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LARGE-SCALE WIND-TUNNEL INVESTIGATION OF A DUCTED-FAN – DEFLECTED-SLIPSTREAM MODEL WITH AN AUXILIARY WING

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16. Abstract

The longitudinal aerodynamic characteristics of a semispan wing deflected-slipstream configuration with a double-slotted flap and an auxiliary wing were determined. The model was powered by two low-pressure-ratio ducted fans. A comparison of static test results with results obtained from various propeller-driven configurations indicates that the turning effectiveness of fan-powered deflected-slipstream configurations can be correlated with propeller-powered configurations with the same flap-chord to slipstream-diameter ratio. The turning effectiveness of the auxiliary wing was essentially the same as would be produced by a conventional slotted flap system with the same flap-chord to slipstream-diameter ratio. The auxiliary wing reduced the thrust required at low speeds as would be expected due to the increase in lifting surface area.

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NOTATION

AR	wing aspect ratio
c	wing chord, ft
c_f	flap chord, maximum projected length parallel to wing chord at $\delta_f = 0$, ft
C_D	drag coefficient, D/qS, wind axis
C_L	lift coefficient, L/qS, wind axis
C_m	pitching-moment coefficient, M/qSc, wind axis
C_T	thrust coefficient, $T/\rho n^2 d^4$
d	fan diameter, ft
D	drag, lb
D_s	slipstream diameter, ducted fan exit diameter or propeller diameter $/\sqrt{2}$, ft (for rectangular ducts it is equivalent diameter)
J	advance ratio, V/nd
L	lift, lb
M	pitching moment about wing quarter chord, ft-lb
n	fan rotational speed, rps
q	free-stream dynamic pressure, $(1/2)\rho V^2$ lb/ft^2
R	resultant force, $\sqrt{L^2 + D^2}$, lb
S	semispan wing area, ft^2
T	total net ducted fan thrust, lb
T_c'	thrust coefficient, T/qS
v	dimensionless velocity, $V/V_w = \sqrt{(\pi/4)(AR/C_L)}$
V	free-stream velocity, ft/sec
V_w	reference wing downwash velocity, analogous to hover jet velocity, $\sqrt{2L/\rho S}$, ft/sec

W	aircraft weight, lb
X	longitudinal force parallel to thrust axis, lb
α	angle of attack with respect to the thrust axis, deg
δ	deflection angle of last element of wing-flap system with respect to wing chord line, deg
δ_1	deflection of foreflap with respect to wing chord, deg
δ_2	deflection of aft flap with respect to foreflap chord, deg
δ_D	deflection of auxiliary wing with respect to wing chord, deg
θ	slipstream turning angle, measured from thrust axis, $\tan^{-1}$ L/D, deg
ρ	air density, slugs/ft^3
γ	descent angle, deg

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SUMMARY

The longitudinal aerodynamic characteristics of a semispan wing deflected-slipstream configuration with a double-slotted flap and an auxiliary wing were determined. The model was powered by two low-pressure-ratio ducted fans. A comparison of static test results with results obtained from various propeller-driven configurations indicates that the turning effectiveness of fan-powered deflected-slipstream configurations can be correlated with propeller-powered configurations with the same flap-chord to slipstream-diameter ratio. The turning effectiveness of the auxiliary wing was essentially the same as would be produced by a conventional slotted flap system with the same flap-chord to slipstream-diameter ratio. The auxiliary wing reduced the thrust required at low speeds as would be expected due to the increase in lifting surface area.

INTRODUCTION

The deflected-slipstream V/STOL concept employs large chord flaps to deflect the propulsive slipstream so as to generate high lift forces. The investigations of several such configurations are reported in references 1 through 3. The present investigation was undertaken to determine the longitudinal aerodynamic characteristics of a semispan wing equipped with a double-slotted flap system and an auxiliary wing.[1] Included was a static test to determine if the performance of geometrically similar propeller and ducted-fan power configurations is comparable when the comparison is based on the fully developed propulsive slipstream. The model was powered by ducted fans with a pressure ratio of approximately 1.03. The tests were performed in the Ames 40- by 80-Foot Wind Tunnel.

[1] This concept was originated by Harlan D. Fowler, who holds U. S. Patent No. 3,312,426.

MODEL AND APPARATUS

Model

The model installed in the wind tunnel is shown in figure 1. Figure 1(a) shows the basic model with two ducted fans and the auxiliary wing. Figure 1(b) shows the model with the outboard ducted fan and auxiliary wing removed. Figure 2 shows the model mounted on the static test stand. Figure 3(a) is a drawing of the model as installed in the wind tunnel. A cross section of the wing showing flap system details is presented in figure 3(b). Basic model dimensions and airfoil coordinates are given in table 1. The ducted-fan blade form curves are shown in figure 4. The ducted fans were the same as those reported in references 4 through 6, except for the shroud diffuser and stators.

Instrumentation

During the wind-tunnel tests, forces and moments on the model were measured by the wind-tunnel balance system. The thrust of the outboard ducted fan was measured independently of the total model thrust by a strain gage balance. The ground plane was attached to the wing and therefore the loads on it are included in the model forces. The fairing under the ground plane was not attached to the model.

During the static tests the forces on the model were measured by three 3-axis load cells. The ducted-fan thrust was determined from calibrations made during the wind-tunnel tests.

Tests

The flap deflection, rotational velocity, and free-stream dynamic pressure were set and the model angle of attack was varied during the tests. The angle of attack ranged from -4° to +16°; the dynamic pressure ranged from 0.5 to 20.0 psf; and the rotational speed ranged from 2000 to 4000 rpm. The basic model was tested with and without the auxiliary wing extended, with the auxiliary wing removed, with the outboard ducted fan removed, and with both ducted fans removed.

The static tests were performed outside the wind-tunnel test section to avoid the effects of flow recirculation (fig. 2). The flaps were deflected upward to prevent any ground effect. The tests were performed by setting the flap deflection and then varying rotational speed from 2000 to 3500 rpm. This was done with and without the auxiliary wing assembly installed.

REDUCTION OF DATA

Corrections

No wind-tunnel wall effects were applied to the data because they were estimated to be within the accuracy of the measuring devices.

Accuracy of Data

The data are accurate within the following limits which include errors in reading and reducing the data as well as the errors of the device itself.

Lift	±3 lb
Drag	±3 lb
Pitching moment	±100 ft-lb
Ducted-fan thrust	±10 lb
Rotational speed	±3 rpm
Free-stream dynamic pressure	±0.1 psf
Angle of attack	±0.5°
Flap deflection	±1°
Static lift	±15 lb
Static drag	±15 lb

RESULTS AND DISCUSSION

Table 2 is an index to the data figures. Ducted-fan thrust coefficient referenced to fan rotational speed and to free-stream dynamic pressure are presented in figures 5 and 6, respectively, as functions of advance ratio. The results of the static tests are shown in figure 7 and the force data are compared with other data in figure 14. Figures 8-13 show the longitudinal aerodynamic characteristics for the various configurations tested. These data are summarized and compared with other data in figure 15.

The static results presented in figure 14 include data for a flapped wing exposed to an air stream from a circular duct (ref. 7), a cruise fan V/STOL model (ref. 3), and a propeller-STOL model (unpublished data for model of ref. 2). The propeller-STOL model has a wing-flap system very similar to the present model with the auxiliary wing removed.

Figure 14(a) shows that the static thrust recovery R/T was approximately the same for the model with or without the auxiliary wing for the same turning angle up to about 40°. The primary effect of the auxiliary wing is to increase the maximum turning angle from 45° to 75°. The model without the auxiliary wing and the propeller STOL model had essentially the same static thrust recovery. In addition it is evident that removing the inboard ducted fan did not change the static performance, indicating there was no interference between the ducted fans.

The static turning effectiveness, θ/δ as a function of flap-chord to slipstream-diameter ratio, c_f/D_s is shown in figure 14(b). To evaluate θ/δ, the summary curve for various propeller-wing-flap configurations in reference 8 is presented. The curve has been replotted versus fully developed slipstream diameter rather than propeller diameter (D_s = duct exit diameter = propeller diameter/$\sqrt{2}$). The turning effectiveness of the various configurations tested in this investigation agreed reasonably well with the summary curve, indicating that the comparison based on the developed slipstream is valid. It is also evident from this figure that the auxiliary wing produced the same θ/δ as would be expected from a flap system with an equivalent c_f/D_s.

The transition performance has been summarized in figure 15 which presents the variation of thrust-to-weight ratio with dimensionless forward velocity for level unaccelerated flight. A theoretical optimum curve developed from the theory of reference 9 is also presented. It can be seen that adding the auxiliary wing resulted in a decrease in thrust required at speeds less than $v = 2.0$ as would be expected due to the increase in lifting surface area. Also as a result of the large flap chord the auxiliary wing configuration can descend at fairly high descent angles as shown in figure 8. The removal of the outboard ducted fan caused no change in thrust required at low speeds which is consistent with the results of reference 10.

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National Aeronautics and Space Administration
Moffett Field, Calif., Sept. 29, 1970

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TABLE 1.– MODEL GEOMETRY

(a) Basic model dimensions

Basic Wing	
Area (semispan), sq ft	79.75
Semispan, ft	14.5
Chord, ft	5.5
Airfoil section	63_2-416 mod.
Aspect ratio	5.275
Foreflap chord, ft	1.10
Aft flap and vane chord, ft	1.33
Auxiliary Wing	
Area, sq ft	22.75
(extended), sq ft	31.35
Semispan, ft	10.34
Chord, ft	2.2
(extended), ft	3.03
Airfoil section	NACA 0015
Duct	
Inside diameter, ft	4
Outside diameter	4 ft, 10.5 in.
Chord	3 ft, 6.5 in.
Exit diameter	3 ft, 11 in.
Exit area, sq ft	12.048
Diffuser angle, deg	0
Fan station, percent of duct chord	22.72
Inlet Guide Vanes	
Chord, in.	3
Number of vanes	7
Airfoil section, percent	NACA 65A010
Position of vane c/4, percent of duct chord	11.25
Twist, deg	0
Fan	
Planform curves	see fig. 4
Number of blades	8
Hub-to-tip diameter ratio	0.333
Design static thrust disk loading, psf	150
Blade angle at tip, deg	11
Approximate blade tip clearance, in.	0.063
Total activity factor	718
Stators	
Chord, in.	6
Number of stators	3
Position of stator centerline, percent of duct chord	38.4

TABLE 1.– MODEL GEOMETRY – Continued

(b) Basic wing coordinates

[All dimensions in inches]

Upper surface		Lower surface	
Chordwise station	Ordinate	Chordwise station	Ordinate
0	0	0	0
.198	.908	.463	-.767
.347	1.119	.645	-.921
.656	1.463	.998	-1.162
1.454	2.092	1.854	-1.566
3.083	3.009	3.532	-2.117
4.728	3.712	5.195	-2.516
6.381	4.288	6.849	-2.829
9.704	5.185	10.141	-3.282
13.035	5.842	13.425	-3.595
16.372	6.309	16.703	-3.782
19.713	6.606	19.977	-3.862
23.055	6.745	23.250	-3.838
26.397	6.722	26.523	-3.699
29.738	6.554	29.797	-3.464
33.075	6.259	33.075	-3.146
36.408	5.855	36.357	-2.764
39.736	5.359	37.000	-2.700
43.059	4.784	39.644	1.850
47.000	4.000	42.936	3.850
		47.000	3.950
L.E. radius – 1.171			

TABLE 1.– MODEL GEOMETRY – Continued

(c) Foreflap, vane, and aft flap coordinates

[All dimensions in inches]

Foreflap			Vane			Aft flap		
Chordwise station	Upper ordinate	Lower ordinate	Chordwise station	Upper ordinate	Lower ordinate	Chordwise station	Upper ordinate	Lower ordinate
0	0	0	0	0	0	0	0	0
.099	.595	-.825	.066	.290	-.240	.165	.740	-.594
.198	.872	-1.070	.132	.420	-.330	.165	1.045	-.820
.330	1.140	-1.320	.198	.510	-.380	.495	1.270	-.960
.495	1.420	-1.550	.264	.580	-.430	.660	1.425	-1.070
.660	1.650	-1.720	.330	.660	-.450	.980	1.650	-1.175
1.320	2.270	-2.080	.495	.780	-.450	1.320	1.835	-1.210
1.980	2.730	-2.200	.660	.880	-.400	1.650	1.950	-1.190
2.640	3.050	-2.170	.980	1.000	-.200	1.980	2.040	-1.160
3.300	3.280	-2.100	1.320	1.070	.026	2.640	2.120	-1.095
3.960	3.450	-2.040	1.650	1.070	.211	3.300	2.150	-1.035
4.620	3.550	-1.980	1.980	1.040	.316	4.950	1.880	-.880
5.280	3.620	-1.920	2.310	.965	.350	6.600	1.550	-.715
5.940	3.660	-1.860	2.640	.845	.350	8.250	1.220	-.560
6.600	3.650	-1.800	2.970	.700	.310	9.900	.880	-.410
8.200	3.520	-1.700	3.300	.515	.238	11.550	.550	-.244
8.410	3.500	.000	3.630	.300	.132	13.200	.210	-.099
9.900	3.250	1.650	3.960	.066	.020	14.200	-.013	-.020
11.550	2.920	2.330						
13.200	2.540	2.510						
L. E. radius - 1.98			L. E. radius - 0.56			L. E. radius - 1.19		

TABLE 1.– MODEL GEOMETRY – Continued

(d) Auxiliary wing coordinates

[All dimensions in inches]

Chordwise station	Upper ordinate	Lower ordinate
0	0	0
.33	.628	-.628
.66	.865	-.865
1.32	1.172	-1.172
1.98	1.390	-1.390
2.64	1.545	-1.545
3.96	1.765	-1.765
5.28	1.890	-1.890
7.92	1.980	-1.980
10.56	1.915	-1.915
13.20	1.750	-1.750
15.84	1.505	-1.505
18.50	1.210	-1.210
21.12	.78	-.78
23.78	.34	-.34
26.40	.042	-.042
L.E. radius – 0.655		

TABLE 1.– MODEL GEOMETRY – Concluded

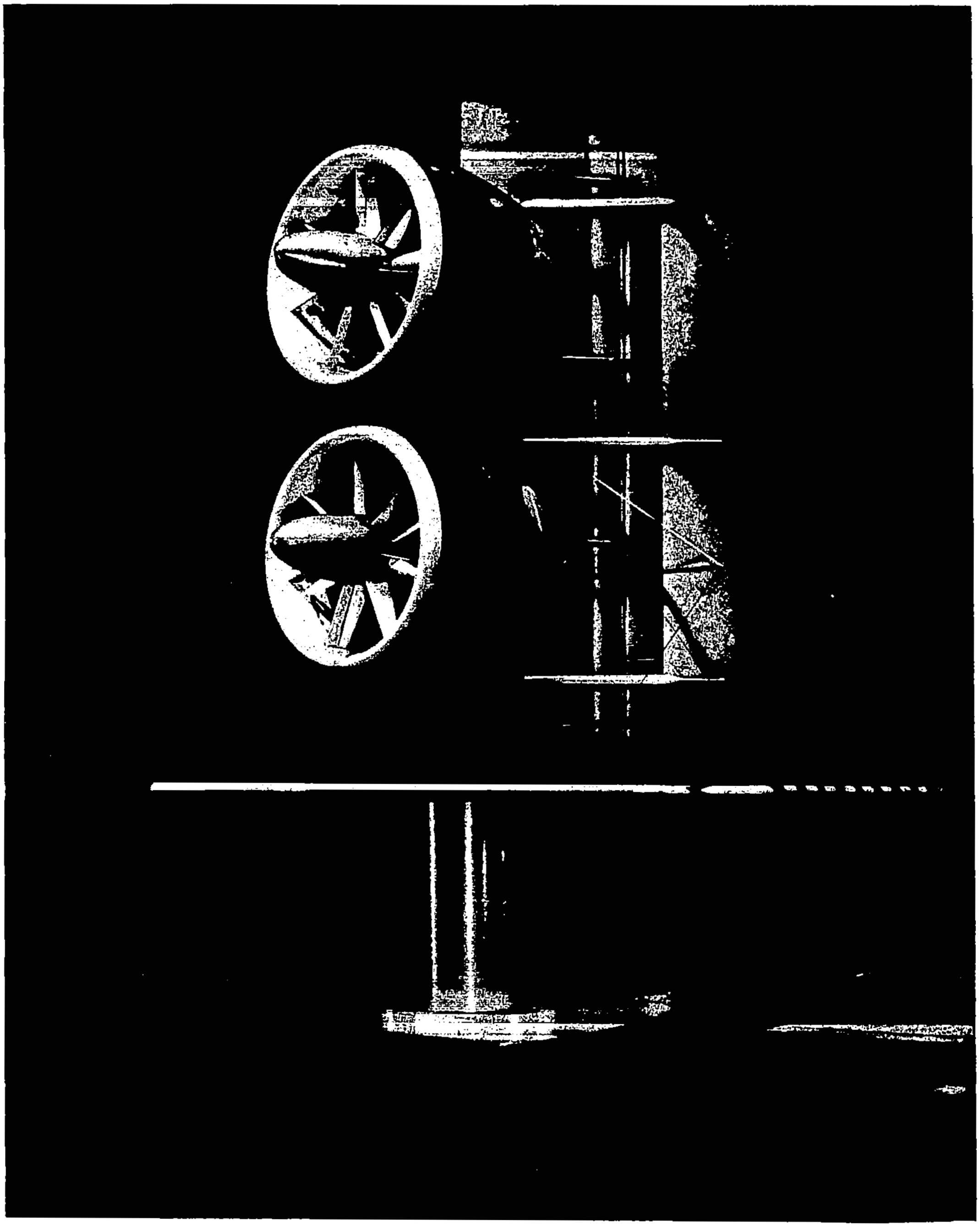
(e) Ducted-fan shroud coordinates

[All dimensions in inches]

Chord length	Outside radius	Inside radius
0	26.86	26.86
.1658	27.54	26.265
.2465	27.625	26.053
.4123	27.838	25.84
.8075	28.178	25.458
1.6575	28.518	24.99
2.465	28.73	24.735
3.315	28.90	24.48
4.973	29.24	24.183
6.588		24.055
8.245		23.97
9.903		
11.56		
13.218		23.843
14.83		23.503
16.49		
18.148		
19.805		
21.42	29.028	
23.12	28.858	
24.735	28.645	
26.393	28.348	
28.05	28.093	
29.708	27.795	
33.49	27.455	
32.98	27.115	
34.00	26.903	
36.125	26.18	
38.25	25.415	
40.375	24.608	
42.5	23.588	

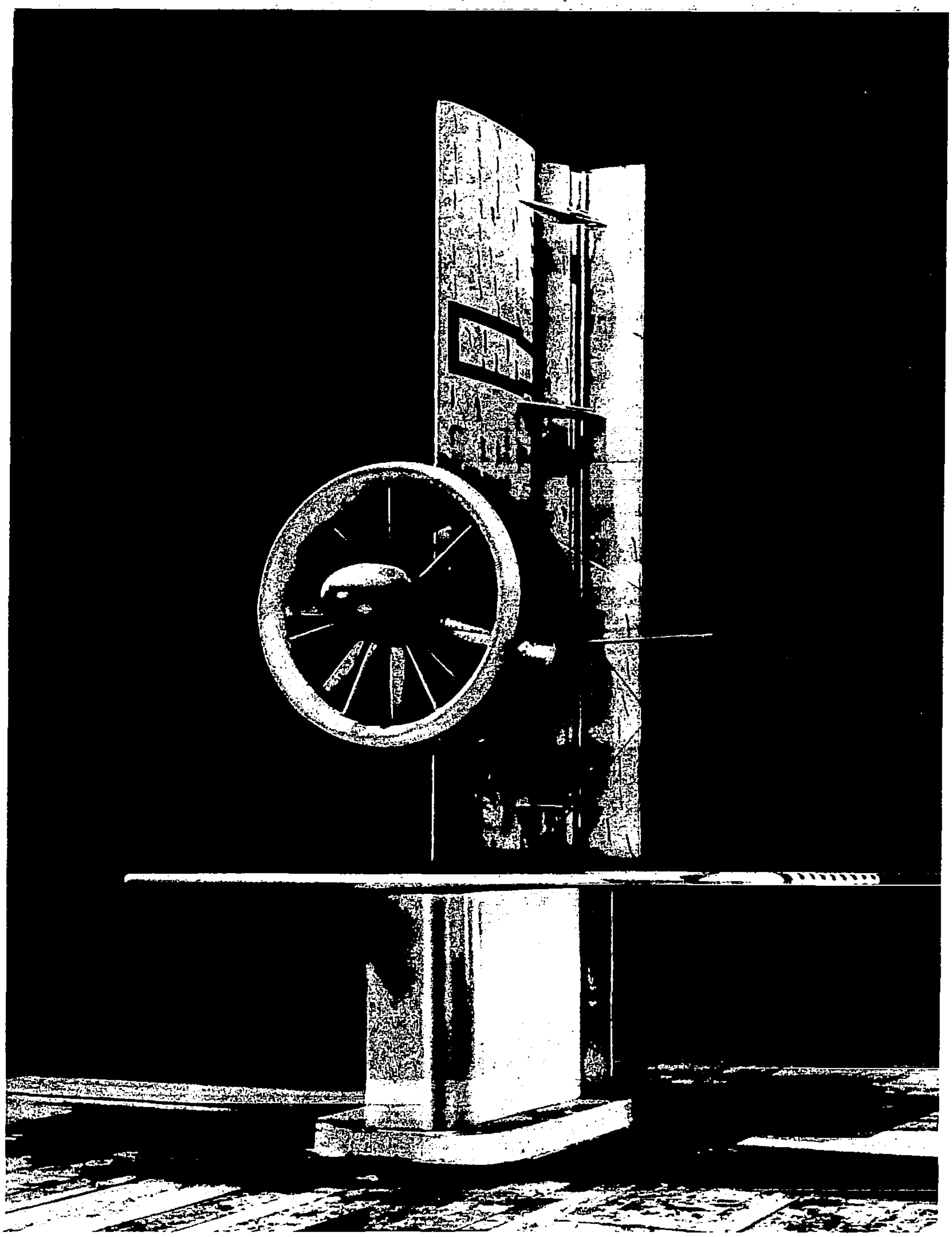
TABLE 2.– INDEX TO FIGURES

Configuration	Type of data	$\delta_1/\delta_2/\delta_D$	Figure
	C_T vs. J		5
	T_c' vs. J		6
Auxiliary wing – 2 ducted fans	Static performance	~	7(a)
Auxiliary wing removed– 2 fans		~	7(b)
Auxiliary wing and inboard fan removed –		~	7(c)
Auxiliary wing – 2 ducted fans	Longitudinal aero. characteristics	50/50/90	8(a)
		40/40/90	8(b)
		30/30/90	8(c)
		40/40/45	8(d)
		30/30/45	8(e)
		40/40/2	8(f)
		30/30/2	8(g)
		0/0/-3	8(h)
		0/0/2	8(i)
Auxiliary wing extension – 2 ducted fans		40/40/90	9(a)
		30/30/45	9(b)
Auxiliary wing struts only – 2 fans		0/0	10
Auxiliary wing removed – 2 ducted fans		40/40	11(a)
		30/30	11(b)
		0/0	11(c)
Auxiliary wing and outboard fan removed		50/40	12(a)
		40/50	12(b)
		40/40	12(c)
		30/30	12(d)
		0/0	12(e)
Auxiliary wing and both fans removed		0/0-40/50	13
	Summary of static performance		14
	Transition performance T/W vs. $\sqrt{(AR/C_L)(\pi/4)}$		15



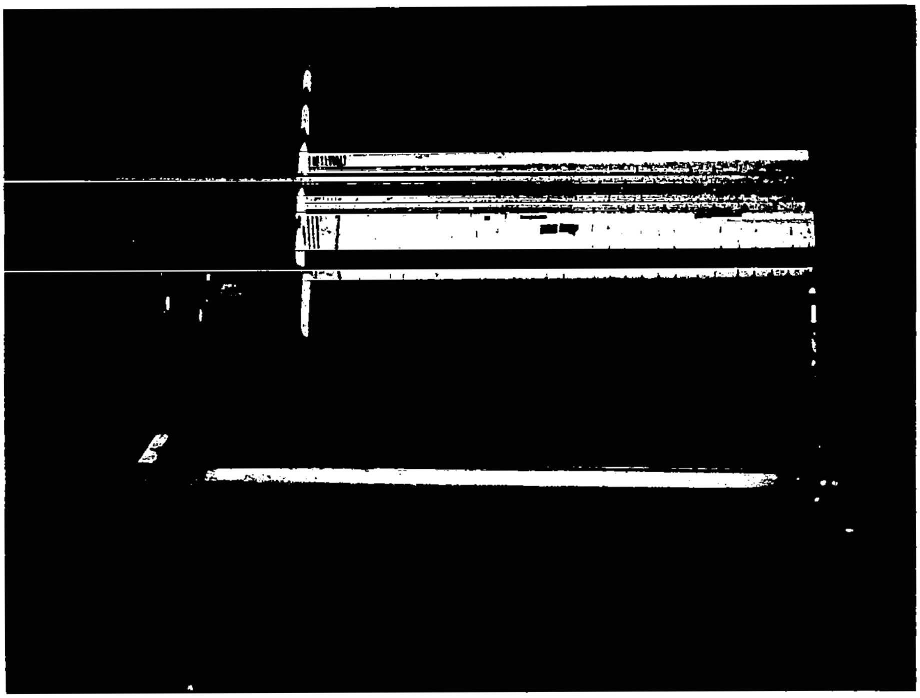
(a) Basic model with two ducted fans and auxiliary wing.

Figure 1.- Ducted fan-deflected slipstream model installed in wind tunnel.



(b) Outboard ducted fan and auxiliary wing assembly removed.

Figure 1.- Concluded.



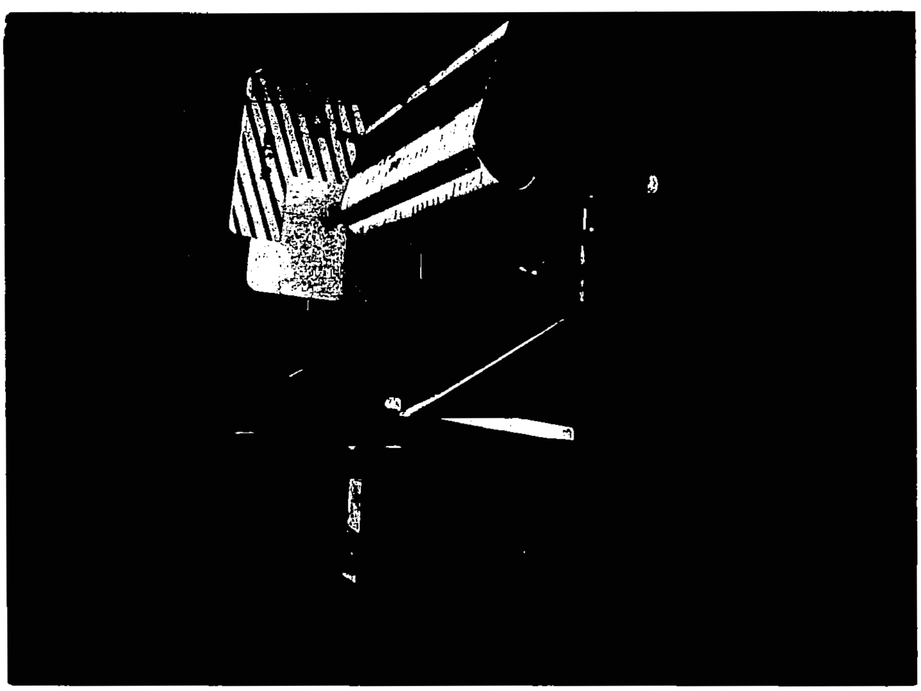
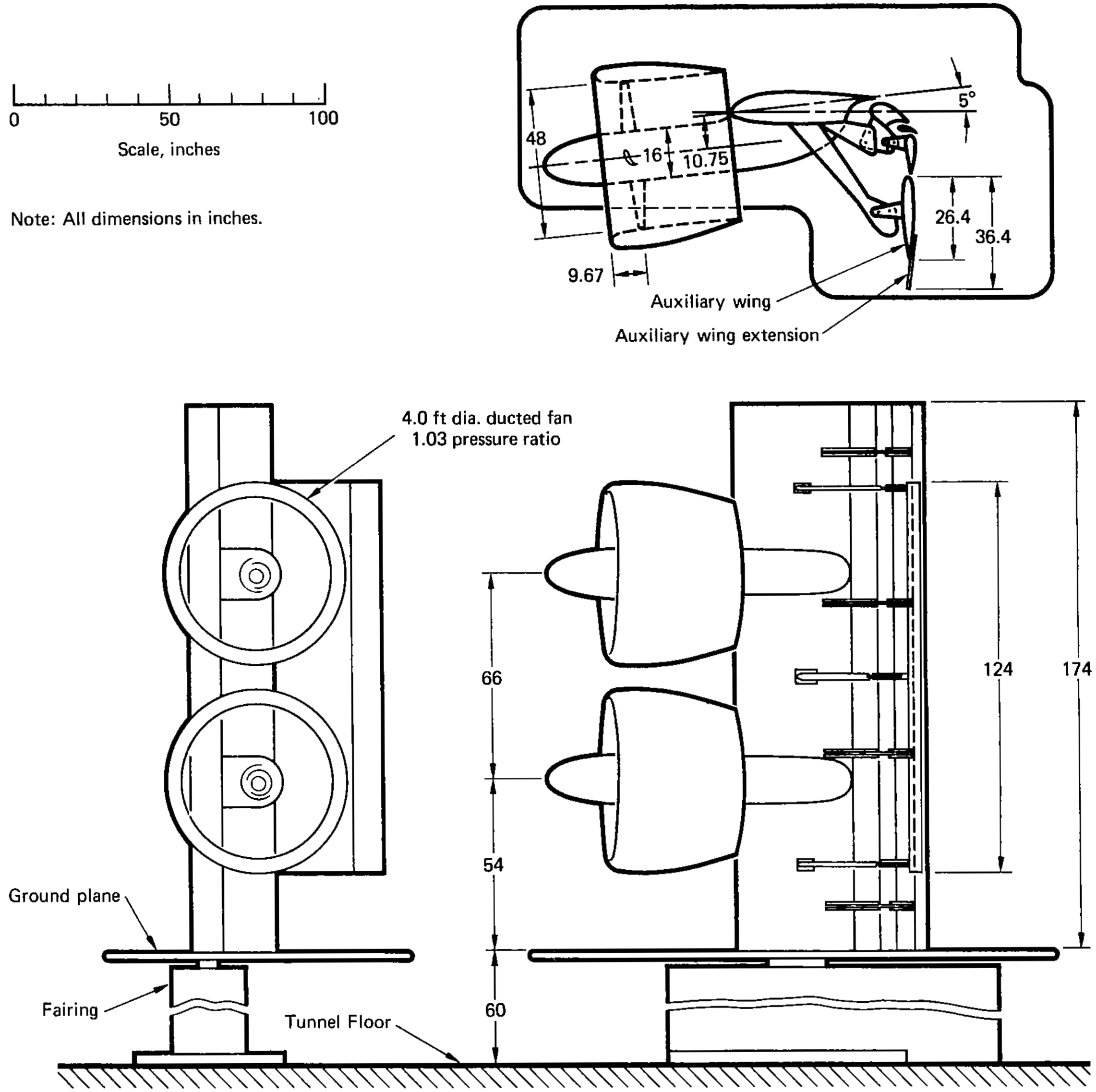
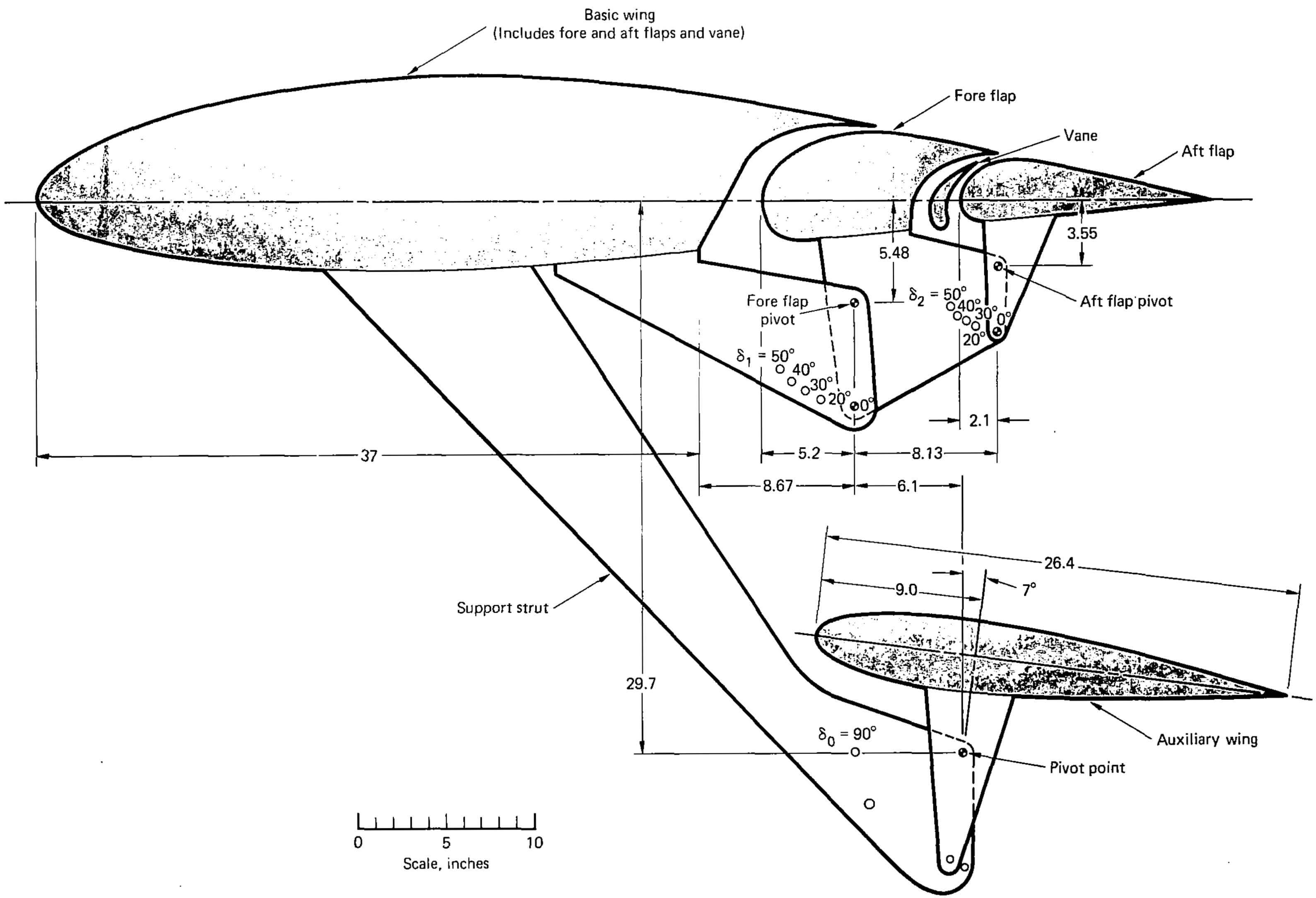


Figure 2.- Ducted fan-deflected slipstream model installed in static test stand with auxiliary wing removed.



(a) Basic arrangement.

Figure 3.- Model dimensions.



Note: All dimensions in inches.

(b) Details of basic wing and auxiliary wing.

Figure 3.- Concluded.

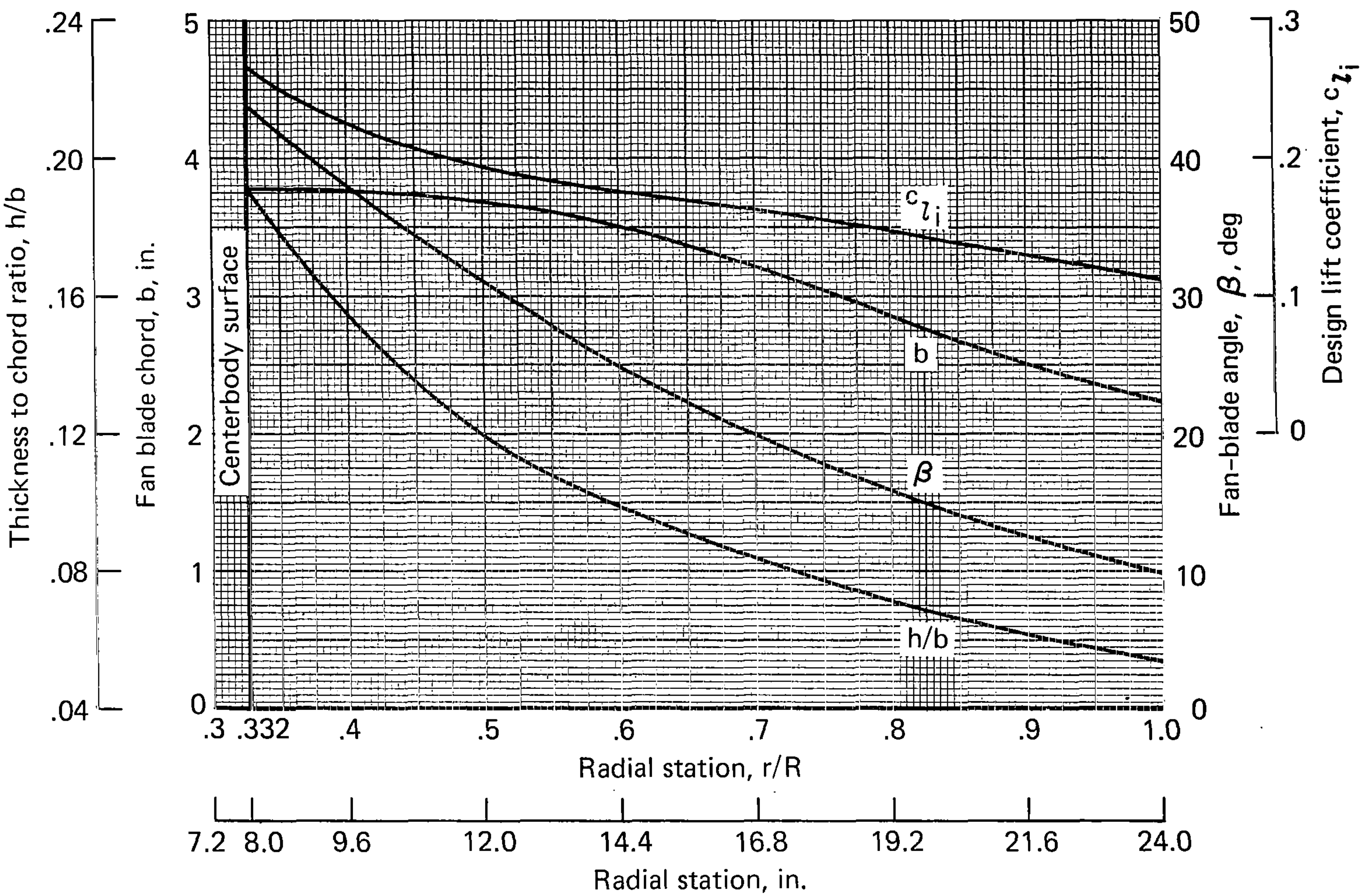


Figure 4.- Fan blade-form curves with the design lift coefficient, blade chord, blade angle, and blade thickness to chord ratio as functions of the radial distance from the duct center.

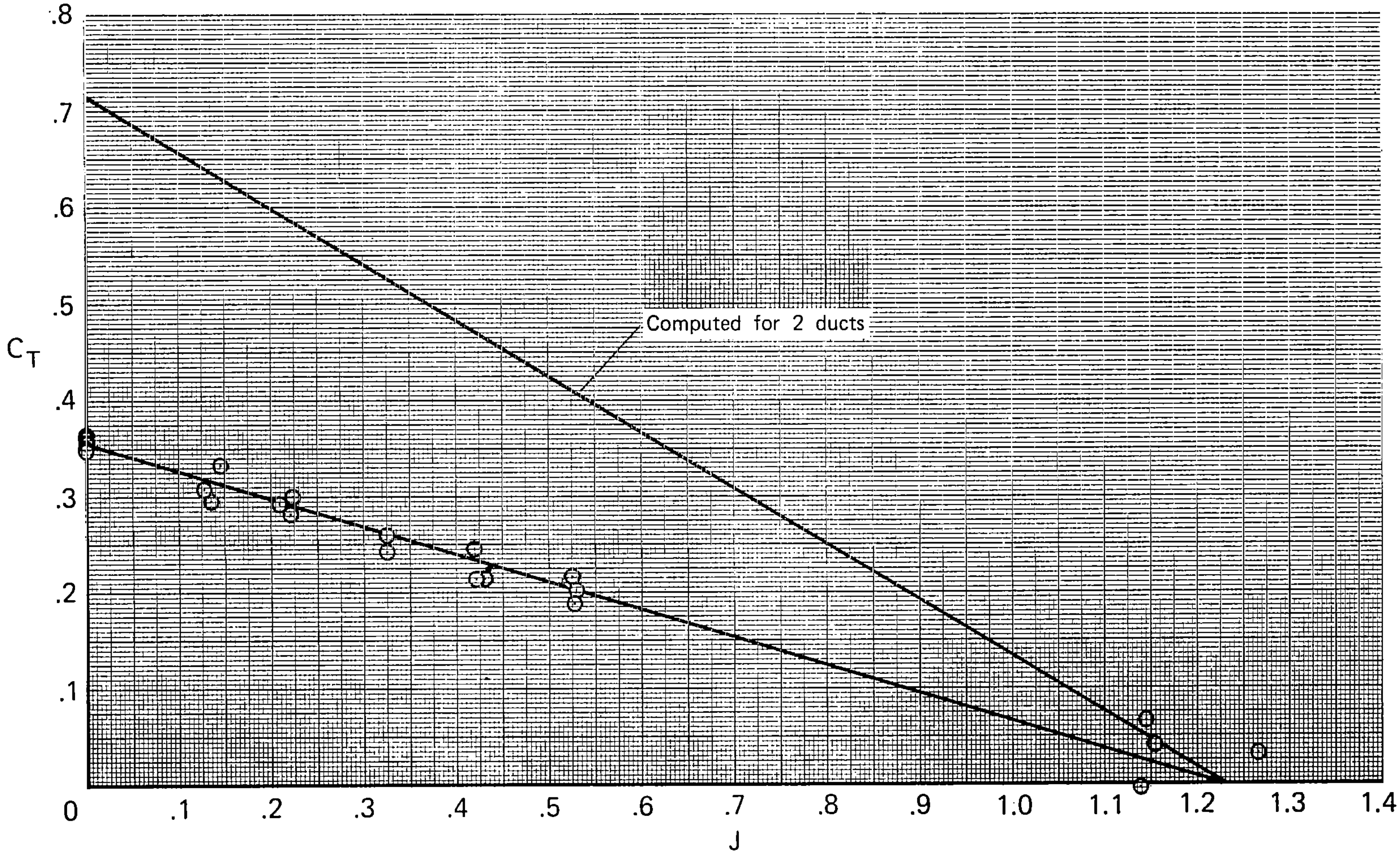


Figure 5.- Thrust coefficient referenced to rotational speed as a function of advance ratio for one and two ducted fans.

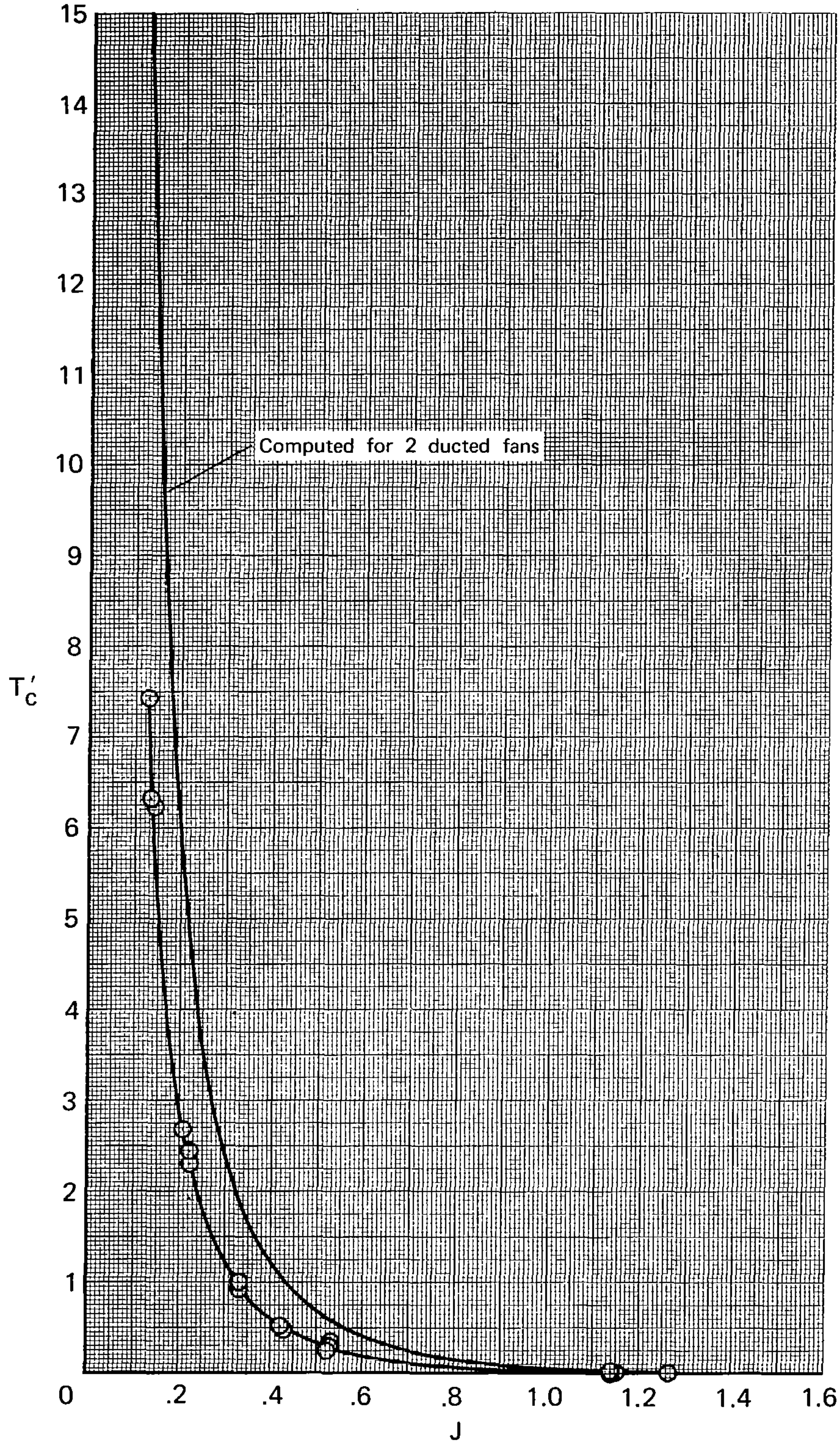
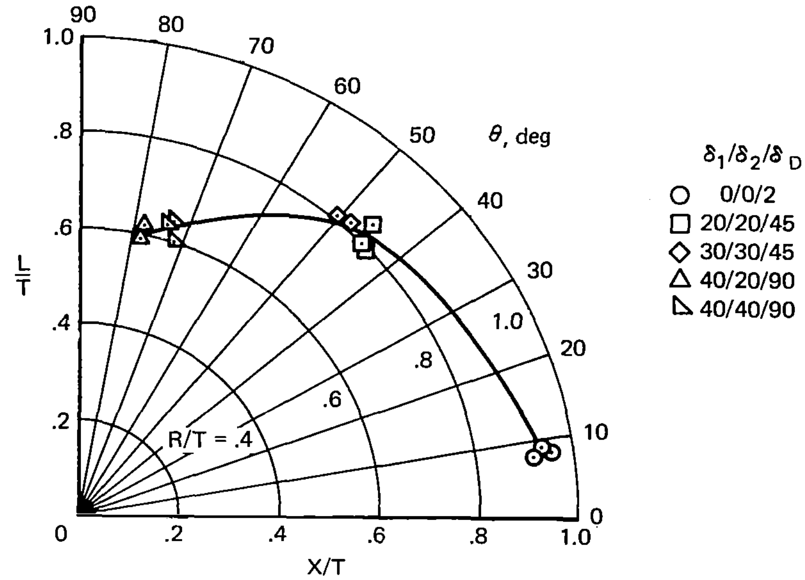
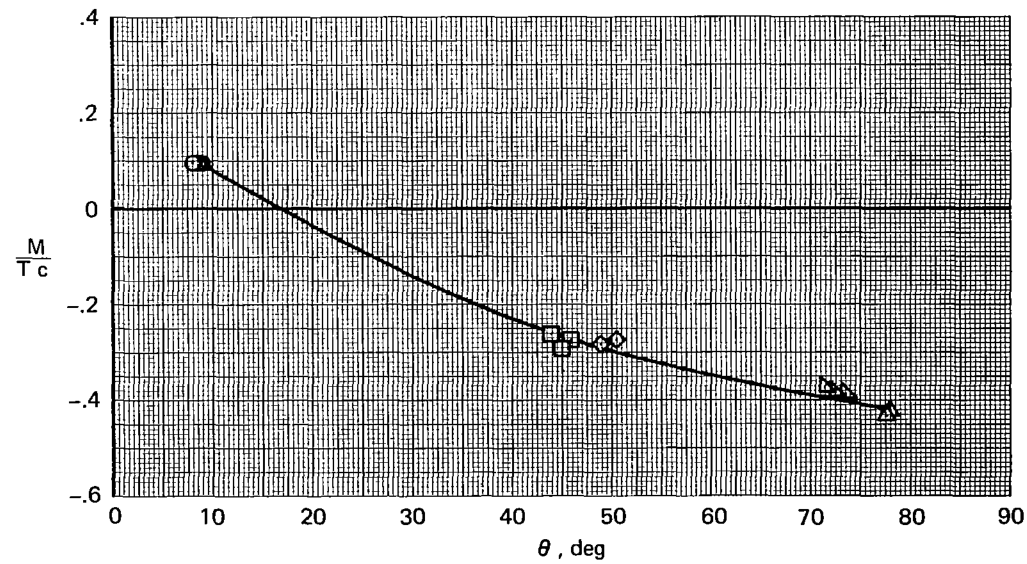


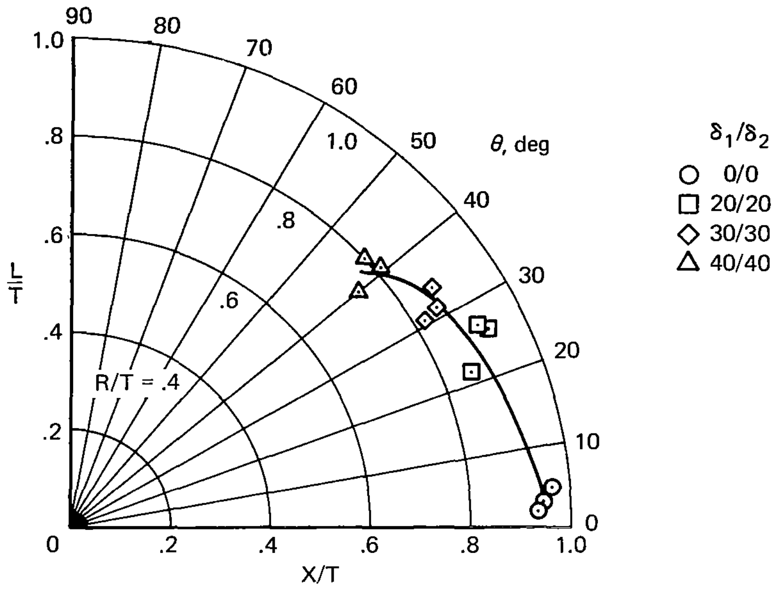
Figure 6.- Thrust coefficient referenced to free-stream velocity as a function of advance ratio for one and two ducted fans.

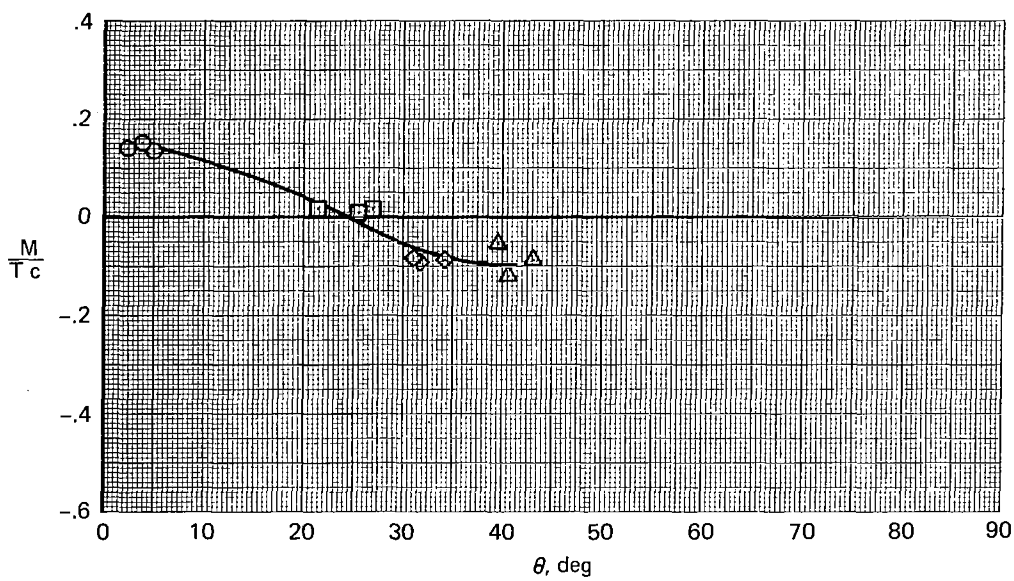




(a) Auxiliary wing with extension.

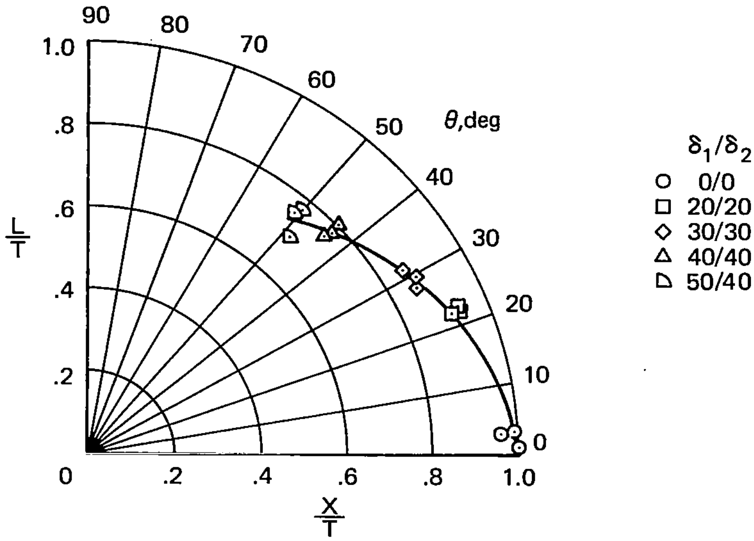
Figure 7.- Static performance characteristics for various flap deflections for model with two ducted fans.

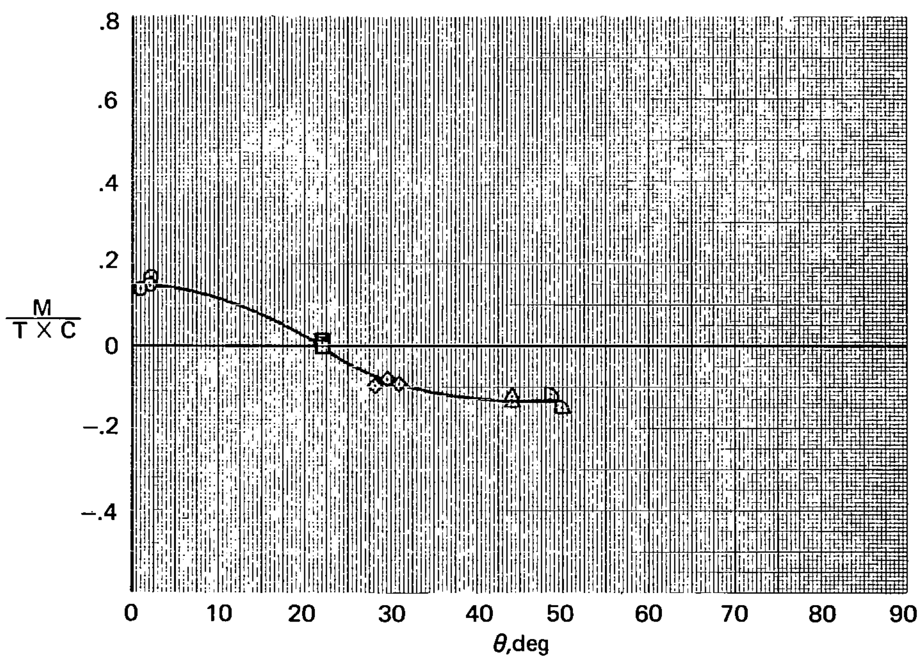




(b) Basic wing with auxiliary wing assembly removed.

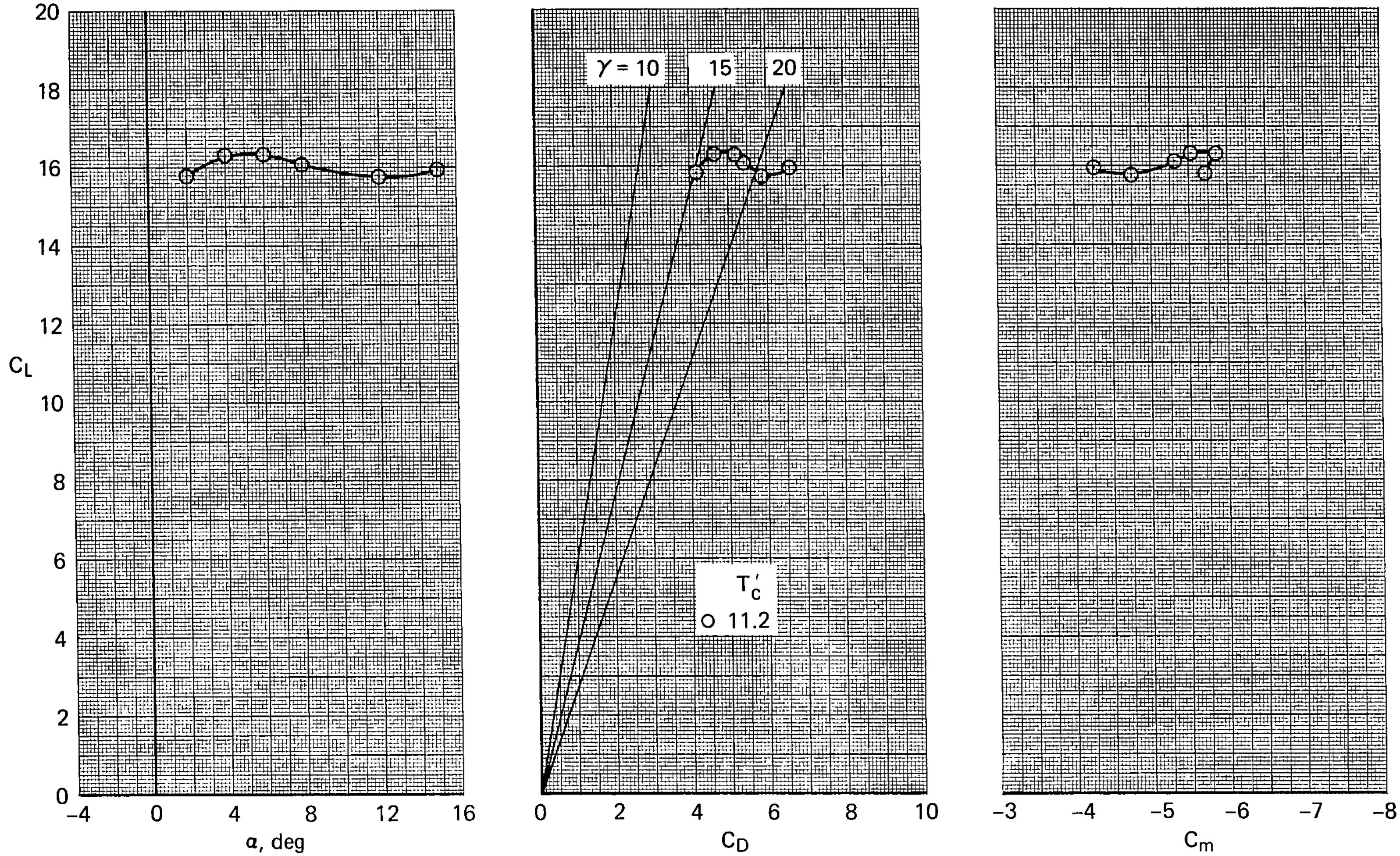
Figure 7.- Continued.





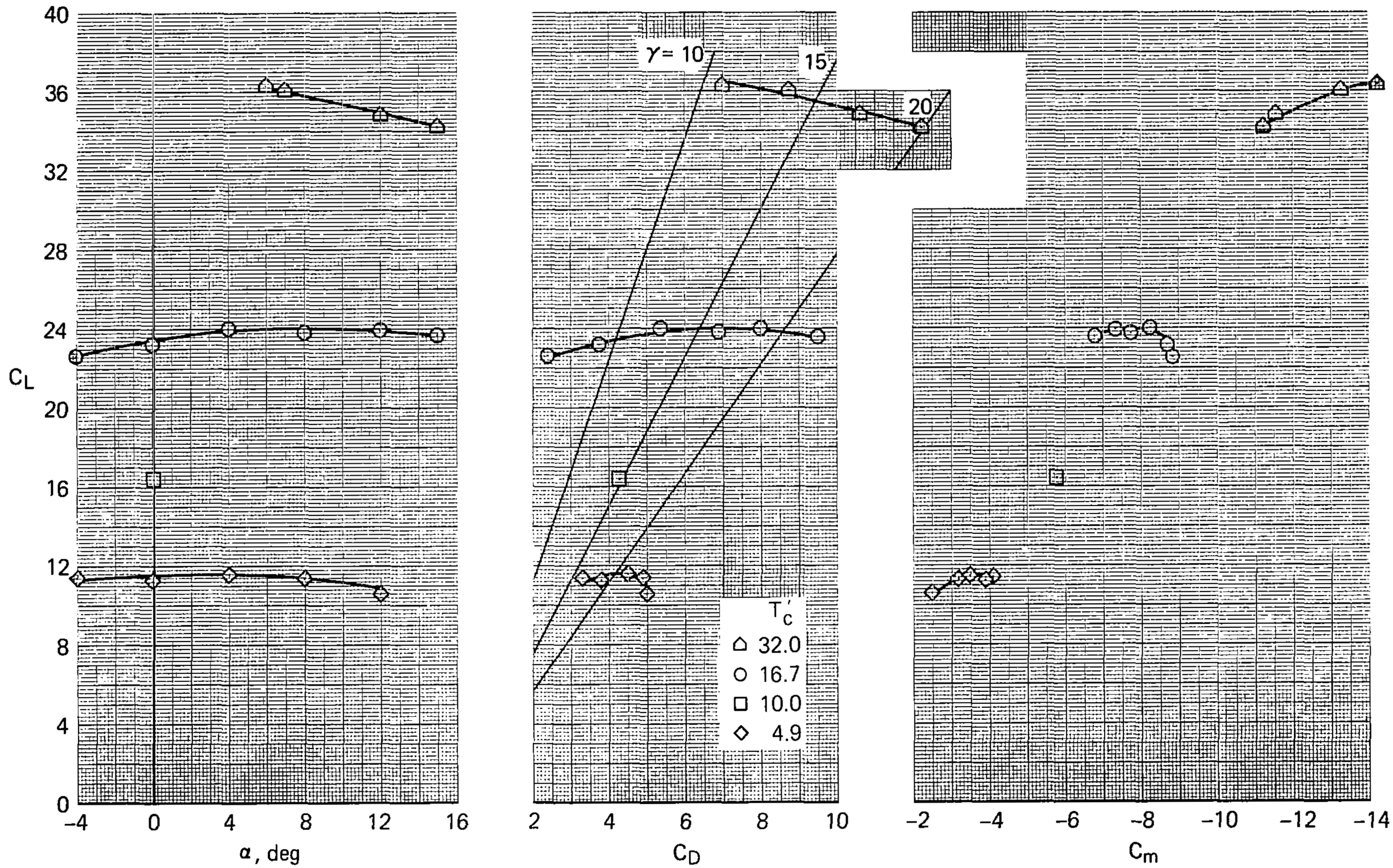
(c) Basic wing with auxiliary wing and inboard ducted fan removed.

Figure 7.- Concluded.



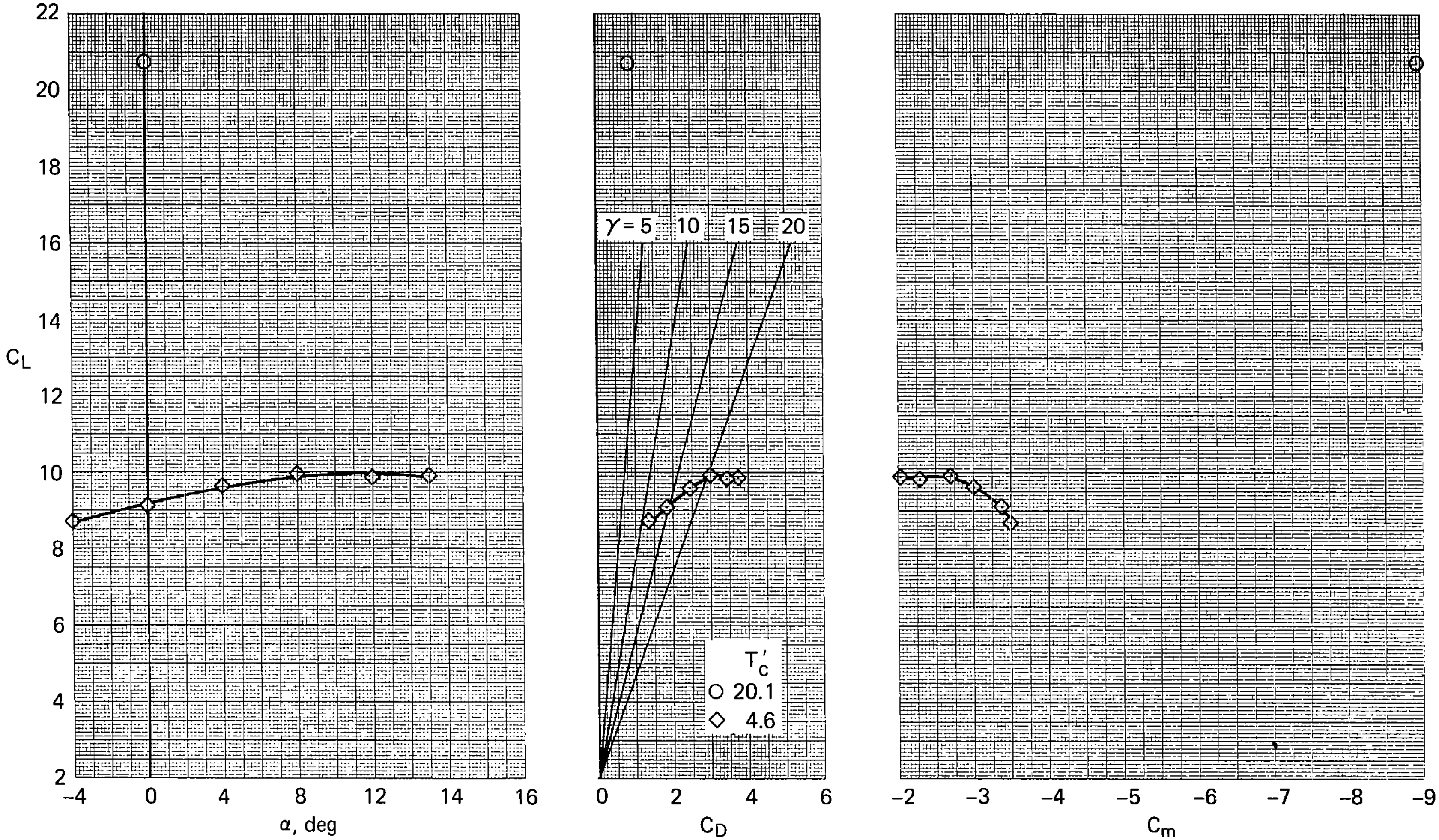
(a) $\delta_1/\delta_2/\delta_D$ = 50°/50°/90°

Figure 8.- Longitudinal aerodynamic characteristics for several flap deflections with auxiliary wing and two ducted fans.



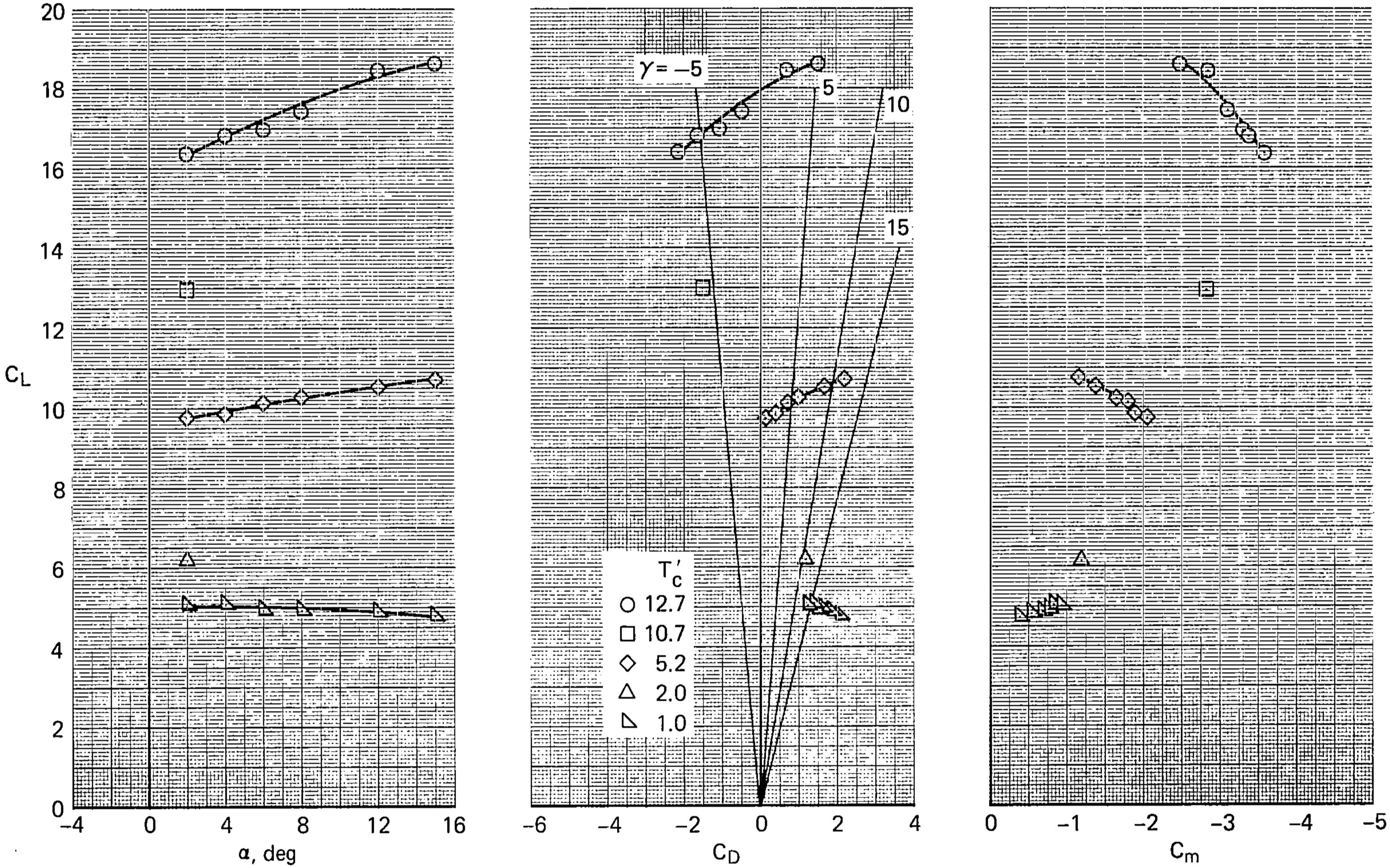
(b) $\delta_1/\delta_2/\delta_D = 40°/40°/90°$

Figure 8.- Continued.



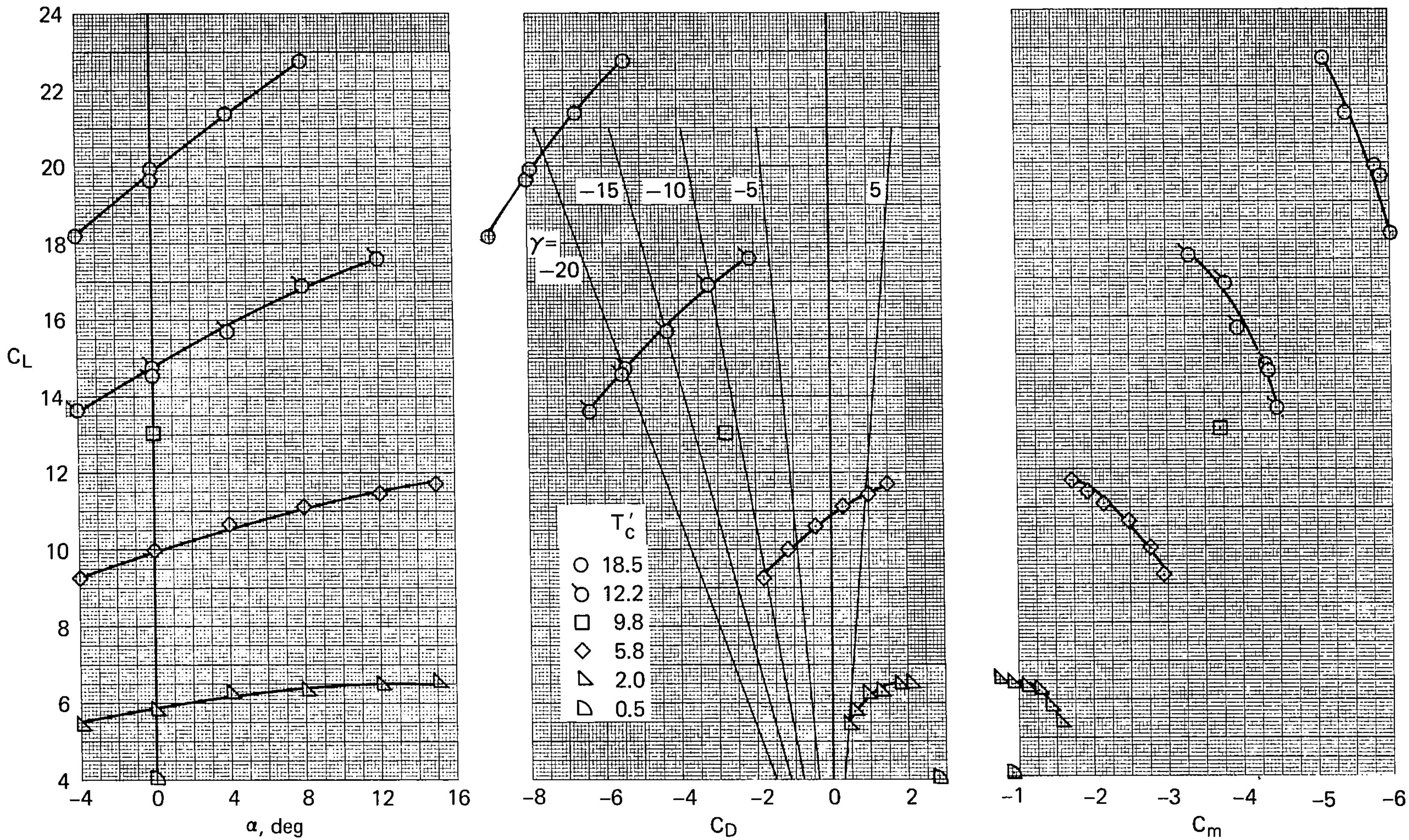
(c) $\delta_1/\delta_2/\delta_D$ = 30°/30°/90°

Figure 8.- Continued.



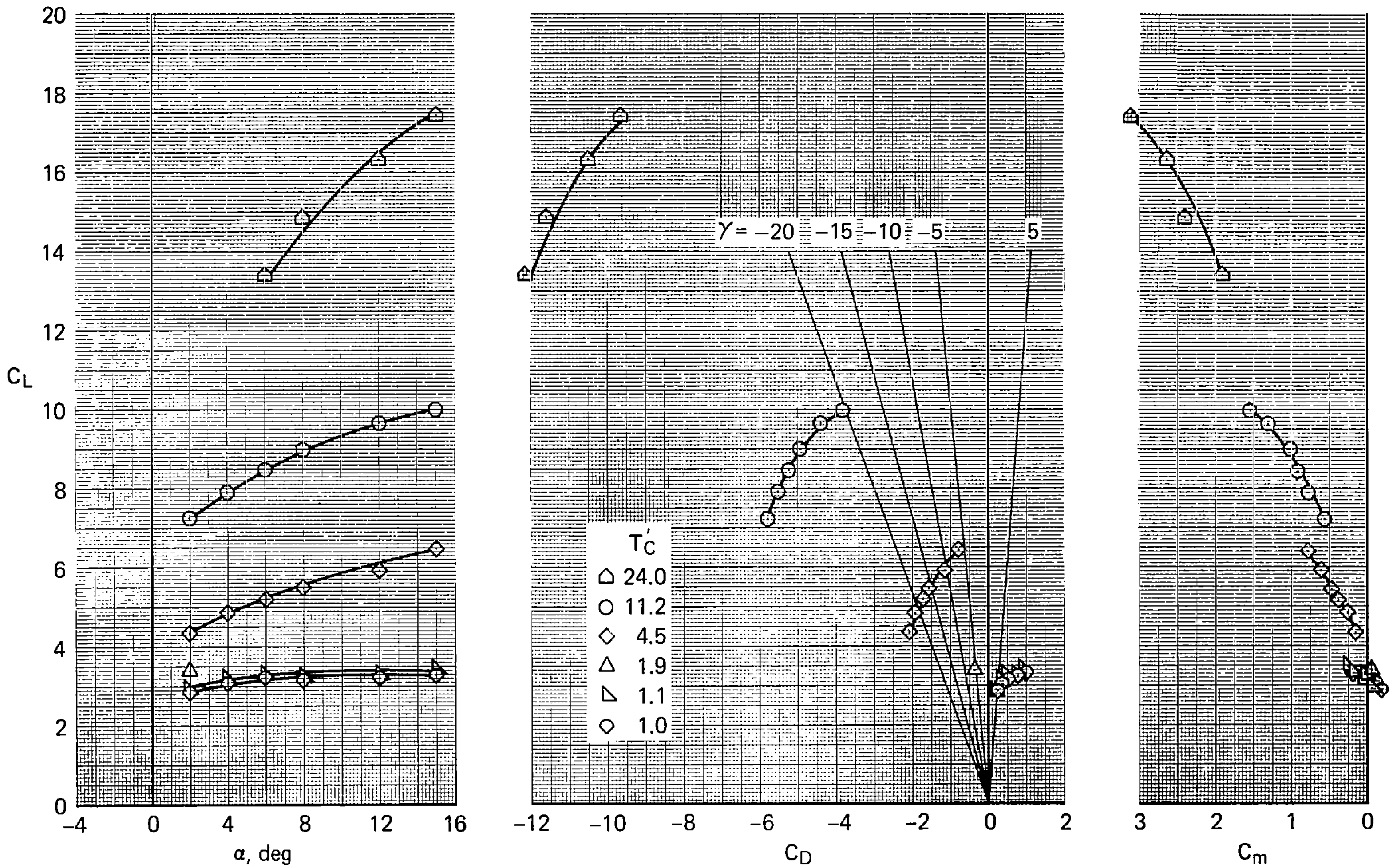
(d) $\delta_1/\delta_2/\delta_D$ = 40°/40°/45°

Figure 8.- Continued.



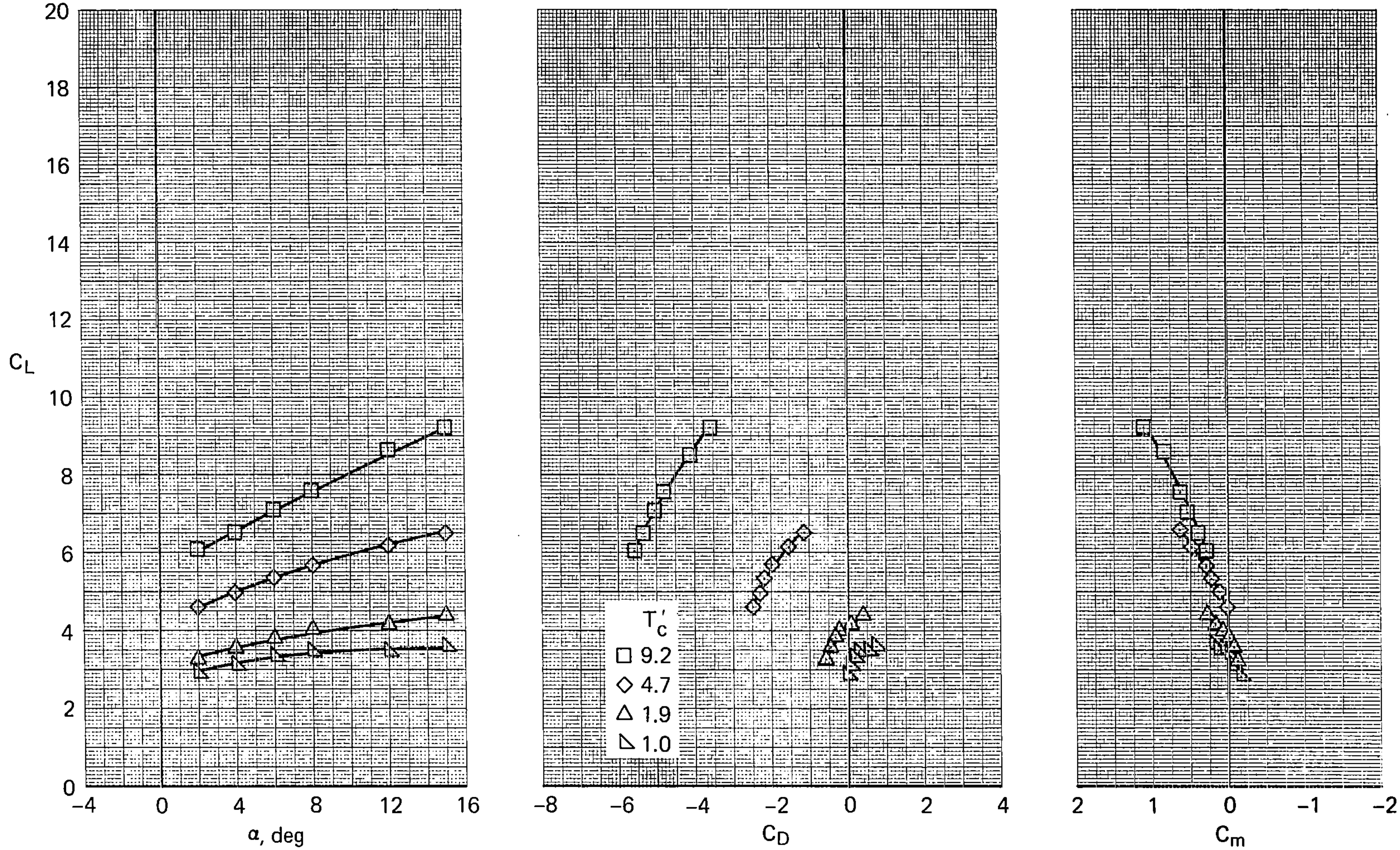
(e) $\delta_1/\delta_2/\delta_D$ = 30°/30°/45°

Figure 8.- Continued.



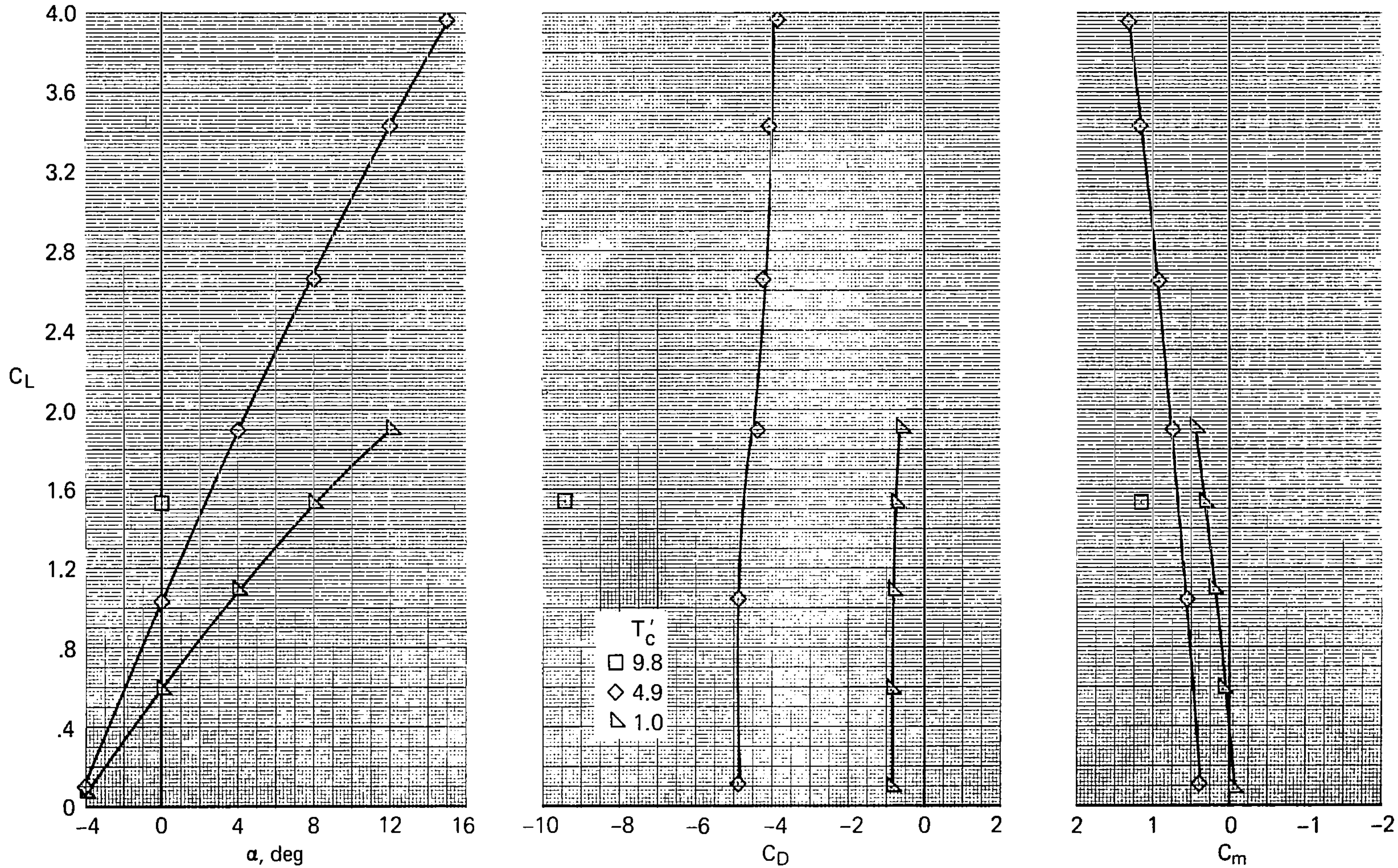
(f) $\delta_1/\delta_2/\delta_D$ = 40°/40°/2°

Figure 8.- Continued.



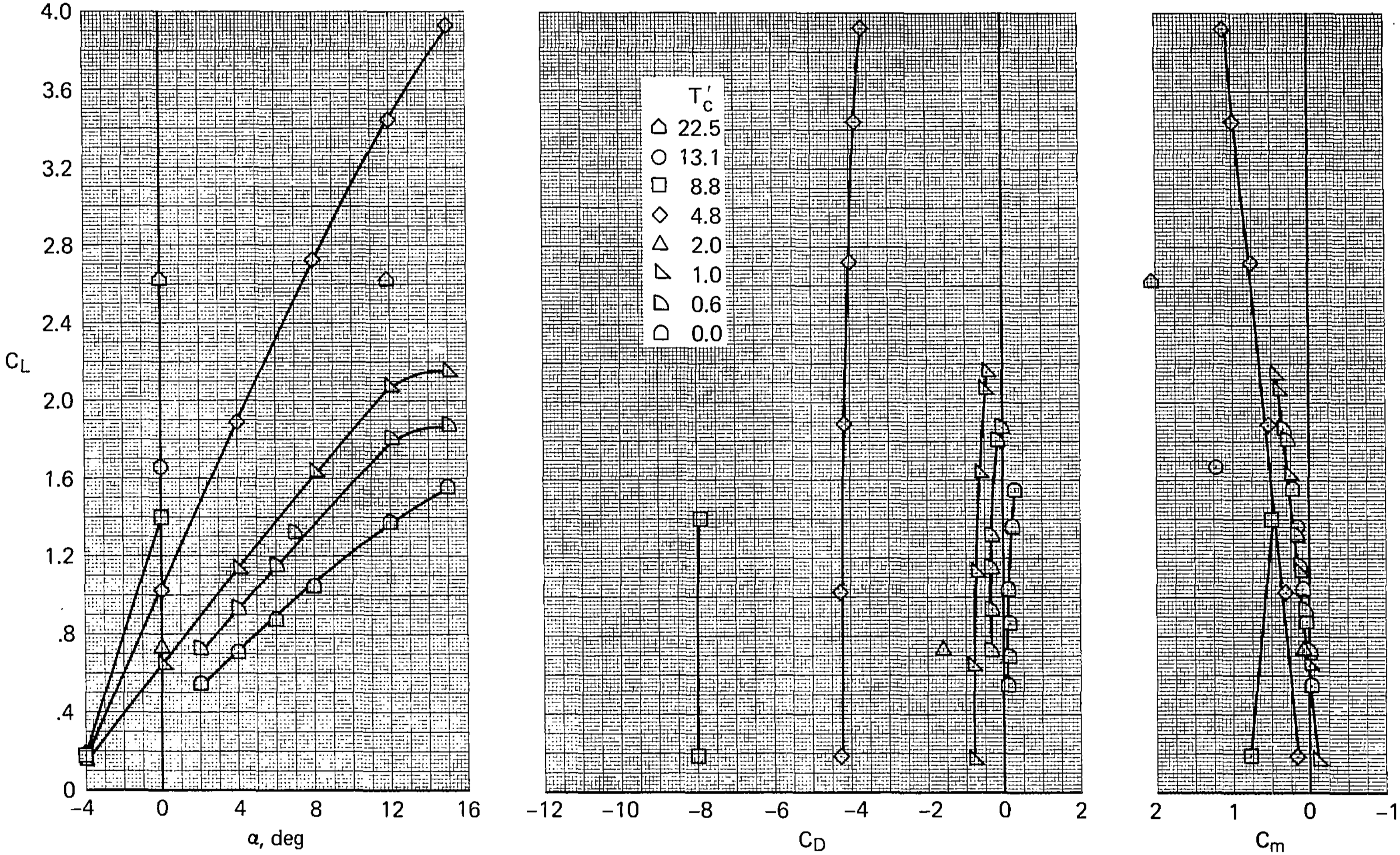
(g) $\delta_1/\delta_1/\delta_D$ = 30°/30°/2°

Figure 8.- Continued.



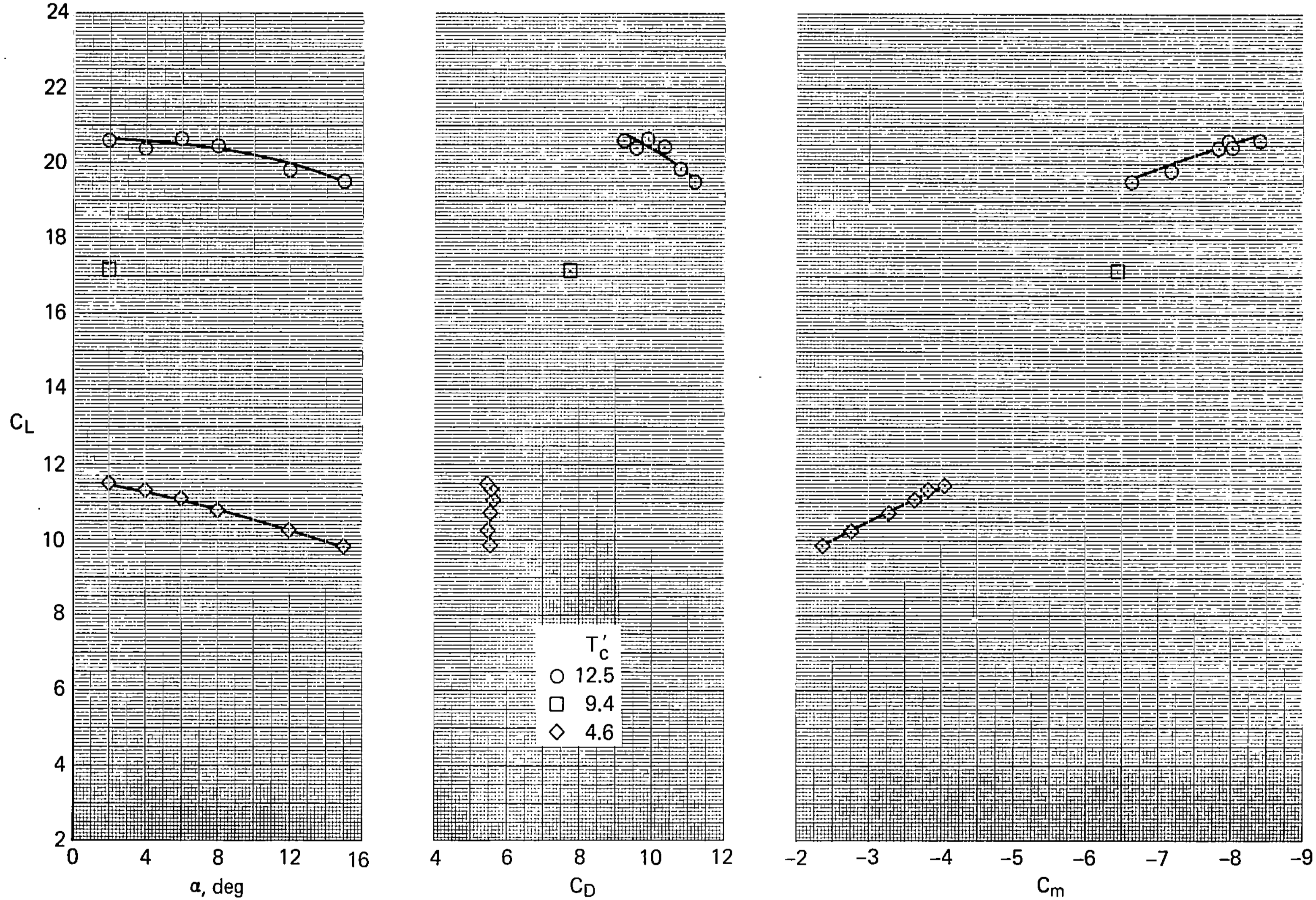
(h) $\delta_1/\delta_2/\delta_D$ = 0°/0°/-3°

Figure 8.- Continued.



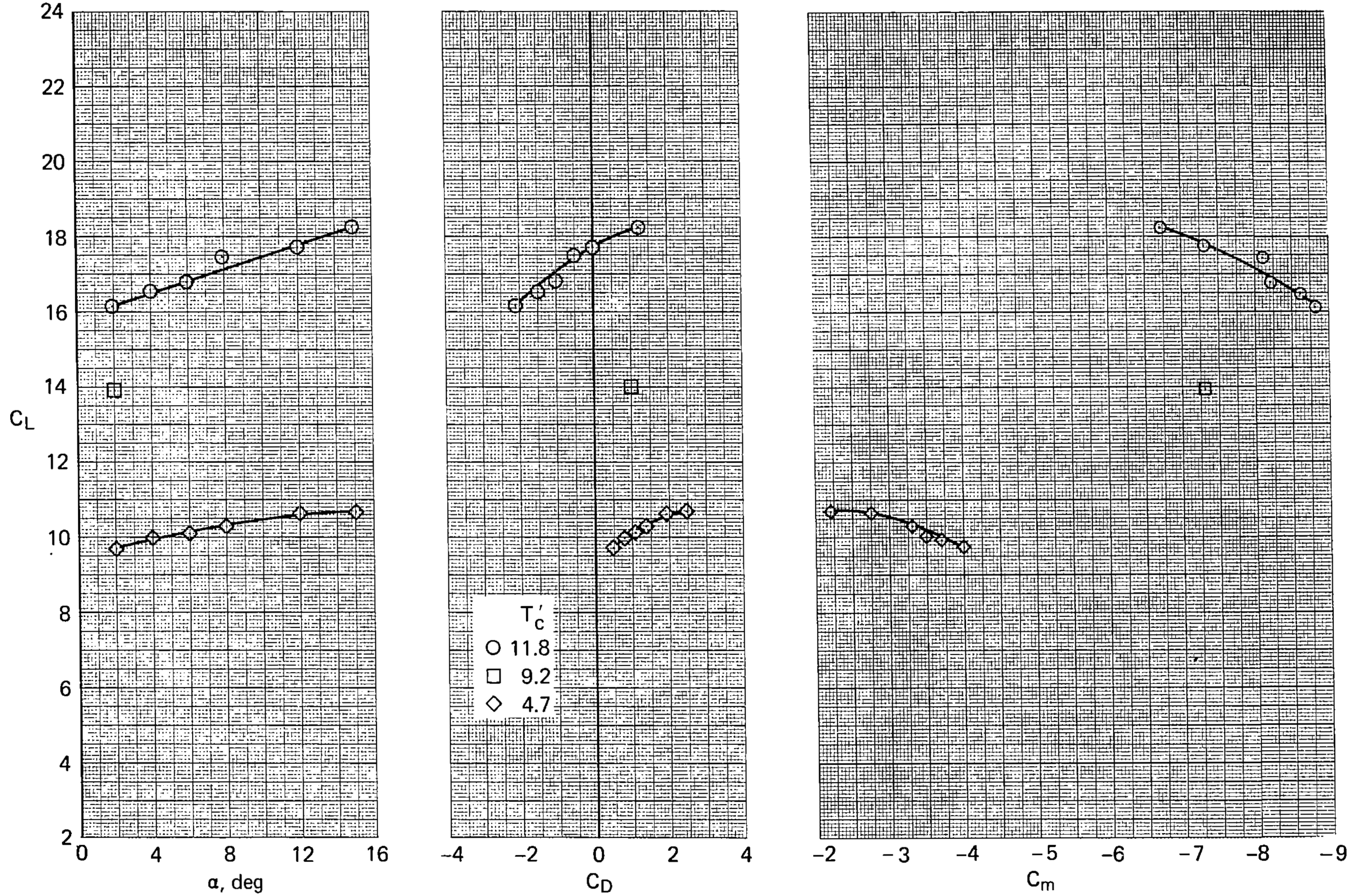
(i) $\delta_1/\delta_2/\delta_D = 0°/0°/2°$

Figure 8.- Concluded.



(a) $\delta_1/\delta_2/\delta_D = 40°/40°/90°$

Figure 9.- Longitudinal aerodynamic characteristics for various flap deflections for model with auxiliary wing extension and two ducted fans.



(b) $\delta_1/\delta_2/\delta_D = 30°/30°/45°$

Figure 9.- Concluded.

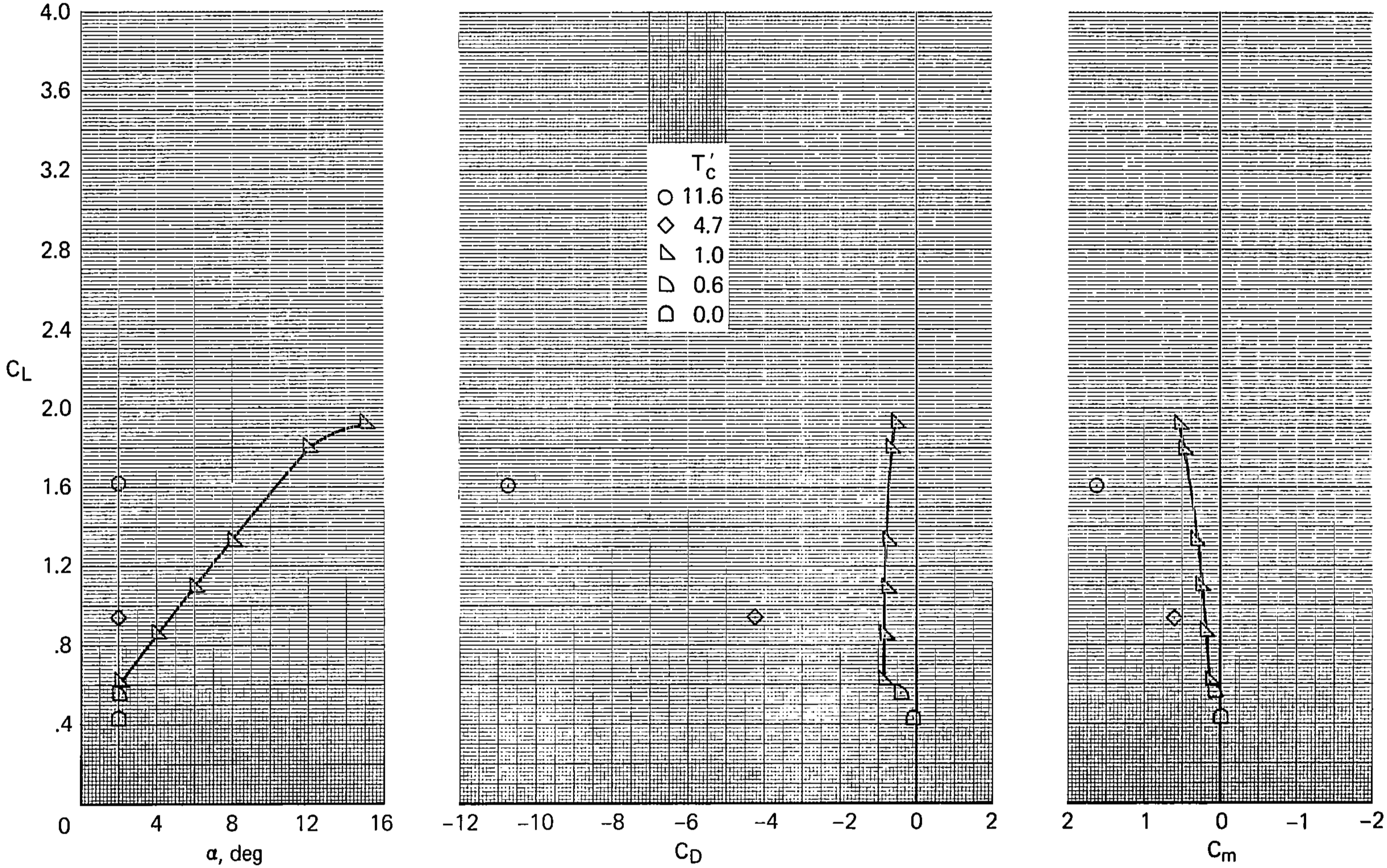
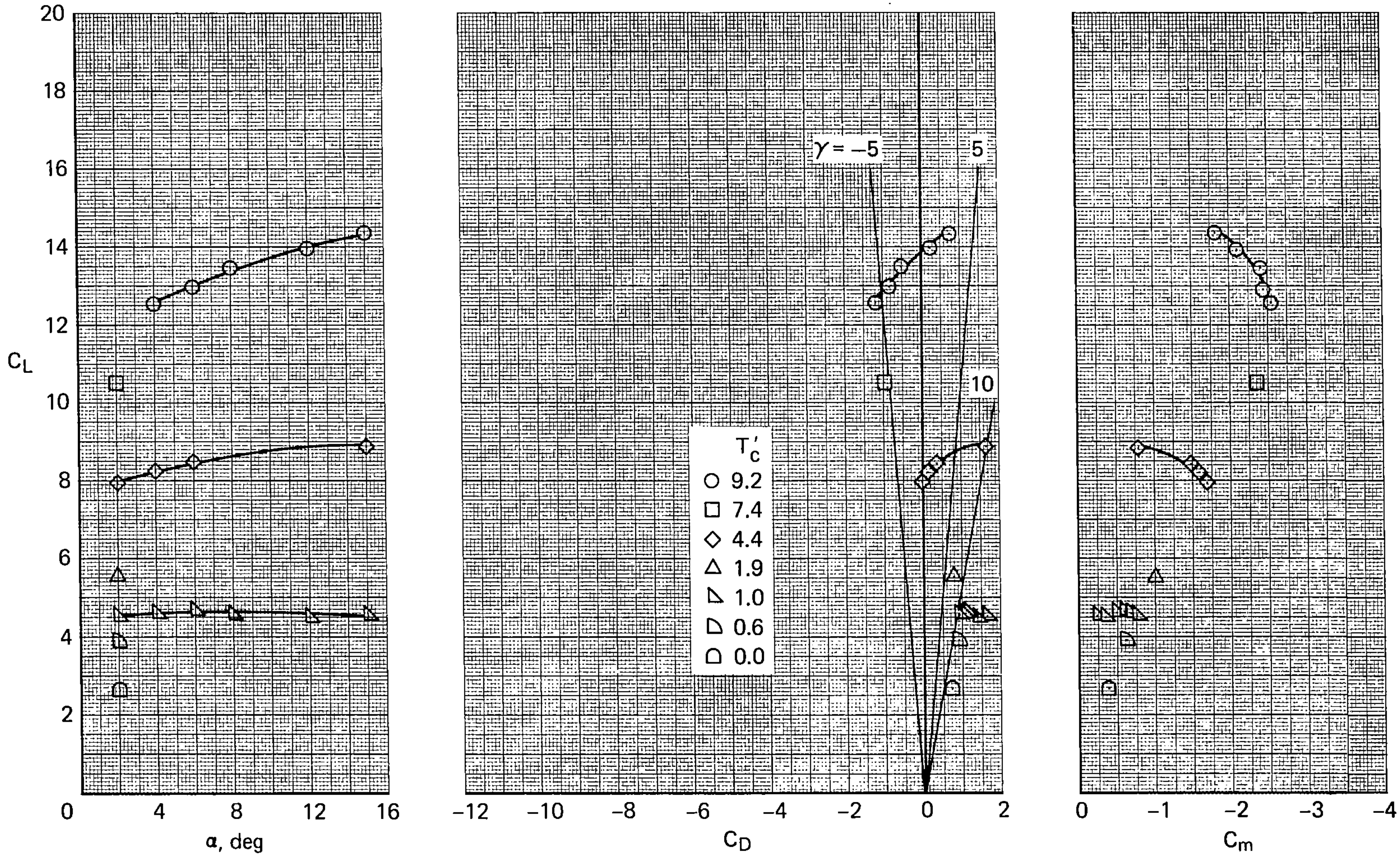
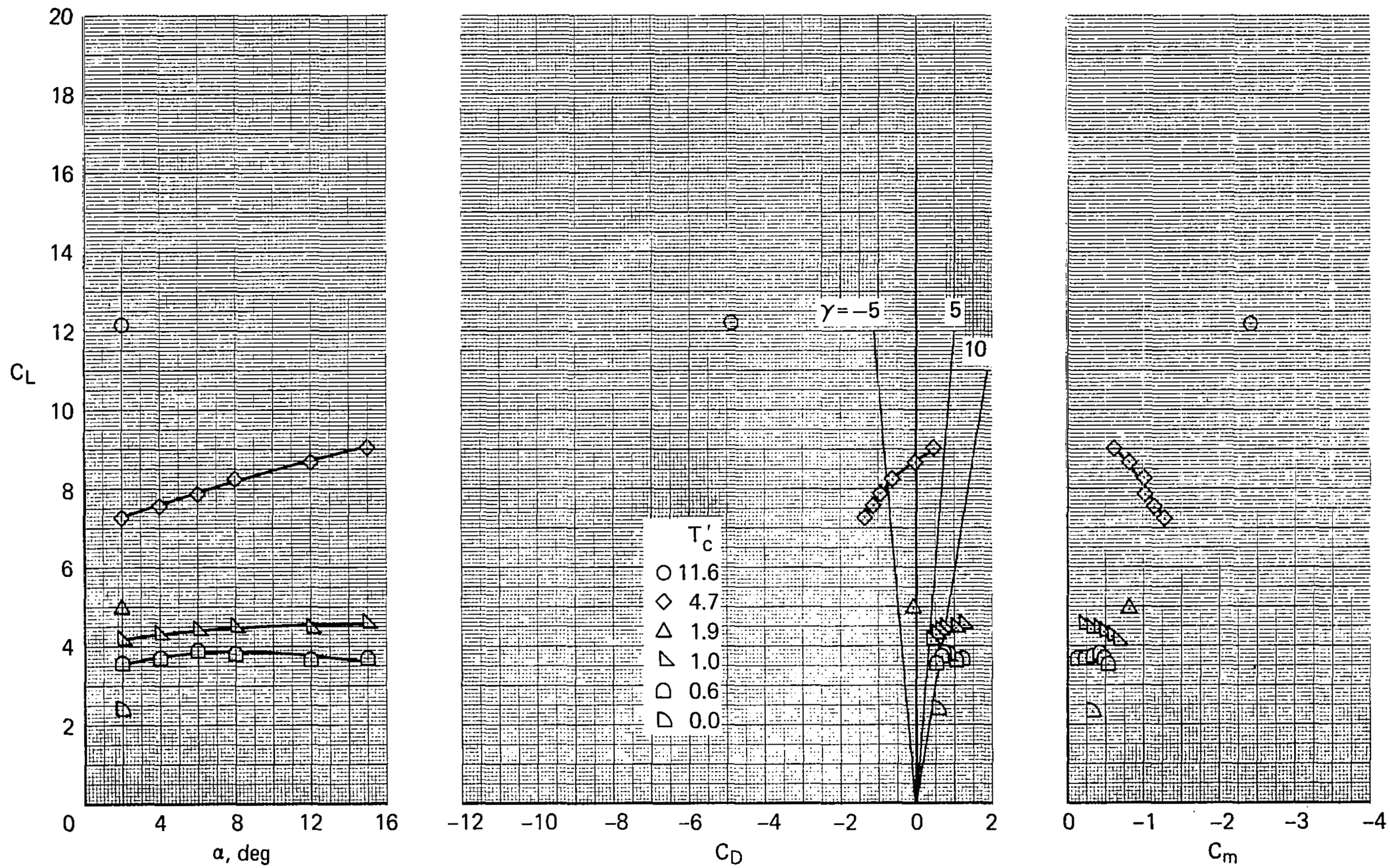


Figure 10.- Longitudinal aerodynamic characteristics for various thrust coefficients for model with auxiliary wing struts only and two ducted fans; $\delta_1/\delta_2 = 0°/0°$.



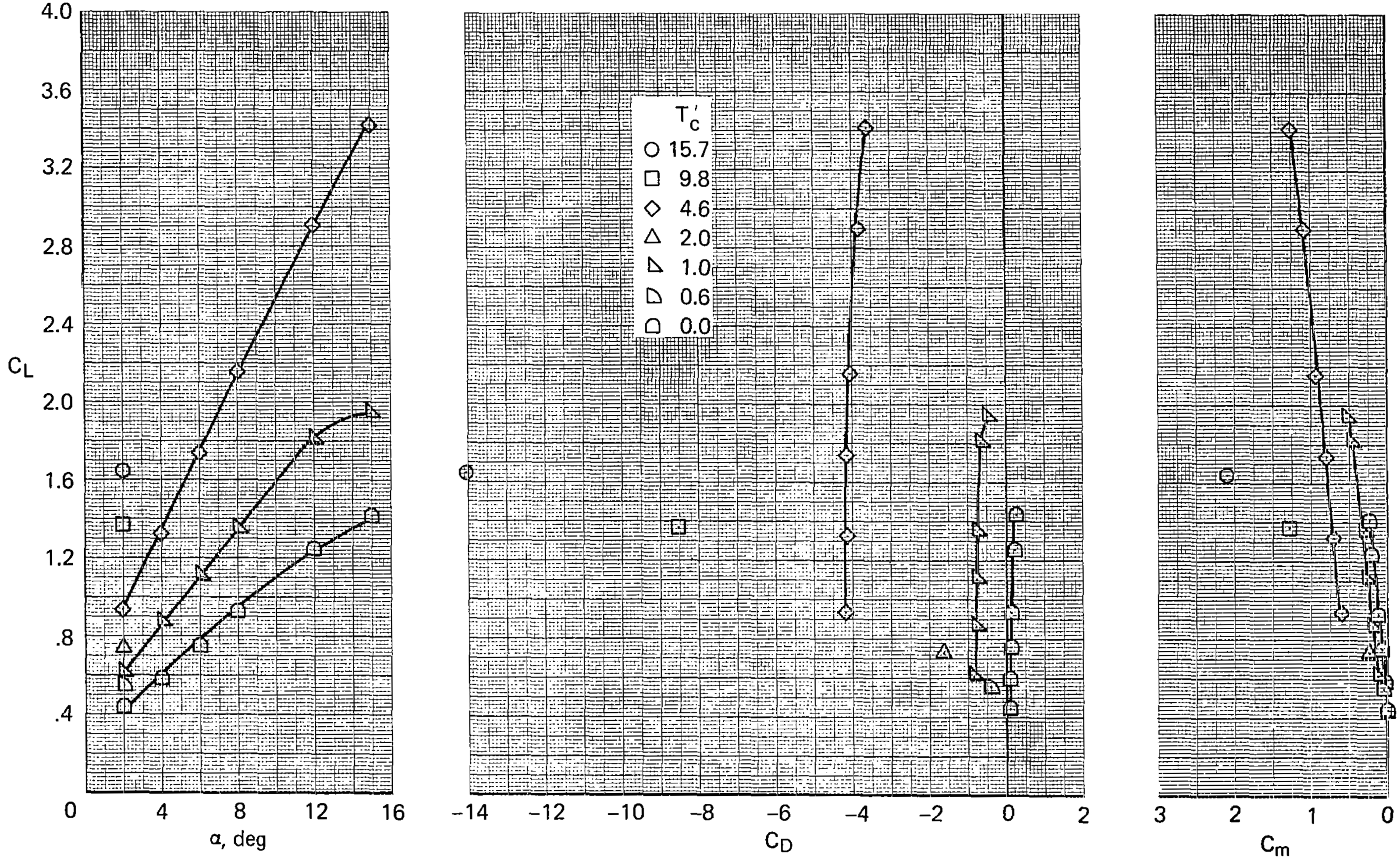
(a) $\delta_1/\delta_2 = 40°/40°$

Figure 11.- Longitudinal aerodynamic characteristics for various flap deflections for model with auxiliary wing removed and two ducted fans.



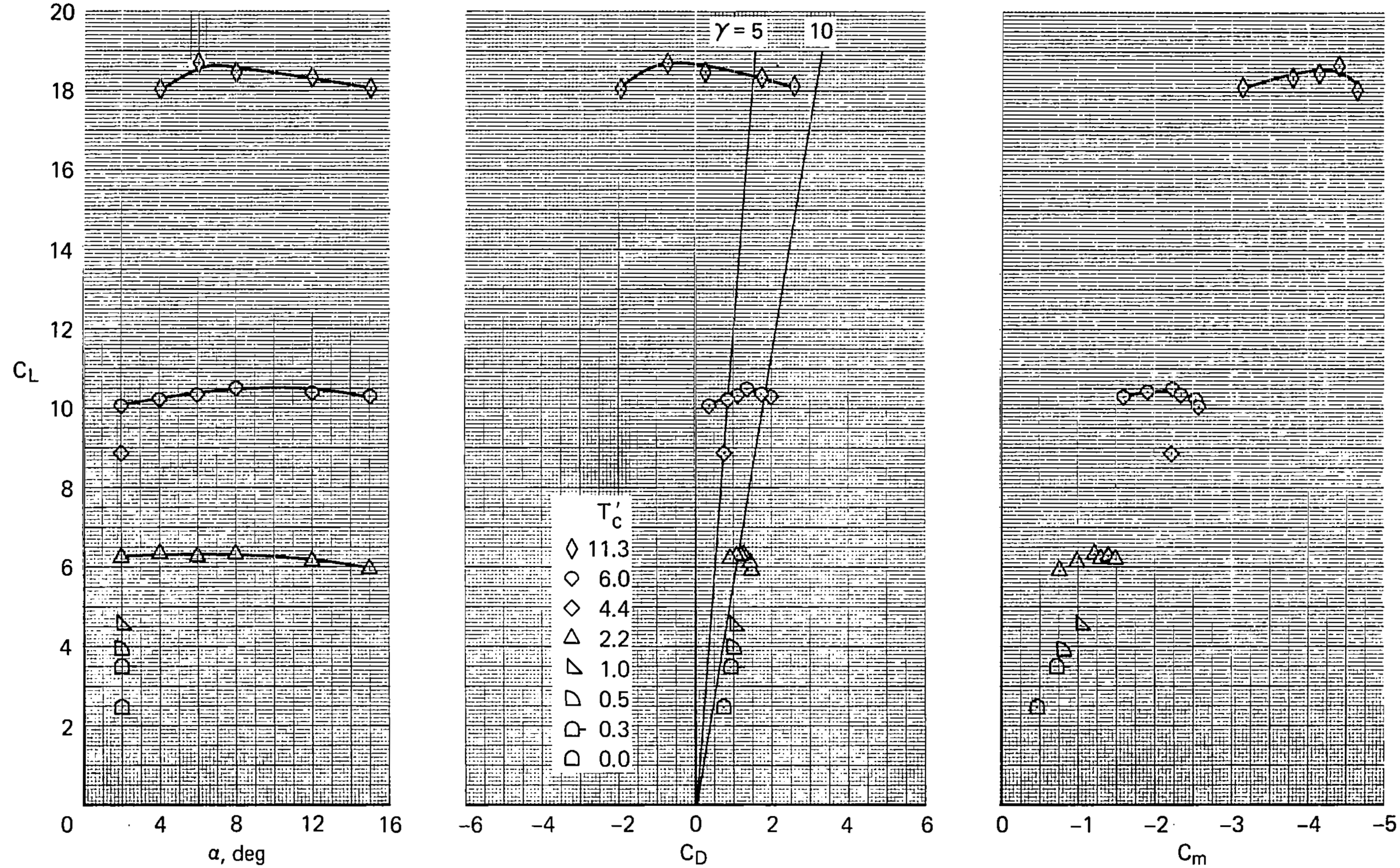
(b) δ_1/δ_2 = 30°/30°

Figure 11.- Continued.



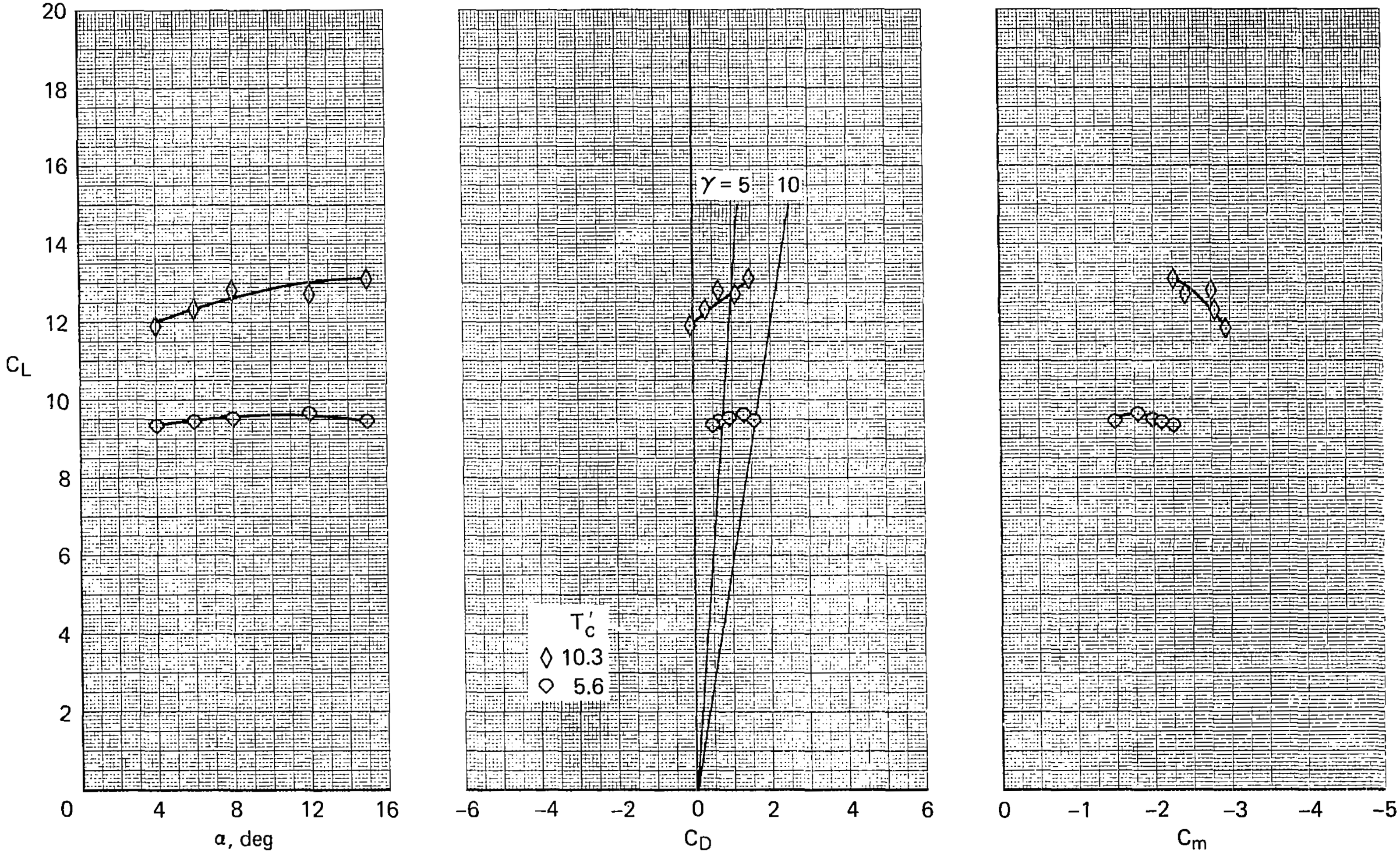
(c) $\delta_1/\delta_2 = 0°/0°$

Figure 11.- Concluded.



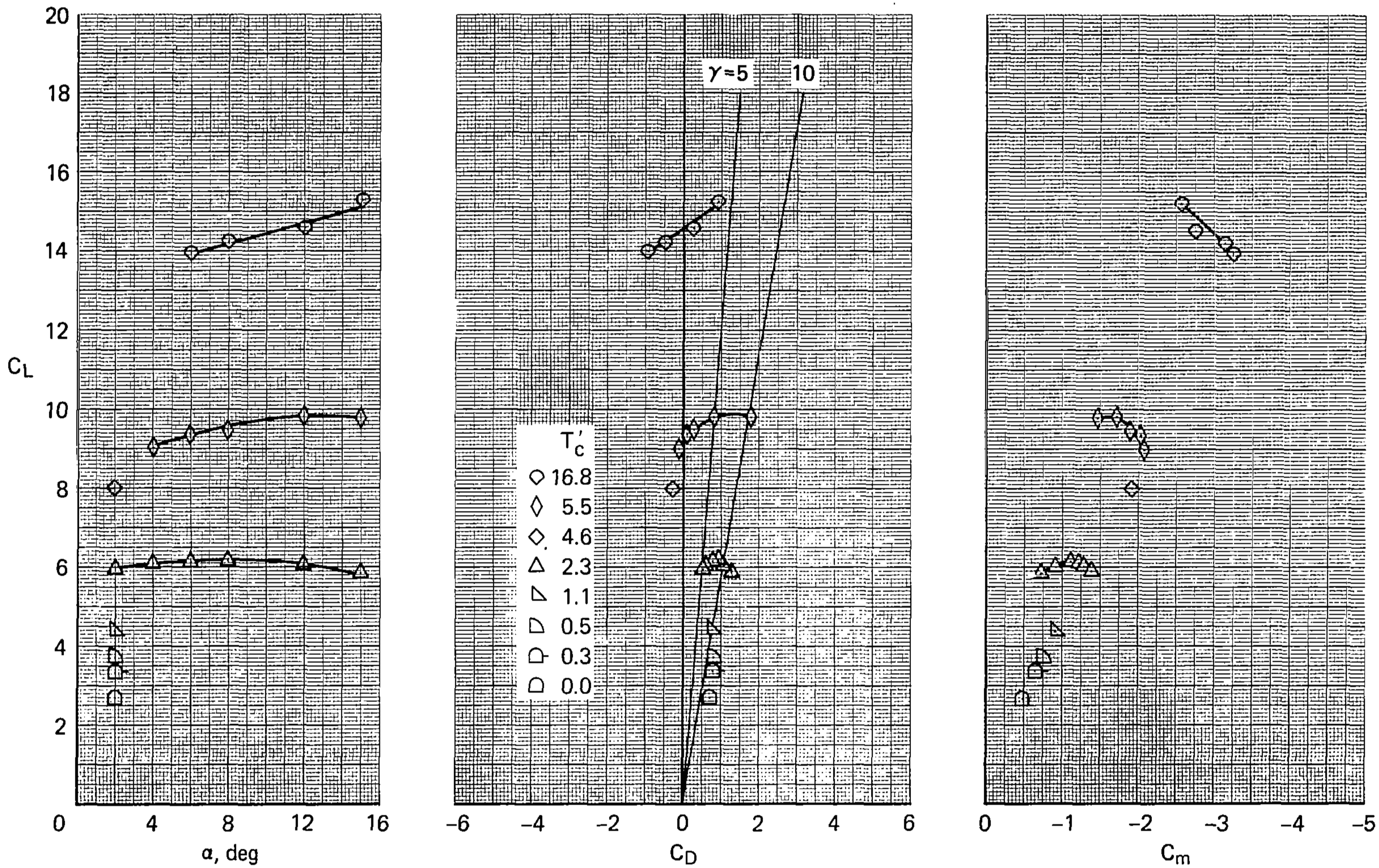
(a) $\delta_1/\delta_2 = 50°/40°$

Figure 12.- Longitudinal aerodynamic characteristics for various flap deflections for model with auxiliary wing and outboard ducted fan removed.



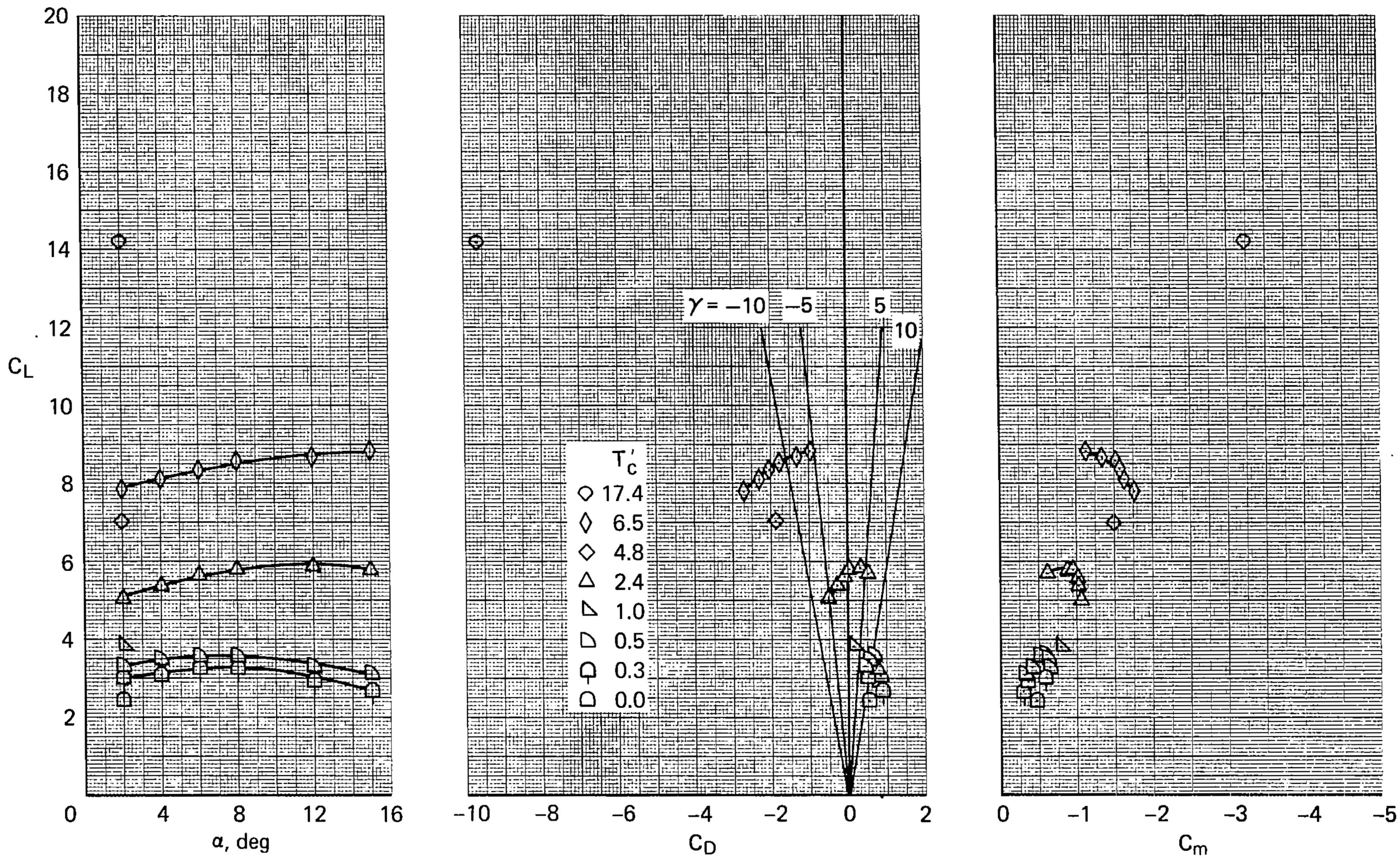
(b) $\delta_1/\delta_2 = 40°/50°$

Figure 12.- Continued.



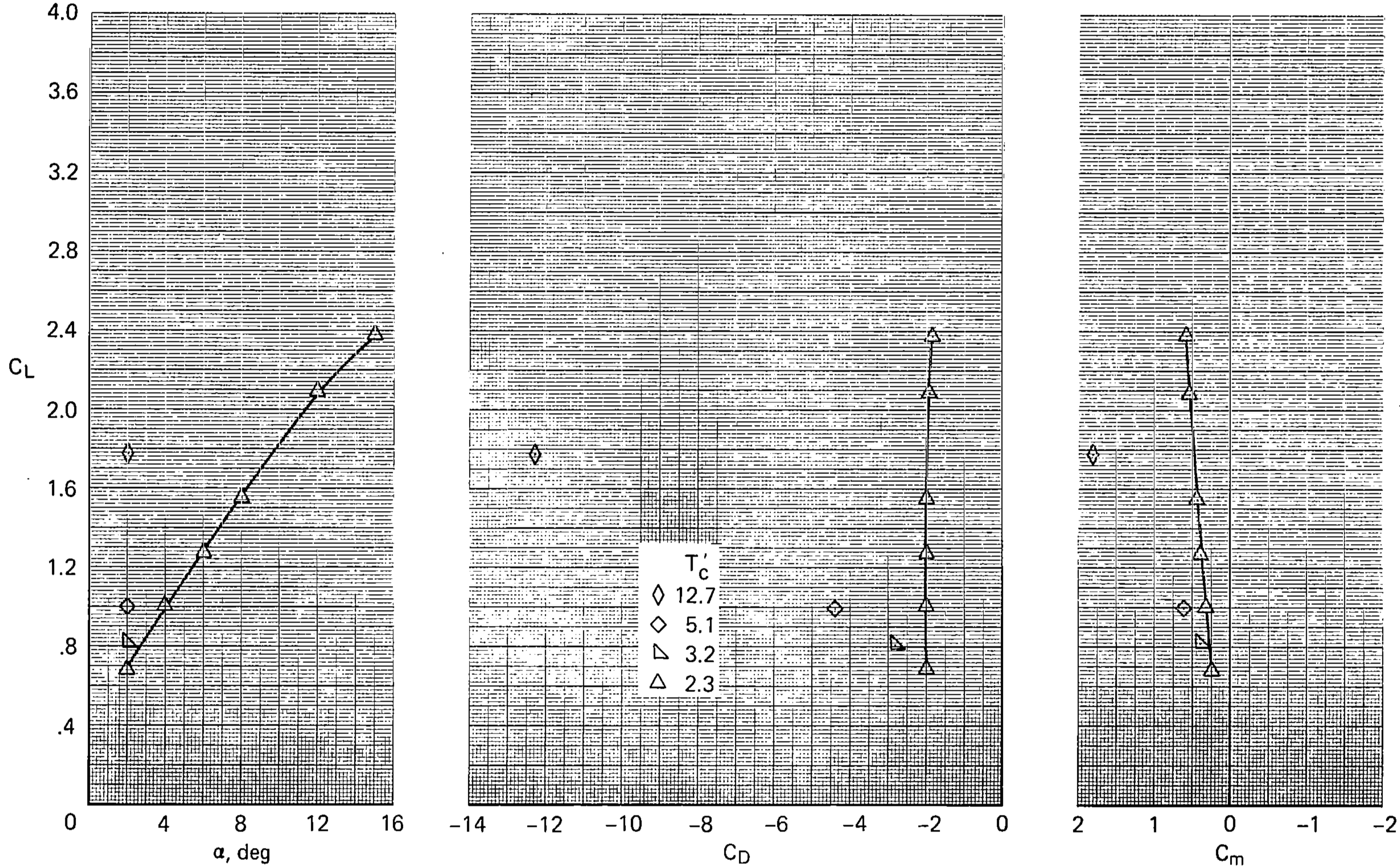
(c) δ_1/δ_2 = 40°/40°

Figure 12.- Continued.



(d) $\delta_1/\delta_2 = 30°/30°$

Figure 12.- Continued.



(e) $\delta_1/\delta_2 = 0°/0°$

Figure 12.- Concluded.

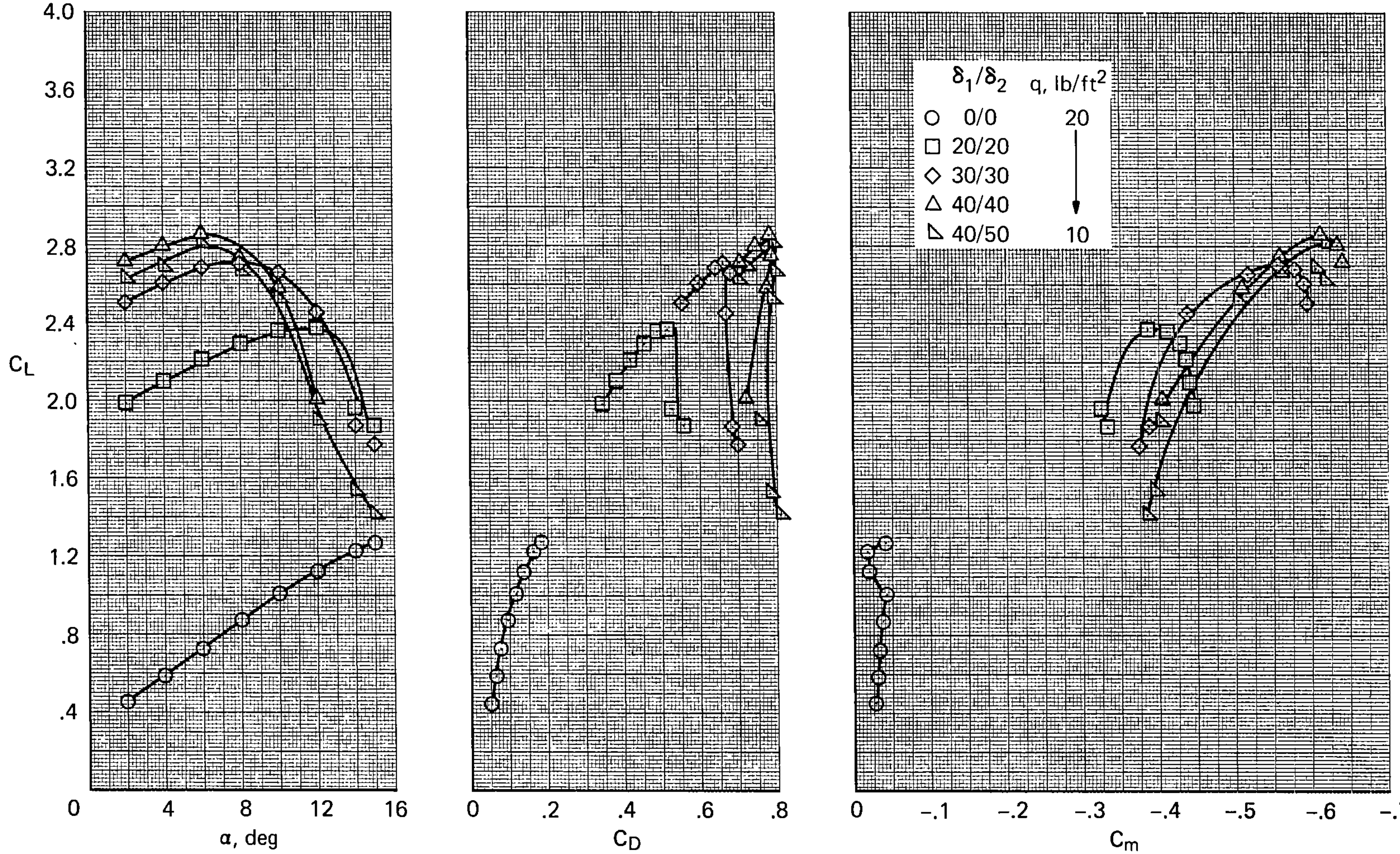
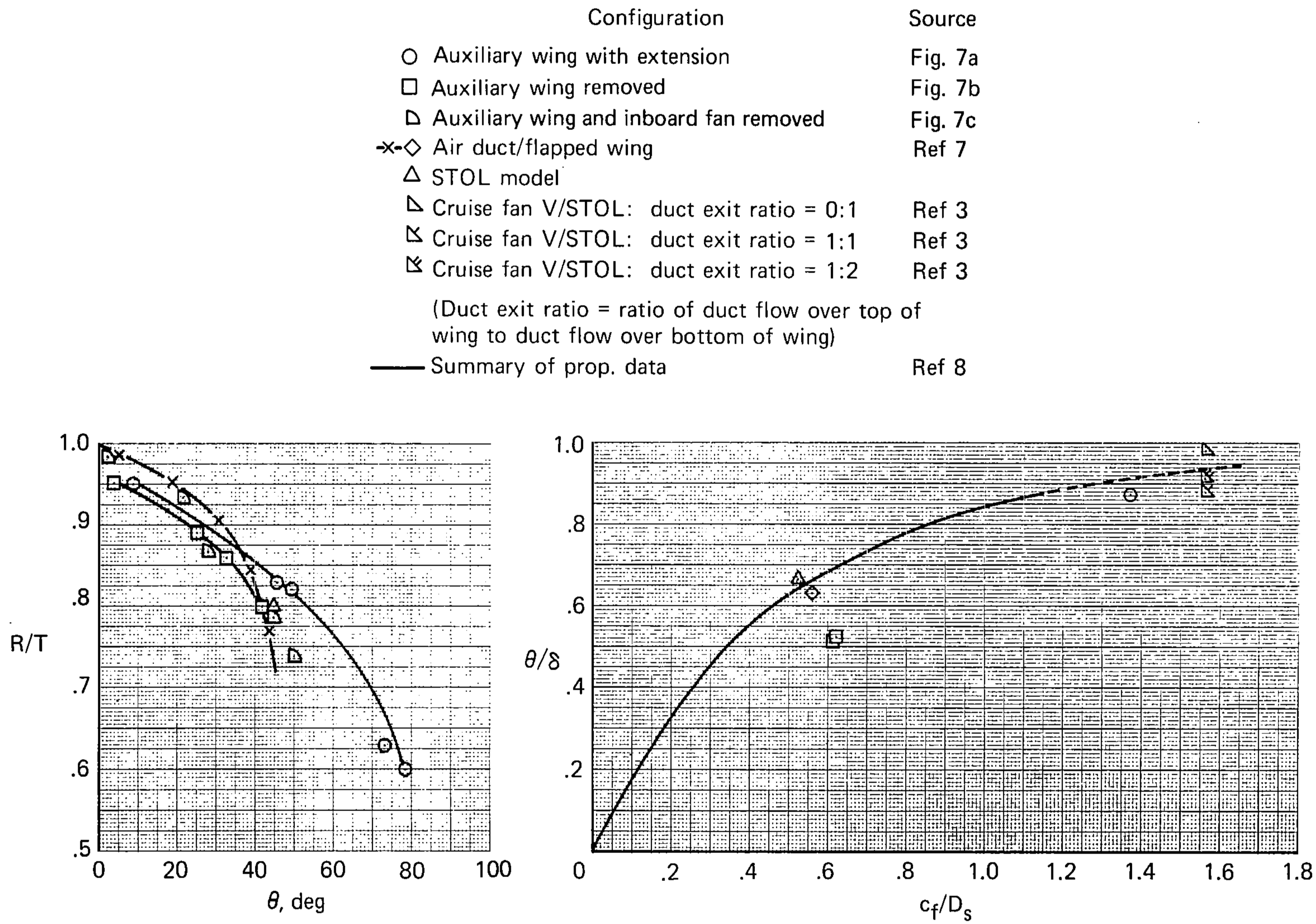


Figure 13.- Longitudinal aerodynamic characteristics for various flap deflections for model with auxiliary wing and both ducted fans removed.



(a) Variation of thrust recovery factor with turning angle.

(b) Variation of turning effectiveness with c_f/D_s.

Figure 14.- Summary of static performance.

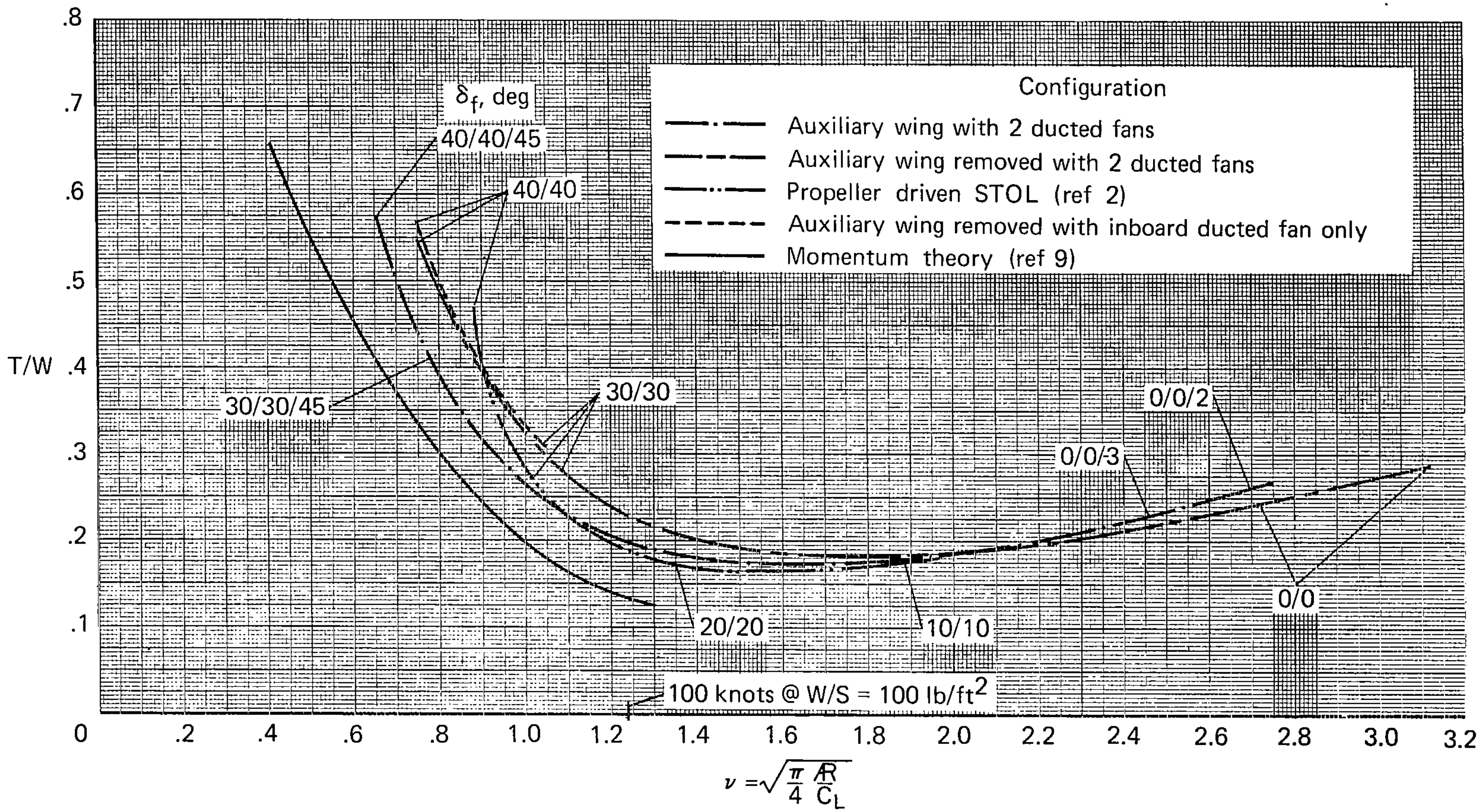


Figure 15.- Summary of transition performance; C_D = 0 and α = 2°.

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