plan forms.

Stability and Control Characteristics

Longitudinal.- Problems of longitudinal instability at high lift for conventional center-tail airplane configurations have been studied extensively in experiments at low and high speeds and some solutions for these problems have been indicated. Large increases in longitudinal stability have been found to occur on conventional airplane arrangements in going from subsonic to supersonic speeds and one of the large contributions to this stability increase has come from the horizontal-tail surfaces. This excessive stability at supersonic speeds can give rise to high drag due to trimming and limit the longitudinal controllability for a given control deflection. A number of solutions for problems of aerodynamic-center shifts with Mach number have been devised, such as control of the center-of-gravity location and variable airplane geometry. The nature of these possible solutions attests the importance of this problem and it is desirable to assess outboard tail configurations from the standpoint of transonic aerodynamic-center shift.

Experimental results have been obtained at subsonic speeds in the Langley high-speed 7- by 10-foot tunnel on the same outboard tail model that was tested at $M = 2.01$ in the Langley 4- by 4-foot supersonic pressure tunnel (ref. 5). Some pitching-moment results obtained in these studies are presented in figure 2. These results show that for this configuration there was an increase in $\frac{\partial C_m}{\partial C_L}$ for the complete model from -0.09 (for lift coefficients between 0.13 to 0.35) at $M = 0.90$ to -0.18 at $M = 2.01$. The stability increase with Mach number is somewhat larger than that for some tailless or canard designs (ref. 1); however, this increase of stability is much less than encountered on many conventional center-tail configurations (ref. 1). Effects of the level of stability at supersonic speeds on trimmed lift-drag ratios are discussed later.

The arrangement of an outboard tail configuration appears to be compatible with the use of wing trailing-edge lift flaps for landing and take-off. This type of airplane would have a rearward location of the center of gravity (perhaps 50 to 70 percent of the wing mean aerodynamic chord) and, therefore, the diving moments normally created by deflection of the high-lift flaps would be less than for a conventional or canard configuration because the flap load would be located closer to the center of gravity.

The outboard location of the horizontal tail would be expected to be favorable from the standpoint of control effectiveness and stability at both subsonic and supersonic speeds inasmuch as the tail would not be located in regions of high losses in dynamic pressure from wing or body wakes. Some experimental results obtained at a Mach number of 0.60 for an outboard tail arrangement having a 45° swept wing of aspect ratio 1.55 are presented in figure 3 to show pitching-moment characteristics of an outboard tail model with two stabilizer settings at subsonic speeds. This configuration was derived from the aspect-ratio-3 modified delta-wing model of reference 6. The pitching-moment curves of figure 3 show gradually increasing stability with lift coefficient up to a lift coefficient of unity, above which an abrupt unstable tendency is indicated. This high-lift instability is caused by both an unstable break in the tail-off characteristics and by a decrease in the tail contribution. This decrease in tail contribution is believed to have resulted from a loss of upwash over the tail at high angle of attack.

Effective upwash angles for the configuration shown in figure 3 were obtained from tail-on and tail-off data and are presented in figure 4 for several high subsonic Mach numbers. These results show a linear variation of upwash with angle of attack at low and moderate angles of attack which suggests that perhaps the wing-tip vortex remained at approximately the same position in relation to the tail at low angles of attack (up to about 10° for $M = 0.60$ and 0.80). A reversal in the slope of the curve for $M = 0.60$ occurred near 20° angle of attack which would have a destabilizing effect on the tail contribution even though the tail was in an upflow. This loss in tail contribution might be expected at high angles to result from an upward and inward movement of the tip-vortex center. This possible loss of upwash at high angles of attack would be undesirable on an airplane unless it was counteracted by a stabilizing shift in tail-off aerodynamic center. It appears that more research is needed to find means for alleviating this possible longitudinal stability problem for outboard tail configurations.

Directional stability.- Location of the vertical-tail surfaces in an outboard position might be expected to have certain directional stability advantages over a conventional centrally mounted surface. As mentioned previously, the results of reference 4 have shown that gains in directional stability at high angles of attack could be obtained with a three-body arrangement with the two rearward bodies placed outboard on the wing. The results of reference 7 have shown also that removal of the afterbody of highly swept wing-body configurations had a favorable effect on the directional stability at high angles of attack. Some experimental directional stability characteristics are summarized in figure 5(a) for both tail-on and tail-off. In order to compare these results with the original wing-body configuration (ref. 6) from which the outboard tail model was derived, the coefficients for all the configurations are based on the geometry of the aspect-ratio-3 modified delta wing. The tail-off results for the 45° swept wing (fig. 5(a)) show significant directional stability gain at high angles compared with the results for a conventional aspect-ratio-3 wing-body configuration.

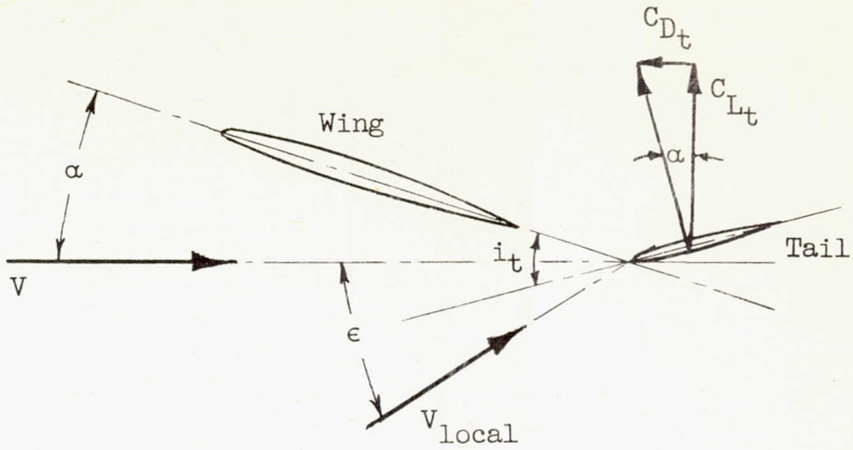
The tail-on results of figure 5(a) show a high level of directional stability for the outboard tail model with a decrease in $C_{n_{\beta}}$ occurring at high angles of attack. These results are not directly comparable with those for the conventional model inasmuch as ventral fins were installed on the outboard tail model. Some results are presented in figure 5(b), however, for a similar outboard tail model having 65° sweep of the wing leading edge which show directional stability characteristics with and without the ventral fins. These results (fig. 5(b)) show the trends with tail volume at low angles of attack that would be expected from the tail-volume coefficients given; however, at high angles of attack the outboard tail model which had less tail volume had more directional stability than the conventional model. Test results presented in reference 5 and unpublished data for a configuration similar to that shown in figure 9 have indicated satisfactory directional stability characteristics at supersonic speeds for two outboard tail configurations.

Lateral control.- The outboard location of the horizontal surfaces provides a relatively long moment arm for producing rolling moments by differential deflection of these surfaces and it would be desirable to consider this control aspect of outboard tail arrangements. Some results are presented in figure 6 for Mach number 0.60 to illustrate the lateral characteristics to be expected with the horizontal surfaces deflected differentially as roll producers. The nominal stabilizer settings of 0° and -14° would represent approximately 7° of differential deflection from a basic trim setting of -7° at a low angle of attack, and the -14° and -25° stabilizer settings would apply to a basic longitudinal trim condition at a higher angle of attack. Rolling-moment results obtained with the 0° and -14° stabilizer settings show a fairly constant effectiveness up to about 10° angle of attack, above which stalling of the tail with 0° stabilizer setting causes the effectiveness to decrease rapidly. Effects of negative tail stall on the tail with the -25° setting are evident at low angles of attack for the -14° and -25° stabilizer settings. At high angles of attack, for the latter combination, only about a 25-percent reduction in rolling power from the low-angle-of-attack rolling power was indicated. Another aspect of interest shown in figure 6 is the comparatively small values of the ratio of yawing moment to rolling moment obtained over the angle-of-attack range when compared with the tail roll control results of reference 8. The fact that the yawing moment changes sign at high angles of attack (fig. 6) may be as undesirable as high yawing moments induced at low angles of attack; however, with the stabilizer settings for trim (-14° and -25°) at high angle of attack the reversal would be much less objectionable than that shown for the lower settings.

Lift and Drag Characteristics

One of the main reasons for considering airplane configurations having outboard tails is the possibility that very small penalties or even favorable increments in L/D due to trimming may be obtained at supersonic speeds. The outboard location of the horizontal tail would be expected to be favorable from the standpoint of drag due to lift inasmuch as the tail operates in the upwash from the wing-tip vortex and would recover part of the vortex energy as positive lift. This effect may be considered as an increase in effective aspect ratio of the basic wing obtained by adding an undeflected outboard tail. Some experimental data illustrating this effect are shown in figure 7 for the 45° swept-wing outboard tail model. These results are compared with the basic aspect-ratio-3 conventional model of reference 6 and the coefficients are based on the geometry of the conventional model. These results show that the outboard tail model had the same lift-curve slope at low angles of attack as the basic aspect-ratio-3 model, and at high angles of attack the outboard tail model had higher values of lift at a given angle than the aspect-ratio-3 model. The wing and tail of the 45° swept-wing outboard tail model were derived from the parent aspect-ratio-3 model by effectively cutting off the tips of the wing and translating them rearward on the outer bodies to form the tail surfaces; this gives the same theoretical total plan-form area. It would, therefore, appear that the surface area was more effectively placed in the rearward position where it could contribute stability and controllability rather than acting as a wing tip.

The drag results presented in figure 7 show that a reduction in drag due to lift accompanied addition of the outboard tails; however, the drag due to lift of the outboard tail model was somewhat higher than the basic aspect-ratio-3 model up to moderately high lift coefficients. A further reduction in drag due to lift for the outboard tail arrangement might be expected to accompany negative deflection of the horizontal tail. An explanation of the possible beneficial effect of negative incidence on drag may be obtained from the following sketch:



In this sketch, the wing is operating at an angle of attack α and the tail angle of attack in the upwash field of the wing tip is $\alpha - \epsilon + i_t$. The tail must, of course, carry a positive lift for trim in order to have a beneficial effect on the lift-drag ratio, and the resultant force on the tail would be inclined forward for positive tail lift at a negative stabilizer setting (assuming that the resultant force was normal to the tail chord plane). This forward inclination of the resultant force on the tail has a forward component in the streamwise direction corresponding to a negative drag increment. This concept may also be extended to drag reduction by means of proper orientation of the twin vertical tails in the sidewash field from the wing-tip vortices. For this application a small amount of "toe out" of the vertical tails might be beneficial; however, use of such a scheme for drag reduction would have to be a carefully tailored arrangement, possibly designed only for a cruise condition.

Experimental results of reference 5 obtained at a Mach number of 2.01 show the expected reduction in drag due to lift with negative incidence on the outboard tails. The drag polars and corresponding lift-drag ratios from reference 5 are repeated in figure 8 of the present report. These results show significant reductions in drag due to lift in going from zero to negative tail settings; however, the corresponding increase in minimum drag had a compensating effect on lift-drag ratios. The lift-drag ratios presented in figure 8 show a relatively small decrease in $(L/D)_{max}$ for negative increments in stabilizer settings from 0° to -7.4°. These results indicate that the maximum lift-drag ratios for the trimmed conditions for the outboard tail configurations may be relatively insensitive to control deflection for moderate negative values of deflection. This would imply as indicated in reference 5 that the maximum trimmed lift-drag ratios for the outboard tail configuration would be relatively insensitive to the amount of stability for low and moderate values of static margin.

Analytical Study of Effects of Some Design Variables

The general arrangement of outboard tail configurations is so different from current conventional airplane arrangements that past experience cannot be utilized with confidence to define the most advantageous proportions and arrangement of the various individual components from the standpoint of performance. For this reason it is desirable to determine some overall trends from approximate calculations of the expected variation of maximum lift-drag ratio with certain basic geometric and aerodynamic parameters. A few estimates have been made which show effects on trimmed $(L/D)_{max}$ of relative size of the wing and outboard tails, effects of changes in static margin, and effects of the flow field in which the tails operate. The various aerodynamic parameters chosen for the estimates were selected to represent values which might be applicable to a flight Mach number of 3.0. Inasmuch as these estimates were intended to establish trends with certain basic geometric variables, the magnitude of the estimated values is not as significant as the trends shown. The characteristics indicated for some of the outboard tail arrangements are not necessarily unique to the outboard tail configuration, and other arrangements, such as a highly swept all-wing design, may provide similar characteristics through careful design. Details of the procedures and equations used in the estimates are given in the appendix. An outboard tail configuration is shown in figure 9 to illustrate the type of arrangement considered in the estimates.

Effect of flow field.- The variation of upwash outboard of the wing tip as determined by the theoretical relationships of reference 9 at $M = 3.0$ is presented in figure 10. This figure shows the expected high values of upwash near the wing tip and the rapid diminishment of upwash away from the tip. It is readily apparent that a short-span tail outboard of the wing tip would be in a large upwash field and a large-span horizontal tail would be in a much smaller overall upwash field. Figure 11 has been prepared to illustrate effects of flow field on trimmed $(L/D)_{max}$ values for airplane configurations having a tail length of one wing mean aerodynamic chord and ratios of tail area to wing area of 10 and 20 percent. The different values of $\frac{\partial\epsilon}{\partial\alpha}$ shown might correspond to tails of various spans or to different positions of the tail behind the wing. For example, positive values of $\frac{\partial\epsilon}{\partial\alpha}$ correspond to conventional center tails and negative values correspond to tails outboard of the wing tip. The overall trend of increasing values of $(L/D)_{max}$ as $\frac{\partial \epsilon}{\partial \alpha}$ becomes more negative is to be expected, and the reduction in trimmed $(L/D)_{max}$ with increased stability for the conditions of conventional configurations $\left(\text{positive values of } \frac{\partial \epsilon}{\partial \alpha}\right)$ is also well known. These estimates also indicate the trends observed in the experimental results of reference 5 with regard to effects of stability in that at negative values of $\frac{\partial \epsilon}{\partial \alpha}$ trimmed $(L/D)_{max}$ values are relatively insensitive to the amount of stability for static margins between 0 and 10 percent $\bar{c}$. This observation should apply to the outboard tail configurations being considered inasmuch as values of $\frac{\partial \epsilon}{\partial \alpha}$ from -0.40 to -0.60 averaged over the tail span have been calculated. The trends of $(L/D)_{max}$ with changes in stability indicated in these estimates were substantiated experimentally at $M = 2.01$ in the results of reference 5. Because of the low sensitivity to the amount of stability, relatively high supersonic stability probably could be tolerated from considerations of trimmed $(L/D)_{max}$. Thus, the problems introduced by the stability change in going from subsonic to supersonic speeds may be less serious than for some other designs.

Effect of horizontal-tail size.- One of the most important variables to consider in achieving an efficient outboard tail arrangement is the relative size of the wing and horizontal tail surfaces. This relationship has a direct effect on the stability and controllability of a given wing-body arrangement and upon the permissible center-of-gravity locations for given stability levels. The tacit assumption made in the estimates for the outboard tail configurations is that for the cruise condition an upload is carried on the tail surfaces when the aircraft is in longitudinal trim. The tail surfaces then are contributing to the airplane lift and may be considered a part of the total lifting surface area. For this reason, the total area of the wing plus tail was held constant for the present calculations as the ratio of tail area to wing area was varied. The plan forms of both the wing and tail remained the same when the area ratio varied; however, the effective upwash over the tail was determined from the curve of upwash presented in figure 10 for each size tail. The values of effective upwash used were -0.627, -0.479, and -0.401 for ratios of tail area to wing area of 0.1, 0.2, and 0.3, respectively. Estimated effects of the ratio of tail area to wing area on maximum L/D presented in figure 12 show a general increase in trimmed $(L/D)_{max}$ with increasing tail size. As shown previously, there is little effect of stability within a certain range of stability values. A significant loss in $(L/D)_{max}$ was indicated at low values of the ratio of tail area to wing area for an increase in static margin from -0.10 to -0.20; however, this loss was greatly diminished for higher values of tail-area—wing-area ratio.

Effect of tail length.- The estimates of effects of tail size were extended to assess the influence of tail length for two values of tail-area—wing-area ratio. Results from these estimates presented in figure 13 show that an overall increase in trimmed $(L/D)_{max}$ occurred with increasing tail length for negative values of $\frac{\partial C_m}{\partial C_L}$. The results show also that, for values of $\frac{\partial C_m}{\partial C_L}$ between 0 and -0.10, little gain in $(L/D)_{max}$ would be expected from increases in tail length above $l/\bar{c} = 1.0$ for the arrangements being considered.

The estimates that have been considered have indicated rather large changes in configuration proportions for given constant values of stability. These constant values of stability were achieved in the estimates by changing the distance between the wing-body aerodynamic center and the reference center of gravity the required amount for the tail contribution of each configuration. This type of adjustment is useful in assessing overall effects in computations; however, not all of the combinations giving a constant value of stability may be realistic for practical application to an airplane. Figure 14 presents the variation of the distance between the tail-off aerodynamic center and center of gravity with both tail-area—wing-area ratio and tail length for the three values of stability used in the estimates. The relationships presented in figure 14 show large variations in $x'/\bar{c}$ for the conditions covered in the estimates. Fairly large positive values of $x'/\bar{c}$ might be expected to accompany configurations with rearward placed engine installations; however, large positive values of $x'/\bar{c}$ would aggravate the problem of attaining sufficient moment arm for the vertical tail. Very small positive or negative values of $x'/\bar{c}$ would be favorable from the standpoint of vertical-tail moment arm; however, a forward center-of-gravity location would probably not be favorably located from consideration of pitching moments resulting from deflection of trailing-edge lift flaps. These two factors are, of course, obvious examples of many factors that enter into determination of an overall configuration, but they illustrate possible limitations that could require selection of a configuration somewhat less desirable than indicated as optimum.

Effect of initial pitching moment.- The tail load required for trim is a function of the tail-off pitching moment, which usually varies with angle of attack, and any additional initial pitching moment existing at zero lift. The estimated results discussed so far have not included the latter effect which is considered invariant with angle of attack. Some additional estimates have been made to illustrate the possible effects on trimmed $(L/D)_{max}$ of using values of C_{m_o} other than zero and the results of these estimates are presented in figure 15. The assumption was made for these calculations that the various values of C_{m_o} were achievable with no change in C_D or C_L. These estimates show that for a given amount of stability there is a value of C_{m_o} which gives a peak value of trimmed $(L/D)_{max}$. Furthermore, it appears that the peak values of $(L/D)_{max}$ are the same for each amount of stability investigated; this suggests that there are many combinations of C_{m_o} and stability which would be expected to give the same maximum value of trimmed $(L/D)_{max}$ for a particular outboard tail configuration. This characteristic of combinations of C_{m_o} and $\frac{\partial C_m}{\partial C_L}$ may be utilized to approach more closely an optimum arrangement which might otherwise be unattainable because of the practical limitations discussed earlier.

CONCLUDING REMARKS

A preliminary study of airplane configurations having the tail surfaces located outboard of the wing tips may be summarized in the following observations.

1. Experimental results indicated that location of the horizontal-tail surfaces in the upwash field of the wing-tip vortices would be expected to be favorable from the standpoint of trimmed lift-drag ratios at subsonic and supersonic speeds.

2. Pitching-moment curves for an outboard tail model showed gradually increasing stability with lift up to a lift coefficient of approximately 1.0 at a Mach number 0.60, above which a pitch-up tendency was indicated. These and other data indicate a possible longitudinal stability problem for outboard tail configurations which is believed to be associated with instability caused by loss of upwash when the wing-tip vortex becomes displaced at high angles of attack.

3. Indications are that outboard tail configurations would be expected to have satisfactory directional stability characteristics at both subsonic and supersonic speeds.

4. An analytical study at Mach number 3.0 of effects of design variables has indicated that values of trimmed maximum lift-drag ratios were relatively insensitive to the amount of stability for static margins

between 0 and 10 percent mean aerodynamic chord. The trends indicated in these estimates were verified experimentally at $M = 2.01$. Introduction of a small amount of pitching moment at zero lift may be used to compensate for losses in L/D occurring as a result of somewhat higher stability.

5. This analysis also indicated a gradual increase in trimmed $(L/D)_{max}$ with both tail length and tail size; however, increases with tail length were generally quite small for lengths in excess of about one wing mean chord.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 13, 1958.

APPENDIX

RELATIONSHIPS USED IN ESTIMATION OF LIFT-DRAG RATIOS

The equation used in estimating the effective upwash over the outboard horizontal tail was derived from reference 9 and is

$$\frac{\partial\epsilon}{\partial\alpha} = \left(\frac{cc_l}{C_L c_{av}}\right)\frac{c_{av}C_{L_\alpha}}{2\frac{b}{2}}\frac{1}{2\pi}\left[\frac{-\sqrt{(mx - 1)^2 - \beta^2 m^2 (y - 1)^2}}{(y - 1)(mx - y)} + \frac{\sqrt{(mx - 1)^2 - \beta^2 m^2 (y + 1)^2}}{(y + 1)(mx + y)} + \frac{2m\sqrt{x^2 - \beta^2 y^2}}{(mx - y)(mx + y)}\right] \qquad (1)$$

where $\frac{cc_l}{C_L c_{av}}$ is assumed to be unity for present computations and

c_{av} wing average chord

C_{L_α} wing lift-curve slope, radians

m cotangent half-chord sweep angle

x distance rearward from apex of swept lifting line in terms of wing semispan

y spanwise distance from plane of symmetry in terms of wing semispan (considered positive for right wing)

$\beta = \sqrt{M^2 - 1}$

Use of equation (1) gives values of $\frac{\partial\epsilon}{\partial\alpha}$ along the span of the tail. Values of effective upwash over the tail were obtained from integration of the product of local $\frac{\partial\epsilon}{\partial\alpha}$ and local chord across the tail span.

The following approximate relationships were used in estimations of trimmed $(L/D)_{max}$. The symbol notation is the same as that given in the body of the report and only symbols not previously defined are defined in this appendix.

The total airplane lift, drag, and pitching-moment coefficients can be represented by the following expressions:

$$C_L = \alpha C_{L_\alpha}' + C_{L,t} \frac{S_t}{S} \cos \epsilon - C_{D,t} \frac{S_t}{S} \sin \epsilon$$

$$C_D = C_{D_o} + \Delta C_D - C_{L,t} \frac{S_t}{S} \sin \epsilon + C_{D,t} \frac{S_t}{S} \cos \epsilon$$

$$C_m = C_{m_o} + \alpha C_{L_\alpha}' \frac{x}{\bar{c}} - C_{L,t} \frac{S_t}{S} \frac{l}{\bar{c}} \cos \epsilon$$

where

C_{L_α}' lift-curve slope of tail-off configuration

C_{D_o} drag coefficient at zero lift of tail-off configuration

C_{m_o} pitching-moment coefficient at zero lift of tail-off configuration

t horizontal-tail surfaces

For low angles of attack, at least to values corresponding to $(L/D)_{max}$, the assumption that $\cos \epsilon = 1$ and $\sin \epsilon = \epsilon$ should be permissible. Substitution of these assumed values into the foregoing lift-, drag-, and pitching-moment-coefficient expressions gives:

$$C_L = \alpha C_{L_\alpha}' + C_{L,t} \frac{S_t}{S} - \alpha \frac{\partial \epsilon}{\partial \alpha} \frac{S_t}{S}\left(C_{D_{o,t}} + C_{L,t}^2 \frac{\partial C_{D,t}}{\partial C_{L,t}^2}\right) \tag{2}$$

$$C_D = C_{D_o} + \alpha^2 \left[\left(C_{L_\alpha}'\right)^2 \frac{\partial C_D}{\partial C_L^2}\right] + \alpha \frac{\partial \epsilon}{\partial \alpha} \frac{S_t}{S} C_{L,t} + \frac{S_t}{S}\left(C_{D_{o,t}} + C_{L,t}^2 \frac{\partial C_{D,t}}{\partial C_{L,t}^2}\right) \tag{3}$$

$$C_m = C_{m_o} + \alpha C_{L_\alpha}' \frac{x'}{\bar{c}} - C_{L,t} \frac{S_t}{S} \frac{l}{\bar{c}} \tag{4}$$

The tail load required for trim is given by the following expression:

$$C_{L,t} = \frac{C_{m_o} + \alpha C_{L_\alpha}' \frac{x'}{\bar{c}}}{\frac{S_t}{S} \frac{l}{\bar{c}}} \tag{5}$$

Values of $C_{L,t}$ determined from equation (5) are used in equations (2) and (3). The static margin for a given arrangement can be expressed as

$$\frac{\partial C_m}{\partial C_L} = \frac{C_{m_\alpha}}{C_{L_\alpha}'} = \frac{C_{L_\alpha}' \frac{x'}{\bar{c}} - \left(1 - \frac{\partial \epsilon}{\partial \alpha}\right) C_{L_{\alpha,t}} \frac{S_t}{S} \frac{l}{\bar{c}}}{C_{L_\alpha}' + \left(1 - \frac{\partial \epsilon}{\partial \alpha}\right) C_{L_{\alpha,t}} \frac{S_t}{S}}$$

$$= \frac{\frac{x'}{\bar{c}} - \frac{l}{\bar{c}} \left[\frac{C_{L_{\alpha,t}}}{C_{L_\alpha}'} \frac{S_t}{S} \left(1 - \frac{\partial \epsilon}{\partial \alpha}\right)\right]}{1 + \left[\frac{C_{L_{\alpha,t}}}{C_{L_\alpha}'} \frac{S_t}{S} \left(1 - \frac{\partial \epsilon}{\partial \alpha}\right)\right]}$$

The distance between the tail-off aerodynamic center and center of gravity required for a given static margin is given by

$$\frac{x'}{\bar{c}} = \frac{\partial C_m}{\partial C_L} \left[1 + \frac{C_{L_{\alpha,t}}}{C_{L_\alpha}'} \frac{S_t}{S} \left(1 - \frac{\partial \epsilon}{\partial \alpha}\right)\right] + \frac{l}{\bar{c}} \left[\frac{C_{L_{\alpha,t}}}{C_{L_\alpha}'} \frac{S_t}{S} \left(1 - \frac{\partial \epsilon}{\partial \alpha}\right)\right]$$

The aerodynamic and geometric parameters used in the preceding equations are included herein for completeness and are not necessarily associated with any particular outboard tail configuration. Two sets of constants were used in the calculations. The constants associated with the results of figure 11 are identified as configuration 1 and those associated with figures 12 to 15 are identified as configuration 2.

For both conditions, the drag-due-to-lift parameter $\frac{\partial C_D}{\partial C_L^2}$ for the wing or tail was assumed equal to the reciprocal of the wing or tail lift slope. The constants are presented in the following table:

	Configuration 1	Configuration 2
C_{L_α}'	1.30	1.312
C_{D_o}	.0100	.0100
$C_{D_{o,t}}$	.0060	.0060
$\frac{\partial C_D}{\partial C_L^2}$	.77	.76
$\frac{\partial C_{D_t}}{\partial C_{L,t}^2}$	.87	.70
$\frac{l}{c}$	1.0	[a]1.0
C_{m_o}	0	[a]0

[a]Except as indicated in the figures.

REFERENCES

1. Spearman, M. Leroy: Some Factors Affecting the Static Longitudinal and Directional Stability Characteristics of Supersonic Aircraft Configurations. NACA RM L57E24a, 1957.

2. Driver, Cornelius: Longitudinal and Lateral Stability and Control Characteristics of Two Canard Airplane Configurations at Mach Numbers of 1.41 and 2.01. NACA RM L56L19, 1957.

3. Sleeman, William C., Jr.: An Experimental Study at High Subsonic Speeds of Several Tail Configurations on a Model Having a 45° Sweptback Wing. NACA RM L57C08, 1957.

4. Fournier, Paul G.: Low-Speed Investigation of Static Longitudinal and Lateral Stability Characteristics of an Airplane Configuration With a Highly Tapered Wing and With Several Body and Tail Arrangements. NACA RM L57A08, 1957.

5. Spearman, M. Leroy, and Robinson, Ross B.: Aerodynamic Characteristics of a Canard and an Outboard-Tail Airplane Model at a Mach Number of 2.01. NACA RM L58B07, 1958.

6. Few, Albert G., Jr.: Investigation at High Subsonic Speeds of the Static Lateral and Directional Stability and Tail-Loads Characteristics of a Model Having a Highly Tapered Swept Wing of Aspect Ratio 3 and Two Horizontal-Tail Positions. NACA RM L56E29, 1956.

7. Polhamus, Edward C., and Spreemann, Kenneth P.: Subsonic Wind-Tunnel Investigation of the Effect of Fuselage Afterbody on Directional Stability of Wing-Fuselage Combinations at High Angles of Attack. NACA TN 3896, 1956.

8. Campbell, John P.: The Use of the Horizontal Tail for Roll Control. NACA RM L55L16a, 1956.

9. Martin, John C.: The Calculation of Downwash Behind Wings of Arbitrary Plan Form at Supersonic Speeds. NACA TN 2135, 1950.

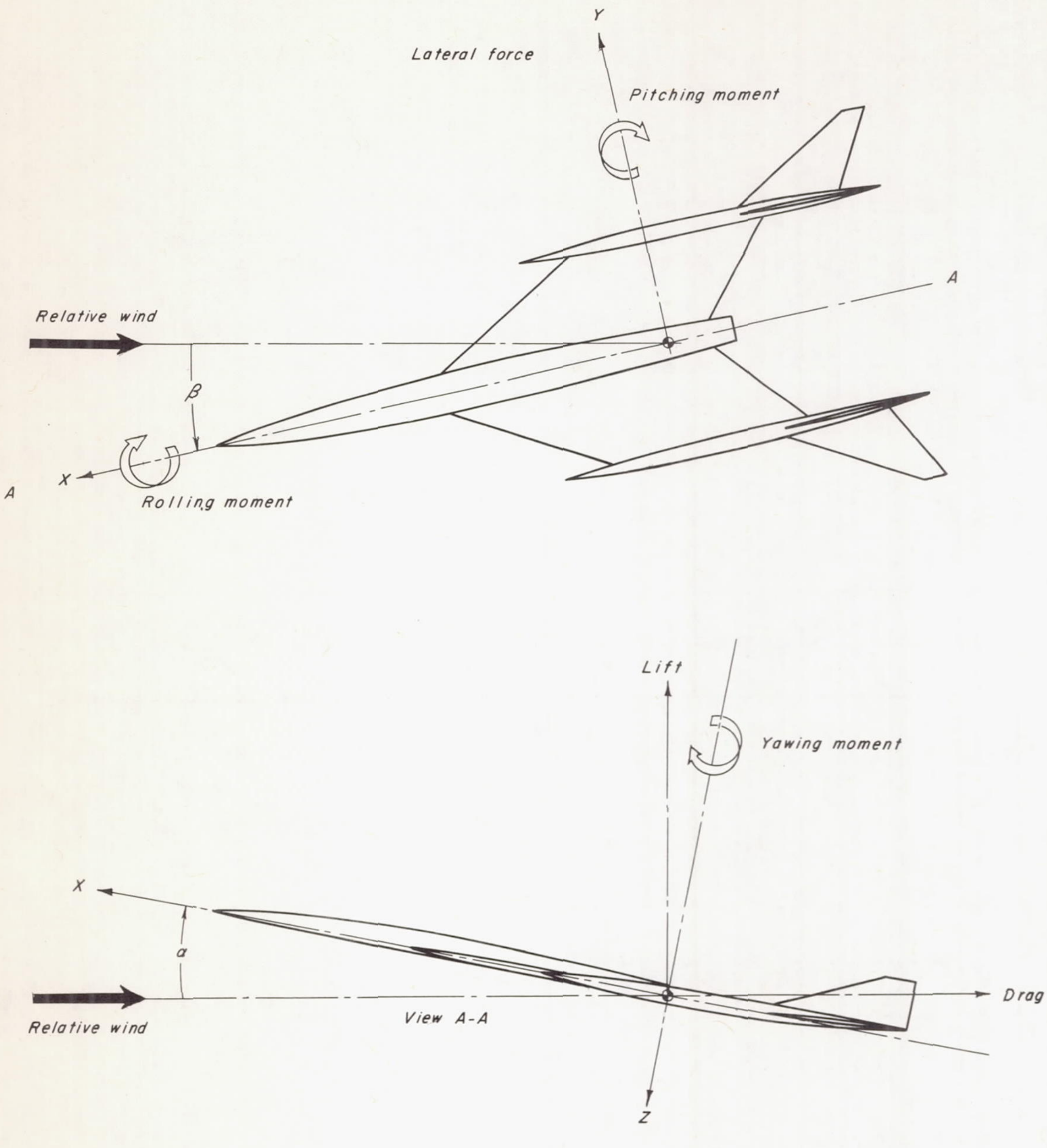
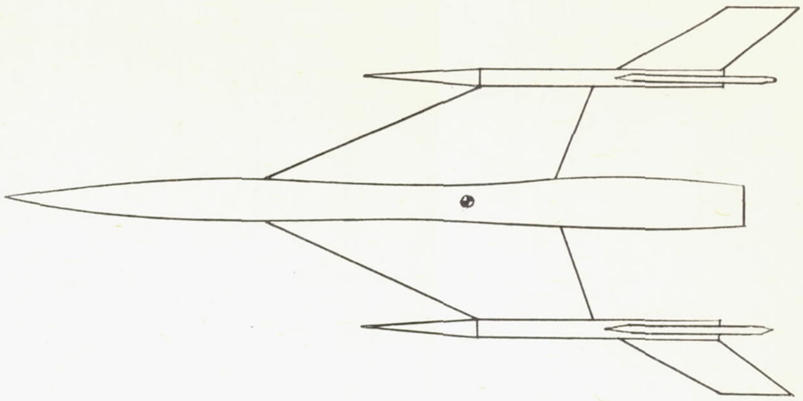


Figure 1.- Body reference axes showing positive directions of forces, moments, and angular deflections.



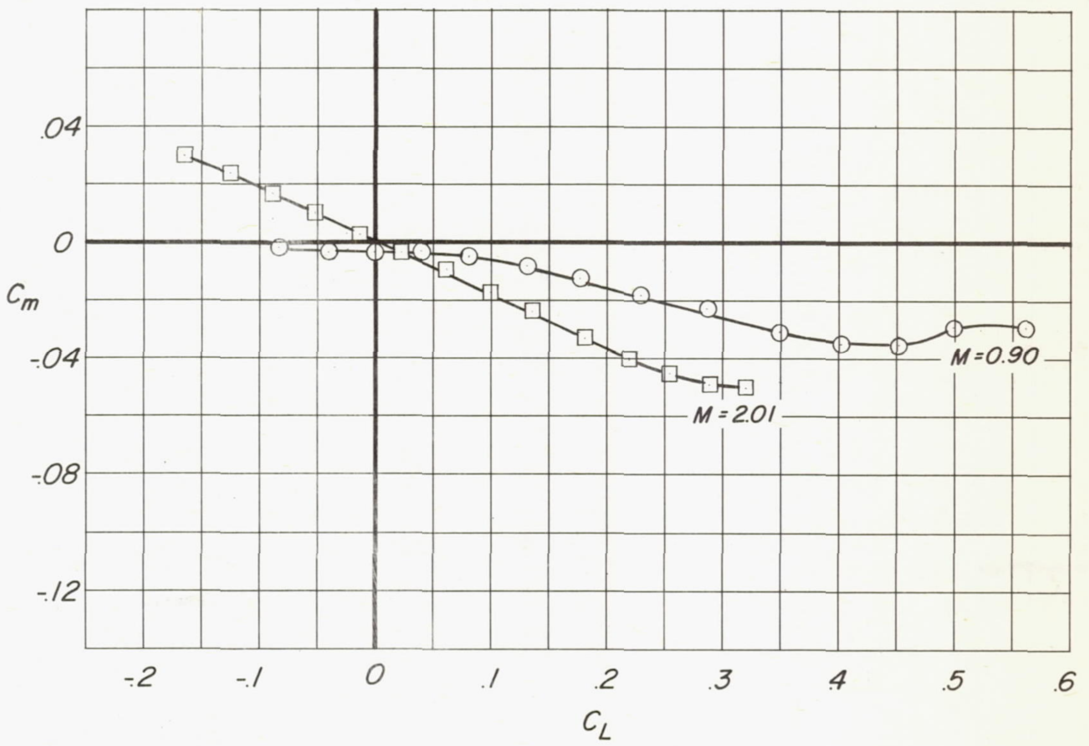
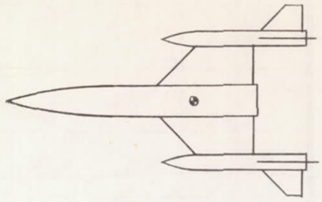


Figure 2.- Pitching-moment characteristics of an outboard tail model having a 67° swept wing of aspect ratio 1.00, with neutral stabilizer setting at Mach numbers of 0.90 and 2.01. Data for M = 2.01 obtained from reference 5. Moment reference at 50 percent $\bar{c}$; coefficients based on geometry of wing and horizontal tail.



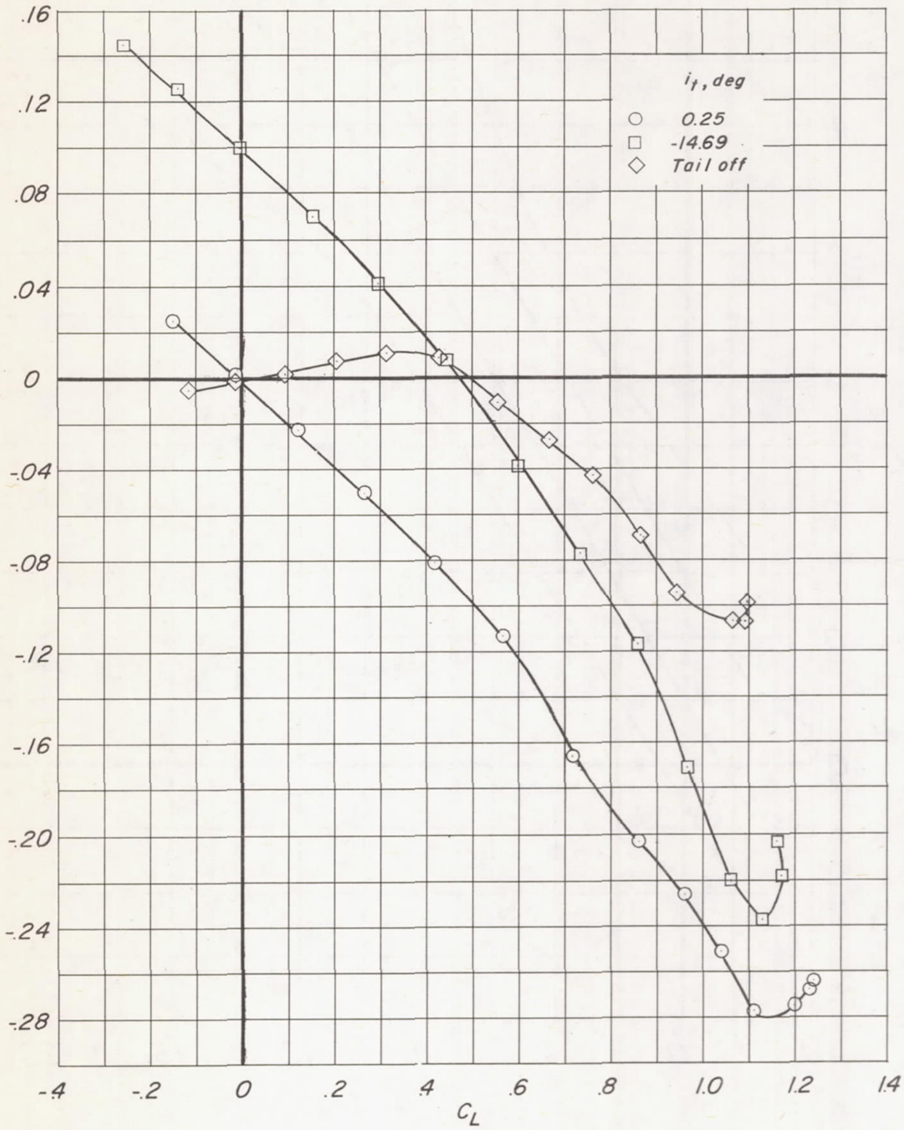


Figure 3.- Pitching-moment characteristics of an outboard tail model having a 45° swept wing of aspect ratio 1.55, with and without tail surfaces at M = 0.60. Moment reference at 25 percent $\bar{c}$; coefficients based on geometry of wing.

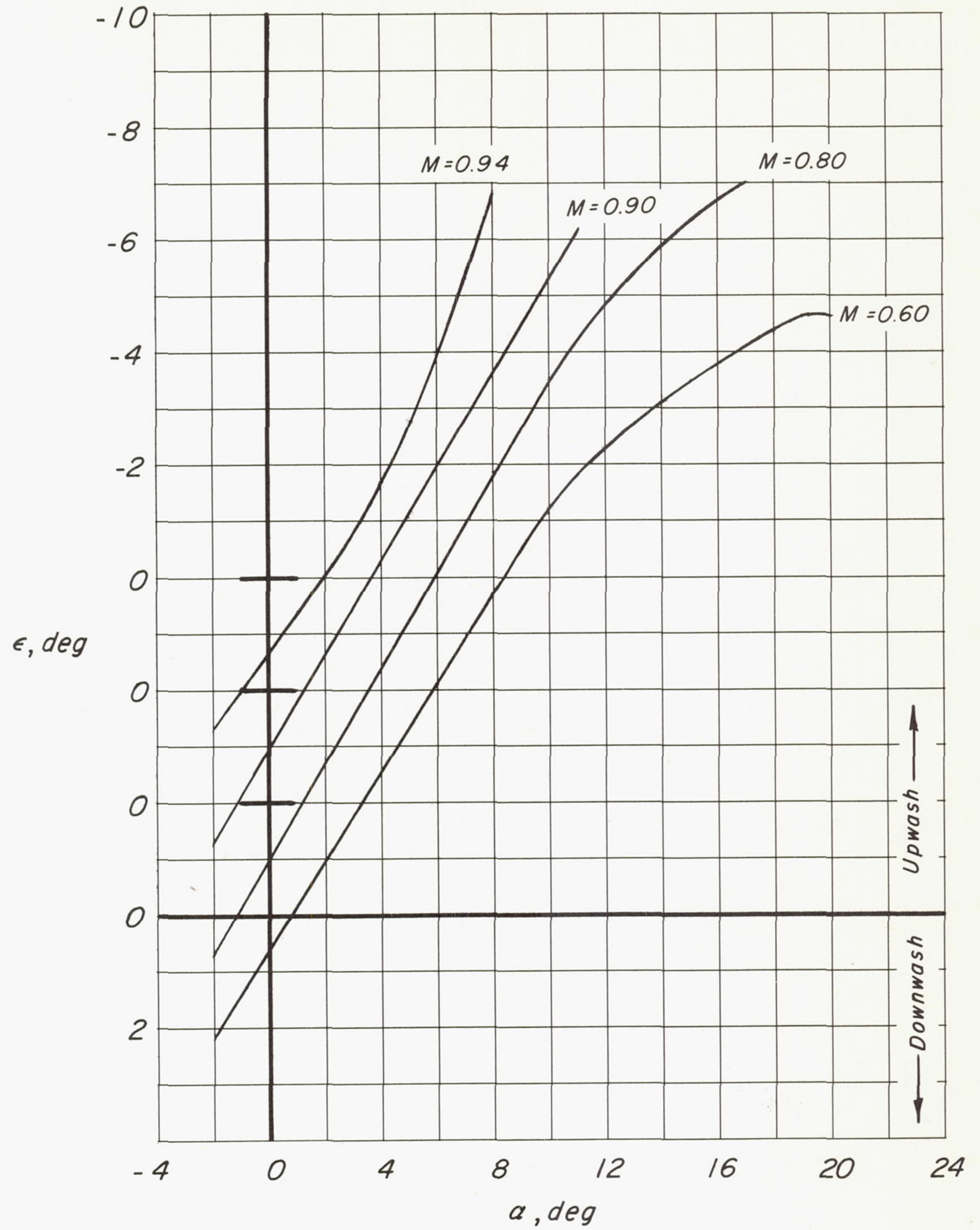
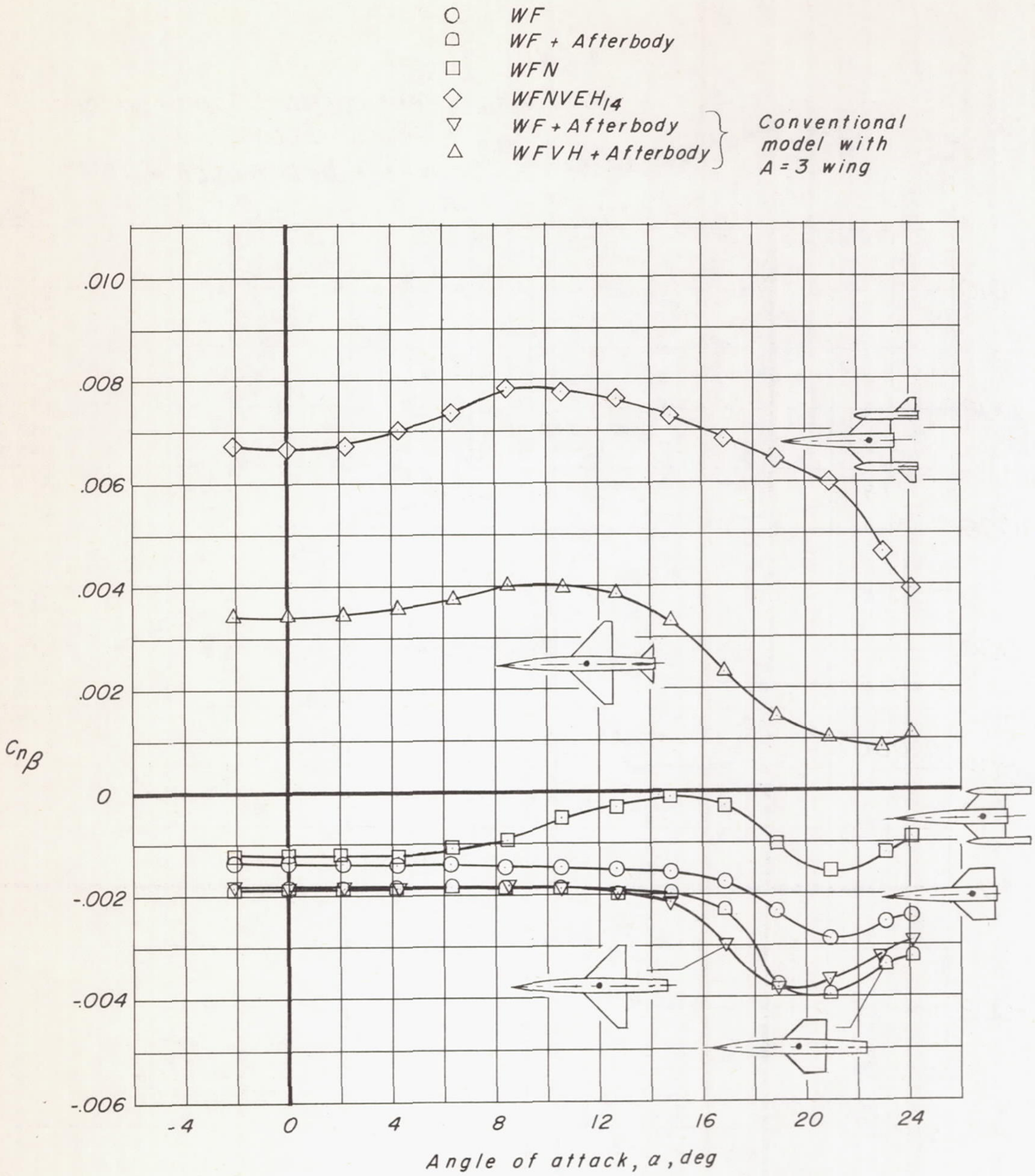
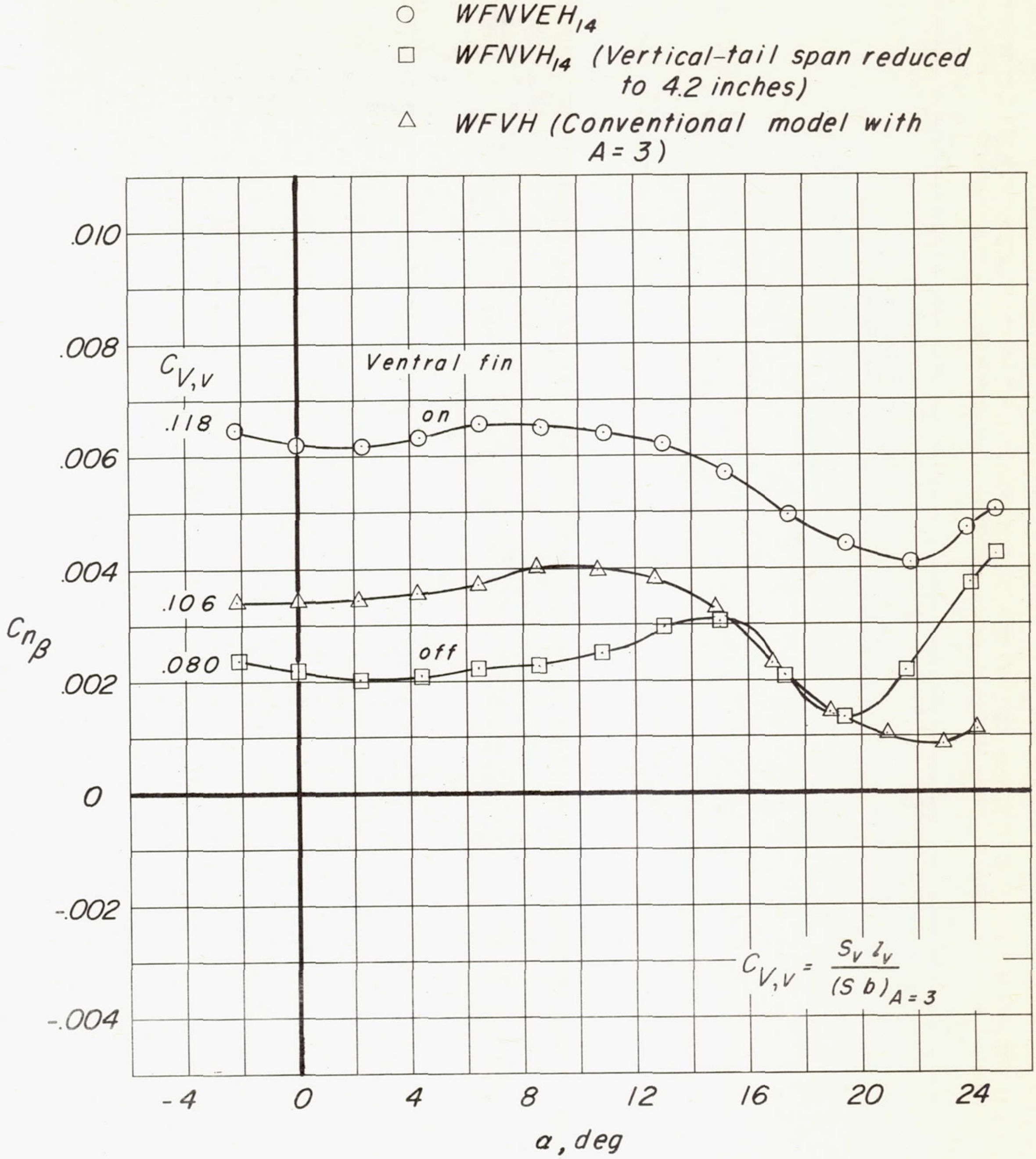


Figure 4.- Variation of effective upwash angle with angle of attack as determined from experimental pitching-moment data for the outboard tail model having a wing of 45° leading-edge sweep and aspect ratio of 1.55.



(a) Effects of afterbody, tip bodies, and tail surfaces with 45° swept wing of aspect ratio 1.55.

Figure 5.- Directional stability characteristics at Mach number 0.60. Moment reference at 25 percent $\bar{c}$ for outboard tail model having a wing of 45° leading-edge sweep; coefficients for all the models based on the geometry of the conventional model having an aspect-ratio-3 modified delta wing.



(b) Characteristics with 65° swept wing of aspect ratio 1.06.

Figure 5.- Concluded.

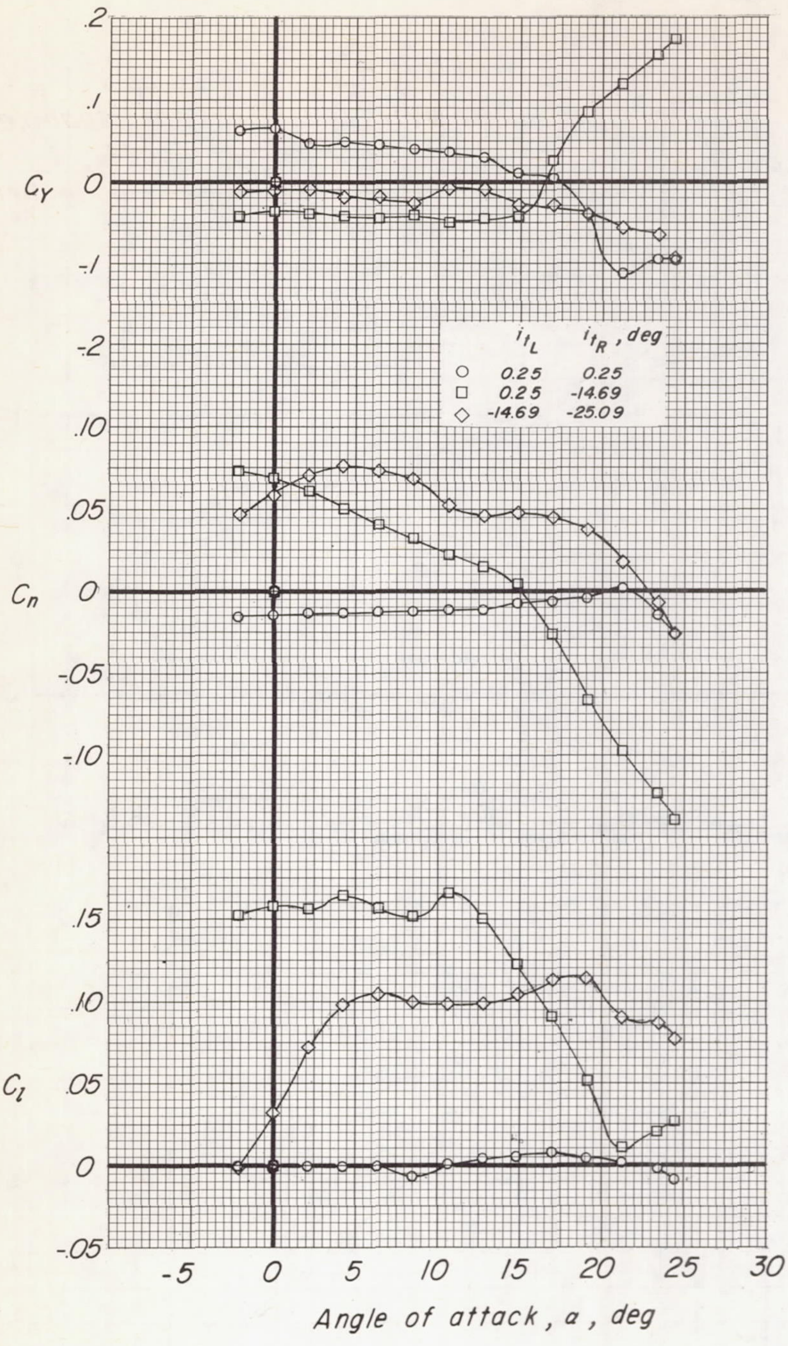


Figure 6.- Lateral control characteristics of the outboard tail model having a 45° swept wing of aspect ratio 1.55, with the horizontal tails deflected differentially. $M = 0.60$; $\beta = 0^\circ$; moment reference at 25 percent $\bar{c}$; coefficients based on geometry of wing.

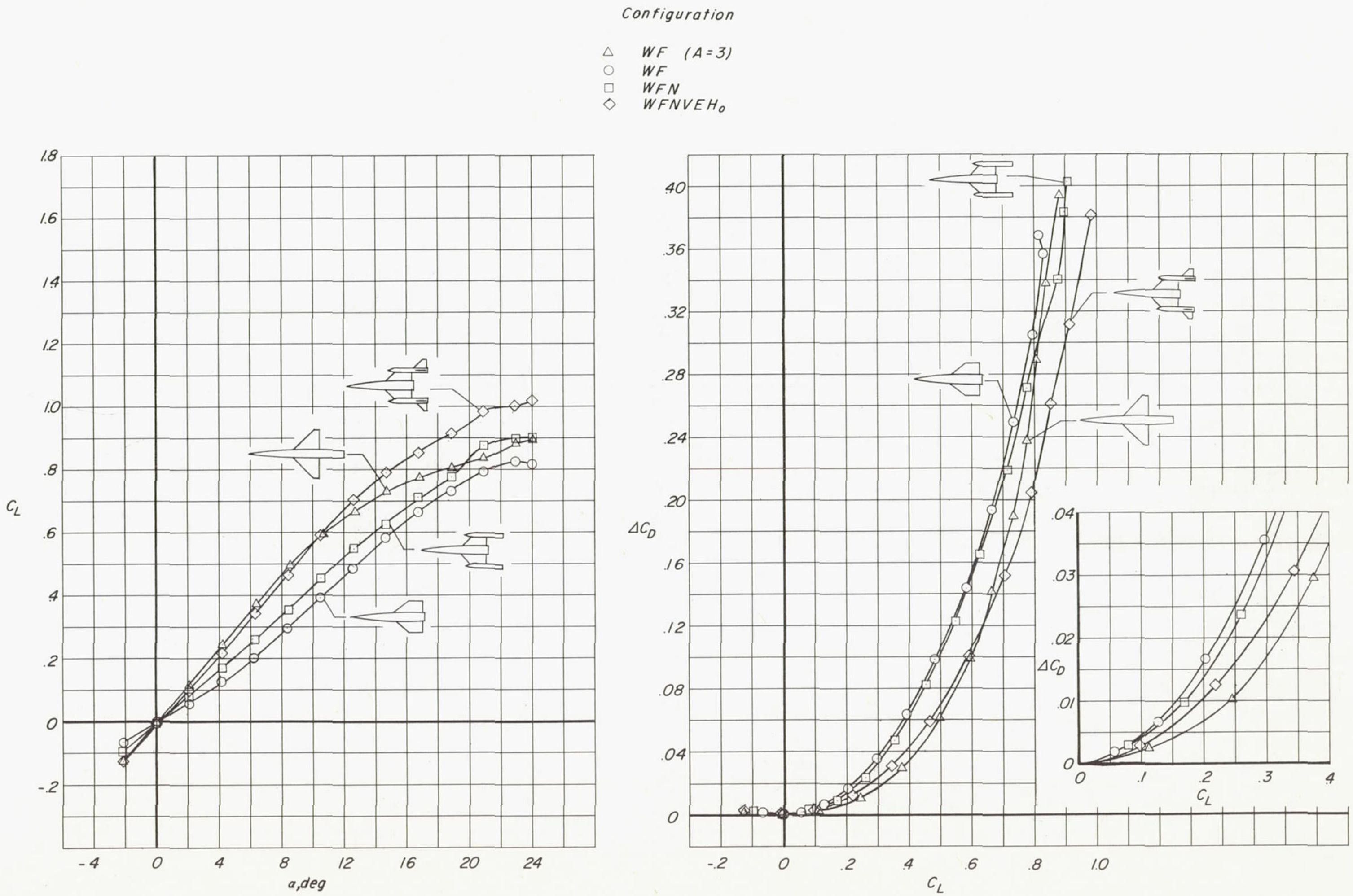


Figure 7.- Summary of the lift and drag-due-to-lift characteristics of the outboard tail model having a 45° swept wing of aspect ratio 1.55 at M = 0.60. All coefficients based on geometry of the conventional model having an aspect-ratio-3 modified delta wing.

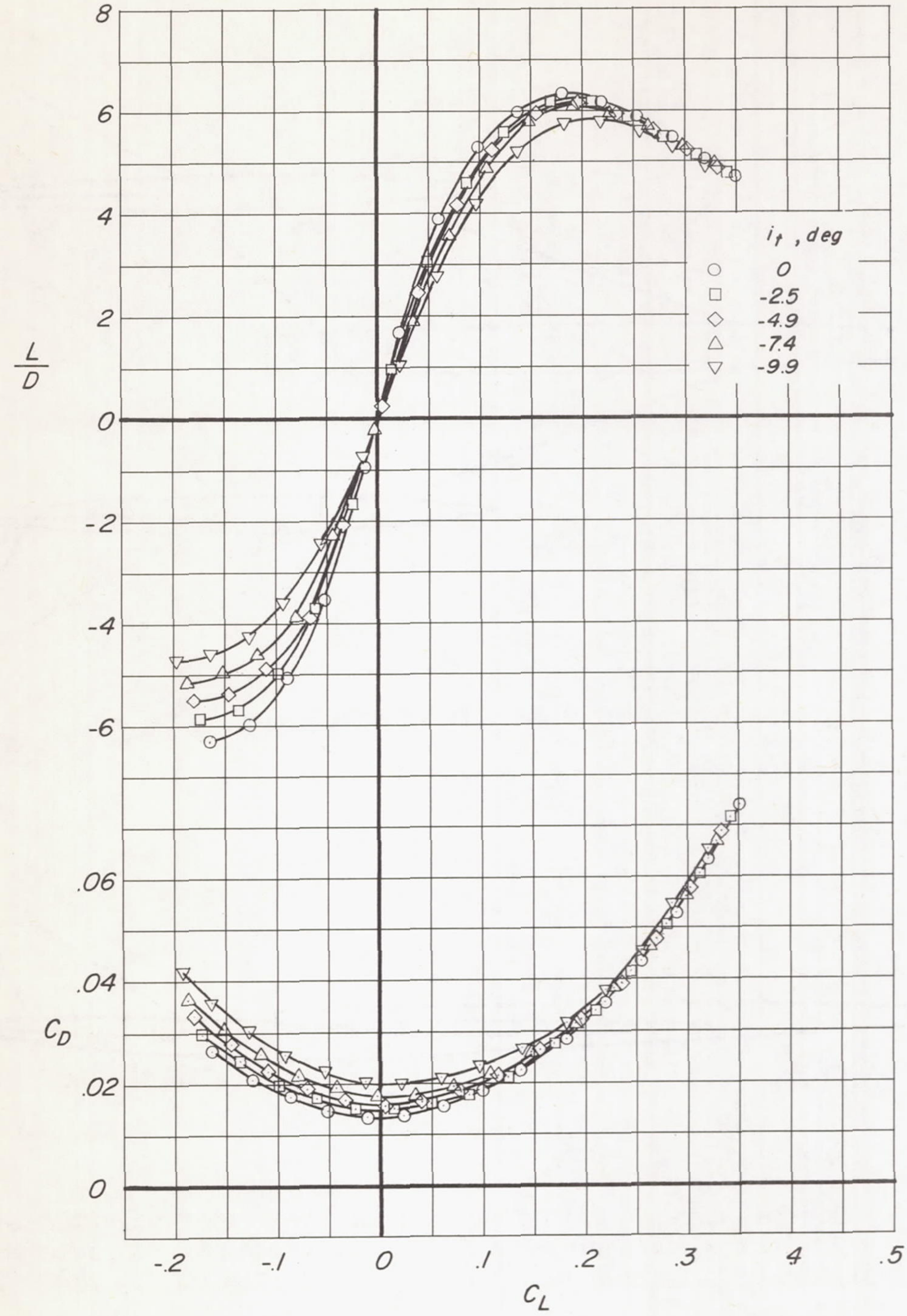


Figure 8.- Effects of stabilizer setting on drag coefficients and lift-drag ratios for an outboard tail model having a 67° swept wing of aspect ratio 1.00 at M = 2.01. Data obtained from reference 5.

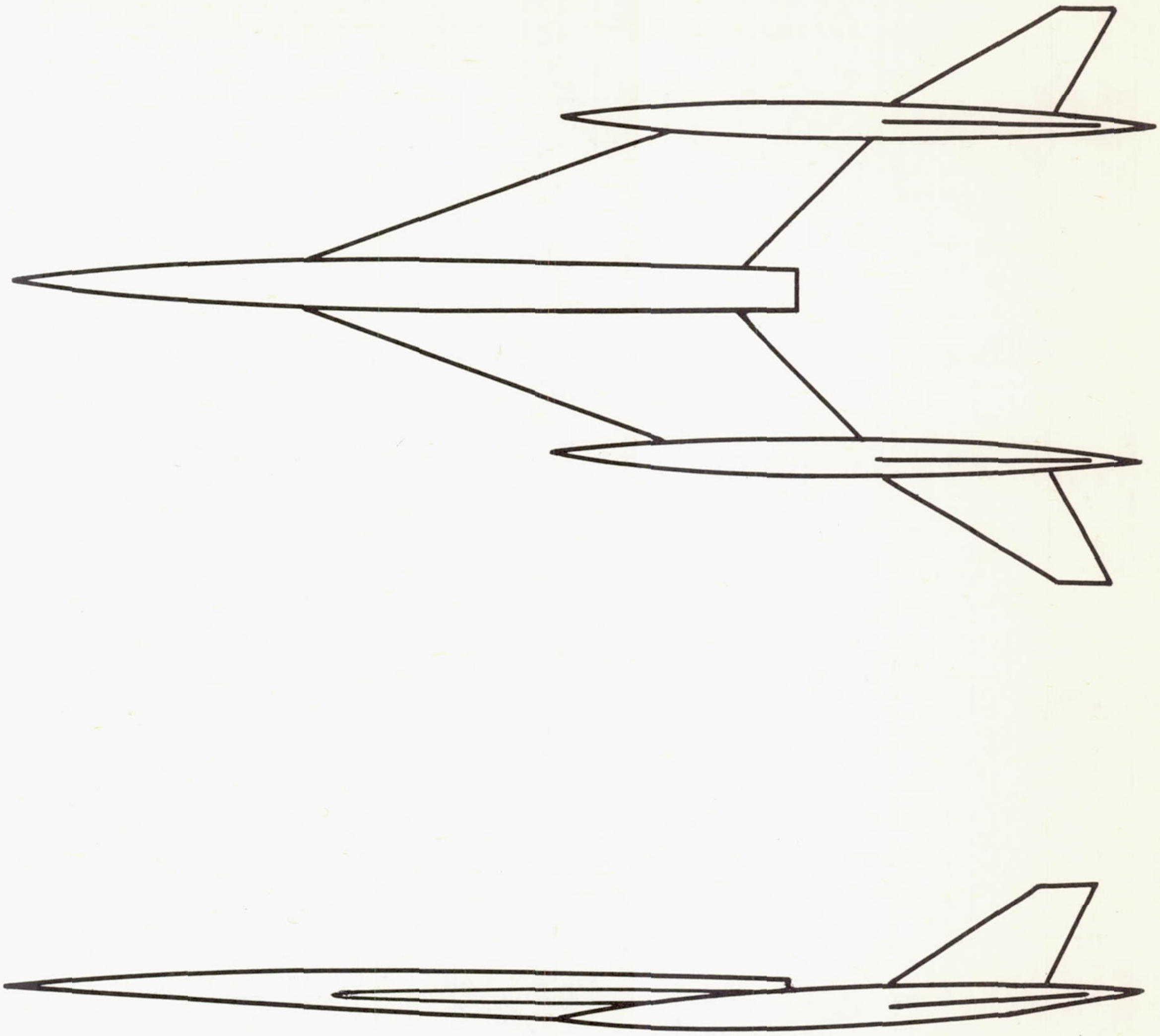


Figure 9.- General arrangement of an outboard tail configuration having a 70° swept wing of aspect ratio 1.00, typical of those included in the analytical study of design variables. $S_t/S = 0.27$; $l/\bar{c} = 1.0$.

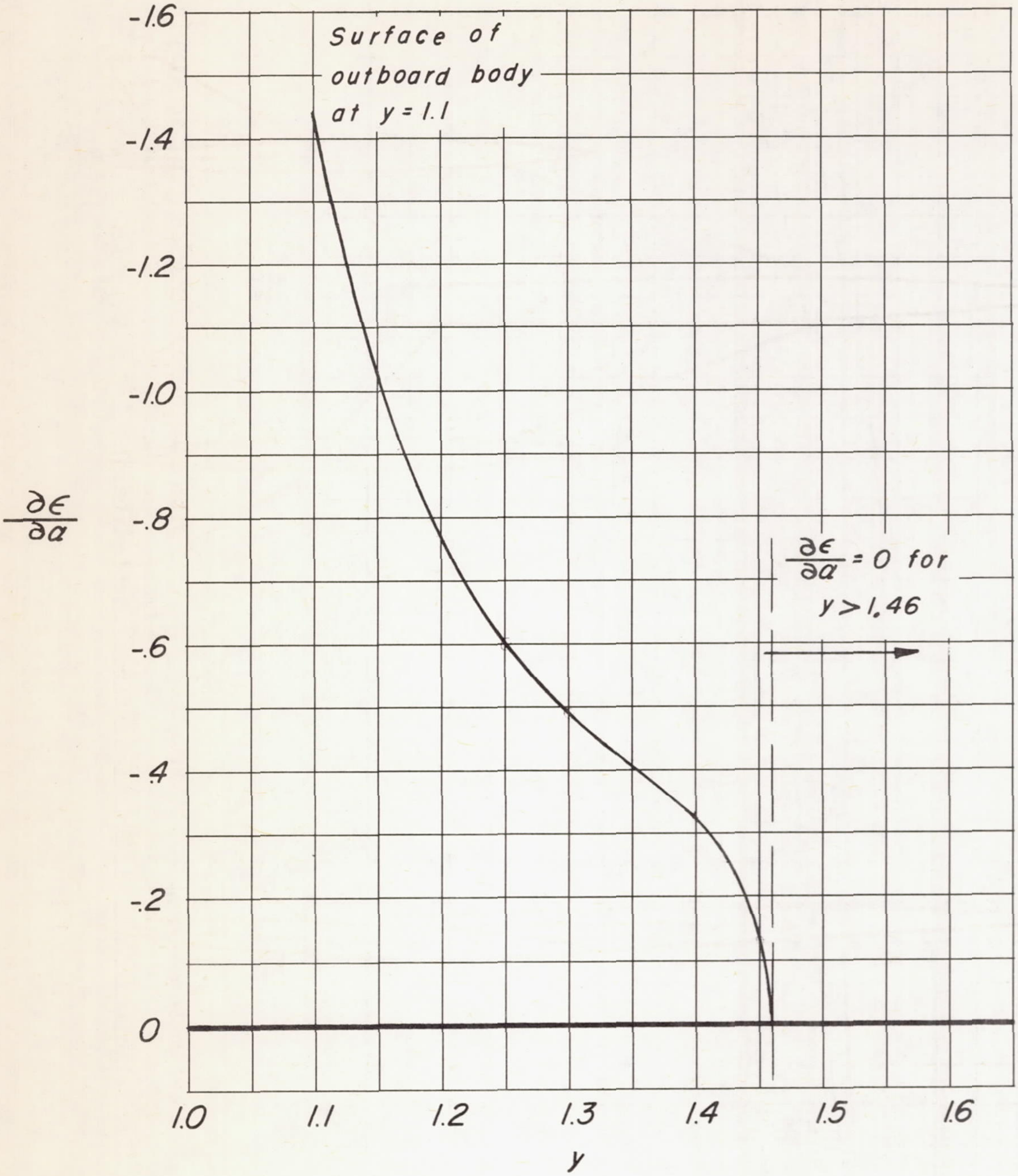


Figure 10.- Variation of theoretical local upwash with spanwise distance for an outboard tail configuration at $M = 3.0$.

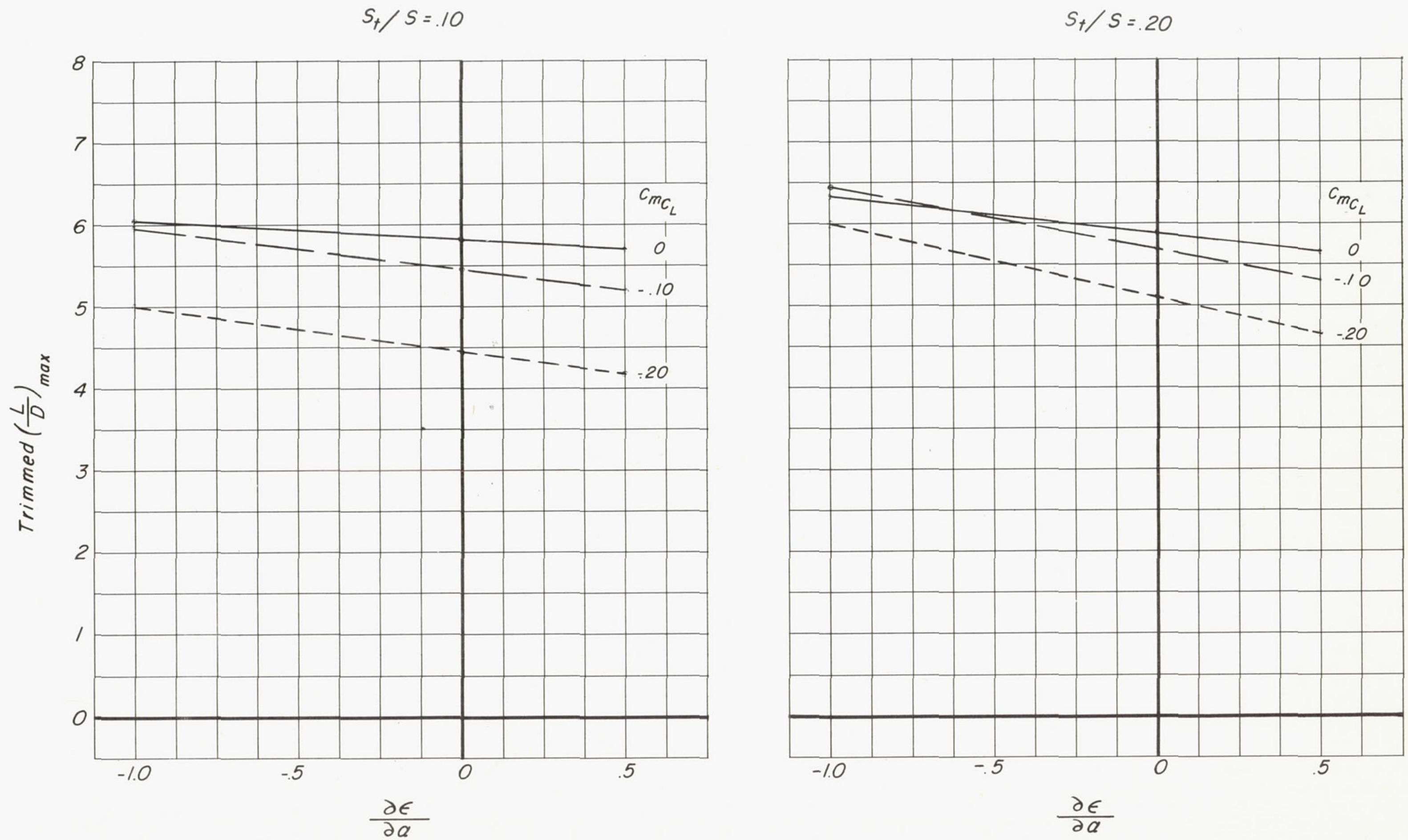


Figure 11.- Estimated variation of trimmed $\left(\frac{L}{D}\right)_{max}$ with $\frac{\partial\epsilon}{\partial\alpha}$ and static margin for airplane configurations having tail surfaces located behind the wing, $l/\bar{c} = 1.0$.

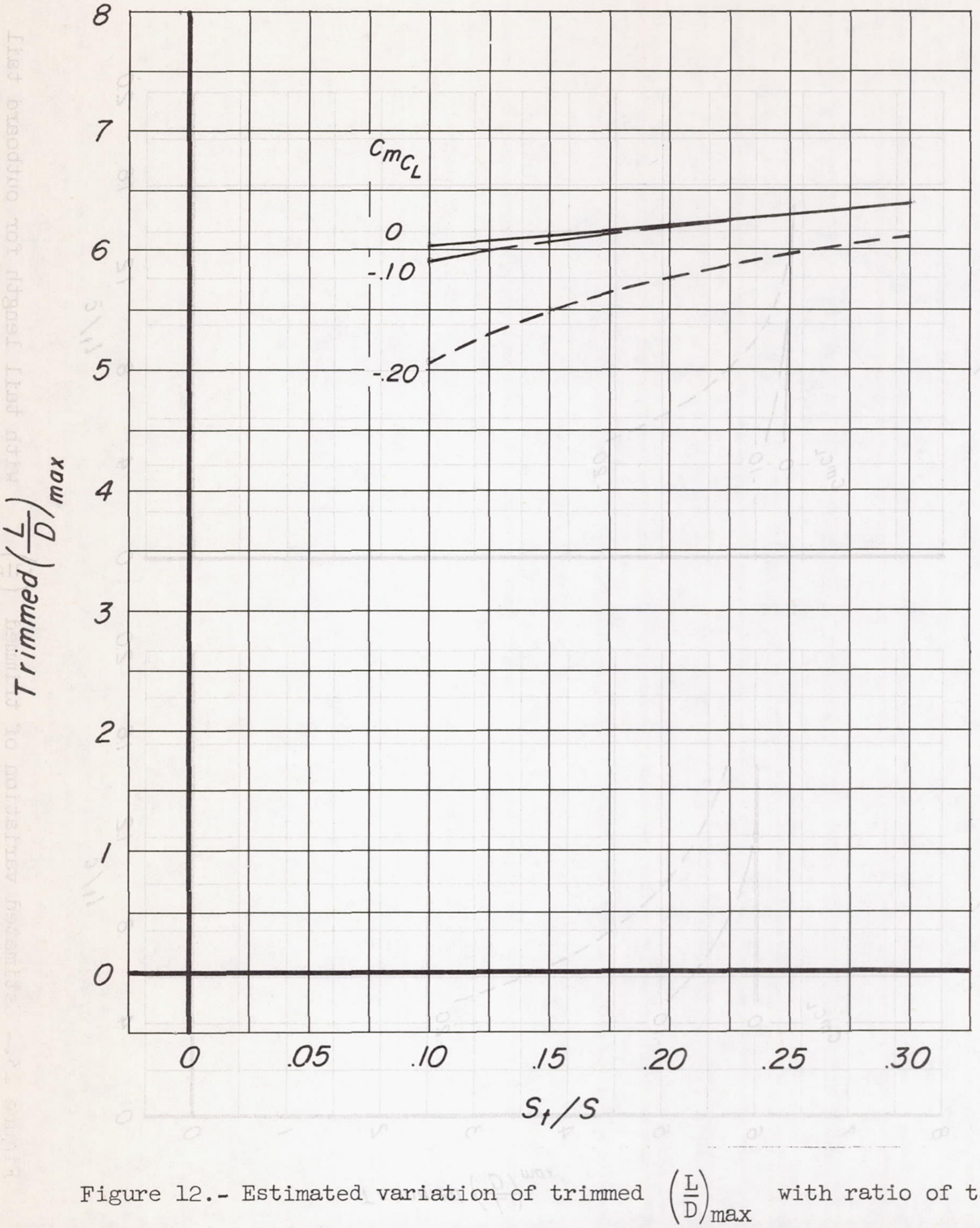


Figure 12.- Estimated variation of trimmed $\left(\frac{L}{D}\right)_{max}$ with ratio of tail area to wing area for outboard tail configurations having a tail length of $l/\bar{c} = 1.0$.

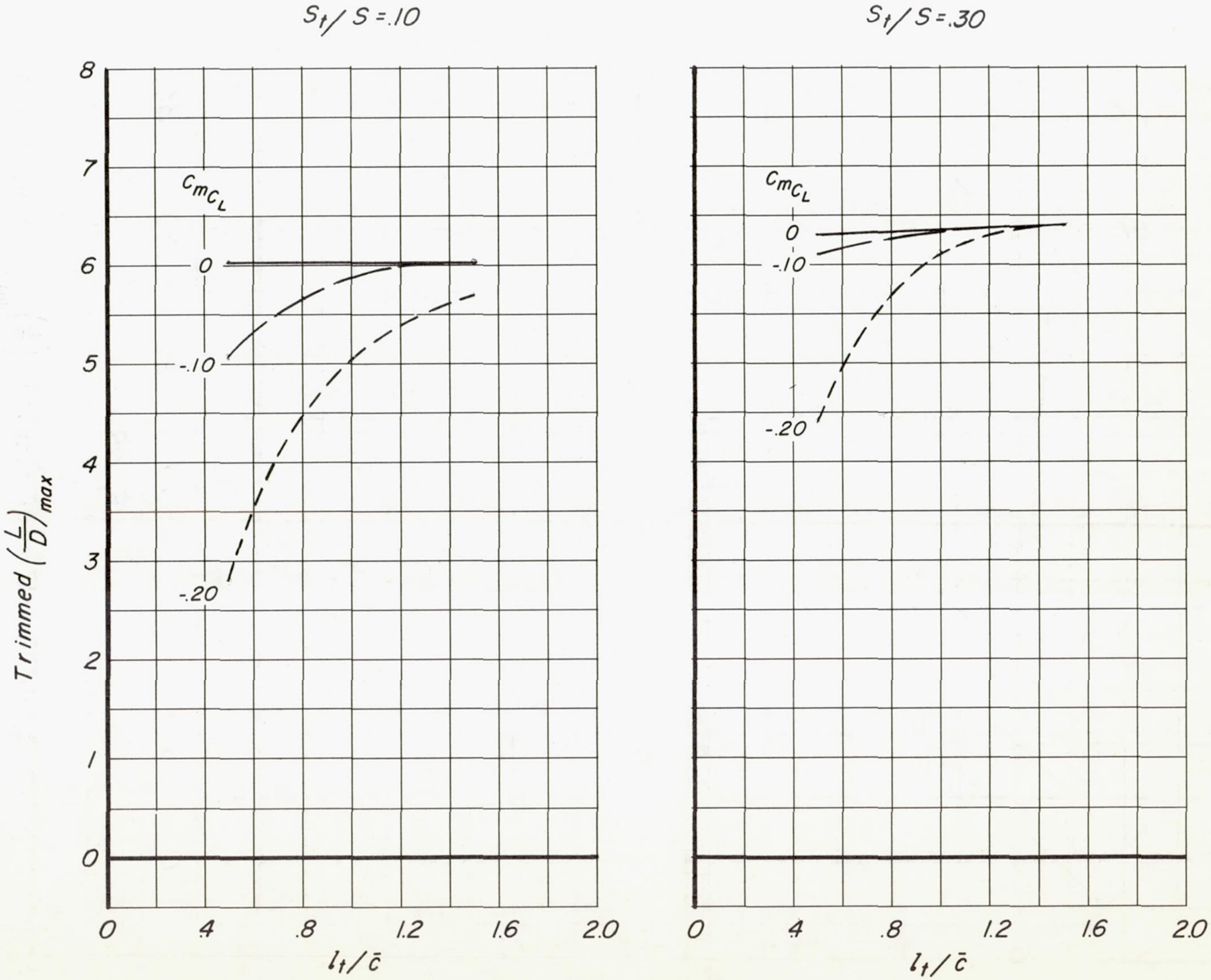


Figure 13.- Estimated variation of trimmed $\left(\frac{L}{D}\right)_{max}$ with tail length for outboard tail configuration.

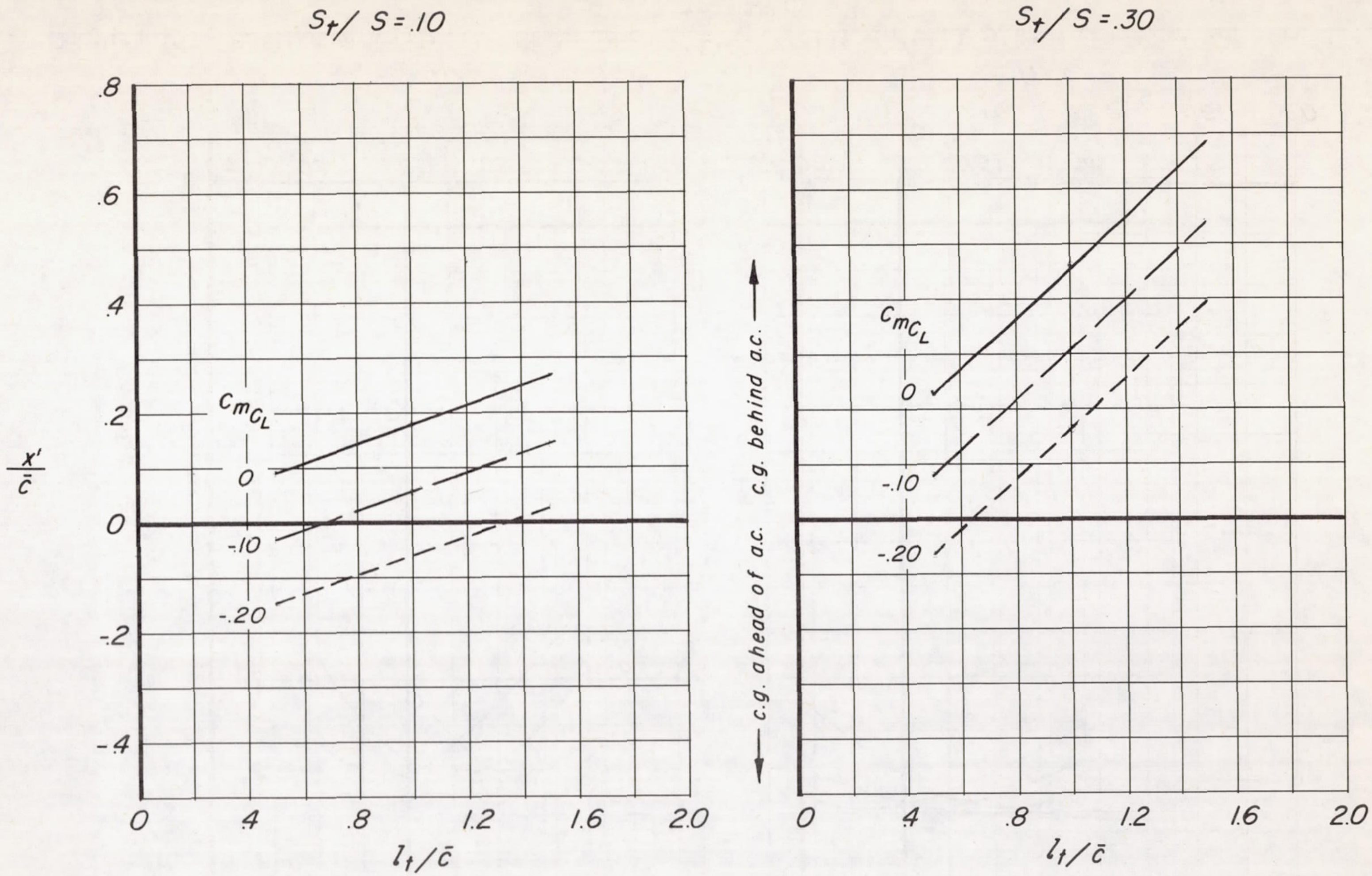


Figure 14.- Estimated variation of the distance of the airplane center of gravity behind the tail-off aerodynamic center with tail length for outboard tail configurations to give various values of constant longitudinal stability.

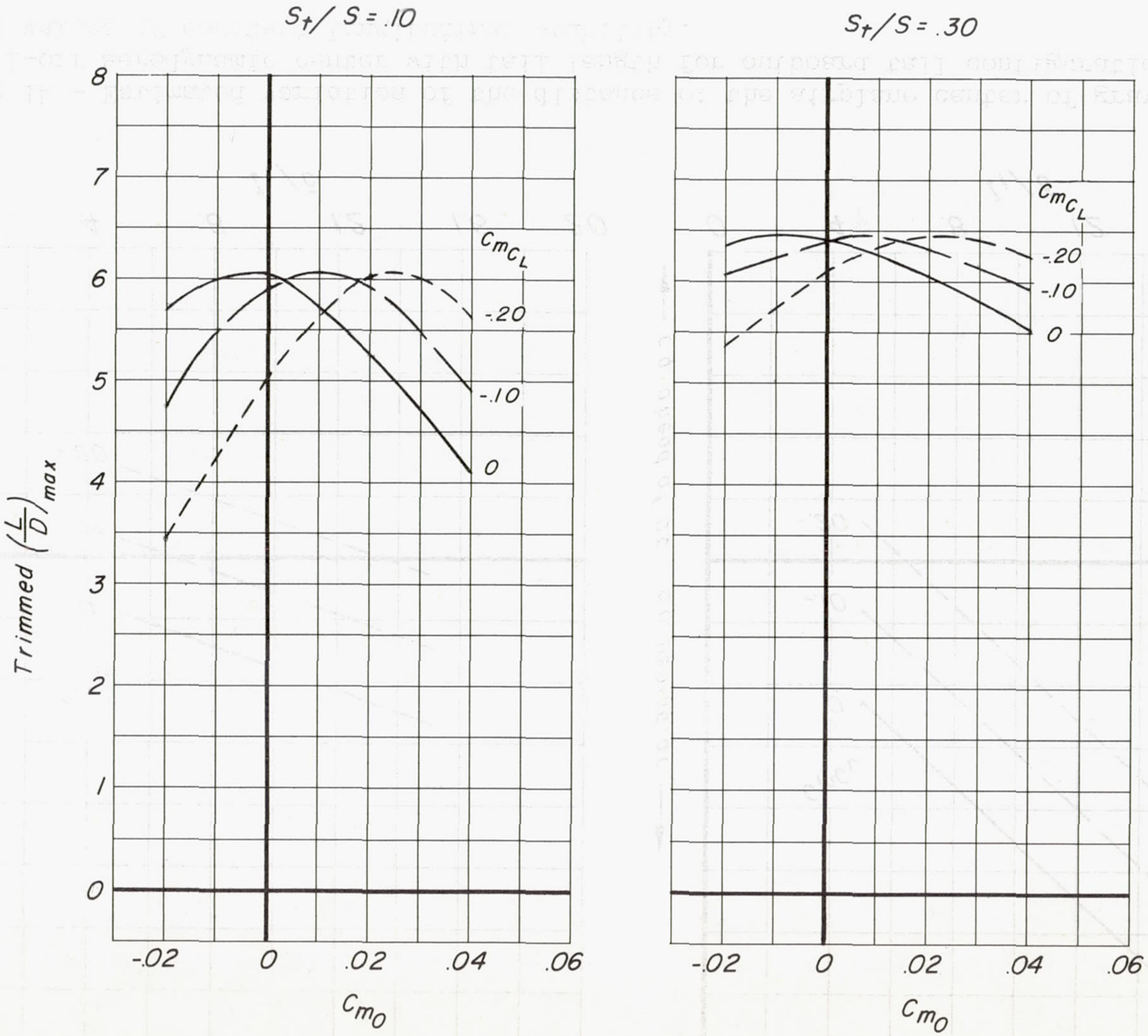


Figure 15.- Estimated variation of trimmed $\left(\frac{L}{D}\right)_{max}$ with initial pitching moment at zero lift for outboard tail configurations having a tail length of $l/\bar{c} = 1.0$.