GENERAL DESIGN CRITERIA

FOR

CABLE-TOWED BODY SYSTEMS

USING

FAIRED AND UNFAIRED CABLE

Prepared under Contract Nonr 3201(00)
Sponsored by the
Office of Naval Research

SYSTEMS ENGINEERING DIVISION
PNEUMODYNAMICS CORPORATION
BETHESDA, MARYLAND

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	RETURNED
	Oct. 1962
	5 Apr 1963
	27 Feb 1964
	29 Aug 64

TN-SEDU-6634-1

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October 1960

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TABLE OF CONTENTS

SUMMARY

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A method for rapid selection of design parameters to satisfy requirements for cable-towed instrument systems is described. The method is applied to both faired and unfaired cable systems. Curves are presented which facilitate the determination of cable diameter, cable length, and required down force without the need for performing laborious cable calculations previously required.

INTRODUCTION

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In the design of cable-towed systems, the problem is complicated by the large number of independent variables which must be considered and the necessity for performing laborious calculations using tables of cable functions such as those in Reference 1*. There is a need, therefore, to provide the designer with a more simplified and rapid method for determining the feasibility of meeting system requirements and selecting system parameters which are in a range of practical interest. This need for a more practical approach to cable-body system design was encountered in the course of studying requirements for a towed instrument array to be used in measuring physical characteristics of the ocean. As a result of this study, sponsored by the Office of Naval Research, a design technique was devised to permit selection of a practical configuration to meet requirements for attaining a particular depth at a given speed using armored electrical cables both with and without cable fairing. Since this method is felt to be generally applicable to a variety of such design problems, it is described in this report as a separate part of the study.

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* References listed on page 32.

TECHNICAL DISCUSSION

TECHNICAL DISCUSSION

SYSTEM CONFIGURATION

The general cable-system configuration to be considered in this discussion is shown in Figure 1. We will restrict our consideration to the case of a body towed from the water surface with the cable lying in a vertical plane and curved concave downward. This configuration is designated as the "Quadrant I Case", in Reference 1.

The forces acting on an element of the cable are shown in Figure 2. These are defined as:

F, the hydrodynamic force per unit length acting normal to the element,

G, the hydrodynamic force per unit length acting tangential to the element,

W, the weight of the element per unit length, and

T, the tension in the cable.

The principal distinction between calculations for bare cable and those for faired cable lies in the description of hydrodynamic forces F and G. This distinction will be discussed in detail in a later section, however, in either case, the hydrodynamic force is generally described in terms of the

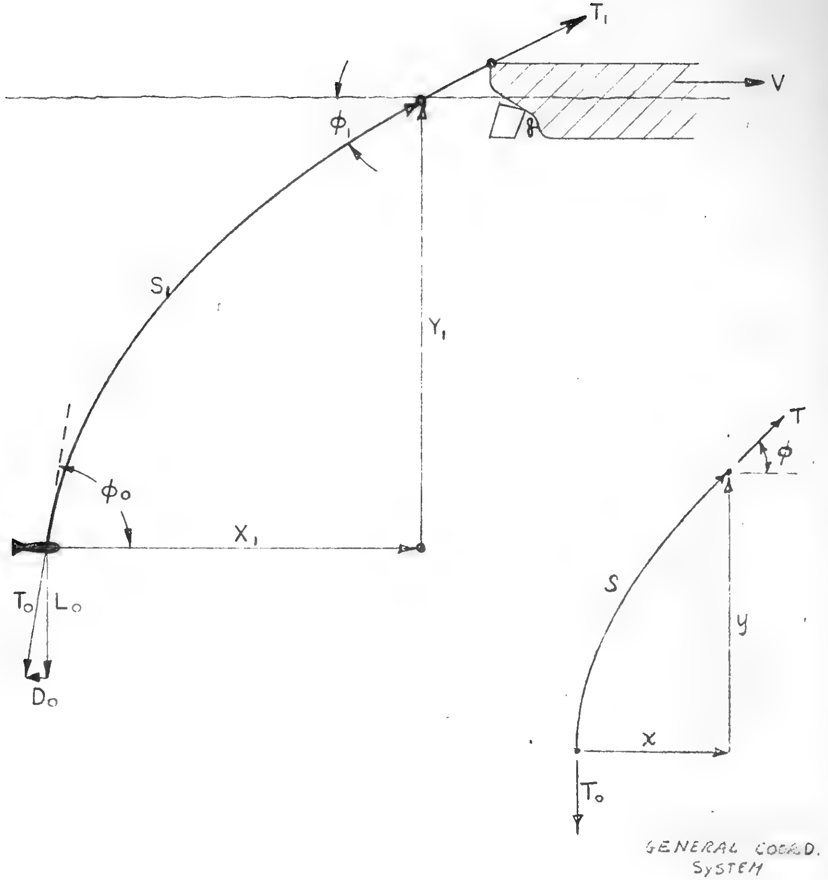


FIG. 1

CABLE CONFIGURATION

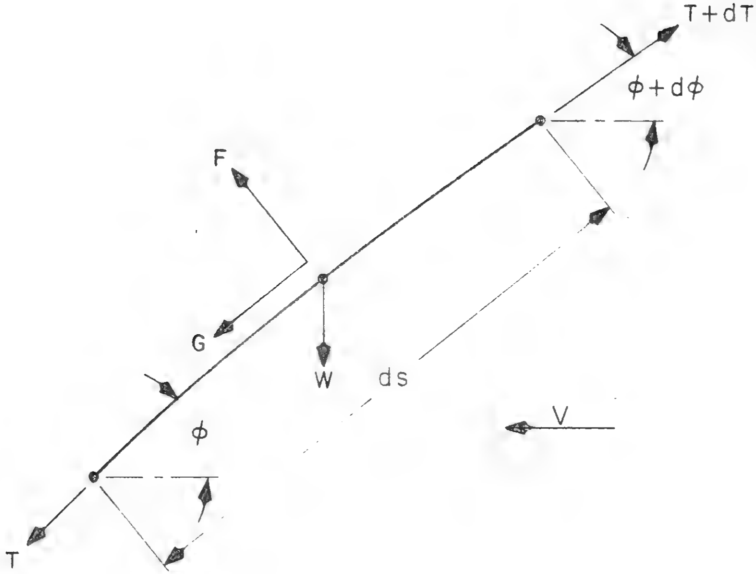


FIG. 2

FORCES ACTING ON AN ELEMENT

OF THE TOWING LINK

drag of the cable per unit length when the cable is normal to the stream. The drag is given by:

$$R = C_D \frac{\rho}{2} dV^2 \qquad (1)$$

where:

C_D is an empirical drag coefficient,

ρ is the mass density of the fluid,

d is the diameter of the cable, and

V is the stream velocity.

To reduce the problem to a case of practical interest several assumptions will be made. These and assumptions already made are listed as follows:

1. The cable is assumed to be completely flexible and thus cannot sustain a bending moment.

2. The cable is assumed to lie in a vertical plane parallel to the direction of motion.

3. It will be assumed that the cable to be used is American Steel and Wire Type H. This cable is of the double-armor type which is available in various diameters with a variety of electrical cores. Table I lists a number of sizes and types presently

TABLE I

Reference: American Steel and Wire

Cable Type	Conductor	Copper Weight (Lbs./1000 ft.)	Cable Weight in Air (Lbs./1000 ft.)	Conductor Resistance (Ohms/1000 ft.)	Breaking Strength (Lbs.)	Prestressing Load (Lbs.)	Diameter	Armor	Insulation	Maximum Temperature
1-H-100	7W .008 A&C Copper	1.37	17.4	24	900	None	.100"	12W .014 18W .014	Ampyrol	[illegible]0°C
1-H-125	7W .008 A&C Copper	1.37	30	24	1500	None	.125"	12W .0175 1[illegible]W .0175	Ampyrol	[illegible]°C
1-H-0	7W .012 Tinned Copper	3.11	54	10.7	2700	None	.1[illegible]2"	1[illegible]W .01[illegible] 1[illegible]W .025	Rubber	100°C
1-H-1	7W .017 Tinned Copper	6.24	139	5.24	7200	2160	.292"	1[illegible]W .02[illegible] 1[illegible]W .039	Rubber	125°C
1-H-2	7W .020 Tinned Copper	8.72	171	3.86	9200	27[illegible]0	.322"	1[illegible]W .031 1[illegible]W .043	Rubber	125°C
1-H-3	5/64"6x7 Copper Sash Cord	9.09	237	4.2	11000	3300	.375"	1[illegible]W .037 18W .051	Rubber	125°C
1-H-4	5/64"6x7 Copper Sash Cord	9.09	298	4.2	16000	4[illegible]00	.425"	18W .0[illegible] 1[illegible]W .05[illegible]	Rubber	125°C
3-H-0	7W .008 A&C Copper	4.11	54	24	2700	None	.1[illegible]2"	1[illegible]W .01[illegible] 1[illegible]W .025	Ampyrol	60°C
3-H-1	7W .012 A&C Copper	9.33	141	11.1	7200	2160	.292"	1[illegible]W .028 18W .039	Polyethylene	80°C
Mod. 3-H-1	7W .012 24 Solid		149	11.1) 25.7)	6500	None	.300"	(18W .032) (24W .032)	Polyethylene Ampyrol	[illegible]0°C
3-H-2	7W .010 A&C Copper	6.45	172	15.4	9200	2760	.322"	1[illegible]W .031 1[illegible]W .043	Nylon	125°C
3-H-3	7W .010 Tinned Copper	6.45	219	15.4	11000	3300	.375"	1[illegible]W .037 1[illegible]W .051	Rubber	100°C
3-H-4	7W .012 Tinned Copper	9.33	302	11.1	16000	4[illegible]00	.425"	1[illegible]W .043 1[illegible]W .05[illegible]	Rubber	1[illegible]0°C
6-H-1	7W .012 Tinned Copper	18.66	427	11.1	18000	8000	.52[illegible]"	24W .044 24W .055	Rubber	100°C
6-H-2	7W .008 A&C Copper	[illegible].22	141	24.6	7200	2160	.292"	18W .028 18W .039	Ampyrol Nylon	[illegible]0°C
6-H-4	7W .012	18.66	332	11.1	16000	6000	.464"	24W .039 24W .049	Rubber	100°C

in use. For these cables the weight in water per unit length and the breaking strength are proportional to the square of the diameter. These relations are:

$$W = 210 \frac{\text{lbs}}{\text{ft}^3} d^2 \qquad (2)$$

$$T_{max} = 1.15 \times 10^7 \frac{\text{lbs}}{\text{ft}^2} d^2 \qquad (3)$$

4. The cable tension at the water surface, T_1, will be assumed to be limited to 1/3 of the rated breaking strength. Thus:

$$T_1 \text{ (design)} = 3.84 \times 10^6 \frac{\text{lbs}}{\text{ft}^2} d^2 \qquad (4)$$

This safety factor of 3 is employed to take account of inertial loads due to motion of the tow point, and the reduction of cable strength due to corrosion and fatigue. Actually, in a conservative design, this factor should probably be as much as 4 or 5.

5. The cable angle at the bottom, φ_o, is assumed to be 90 degrees. This means that the drag, D_o, of any body attached to the cable is assumed to be

very small compared to the down force, L_o. This assumption considerably reduces the effort in making cable calculations since the tables of functions, such as Reference 1, are usually set up with $\varphi = 90°$ as a reference point. Furthermore, it is usually feasible to achieve a value of at least 9 or 10 for $\frac{L_o}{D_o}$ using either weight or a combination of weight and a depressing wing to produce the down force.

In carrying out calculations of the cable configuration, the cable characteristics, defined in Figure 1, are generally expressed in non-dimensional form in the following manner:

$$\tau = \frac{T}{T_o} \tag{5}$$

$$\eta = \frac{Ry}{T_o} \tag{6}$$

$$\xi = \frac{Rx}{T_o} \tag{7}$$

$$\sigma = \frac{Rs}{T_o} \tag{8}$$

We will now consider the use of these functions, which have been tabulated for a range of variables, in calculating the configuration of a system using bare cable.

CALCULATIONS FOR UNFAIRED CABLE

As a result of a considerable number of experiments it can be assumed that the drag coefficient, C_D , of a circular cable is about 1.2 over the range of interest. The validity of this assumption is subject to question depending upon the roughness of the surface, vibration, free-stream turbulence, and the Reynolds Number. The Reynolds Number is defined by $R_e = \frac{Vd}{\nu}$, where ν is the kinematic viscosity of the fluid. Figure 3 shows the variation of C_D with R_e for a smooth cylinder normal to the stream, and it can be seen that C_D falls considerably below 1.2 at the so-called transition point. The value of R_e at which transition occurs, as well as the values of C_D, are highly dependent on the cable roughness, the free-stream turbulence level, and the vibration of the cable. Nevertheless, it is believed that a value of 1.2 is a good compromise for use in these calculations. With this value for C_D we can therefore write

$$R = 1.2 \frac{\text{lb sec}^2}{\text{ft}^4} dV^2 \qquad (9)$$

We must now consider the manner in which the hydrodynamic loading on the bare cable depends on the angle φ. It has been

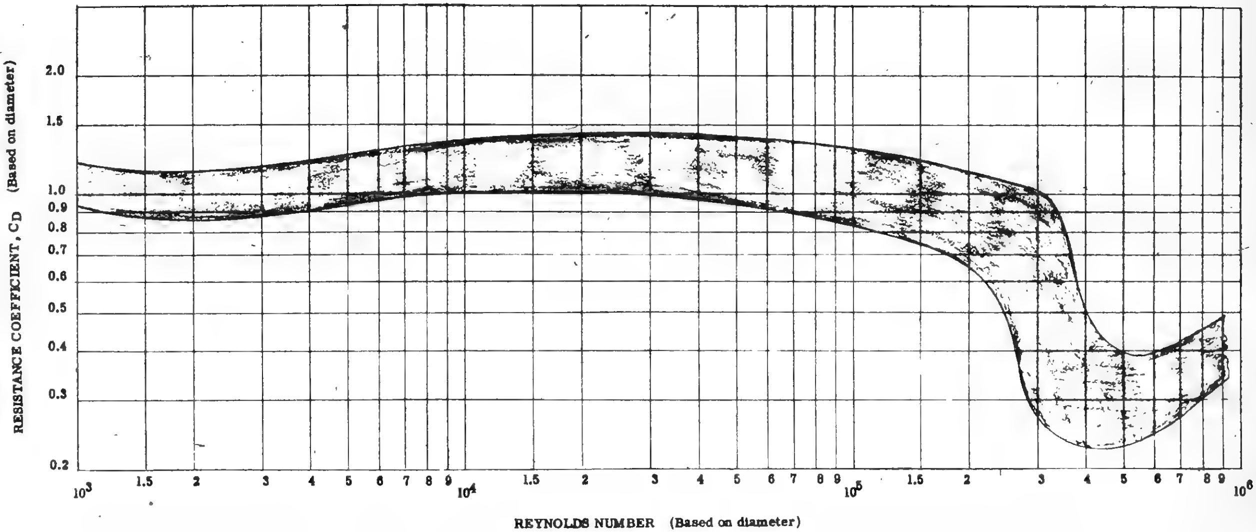


Figure 3 - Envelope of Experimental Data on the Resistance Coefficient of a Circular Cylinder at 90° to the Stream

determined by a number of experiments that the normal force, F, per unit length of cable is given by:

$$F = R \sin^2 \varphi \qquad (10)$$

For the tangential force, G, we will make the same assumption as that made in Reference 1, namely that G is independent of angle and $\frac{G}{R}$ for a reasonably smooth cable is approximately equal to .02. This is obviously not a completely valid assumption but, for a wide range of values of φ it has been found to be of sufficient accuracy for engineering calculations. Actually, the value of G is, in general, quite small compared to F for the case of a circular element, and does not have much influence on the calculations for values of φ greater than about 25 degrees. For smaller angles the value of G is of importance in determining the tension, however, and this should be borne in mind in assessing the accuracy of these calculations.

To further facilitate the calculation of cable configurations it is conventional to define another parameter known as the "critical angle" of the cable. If a completely flexible cable is towed in a fluid and there is no force applied to the unsupported end, then the cable will lie in a perfectly straight line inclined at some angle, φ_c, to the stream.

For the case of an unfaired cable, as a result of equation (10), φ_c is a function only of the ratio $\frac{W}{R}$. The functional relationship for a cable having positive weight in water is:

$$\cos \varphi_c = - \frac{W}{2R} + \sqrt{\left(\frac{W}{2R}\right)^2 + 1} \qquad (11)$$

It can be seen that if $\varphi_o = \varphi_c$ then the cable will remain in a straight line regardless of the value of the tension, T_o, applied at the bottom. If $\varphi_o < \varphi_c$ then the cable will be curved concave upward. If $\varphi_o > \varphi_c$ then the configuration will be concave downward. It may be further noted that the angle, φ_o, at the bottom end of the cable is determined only by the ratio of down force, L_o, to the drag, D_o . Thus:

$$\varphi_o = \arctan \frac{L_o}{D_o} \qquad (12)$$

As previously noted, this discussion will be restricted to the cases where $\varphi_o \geq \varphi_c$.

As a result of equations (2) and (9) we can now specify the value of $\frac{W}{R}$ and, hence, the critical angle in terms of stream velocity and the diameter of the cable. Thus:

$$\frac{W}{R} = 175 \frac{ft}{sec^2} \frac{d}{V^2} \qquad (13)$$

If we now consider that the tension at the top, T_1, is limited, as specified in equation (4), we can calculate the limiting case of the maximum amount of cable, s_m, that can be towed at the critical angle with nothing on the bottom end, by simple geometry. These values and the corresponding values of x_m and y_m are given as follows:

$$s_m\ (W \sin \varphi_c + 0.02\ R) = 3.84 \times 10^6 \frac{\text{lbs}}{\text{ft}^2}\ d^2 \qquad (14a)$$

Substituting from equations (2) and (9)

$$s_m = \frac{3.84 \times 10^6\ \text{ft}^2 \left(\frac{d}{V^2}\right)}{(210\ \text{ft}) \sin \varphi_c \left(\frac{d}{V^2}\right) + 0.024\ \sec^2} \qquad (14b)$$

$$y_m = s_m \sin \varphi_c \qquad (15)$$

$$x_m = s_m \cos \varphi_c \qquad (16)$$

The results of these calculations are given in Table II.

TABLE II

φ_c deg.	$\frac{d}{V^2}$ sec²/ft	s_m ft	y_m ft	x_m ft
5	0.435×10^{-4}	6,740	586	6,700
10	1.74×10^{-4}	22,000	3,830	21,700
15	4.00×10^{-4}	33,700	8,730	32,500
20	7.15×10^{-4}	36,400	12,400	34,200
25	11.4×10^{-4}	35,100	14,800	31,800
30	16.6×10^{-4}	32,200	16,100	27,900
35	23.0×10^{-4}	29,400	16,900	24,100
40	30.9×10^{-4}	26,800	17,200	20,500
45	40.5×10^{-4}	24,800	17,500	17,500
50	51.5×10^{-4}	23,200	17,800	14,900
55	68.5×10^{-4}	21,800	17,900	12,500
60	88.5×10^{-4}	20,800	18,000	10,400
65	114×10^{-4}	19,900	18,100	8,440
70	149×10^{-4}	19,300	18,100	6,600

The values for the general cable characteristics can now also be expressed in terms of the diameter of the cable, the free-stream velocity, and the non-dimensional cable functions which have been tabulated in Reference 1. Thus:

$$\frac{T_o}{d^2} = \frac{3.84 \times 10^6}{\tau_1} \ \frac{\text{lbs}}{\text{ft}^2} \tag{17}$$

$$y_1 = 3.20 \times 10^6 \ \frac{\text{ft}^2}{\text{sec}^2} \left(\frac{\eta_1}{\tau_1}\right)\left(\frac{d}{V^2}\right) \tag{18}$$

$$x_1 = 3.20 \times 10^6 \ \frac{\text{ft}^2}{\text{sec}^2} \left(\frac{\xi_1}{\tau_1}\right)\left(\frac{d}{V^2}\right) \tag{19}$$

$$s_1 = 3.20 \times 10^6 \ \frac{\text{ft}^2}{\text{sec}^2} \left(\frac{\sigma_1}{\tau_1}\right)\left(\frac{d}{V^2}\right) \tag{20}$$

Values of these parameters have been calculated for a range of critical angles (hence a range of values of $\frac{d}{V^2}$) and results are given in Appendix I. Results have also been plotted and the resulting curves are given in Appendix II.

CALCULATIONS FOR FAIRED CABLE

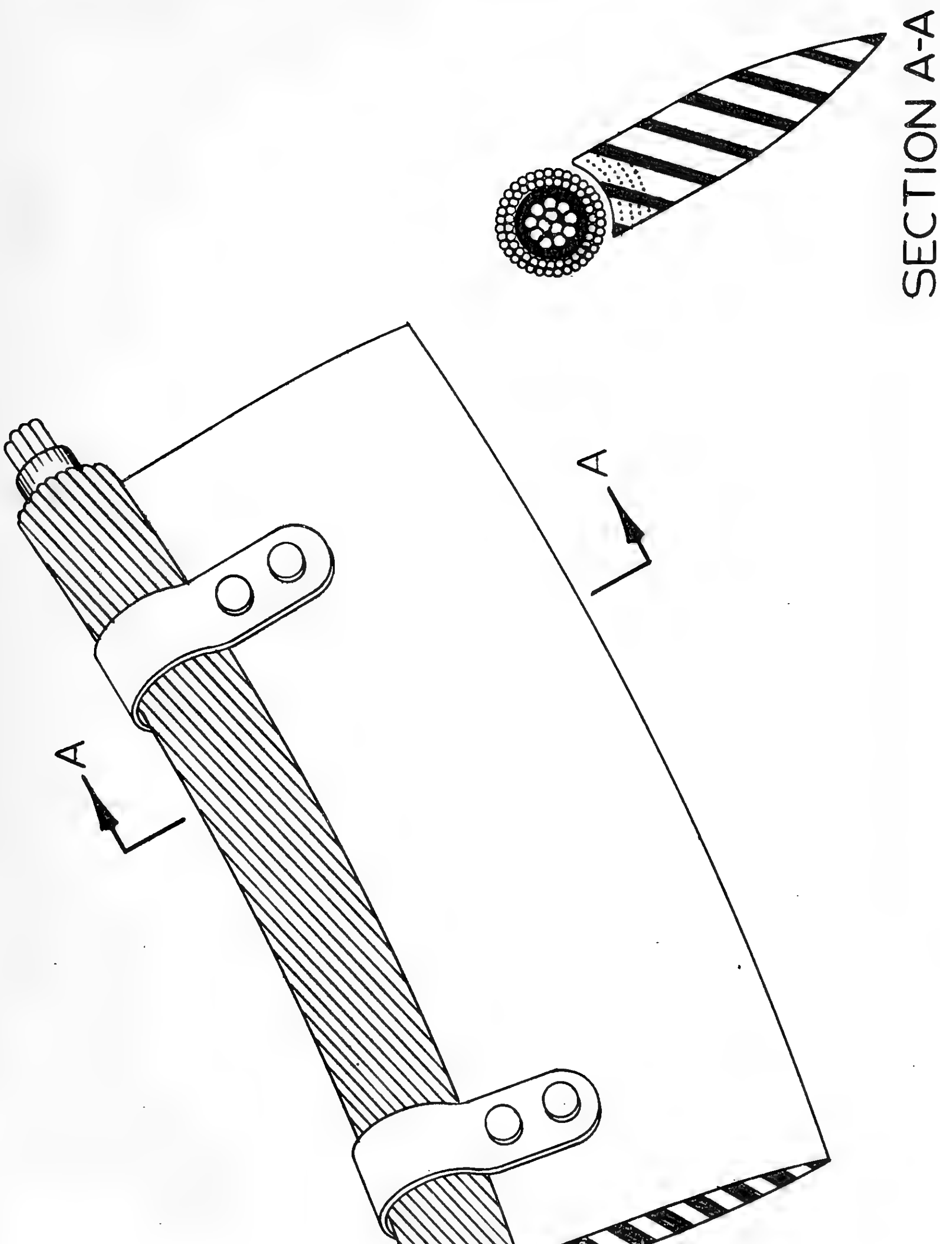
As pointed out previously, the principal difference between the faired-cable case and the unfaired case lies in specification of the hydrodynamic loading. This is, providing the forces acting on the fairing are assumed to be transferred into the cable at intervals along its length, as will be the case here.

It appears that the clip-type fairing, illustrated in Figure 4, is a reasonable design upon which to base design calculations. Experimental evidence indicates that a configuration having a thickness-to-chord ratio of about 1/4 and a ratio of fairing thickness to cable diameter of about 0.8 is an optimum design. This configuration will have a drag coefficient, C_D, of about 0.2 in which case the expression for R becomes:

$$R = 0.2 \frac{\text{lb sec}^2}{\text{ft}^4} dV^2 \qquad (21)$$

If it is assumed that the fairing, which is constructed of rubber, is weightless in water, then the expression for W is still that given in equation (2). Namely,

$$W = 210 \frac{\text{lbs}}{\text{ft}^3} d^2 \qquad (2)$$



Double-Armor Cable with Clip-Type Fairing

Figure 4

We must now consider the question of how to express F and G. Actually, there is presently a great need for experimental data on the values of these loading functions for faired shapes at angles to the stream. As a result, there is still considerable disagreement as to the functional relationship between F and G and the stream angle, φ. Eames, in Reference 2, adopted a simplified approach to the problem and made the following assumption:

$$\frac{F}{R} = \sin \varphi \tag{22}$$

$$\frac{G}{R} = \cos \varphi \tag{23}$$

This results from the assumption that the drag, R, is always parallel to the stream which would appear reasonable if the total drag were due only to shear forces on the surface. This would not be the case unless the faired cable approached a flat plate of vanishingly small thickness. Eames contends, however, that for reasonably high chord-to-thickness ratios, this is a good approximation and the resulting simplification of the equations for the cable configuration justifies its use. Whicker, in Reference 3, attempts to reconcile data on faired struts and arrives at the following expressions which

actually involve the thickness-to-chord ratio, $\left(\frac{t}{c}\right)$:

$$\frac{F}{R} = \left(1 - \frac{t}{c}\right) \sin \varphi + \frac{t}{c} \sin^2 \varphi \tag{24}$$

$$\frac{G}{R} = \left(0.386 - 0.303\frac{t}{c}\right) \cos \varphi - \left(0.055 - 0.020\ \frac{t}{c}\right) \cos^2 \varphi \tag{25}$$

For a thickness-to-chord ratio of 1/4 these expressions reduce to

$$\frac{F}{R} = 0.75 \sin \varphi + 0.25 \sin^2 \varphi \tag{24a}$$

$$\frac{G}{R} = 0.31 \cos \varphi - 0.05 \cos^2 \varphi . \tag{25a}$$

Actually, there appears to be only a small difference in the two expressions for $\frac{F}{R}$ and the simpler one used by Eames is probably acceptable. There is, however, a serious difference in the two expressions for $\frac{G}{R}$, Whicker's values being only about 1/3 of those given by Eames. Since the relationship given by Whicker is based on some actual data it is likely that it is much closer to the actual case, and use of Eames' expression would probably result in an overestimate of the resulting tension. Nevertheless, there is a compelling argument for using the relation suggested by Eames in that he has tabulated the resulting evaluation of the integral functions for the cable configuration. Tables computed with the relation proposed by Whicker are not available, although it is

understood that such a formulation has been programmed for machine calculation by the Taylor Model Basin. Should tables using Whicker's expressions for F and G become available, the calculations made herein should be repeated but, for the present purpose, we will make use of Eames' calculations. In doing so, however, the caution must be made that computed values of the tension are apt to be greater than might reasonably be expected in actual fact.

If we adopt the relations expressed in equations (22) and (23) for the loading functions, then the critical angle (designated as ψ to avoid confusion) is given by:

$$\psi = \text{arc tan} \frac{W}{R} , \tag{26}$$

which, upon substitution, becomes:

$$\tan \psi = 1050 \frac{\text{ft}}{\text{sec}^2} \frac{d}{V^2} \tag{27}$$

As in the previous case for unfaired cable, we can now determine, by simple geometry, the limiting case for the maximum amount of faired cable which can be towed with nothing on the bottom end. Thus, with the limitation imposed on the maximum value of T_1 we obtain:

$$s_m = 1.83 \times 10^4 \, (\sin \psi) \text{ ft} \tag{28}$$

$$x_m = 1.83 \times 10^4 \, (\sin \psi \cos \psi) \text{ ft} \tag{29}$$

$$y_m = 1.83 \times 10^4 \, (\sin^2 \psi) \text{ ft} \tag{30}$$

The values obtained from equations (27), (28), (29), and (30) for a range of values of ψ are given in Table III.

TABLE III

ψ deg.	$\frac{d}{V^2}$ sec²/ft	s_m ft	y_m ft	x_m ft
5	8.33×10^{-5}	1,600	140	1,595
10	16.8×10^{-5}	3,180	560	3,130
15	25.5×10^{-5}	4,740	1,200	4,470
20	34.7×10^{-5}	6,260	2,140	5,880
25	44.4×10^{-5}	7,740	3,270	7,010
30	55.0×10^{-5}	9,150	4,570	7,920
35	66.0×10^{-5}	10,480	6,010	8,580
40	79.9×10^{-5}	11,740	7,550	9,000
45	95.2×10^{-5}	12,930	9,140	9,140
50	113×10^{-5}	13,950	10,700	8,960
55	136×10^{-5}	14,980	12,270	8,600
60	165×10^{-5}	15,850	13,710	7,910
65	204×10^{-5}	16,600	14,400	7,030
70	262×10^{-5}	17,200	16,200	5,880

The general relations for the faired cable configuration can now also be expressed in terms of the cable diameter, the free-stream velocity, and the non-dimensional cable functions. These relations are:

$$\frac{T_o}{d^2} = \frac{3.84 \times 10^6}{\tau_1} \frac{\text{lbs}}{\text{ft}^2} \tag{31}$$

$$s_1 = 19.2 \times 10^6 \frac{\text{ft}^2}{\text{sec}^2} \left(\frac{\sigma_1}{\tau_1}\right)\left(\frac{d}{V^2}\right) \tag{32}$$

$$y_1 = 19.2 \times 10^6 \ \frac{ft^2}{sec^2} \left(\frac{\eta_1}{\tau_1}\right)\left(\frac{d}{V^2}\right) \tag{33}$$

$$x_1 = 19.2 \times 10^6 \ \frac{ft^2}{sec^2} \left(\frac{\xi_1}{\tau_1}\right)\left(\frac{d}{V^2}\right) \tag{34}$$

The values of these parameters have been calculated for a range of critical angles using thetabulated cable functions (for the "heavy fine" case) given in Reference 2. Results are tabulated in Appendix III and plotted in Appendix IV.

For the faired-cable case an interesting result is obtained as a consequence of the particular chosen expressions for the loading functions. In this case it can be seen, by examination of the curves in Appendix IV, that there is a maximum value of y_1 for a particular value of $\frac{d}{V^2}$. Cross-plots of these maximum attainable depths and the corresponding values of $\left(\frac{T_0}{d^2}\right),\left(\frac{d}{V^2}\right)$, s_1 and x_1 are shown in Figures 5, 6 and 7. These curves provide a means for determining the greatest depth which can be obtained for a particular value of $\frac{d}{V^2}$ and the corresponding down force which must be applied at the bottom end of the cable within the limitation of 1/3 the breaking strength of the cable.

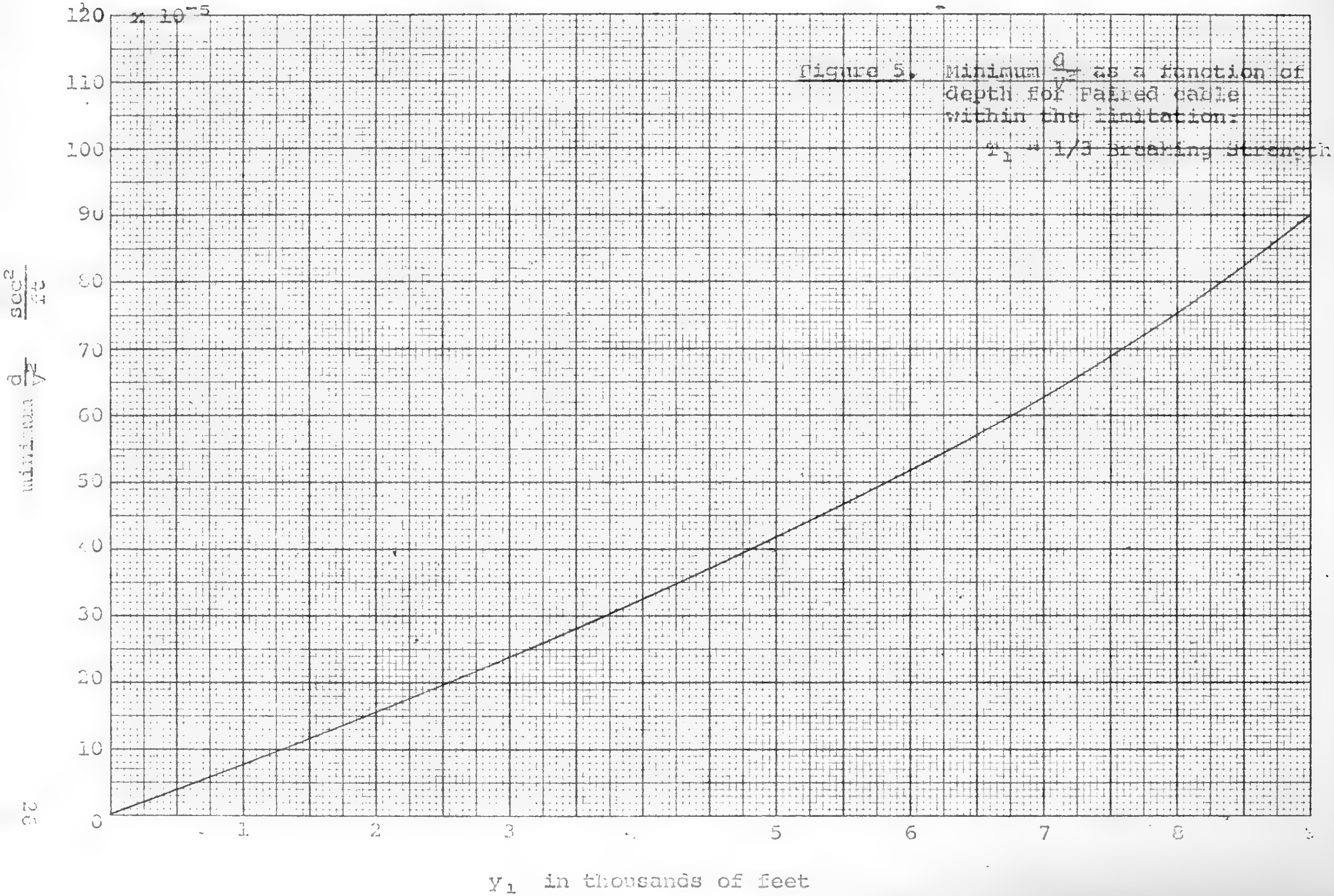


Figure 5. Minimum $\frac{d}{V^2}$ as a function of depth for Faired cable within the limitation: T_1 = 1/3 Breaking Strength

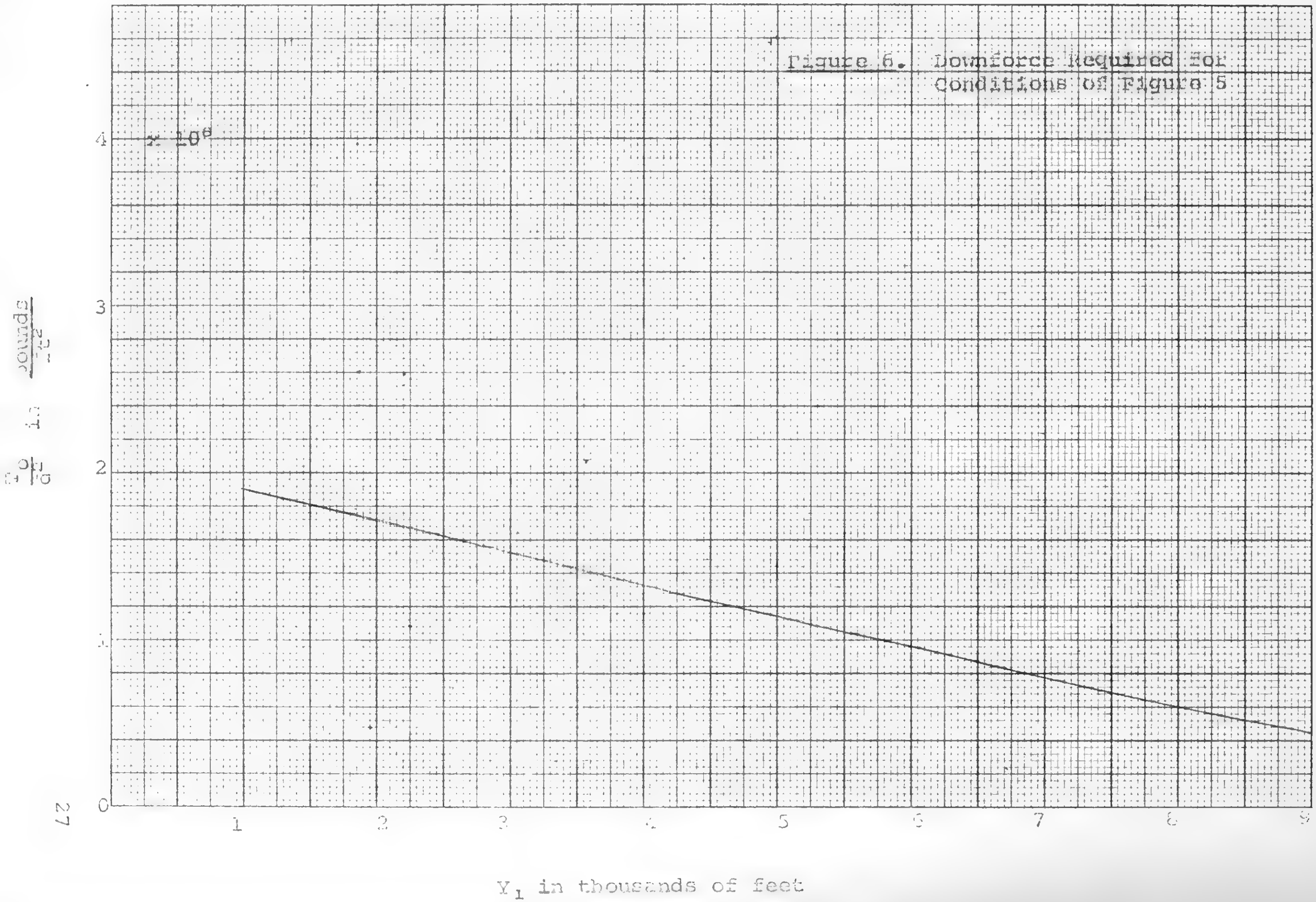


Figure 6. Downforce Required for Conditions of Figure 5

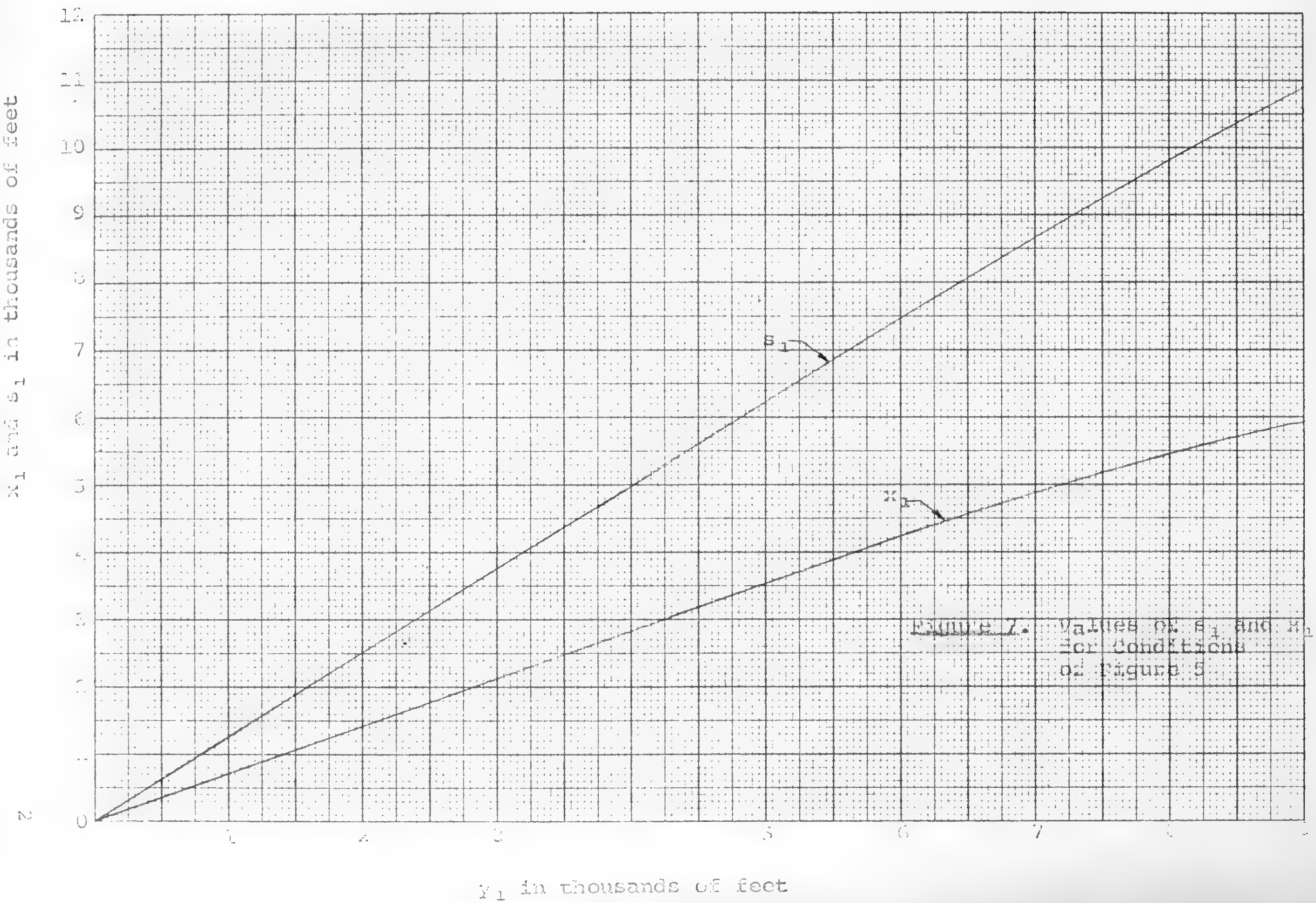


Figure 7. Values of s_1 and x_1 for Conditions of Figure 5

Illustrative Example

To illustrate the use of these results in selecting a cable configuration to meet given requirements, consider the case where it is desired to attain a depth of 5,000 feet at a towing speed of 10 ft/sec.

Unfaired Cable

From the curves in Appendix II we can determine the values of $\frac{T_o}{d^2}$ and s_1 corresponding to a value of y_1 = 5000 ft for each value of $\frac{d}{V^2}$. These values are given in Table IV.

TABLE IV

$\frac{d}{V^2} \times 10^5$ sec^2/ft	d ft	d in.	s_1 ft	$\frac{T_o}{d^2} \times 10^{-6}$ lbs/ft^2	T_o lbs
22.5	.0225	.270	22,500	0	0
40.0	.0400	.480	13,900	2.06	3,300
71.5	.0715	.857	9,300	2.54	13,000
114	.114	1.37	7,000	2.64	34,300
166	.166	1.99	6,000	2.70	74,500

These results may be cross plotted and a particular configuration selected on the basis of a compromise between the length of cable required, the down force required, and the size of electrical core desired.

Faired Cable

In the case of faired cable we can refer directly to Figures 5, 6 and 7 for the maximum value of y_1 attainable for a particular value of $\frac{d}{V^2}$. In this case we obtain:

$$\frac{T_o}{d^2} = 1.14 \times 10^6 \quad \frac{lbs}{ft^2}$$

$$\frac{d}{V^2} = .42 \times 10^{-5} \quad \frac{sec^2}{ft}$$

whence:

$$d = 0.042 \text{ ft} = 0.504 \text{ inches}$$

$$T_o = 2010 \text{ lbs}$$

$$s_1 = 6200 \text{ ft}$$

$$x_1 = 3500 \text{ ft} .$$

There are other combinations of values, obtainable from the curves in Appendix IV, which will satisfy these requirements. The above values, however, represent the minimum cable diameter for the given depth within the limitation of a maximum tension equal to 1/3 the breaking strength of the cable.

REFERENCES

REFERENCES

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2. M. C. Eames, "The Configuration of a Cable Towing a Heavy Submerged Body from a Surface Vessel", Naval Research Establishment (Canada) Report PHx-103, November 1956.

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APPENDIX I

TABULATION OF CALCULATIONS FOR UNFAIRED CABLE

$\varphi_c = 5°\quad \frac{d}{V^2} = 4.35 \times 10^{-5}\ \frac{sec^2}{ft}$

φ_1	τ_1	σ_1	η_1	ξ_1	$\frac{T_o}{d^2} \times 10^{-6}$	y_1	x_1	s_1
Deg.					lbs/ft²	ft	ft	ft
5*	--	--	--	--	0	586	6700	6740
6	1.3517	16.0926	3.9144	15.0525	2.84	402	1550	1650
10	1.1554	6.7358	2.7191	5.7741	3.33	327	695	810
15	1.0981	4.0820	2.1639	3.1798	3.50	274	403	516
20	1.0722	2.9148	1.8182	2.0654	3.58	235	268	378
30	1.0462	1.7913	1.3561	1.0429	3.68	181	138	238
40	1.0322	1.2184	1.0315	0.5717	3.72	139	77	164
50	1.0229	0.8520	0.7741	0.3115	3.75	105	42	116
60	1.0159	0.5833	0.5549	0.1568	3.76	76	21	80
70	1.0101	0.3663	0.3587	0.0647	3.80	49	9	50
80	1.0049	0.1769	0.1760	0.0155	3.82	24	2	24

$\varphi_c = 10°\quad \frac{d}{V^2} = 17.4 \times 10^{-5}\ \frac{sec^2}{ft}$

φ_1	τ_1	σ_1	η_1	ξ_1	$\frac{T_o}{d^2} \times 10^{-6}$	y_1	x_1	s_1
Deg.					lbs/ft²	ft	ft	ft
10*	--	--	--	--	0	3830	21700	22000
11	1.3126	10.1330	3.5891	9.0405	2.92	1940	3830	5450
15	1.1753	4.9662	2.4799	3.9952	3.24	1170	1900	2350
20	1.1252	3.2404	1.9718	2.3464	3.41	976	1160	1600
30	1.0811	1.8857	1.4173	1.1123	3.55	731	578	970
40	1.0577	1.2574	1.0617	0.5953	3.635	560	313	662
50	1.0416	0.8699	0.7896	0.3201	3.79	4421	171	464
60	1.0290	0.5915	0.5624	0.1597	3.74	305	86	321
70	1.0185	0.3695	0.3617	0.0655	3.775	198	36	202
80	1.0090	0.1776	0.1767	0.0156	3.81	98	9	98

* Special case of cable towed at critical angle.

$\varphi_c = 15°$ $\frac{d}{V^2} = 40.0 \times 10^{-5} \frac{sec^2}{ft}$

φ_1	τ_1	σ_1	η_1	ξ_1	$\frac{T_o}{d^2} \times 10^{-6}$	y_1	x_1	s_1
Deg.					lbs/ft^2	ft	ft	ft
15	--	--	--	--	0	8730	32500	33700
16	1.4019	7.9397	3.5062	6.7658	2.74	4310	6170	7250
20	1.2457	4.1057	2.3590	3.1082	3.083	2420	3190	4220
25	1.1835	2.7569	1.8507	1.8594	3.24	2000	2010	2970
30	1.1481	2.0741	1.5378	1.2527	3.35	1710	1400	2310
40	1.1041	1.3296	1.1173	0.6394	3.475	1290	740	1540
50	1.0747	0.9020	0.8173	0.3356	3.57	974	400	1070
60	1.0520	0.6057	0.5756	0,1648	3.65	700	200	736
70	1.0329	0.3749	0.3670	0.0667	3.71	454	83	465
80	1.0159	0.1788	0.1779	0.0157	3.78	224	20	225

$\varphi_c = 20°$ $\frac{d}{V^2} = 71.5 \times 10^{-5} \frac{sec^2}{ft}$

φ_1	τ_1	σ_1	η_1	ξ_1	$\frac{T_o}{d^2} \times 10^{-6}$	y_1	x_1	s_1
Deg.					lbs/ft^2	ft	ft	ft
20	--	--	--	--	0	12400	34200	36400
21	1.5794	6.8861	3.5481	5.6003	2.43	5470	8130	10400
25	1.3580	3.6036	2.2968	2.5664	2.83	4040	4330	6350
30	1.2685	2.4378	1.7649	1.5294	3.03	3320	2760	4570
35	1.2166	1.8376	1.4444	1.0222	3.16	2840	1920	3600
40	1.1795	1.4496	1.2091	0.7139	3.26	2445	1390	2935
50	1.1262	.9523	.8605	0.3600	3.41	1825	730	2020
60	1.0867	.6273	.5955	0.1725	3.535	1310	364	1378
70	1.0543	.3829	.3747	0.0686	3.64	850	149	866
80	1.0260	.1806	.1797	0.0159	3.745	417	35	420

$\varphi_c = 25°$ $\frac{d}{V^2} = 114 \times 10^{-5} \frac{sec^2}{ft}$

φ_1	τ_1	σ_1	η_1	ξ_1	$\frac{T_o}{d^2} \times 10^{-6}$	y_1	x_1	s_1
Deg.					lbs/ft^2	ft	ft	ft
25	--	--	--	--	0	14800	31800	35100
26	1.8528	6.3531	3.6828	4.9197	2.07	7250	9700	12500
30	1.5126	3.2795	2.2684	2.1915	2.54	5470	5290	7900
35	1.3784	2.2044	1.6964	1.2816	2.79	4490	3400	5840
40	1.3011	1.6501	1.3607	0.8407	2.95	3820	2360	4620
50	1.2030	1.0282	.9256	0.3975	3.19	2850	1210	3120
60	1.1361	.6581	.6241	0.1837	3.38	2010	590	2220
70	1.0838	.3939	..3844	0.0713	3.54	1800	240	1330
80	1.0395	.1830	.1821	0.0162	3.70	640	57	642

$\varphi_c = 30°$ $\frac{d}{V^2} = 166 \times 10^{-5} \frac{sec^2}{ft}$

φ_1	τ_1	σ_1	η_1	ξ_1	$\frac{T_o}{d^2} \times 10^{-6}$	y_1	x_1	s_1
Deg.					lbs/ft^2	ft	ft	ft
30	--	--	--	--	0	16100	27900	32200
31	2.2478	6.1162	3.8988	4.4917	1.71	9200	10600	14450
35	1.7128	3.0521	2.2579	1.9047	2.24	7010	5900	9450
40	1.5116	2.0163	1.6326	1.0794	2.54	5740	3780	7060
45	1.3983	1.4872	1.2767	0.6881	2.75	4850	2620	5630
50	1.3187	1.1444	1.0247	0.4560	2.82	4130	1840	4610
60	1.2058	0.7018	0.6644	0.1997	3.19	2920	879	3100
70	1.1236	0.4089	0.3999	0.0748	3.41	1880	350	1930
80	1.0572	0.1862	0.1852	0.0166	3.64	930	83	935

$\varphi_c = 35° \quad \frac{d}{V^2} = 230 \times 10^{-5} \frac{sec^2}{ft}$

φ_1	τ_1	σ_1	η_1	ξ_1	$\frac{T_o}{d^2} \times 10^{-6}$	y_1	x_1	s_1
Deg.					lbs/ft^2	ft	ft	ft
35	--	--	--	--	0	16900	24100	29400
36	2.8043	6.0705	4.1902	4.2030	1.37	11000	11050	15950
40	1.9617	2.8751	2.2513	1.6638	1.96	8450	6240	10780
45	1.6645	1.8482	1.5626	0.9025	2.31	6920	3990	8170
50	1.5024	1.3334	1.1844	0.5534	2.56	5800	2710	6540
60	1.3053	.7646	.7222	0.2232	2.94	4070	1250	4300
70	1.1770	.4289	.4192	0.0797	3.27	2620	498	2685
80	1.0795	.1902	.1892	0.0171	3.56	1290	117	1300

$\varphi_c = 40° \quad \frac{d}{V^2} = 309 \times 10^{-5} \frac{sec^2}{ft}$

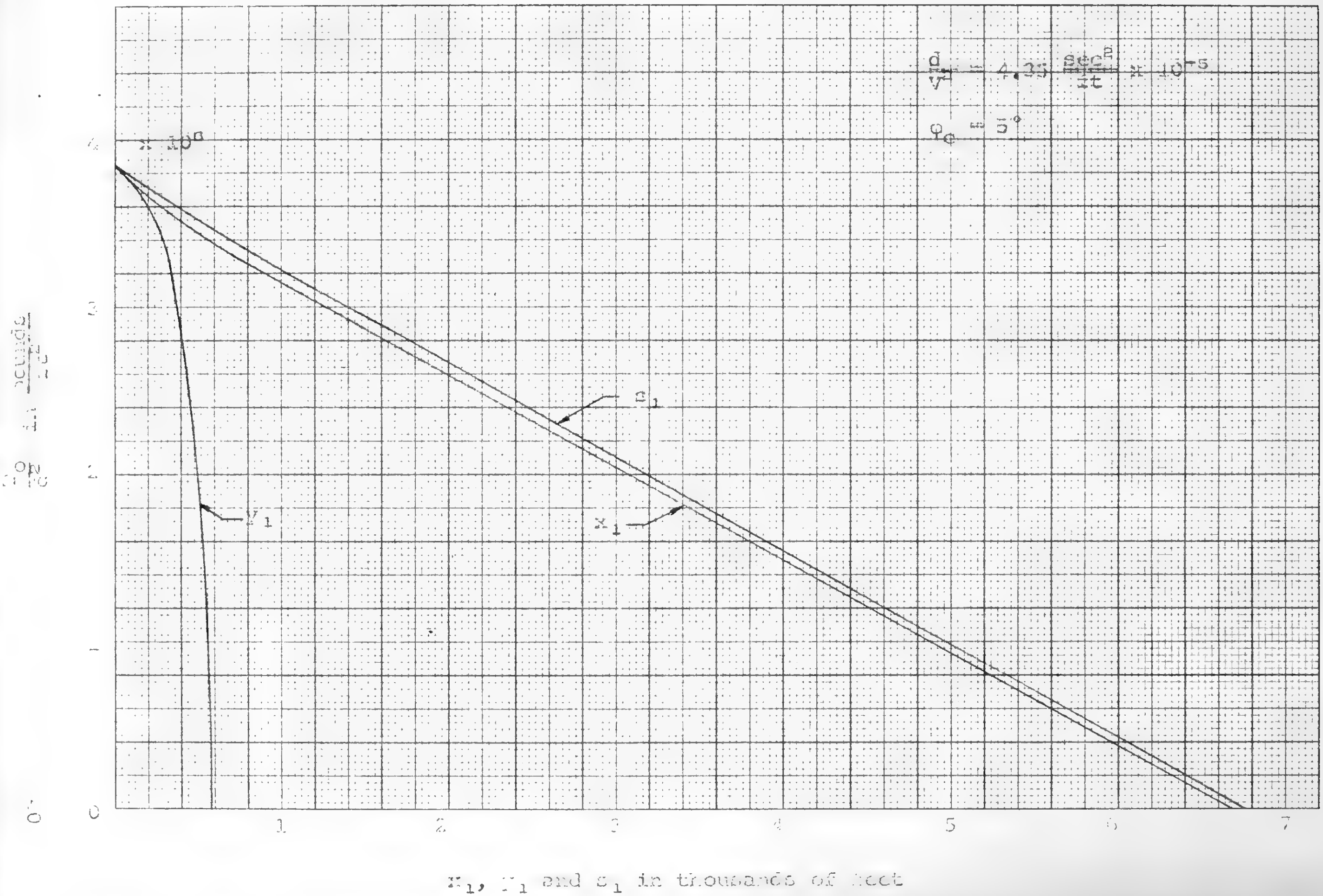
φ_1	τ_1	σ_1	η_1	ξ_1	$\frac{T_o}{d^2} \times 10^{-6}$	y_1	x_1	s_1
Deg.					lbs/ft^2	ft	ft	ft
40	--	--	--	--	0	17200	20500	26800
41	3.5754	6.1516	4.5467	3.9821	1.07	12600	11000	17000
45	2.2587	2.7156	2.2331	1.4427	1.70	9790	6330	11900
50	1.8296	1.6819	1.4758	0.7395	2.10	7980	3990	9100
55	1.6044	1.1775	1.0770	0.4310	2.39	6640	2650	7250
60	1.4534	.8589	.8088	0.2591	2.64	5500	1760	5850
70	1.2495	.4562	.4456	0.0864	3.07	3530	684	3610
80	1.1087	.1953	.1942	0.0177	3.47	1735	158	1745

$\varphi_c = 45°$ $\frac{d}{V^2} = 405 \times 10^{-5} \frac{sec^2}{ft}$

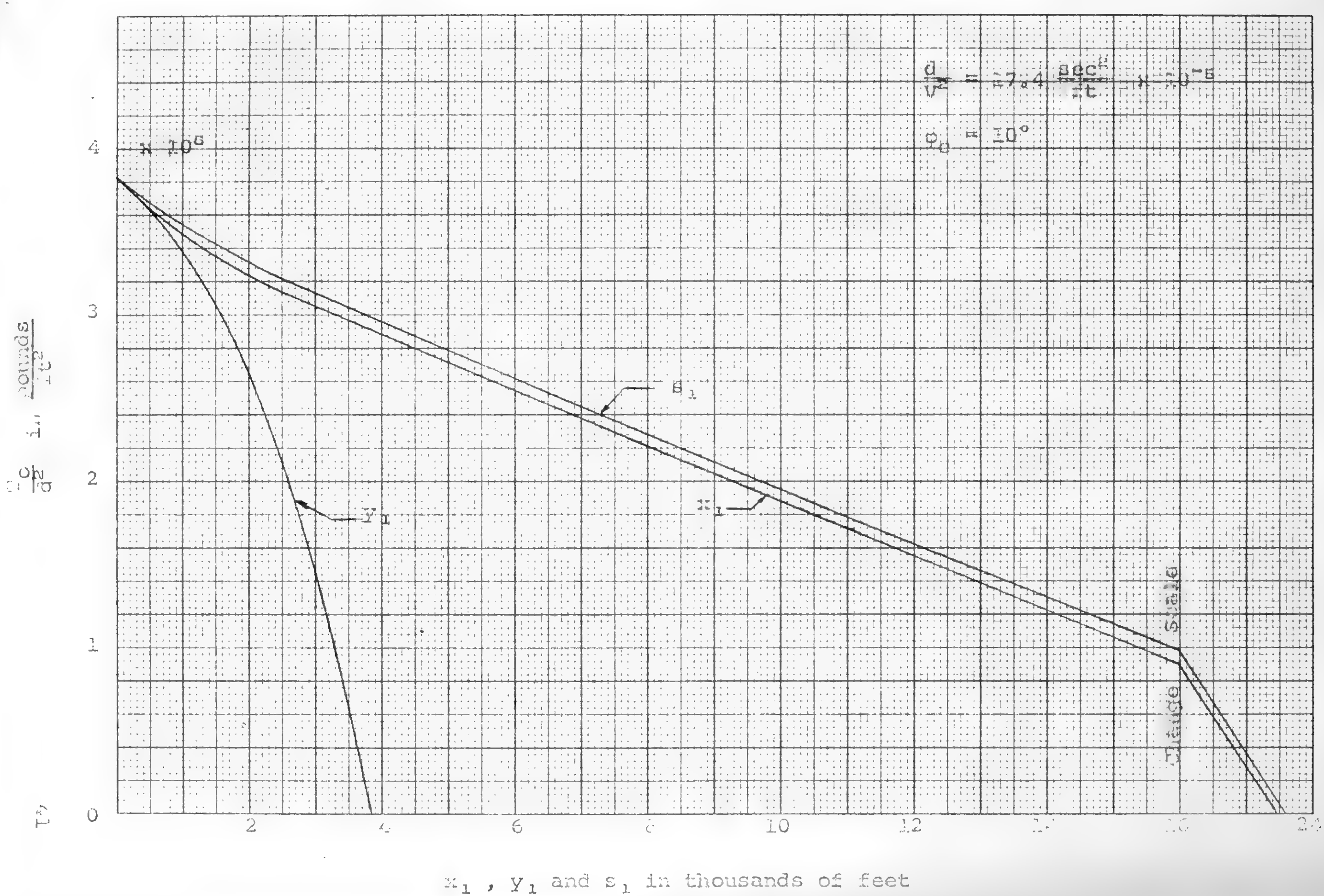
φ_1	τ_1	σ_1	η_1	ξ_1	$\frac{T_o}{d^2} \times 10^{-6}$	y_1	x_1	s_1
Deg.					lbs/ft^2	ft	ft	ft
45	--	--	--	--	0	17500	17500	24800
46	4.6219	6.3013	4.9439	3.7710	.83	13850	10600	17700
50	2.5954	2.5457	2.1843	1.2247	1.48	10900	6130	12700
55	1.9932	1.5034	1.3621	0.5847	1.93	8850	3800	9760
60	1.6913	1.0123	0.9491	0.3192	2.27	7280	2450	7750
65	1.4950	0.7084	0.6800	0.1782	2.57	5900	1550	6150
70	1.3512	0.4947	0.4827	0.0959	2.84	4630	920	4740
75	1.2385	0.3321	0.3279	0.0468	3.11	3430	490	3480
80	1.1460	0.2019	0.2008	0.0185	3.35	2270	210	2280

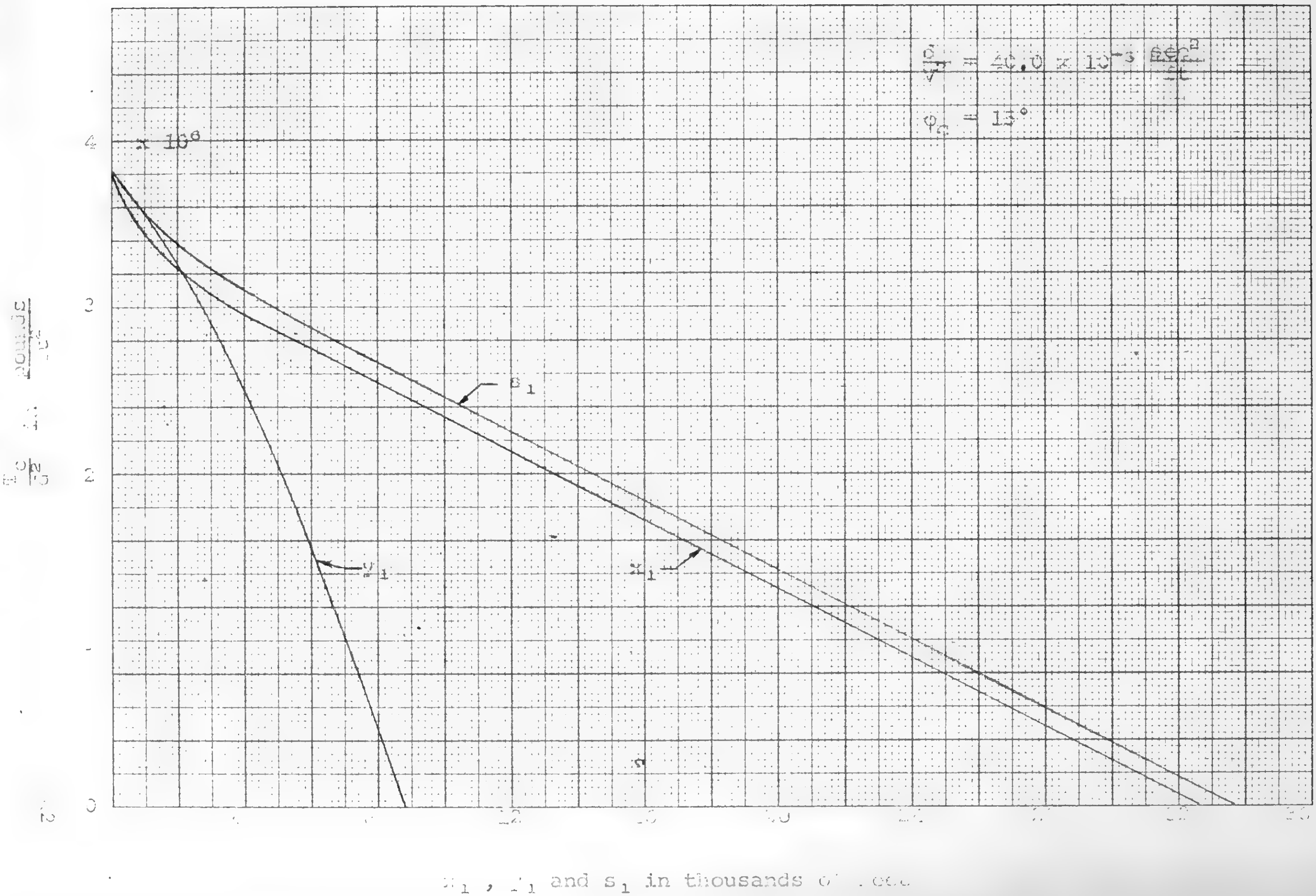
APPENDIX II

DESIGN CURVES FOR UNFAIRED CABLE

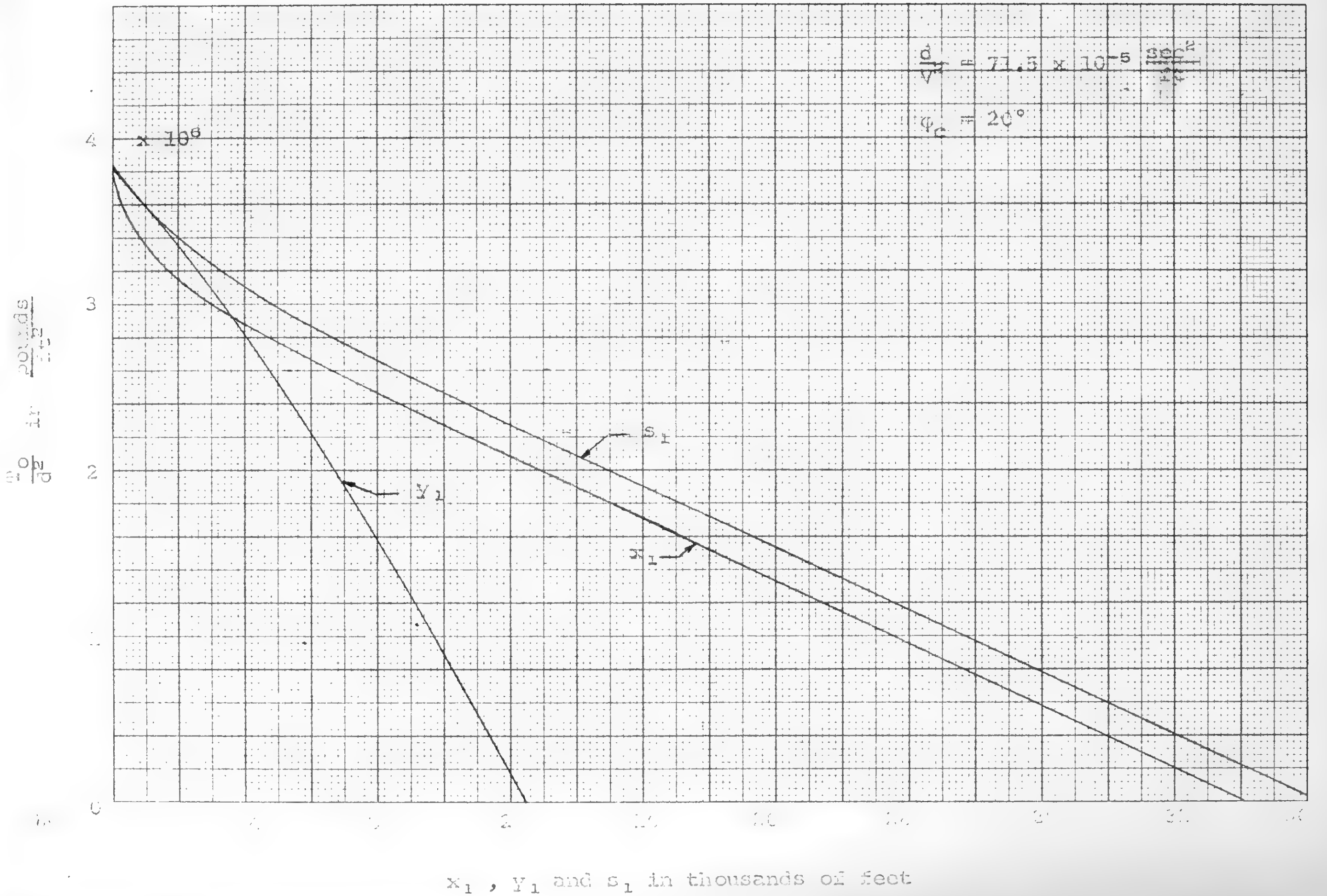


d/V = 4.35 sec²/ft x 10⁻⁵
φ = 5°
s1
x1
y1
0
1
2
3
4
5
6
7
x1, y1 and s1 in thousands of feet

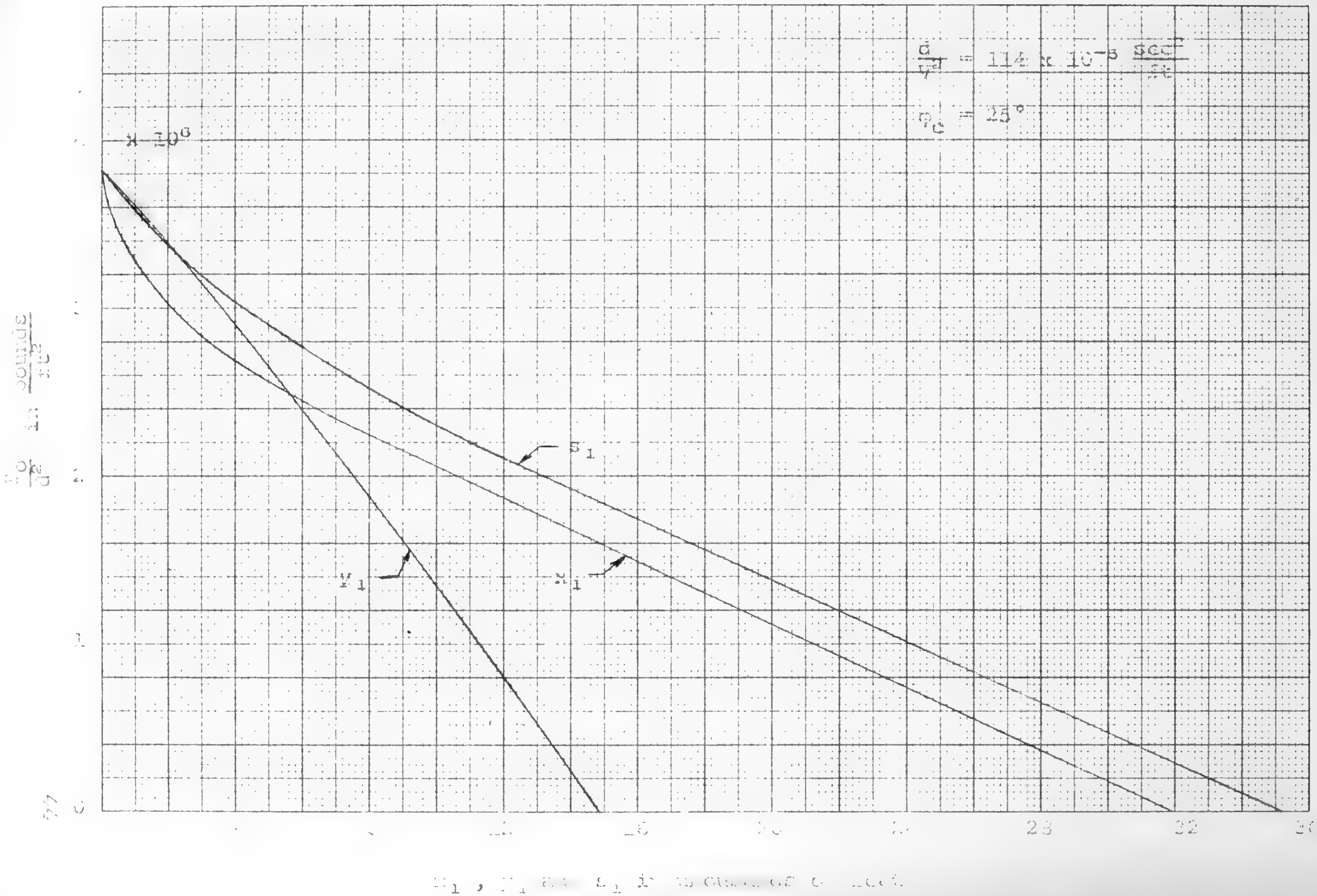

$\times 10^6$
$\varphi_0 = 10^\circ$
s_1
x_1
y_1
Fledge Stable
0
1
2
3
4
2
4
6
8
10
12
14
16
18
20
in pounds/ft²
x_1, y_1 and s_1 in thousands of feet



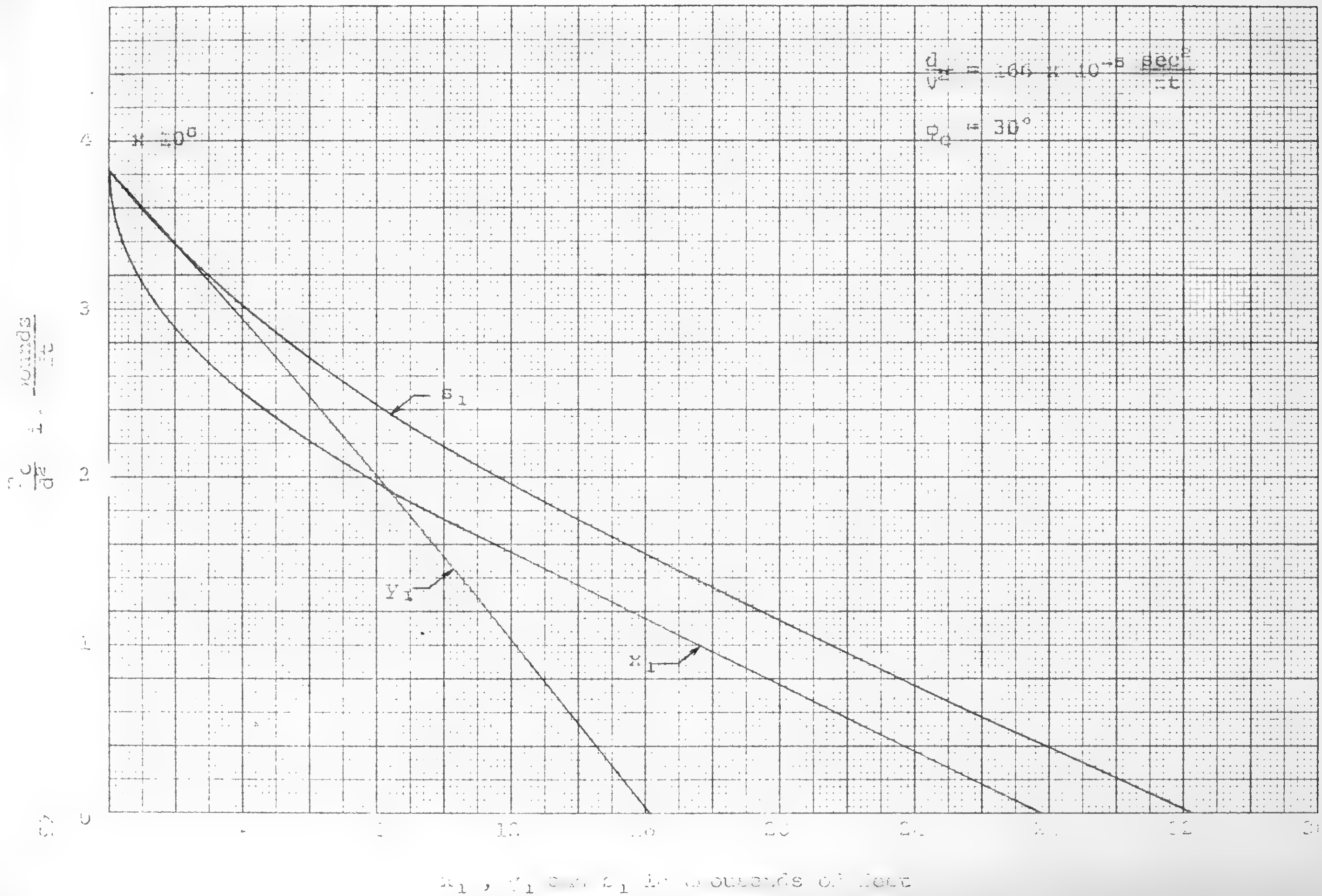
x 10^6
4
3
2
0
s 1
and s 1 in thousands



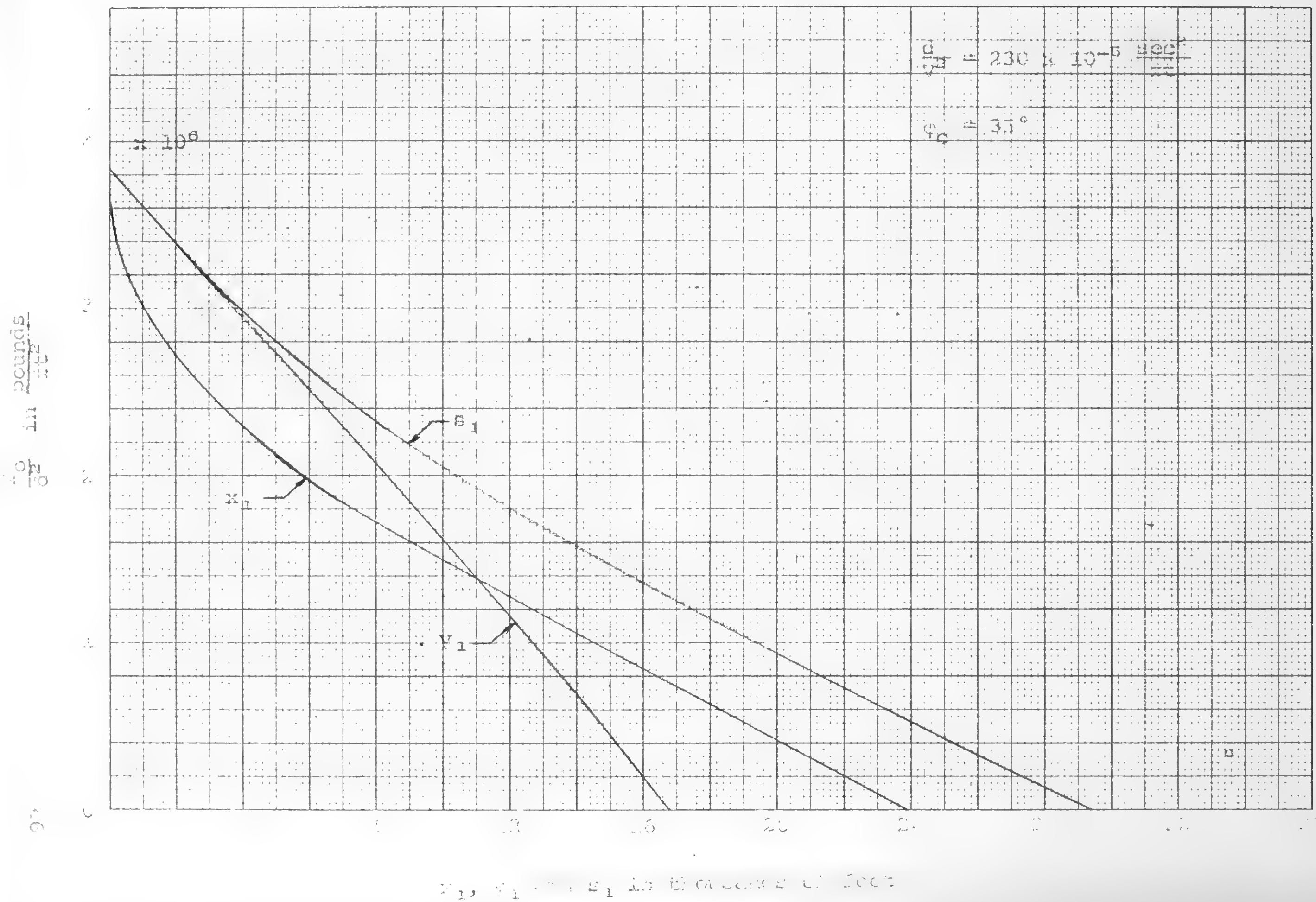
$\frac{d}{V^2} = 71.5 \times 10^{-5}$
$\varphi_c = 20°$
x 10^6
4
3
2
0
s_1
x_1
y_1
x_1, y_1 and s_1 in thousands of feet

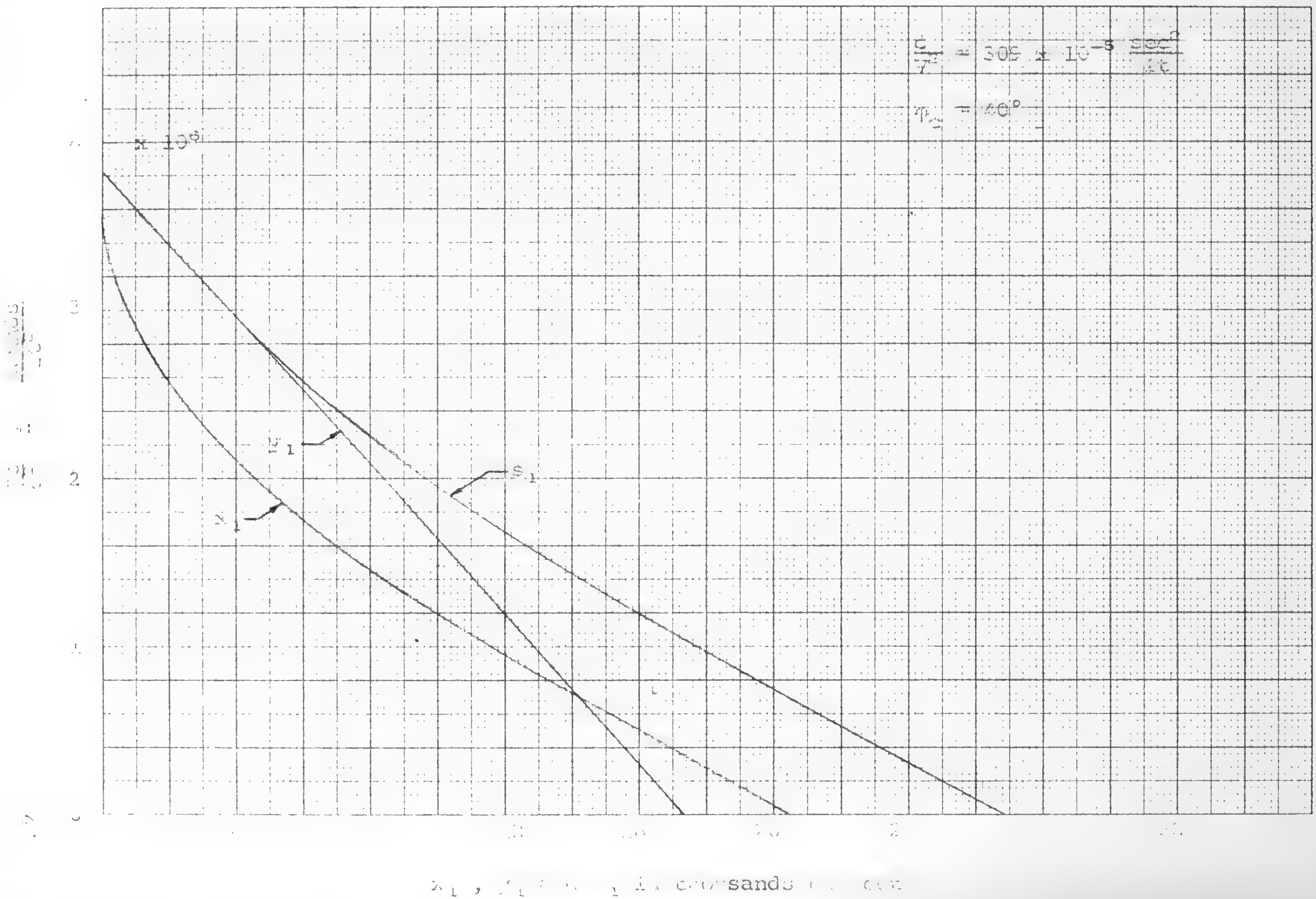


x 10^6
a/V^a = 114 x 10^-6 sec/ft
φ_c = 25°
s1
y1
x1
0
28
32
36

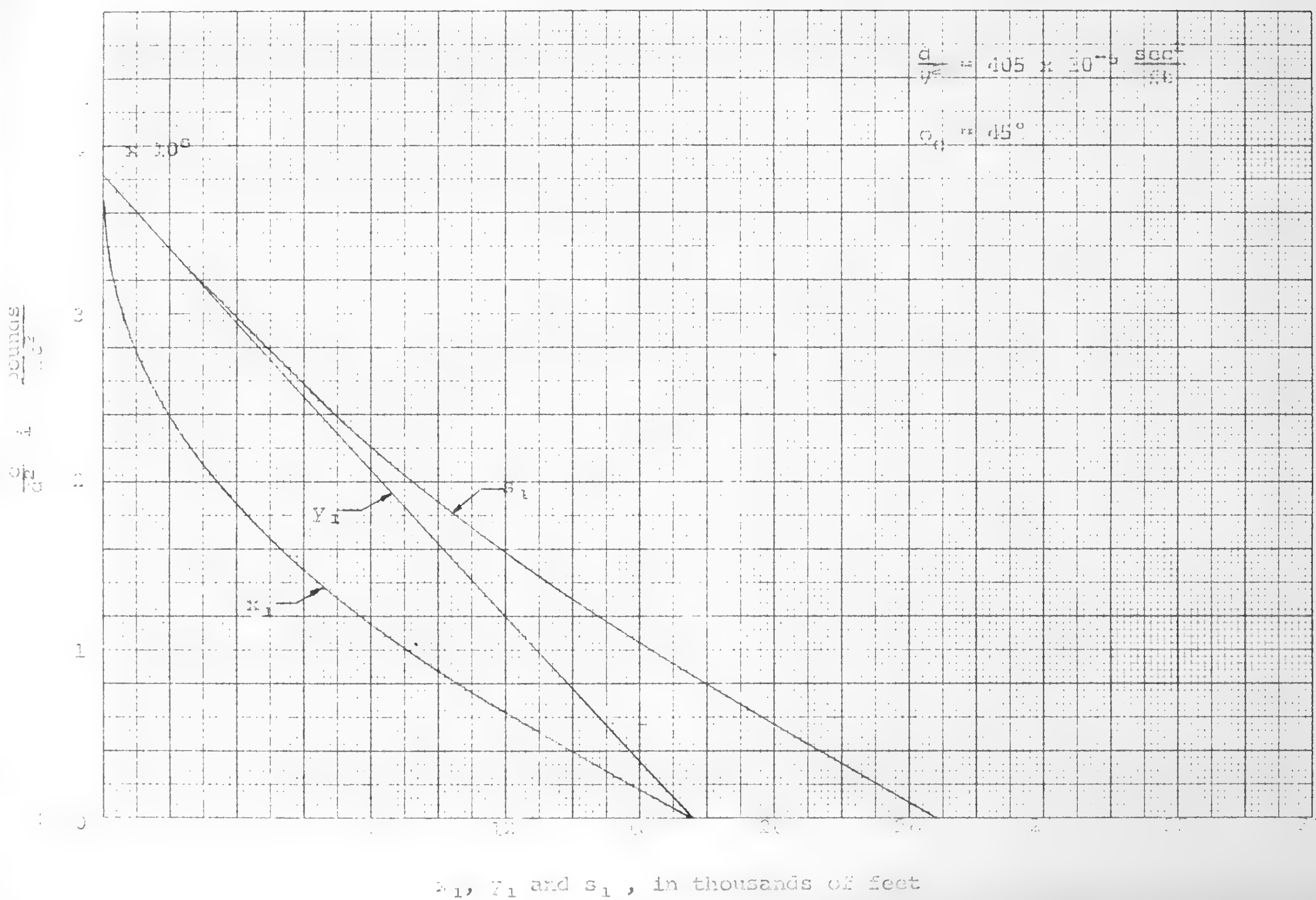


$\frac{d}{V^2}$ = .66 x 10^{-5} $\frac{sec^2}{ft}$
φ_0 = 30°
s_1
y_1
x_1
0
1
2
3
4
10
20


x 10^8
s_1
x_1
y_1



x 10⁴
= 308 x 10⁻⁵ sec²/ft
= 40°
y₁
x₁
s₁
3
2
1
0
sands



$\frac{d}{V^2}$ = 405 x 10^{-5} $\frac{sec^2}{ft}$
θ_0 = 45°
x 10^6
S_1
Y_1
X_1
0
1
2
3
x_1, y_1 and s_1, in thousands of feet

APPENDIX III

TABULATION OF CALCULATIONS FOR FAIRED CABLE

$\psi = 5° \quad \frac{d}{V^2} = 8.33 \times 10^{-5} \frac{sec^2}{ft}$

φ_1	σ_1	ξ_1	η_1	$1/\tau_1$	$\frac{T_o}{d^2} \times 10^{-6}$	s_1	x_1	y_1
Deg.					lbs/ft²	ft	ft	ft
5*	--	--	--	--	0	1600	1595	140
15	5.5413	4.4993	2.7138	.175	.672	1552	1260	760
20	3.6169	2.6594	2.1655	.260	.998	1504	1106	901
25	2.6397	1.7556	1.7953	.344	1.32	1452	966	988
30	2.0413	1.2241	1.5206	.424	1.63	1385	830	1032
40	1.3303	0.6388	1.1186	.576	2.21	1226	589	1031
50	0.9055	0.3370	0.8202	.710	2.73	1029	383	932
60	0.6081	0.1656	0.5777	.822	3.16	800	218	760
70	0.3760	0.0670	0.3679	.910	3.49	547	98	536
80	0.1790	0.0157	0.1781	.970	3.73	278	24	276
90	0	0	0	1.000	3.84	0	0	0

$\psi = 10° \quad \frac{d}{V^2} = 16.8 \times 10^{-5} \frac{sec^2}{ft}$

φ_1	σ_1	ξ_1	η_1	$1/\tau_1$	$\frac{T_o}{d^2} \times 10^{-6}$	s_1	x_1	y_1
Deg.					lbs/ft²	ft	ft	ft
10*	--	--	--	--	0	3180	3130	560
15	10.9142	9.4884	4.6189	.089	.342	3130	2720	1325
20	5.3292	4.1497	2.9580	.177	.680	3040	2370	1690
25	3.4485	2.4085	2.2487	.264	1.015	2930	2050	1910
30	2.4935	1.5600	1.8113	.348	1.335	2790	1750	2030
40	1.5087	0.7481	1.2561	.508	1.95	2470	1230	2060
50	0.9848	0.3754	0.8888	.653	2.51	2070	789	1870
60	0.6428	0.1780	0.6099	.778	2.99	1610	446	1530
70	0.3889	0.0701	0.3806	.880	3.38	1100	198	1080
80	0.1819	0.0161	0.1810	.954	3.66	558	49	556
90	0	0	0	1.00	3.84	0	0	0

* Special case of cable towed at critical angle.

$\psi = 20°$ $\frac{d}{V^2} = 34.7 \times 10^{-5} \frac{sec^2}{ft}$

φ_1	σ_1	ξ_1	η_1	$1/\tau_1$	$\frac{T_o}{d^2} \times 10^{-6}$	s_1	x_1	y_1
Deg.					lbs/ft^2	ft	ft	ft
20	0	0	0	0	0	6260	5880	2140
25	9.7718	7.7999	5.4469	.093	0.357	6050	4820	3370
30	4.6864	3.2673	3.1439	.185	0.710	5770	4030	3870
35	2.9742	1.8183	2.2324	.276	1.06	5460	3340	4100
40	2.1046	1.1265	1.7060	.364	1.40	5110	2730	4140
50	1.2081	0.4863	1.0798	.532	2.04	4280	1720	3820
60	0.7310	0.2102	0.6915	.684	2.63	3330	958	3150
70	0.4195	0.0774	0.4103	.816	3.14	2280	421	2230
80	0.1885	0.0168	0.1875	.922	3.54	1160	103	1150
90	0	0	0	1.00	3.84	0	0	0

$\psi = 30°$ $\frac{d}{V^2} = 55.0 \times 10^{-5} \frac{sec^2}{ft}$

φ_1	σ_1	ξ_1	η_1	$1/\tau_1$	$\frac{T_o}{d^2} \times 10^{-6}$	s_1	x_1	y_1
Deg.					lbs/ft^2	ft	ft	ft
30	0	0	0	0	0	9150	7920	4570
35	8.1400	5.7341	5.5470	.101	0.388	8670	6110	5910
40	3.8201	2.2827	2.9522	.201	0.772	8110	4850	6260
45	2.3659	1.2051	1.9761	.299	1.15	7490	3810	6250
50	1.6276	0.7107	1.4338	.395	1.48	6780	2960	5970
60	0.8660	0.2612	0.8156	.577	2.22	5280	1590	4970
70	0.4607	0.0874	0.4501	.743	2.85	3620	685	3530
80	0.1963	0.0178	0.1952	.885	3.40	1830	166	1820
90	0	0	0	1.00	3.84	0	0	0

$\psi = 40°$ $\frac{d}{V^2} = 79.9 \frac{sec^2}{ft}$

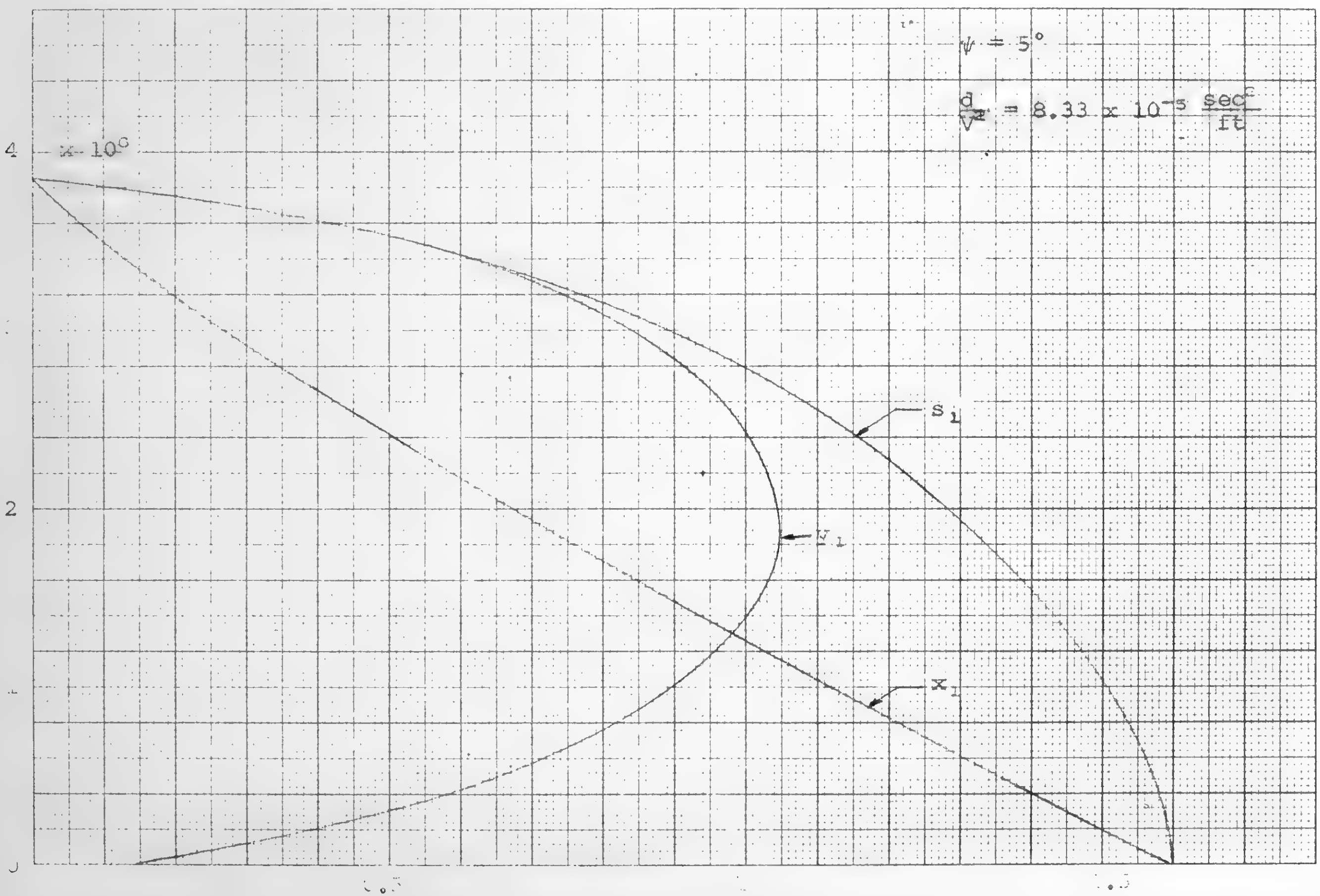
φ_1	σ_1	ξ_1	η_1	$1/\tau_1$	$\frac{T_o}{d^2} \times 10^{-6}$	s_1	x_1	y_1
Deg.					lbs/ft²	ft	ft	ft
40	0	0	0	0	0	11740	9000	7550
45	6.2147	3.6774	4.8999	.114	.438	10870	6420	8550
50	2.8356	1.3707	2.4318	.227	.872	9870	4770	8470
55	1.7035	0.6729	1.5334	.338	1.30	8840	3490	7950
60	1.1198	0.3606	1.0476	.447	1.72	7670	2470	7180
70	0.5239	0.1032	0.5110	.653	2.51	5240	1035	5120
80	0.2070	0.0190	0.2058	.839	3.22	2660	244	2640
90	0	0	0	1.00	3.84	0	0	0

$\psi = 50°$ $\frac{d}{V^2} = 113 \frac{sec^2}{ft}$

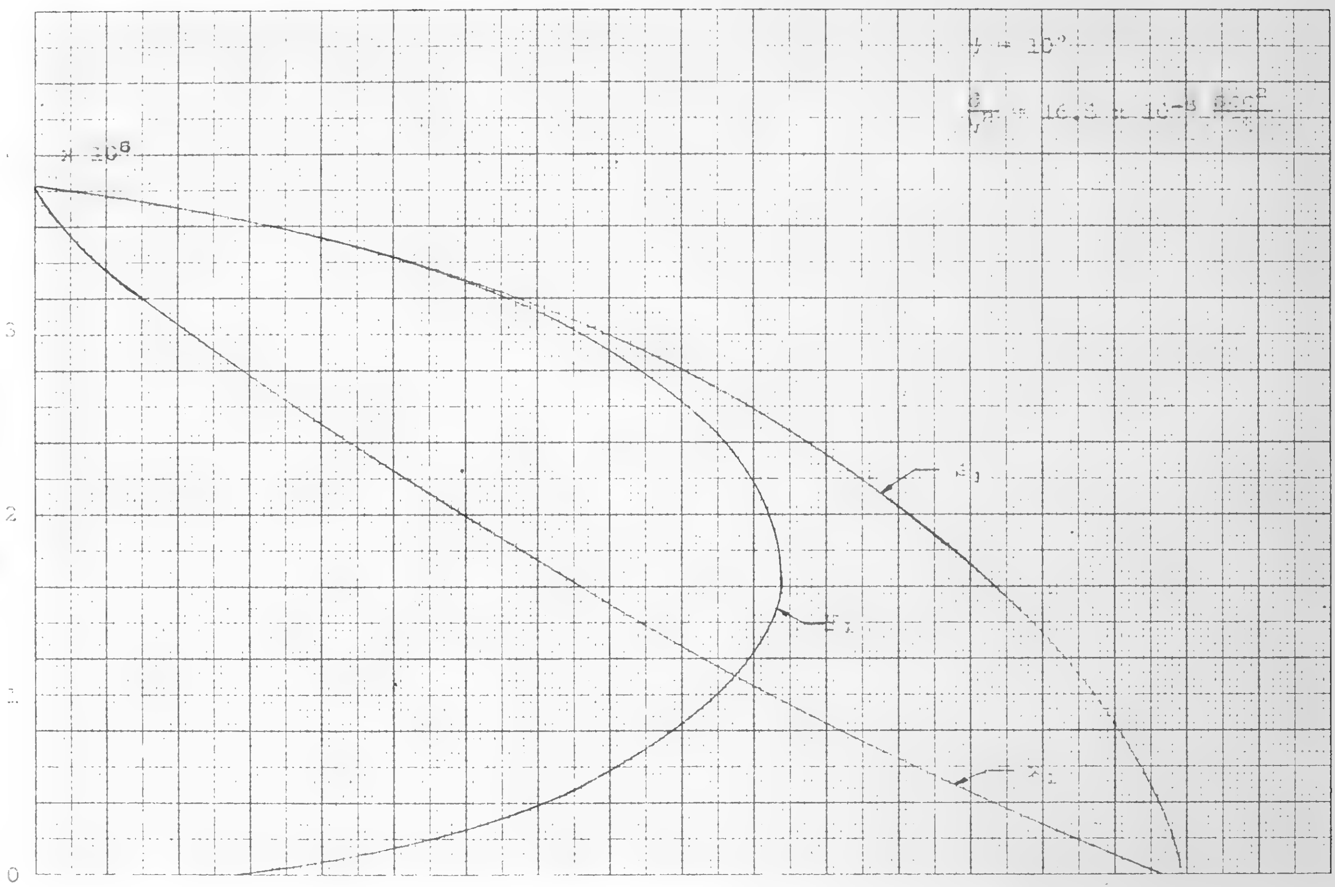
φ_1	σ_1	ξ_1	η_1	$1/\tau_1$	$\frac{T_o}{d^2} \times 10^{-6}$	s_1	x_1	y_1
Deg.					lbs/ft²	ft	ft	ft
50	0	0	0	0	0	13950	8960	10700
55	4.2453	1.9630	3.7028	.136	.523	12500	5790	10920
60	1.8509	0.6651	1.7090	.271	1.04	10900	3910	10050
65	1.0496	0.2911	1.0007	.402	1.55	9170	2540	8750
70	0.6427	0.1340	0.6255	.534	2.05	7440	1550	7240
75	0.3937	0.0584	0.3882	.658	2.53	5620	834	5550
80	0.2233	0.0211	0.2220	.776	2.98	3760	356	3740
90	0	0	0	1.00	3.84	0	0	0

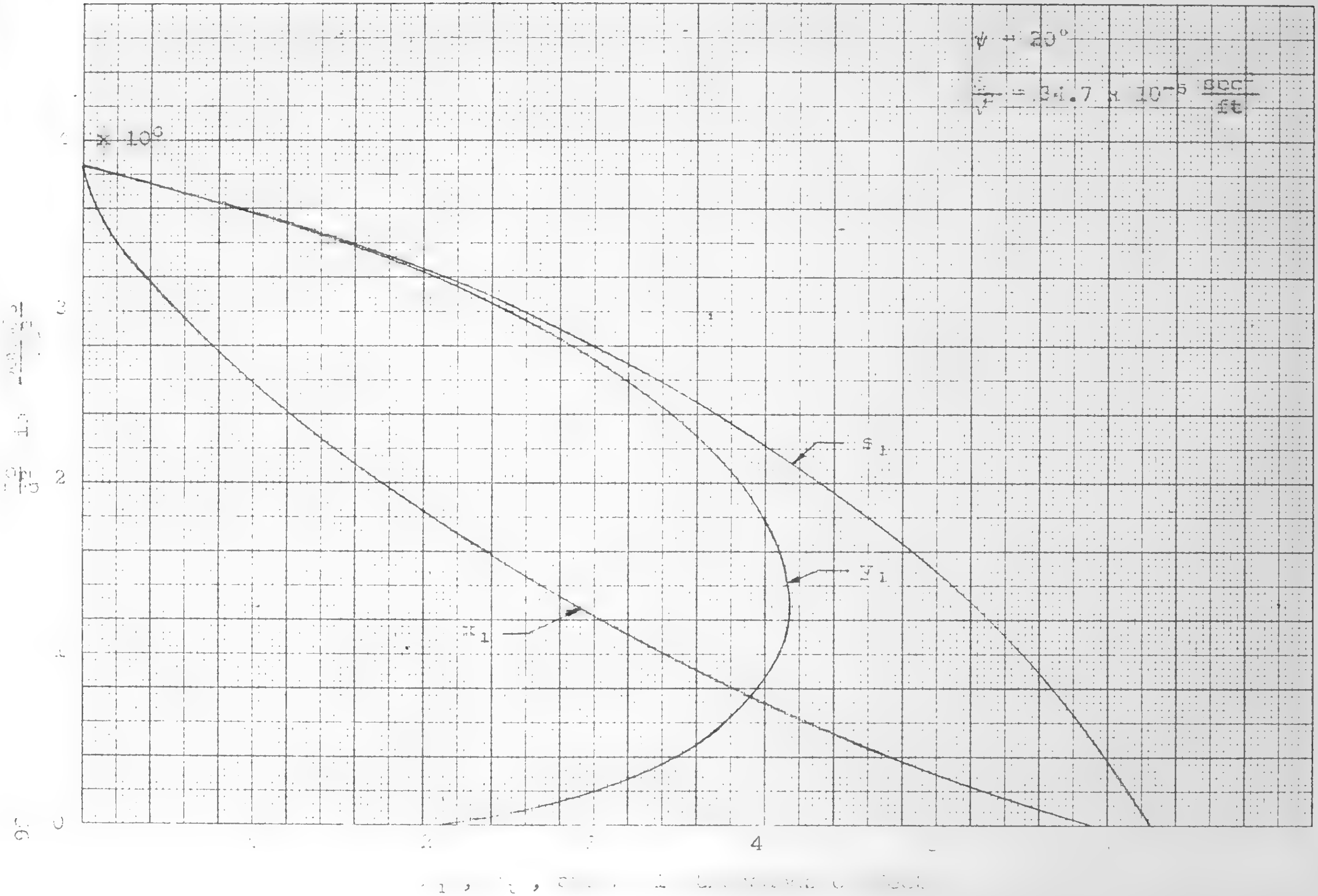
APPENDIX IV

DESIGN CURVES FOR FAIRED CABLE

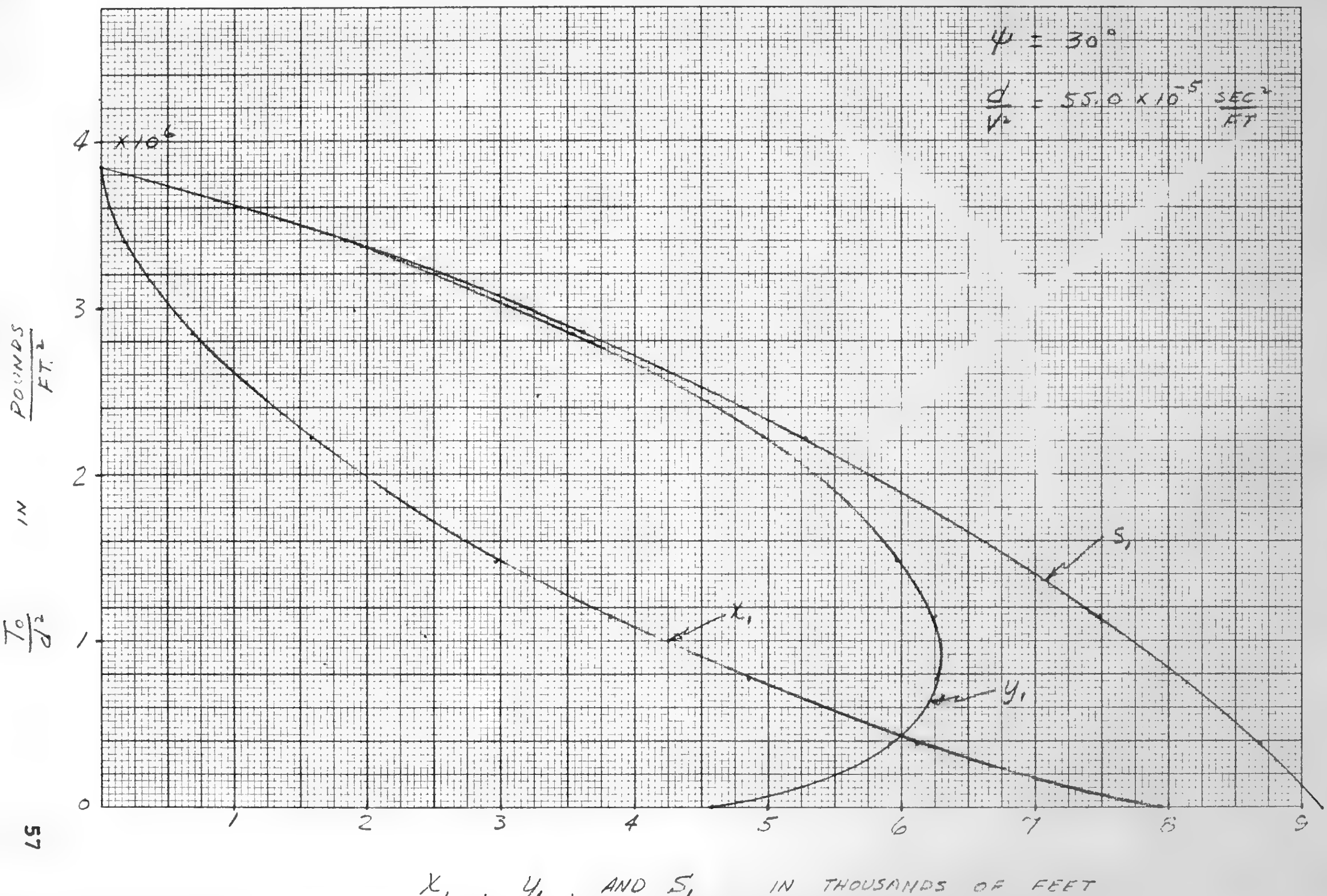


X_1, Y_1, and S_1 in thousands of feet

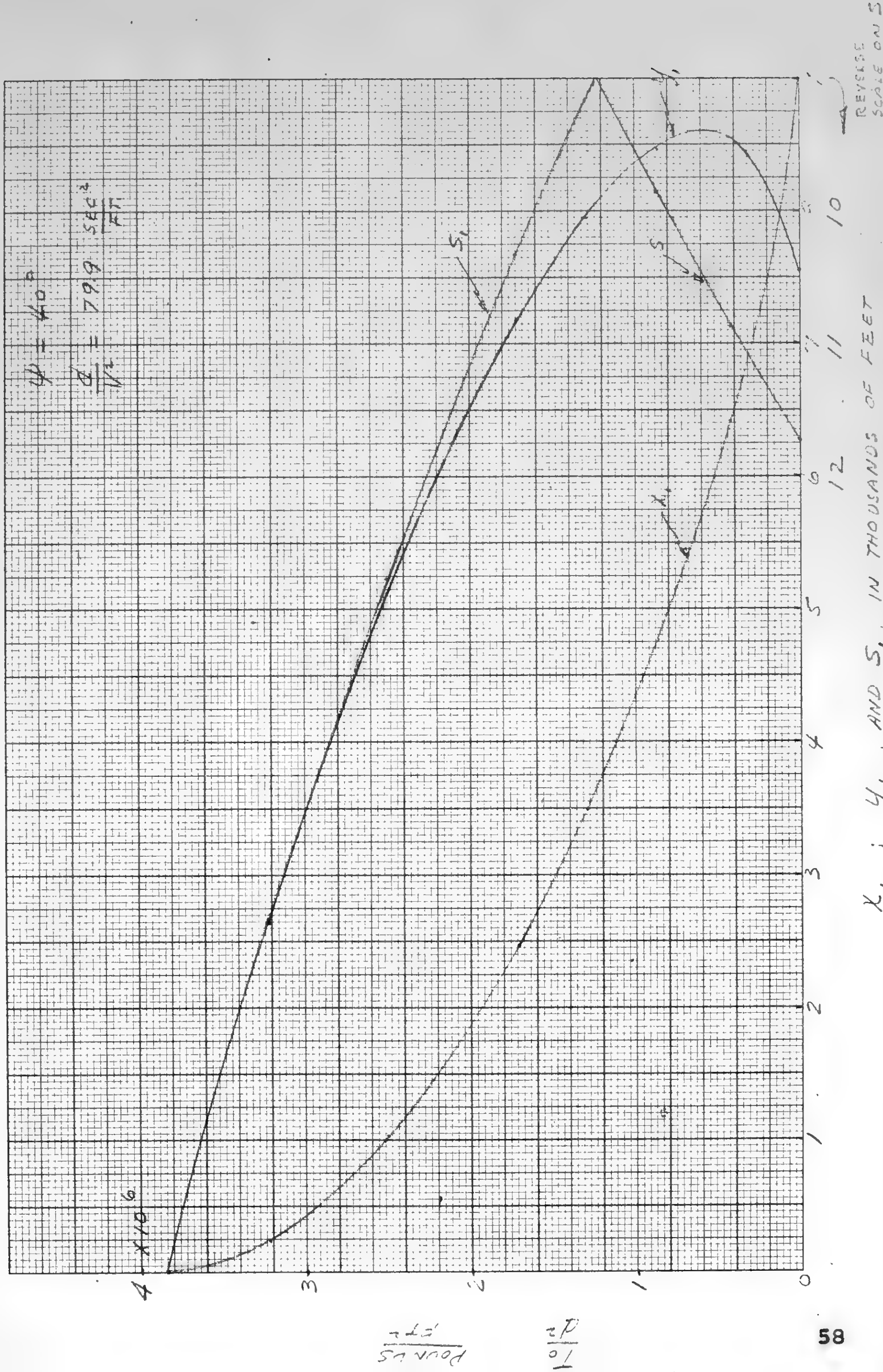

pounds
0
1
2
3

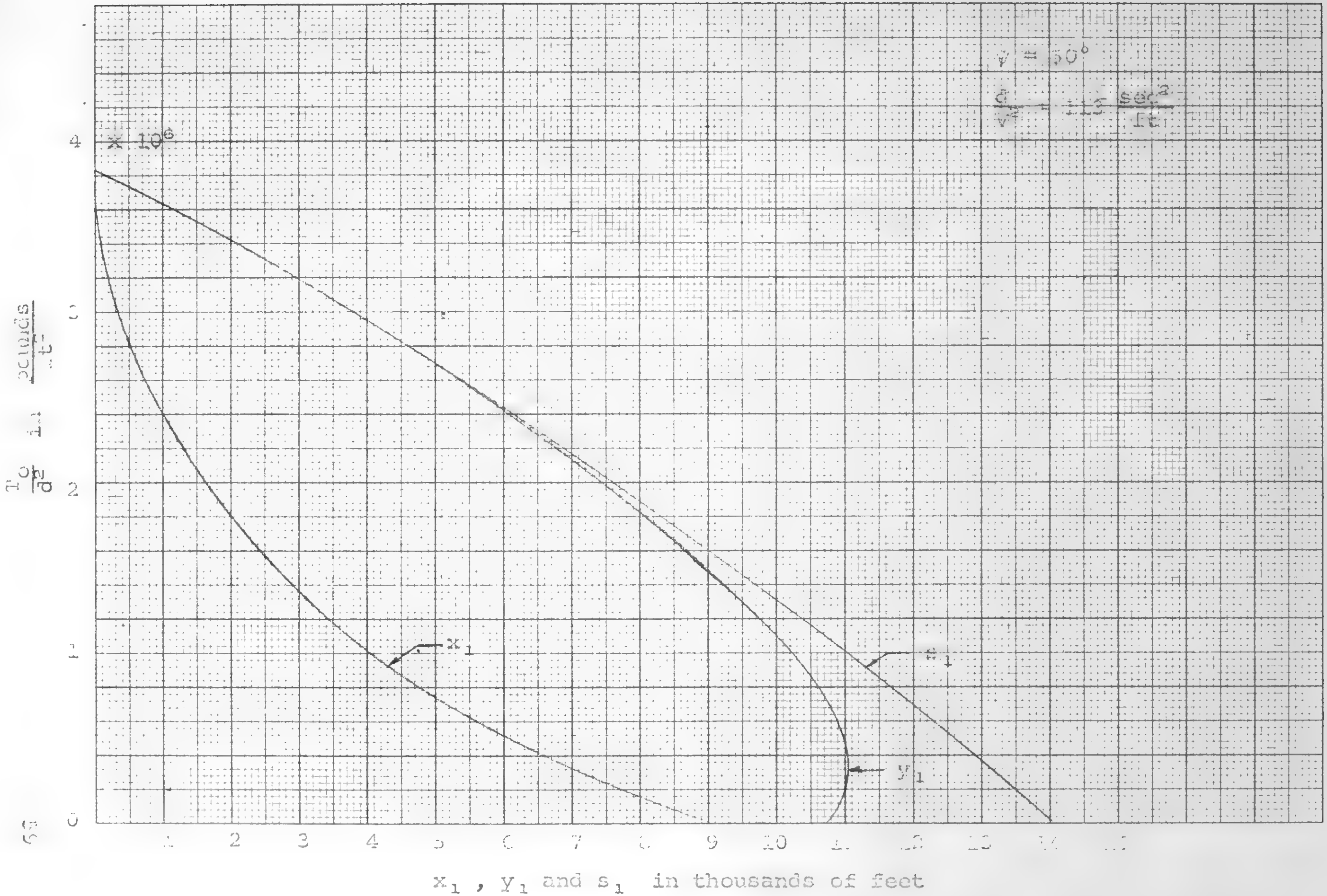


ψ = 20°
34.7 x 10⁻⁵ sec/ft
x 10⁶
s1
y1
x1
4
3
2
0



$\psi = 30°$
$\frac{d}{V^2} = 55.0 \times 10^{-5} \frac{SEC^2}{FT}$
$\times 10^6$
$\frac{T_0}{d^2}$ IN $\frac{POUNDS}{FT^2}$
x_1
y_1
S_1
x_1, y_1, AND S_1 IN THOUSANDS OF FEET
0
1
2
3
4
5
6
7
8
9


ψ = 40°
S₁
S
y₁
x₁
REVERSE SCALE ON S
x₁ ; y₁ , AND S₁ IN THOUSANDS OF FEET
x10⁶
0 1 2 3 4 5 6 7 8 9 10 11 12
0 1 2 3 4
POUNDS/FT²



x 10^6
x₁
y₁
s₁
x₁ , y₁ and s₁ in thousands of feet

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