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AERODYNAMIC CHARACTERISTICS OF SOME LIFTING REENTRY CONCEPTS APPLICABLE TO TRANSATMOSPHERIC VEHICLE DESIGN STUDIES

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SUMMARY

A review has been made of the aerodynamic characteristics of some manned lifting reentry concepts to determine the applicability of such concepts to the design of possible transatmospheric vehicles (TAV). The concepts included some hypersonic-body shapes with and without variable geometry surfaces, and a blunt lifting-body configuration.

The review indicated that some features developed in the course of the manned lifting reentry studies could have possible application in the design of a TAV from the standpoint of stability and control, maneuverability, and cross-range capability. In addition to the U.S. studies, there is evidence that the U.S.S.R. is pursuing a course that could lead to a TAV concept.

INTRODUCTION

The U.S. Air Force currently has studies underway for a future transatmospheric vehicle (TAV). The objective is to develop a vehicle that would be able to take off from the earth and fly to the upper edge of the atmosphere and the lower edge of space and return to an earth landing. Such a vehicle could circle the earth in 90 minutes in space orbit and be able to enter and exit the atmosphere under control for the purpose of performing various space, strategic, and tactical missions. Thus a global capability to rapidly perform reconnaissance missions or to deliver a payload would be available.

Beginning in the late 1950's, NASA investigations were underway to study the possibility of reentering the atmosphere with manned space vehicles that could return to earth and land. Some of the features of these early concepts could conceivably have application to the current TAV studies. It is the purpose of this paper to consider some of these possible applications.

SYMBOLS

$C_{D,o}$	drag coefficient at zero lift
C_L	lift coefficient
C_m	pitching-moment coefficient
C_{l_β}	effective dihedral parameter
C_{n_β}	directional stability parameter
C_{L_α}	lift-curve slope

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$\frac{\partial C_m}{\partial C_L}$	longitudinal stability parameter
L/D	lift-to-drag ratio
M	Mach number
x	longitudinal distance from body nose
l	body length
c.g.	center of gravity
c.p.	center of pressure
α	angle of attack, deg
δ	control deflection, deg
Λ	sweep angle, deg
Γ	dihedral angle, deg
V_c	center vertical tail
V_t	twin vertical tails
B	body
H	horizontal tail
W	weight
S	reference area
h	altitude
g	measure of instantaneous normal acceleration

Coefficients for the configurations presented herein are nondimensionalized in various ways. Detailed information for each configuration may be found in the referenced papers. The numerical value of the coefficients, however, does not affect the interpretations of the results.

DISCUSSION

Elliptical-Body-Tail Concept

Numerous studies have been directed toward increasing the aerodynamic performance attainable with volumetrically efficient lifting bodies designed for minimum wave drag at hypersonic speeds. Some of these studies are presented in references 1 to 11. One of these concepts (Fig. 1) has a 2-to-1 elliptic cross section with a fineness ratio of 6.14. Delta tail surfaces were placed at the rear of the body.

The pitch stabilizers were tested at dihedral angles from 90° to -90° with and without a single vertical tail or a 30° vee-tail. Results for this concept may be found in references 9 to 11.

Some supersonic aerodynamic characteristics, extracted from reference 11, are presented in Figures 2 to 5. Typical longitudinal characteristics for various configurations at $M = 1.50$ and 4.63 (Fig. 2) indicate a not unexpected increase in lift and longitudinal stability with the addition of tails--the change being dominated by the horizontal pitch stabilizer. Varying the dihedral angle of the pitch stabilizer as a means of longitudinal control (Fig 3) indicates substantial changes in the level of stability for dihedral angles of 90° and -90°. However, out-of-trim moments still remain that would probably require additional means of control. A summary of some of the longitudinal parameters as a function of Mach number (Fig. 4) indicates the increase in lift-curve slope and the accompanying increase in minimum drag when tails are added to the basic body. However, the maximum lift-to-drag ratio is increased by the addition of tails and tends to increase with increasing Mach number--a reasonably high value of about 3 being achieved near $M = 4.6$. The center of pressure moves considerably aft when the tails are added and, over the speed range shown, would provide positive static longitudinal stability for a center of gravity as far aft as about 65 percent of the body length.

The lateral-directional characteristics for the elliptic body concept (Fig. 5) indicates that static directional stability is maintained to at least $\alpha = 26^0$ for the twin-tail arrangement at $M = 1.50$ and 4.63 with the c.g. at 55 percent of the body length. The single centerline tail arrangement becomes unstable near $\alpha = 16^0$ probably because of an adverse forebody vortex flow in the vicinity of the tail. The vortex flow diminishes with increasing Mach number and static directional stability is indicated at $M = 4.63$, not only for the single and twin-tail arrangements, but even minimally for the configurations without directional surfaces. Positive effective dihedral is indicated in all cases shown.

In any event, the elliptic-body-tail concept shows promise as a possible TAV candidate with reasonably good stability and lift-drag characteristics. Some provision for adequate control, however, is required.

Variable Wing-Sweep Concept

Several studies have been made of a lifting reentry configuration with a modified elliptical body with relatively high volume and with variable wing-sweep as a means of improving maneuvering capability, cross-range capability, and combining good low-speed and high-speed characteristics. Some of these studies are presented in references 12 to 16. The general concept, illustrated in Figure 6, has a wing that, when fully swept to 90° is merged with the top of the body, but can also be varied in sweep position to as low as 0° to form a high aspect ratio for low-speed flight conditions.

Longitudinal characteristics extracted from reference 16 (Fig. 7) show the effects of various components at $M = 2.86$ with the c.g. at $0.58\ l$. The effect of wing sweep with the tail off is to progressively increase the longitudinal stability as the wing is rotated forward from the retracted (90°) position. Note that a favorable positive value of C_{m_0} occurs at zero lift for this configuration. The addition of the tail with $\Lambda = 75^0$ provides a substantial increase in longitudinal stability that is little affected by the dihedral (anhedral) angle.

Deflection of the tail to -20° with $\Lambda = 75^0$ and $\Gamma = 30^0$ is effective in providing longitudinal trim and control to reasonably high values of C_L.

Positive static directional stability was indicated for the configuration with $\Lambda = 75^0$, M = 2.86, and c.g. = 0.58 ι for all tail angles (Fig. 8). The directional stability increases with increasing α and is greatest, of course, with $\Gamma = 60^0$. The favorable directional stability traits are a result, primarily, of a favorable dynamic pressure field induced at the tail by the high wing and, to some extent, to a favorable dynamic pressure field induced on a portion of the body by the tail itself. Further data contained in reference 16 indicates that, with the wing fully retracted, some regions of directional instability occur except for the $\Gamma = 60^0$ tail.

Some low-speed characteristics (ref. 12) and some body flap control data at low- and high-speed (refs. 12 and 13) are presented in Figure 9. These results are for the tail-off configuration and with the c.g. at 0.655 ι. The results at M = 0.40 and $\Gamma = 0^0$ indicate a maximum value of lift-drag ratio of about 6 with the body flap at 0°. The body flap, which extends aft of the upper side of the body base, was effective in providing pitch control up to the maximum test value of C_L (corresponding to α of about 25°). The pitching moments are unstable for the reference c.g. position; however, a forward movement of the c.g. of only 0.075 ι (c.g. = 0.58 ι) would provide a low-speed static margin of about 1.5 percent. A forward movement of the c.g. would also produce some increase in body flap pitch control effectiveness. The body flap maintained control effectiveness with the wing retracted at M = 3.0 for lifts that again correspond to about $\alpha = 25^0$. A shift in c.g. to 0.58 ι would provide for static stability and increased control effectiveness.

Some aerodynamic characteristics at M = 10 (ref. 14) indicate essentially constant levels of directional stability with angle of attack up to about 20°. Positive levels of stability would be achieved with a small forward movement of the c.g. The higher level of stability with the 75° wing results again from the high dynamic pressure field produced beneath the wing. The pitching moment results also indicate a stabilizing increment for the 75° wing and, of course, with the addition of the tail.

A summary of some longitudinal characteristics as a function of Mach number for the variable-sweep concept with the tail off are shown in Figure 11. The c.p. location for the retracted wing case is essentially constant up to M = 10. Intermediate sweep angles provide increased stability (aft c.p. shifts) whereas the 0° wing at low speeds (ref. 12) returns the c.p. to about the same location as that for the retracted wing. The addition of the tail would, of course, provide a rearward shift in c.p. for all configurations. In any event, all configurations could be made longitudinally stable to varying degrees for c.g. locations aft of about 50 percent ι. Reducing the sweep was effective in significantly increasing the lift-curve slope and the lift-drag ratio at low speeds. Smaller changes occurred in the lift-curve slope and lift-drag ratio at supersonic speeds. The maximum value of lift-drag ratio appears to be constant at about 2.5 to 3 for Mach numbers from 3 to 10. All things considered, the high-volume elliptic-body concept with variable-sweep wings appears to be a reasonable TAV candidate configuration.

Skewed-Wing Concept

Some studies of a skewed-wing lifting reentry concept are presented in references 17 and 18. The concept (Fig. 12) has a body with a trapezoidal cross-section designed to minimize hypersonic wave drag within given volume constraints. A single-pivot two-position skewed wing was employed to enhance the low-speed flight characteristics. The concept was studied with both a single centerline vertical tail and with twin-canted tails. A horizontal stabilizer was located near the bottom of the body.

Some longitudinal characteristics with the single and the twin-tail arrangements (Fig. 13) at $M = 4.6$ indicate maximum values of L/D of about 3. The variation of pitching-moment with α is linear and positive longitudinal stability is indicated even for the relatively far-aft c.g. location of 0.628 ι. Deflection of the stabilizer is effective in providing pitch control and, coupled with a positive increment of pitching moment at $\alpha = 0^0$, trim to high values of α should be possible.

A summary of some of the longitudinal characteristics at supersonic speeds (Fig. 14) shows maximum values of lift-drag ratio of about 3 over the speed range--increasing slightly with increasing speed. While both tail arrangements were longitudinally stable for the reference c.g., the twin-tail arrangement was considerably less stable than the single center tail arrangement. This difference is presumably caused by an interference flow field between the tail surfaces wherein the twin tails may impose a download on the stabilizer and the stabilizer may induce a dynamic pressure reduction in the vicinity of the twin tails.

The lateral-directional characteristics at $M = 4.6$ (Fig. 15) shows positive static directional stability for both tail arrangements up to the test limit of about $\alpha = 20^0$. The tail contribution to directional stability decreased with α for the centerline tail because of the adverse sidewash induced by the forebody vortex field but increased with α for the twin tail, partly because of an increase in total tail area, but primarily because of a favorable sidewash field at the tail. A positive effective dihedral was generated by both tail arrangements.

A measure of the maneuver potential for the skewed-wing concept with the wing stowed on the body at $M = 4.6$ can be illustrated by the use of Figure 16. This figure shows the lift as a function of wing loading for level flight at various altitudes. The lower dashed line indicates the lift required for trimmed level flight at maximum L/D for a c.g. of 0.628 ι. This boundary indicates combinations of altitude and wing loading for which cruise at maximum L/D could be achieved. For this illustration, the boundary varies from about 70,000 feet for W/S = 200 up to 110,000 feet for W/S of about 30. Other boundaries, of course, could be generated for other speeds from which various indicators of cross-range cruise potential could be determined.

The upper dashed line (Fig. 16) is the maximum attainable trim lift for these data ($\alpha = 19^0$) from which certain other performance indicators may be obtained. For example, the maximum level flight altitude and loading combinations vary from 110,000 feet with a W/S of about 80 to 90,000 feet with a W/S of about 200. An indication of the maximum instantaneous normal acceleration in g units can also be obtained by comparing the maximum lift available with the lift required for a given set of conditions. As the table indicates, for a vehicle 32-feet long and a weight of 15,500 pounds (W/S = 100), the g capability would vary from 2 at 90,000 feet to

22 at 40,000 feet. Again, this vehicle offers some features that may be congruent with TAV missions.

Blunt Lifting Body Concept

One of the earliest vehicle types to be included in the manned reentry studies was the class of blunt lifting bodies. One of this class, for which results are contained in references 10 to 26, is shown in Figure 17. The concept is a modified blunt 13° half-cone body with extensive boattailing and various tail arrangements. Limited tests were included in reference 26 for a variable-sweep wing addition.

Some of the basic aerodynamic characteristics (Fig. 18) indicate static directional stability up to $M = 5$ (except for uncertainties in the data near $M = 1$). The trimmed lift-drag ratio of about 1.2 in the supersonic range is equivalent to about 900 nautical miles cross-range according to reference 23. The addition of the wing at low speed ($M = 0.4$) increased L/D from about 3 to 6 which should enhance the low speed flight and landing performance.

The maneuver potential for this concept at $M = 5$ is shown in Figure 19 in the form of trimmed C_L and C_m, as obtained from reference 23, for a low α regime (10°) and a high α regime (50°). For an assumed length of 30 feet and a weight of 30,200 pounds (W/S = 100), the g capability for the low α regime is 3.2 at 80,000 feet and 22 at 40,000 feet. For the high α regime, the g's are 4.5 at 80,000 feet and 31 at 40,000 feet. Characteristics such as these may again find some application in TAV concepts.

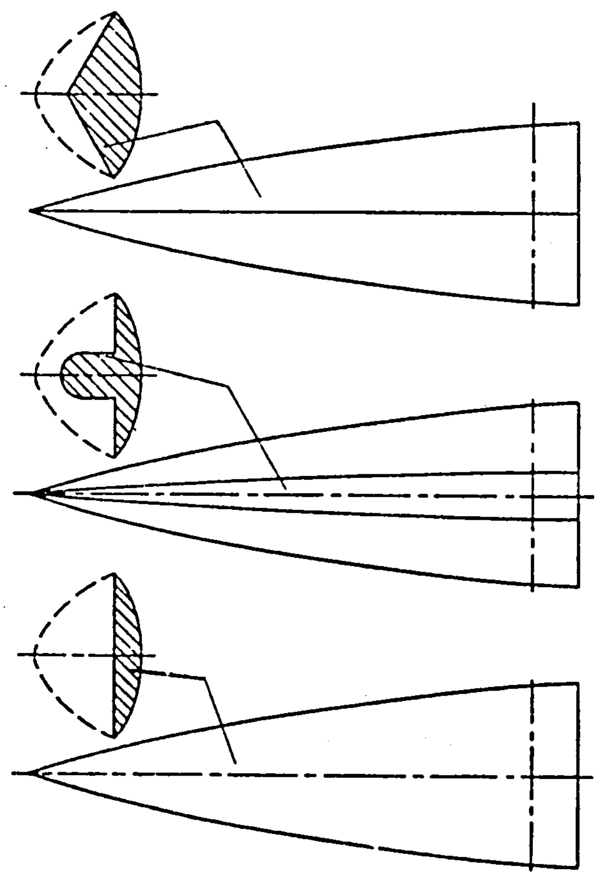
Other Program Histories

A brief summary of some other program histories related to lifting entry technology is included herein for general interest. Some of the early origins go back at least to 1903 when Konstantin Tsiolkovskiy, a Russian teacher, published an article forecasting the eventual development of rocket-propelled space vehicles. Later, Robert Goddard, an American, and Hermann Oberth, a German, independently reached similar conclusions about the time of World War I. These three progenitors of modern space flight were followed by a host of individuals advocating space flight such as Max Valier, Fritz von Opel, Alexander Lippisch, and Walter Hohmann (all Germans). A young Austrian, Eugen Sanger, inspired by these leaders, began to advocate a winged spacecraft that, in 1933, became known as the "Silver Bird." By Sanger's predictions, the concept would reach about $M = 13$ at an altitude of about 100 mile , than decelerate into the upper atmosphere for supersonic cruise at $M = 3.3$ for a range of about 3100 miles. A wave-rider type vehicle called "Rocket Spaceplane" was also conceived by 1938. Sanger also conceived a global rocket bomber, Rabo, after the start of World War II, and the results for the conceptual study were published in 1944.

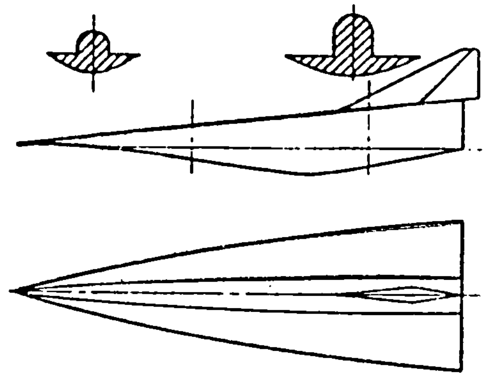
In the same time period, other German groups under Wernher von Braun at Peenemunde were developing the V-2 ballistic rocket. A winged version of the V-2, the A-4, was also developed with the intended purpose of delivering a 1-ton warhead to a distance of 3000 miles. The vehicle would follow a ballistic path and then perform a transition into the atmosphere for $M = 4$ glide. Flight tests with the A-4 were conducted in 1945.

Much of this work was used in U.S. programs that became the early X-series research aircraft. The most noteable hypersonic X aircraft was the X-15 which achieved M = 6.7 and altitudes in excess of 50 miles. The X-15 was eventually used in making entry flights of angles of attack up to 26°.

Other U.S. programs of an aerospace-plane nature included BOMI, BRASS BELL, ROBO, HYWARDS, DYNA-SOAR (X-20), SAINT, START, ASSET, PRIME, SV-5 (X-23 and X-24), M2, HL-10, Starclipper, and Triamese. Other developments were underway in Great Britain, France, and Germany. Work in the Soviet Union on rocket aircraft (Raketoplan) was apparently underway as early as 1962. In 1978, it was announced that a Soviet lifting reentry spacecraft had been drop-tested from a Bear bomber. It was thought that the vehicle was similar to the U.S. X-20 Dyna-Soar. In 1982 and again in 1983, the U.S.S.R. made test flights of a delta lifting reentry vehicle resembling the Dyna-Soar, ASSET, and PRIME vehicles. Recovery was first made in the Indian Ocean and, later, in the Black Sea, indicating the probability of some range control capability. Some U.S.S.R. reentry concepts that have appeared in unclassified publications are shown in the following sketches.



Modified elliptic bodies.



Spaceplane concept.

Clearly, the Soviets appear to be active in the field of controlled, lifting, reentry vehicles.

CONCLUDING REMARKS

It has been the purpose of this paper to review the characteristics of some lifting reentry concepts for manned recoverable spacecraft that might also have application to the design studies of transatmospheric vehicles (TAV's).

Some concluding observations are:

- Several concept features developed during the course of manned recoverable spacecraft programs appear to be of possible use in the design of a TAV from the standpoint of stability and control, maneuverability, and cross-range capability.

- Many spacecraft features have, in principle, been in existence since the turn of the century.

- In addition to the U.S. planned activity with TAV's, the U.S.S.R. appears to be pursuing a course that could lead to a similar type vehicle.

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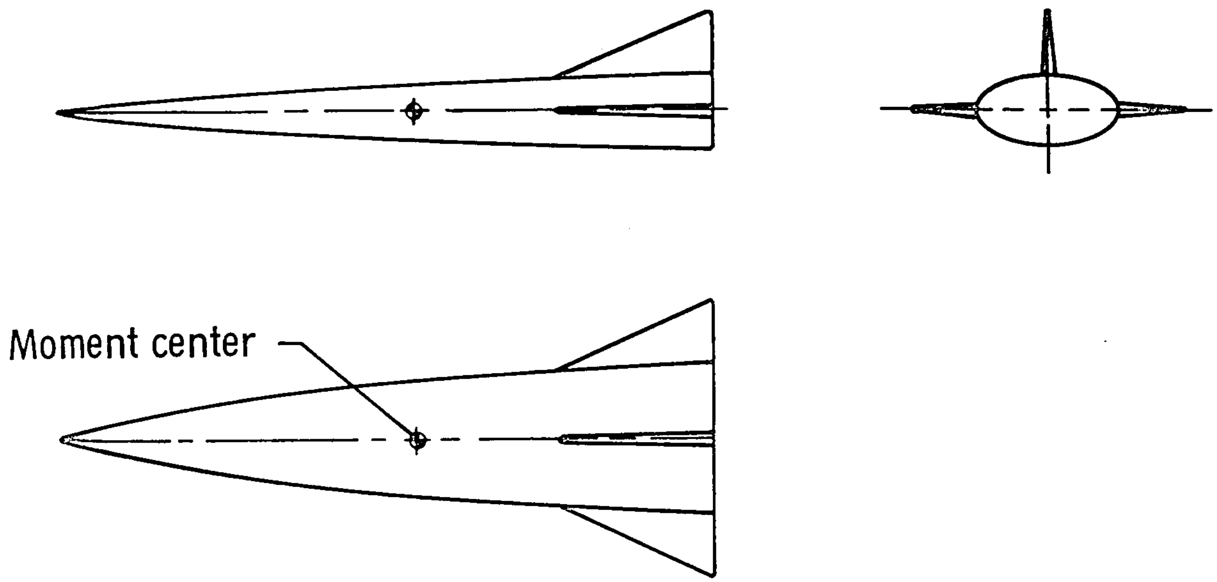

Figure 1.- Elliptical body-tail concept.

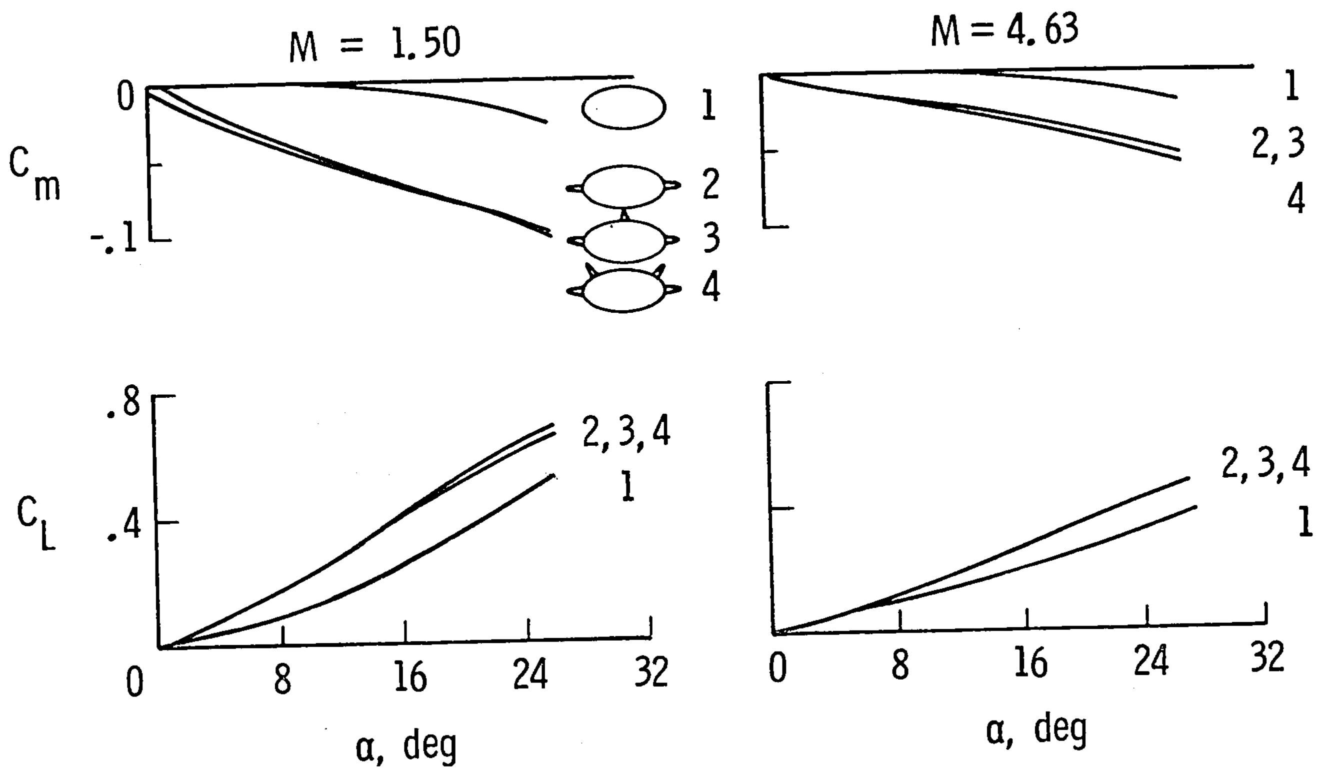

Figure 2.- Longitudinal characteristics, elliptical body-tail concept, c.g. = 0.55_l.

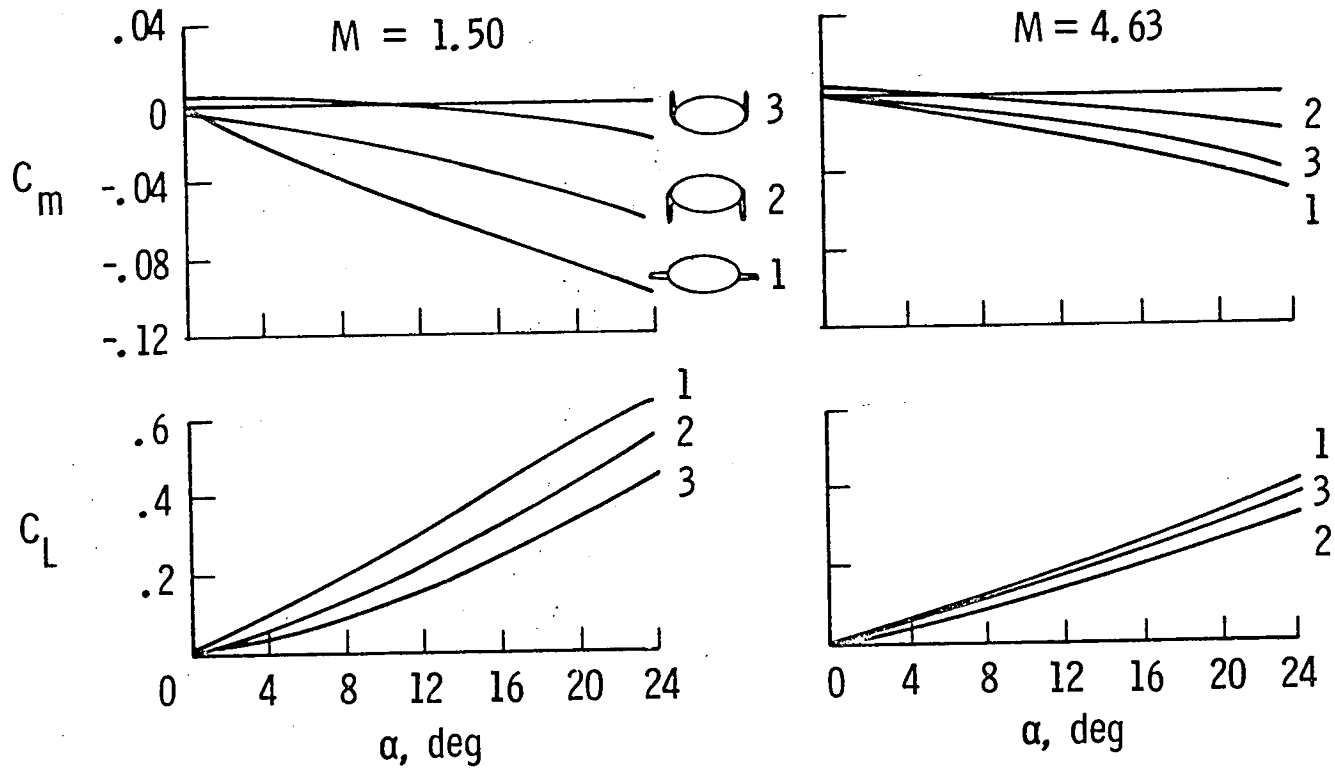

Figure 3.- Longitudinal control, elliptical body-tail concept, c.g. = 0.55_l.

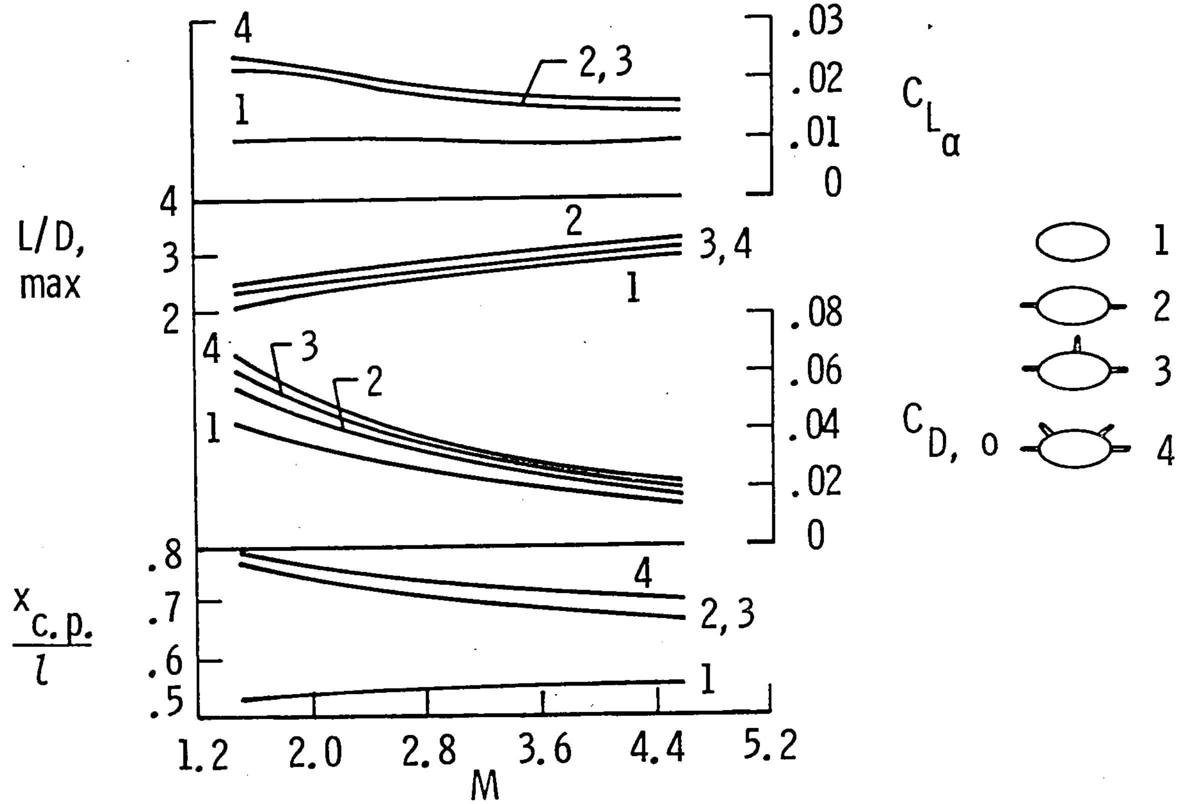

Figure 4.- Longitudinal summary, elliptical body-tail concept, c.g. = 0.55_l.

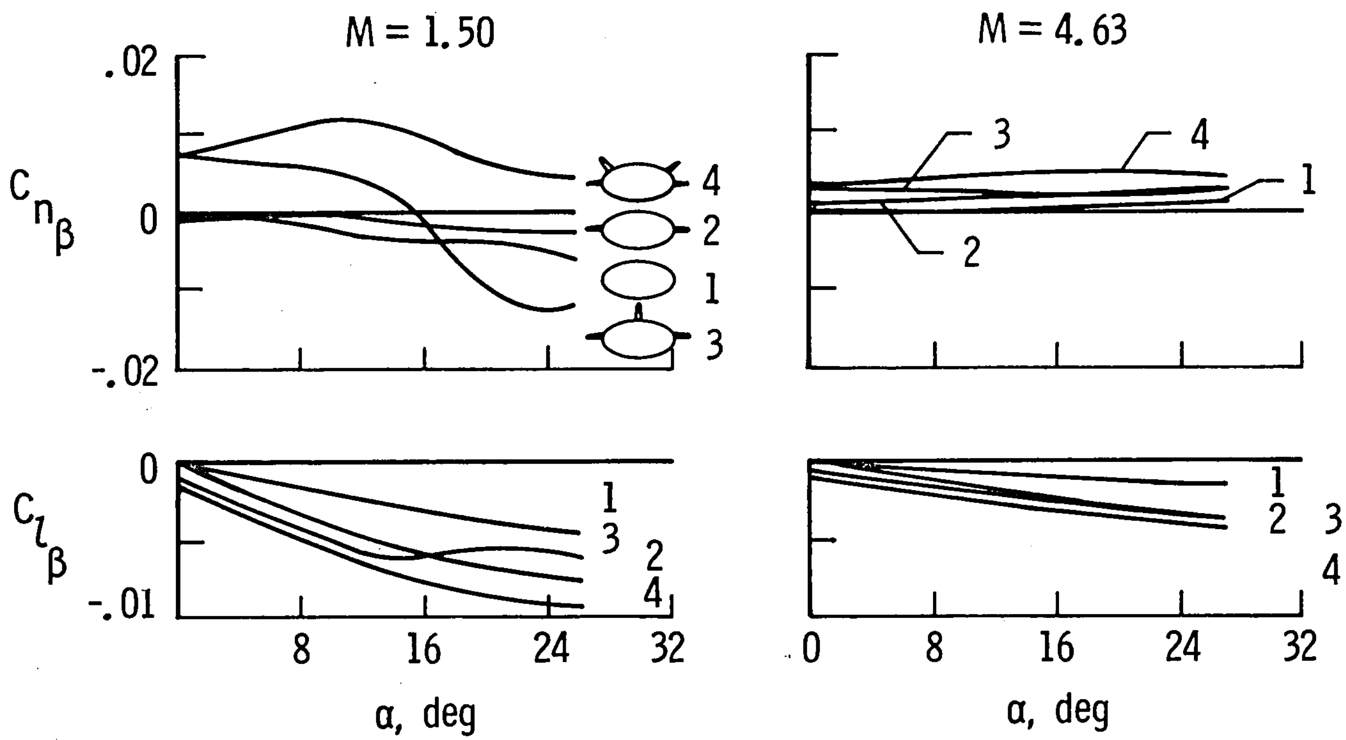

Figure 5.- Lateral-directional characteristics, elliptical body-tail concept, c.g. = 0.55_l.

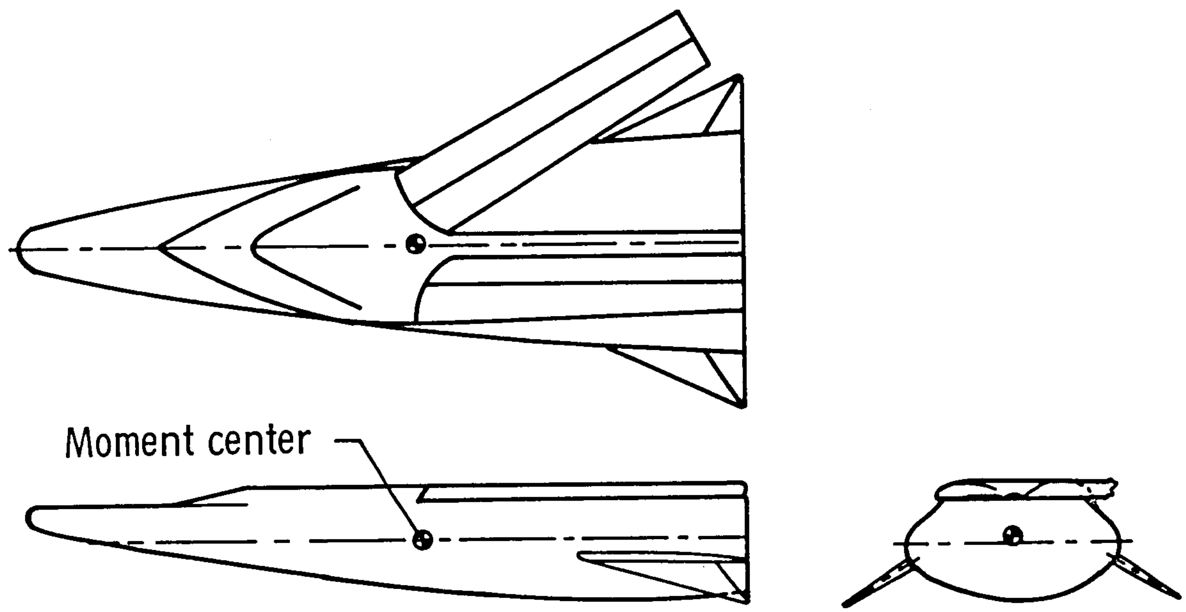

Figure 6.- Variable wing-sweep concept.

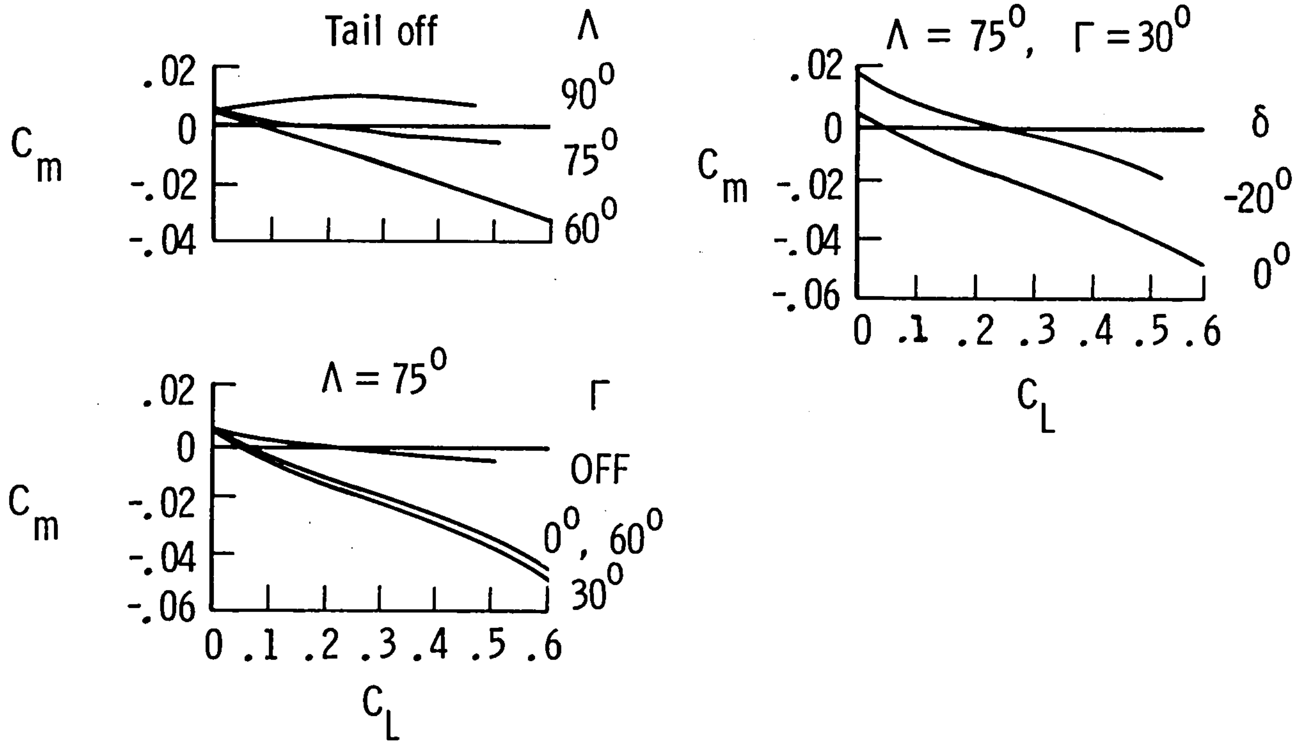

Figure 7.- Longitudinal characteristics, variable wing-sweep concept, M = 2.86, c.g. = $0.58l$.

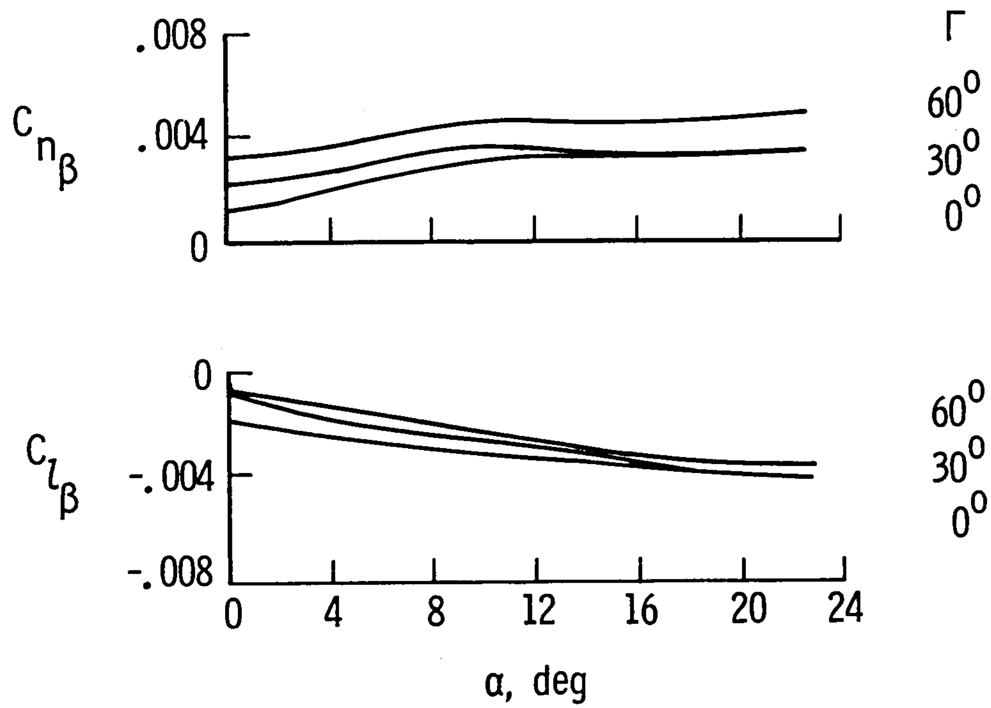

Figure 8.- Lateral-directional characteristics, variable wing-sweep concept, M = 2.86, Λ = 75°, c.g. = 0.58l.

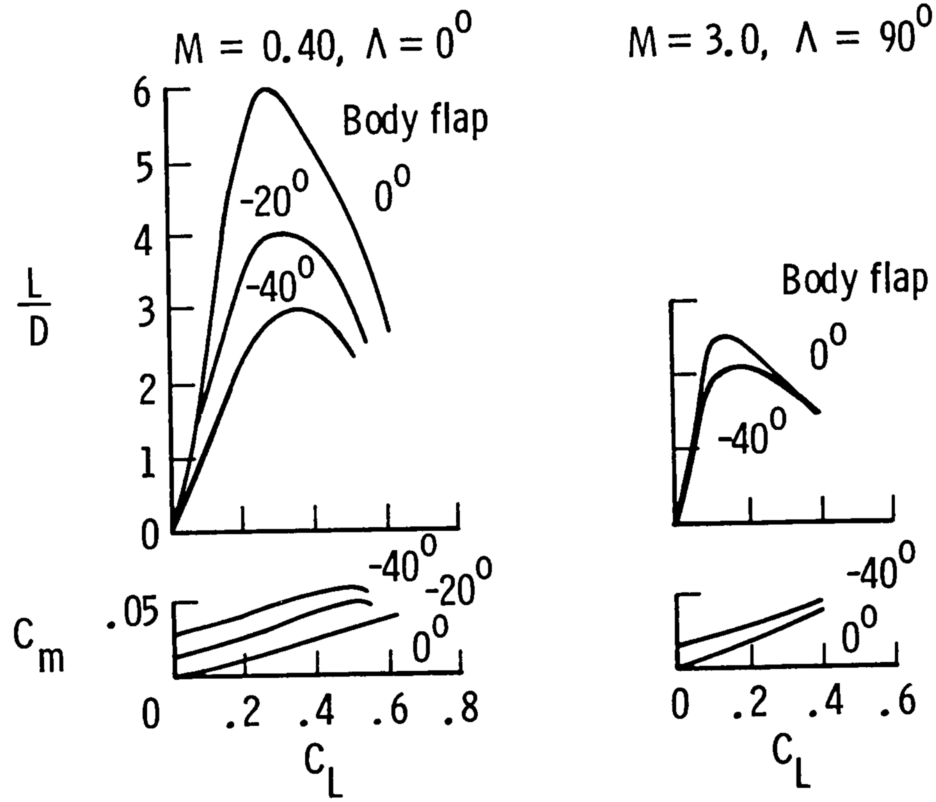

Figure 9.- Body base flap control, variable wing-sweep concept, tail off, c.g. = 0.655l.

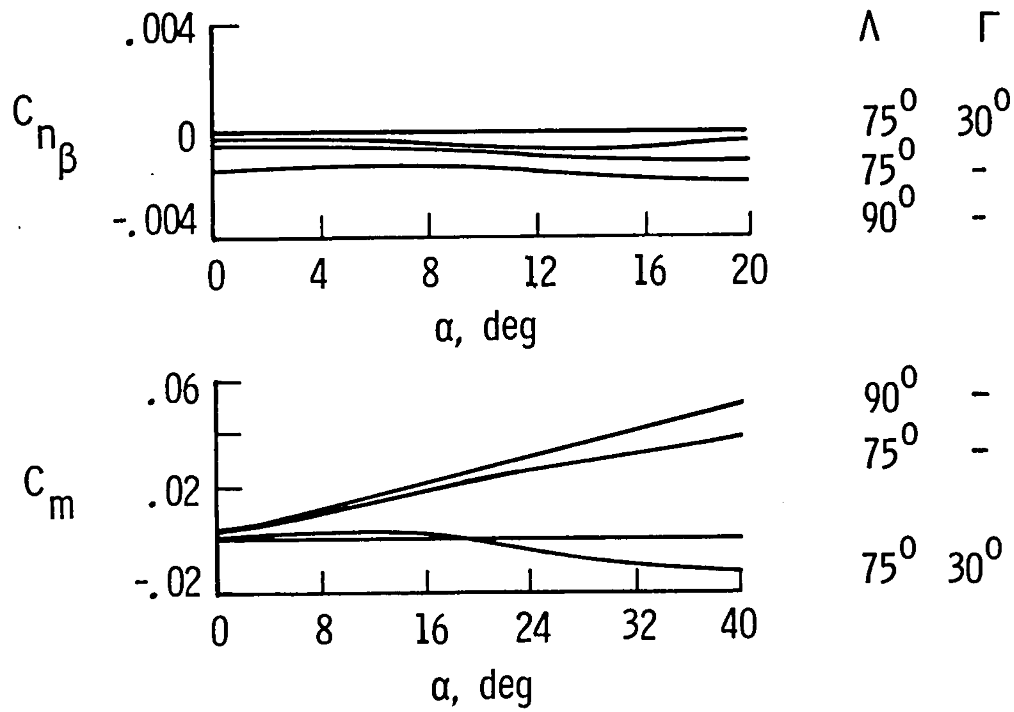

Figure 10.- Aerodynamic characteristics, variable wing-sweep concept, M = 10, c.g. = 0.655l.

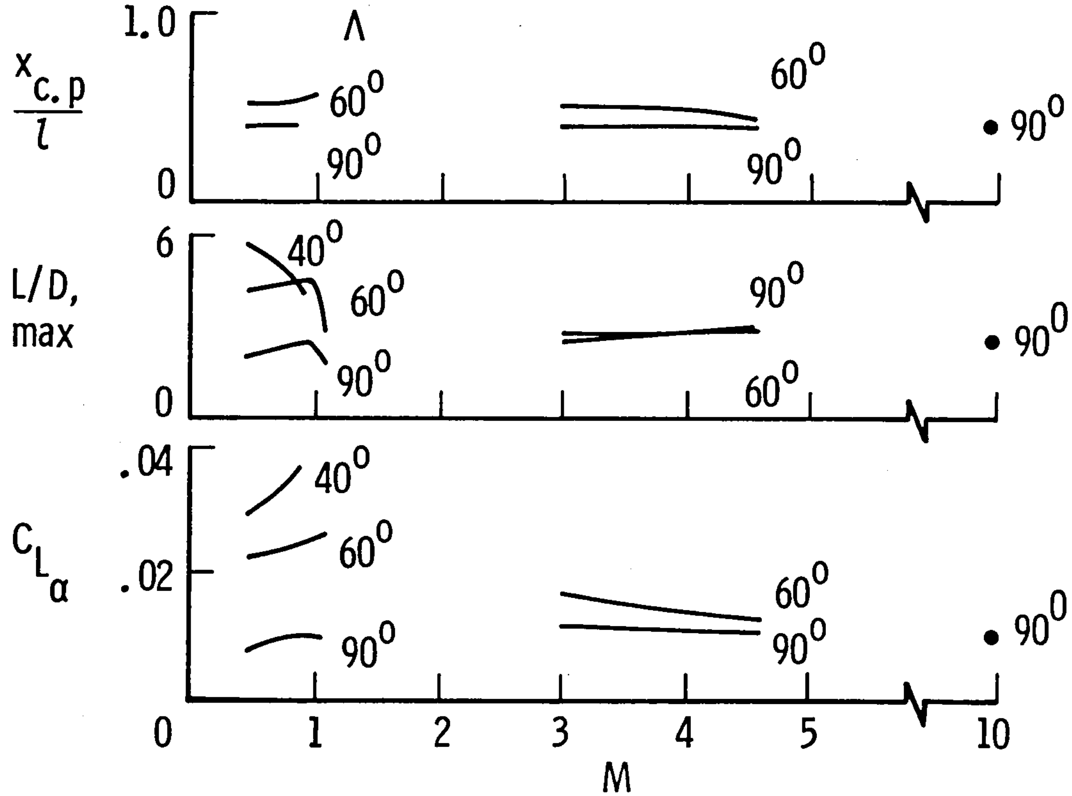

Figure 11.- Longitudinal summary, variable wing-sweep concept, tail off.

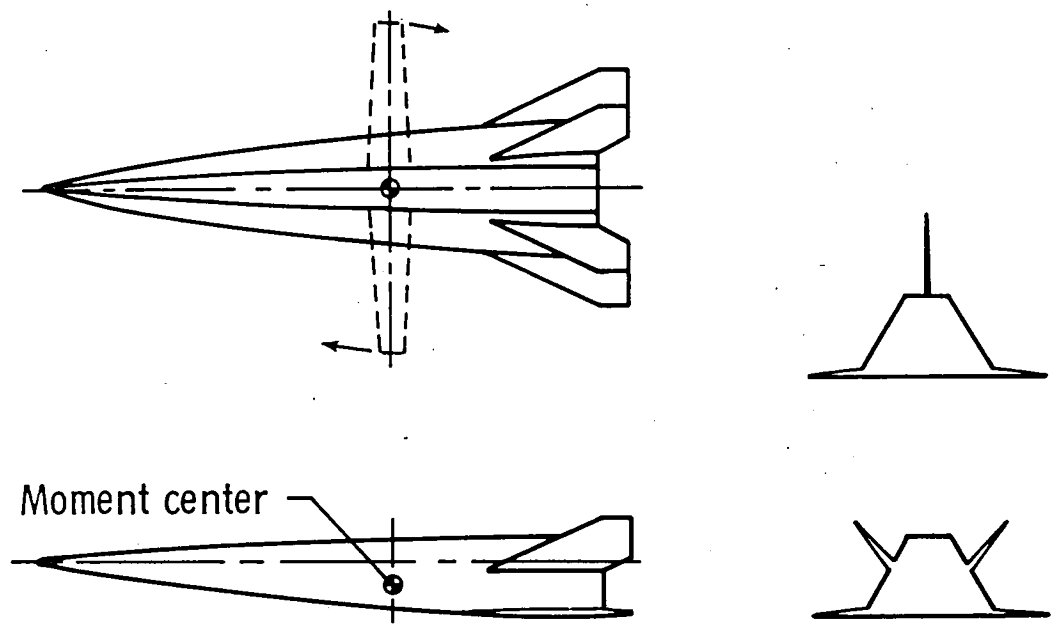

Figure 12.- Skewed-wing concept.

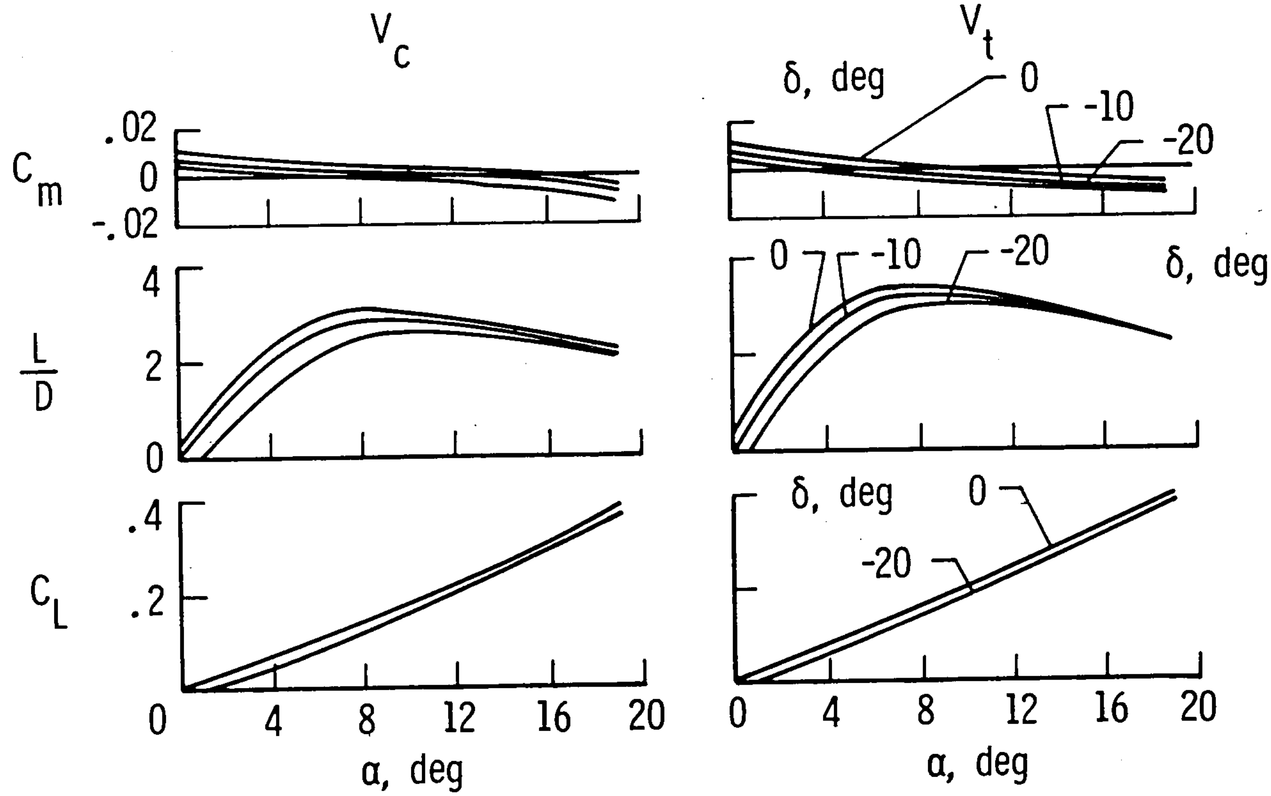

Figure 13.- Longitudinal characteristics, skewed-wing concept, $M = 4.6$, c.g. = $0.628l$, $\Lambda = 90°$.

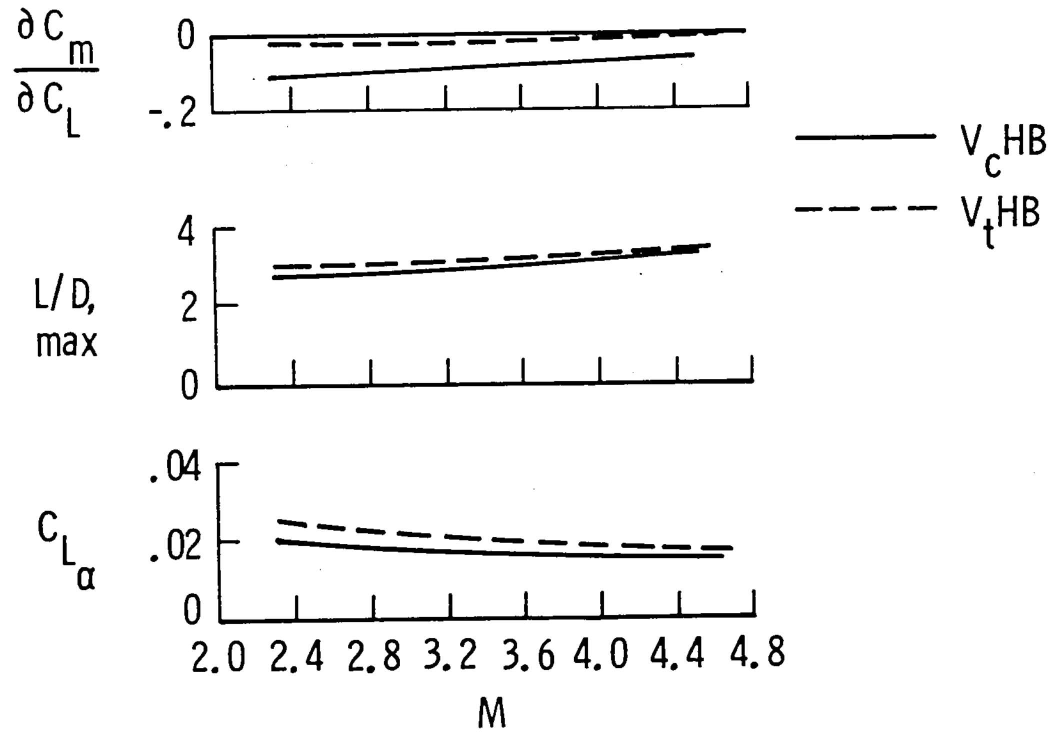

Figure 14.- Longitudinal summary, skewed-wing concept, c.g. = 0.628_l, Λ = 90°.

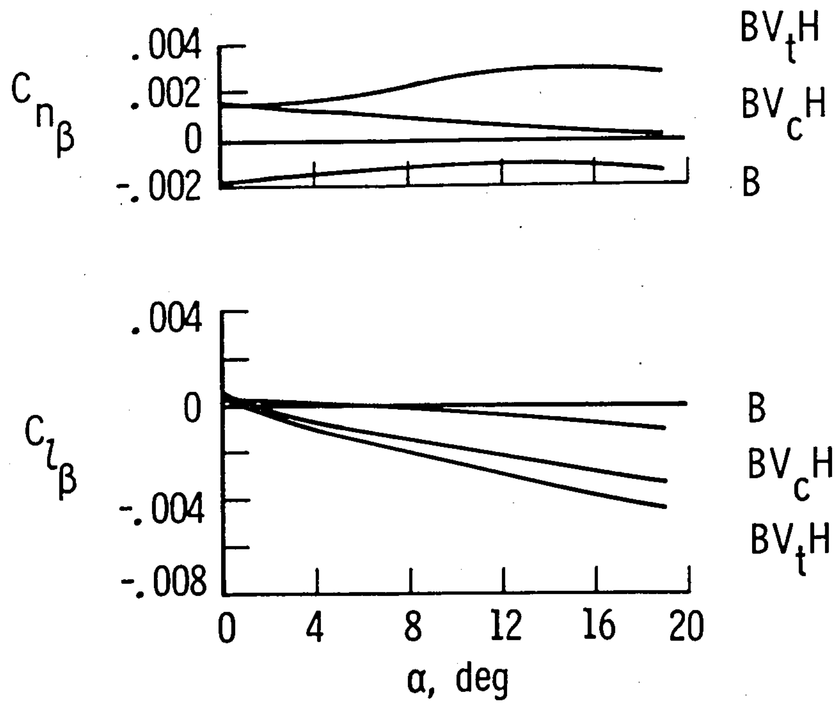

Figure 15.- Lateral-directional characteristics, skewed-wing concept, $M = 4.6$, c.g. = 0.628_l, $\Lambda = 90°$.

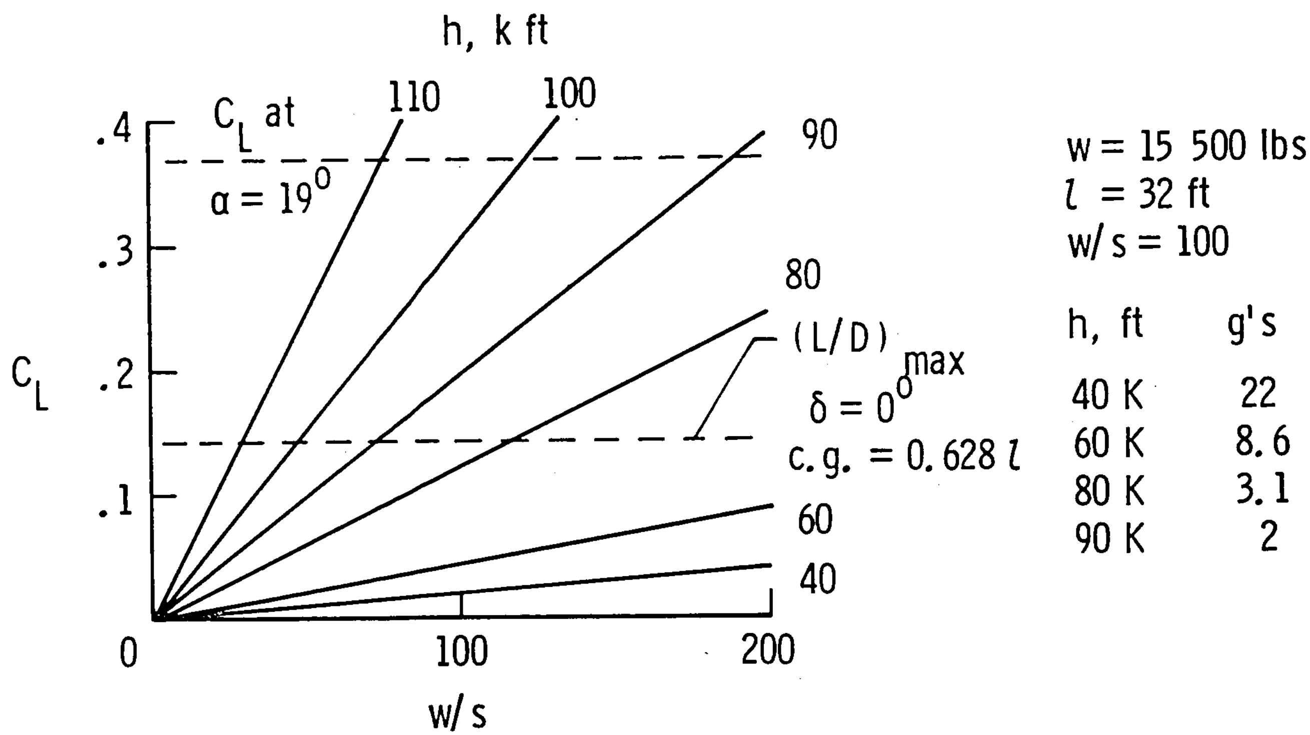

Figure 16.- Maneuver potential, skewed-wing concept, $M = 4.6$, $\Lambda = 90°$.

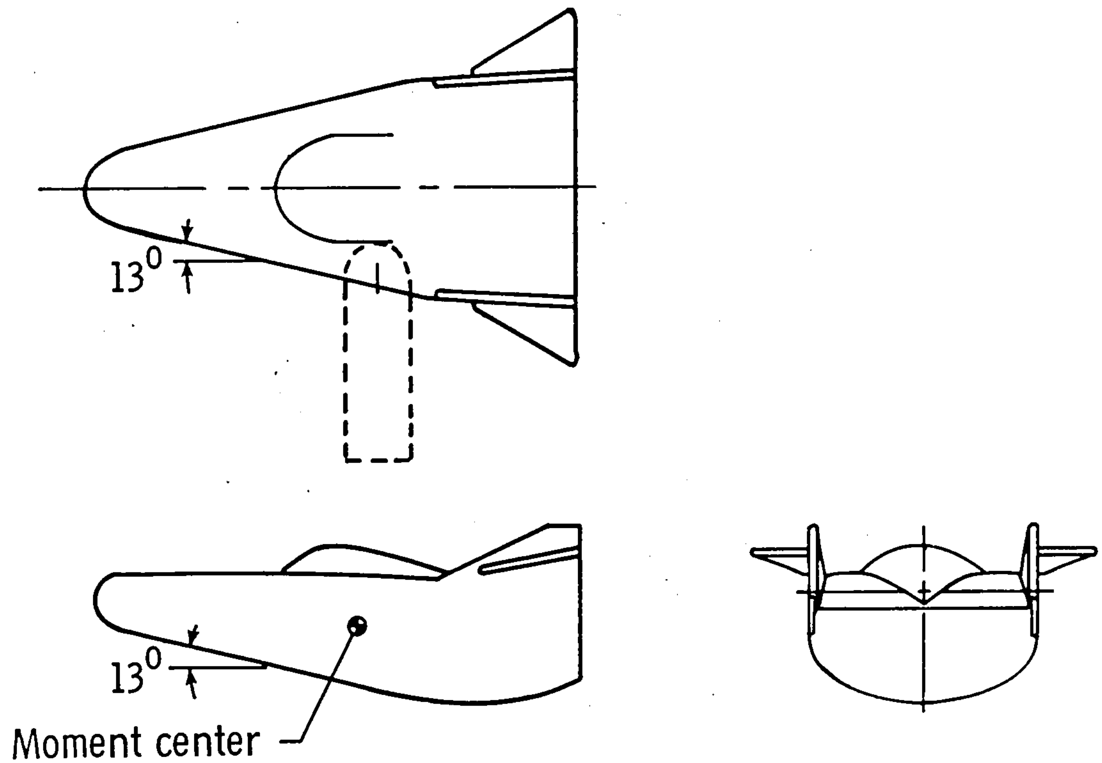

Figure 17.- Blunt lifting body concept.

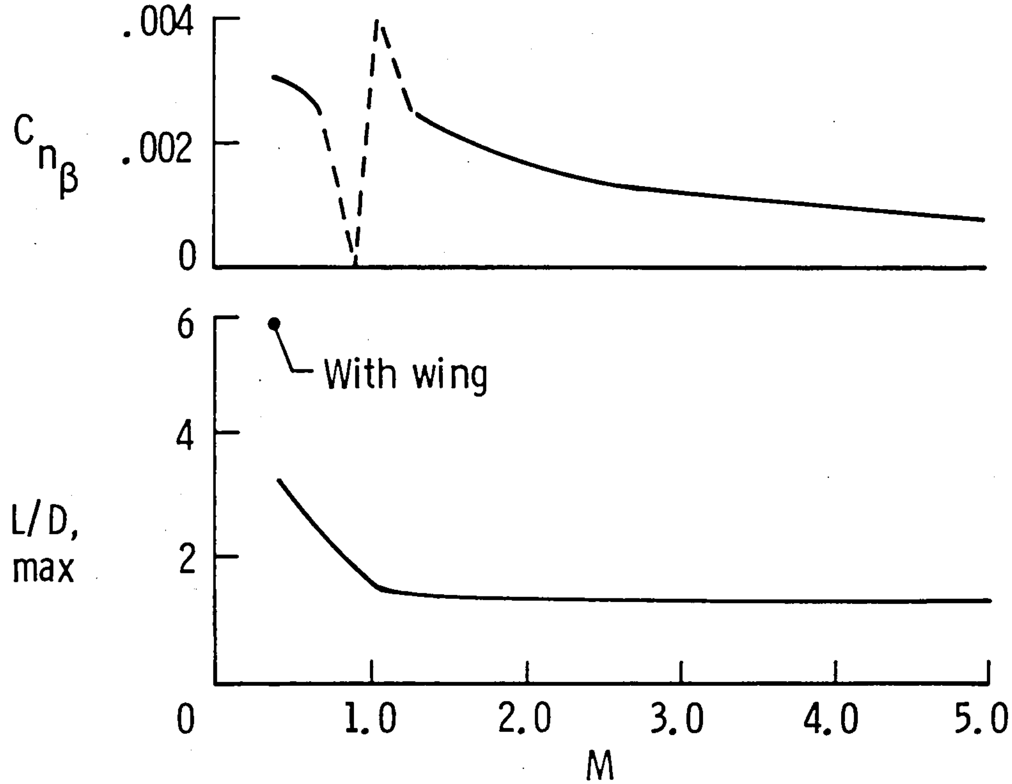

Figure 18.- Aerodynamic characteristics, blunt lifting body concept, c.g. = 0.55_l.

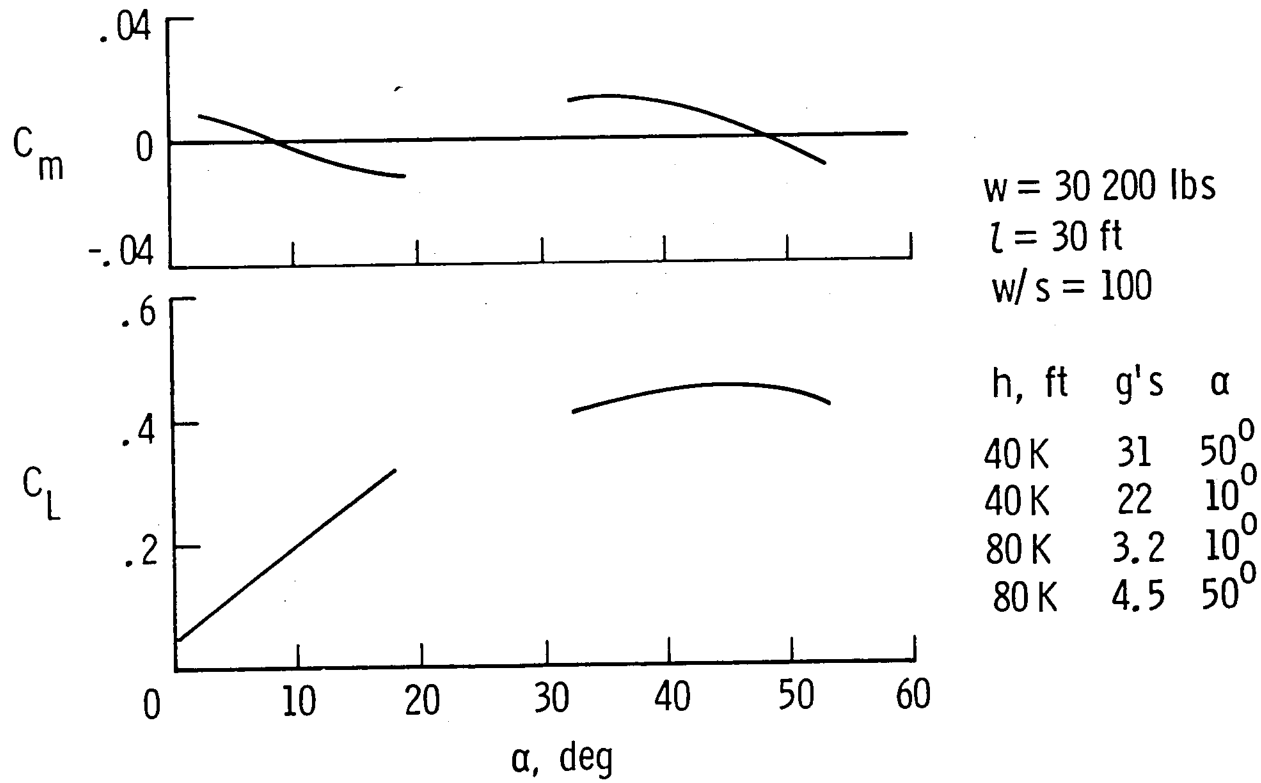

Figure 19.- Maneuver potential, blunt lifting body concept, M = 5.

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16. Abstract

The aerodynamic characteristics of some lifting reentry concepts are examined with a view to the applicability of such concepts to the design of possible transatmospheric vehicles (TAV). A considerable amount of research has been done in past years with vehicle concepts suitable for manned atmospheric-entry, atmospheric flight, and landing. Some of the features of these concepts that permit flight in or out of the atmosphere with maneuver capability should be useful in the mission requirements of TAV's. The concepts illustrated include some hypersonic-body shapes with and without variable geometry surfaces, and a blunt lifting-body configuration. The merits of these concepts relative to the aerodynamic behavior of a TAV are discussed.

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