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THE PLANING CHARACTERISTICS OF A V-SHAPED PRISMATIC SURFACE WITH 50 DEGREES DEAD RISE

by

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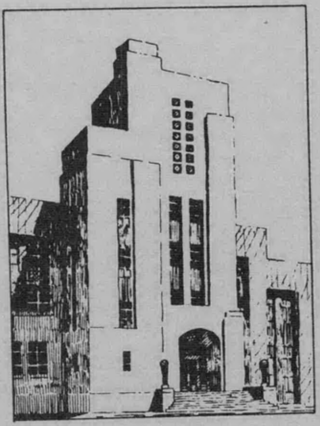
Clifford L. Sayre, Jr.



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Report 920

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NOTATION

b	Beam of planing surface, ft
C_f	Skin friction drag coefficient, $\dfrac{F}{\frac{\rho}{2} S_f V_m^2}$
C_R	Resistance coefficient, R/wb^3
C_V	Speed coefficient or Froude number, $V/\sqrt{gb}$
C_Δ	Load coefficient or beam loading, Δ/wb^3
C_{D_b}	Drag coefficient based on beam, $\dfrac{R}{\frac{\rho}{2} V^2 b^2} = \dfrac{2 C_R}{C_V{}^2}$
C_{D_s}	Drag coefficient based on principal wetted area, $\dfrac{R}{\frac{\rho}{2} V^2 S} = \dfrac{C_{D_b}}{\frac{l_m}{b}}$
C_{L_b}	Lift coefficient based on beam, $\dfrac{\Delta}{\frac{\rho}{2} V^2 b^2} = \dfrac{2 C_\Delta}{C_V{}^2}$
C_{L_s}	Lift coefficient based on principal wetted area, $\dfrac{\Delta}{\frac{\rho}{2} V^2 S} = \dfrac{C_{L_b}}{\frac{l_m}{b}}$
d	Draft, ft
F	Friction, parallel to planing surface, lb
g	Acceleration due to gravity, 32.155 ft/sec^2
l_c	Chine wetted length, ft
l_k	Keel wetted length, ft
l_m	Mean wetted length, $\dfrac{l_c + l_k}{2}$, ft
l_p	Center-of-pressure location (measured along keel forward of trailing edge), $\dfrac{M}{\Delta \cos \tau + R \sin \tau}$, ft
M	Trimming moment about trailing edge of model at keel, ft-lb
R	Horizontal resistance, lb
Re	Reynolds number, $\dfrac{V_m l_m}{\nu_m}$

S	Principal wetted area (bounded by trailing edge, chines, and heavy spray line) projected on plane parallel to keel, $l_m b$, sq ft
S_f	Actual wetted area aft of stagnation line, sq ft
V	Horizontal velocity, ft/sec
V_m	Mean velocity over planing surface, ft/sec
w	Specific weight of water, lb/cu ft
β	Angle of dead rise, deg
Δ	Vertical load, lb
ν	Kinematic viscosity, ft^2/sec
ρ	Mass density of water, slugs/cu ft
τ	Trim (angle between keel and horizontal), deg

ABSTRACT

This report is one of a series on the experimental investigation of the planing characteristics of a series of related prismatic surfaces.

The principal planing characteristics have been obtained for a V-shaped prismatic surface having an angle of dead rise of 50 deg. Wetted lengths, resistance, and center-of-pressure location were determined at speed coefficients up to approximately 20.0, beam-loading coefficients from 0.87 to 71.51, and trims up to 30 deg. Keel-wetted-length–beam ratios were extended to approximately 8.0 in all cases where excessive loads or excessive spray conditions were not encountered.

The data obtained indicate that the important planing characteristics are independent of speed and load for a given trim and are dependent primarily upon lift coefficient. The difference between keel wetted length and chine wetted length is constant for a given trim angle and the variation of this difference with trim has the same general trend as indicated by theory. For practical purposes the ratio of center-of-pressure location forward of the trailing edge to the mean wetted length is a constant equal to 0.58 and is independent of trim angle. The drag data indicate that the friction-drag component is a large percentage of the total drag at the low trims, but decreases rapidly with increase in trim to a small percentage at the higher trims.

INTRODUCTION

The National Advisory Committee for Aeronautics and the David Taylor Model Basin have undertaken an experimental investigation of the planing characteristics of a series of related prismatic surfaces. The primary objective of this program is an extension of the range of experimental data on planing surfaces to cover the high trims, loads, and wetted lengths which are important in the design of high-speed boats and water-based aircraft.

A testing program was established to include basic angles of dead rise up to 70 deg, trims up to 30 deg, wetted-length–beam ratios up to 7.0, and Froude numbers, based on beam, up to 25.0. The principal planing characteristics to be determined for appropriate combinations of speed, load, and trim were resistance, center of pressure, and wetted lengths. In addition to straight V-shaped cross sections of fundamental interest, modified sections with horizontal chine flare and with vertical chine strips were included. The detailed specifications for the test program were set forth by the NACA in Reference 1.*

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*References are listed on page 8.

This report presents the hydrodynamic force data for a V-shaped planing surface having an angle of dead rise of 50 deg. Similar data for other surfaces in this test program are presented in References 2 to 6.

DESCRIPTION OF MODEL

A photograph of the model is shown in Figure 1 and a cross section showing the pertinent dimensions is presented in Figure 2. The model is made of brass, has a beam of 4 in., and a dead rise angle of 50 deg. The length, exclusive of the sheet-metal fairing on the bow, is 36 in.

The planing bottom of the model was machined to a tolerance of ±0.002 in. and polished to a finish corresponding to the finish of the "A" block in the General Electric Standard Roughness Specimen set. This finish was maintained throughout testing by daily polishing. The bottom was also machined longitudinally straight to a tolerance of ±0.005 in. and the chines and keel were machined knife-sharp. The agreement of subsequent check data with that obtained early in the testing program indicates that any reduction in sharpness of the keel and chines produced by daily polishing did not affect the results.

APPARATUS AND PROCEDURES

GENERAL

The test program was conducted in the high-speed basin on Carriage 3. A brief description of the basin and carriage is given in Reference 7. The apparatus for towing the model and the instrumentation for measuring the lift, drag, and trimming moment are similar to that described in Reference 8. A diagram of the model and towing gear is presented in Figure 3.

WETTED LENGTH AND AREA

The wetted areas were determined from underwater photographs. The apparatus used to obtain the photographs is illustrated in Figure 4. The camera was placed in a watertight box with a lucite top and located in the center of the basin. As the model passed over the camera, the shutter was opened and then closed by photocell units. The three kodatron lamps, which illuminated the model, were actuated by an electrical contact. The presence of the box, which was about 48 in. (12 model beams) under the undisturbed water surface, had no measurable effect on the hydrodynamic forces acting on the planing surface.

The requirement of a highly polished metal surface precluded the use of painted or scribed grids on the model for measuring wetted length. In order to make this measurement, a wood model with painted grids was photographed at each trim with the underwater camera. A plot of wetted-length–beam ratio (as measured on the photographs) versus true wetted length (as determined from the grid) was made for each trim, and these plots were used to determine the wetted lengths of the brass model. A typical underwater photograph of the brass model is shown in Figure 5.

The wetted lengths were arbitrarily measured from the trailing edge to the intersection of the keel and chines with the heavy spray line as shown in Figure 5. This spray line was essentially straight from keel to chine throughout the range of the tests, and the mean wetted length was therefore the average of the keel and chine wetted lengths. The principal wetted area, analogous to wing area in aerodynamics, was then taken as the area aft of the spray line projected in a plane parallel to the keel, or the mean wetted length times the beam. The area wetted by light spray forward of the heavy spray line was not included in the principal wetted area since it is assumed that this area does not contribute appreciably to the lift force and should not be included in the fundamental lift coefficient C_{L_s}.

DRAFT

Reference 1 specified that draft should be calculated from the trim and the precisely-determined wetted length at keel. Accordingly, draft was not measured directly, but should be calculated from the relationship $d = l_k \sin \tau$. In Reference 6 some measured values of draft for V-shaped prismatic surfaces having angles of dead rise of 20 deg and 40 deg are compared with the values computed from the keel wetted length. At the high trims the measured values of draft are slightly lower than the calculated values. This difference is evidently caused by some pile-up of water at the keels of the models. It is assumed that a similar effect exists for the 50-deg dead rise surface and that the calculated values of draft will therefore be slightly high at the high trims.

A careful survey of the water surface in the test area indicated no appreciable gradient in height due to the towing carriage or wind screen.

AERODYNAMIC TARES

The aerodynamic forces on the model and towing gear were held to a minimum by the use of a wind screen housing the test section of the towing carriage. The wind screen, which was constructed of 1/16-in. aluminum, was similar in shape to that described in Reference 2. Curved spray shields were installed on both sides of the test area to prevent spray from striking the towing carriage.

The residual windage tares were determined by making a series of runs at various speeds with the model barely clearing the surface of the water. The tares for drag, load, and moment were found to be negligible over the speed range.

PRECISION

The quantities measured are generally believed to be accurate within the following limits:

Load, lb	±0.15
Resistance, lb	±0.15
Trimming moment, ft-lb	±0.50
Wetted length, in.	±0.25
Trim, deg	±0.10
Speed, ft/sec	±0.20

TEST PROGRAM

The basic schedule of points for which the data were obtained is shown in Figure 6. The schedule was bounded by the maximum load limit of the apparatus, the maximum speed of the towing carriage, and the curve representing the maximum value of 0.5 of the parameter $\sqrt{C_\Delta}/C_V$. Combinations of load and speed within the boundaries were selected to correspond to approximately equal increments of $\sqrt{C_\Delta}/C_V$.

The measurements were made at trims of 2, 4, 6, 9, 12, 18, 24, and 30 deg. At each trim, the basic schedule was followed up to loads where the keel-wetted-length–beam ratio exceeded 8.0 or spray on the apparatus became unacceptable.

Supplementary combinations of speed and load were used as required to define variations of the measurements with speed, load, and trim.

RESULTS AND DISCUSSION

TABULAR DATA

The experimental data obtained for all planing conditions where the chines were wetted are presented in Table 1. The corresponding data for the chine-dry condition have been omitted, since in this condition the precision of measurement became marginal for the size of model used. For this reason, no data for 2-deg trim angle appear in Table 1.

The load, resistance, speed, wetted lengths, and center of pressure are expressed as conventional nondimensional hydrodynamic coefficients based on beam. The lift and drag coefficients are expressed both in terms of the square of the beam and the principal wetted area. Both forms are included because the former has been used universally in the literature on planing and the latter is analogous to the fundamental coefficients of aerodynamic lifting elements.

ANALYSIS

During planing, where forces due to buoyancy are negligible, the dynamic planing characteristics would be expected to be primarily functions of lift coefficient and trim. The data in Table 1, therefore, were plotted against C_{L_b} with trim as a parameter.

In general, the experimental data when plotted against C_{L_b} group along a single curve for each trim. This "collapsing" indicates the independence of the data from speed and load. Because of the simple relation between C_{L_b} and C_{L_s} when the chines are wetted, $(l_m/b)\, C_{L_s} = C_{L_b}$, corresponding curves of collapsed data against C_{L_s} may be easily constructed when the use of the more fundamental lift coefficient is preferable.

Wetted Length

The variation of the mean-wetted-length–beam ratio with C_{L_b} is shown in Figure 7. For a given value of C_{L_b}, the mean-wetted-length–beam ratio increased with decrease in trim and at low trims the wetted length increased rapidly with a small increase in C_{L_b}.

The relation between the chine-wetted-length–beam ratio l_c/b and the keel-wetted-length–beam ratio l_k/b is shown in Figure 8. The difference between the chine wetted length and the keel wetted length is constant for a given trim. By definition a similar variation necessarily holds for the relation between the mean wetted length and the keel wetted length.

The variation of the difference between the keel and chine wetted lengths with trim is shown in Figure 9. The variation predicted by the two-dimensional theory of Wagner, as applied in Reference 9, is also shown. The experimental curve is in reasonable agreement with the theoretical curve, although its absolute values fall somewhat below those of the theoretical curve.

Center of Pressure

The center-of-pressure location l_p is defined as the distance from the trailing edge to the intersection of the resultant hydrodynamic force vector with the keel of the model. A plot of center-of-pressure location in beams against C_{L_b} is presented in Figure 10. Since for a given trim all the data for different loads and speeds form a single curve against C_{L_b}, it follows that l_p/b is independent of speed and load and is dependent only on lift coefficient.

Figure 11 presents plots of l_p/b against l_m/b for each of the trim angles. The ratio of center-of-pressure location to mean wetted length is a constant equal to 0.58 for trims of 9, 12, 18, 24, and 30 deg. The data obtained indicate a slightly higher value of the ratio for 4-deg and 6-deg trim. (In contradistinction, the data of Reference 6 indicate that for dead rise angles of 20 deg and 40 deg, the ratio l_p/l_m is constant at the low trims and decreases at high trims.)

Buoyancy

It was reported in References 2 to 6 that some of the light-load and low-speed planing conditions at the lower trims were strongly influenced by buoyancy. The data obtained for those conditions did not fit the curve for which C_{L_b} is the governing parameter. The results indicated that for a 40-deg dead rise surface the bulk of the conditions affected are those for which buoyancy, based on the displaced volume, equals at least 20 percent of the load. Accordingly, in Reference 6 all data for the 40-deg dead rise planing surface were omitted where buoyancy exceeded 20 percent of the total load. Corresponding effects were noted for the data of the 50-deg dead rise planing surface, and accordingly, in the present report, test conditions where buoyancy exceeded 20 percent of the total load were considered nonplaning and are not included.

Resistance

The drag coefficients from Table 1 are plotted against lift coefficient in Figure 12. The data for the various speeds and loads collapse into a single straight line through the origin for each trim.

The total drag of a prismatic planing surface is made up of the horizontal components of the normal force or induced drag and the friction force. The induced drag coefficient for the clean-planing condition at each trim is represented in Figure 12 by a dashed line with slope equal to the tangent of the trim angle. The difference between the total and induced drag coefficients is the friction drag coefficient. At low trims the friction drag is seen to be a large part of the total, whereas, at large trims it is almost negligible.

Skin-friction drag coefficients were calculated directly from the tabular data. The skin-friction drag coefficient was assumed to be

$$C_f = \frac{F}{\frac{\rho}{2} S_f V_m^2}$$

where F is the friction force parallel to keel, $R \cos\tau - \Delta \sin\tau$,

S_f is the actual wetted area aft of the stagnation line or $S/\cos\beta$, and

V_m is the mean speed over the surface.

The mean speed was assumed to be that given by Bernoulli's theorem for a surface streamline, with a uniform pressure on the model assumed equal to $\Delta/S \cos\tau$. Then V_m is given by

$$V_m^2 = V^2\left(1 - \frac{C_{L_b}}{\cos\tau \frac{l_m}{b}}\right)$$

and C_f may be shown to be

$$C_f = \cos\beta \cos\tau \frac{C_{D_b} - C_{L_b} \tan\tau}{\frac{l_m}{b} - \frac{C_{L_b}}{\cos\tau}}$$

The Reynolds number for the planing surface was assumed to be $V_m l_m / \nu_m$ where ν is the kinematic viscosity.

The results of the calculations for trims at which the friction is appreciable are plotted in Figure 13 together with the Schoenherr line[10] for fully turbulent boundary layer and the Blasius line for laminar flow on flat plates. Most of the coefficients for the lighter loads and lower Reynolds numbers were erratic because of the marginal accuracy. All conditions, therefore, where the precision of measurement changed the coefficient by more than 20 percent were omitted from this plot. The grouping of the data along the Schoenherr turbulent-flow line indicates that, at low trims and high Reynolds numbers, the friction drag can be calculated with reasonable accuracy by use of the Schoenherr equation.

CONCLUSIONS

The results obtained from an experimental investigation of a V-shaped planing surface having an angle of dead rise of 50 deg indicate that, during steady-state planing, the important planing characteristics are independent of speed and load for a given trim and are dependent only on lift coefficient. The difference between keel wetted length and chine wetted length is constant for a given trim angle and the variation of this difference with trim is shown to be in fair agreement with theory. For practical purposes the ratio of center-of-pressure location forward of the trailing edge to the mean wetted length is a constant equal to 0.58 and is independent of trim angle. The drag data indicate that the friction-drag component is a large percentage of the total drag at the low trims, but decreases rapidly with increase in trim to a small percentage at the higher trims.

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TABLE 1

Experimental Data Obtained for 50-deg Dead Rise Planing Surface

Average kinematic viscosity = 1.113×10^{-5} ft^2/sec; average specific weight of basin water = 62.29 lb/ft^3.

τ deg	C_Δ	C_V	C_R	$\frac{l_c}{b}$	$\frac{l_m}{b}$	$\frac{l_k}{b}$	$\frac{l_p}{b}$	C_{L_b}	C_{D_b}	C_{L_s}	C_{D_s}
4	2.17	14.70	1.97	0.40	3.04	5.68	2.16	0.0200	0.0182	0.0066	0.0006
4	4.33	13.93	3.29	3.23	5.82	8.40	3.57	.0447	.0339	.0077	.0058
4	4.33	19.60	3.94	1.15	3.63	6.10	2.34	.0226	.0205	.0062	.0056
4	6.50	19.60	5.29	2.35	4.88	7.40	3.06	.0339	.0276	.0069	.0057
6	2.17	9.80	1.00	1.20	2.93	4.65	1.77	.0451	.0208	.0154	.0071
6	4.33	13.93	2.04	1.35	3.04	4.73	1.89	.0447	.0210	.0147	.0069
6	6.50	12.74	2.84	3.43	5.18	6.93	3.00	.0801	.0350	.0155	.0068
6	6.50	17.02	3.12	1.35	3.04	4.73	1.95	.0449	.0215	.0148	.0071
6	6.50	19.60	3.29	0.68	2.37	4.05	1.83	.0339	.0171	.0143	.0072
6	6.50	19.60	3.38	0.65	2.40	4.15	1.62	.0339	.0176	.0141	.0073
6	8.67	19.60	4.18	1.30	3.07	4.83	2.01	.0452	.0218	.0147	.0071
6	10.84	16.46	4.83	3.73	5.41	7.08	3.21	.0800	.0356	.0148	.0066
6	10.84	19.60	5.03	2.20	3.93	5.65	2.22	.0565	.0262	.0144	.0067
6	10.84	19.60	5.07	2.18	3.94	5.70	2.52	.0565	.0264	.0143	.0067
6	10.84	19.60	5.09	2.23	3.92	5.60	2.46	.0565	.0265	.0144	.0068
6	15.17	19.45	6.85	4.05	5.77	7.48	3.42	.0802	.0362	.0139	.0063
9	0.87	6.20	0.20	0.20	1.28	2.35	1.41	.0451	.0101	.0352	.0079
9	2.17	7.35	0.48	1.25	2.32	3.38	1.29	.0803	.0177	.0346	.0076
9	2.17	9.82	0.59	0.35	1.40	2.45	0.84	.0449	.0121	.0321	.0086
9	4.33	13.91	1.37	0.43	1.51	2.58	0.93	.0448	.0142	.0297	.0094
9	4.33	13.92	1.41	0.40	1.48	2.55	0.96	.0447	.0146	.0302	.0099
9	6.50	10.19	1.99	2.88	3.98	5.08	2.28	.1253	.0383	.0315	.0096
9	6.50	10.25	1.97	2.90	3.95	5.00	2.31	.1237	.0375	.0313	.0095
9	6.50	12.79	2.04	1.48	2.57	3.65	1.65	.0794	.0249	.0309	.0097
9	6.50	17.02	2.21	0.40	1.49	2.58	0.96	.0449	.0152	.0301	.0102
9	6.50	19.60	2.30	0.03	1.13	2.23	0.87	.0339	.0120	.0300	.0106
9	8.67	19.60	3.12	0.13	1.18	2.23	0.99	.0452	.0163	.0380	.0138
9	10.84	11.02	3.40	4.65	5.72	6.78	3.42	.1785	.0560	.0312	.0098
9	10.84	13.16	3.55	3.13	4.19	5.25	2.55	.1251	.0410	.0299	.0098
9	10.84	13.20	3.49	3.03	4.11	5.18	2.46	.1244	.0401	.0303	.0098
9	10.84	16.44	3.71	1.55	2.67	3.78	1.59	.0802	.0275	.0300	.0103
9	10.84	19.45	3.68	0.83	1.94	3.05	1.29	.0573	.0195	.0295	.0101
9	15.17	19.35	5.03	1.58	2.68	3.78	1.65	.0810	.0269	.0302	.0100
9	15.17	19.50	5.09	1.58	2.64	3.70	1.68	.0798	.0268	.0302	.0102
9	19.50	14.72	6.39	5.28	6.38	7.48	3.64	.1800	.0590	.0282	.0092
9	19.50	17.67	6.41	3.15	4.27	5.38	2.59	0.1250	0.0411	0.0293	0.0096

TABLE 1 (Continued)

τ deg	C_Λ	C_V	C_R	$\frac{l_c}{b}$	$\frac{l_m}{b}$	$\frac{l_k}{b}$	$\frac{l_p}{b}$	C_{L_b}	C_{D_b}	C_{L_s}	C_{D_s}
9	19.50	19.35	6.44	2.35	3.45	4.55	2.08	0.1041	0.0344	0.0302	0.0100
9	28.17	17.75	9.27	5.33	6.44	7.55	3.77	.1789	.0589	.0278	.0091
9	28.17	19.60	9.23	4.08	5.19	6.30	3.11	.1468	.0481	.0283	.0093
9	36.84	19.60	12.14	5.83	6.96	8.08	4.07	.1919	.0632	.0276	.0091
12	0.87	4.65	0.22	0.63	1.41	2.18	0.60	.0803	.0201	.0570	.0143
12	2.17	5.91	0.52	1.48	2.24	3.00	1.17	.1242	.0298	.0554	.0133
12	2.17	7.38	0.54	0.80	1.59	2.38	0.81	.0796	.0199	.0501	.0125
12	4.33	13.91	1.17	0	0.84	1.68	0.51	.0448	.0121	.0533	.0144
12	6.50	8.51	1.82	2.75	3.55	4.35	2.07	.1795	.0503	.0506	.0142
12	6.50	10.16	1.73	1.65	2.45	3.25	1.44	.1260	.0335	.0514	.0137
12	6.50	10.21	1.71	1.68	2.48	3.28	1.35	.1248	.0328	.0503	.0132
12	6.50	12.74	1.76	0.75	1.59	2.43	0.87	.0801	.0217	.0504	.0136
12	10.84	9.39	3.21	4.10	4.92	5.73	2.79	.2460	.0728	.0500	.0148
12	10.84	10.94	3.29	2.83	3.68	4.53	2.19	.1811	.0550	.0492	.0149
12	10.84	13.21	3.32	1.75	2.53	3.30	1.47	.1242	.0380	.0491	.0150
12	10.84	16.52	3.36	0.83	1.61	2.38	1.08	.0795	.0246	.0494	.0153
12	10.84	19.60	3.47	0.35	1.19	2.03	0.84	.0565	.0181	.0475	.0152
12	15.17	19.45	4.77	0.88	1.67	2.45	1.11	.0802	.0252	.0480	.0151
12	19.50	12.64	6.00	4.60	5.30	6.00	3.03	.2441	.0751	.0461	.0142
12	19.50	14.70	6.07	2.93	3.79	4.65	2.25	.1804	.0561	.0476	.0148
12	19.50	17.70	6.15	1.70	2.52	3.33	1.56	.1244	.0392	.0494	.0156
12	19.50	19.60	6.15	1.23	2.01	2.78	1.26	.1016	.0320	.0505	.0159
12	23.84	19.60	7.50	1.75	2.55	3.35	1.59	.1242	.0391	.0487	.0153
12	28.17	16.63	8.88	3.08	3.94	4.80	2.34	.2037	.0642	.0517	.0163
12	28.17	19.60	8.75	2.28	3.08	3.88	1.89	.1468	.0456	.0477	.0148
12	36.84	15.17	11.59	6.50	7.33	8.15	4.17	.3201	.1007	.0437	.0137
12	36.84	15.17	11.70	6.43	7.23	8.03	4.20	.3201	.1017	.0443	.0141
12	36.84	17.33	11.70	4.70	5.49	6.28	3.24	.2454	.0779	.0447	.0142
12	36.84	19.86	11.66	3.33	3.94	4.93	2.52	.1868	.0591	.0452	.0143
12	45.51	19.22	14.37	4.68	5.47	6.25	3.27	.2462	.0777	.0450	.0142
12	54.18	18.42	17.16	6.33	7.12	7.90	4.20	.3191	.1011	.0448	.0142
12	54.18	19.60	17.12	5.60	6.44	7.28	3.81	.2823	.0892	.0438	.0139
18	0.87	3.74	0.30	0.70	1.22	1.73	0.78	.1239	.0433	.1016	.0355
18	0.87	4.66	0.30	0.30	0.82	1.33	0.51	.0798	.0279	.0973	.0340
18	2.17	4.89	0.72	1.28	1.73	2.18	0.87	.1813	.0598	.1048	.0346
18	2.17	4.89	0.82	1.33	1.83	2.13	1.14	.1813	.0688	.0991	.0376
18	2.17	5.88	0.74	0.80	1.29	1.78	0.75	.1254	.0426	.0972	.0330
18	2.17	5.88	0.74	0.73	1.21	1.68	0.87	.1254	.0426	.1036	.0352
18	2.17	7.38	0.78	0.35	0.87	1.38	0.42	.0796	.0286	.0915	.0329
18	6.50	10.20	2.30	0.88	1.37	1.85	0.84	0.1250	0.0442	0.0912	0.0323

TABLE 1 (Continued)

τ deg	C_Δ	C_V	C_R	$\frac{l_c}{b}$	$\frac{l_m}{b}$	$\frac{l_k}{b}$	$\frac{l_p}{b}$	C_{L_b}	C_{D_b}	C_{L_s}	C_{D_s}
18	6.50	12.72	2.32	0.38	0.88	1.38	0.60	0.0803	0.0287	0.0913	0.0326
18	6.50	16.99	2.43	0	0.53	1.05	0.48	.0450	.0168	.0849	.0317
18	8.67	19.60	3.21	0	0.50	1.00	0.48	.0452	.0167	.0904	.0334
18	8.67	19.66	3.21	0	0.52	1.03	0.45	.0448	.0166	.0862	.0319
18	10.84	9.35	3.75	2.13	2.61	3.08	1.50	.2480	.0858	.0950	.0329
18	10.84	10.99	3.86	1.38	1.86	2.33	1.29	.1795	.0639	.0965	.0344
18	10.84	13.18	3.77	0.83	1.32	1.80	0.81	.1248	.0434	.0945	.0329
18	10.84	16.49	4.01	0.38	0.89	1.40	0.63	.0798	.0295	.0897	.0331
18	10.84	19.60	4.01	0.08	0.61	1.13	0.45	.0565	.0209	.0926	.0343
18	15.17	19.40	5.50	0.35	0.88	1.40	0.60	.0806	.0292	.0916	.0332
18	19.50	9.80	7.00	3.98	4.47	4.95	2.58	.4060	.1457	.0908	.0326
18	19.50	11.04	6.98	2.98	3.46	3.93	2.16	.3200	.1145	.0925	.0331
18	19.50	12.59	6.89	2.20	2.67	3.13	1.62	.2461	.0870	.0922	.0326
18	19.50	14.68	6.85	1.45	1.93	2.40	1.26	.1810	.0636	.0938	.0330
18	19.50	17.67	6.85	0.85	1.34	1.83	0.90	.1250	.0439	.0933	.0328
18	19.50	19.60	6.93	0.55	1.07	1.58	0.75	.1016	.0361	.0950	.0337
18	23.84	19.45	8.43	0.85	1.32	1.78	0.90	.1261	.0446	.0955	.0338
18	28.17	19.60	10.03	1.10	1.58	2.05	0.96	.1468	.0523	.0929	.0331
18	36.84	12.12	13.65	5.33	5.81	6.28	3.36	.5014	.1858	.0863	.0320
18	36.84	13.43	13.87	4.28	4.74	5.20	2.79	.4086	.1538	.0862	.0324
18	36.84	15.12	13.59	3.15	3.63	4.10	2.22	.3224	.1189	.0888	.0328
18	36.84	17.33	13.39	2.20	2.67	3.13	1.62	.2454	.0892	.0919	.0334
18	45.51	19.24	16.69	2.25	2.72	3.18	1.62	.2458	.0901	.0904	.0331
18	54.18	14.68	20.33	5.40	5.87	6.33	3.42	.5028	.1887	.0857	.0321
18	54.18	16.28	20.41	4.33	4.77	5.20	2.82	.4091	.1541	.0858	.0323
18	54.18	18.42	20.52	3.23	3.69	4.15	2.19	.3191	.1209	.0865	.0328
18	54.18	19.60	19.94	2.65	3.10	3.55	1.92	.2823	.1039	.0911	.0335
24	6.50	10.19	3.03	0.58	0.89	1.20	0.54	.1253	.0584	.1408	.0656
24	6.50	12.76	3.03	0.20	0.57	0.93	0.45	.0799	.0372	.1402	.0653
24	10.84	9.41	4.98	1.45	1.75	2.05	0.84	.2449	.1125	.1399	.0643
24	10.84	11.00	5.01	0.98	1.29	1.60	0.81	.1792	.0828	.1389	.0642
24	10.84	13.10	5.05	0.58	0.92	1.25	0.57	.1264	.0589	.1374	.0640
24	10.84	16.46	5.05	0.20	0.58	0.95	0.42	.0800	.0373	.1379	.0643
24	15.17	19.40	7.02	0.23	0.59	0.95	0.42	.0806	.0373	.1366	.0632
24	19.50	8.82	8.97	3.43	3.73	4.03	2.13	.5013	.2306	.1344	.0618
24	19.50	9.75	9.12	2.75	3.04	3.33	1.80	.4103	.1919	.1350	.0631
24	19.50	9.83	9.06	2.65	2.95	3.25	1.77	.4037	.1875	.1368	.0636
24	19.50	11.06	9.04	2.03	2.36	2.68	1.41	.3188	.1478	.1351	.0626
24	19.50	12.59	8.95	1.48	1.78	2.08	1.11	0.2461	0.1129	0.1383	0.0634

TABLE 1 (Continued)

τ deg	C_Λ	C_V	C_R	$\frac{l_c}{b}$	$\frac{l_m}{b}$	$\frac{l_k}{b}$	$\frac{l_p}{b}$	C_{L_b}	C_{D_b}	C_{L_s}	C_{D_s}
24	19.50	14.65	8.95	1.00	1.33	1.65	0.81	0.1817	0.0834	0.1366	0.0627
24	19.50	17.65	8.93	0.55	0.89	1.23	0.63	.1252	.0573	.1407	.0644
24	19.50	19.60	8.97	0.40	0.74	1.08	0.48	.1016	.0467	.1373	.0631
24	23.84	19.45	10.99	0.58	0.92	1.25	0.63	.1261	.0581	.1371	.0632
24	28.17	17.66	12.79	0.95	1.27	1.58	0.77	.1806	.0820	.1422	.0646
24	28.17	17.70	12.79	1.00	1.32	1.63	0.81	.1797	.0816	.1361	.0618
24	28.17	19.60	12.96	0.75	1.08	1.40	0.66	.1468	.0675	.1359	.0625
24	28.17	19.63	12.87	0.70	1.04	1.38	0.69	.1462	.0668	.1406	.0642
24	36.84	12.18	17.12	3.58	3.87	4.15	2.22	.4966	.2308	.1283	.0596
24	36.84	13.50	17.01	2.75	3.08	3.40	1.83	.4041	.1866	.1312	.0606
24	36.84	15.16	16.97	2.00	2.32	2.63	1.44	.3205	.1476	.1381	.0636
24	36.84	15.17	16.99	2.13	2.46	2.78	1.44	.3201	.1476	.1301	.0600
24	36.84	17.39	16.90	1.48	1.79	2.10	1.08	.2435	.1117	.1360	.0624
24	36.84	19.50	17.03	1.08	1.39	1.70	0.92	.1938	.0896	.1394	.0645
24	45.51	19.24	21.06	1.45	1.75	2.05	1.14	.2458	.1137	.1405	.0650
24	54.18	14.69	25.25	3.55	3.84	4.13	2.25	.5022	.2341	.1308	.0610
24	54.18	14.73	25.53	3.63	3.92	4.20	2.28	.4995	.2354	.1274	.0601
24	54.18	16.25	25.57	2.83	3.12	3.40	1.83	.4101	.1936	.1314	.0621
24	54.18	16.30	24.92	2.80	3.09	3.38	1.83	.4080	.1876	.1320	.0607
24	54.18	16.32	25.40	2.80	3.10	3.40	1.81	.4069	.1908	.1313	.0615
24	54.18	18.37	25.38	2.08	2.36	2.63	1.46	.3213	.1505	.1361	.0638
24	54.18	19.60	25.18	1.75	2.05	2.35	1.31	.2823	.1312	.1377	.0640
24	71.51	16.90	34.43	3.58	3.87	4.15	2.31	.5006	.2410	.1294	.0623
24	71.51	16.92	34.33	3.60	3.90	4.20	2.30	.4999	.2400	.1282	.0615
24	71.51	16.92	34.37	3.58	3.89	4.20	2.32	.4999	.2402	.1285	.0617
24	71.51	18.78	33.76	2.83	3.13	3.43	1.84	.4055	.1914	.1296	.0612
24	71.51	18.78	33.89	2.83	3.12	3.40	1.84	.4055	.1922	.1300	.0616
24	71.51	19.60	34.02	2.58	2.86	3.13	1.71	.3726	.1772	.1303	.0620
30	0.87	3.72	0.52	0.53	0.76	0.98	0.66	.1253	.0751	.1649	.0998
30	0.87	4.65	0.52	0.25	0.50	0.75	0.66	.0802	.0481	.1604	.0962
30	2.17	4.21	1.28	1.20	1.39	1.58	0.69	.2446	.1445	.1760	.1040
30	2.17	4.87	1.28	0.85	1.04	1.23	0.69	.1827	.1079	.1757	.1038
30	2.17	5.89	1.30	0.53	0.74	0.95	0.57	.1249	.0749	.1688	.1012
30	2.17	7.36	1.30	0.28	0.52	0.75	0.42	.0800	.0480	.1538	.0923
30	6.50	10.21	3.81	0.48	0.71	0.93	0.45	.1248	.0731	.1758	.1030
30	6.50	12.77	3.81	0.25	0.50	0.75	0.33	.0797	.0467	.1594	.0934
30	10.84	9.39	6.41	1.25	1.44	1.63	0.87	.2459	.1454	.1708	.1010
30	10.84	11.00	6.44	0.88	1.07	1.25	0.63	.1792	.1065	.1675	.0995
30	10.84	13.18	6.37	0.53	0.74	0.95	0.72	.1248	.0733	.1686	.0991
30	10.84	16.51	6.41	0.25	0.50	0.75	0.39	0.0796	0.0470	0.1592	0.0940

TABLE 1 (Concluded)

τ deg	C_Δ	C_V	C_R	$\frac{l_c}{b}$	$\frac{l_m}{b}$	$\frac{l_k}{b}$	$\frac{l_p}{b}$	C_{L_b}	C_{D_b}	C_{L_s}	C_{D_s}
30	10.84	19.60	6.41	0	0.30	0.60	0.27	0.0565	0.0334	0.1883	0.1113
30	15.17	19.35	9.01	0.28	0.49	0.70	0.36	.0810	.0481	.1653	.0982
30	19.50	8.82	11.49	2.70	2.84	2.98	1.65	.5013	.2954	.1765	.1040
30	19.50	9.80	11.40	2.13	2.31	2.48	1.38	.4060	.2373	.1758	.1027
30	19.50	11.04	11.62	1.65	1.83	2.00	1.17	.3200	.1907	.1749	.1042
30	19.50	12.60	11.62	1.25	1.44	1.63	0.96	.2455	.1463	.1705	.1016
30	19.50	14.70	11.53	0.88	1.06	1.23	0.75	.1804	.1067	.1702	.1007
30	19.50	17.67	11.53	0.55	0.74	0.93	0.54	.1250	.0739	.1689	.0999
30	19.50	19.60	11.59	0.38	0.63	0.88	0.45	.1016	.0604	.1613	.0959
30	19.50	19.60	11.49	0.38	0.58	0.78	0.39	.1016	.0599	.1752	.1033
30	23.84	19.50	14.13	0.58	0.76	0.93	0.51	.1254	.0743	.1650	.0978
30	28.17	17.75	16.82	0.88	1.07	1.25	0.72	.1789	.1068	.1672	.0998
30	28.17	19.60	16.69	0.68	0.88	1.08	0.60	.1468	.0870	.1668	.0989
30	36.84	12.18	21.76	2.68	2.86	3.03	1.62	.4966	.2933	.1736	.1026
30	36.84	13.43	21.67	2.18	2.36	2.53	1.38	.4086	.2403	.1731	.1018
30	36.84	13.49	21.89	2.15	2.34	2.53	1.38	.4049	.2406	.1730	.1028
30	36.84	15.16	21.50	1.65	1.82	1.98	1.08	.3205	.1871	.1761	.1028
30	36.84	17.33	21.76	1.23	1.41	1.58	0.87	.2454	.1449	.1740	.1028
30	36.84	19.60	21.78	0.93	1.11	1.28	0.72	.1919	.1135	.1729	.1023
30	45.51	19.24	26.87	1.23	1.41	1.58	0.90	.2458	.1451	.1743	.1029
30	54.18	14.70	32.64	2.73	2.91	3.08	1.71	.5012	.3019	.1722	.1037
30	54.18	14.70	32.03	2.75	2.92	3.08	1.68	.5012	.2963	.1716	.1015
30	54.18	16.35	31.98	2.18	2.37	2.55	1.38	.4053	.2392	.1710	.1009
30	54.18	16.35	31.85	2.10	2.29	2.48	1.35	0.4053	0.2382	0.1770	0.1040

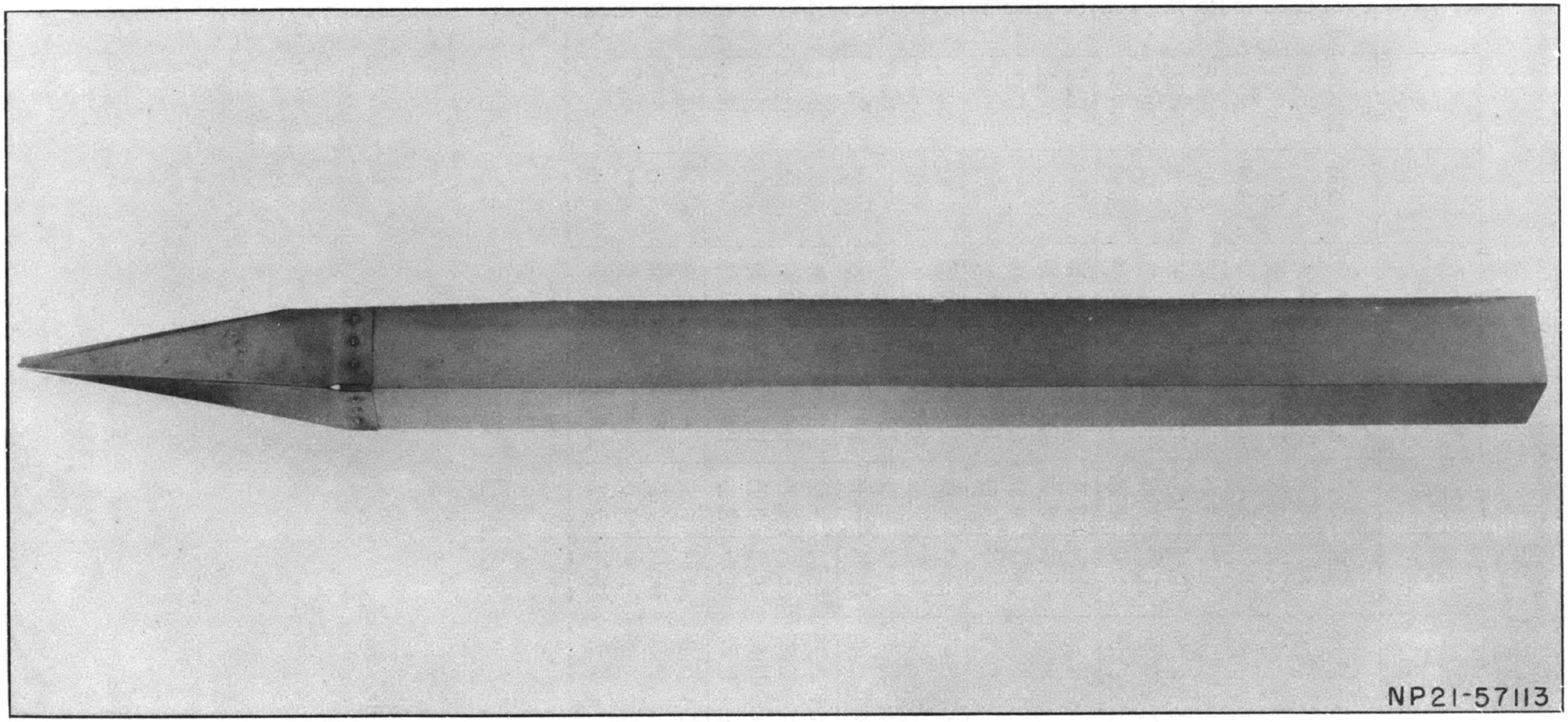


Figure 1 - Bottom of TMB Model 4356

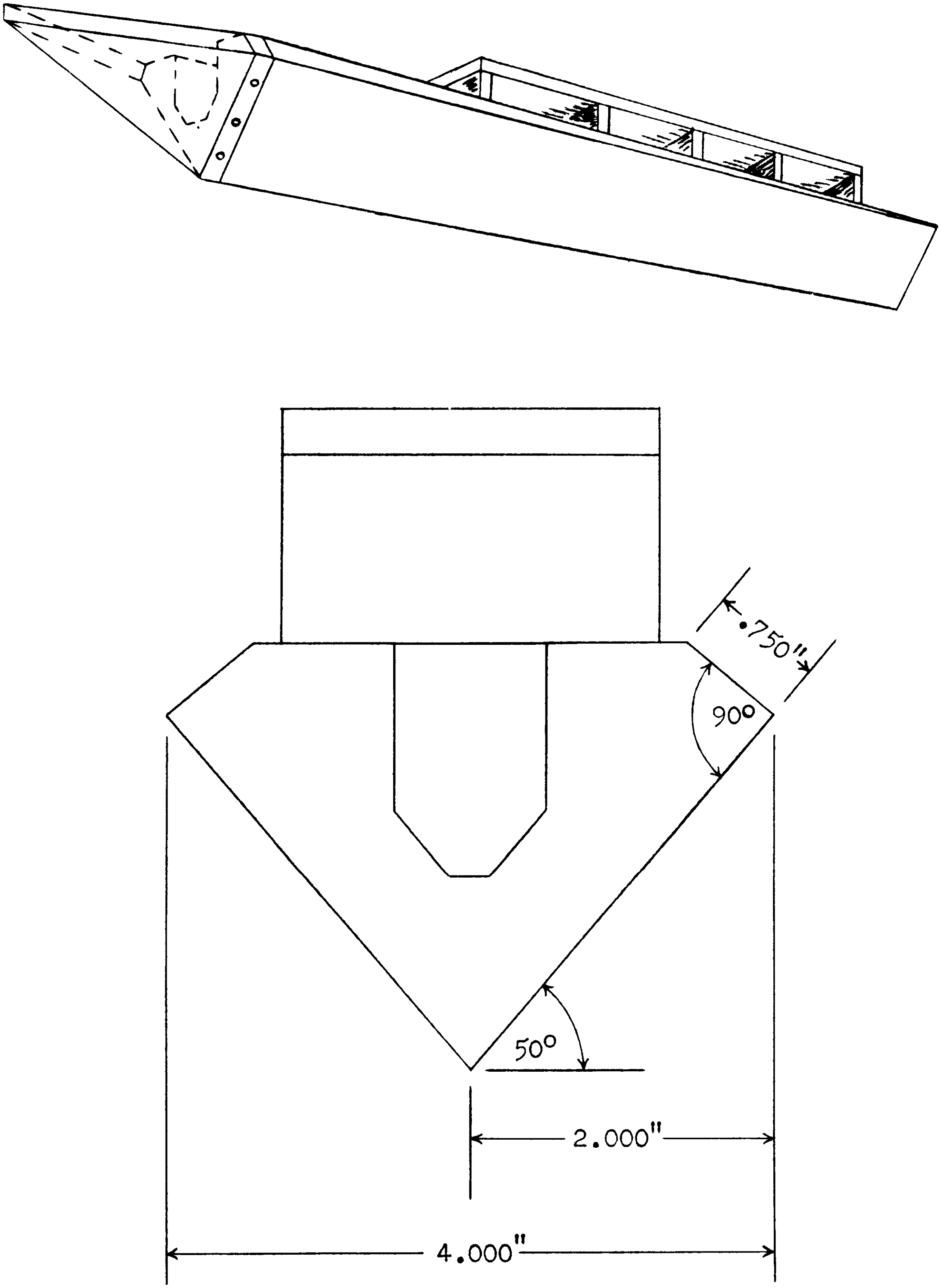


Figure 2 - Cross Section and Sketch of Model

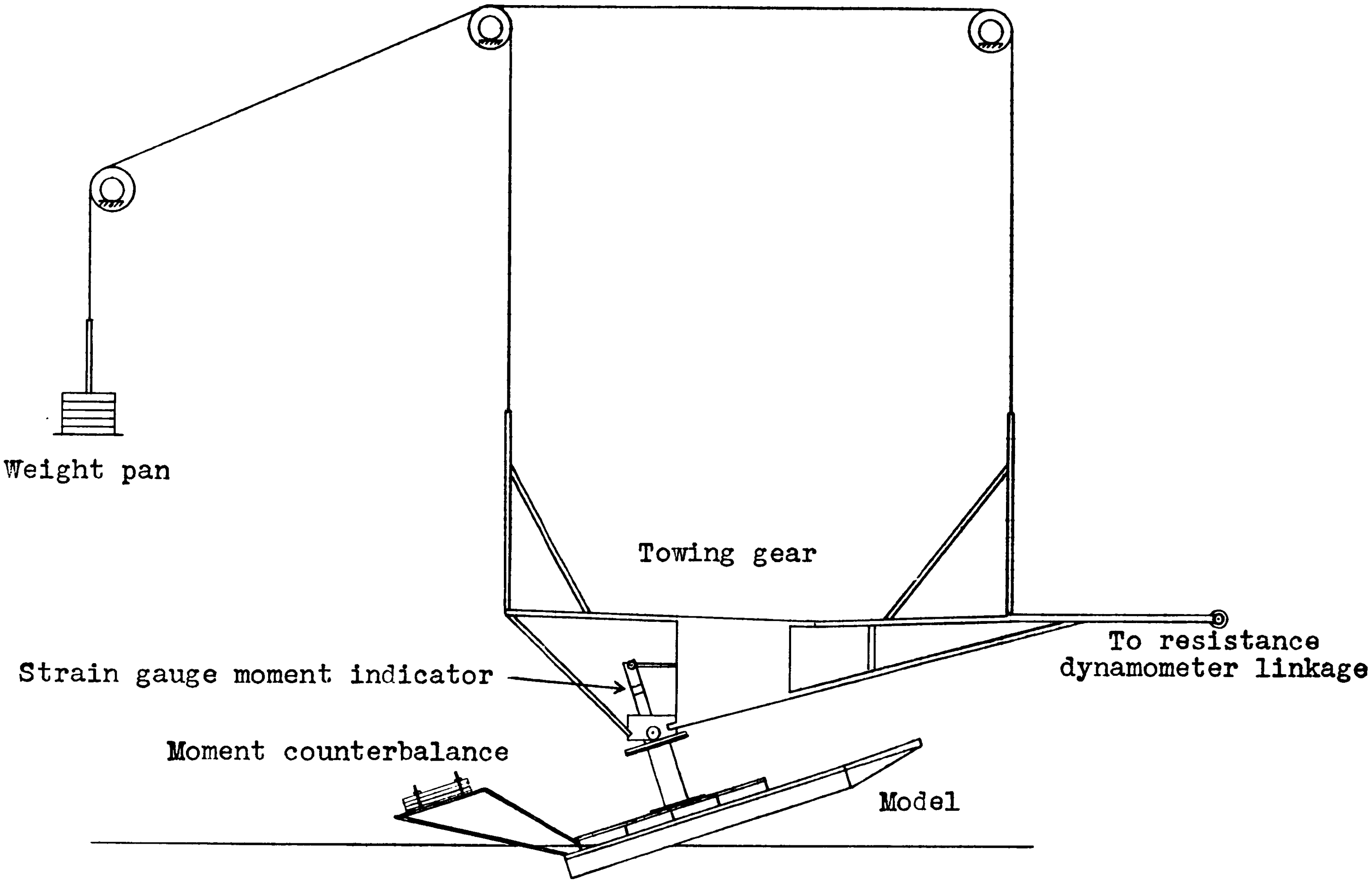


Figure 3 - Setup of Model and Towing Gear

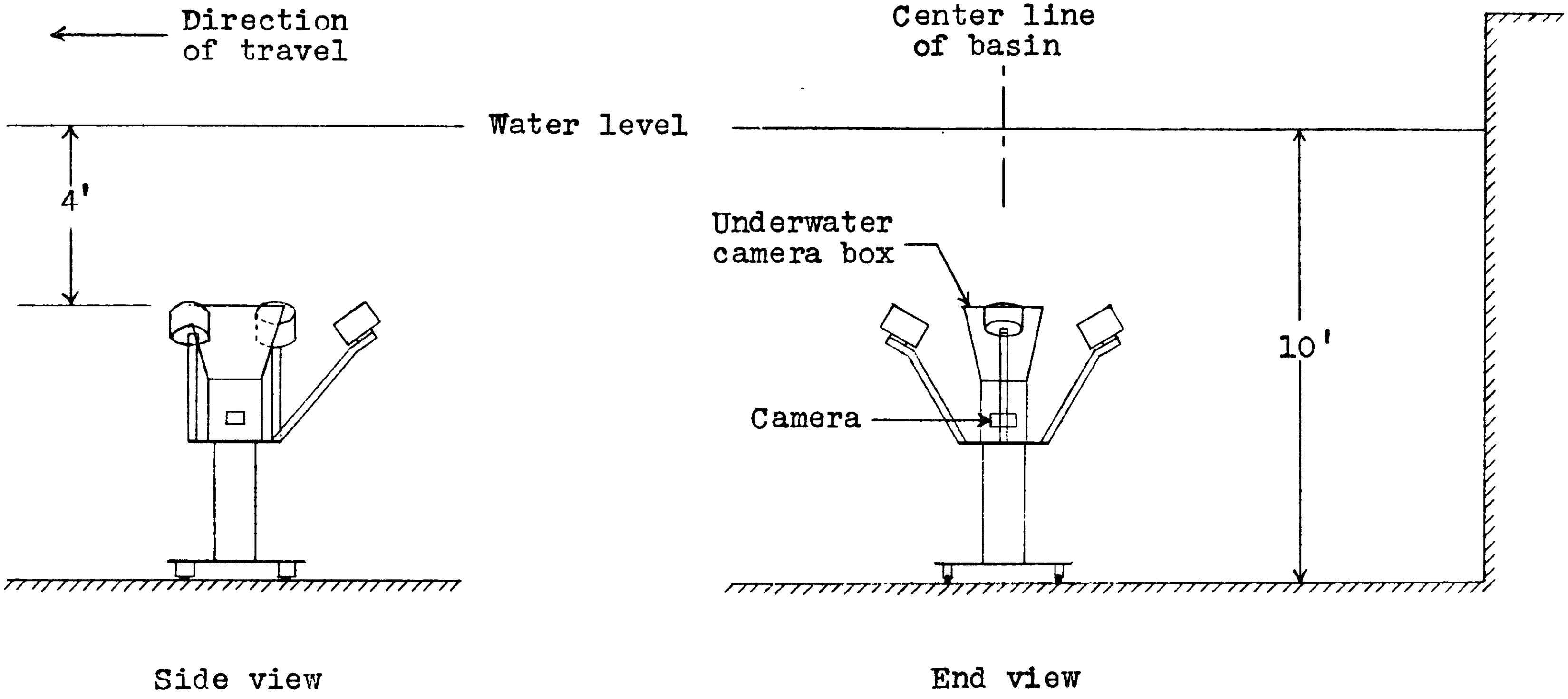


Figure 4 - Setup Used for Obtaining Underwater Photographs

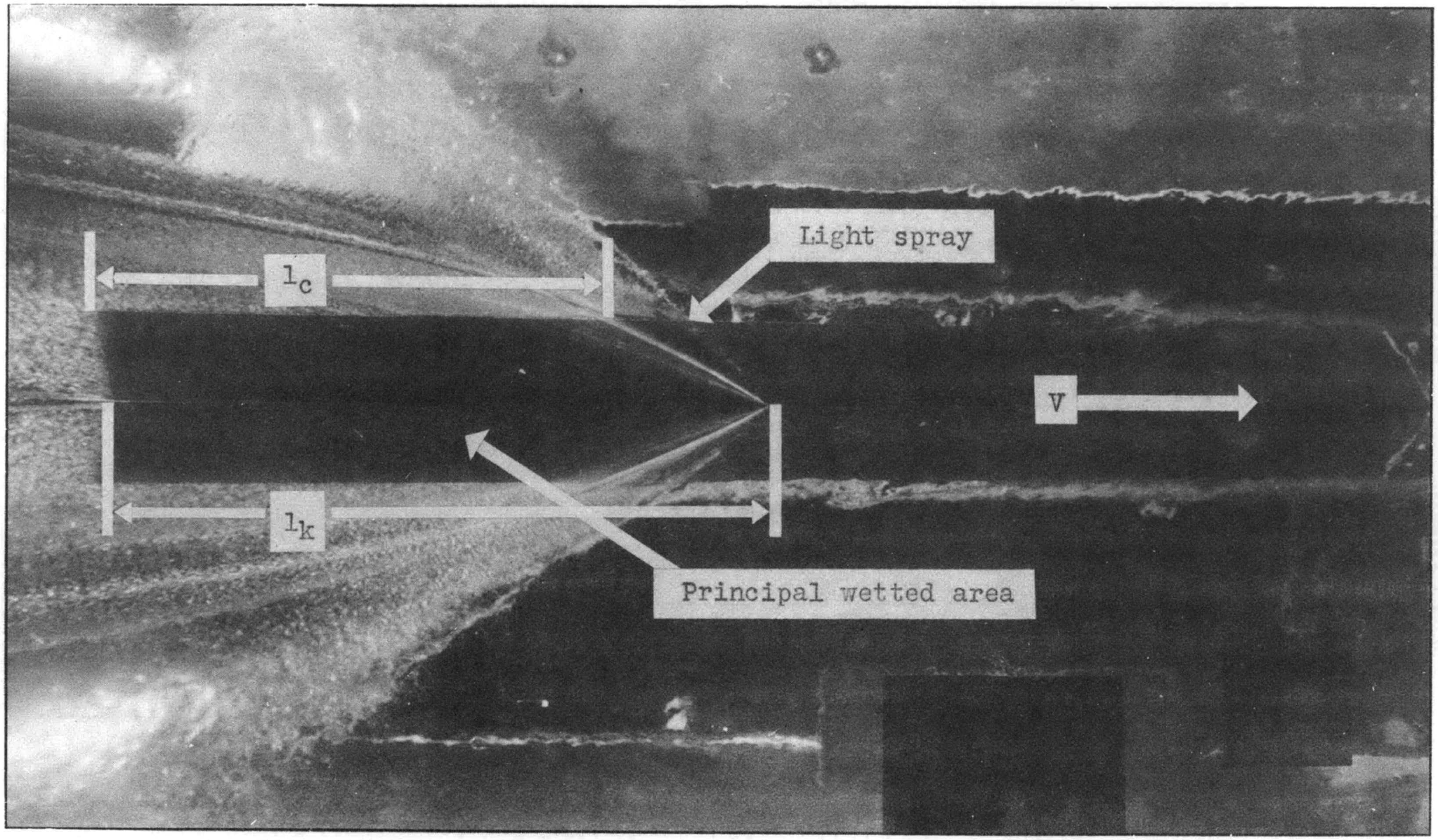


Figure 5 - Typical Underwater Photograph

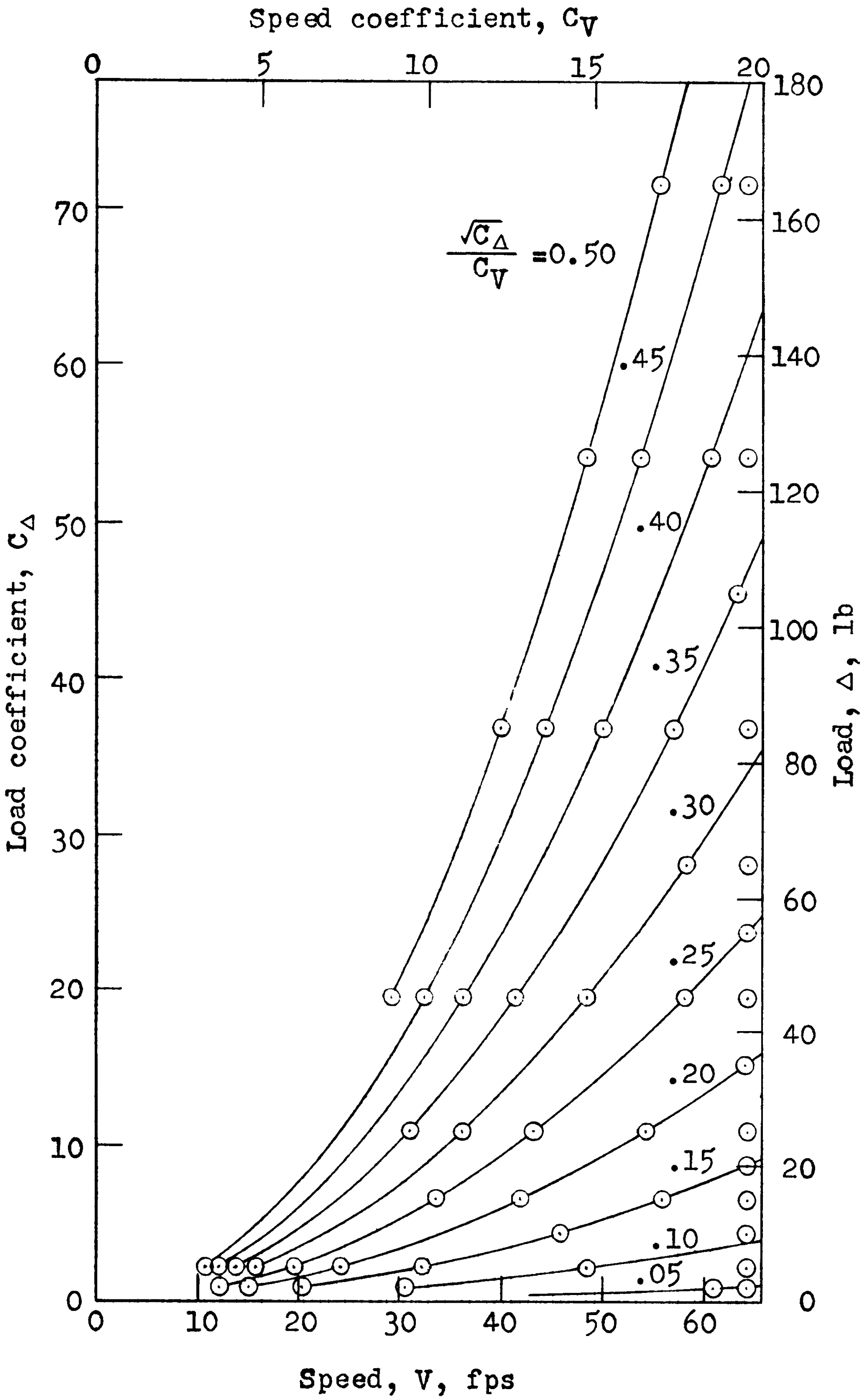


Figure 6 - Load-Speed Schedule for Test Program

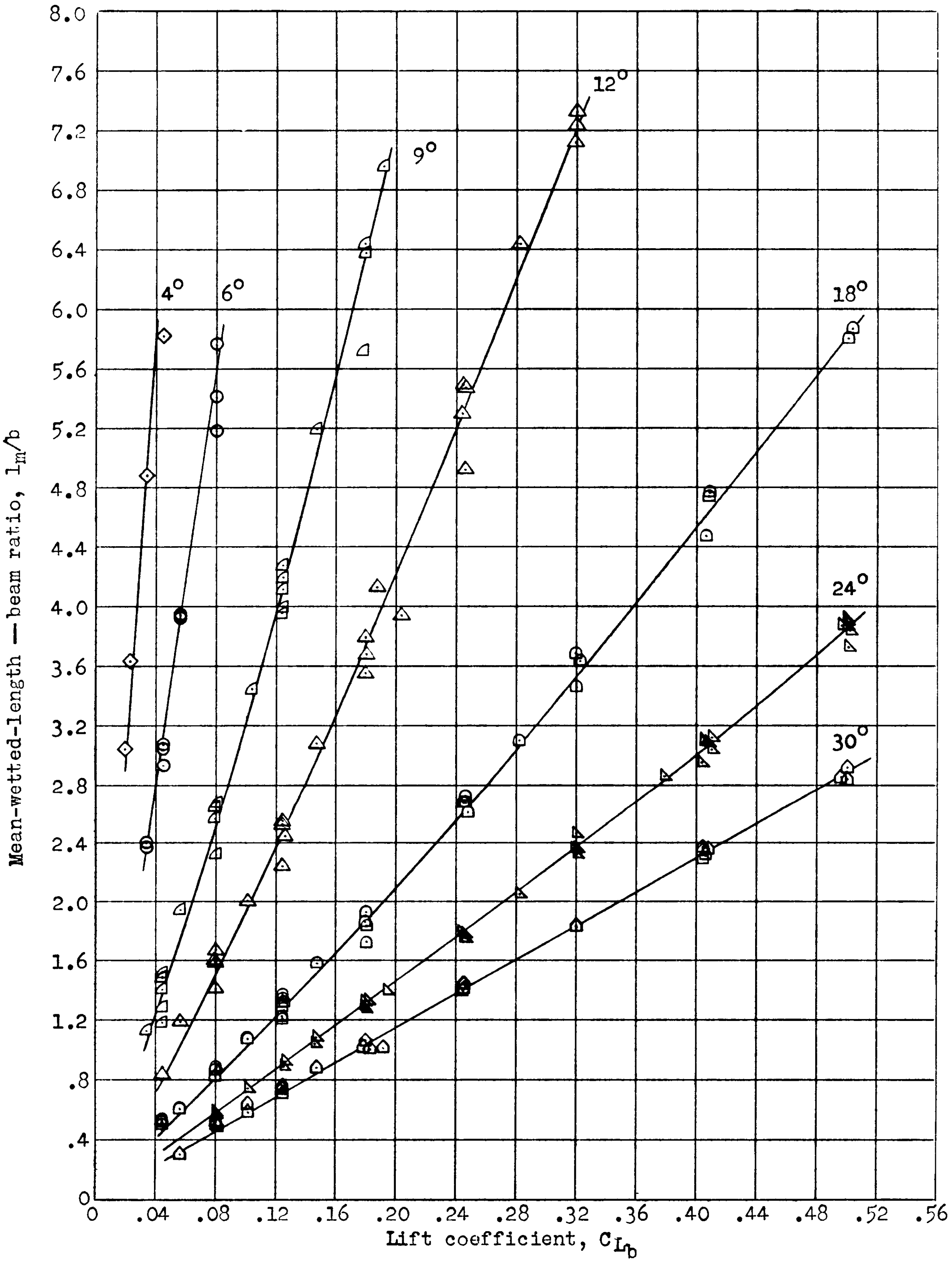


Figure 7 - Variation of Mean-Wetted-Length–Beam Ratio l_m/b with Lift Coefficient C_{L_b}

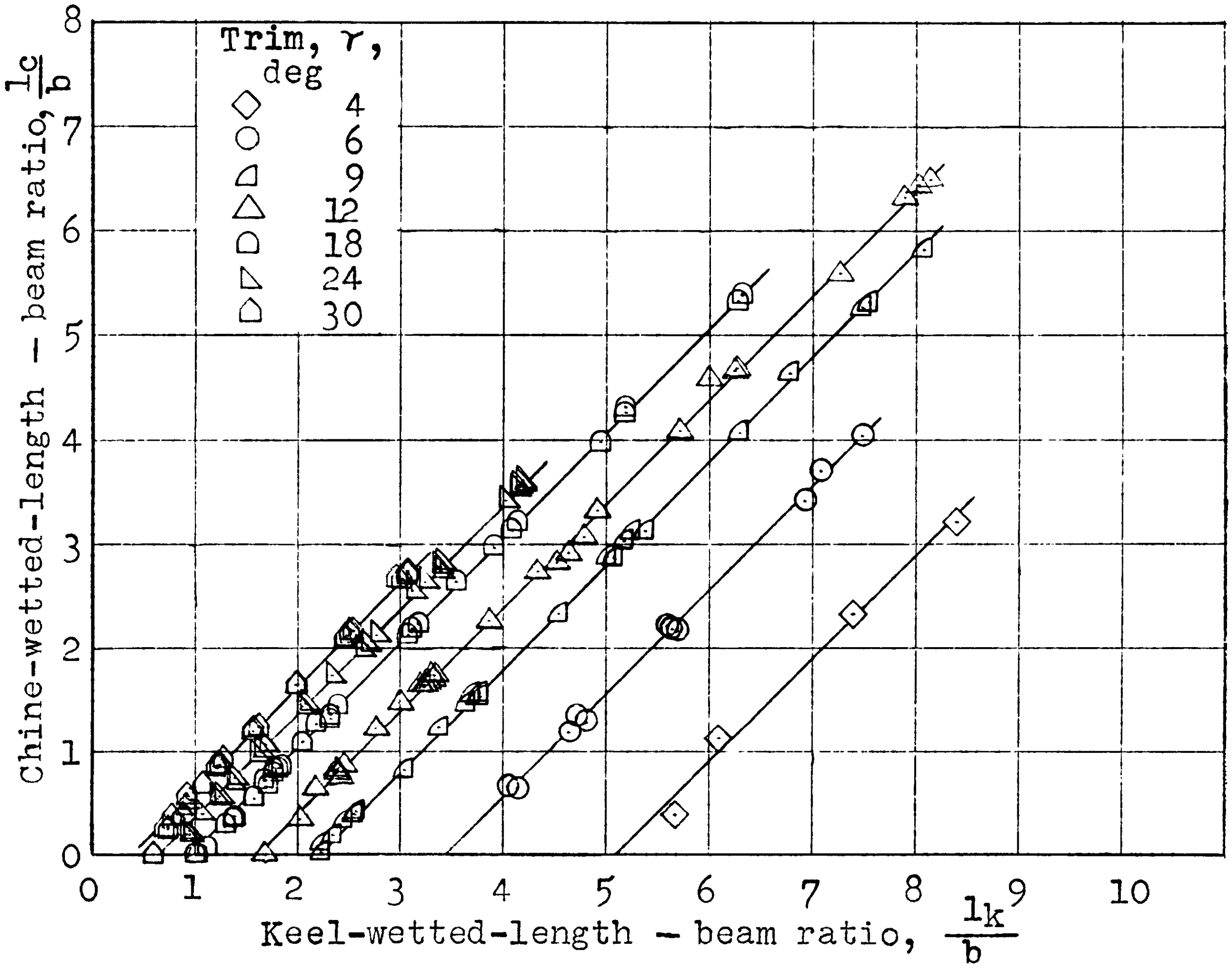


Figure 8 - Variation of Chine-Wetted-Length–Beam Ratio with Keel-Wetted-Length–Beam Ratio

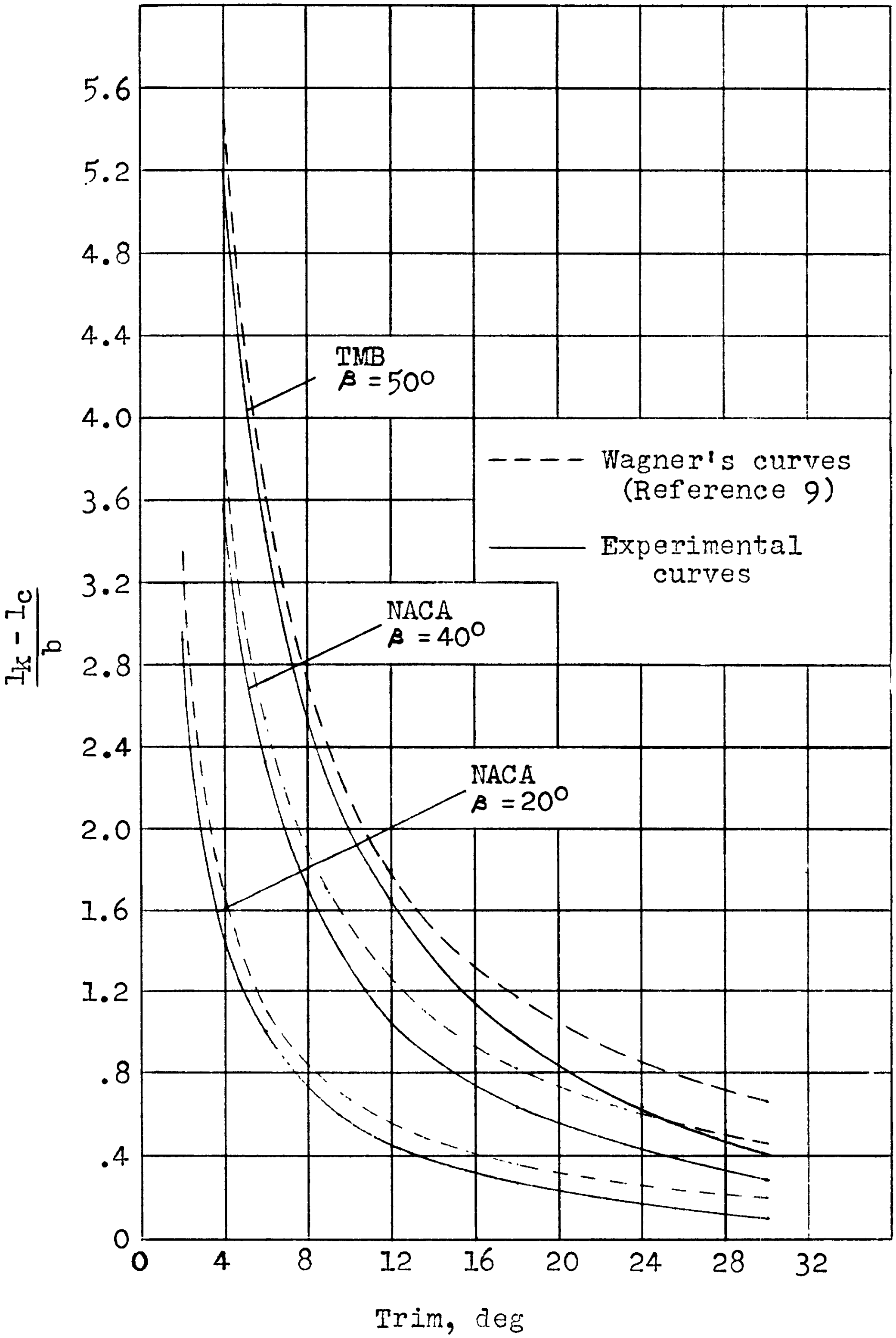


Figure 9 - Variation of $\frac{l_k - l_c}{b}$ with Trim

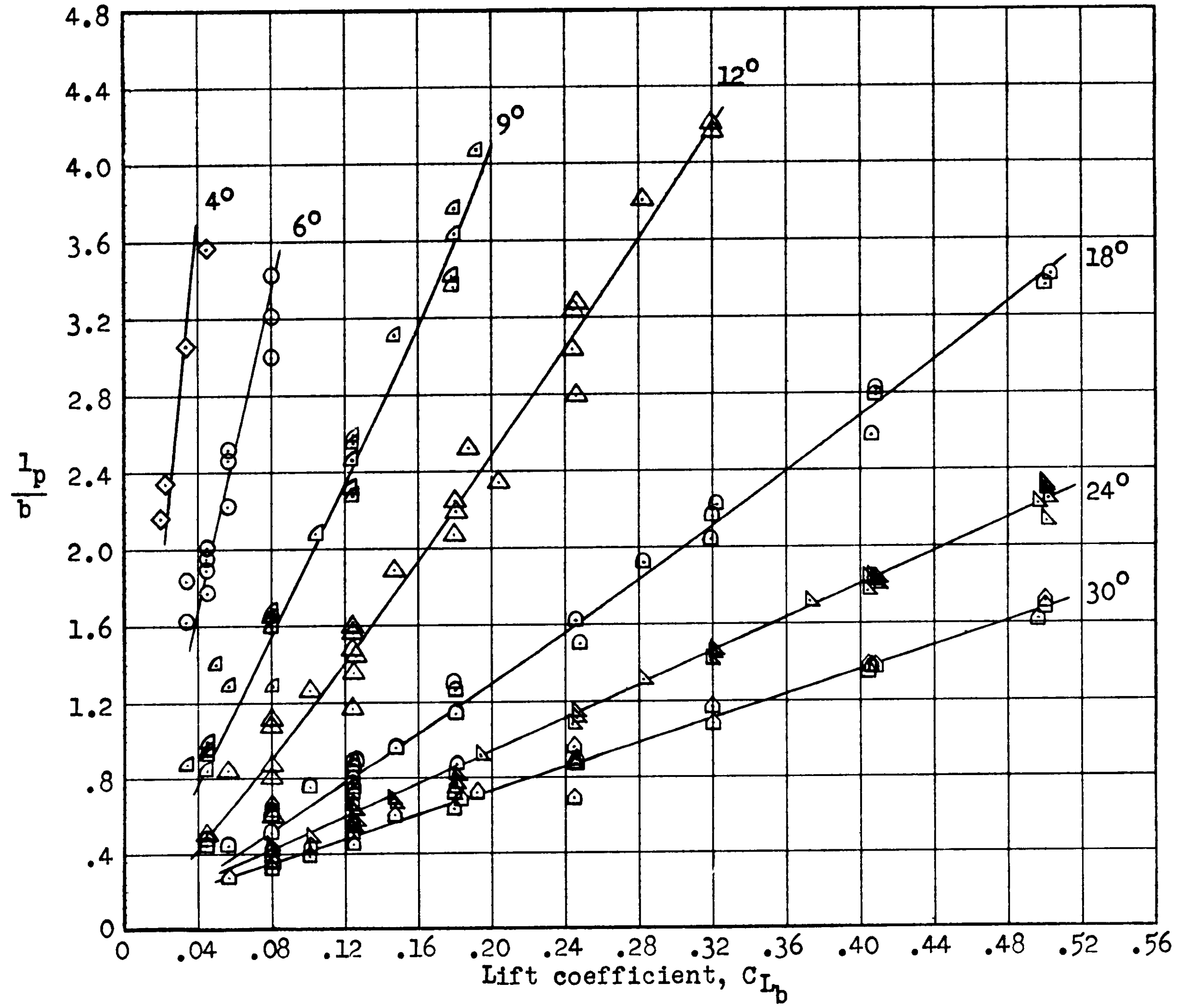
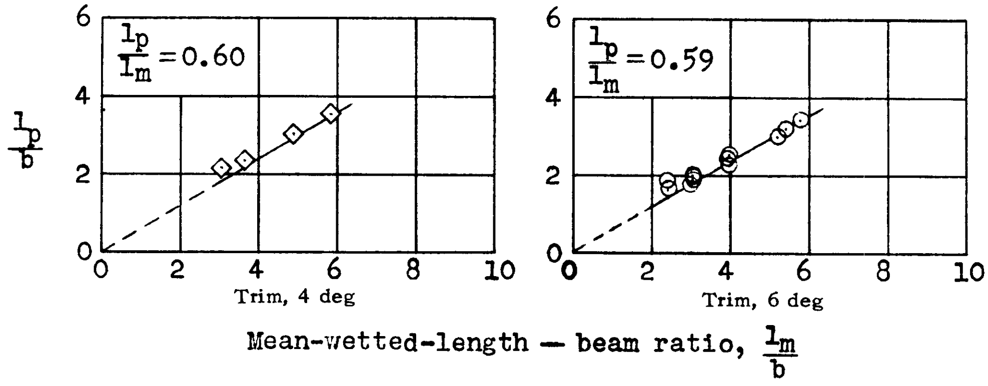
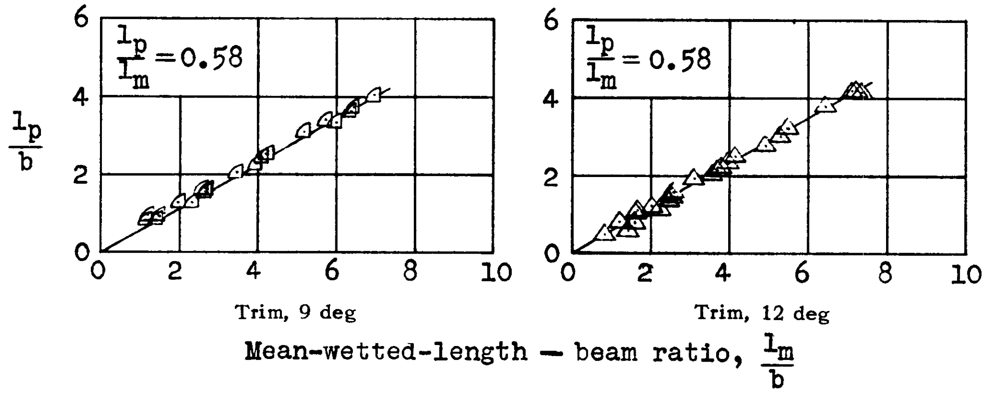


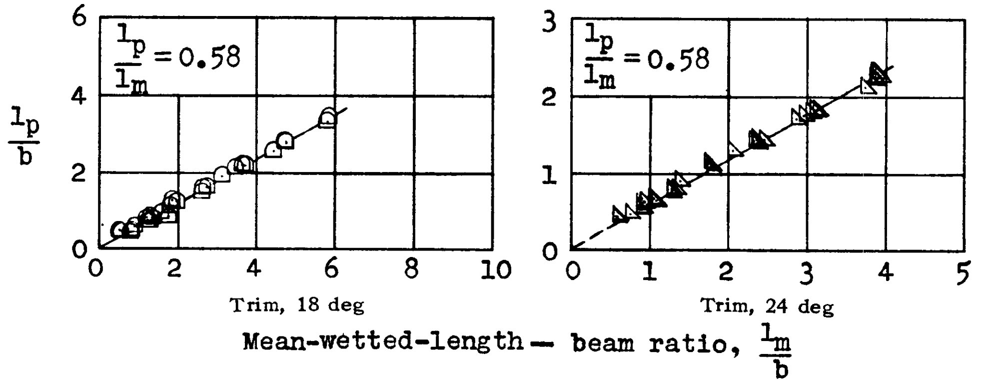
Figure 10 - Variation of Nondimensional Center-of-Pressure Location l_p/b with Lift Coefficient C_{L_b}


Trim, 4 deg

Trim, 6 deg


Trim, 9 deg

Trim, 12 deg


Trim, 18 deg

Trim, 24 deg

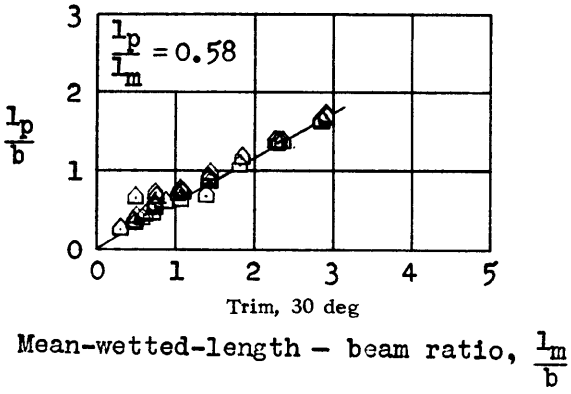

Trim, 30 deg

Figure 11 - Variation of l_p/b with l_m/b

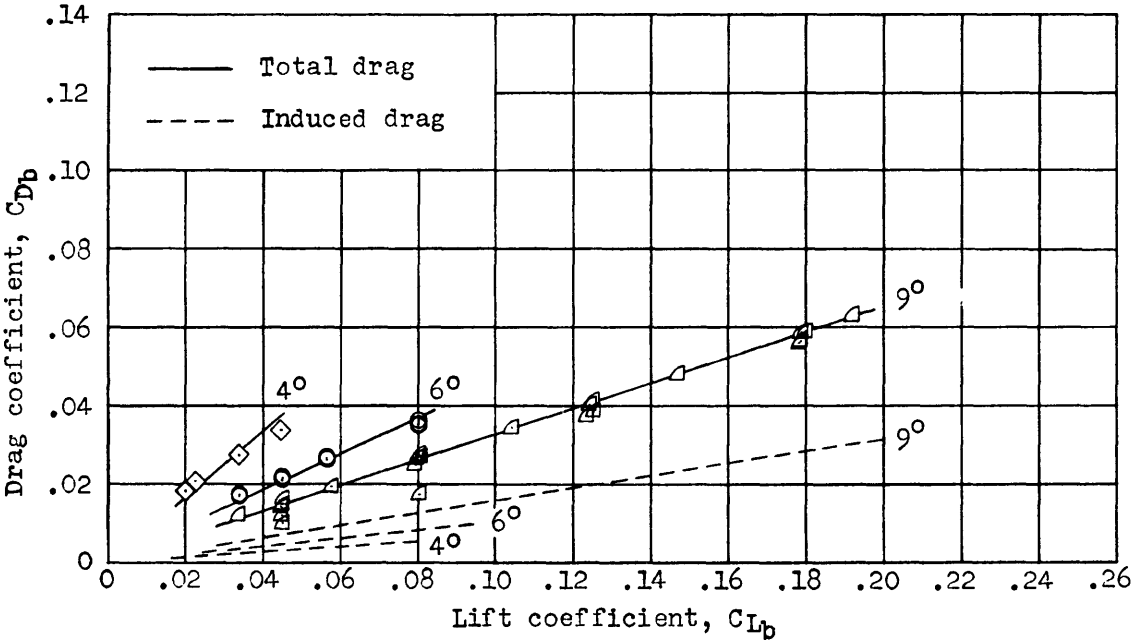


Figure 12a - Trim, 4, 6, and 9 deg

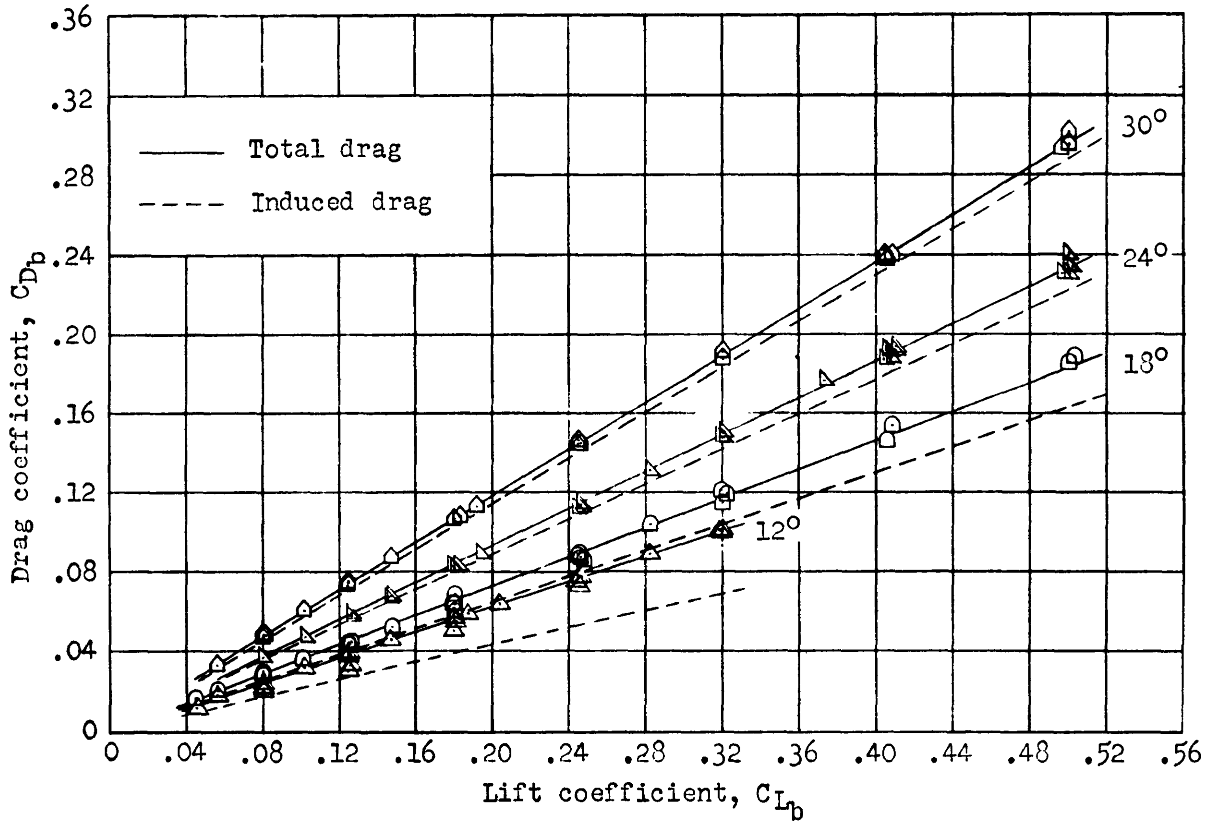


Figure 12b - Trim, 12, 18, 24, and 30 deg

Figure 12 - Variation of Drag Coefficient C_{D_b} with Lift Coefficient C_{L_b}

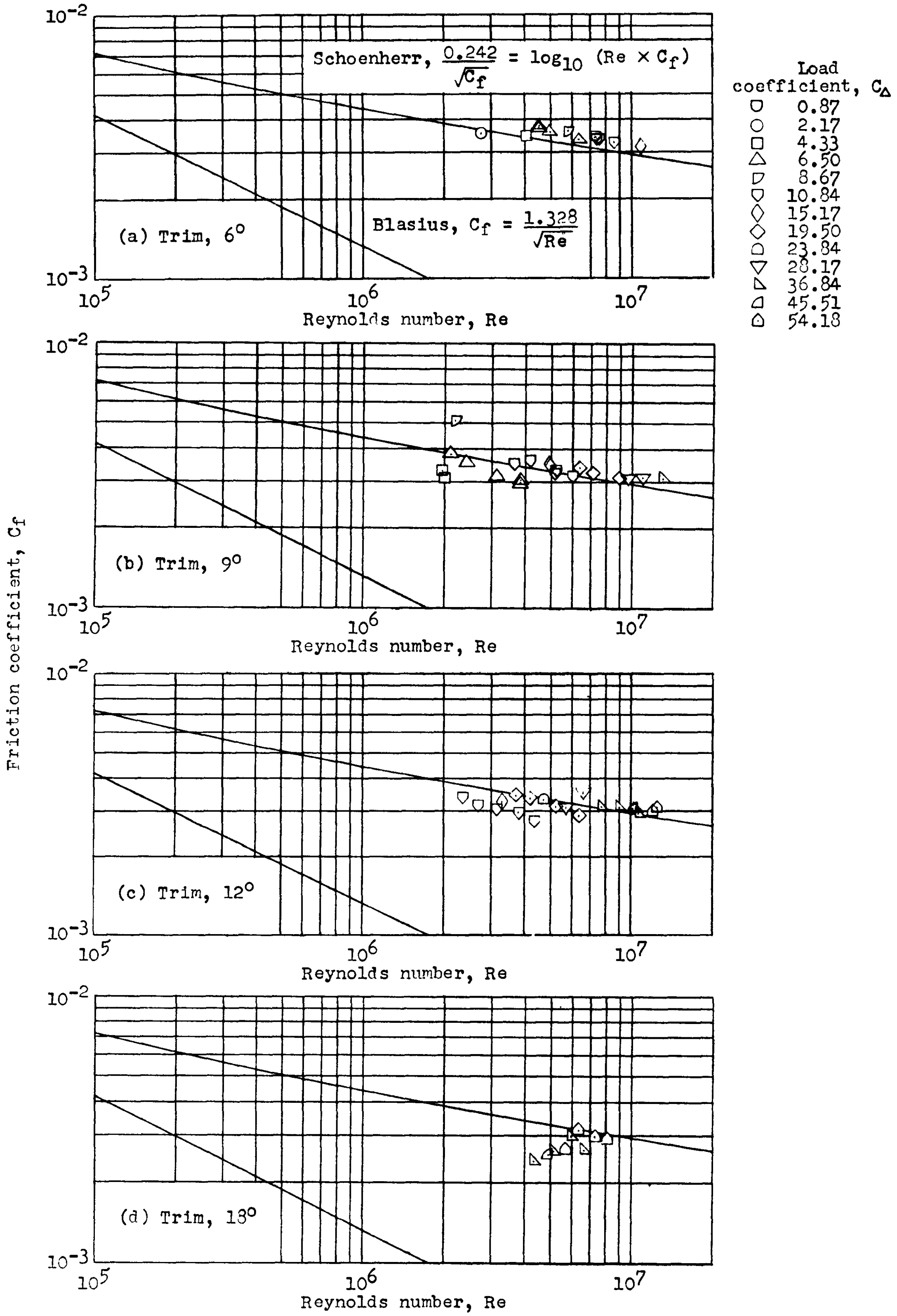


Figure 18 - Variation of Friction Coefficient with Reynolds Number

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