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INTRODUCTION

The Langley Research Center of the National Aeronautics and Space Administration is continuing its support in the refinement and updating of the Space Shuttle Orbiter Aerodynamic Design Data Base (ref. 1, ADDB). These efforts include wind-tunnel investigations in areas where anomalies have been noted between flight and the predicted aerodynamic characteristics (see ref. 2), refinement in the aerodynamic data base by supplementing previously obtained data, and continued studies of control-surface combinations which may enhance vehicle handling qualities or improve aerodynamic performance. In addition, new areas of investigation are considered on an "as requested" basis.

One such area is the ability to provide a safe crew escape from the orbiter during an off-the-pad abort. This situation could occur during a launch condition in which the solid rocket boosters (SRB's) ignite and either one, two, or all three Space Shuttle main engines (SSME's) fail to operate. The realization that this event could occur was illustrated during the June 24, 1984, scheduled launch of the "Discovery" at which time SSME's one and three failed to operate properly, and the mission was aborted four seconds prior to SRB ignition. If the SRB's had ignited with the SSME's working improperly, the following scenario could have occurred: The vehicle could have been carried too far downrange to return to the launch site (RTLS) for a safe landing at the Kennedy Space Center, and the vehicle would have had insufficient thrust to make orbit or reach a primary downrange landing site. This would have resulted in orbiter impact in the ocean which is unacceptable, since it is anticipated that the orbiter cannot withstand a water ditch.

Wind-tunnel studies were performed at Langley to examine the feasibility of crew bailout from the orbiter side hatch located forward on the fuselage near the wing-fillet juncture. (See ref. 3.) Results of these tests at low subsonic speeds indicated that without considerable structural modification to the vehicles in the forward hatch area, a safe crew bailout may be only marginally successful. In an effort to avoid major structural modifications, other means of crew escape were examined.

Consistently successful bailouts were obtained and documented in reference 3 by flying the orbiter inverted and exiting through the top hatches which exist on the "Columbia" and "Enterprise." Because of problems associated with the "inverted" crew attaining access to the top hatch, this approach may also be unacceptable. However, if the vehicle could be maintained in an upright position and trimmed to extremely high angles of attack (>60°) in a stable condition, an exit from the top hatch appears feasible. This condition would also ensure that the crew would not have to contend with impact on the vehicle wings, fuselage, orbital maneuvering system (OMS) pods, or vertical tail during escape. (See side-hatch-exit cases of ref. 3.) The scenario, therefore, would be to ride the launch to SRB burnout, separate from the external tank (ET), and achieve and maintain a high-angle-of-attack condition until subsonic low-altitude conditions are reached. The Langley Research Center has therefore initiated studies to determine orbiter aerodynamic characteristics in the angle-of-attack range from 20° to 90° at Mach numbers from 4.6 to 0.30, with emphasis on vehicle stability, control, and trim characteristics above 60° angle of attack. This Mach number range spans those possible for off-the-pad abort situations.

The present paper presents the results of these studies obtained in the Unitary Plan Wind Tunnel in the Mach number range from 4.60 to 1.60 at Reynolds numbers, based on body length, of 2.15×10^6 and 4.30×10^6. The model used in this investigation was a 0.00986-scale orbiter, having a blade-mounted support system entering the model in the region of the vertical tail. Elevon deflections of 0°, -10°, -20°, and -40° and body-flap deflections of 0°, ±6°, and -12° were investigated individually and in combination. Schlieren photographs are also presented for selected configurations and Mach numbers.

SYMBOLS

The forces and moments have been reduced to nondimensional coefficients based on the area, mean aerodynamic chord, and span of the reference wing. The moment reference point is located at 65 percent of the reference body length. (See fig. 1.)

ADDB	Aerodynamic Design Data Book - Vol. I Orbiter Vehicle
b	wing span, in.
C_D	drag coefficient, Drag/qS
C_L	lift coefficient, Lift/qS
C_m	pitching-moment coefficient, Pitching moment/$qS\bar{c}$
$\bar{c}$	mean aerodynamic chord, in.
ℓ	reference length, in.
L/D	lift-drag ratio
M	Mach number
p_t	stagnation pressure, psf
q	free-stream dynamic pressure, psf
R	unit free-stream Reynolds number, ft^{-1}

S wing reference area, ft^2

T_t stagnation temperature, °F

X_{cp} longitudinal center of pressure, in.

α angle of attack, deg

δ_{BF} body-flap deflection, positive with trailing edge down, deg

δ_e elevon deflection, positive with trailing edge down, deg

Subscripts:

max maximum

min minimum

trim trimmed conditions

ref reference

t reservoir conditions

MODELS

The model used in this investigation was a cast aluminum 0.00986-scale orbiter, based on vehicle 101 (Enterprise) outer mold-line dimensions. (See fig. 1 for a vehicle sketch and fig. 2 for a photograph of the launch configuration showing the top hatch exit location.) Reference dimensions for the full-scale orbiter and for the model of this investigation are presented in figure 1.

The base of the model was modified to accommodate a blade-sting arrangement which entered the model in the region where the vertical tail would be located. A sketch of the model-support arrangement is shown in figure 3, and a photograph of the model mounted in the Unitary Plan Wind Tunnel and showing the blade-sting arrangement in the rear of the model is presented in figure 4.

Elevon deflections of 0°, -10°, -20°, and -40° (trailing edge up), and body-flap deflections of 0° and -12° (trailing edge up), set manually with fixed brackets, were tested in various combinations. Also tested were additional body-flap settings of ±6° to determine body-flap effectiveness for a fixed elevon setting at Mach numbers of 3.00, 3.40, 3.82, 4.20, and 4.60.

TESTS AND CORRECTIONS

The investigation was performed in the low and high Mach number test sections of the Langley Unitary Plan Wind Tunnel. A description and calibration of both test sections are presented in reference 4. The Mach numbers, stagnation pressures, stagnation temperatures, and Reynolds numbers for the present investigation were as follows:

Mach	P_t (psf)	T_t (°F)	R (10^6/ft)
1.60	1079	125	2.0
1.60	2157	125	4.0
1.80	1154	125	2.0
1.80	2308	125	4.0
2.00	1253	125	2.0
2.40	1520	125	2.0
2.80	1873	125	2.0
3.00	2083	125	2.0
3.40	2568	125	2.0
3.82	3387	150	2.0
4.20	4067	150	2.0
4.60	4878	150	2.0

The stagnation dewpoint was maintained sufficiently low (-30°F) to insure that no condensation effects would be encountered in either test section. The tests were made for an angle-of-attack range from about 0° to 90° at a sideslip angle of 0°.

Forces and moments were measured by use of a six-component, strain-gage balance. The angles of attack were corrected for deflection of the balance and sting due to aerodynamic loads, as well as for measured tunnel-flow angularity. The drag results presented herein are total drag, which includes the effects of base drag. Boundary-layer transition was artifically fixed with single-spaced carborundum grains (1/16-inch spacing) having a nominal diameter of 0.012 inch and affixed 1.2 inch behind the nose of the model, and located 0.365 inch behind the leading edge of the 45° portion of the wing, and 0.125 inch behind the leading edge of the 81° portion of the wing. Grit sizing was selected by use of the methods described in reference 5 in an effort to assure turbulent flow over the model.

RESULTS AND DISCUSSION

Presentation of Results

Valid Angle-of-Attack Range.- As previously stated (and shown in fig. 4), the model was supported by a blade-sting arrangement which adversely influences the data in the low-to-moderate angle-of-attack range. (See fig. 5.) Therefore, only data in the angle-of-attack range from 20° to 90° are presented.

Valid Mach Numbers.- At the lowest test Mach number of 1.60, a tunnel wall shock reflection impinged on the support system just aft of the model, as indicated by the schlieren photograph shown in figure 6a at 53° angle of attack. At $\alpha = 70°$ (fig. 6b), the interference shock is shown impinging on the model, thus limiting the maximum valid test angle of attack at M = 1.60. The force-and-moment data obtained at M = 1.60 are clearly affected by this shock impingement and therefore are invalid. (See figs. 7 and 9a.) The trends (even for controls deflected) seem to indicate similar stable, trimmable conditions as was noted for the higher Mach number interference-free cases. However, no summary data for this Mach number (M = 1.60) are presented.

Figures 7a and 7b present the effects of Mach number in the range 1.60 to 2.80 for elevon deflection (δ_e) and body-flap deflection (δ_{BF}) equal to zero, and for $\delta_e = -40°$, $\delta_{BF} = -12°$, respectively. Figures 8a and 8b present the effects of Mach number in the range 3.00 to 4.60 for $\delta_e = \delta_{BF} = 0°$ and for $\delta_e = -40°$, $\delta_{BF} = -12°$, respectively. Figures 9 and 10 present the effect of elevon deflection on the longitudinal aerodynamic characteristics at each test Mach number with the body-flap deflected 0° and -12°, respectively. Figure 11 presents the effects of body-flap deflection on the longitudinal aerodynamic characteristics of the model with elevons fixed at -20° for Mach numbers of 3.00, 3.40, 3.82, 4.20, and 4.60.

Discussion

Effect of Mach Number.- Increasing Mach number produced a progressive reduction in the value of $C_{L,max}$ resulting from reduction in positive lift-curve slope associated with the increase in Mach number. It is interesting to note that the angle of attack for $C_{L,max}$ remains essentially constant (between 45° and 50°). The associated variations of pitching moment, however, being generally and radically changing, indicate this angle-of-attack range probably would be a difficult and undesirable area for flight, from both handling qualities and control considerations.

Increasing the angle of attack to 60° or higher provided a stable vehicle, with stability increasing with increasing angle of attack. This is interesting, since changes in orbiter longitudinal stability in normal flight attitudes (i.e., $\alpha \leq 30°$) are maximum in the Mach range from about 4 to 0.90. (See ref. 1, ADDB.) The indication is that X_{cp} at these high angles of attack is relatively insensitive to changes in Mach number, at least at supersonic speeds. These results are similar to some limited high-angle-of-attack data taken at a Mach number of 0.30. (See ref. 3.) The model used in reference 3, however, was sting-mounted and may have experienced some interference effects. Still the possibility exists that the vehicle may be stable at high angles of attack in the Mach range of interest in the overall study (i.e., M = 0.30 to 4.60).

With regard to the associated lift and lift-drag ratio at these higher angles of attack, there are little or no changes in C_L or L/D at a given angle of attack as the Mach number is increased.

Control Effectiveness.- The elevons and body flap, individually and in combination, provided sufficient control to trim the vehicle in the stable angle-of-attack range of interest, generally from about 60° to 80° for all valid Mach numbers (i.e., M = 1.8 to 4.6; see figs. 9 and 10). This wide range of trim results primarily from "removal" of area behind the moment reference point, since there are only small losses in C_L due to control deflection and little or no effect on L/D.

Figure 11 presents body-flap effectiveness for a fixed elevon setting at Mach numbers $\geq$ 3.00. The body flap could be considered as a "trim tab" to maintain trim about a given angle of attack during flight, depending on which surface (elevons or body flap) moves the fastest. For $\alpha \geq 60°$, control effectiveness is favorable for the body flap, indicating about a 10° angle-of-attack increment for the range of settings investigated.

Trimmed Characteristics.- A summary of the orbiter model high-angle-of-attack trimmed characteristics is presented in figure 12. These data indicate the vehicle has a range of α_{trim} from about 78° to 62° at M = 4.60, to about 78° to 58° at M = 1.80, with positive trimmed lift and lift-to-drag ratios in the Mach range of this investigation. Because of the wide range of available stable trimmed lift and lift-to-drag ratios noted for the vehicle, considerable range modulation should be available to the orbiter flying in this high-angle-of-attack attitude.

CONCLUDING REMARKS

Results of a study to determine the Space Shuttle Orbiter aerodynamic characteristics at high angles of attack in the Mach number range from 1.80 to 4.60, and at Reynolds numbers based on body length of 2.15×10^6 and 4.30×10^6, lead to the following observations:

1. The orbiter is longitudinally stable and trimmable in the angle-of-attack range from approximately 60° to 80°.

2. Both the elevon and body flap indicate positive pitch control-effectiveness at the angles of attack (60° to 80°) and Mach numbers of this study.

3. For the range of neutral-to-stable trim in the angle of attack range above about 60°, the deflected elevon/body-flap combinations provide positive trimmed lift and lift/drag ratios at the Mach numbers of this study.

REFERENCES

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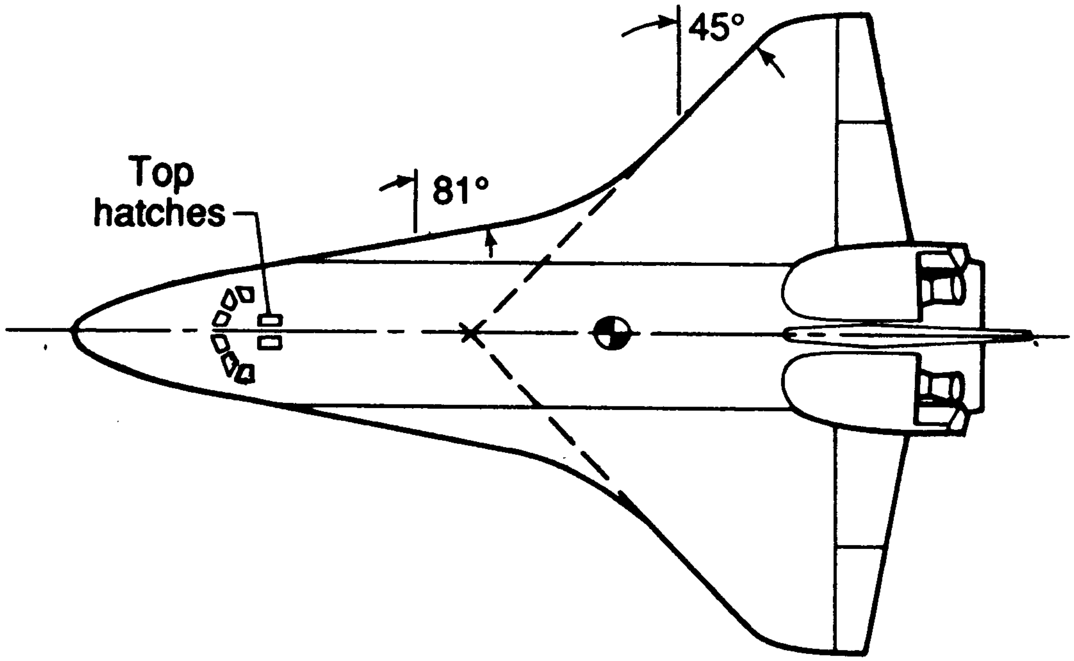
2. Findlay, John T.; Compton, Harold R.; et. al.: Shuttle "Challenger" Aerodynamic Performance from Flight Data-Comparisons with Predicted Values and "Columbia" Experience. AIAA Paper No. 84-0485, January 1984.

3. Scallion, W. I.; Spencer, Bernard, Jr.; et. al.: Study of Several Factors Affecting Crew Escape Trajectories from the Space Shuttle Orbiter at Low, Subsonic Speeds. NASA TM-86303, February 1985.

4. Jackson, C. M.; Corlett, W. A.; and Monta, J. M.: Description and Calibration of the Langley Unitary Plan Wind Tunnel. NASA TP 1905, 1981.

5. Braslow, A. L. and Knoxx, E. C.: Simplified Method for Determination of Critical Height of Distributed Roughness Particles for Boundary-Layer Transition at Mach Numbers from 0 to 5. NACA TN 4363, September 1958.



Reference dimensions

	Full scale	Model
S	2690 ft^2	0.2615 ft^2
b	936.68 in.	9.236 in.
$\bar{c}$	474.81 in.	4.682 in.
ℓ	1290.30 in.	12.723 in.

(based on 0.0098 scale)

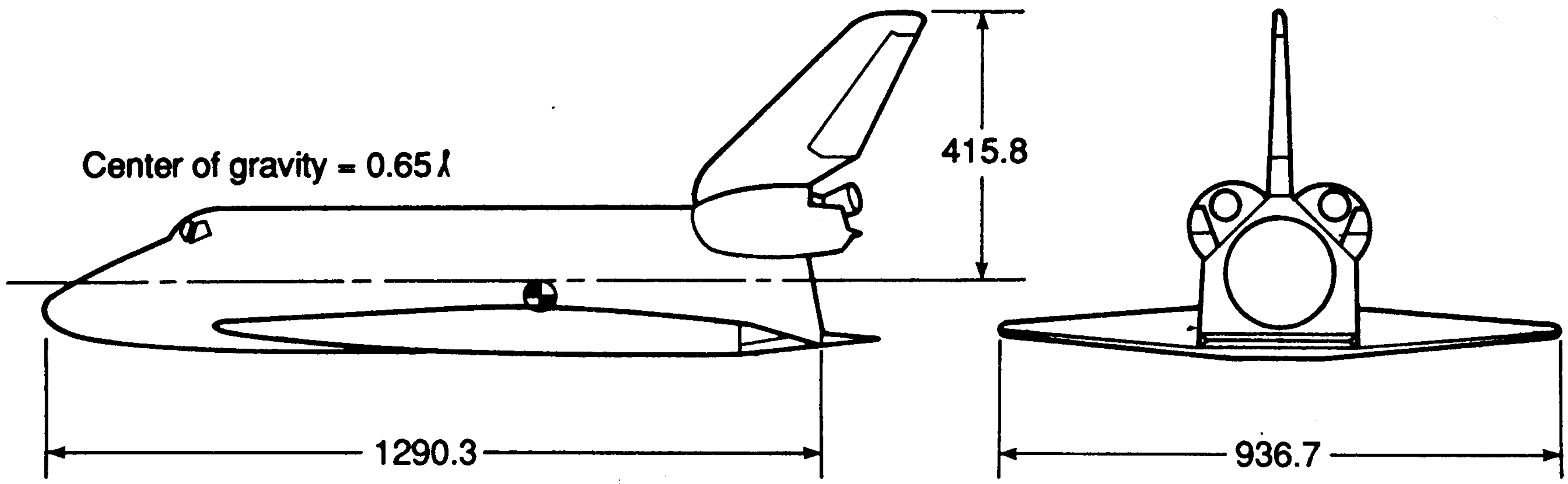


Figure 1.- Sketch of Orbiter 101. All dimensions given in inches unless otherwise noted.

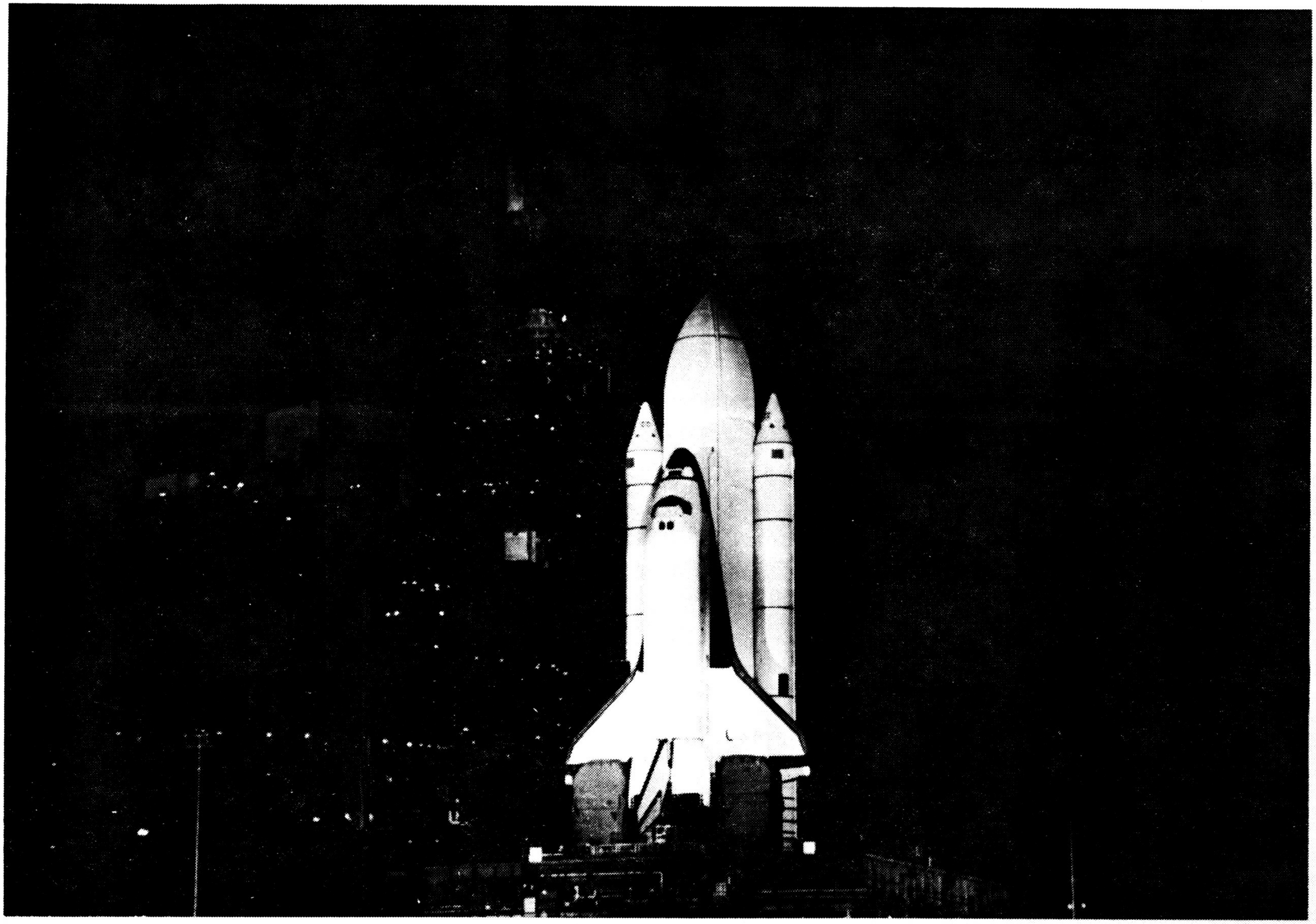


Figure 2.- Orbiter 101 in launch position. Note location of top-hatches aft of canopy.

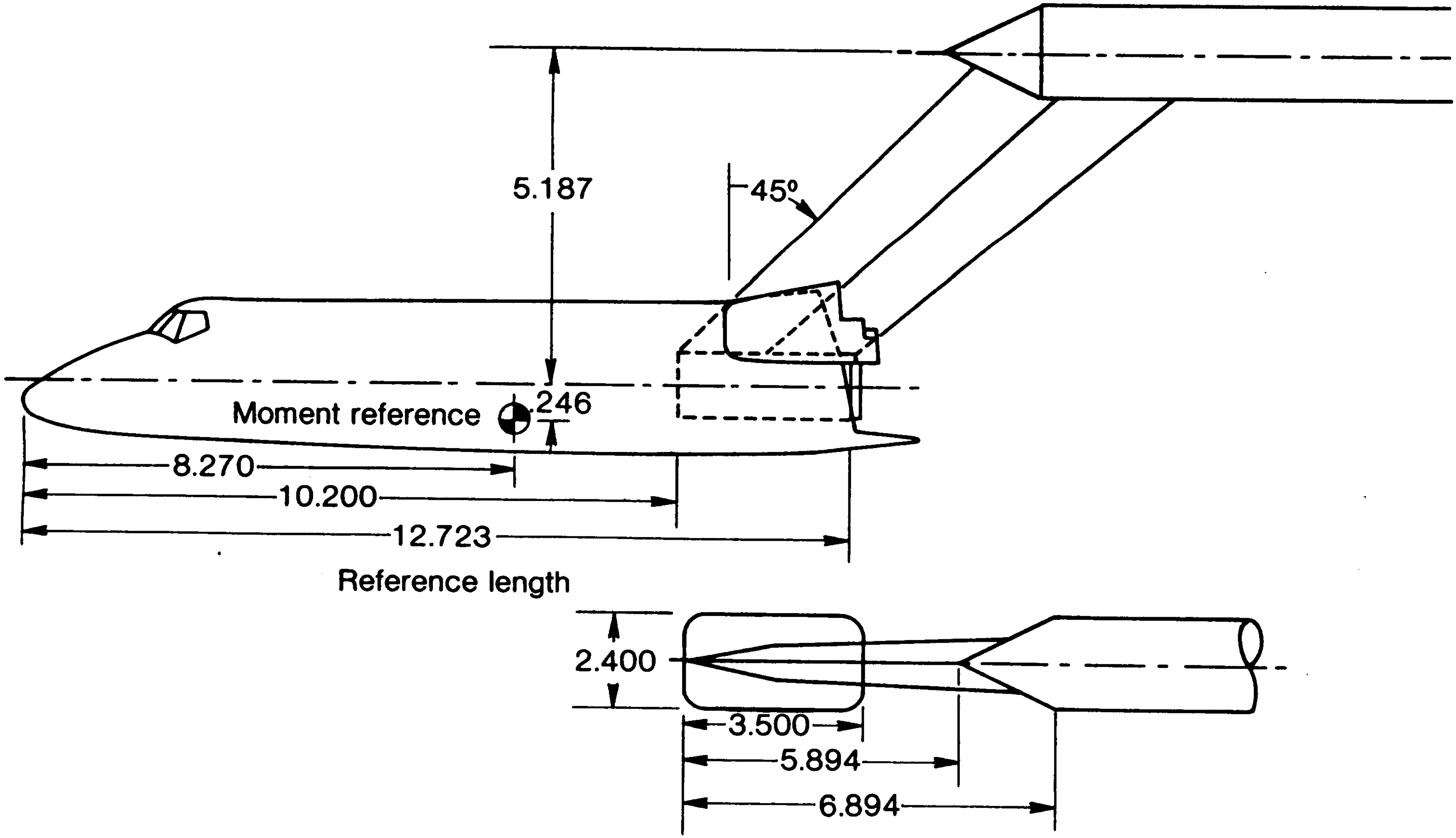


Figure 3.- Sketch of model and model support system showing blade location in model base.

Figure 4.- Photograph of the model mounted in the Unitary Plan Wind Tunnel.

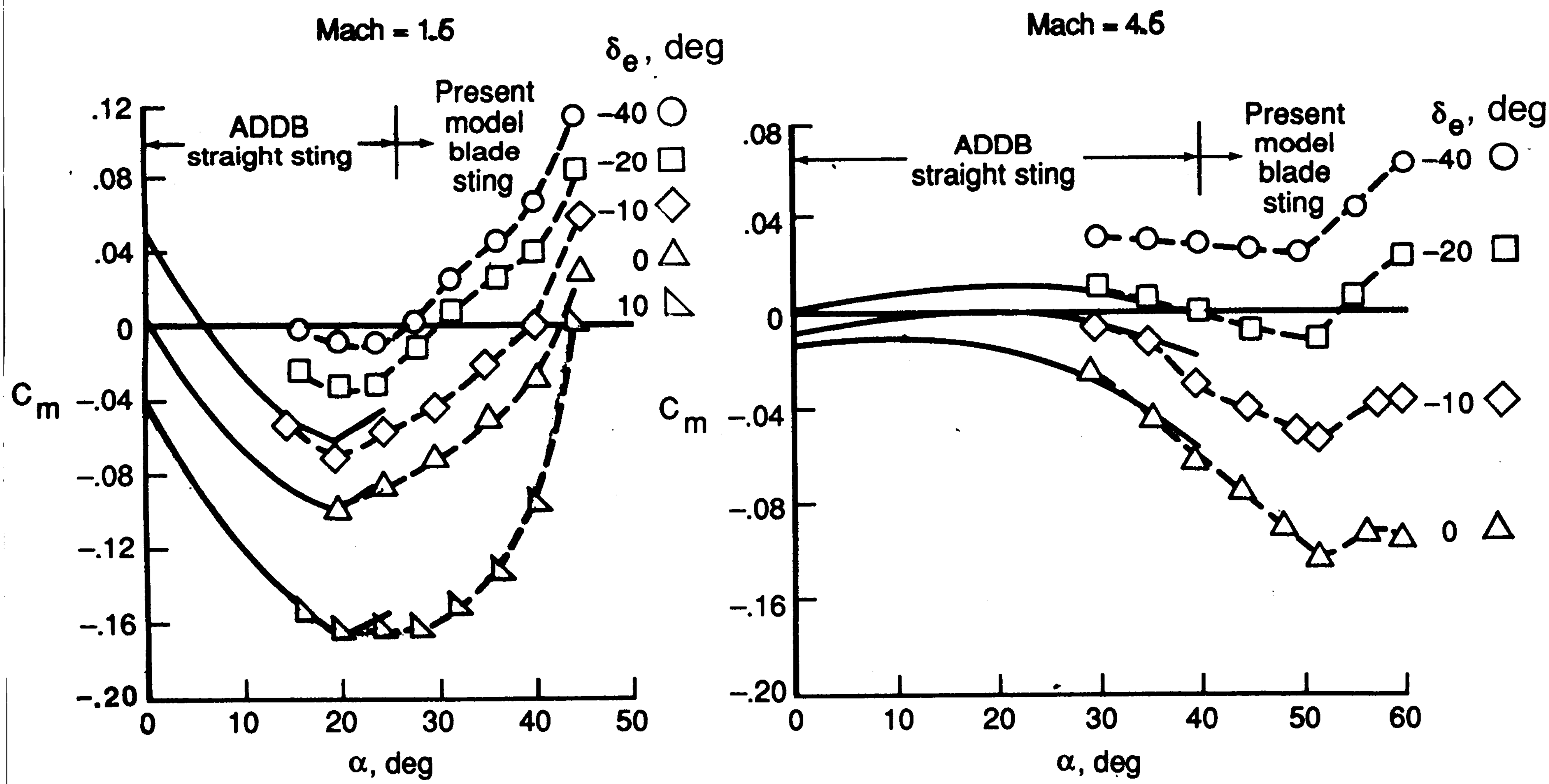
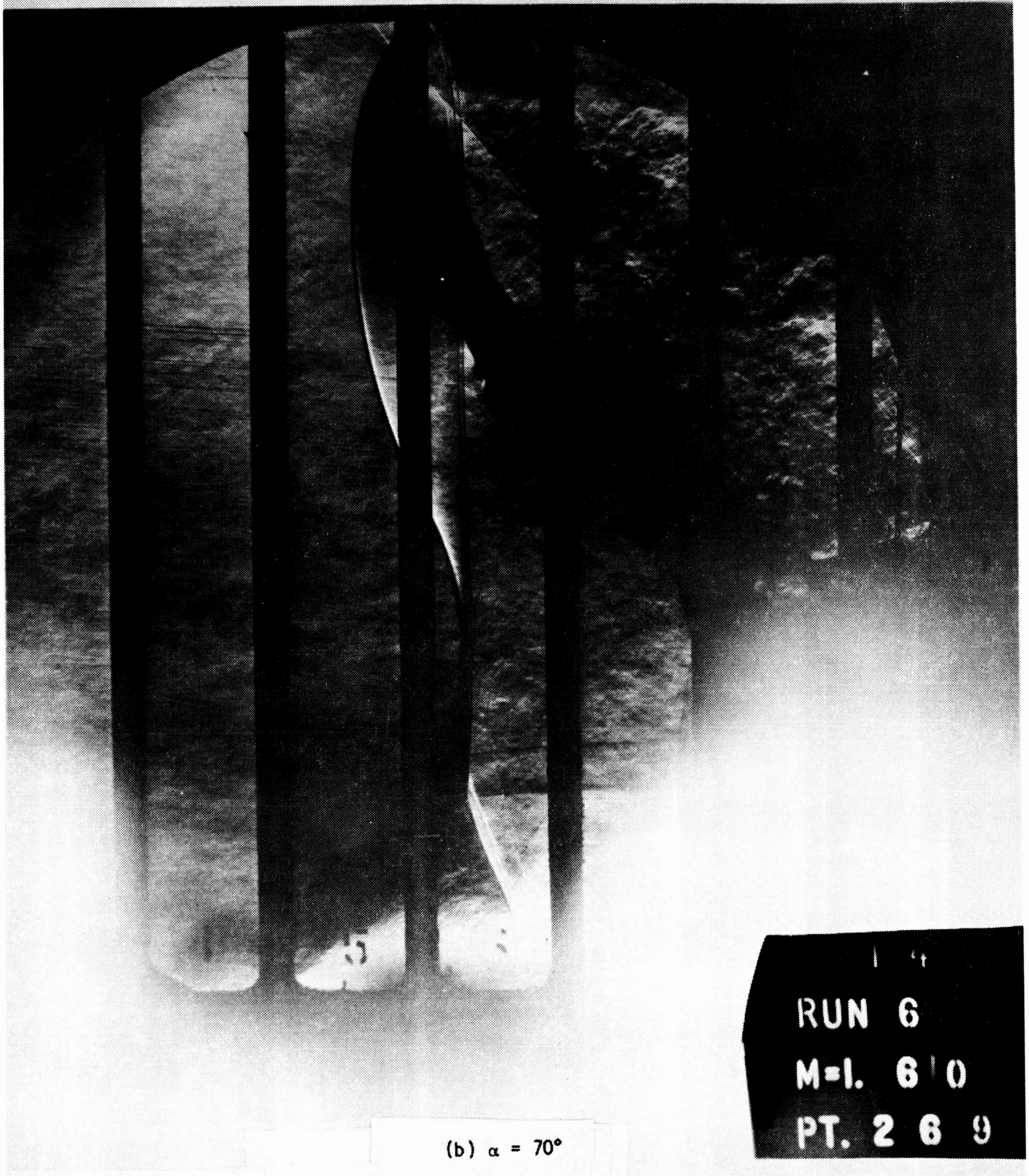


Figure 5.- Pitching-moment data at M = 1.6 and 4.6 for the blade-sting vs straight-sting arrangement.

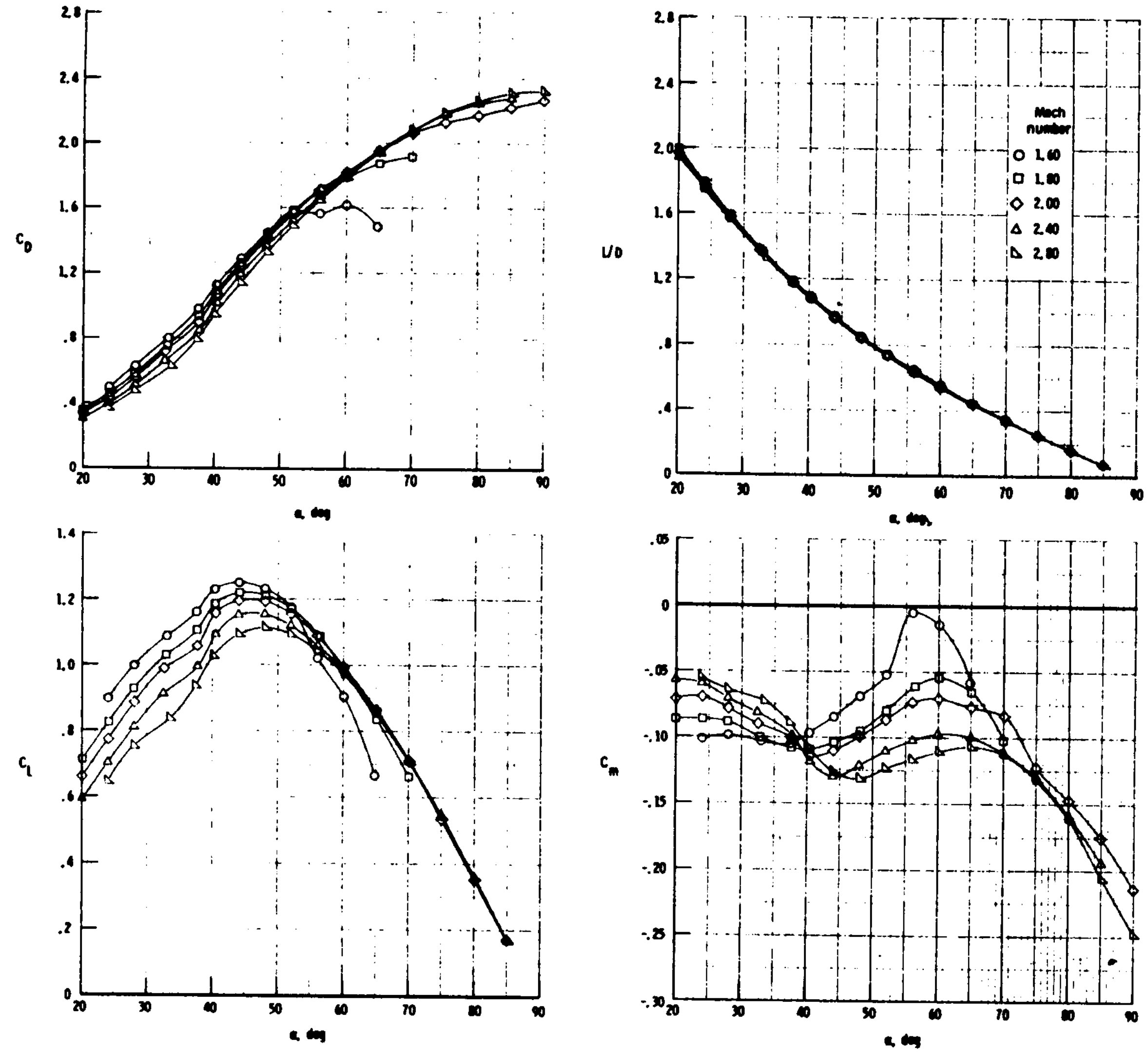
(a) α = 53°

Figure 6.- Schlerien photographs of the model. Mach number = 1.60



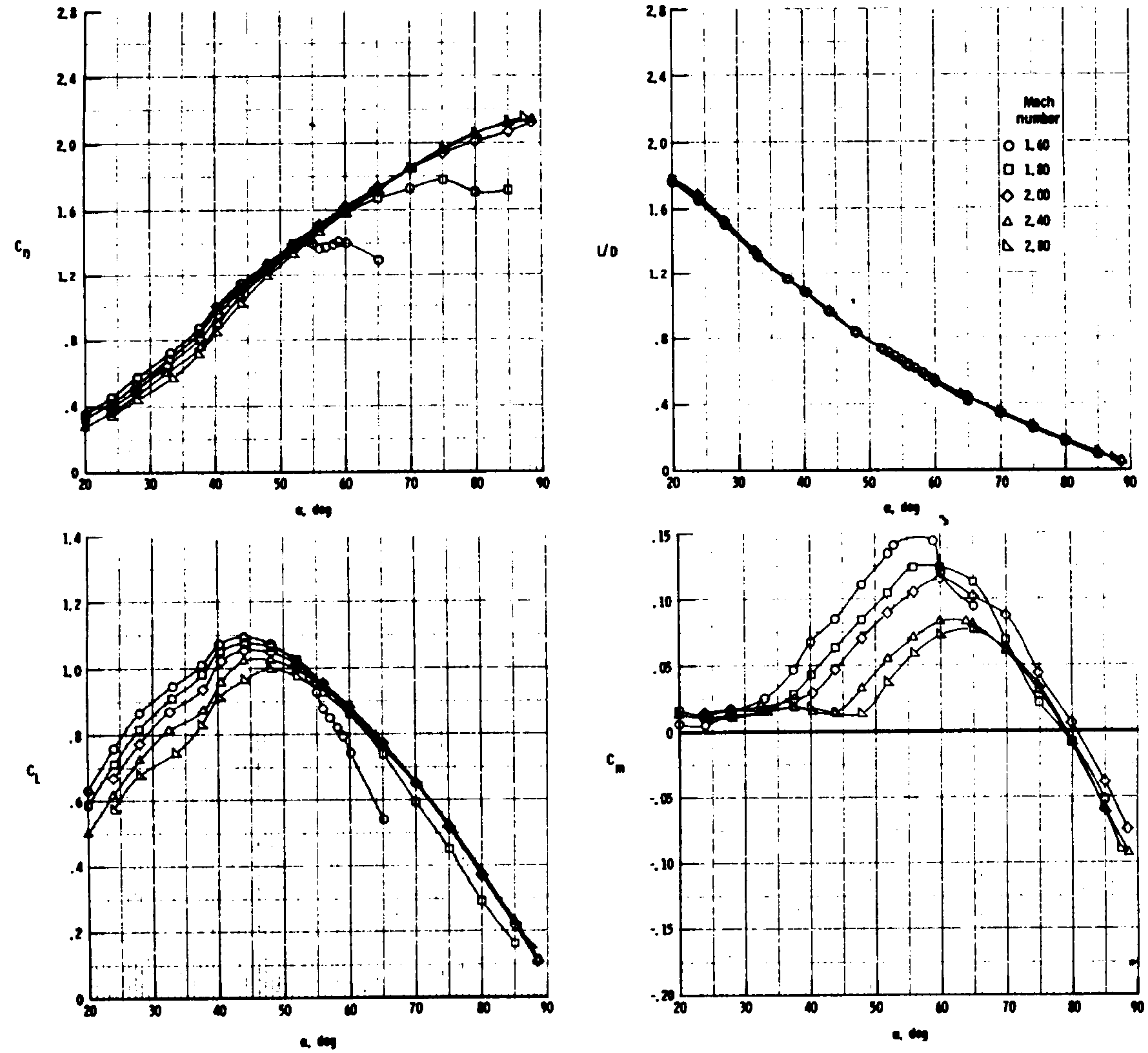
(b) α = 70°

Figure 6 - Concluded.



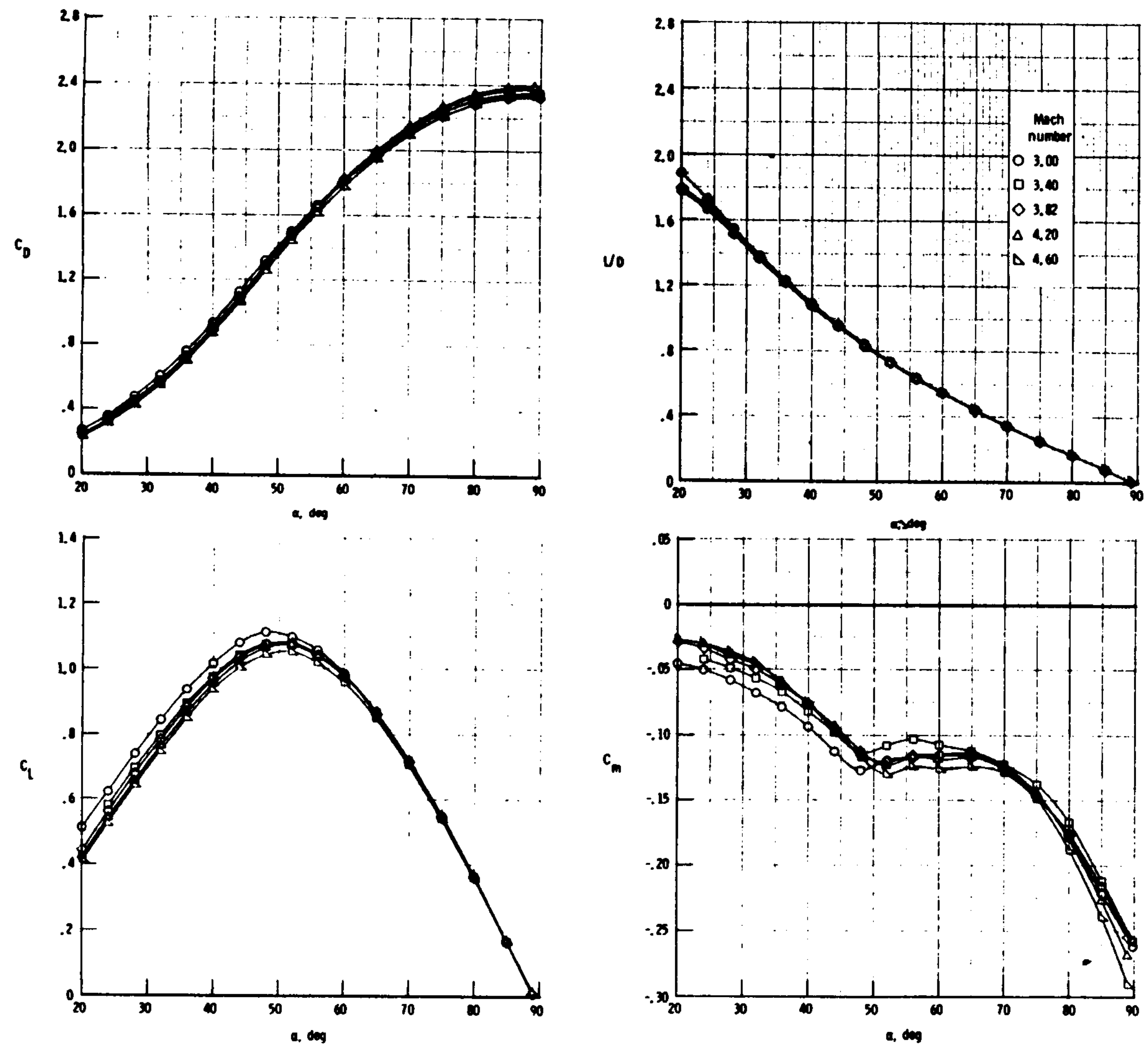
(a) $\delta_e = 0°$; $\delta_{BF} = 0°$

Figure 7.- Effect of Mach number on the longitudinal aerodynamic characteristics of the orbiter model, M = 1.60 to 2.80.



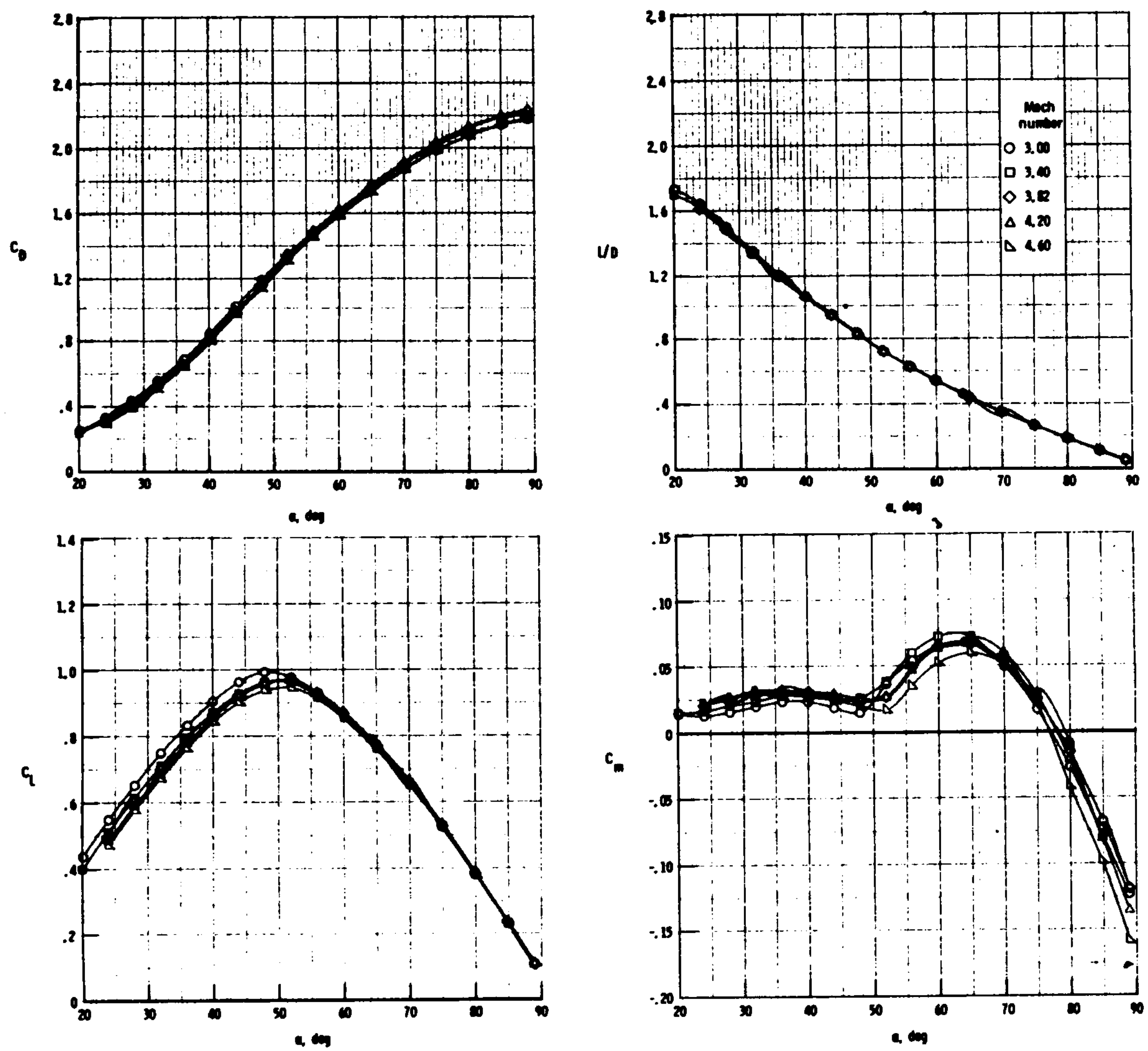
(b) $\delta_e = -40°$; $\delta_{BF} = -12°$

Figure 7.- Concluded.



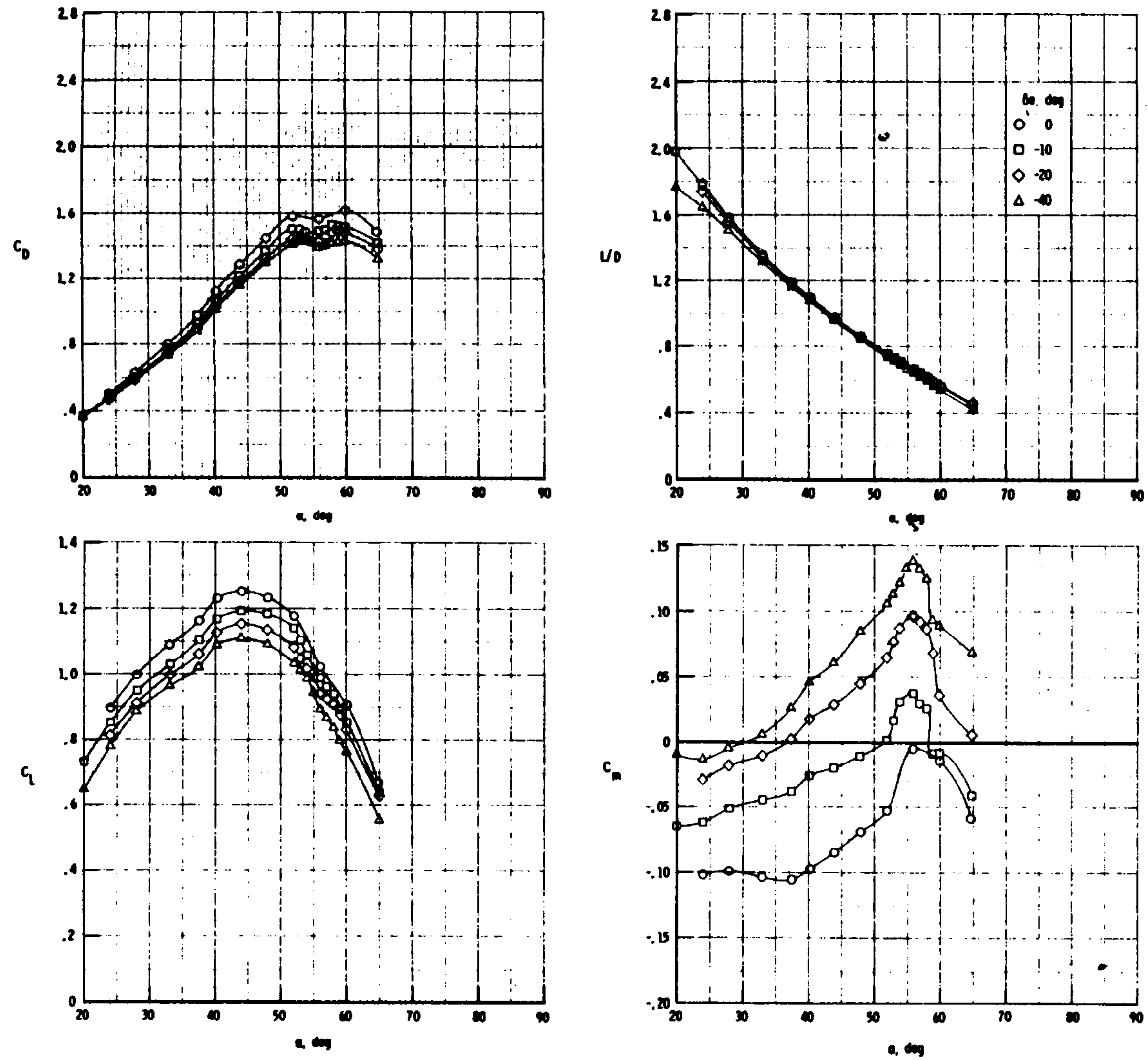
(a) $\delta_e = 0°$; $\delta_{BF} = 0°$

Figure 8.- Effects of Mach number on the longitudinal aerodynamic characteristics of the orbiter model, M = 3.00 to 4.60.



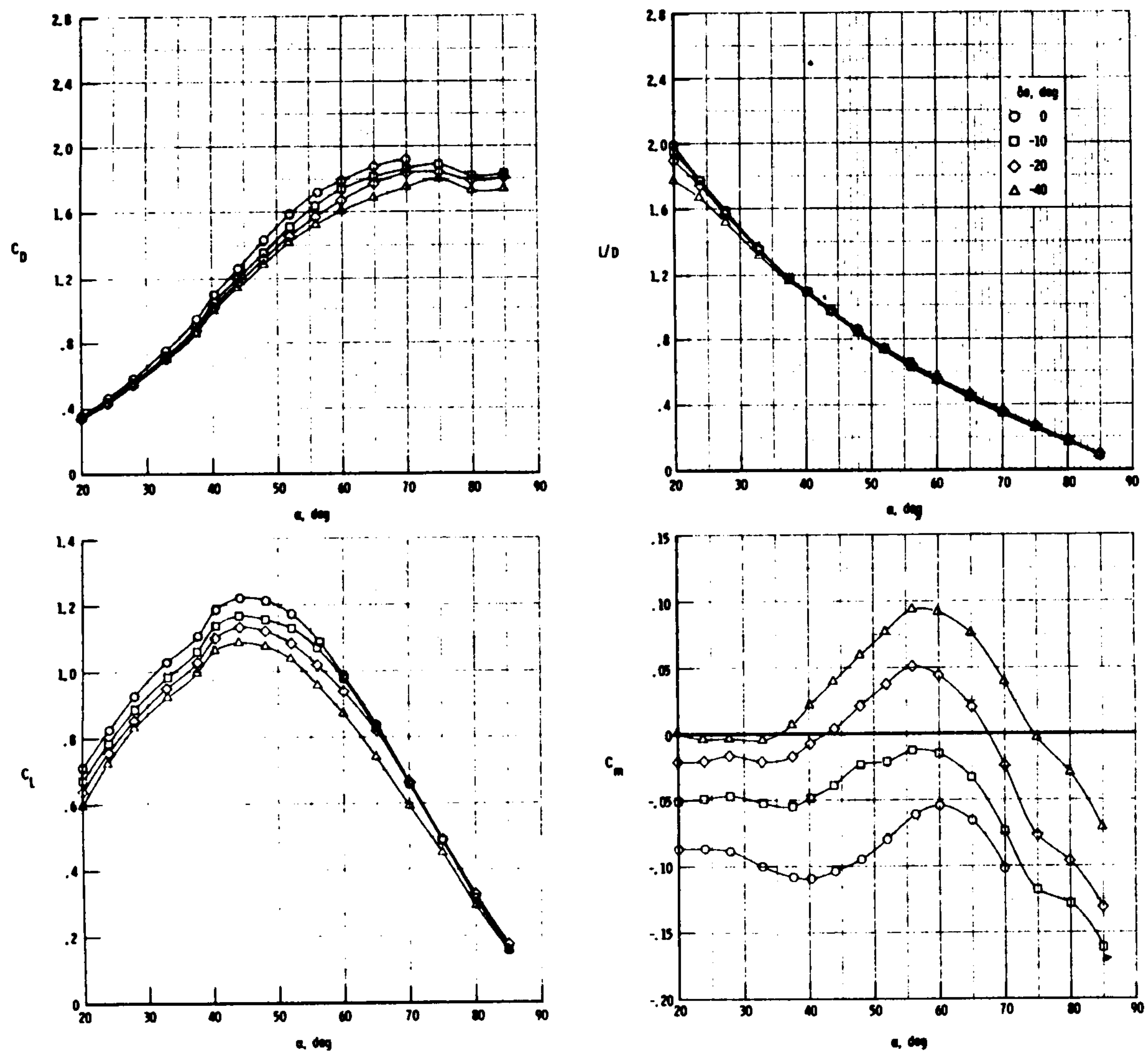
(b) $\delta_e = -40°$; $\delta_{BF} = -12°$

Figure 8.- Concluded.



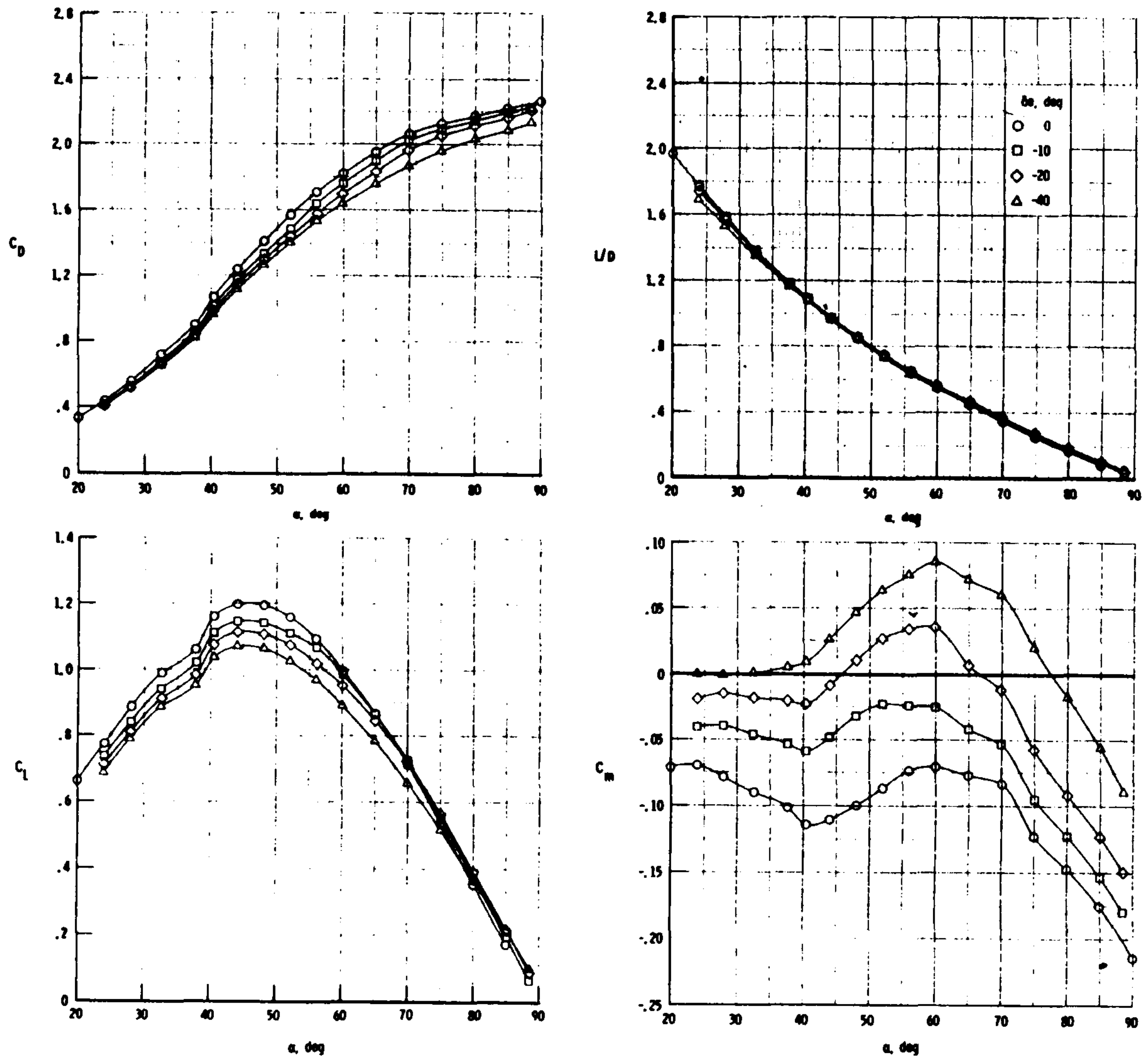
(a) M = 1.60

Figure 9.- Effect of elevon deflection on the longitudinal aerodynamic characteristics of the orbiter model with δ_{BF} = 0°.



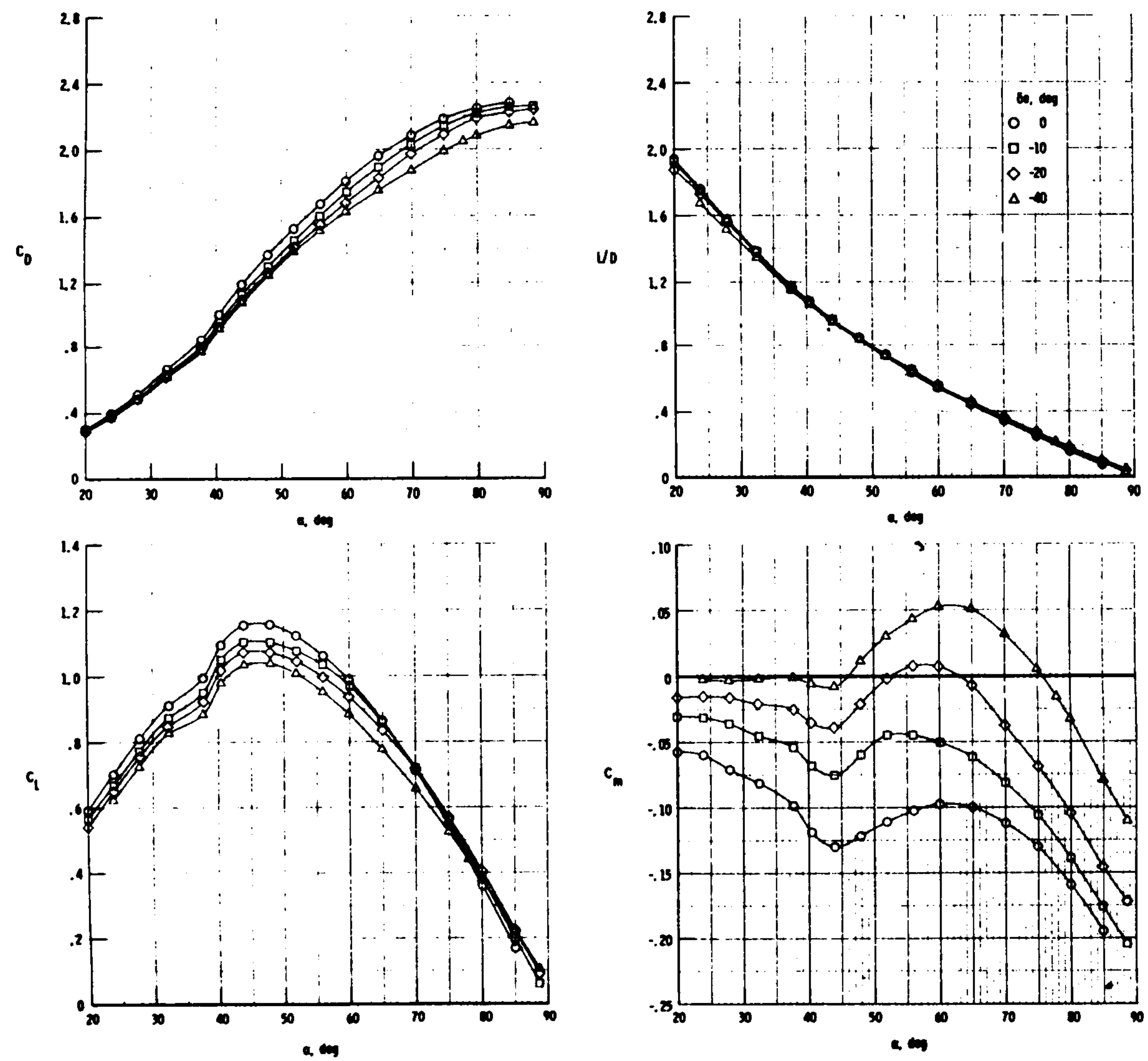
(b) M = 1.80

Figure 9.- (Continued).



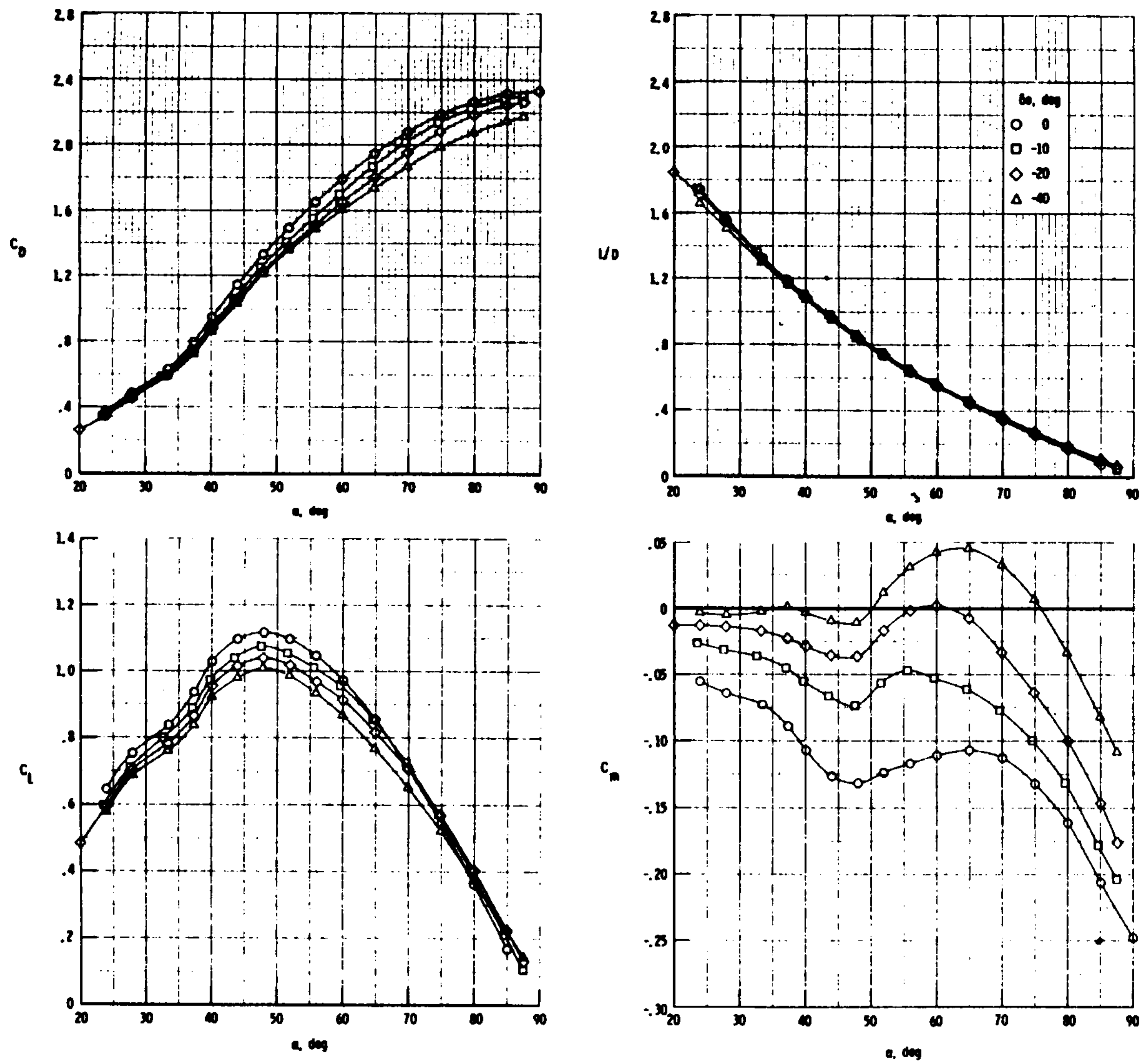
(c) M = 2.00

Figure 9.- (Continued).



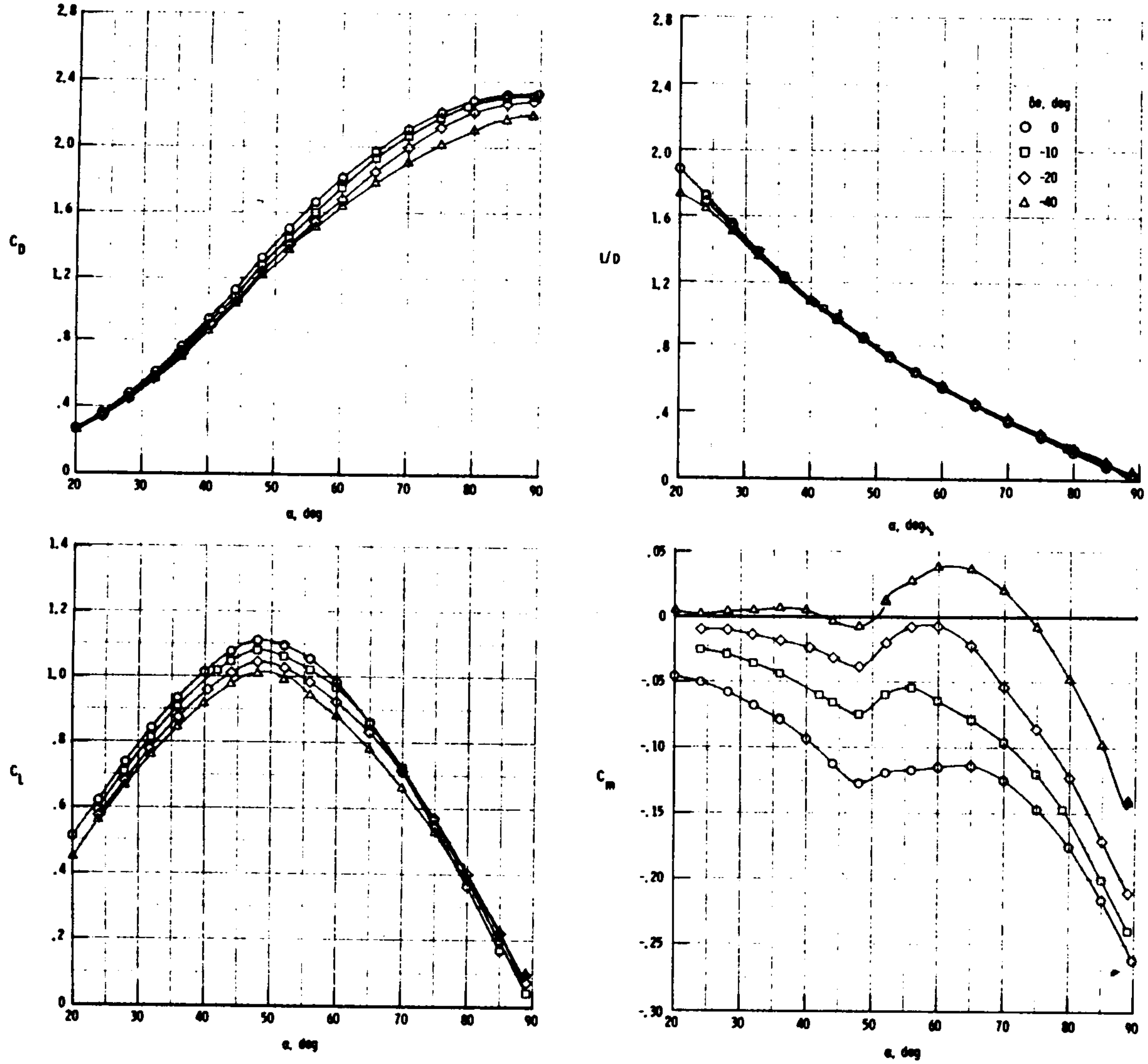
(d) M = 2.40

Figure 9.- (Continued).



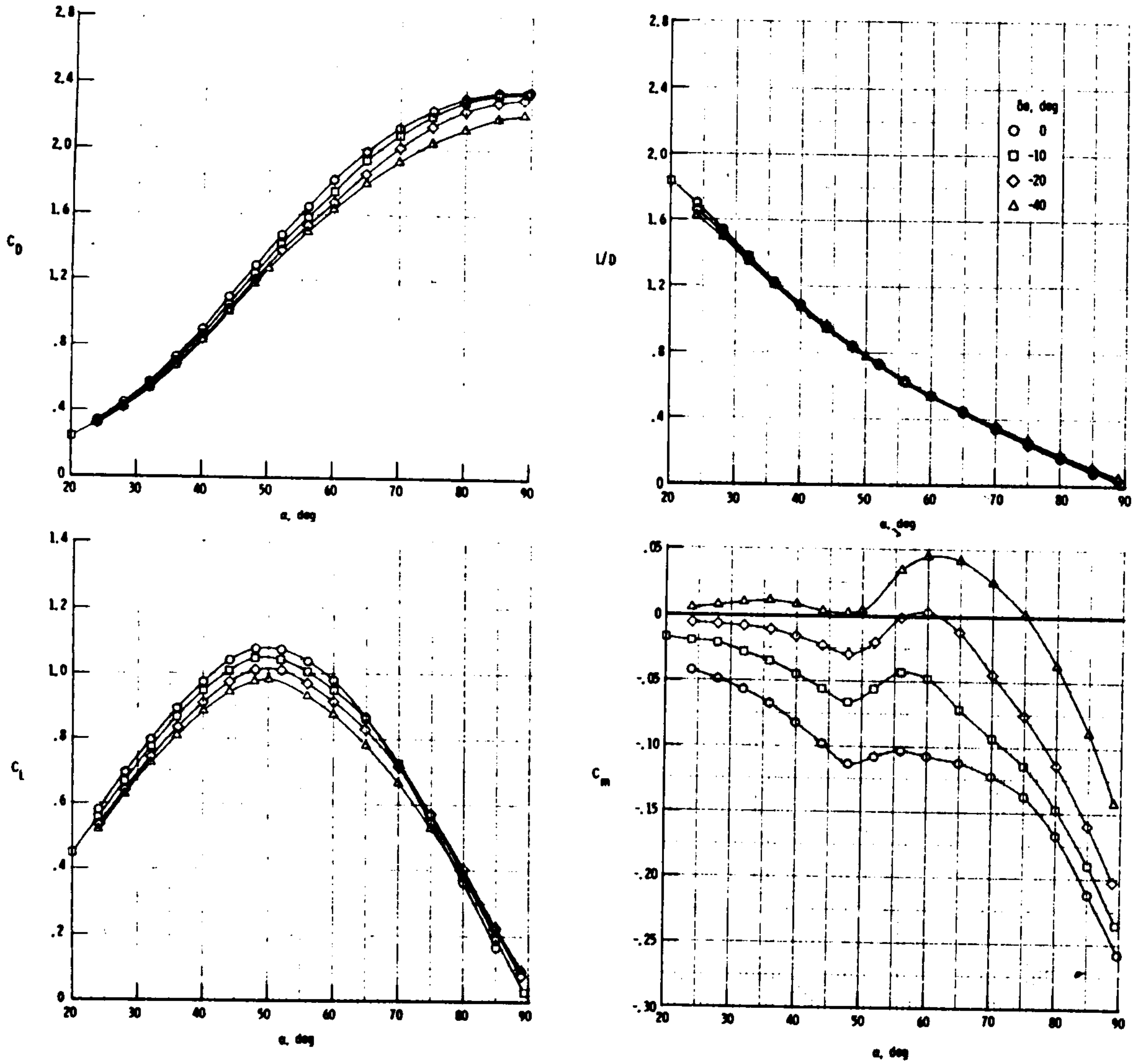
(e) M = 2.80

Figure 9.- (Continued)



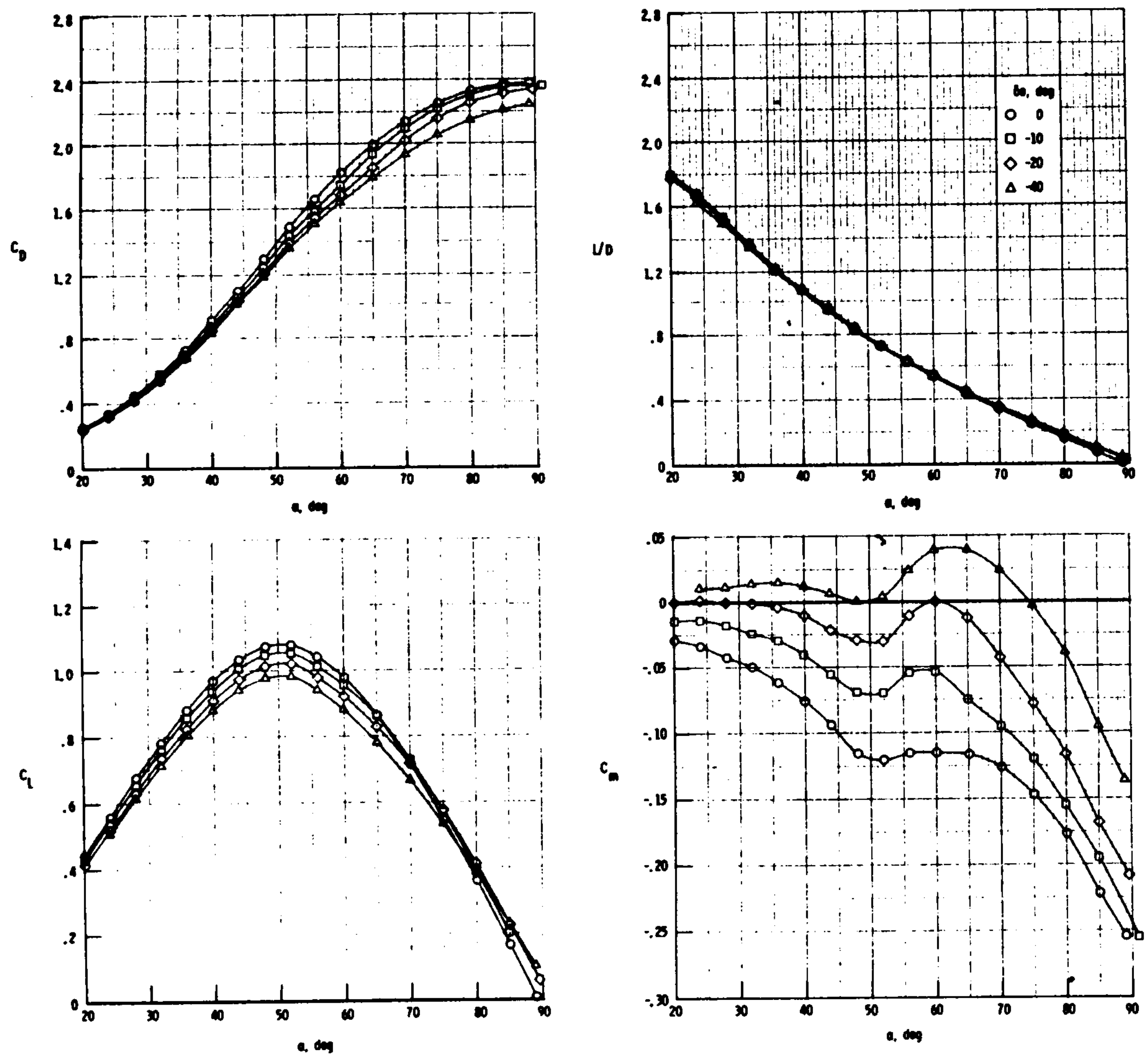
(f) M = 3.00

Figure 9.- (Continued).



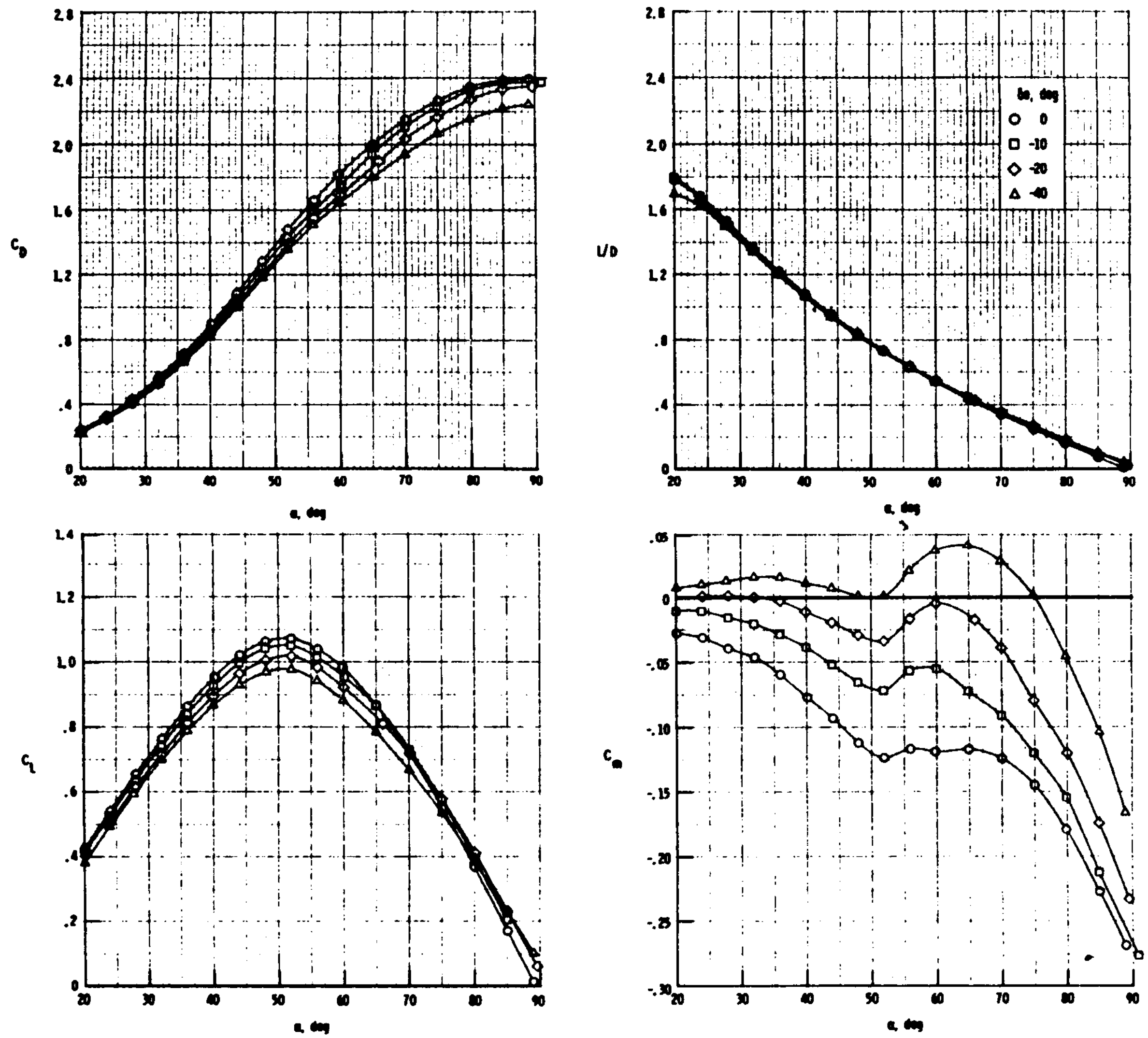
(g) M = 3.40

Figure 9.- (Continued).



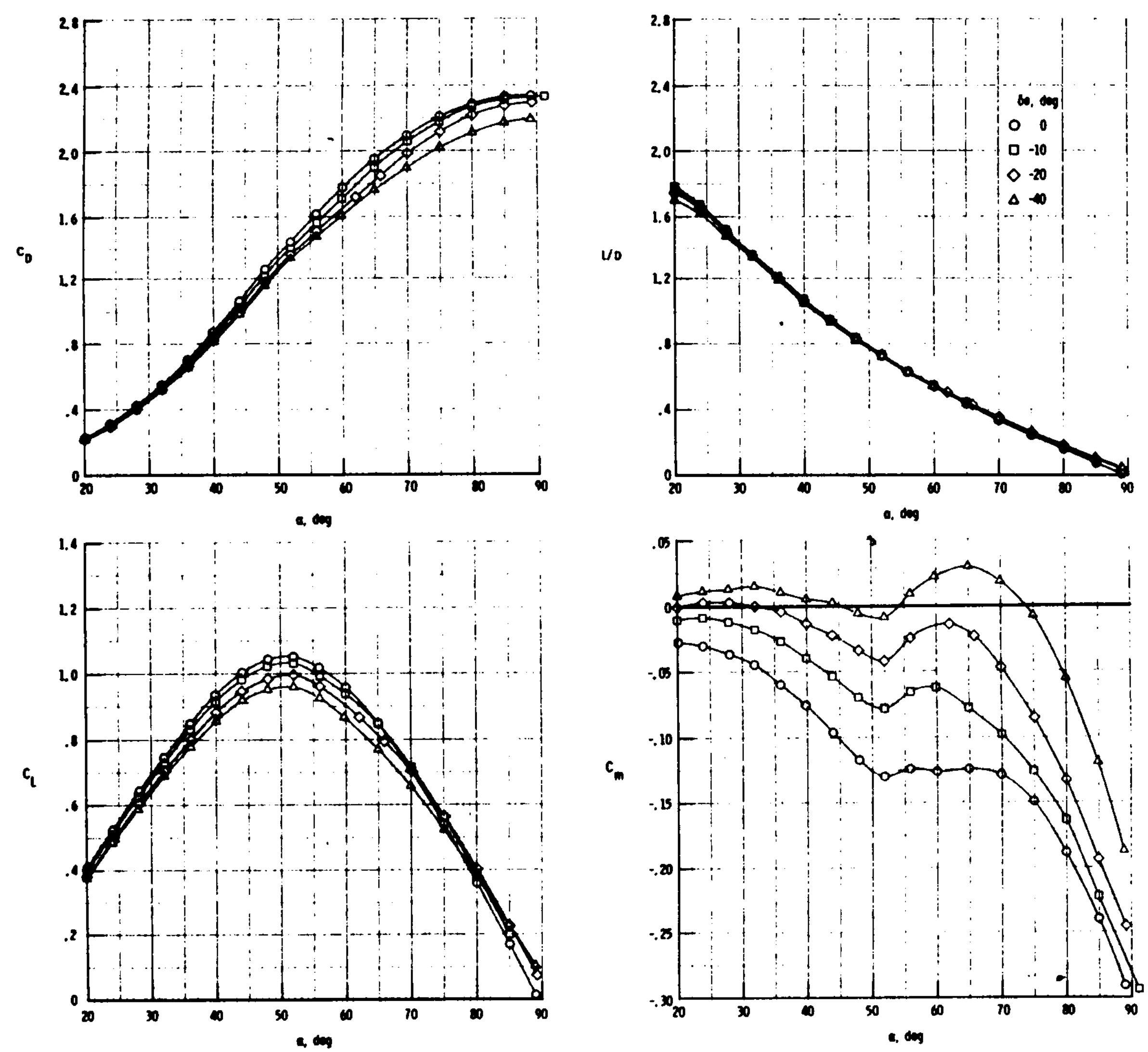
(h) M = 3.82

Figure 9.- (Continued)



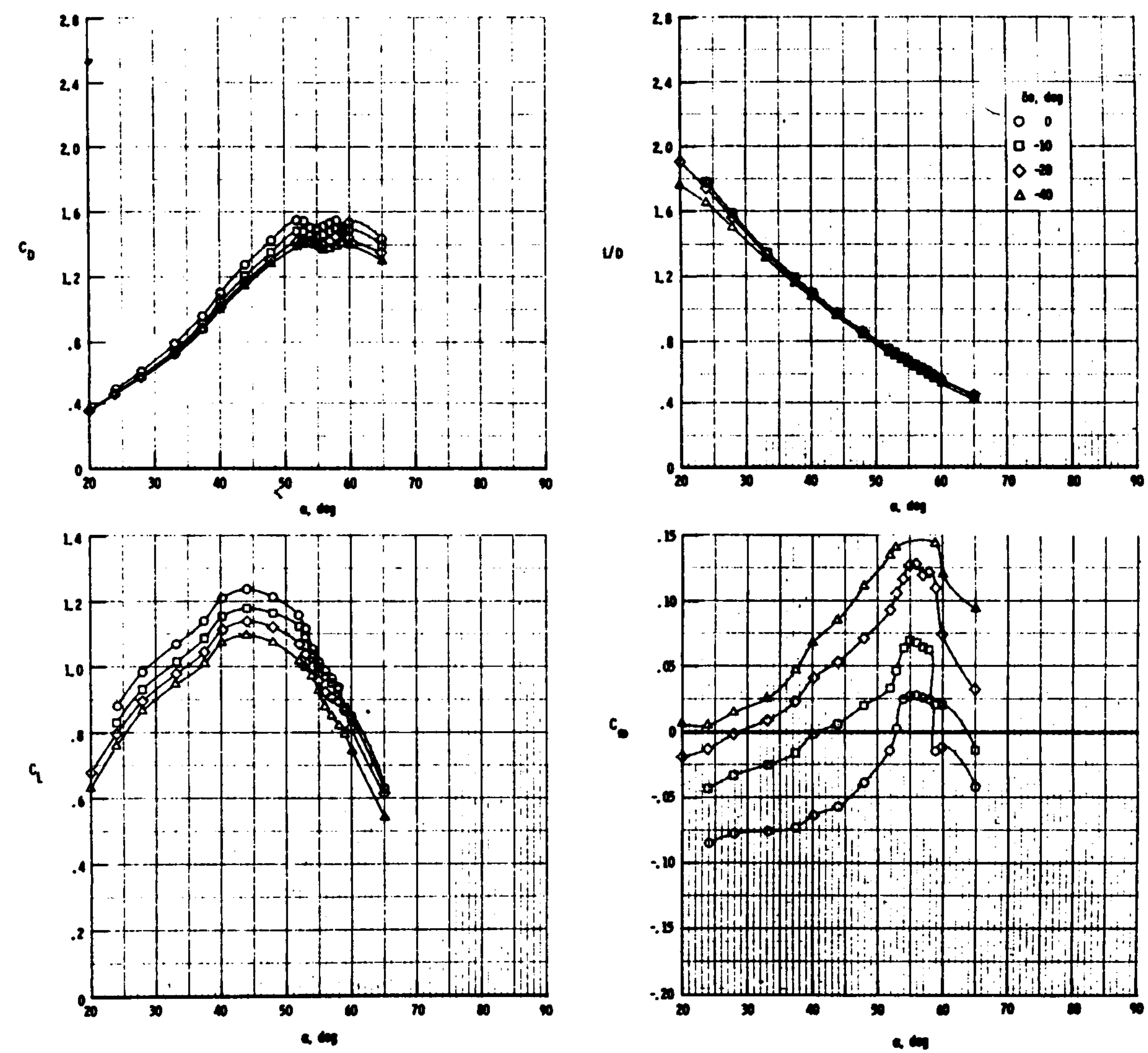
(i) M = 4.20

Figure 9.- (Continued)



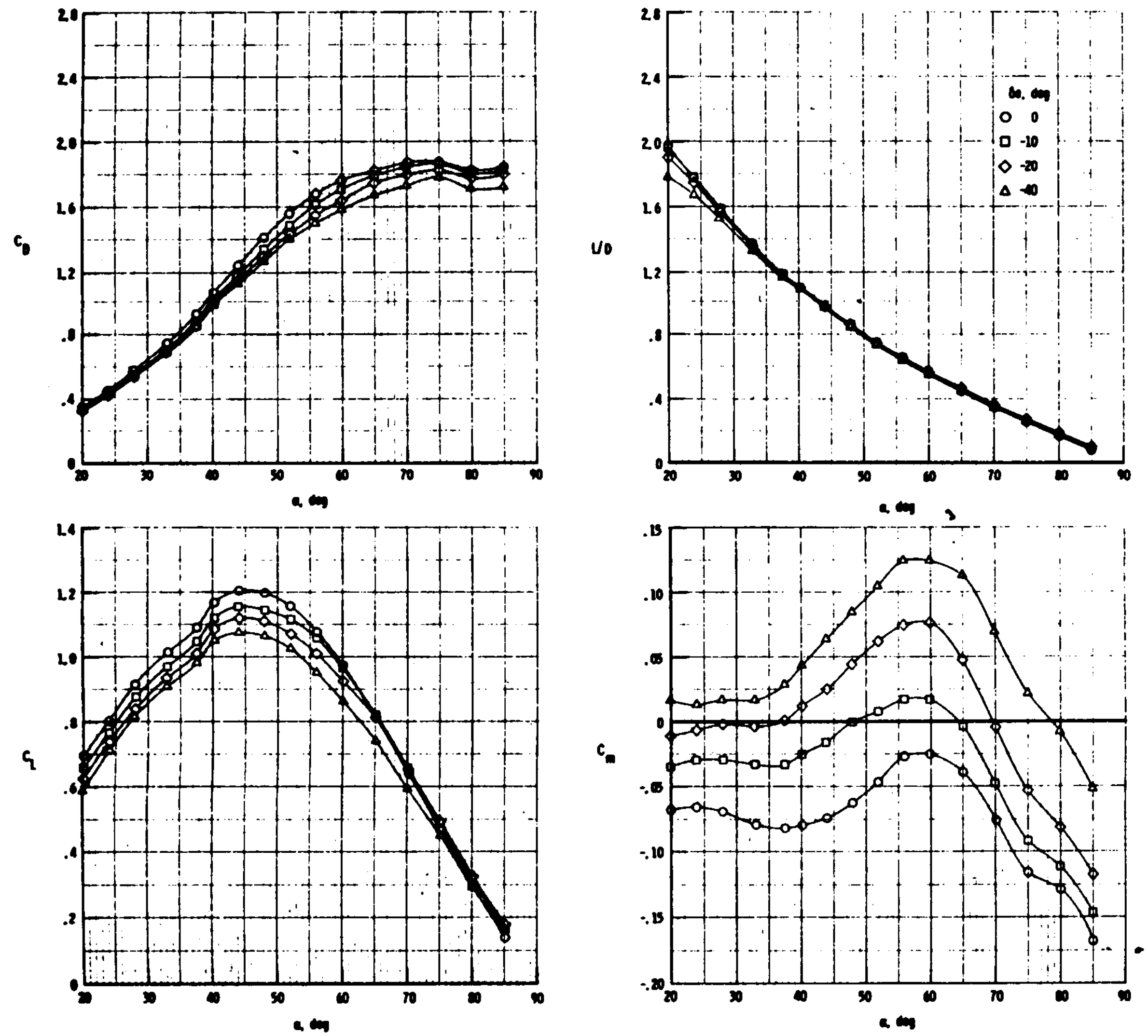
(j) M = 4.60

Figure 9.- (Concluded).



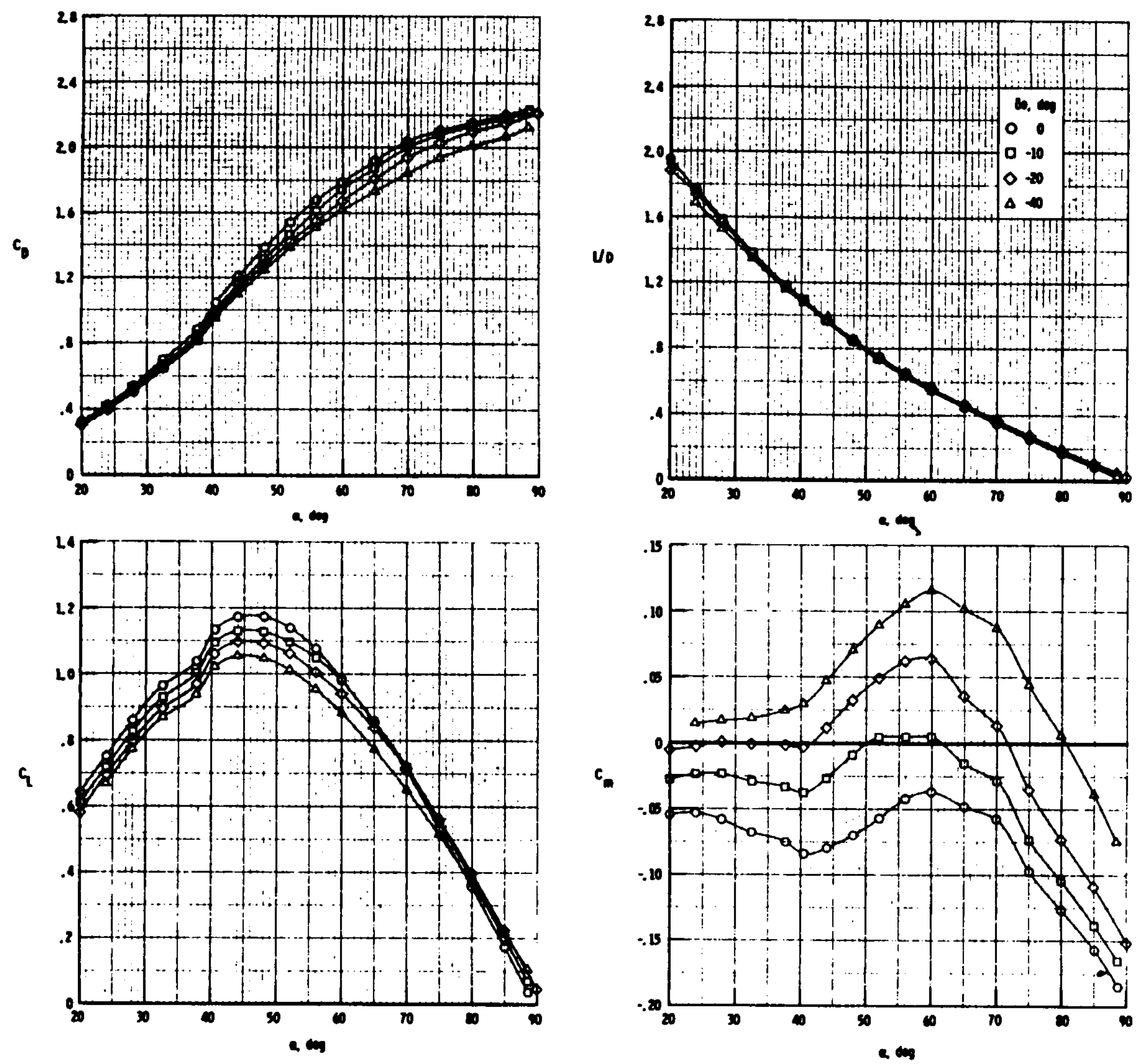
(a) M = 1.60

Figure 10.- Effects of elevon deflection on the longitudinal aerodynamic characteristics of the orbiter model with δ_{BF} = -12°.



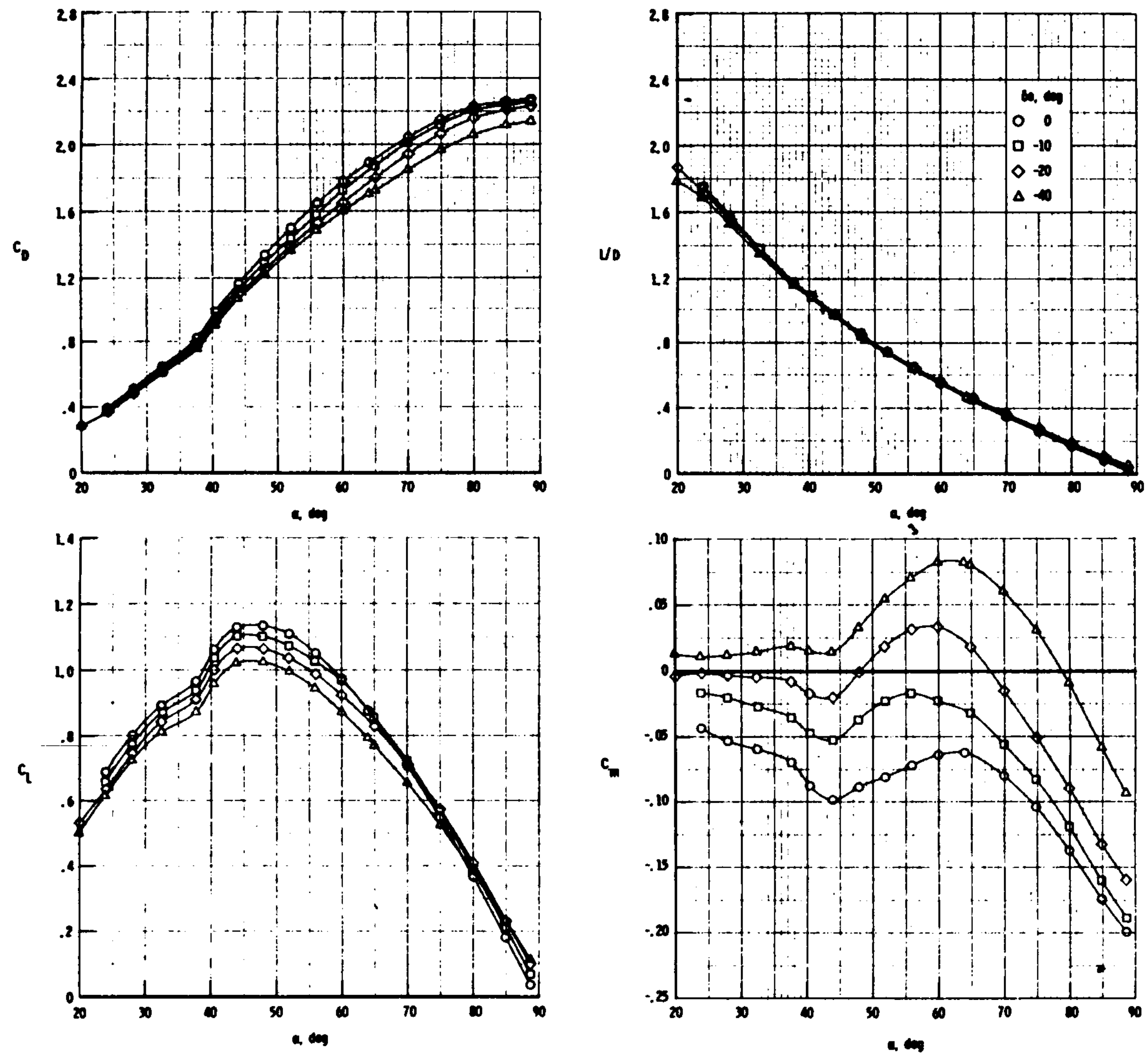
(b) M = 1.80

Figure 10.- (Continued).



(c) M = 2.00

Figure 10.- (Continued)



(d) M = 2.40

Figure 10.- (Continued).

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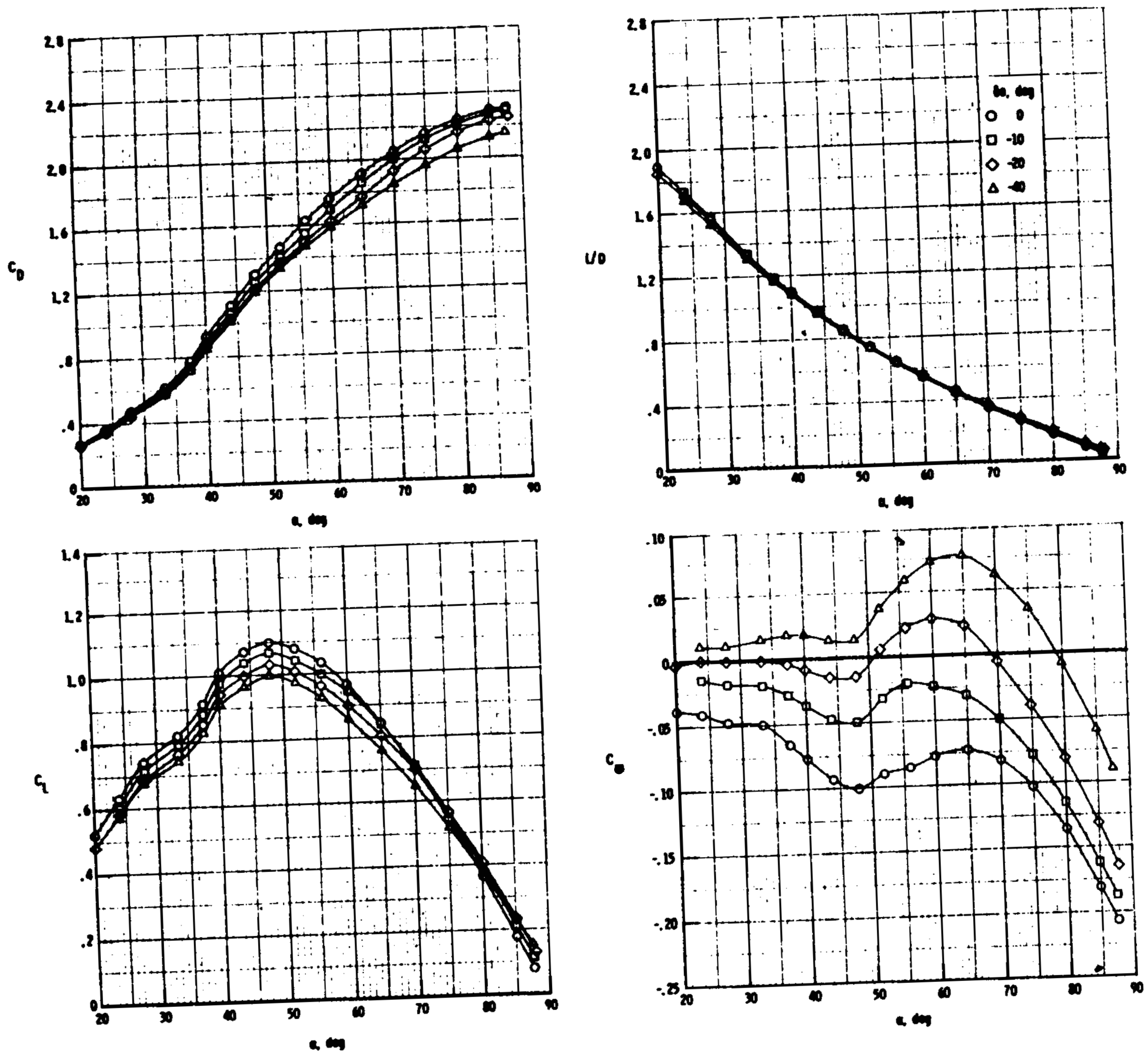
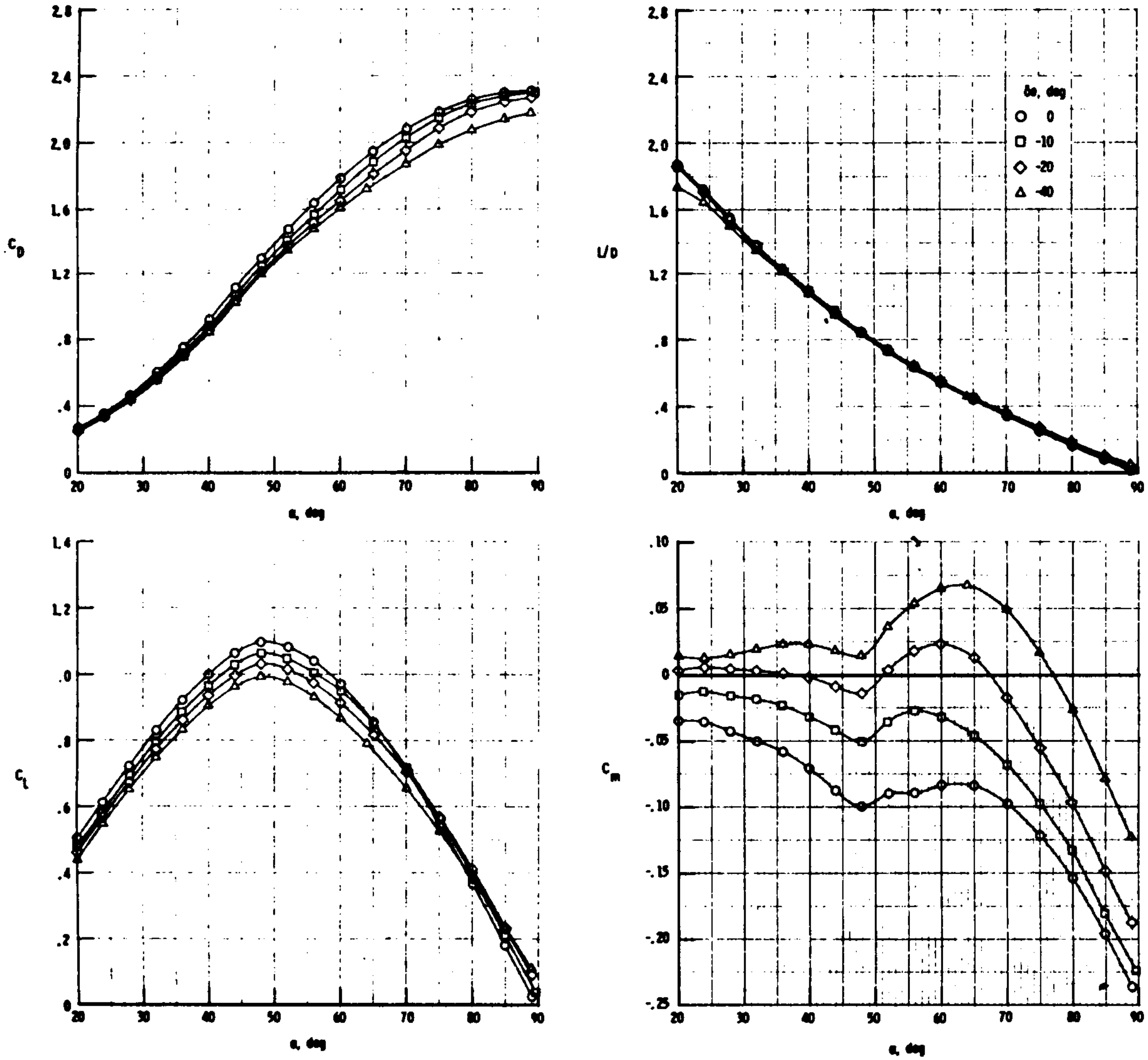


(e) M = 2.80

Figure 10.- (Continued).



(f) M = 3.00

Figure 10.- (Continued)

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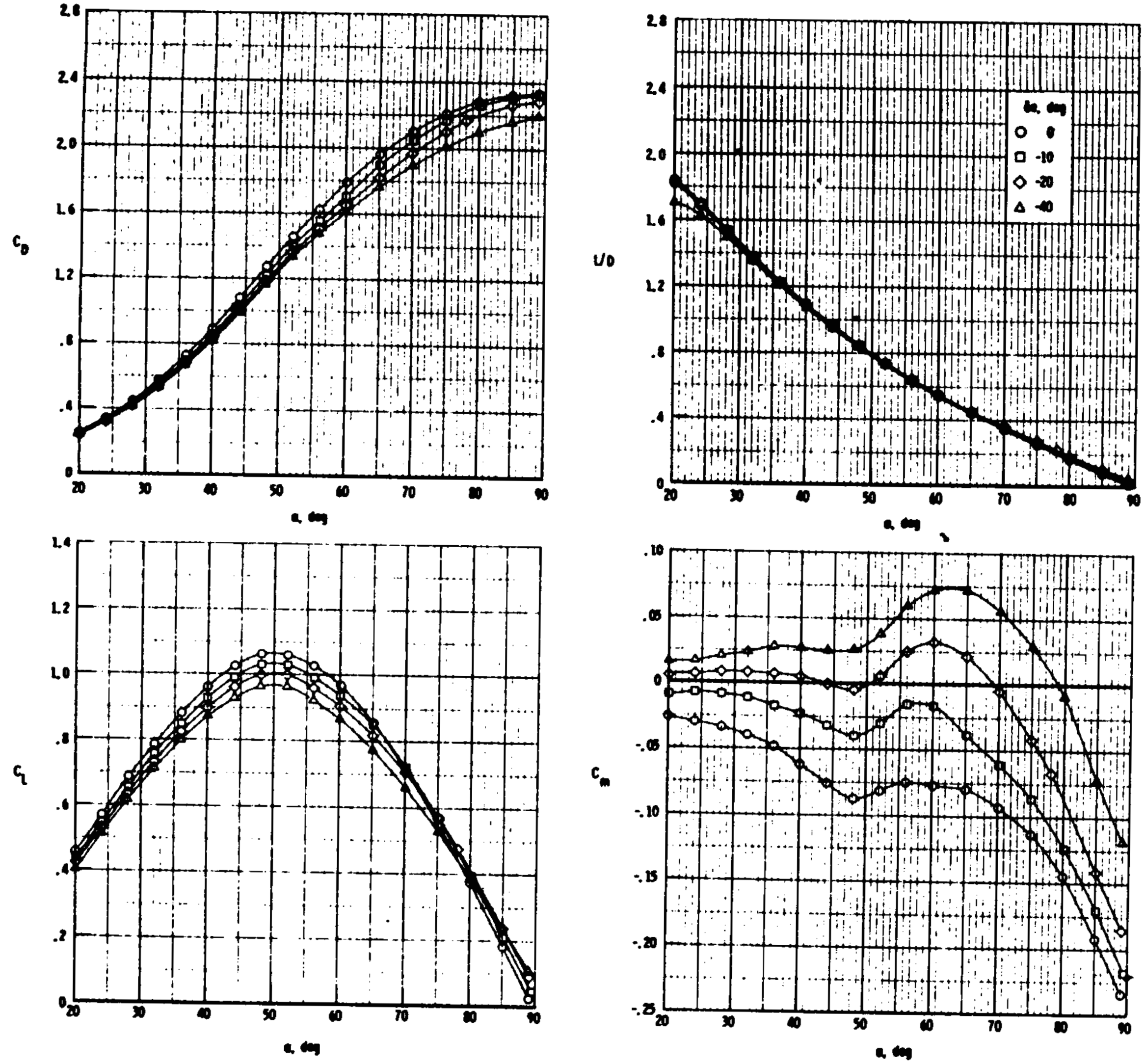
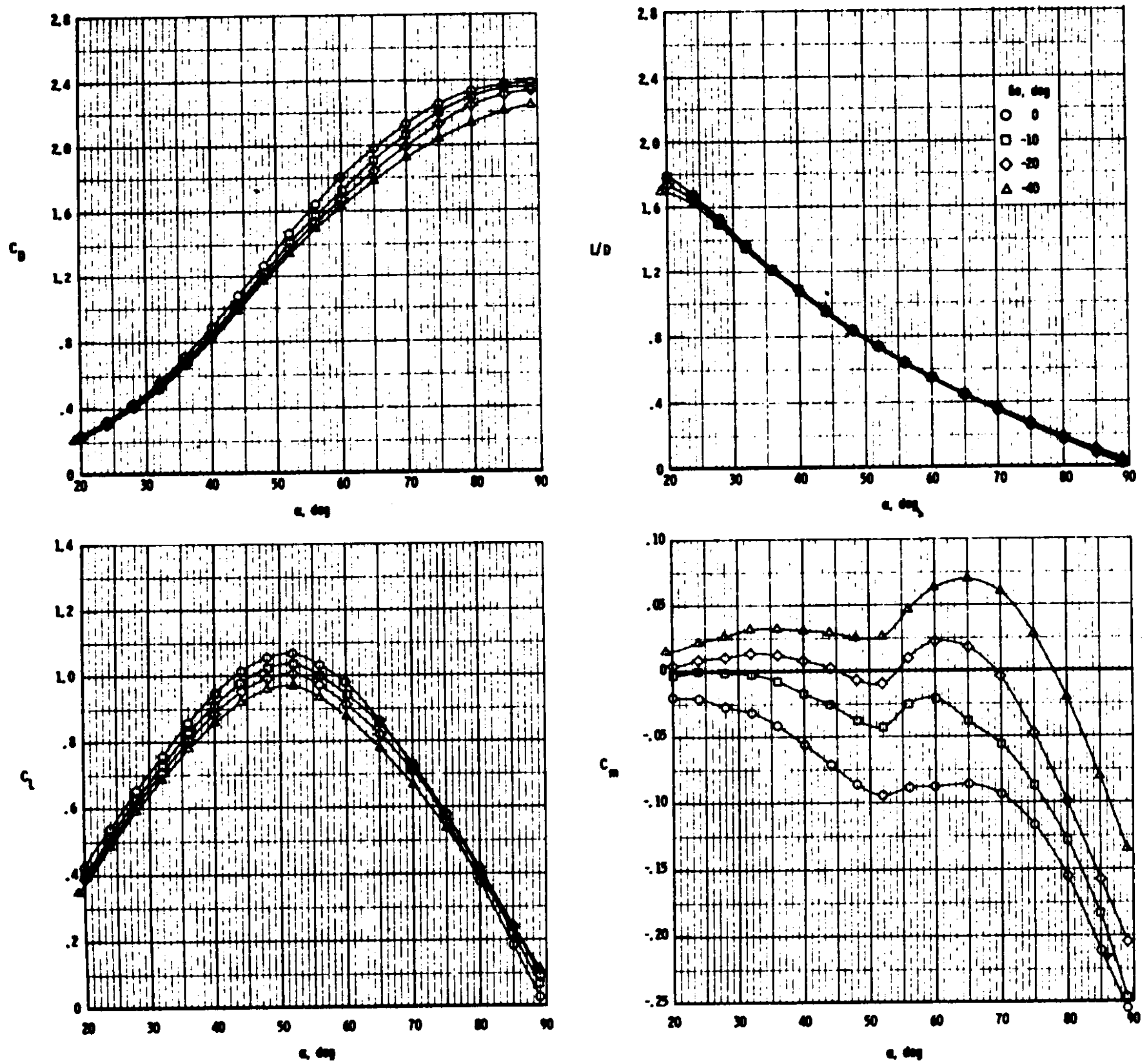
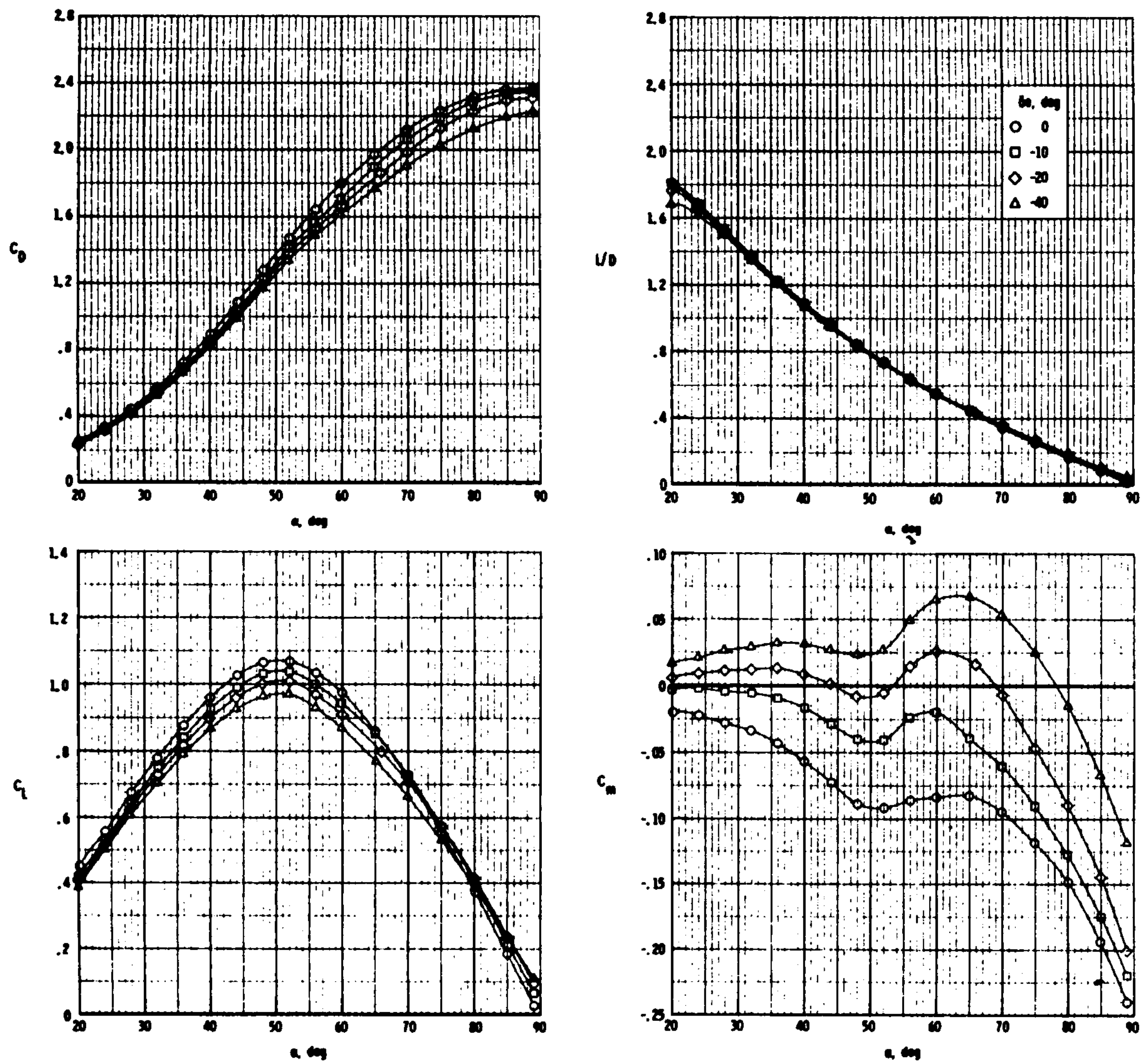


Figure 10.- (Continued)   (g) M = 3.40



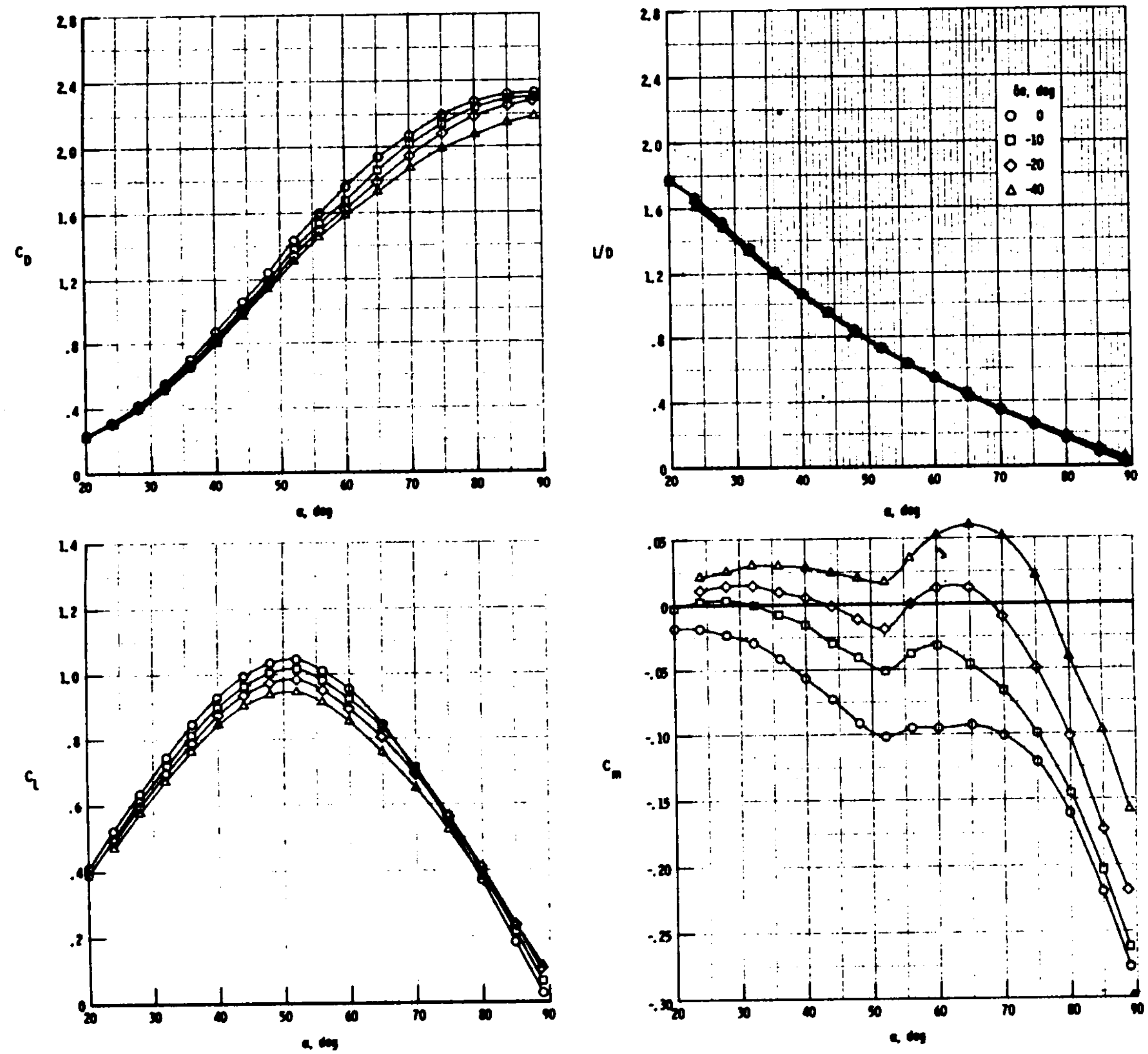
(h) M = 3.82

Figure 10.- (Continued).



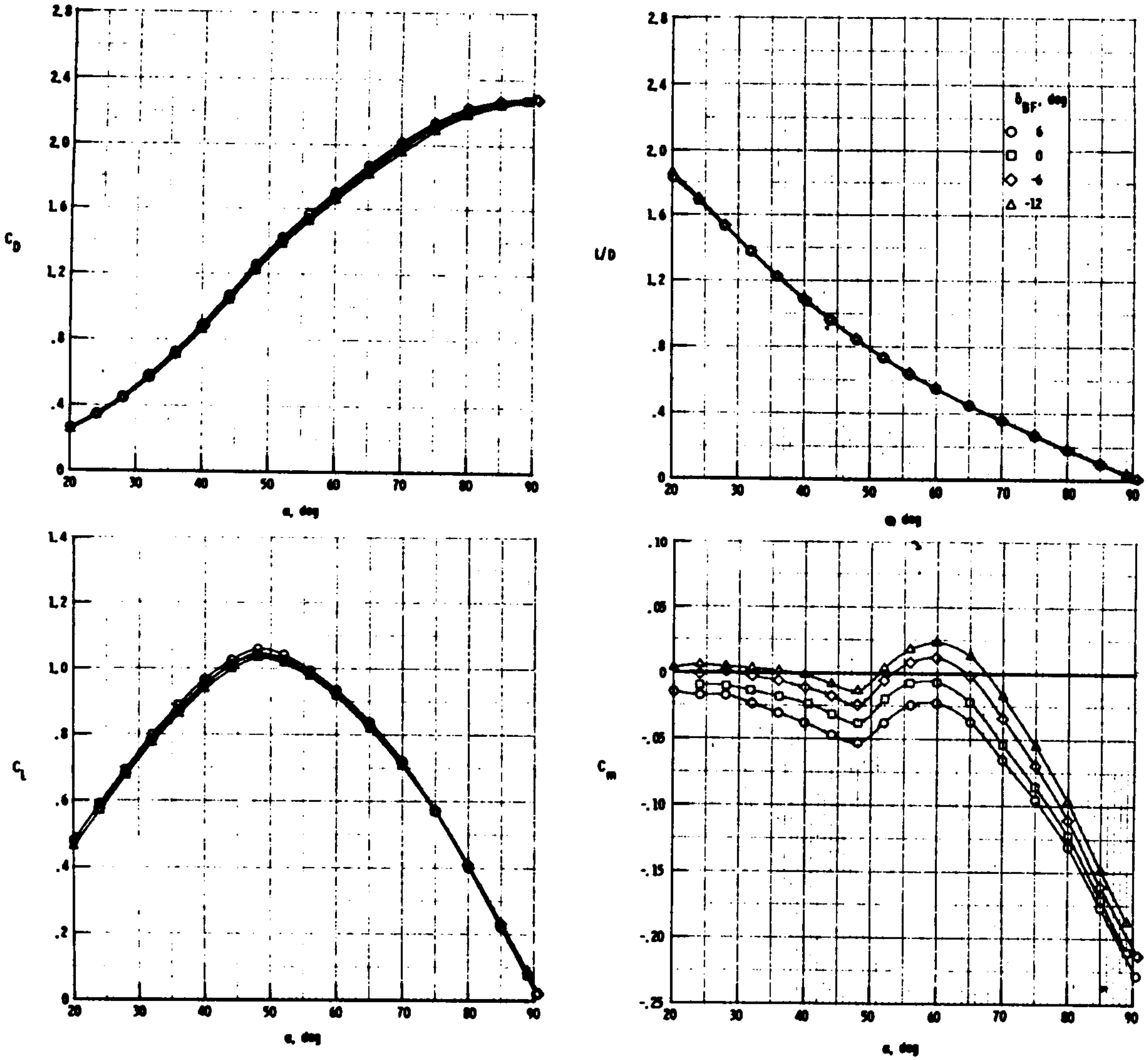
(i) M = 4.20

Figure 10.- (Continued).



(j) M = 4.60

Figure 10.- (Concluded).



(a) M = 3.00

Figure 11.- Effect of body-flap deflection on the longitudinal aerodynamic characteristics of the orbiter model with $\delta_e = -20°$.

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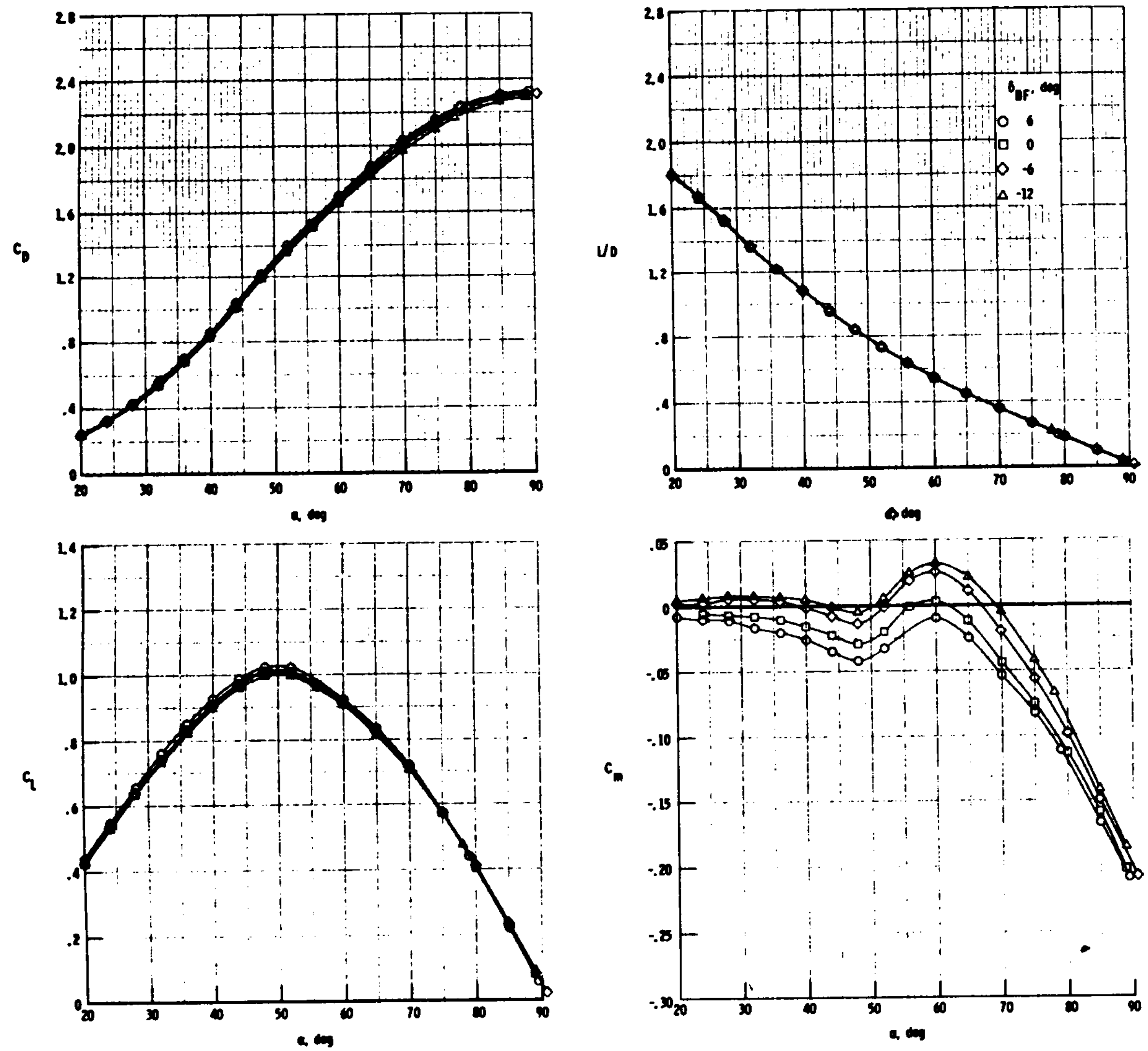
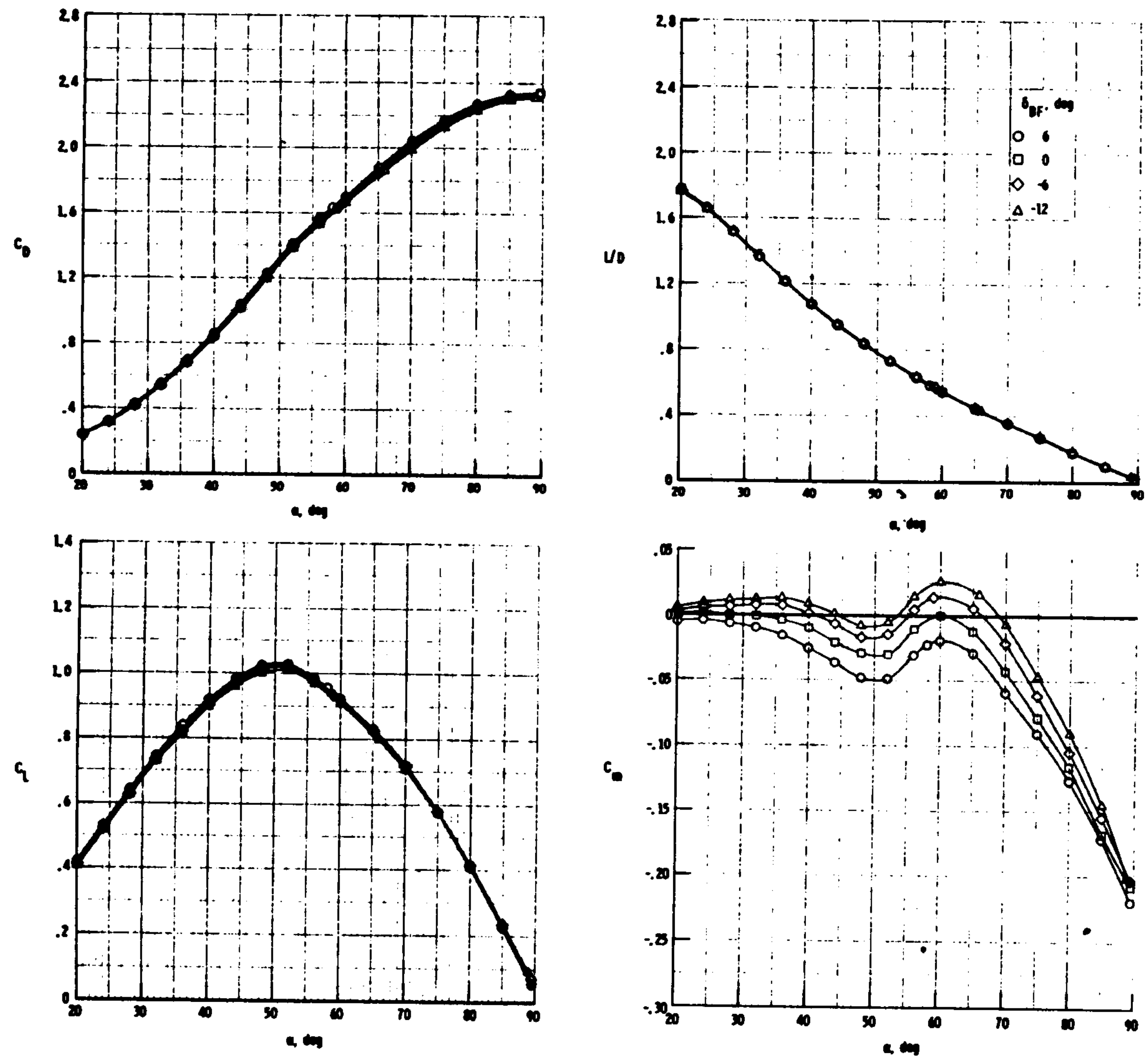


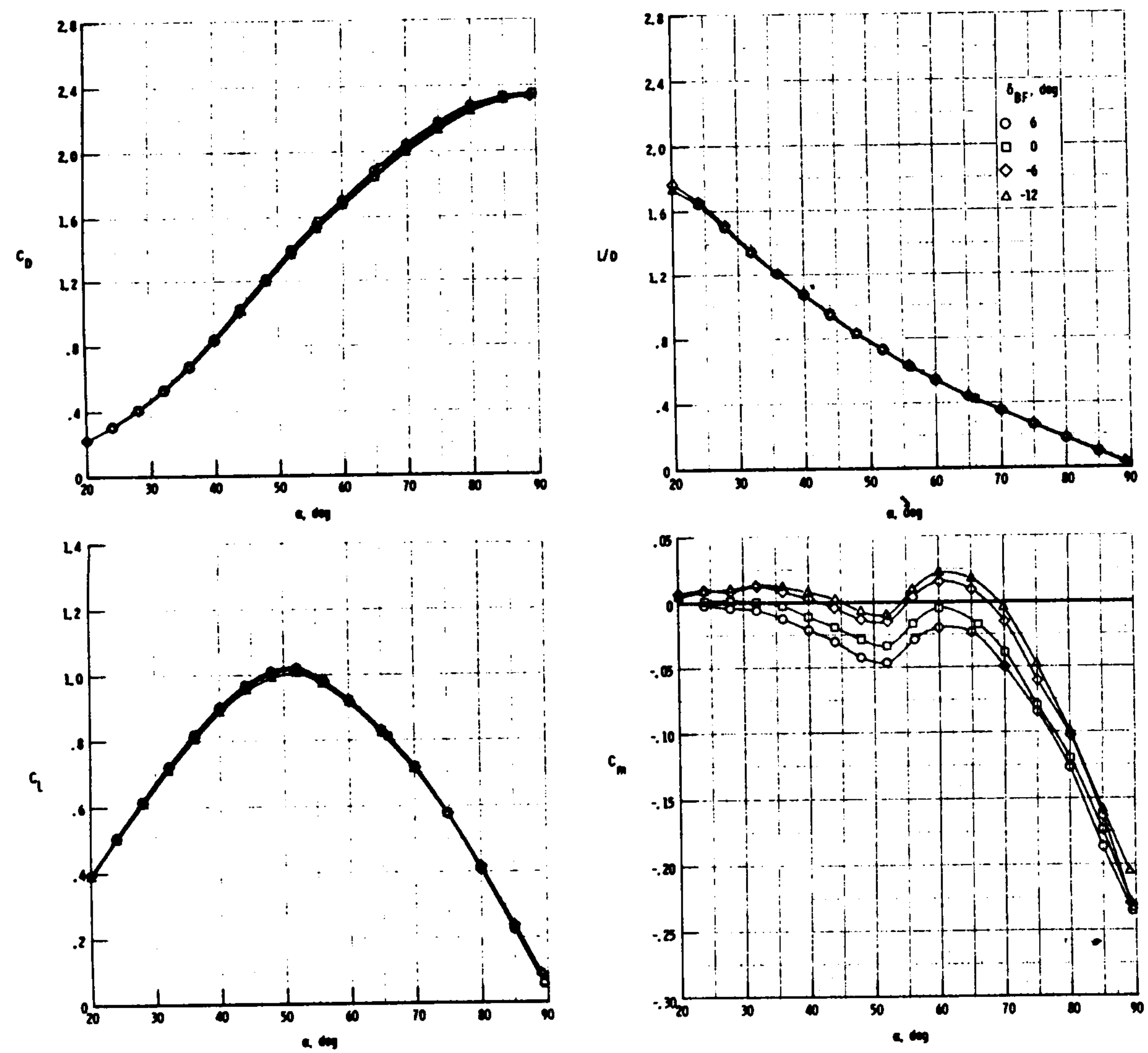
(b) M = 3.40

Figure 11.- (Continued).



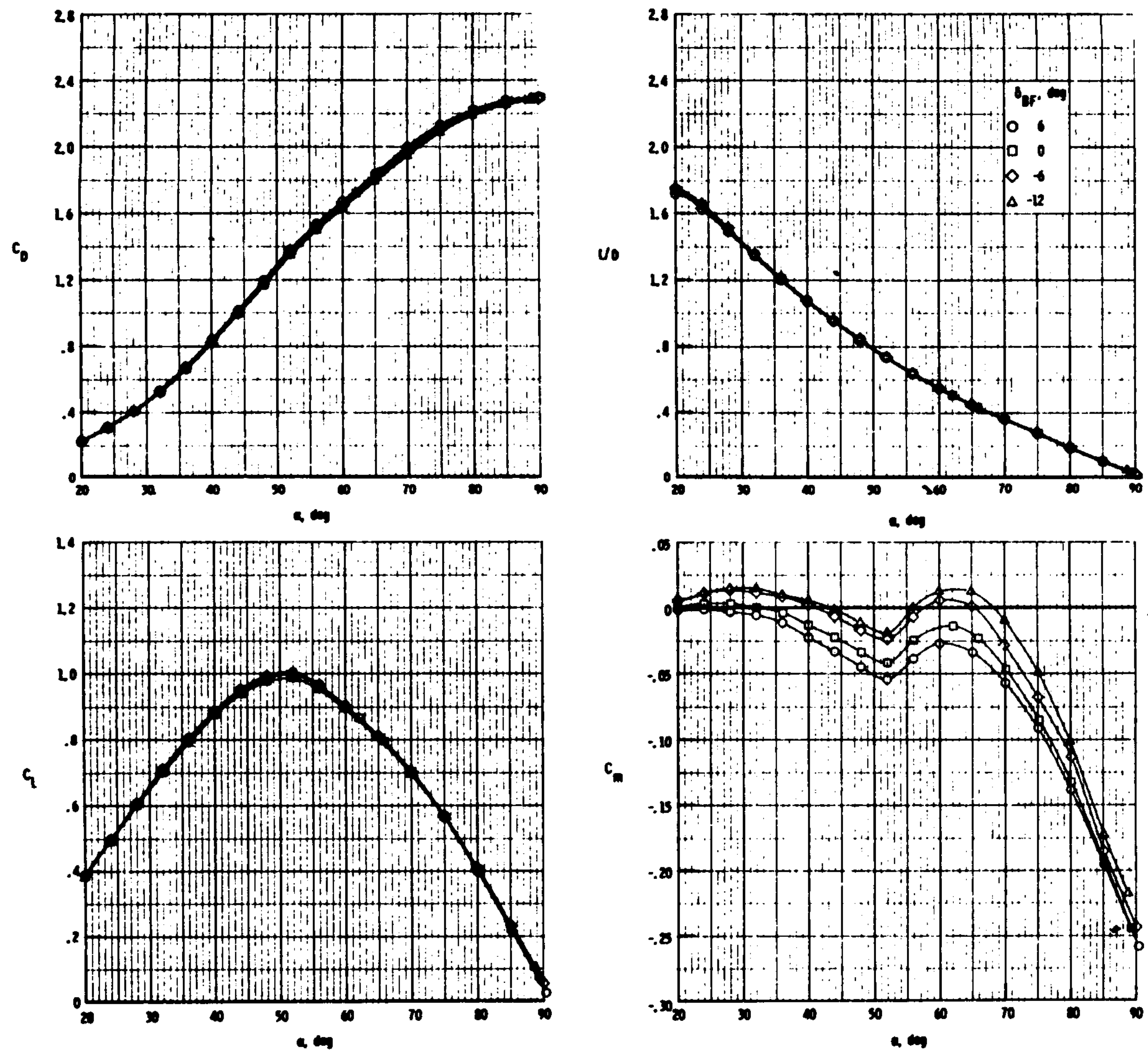
(c) M = 3.82

Figure 11.- (Continued)



(d) M = 4.20

Figure 11.- (Continued).



(e) M = 4.60

Figure 11. (Concluded).

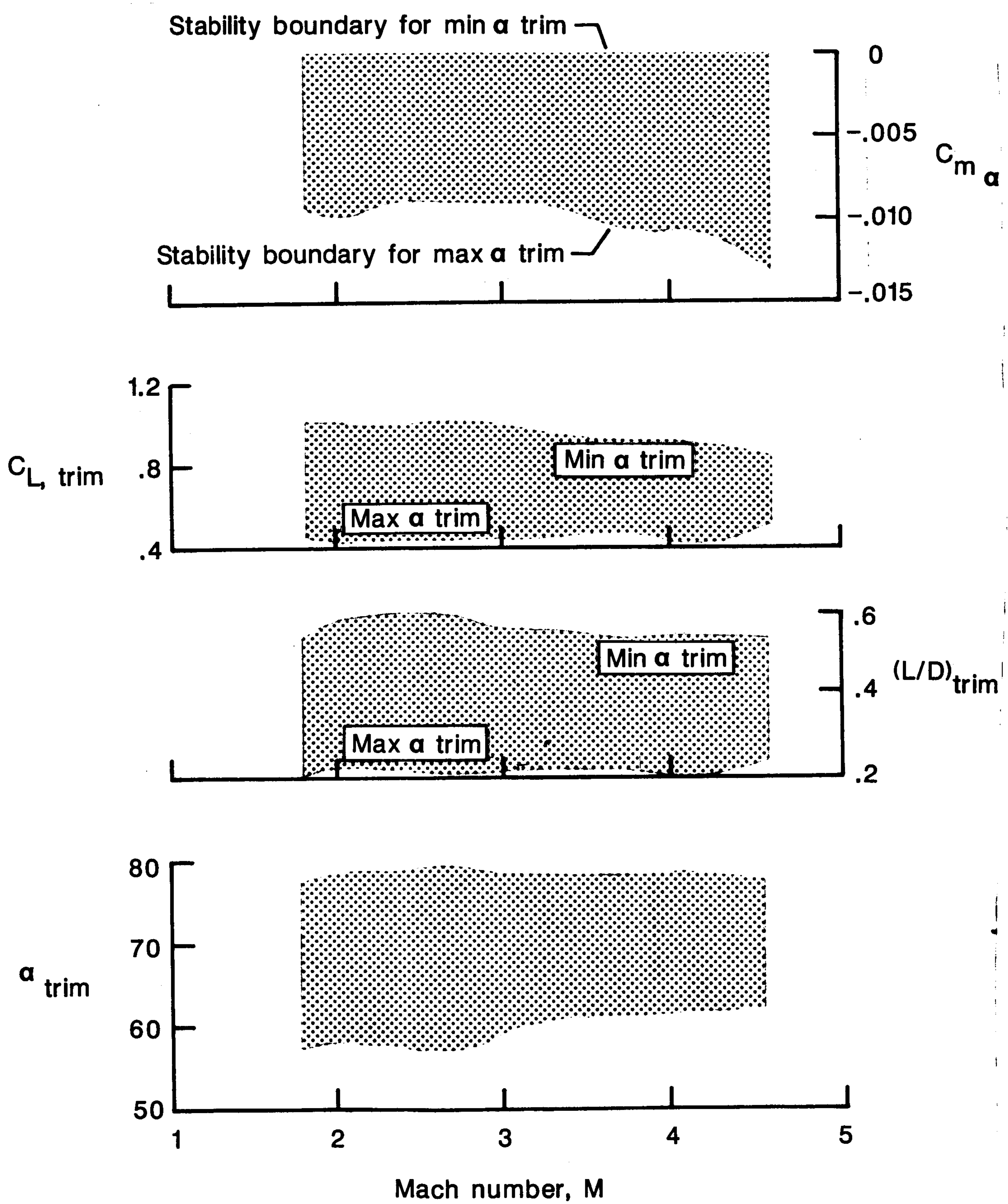


Figure 12.- Summary of orbiter model high-angle-of-attack stable trimmed characteristics.

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15. Supplementary Notes

16. Abstract

An investigation has been performed to determine Space Shuttle Orbiter aerodynamic characteristics in the angle-of-attack range from 20° to 90° and Mach numbers from 4.60 to 1.80 at Reynolds numbers, based on body length, of 2.15×10^6 and 4.30×10^6. Emphasis is on vehicle stability, control, and trim characteristics above 60° angle of attack. The model used in this investigation was a 0.986 percent scale Orbiter, having a blade-mounted support system entering the model in the region of the vertical tail. Elevon deflections of 0°, -10°, -20°, and -40° and body-flap deflections of 0°, ±6, and -12° were investigated individually and in combination. Schlieren photographs are also presented for selected configurations and Mach numbers. The Orbiter was found to be longitudinally stable and trimmable in the angle-of-attack range from approximately 60° to 80°. Both the elevon and body flap provided positive pitch control-effectiveness at angles of attack from 60° to 80° and the Mach numbers of this study. For the range of neutral to stable trim in the angle-of-attack range above about 55°, the deflected elevon/body-flap combination provided positive trimmed lift and lift/drag ratios.

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