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TENSION AND GEOMETRY OF SINGLE POINT MOORED SURFACE BUOY SYSTEM. A COMPUTER PROGRAM STUDY.

by

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TECHNICAL REPORT

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Approved for Distribution ______________________

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ABSTRACT

Analysis of an Oceanographic Buoy System
by Wayne D. Martin

Submitted to the Department of Naval Architecture and Marine Engineering on November 8, 1968, in partial fulfillment of the requirements for the degree of Master of Science.

A computer program is developed to study the steady-state geometry and cable tensions of the single-point, moored oceanographic buoy system as used by the Woods Hole Oceanographic Institution. This mooring is a combination of wire and nylon rope. The program numerically integrates the cable equations allowing for: elastic cables, variation of current speed with depth, drag and weight forces, instruments supported in the mooring line, and the effects of specific buoy shapes.

Model experiments performed to determine buoy drag as a function of hull shape, current speed and mooring cable tension are discussed. An experiment performed to determine the elastic properties of nylon ropes in a deep-sea mooring application is also described.

A series of representative mooring systems have been examined to determine the effect of nylon scope, current speed, rope size, buoy type, cable drag coefficient, and nylon elasticity on rope safety factor and buoy excursion. These results are presented and discussed.

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INTRODUCTION

Buoy systems are used by oceanographers to place instruments at relatively fixed points in the deep ocean. Maintaining these moorings for extended periods of time has proven to be a very difficult engineering problem. Only very recently has a reasonable reliability been achieved.

New understanding of the causes of mooring failure has underscored the need to better predict the at-sea response of buoy systems (1). Furthermore, because deflections of the mooring system, with currents, may introduce errors into the scientific measurements, the prediction of these deflections is of great interest to the scientist.

For these reasons a computer program has been developed to study the single-point, moored buoy system presently used by the Woods Hole Oceanographic Institution. This program numerically integrates the pertinent cable equations, yielding the system's steady state configurations with regard to geometry and cable tension. Although solutions to these equations have been presented, for other special cases, none was considered applicable to the Woods Hole mooring. Several important features of this program, which are considered necessary in order to attain realistic solutions, are listed below:

1) elasticity is allowed in the mooring line
2) current speed may be a function of depth
3) weight, tangential and normal drag forces are considered
4) instrumentation supported in the mooring line is considered
5) calculations are based on the use of specific buoy hulls.

A typical mooring is shown in fig. (1). In most cases these are compound moorings, i.e. a combination of wire and nylon rope. The wire is used to pass through the "fish-bite zone" and the nylon to supply elasticity to the system. They are all taut-line moorings, i.e. the unstretched length is always elongated to some extent and places a residual tension in the system. Such a

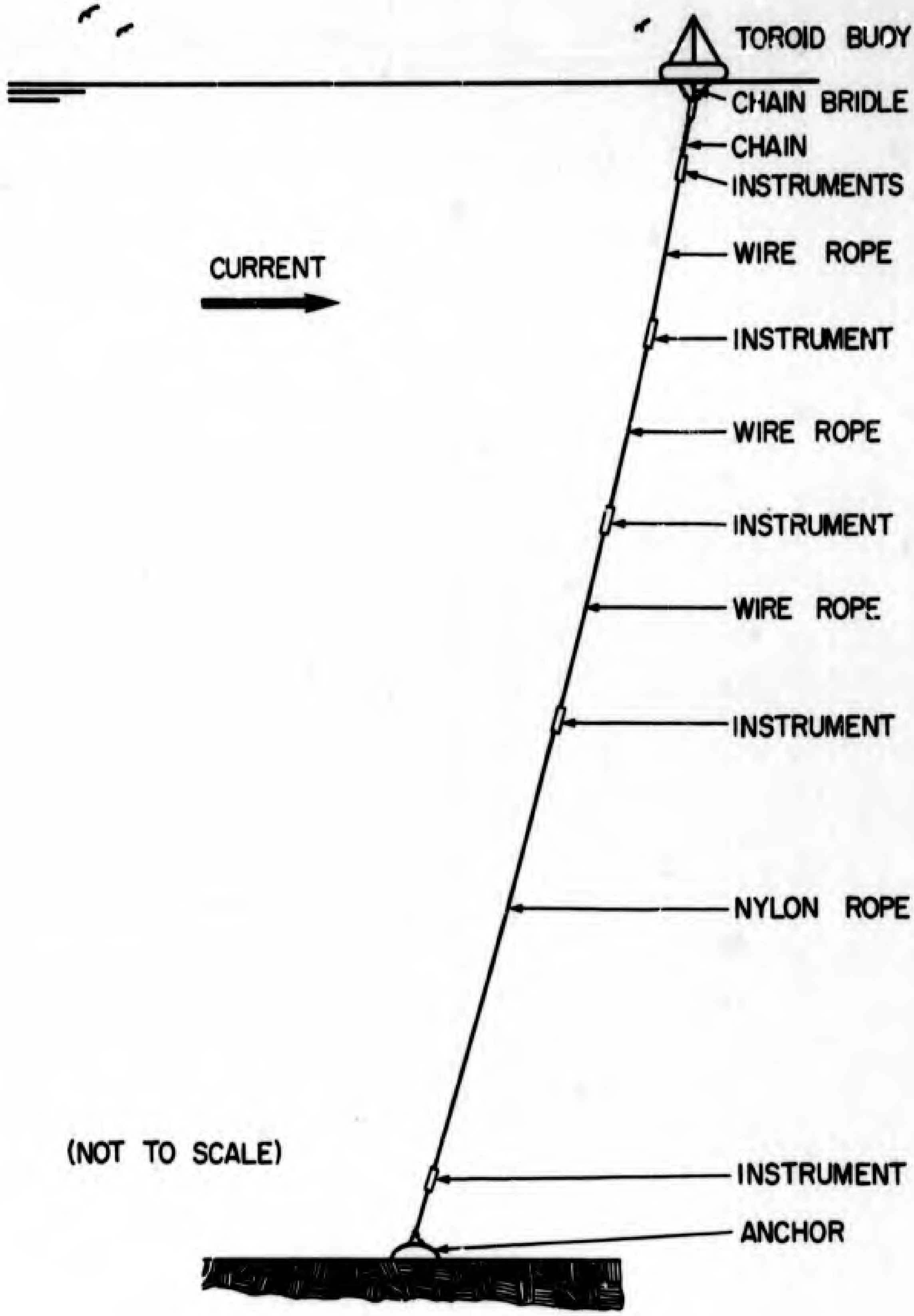


Figure 1. Single-Point, Compound, Oceanographic Buoy System

mooring has a nylon scope less than one, where:

$$\text{nylon scope} = \frac{\text{slack nylon length}}{(\text{water depth-length of wire and instruments})}$$

The solution of this problem is presented in two parts. The first discusses program logic, some necessary input information, and two series of experiments which were performed to supply this information. The second part discusees the program's; capabilities and limitations and presents some useful and representative results obtained from the working program.

PART I

CHAPTER I - PROGRAM LOGIC

The differential cable equations are simple and quite well known. Referring to fig. (2) they be stated as:

$$dT = pds, \qquad 2$$

$$d\Theta = -\frac{n}{T}\, ds \qquad 3$$

where: T is cable tension; Θ is the orientation angle; p is the sum of all tangential forces acting at s; n the sum of all normal forces; and ds the increment of cable length. Restrictions are imposed that the cable be flexible, and that it and all forces lie in a single plane. These equations simply state that, for each increment of length, the tangential forces acting on the cable are balanced by a change in internal tension and the normal forces balanced by a change in orientation.

Within the solution program the entire mooring line is broken into 100 straight line segments. The coordinate system and important parameters are shown in fig. (3). For convenience they are shown at the second segment. A complete list of symbols and definitions is presented in Appendix (1-a).

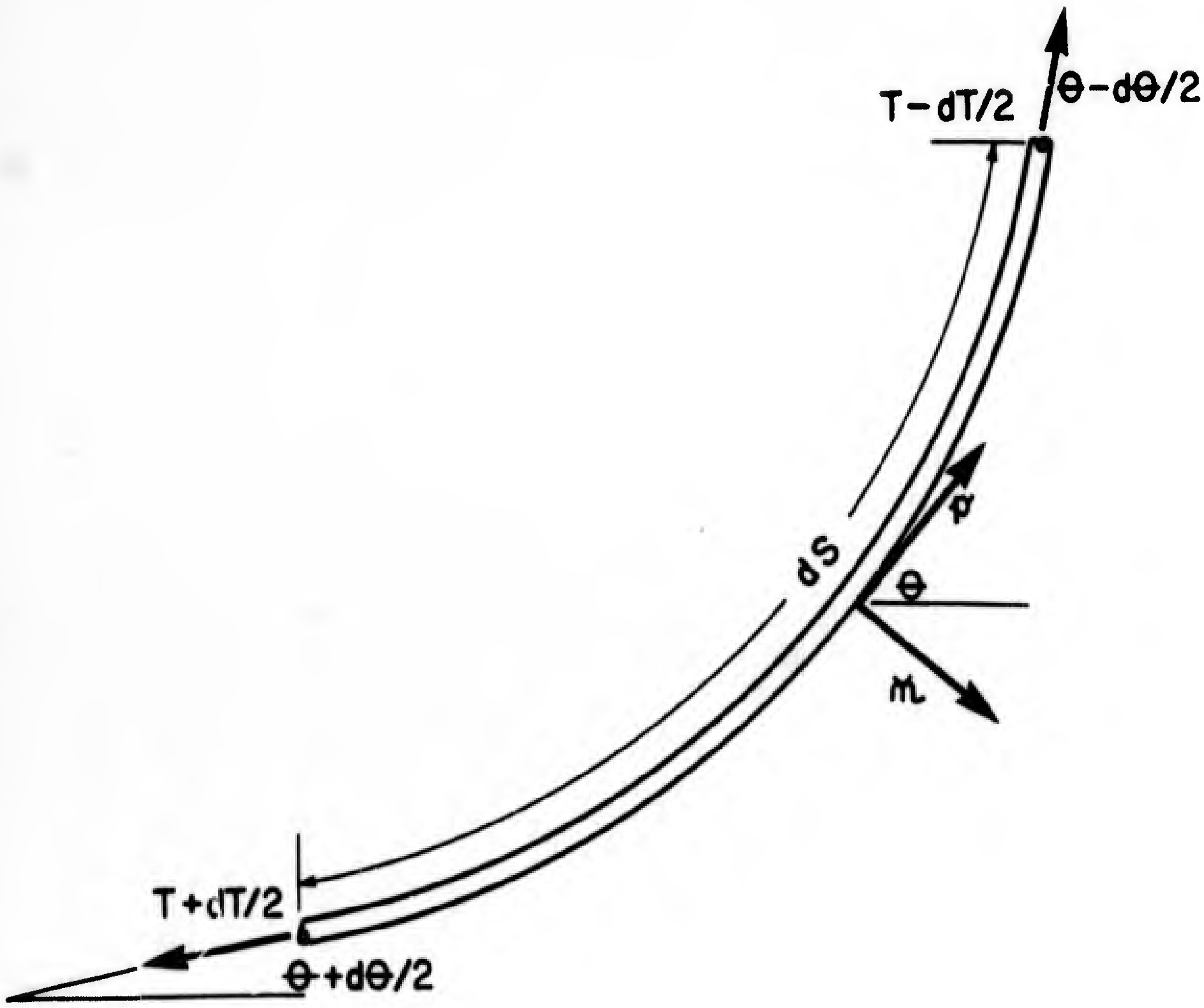
Treating the cable as a series of finite segments, the cable equations may be expressed as:

$$\Delta T = P \qquad 4$$

$$\Delta\Theta = -\frac{N}{T} \qquad 5$$

where P is the sum of tangential forces, and N the sum of normal forces acting on the entire segment. These forces will be due to cable drag in currents and segment weight. Evaluating these forces and applying the incremental cable equations, segment by segment, constitutes the numerical integration.

To begin the solution procedure a tension value is assumed in the first segment. In order to position this segment it is necessary to determine the surface cable angle, Θ. This angle is due to buoy drag, and is a function of the cable tension, the buoy type and the surface current, V. Assuming this relationship is known, the



$$dT = p\,dS$$

$$d\theta = -\frac{n}{T}\,dS$$

Figure 2. Differential Cable Equations

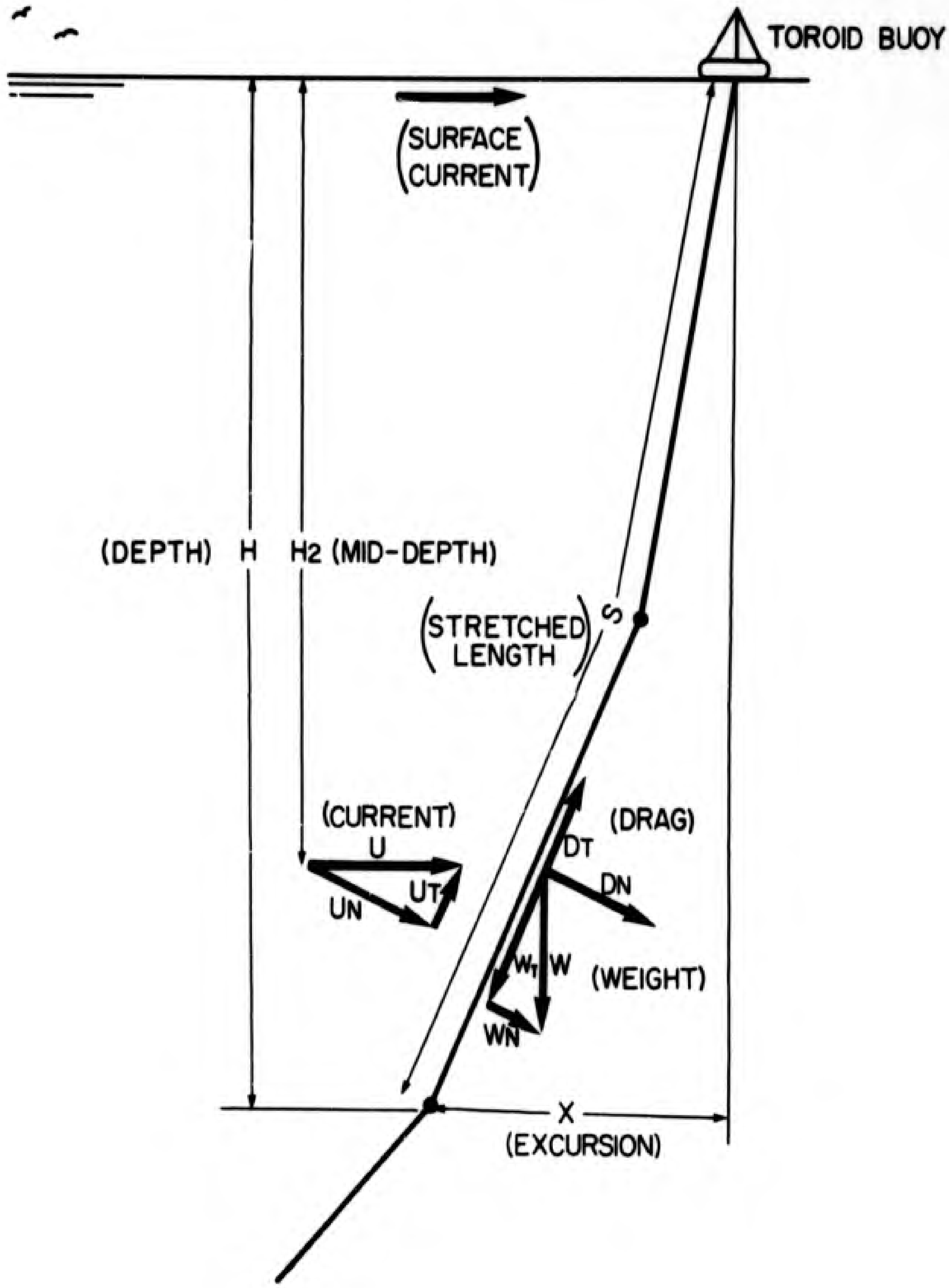


Figure 3. Coordinate System and Nomenclature

orientation of the first segment is established. Knowing the tension and the elasticity of the cable, elongation is calculated, and the position of the end of the first segment is determined, i.e. H, S, and X.

In order to calculate the segment drag, a representative current is determined by entering the current velocity profile at the mid-depth of the segment, H2. The mid-depth current is then resolved into components normal and tangential to the cable, UN and UT. The normal drag component, DN, is calculated by using the normal component of current and the pertinent pressure drag coefficient, CDN. For this calculation the stretched length and stretched diameter are used to determine the cross-sectional area, A, in the standard formulation:

$$DN = \rho/2 \cdot CDN \cdot A \cdot (UN)^2 \qquad 6$$

A similar formulation is used to determine the tangential drag, DT, employing the tangential component of current and the pertinent frictional drag coefficient, CDT. This procedure for predicting cable drag is in accordance with accepted practice and is in good agreement with experimental results (5).

The segment weight in water is resolved into components normal and tangential to the cable, WN and WT. These are summed with the corresponding drag components to obtain N and P in the cable equations (4,5). ΔT and $\Delta\Theta$ are then added to the tension and the angle of the first segment to determine the tension and orientation of the second. This procedure is repeated until all segments have been used and the position and tension at the anchor are known.

At the top of each segment a check is made to determine whether an instrument has been placed there. If so, a special subroutine is called which introduces an additional segment with the instrument's length, weight and drag characteristics. At the end of each segment a check is made to determine whether a change should be made from wire rope to nylon rope. If so, all cable characteristics are changed accordingly. Fig. (4) is a block diagram of the integration procedure.

On the first attempt, the depth reached by the end of the cable will probably

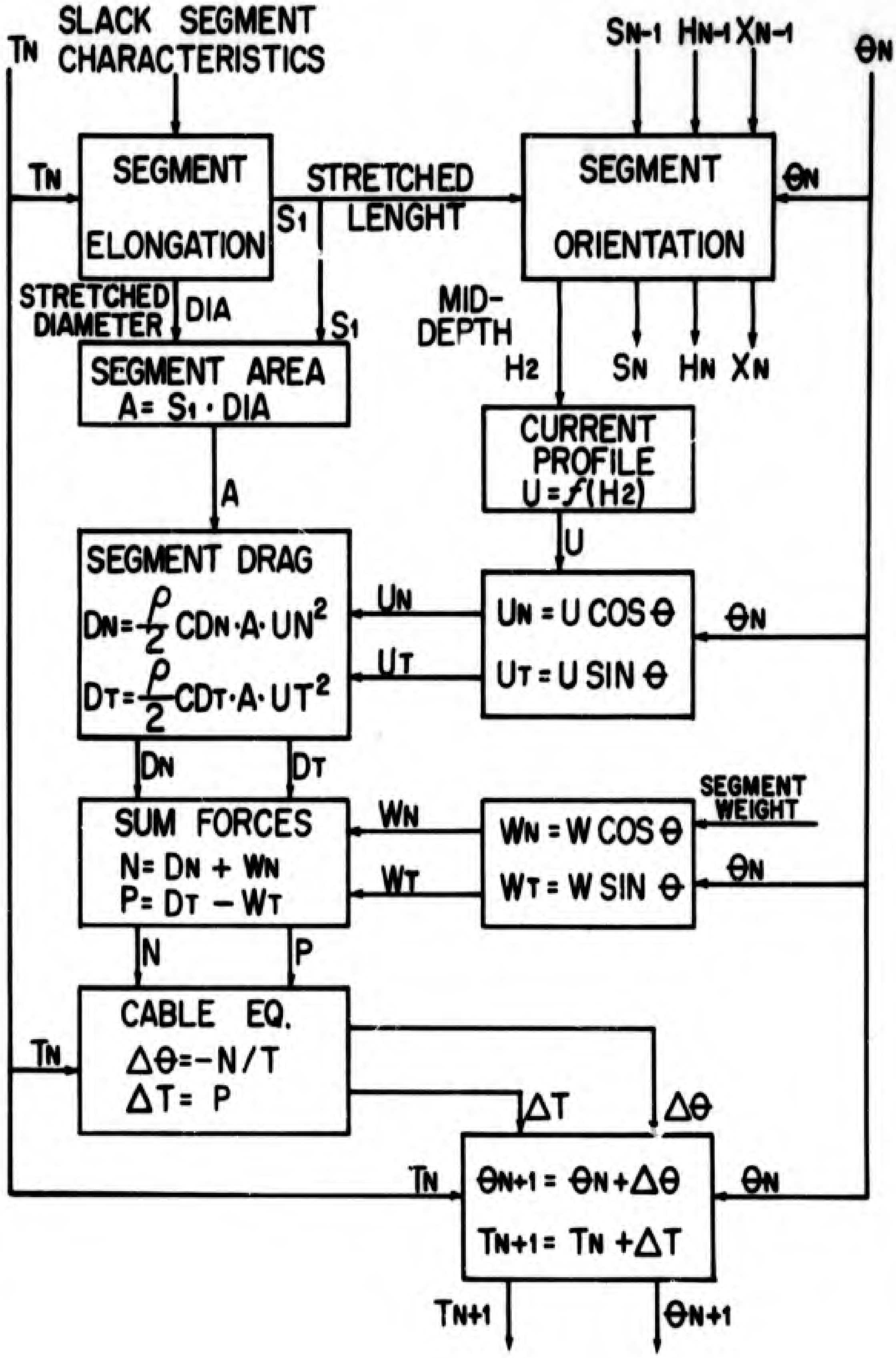


Figure 4. Integration Procedure

not agree with the actual water depth. This would be due to an error in the original surface cable tension assumption, and results in an iterative solution.

At the end of the first computation the depth error, E, the difference in cable depth and actual depth, is computed. If this error lies within prescribed limits (± five meters) then the problem is solved. If it does not, fifty pounds is added to the surface cable tension, and the entire computation is repeated. This second computation yields a new depth error, E1. The difference, DE, between this error and that obtained on the previous computation is due to the fifty pound change in surface cable tension. This weighting factor is used to determine an improved tension assumption, i.e.

$$\text{if} \quad DE = E - E1 \tag{7}$$

$$\text{then} \quad T\,\text{new} = T\text{old} + \left[\frac{E}{DE}\right] \cdot (50)\ \text{lbs.} \tag{8}$$

Due to non-linearities in this problem, using the corrected surface tension may not bring the depth error within the prescribed limits. If it does not, the procedure is repeated. In most cases three to five cycles are required to obtain a valid solution. Computation time required with the Scientific Data Systems Sigma 7 computer is approximately four second. Appendix (1) discusses the details of the program and presents comparisons with previous solutions for special cases.

CHAPTER II - NECESSARY INPUT INFORMATION

Within the solution procedure knowledge is required of several important parameters and functional relationships:

1) surface cable angle as a function of tension, buoy type and current speed

2) cable elongation as a function of tension

3) current speed as a function of depth

4) cable drag coefficients

It is obvious that the theoretical solution discussed above will be of little practical value unless realistic inputs can be supplied in these areas. Surface wire angle and cable elongation have been investigated in a series of specialized experiments which are discussed in Chapters III and IV. Current profile and drag coefficients are discussed below.

The variation of current speed with depth is usually a difficult relationship to predict. Many times it is the desire to obtain this relationship which first leads to the use of a buoy system. In most cases it will provide a potential source of uncertainty and error.

The current profile presented with this program is a result of recent findings by Woods Hole oceanographers, and represents an average of many readings at a single site (4). It represents a rapid decrease in current with depth, as is generally apparent in most portions of the ocean. The general formulation is:

$$U = \delta(H2)^{-.4} \qquad 9$$

where U is current speed, δ a constant, and H2 the depth. For this solution, the amplitude of the entire profile is assumed to vary directly with the surface current. The result has the form:

$$U = VT(H2)^{-.4} \qquad 10$$

where V is the surface current speed and T a constant.

The shape of the current profile may, of course, be varied by the user. The program will acept currents at different depths acting in opposite directions. Any continuous mathematical relationship may be employed, and with a few simple modifications stepped currents could be used. (This procedure is discussed in Appendix 1-c)

The value of the transverse drag coefficient, CN, for a cable in a mooring application is also difficult to specify. It is generally believed that the long lengths of mooring line experience transverse oscillations (strumming) due to vortex shedding. It is also generally agreed that this increases the drag coefficient, but the magnitude of this increase is not well known.

A value of $C_D = 1.8$ has been assumed by Paquette (2) and is used in this study. Some insight into the effect of this parameter may be gained from figs. (20) and (24) in Chapter VI, where the effect of variations in C_D on excursion and safety factor and presented for a typical mooring.

The tangential drag coefficient is taken as:

$$CT = .02\ CN \qquad 11$$

This is in general agreement with a compilation of experimental data presented by Wilson (5). In a taut-line mooring the effect of tangential drag is relatively small and an error in this parameter will have little effect on the validity of the solution.

CHAPTER III - BUOY MODEL TEST EXPERIMENT

As discussed above the solution program requires the surface cable angle as a function of cable tension, buoy type and current speed.

The mooring line is essentially the resultant vector of the forces acting on the buoy. These forces are a complex combination of form drag, wave drag, friction drag, static and dynamic lift, and are amenable to theoretical calculation. For this reason a series of physical model tests has been carried out on tne buoy shapes of interest: the toroid and the disk (with and without supporting feet). A brief description of the testing procedure is given below. For a complete discussion of the models, testing procedure and scale effects, see Appendix (2).

Scale models, two feet in diameter, were towed in the ship model basin at the MIT Hydrodynamics Laboratory. The towing point was near the bottom of the tank at the end of an "L" shaped arm which extended down and forward of the carriage (see fig. 5). The mooring, or in this case, towing cable was led around pulleys to a tensiometer located on the carriage. Cable angle was read visually against a protractor attached to the forward end of the towing arm. Tests were run at several speeds, corresponding to expected ocean currents. Froude scaling was employed. At each speed, tension and angle were varied by adjusting the wire length. The results are shown in figs. (6-8).

The results have been nondimensionalized according to Froude number, so that they may be applied to any geometrically similar buoy. The ordinate represents the towing angle in radians, and the abscissa represents cable tension, as a percentage of the buoy's total submerged buoyancy. The individual curves correspond to different Froude numbers, or more simply, to the different speeds at which tests were run. It can be seen the Θ_R increases with Froude number, or speed, and decreases with increasing cable tension. The toroid generated the greatest drag and the disk-without-feet generated the least.

As indicated on the diagrams, it has been possible to collapse the data for

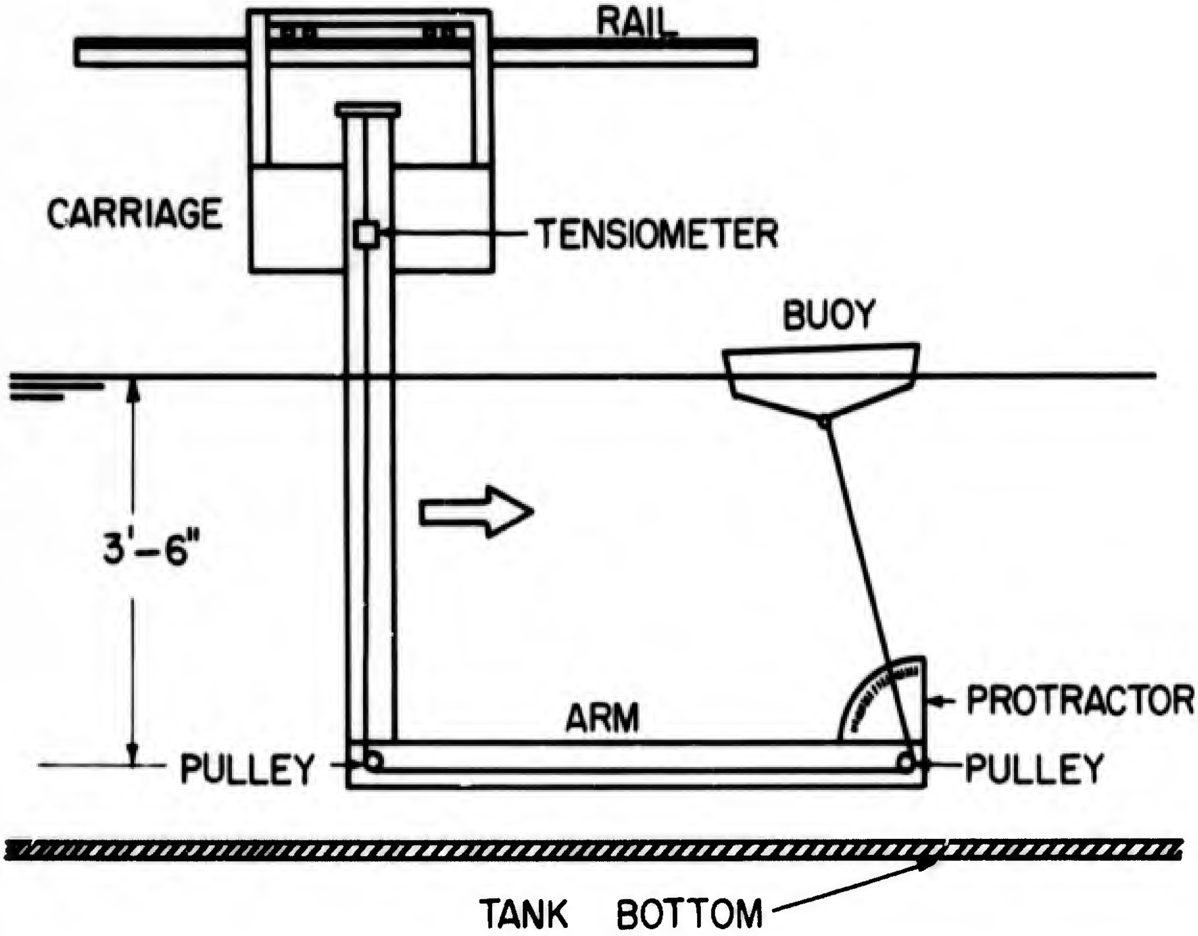


Figure 5. Model Test Apparatus

each hull into a single expression. These equations (see figs. 6-8) are functions in V^2 as might be expected for bluff bodies experiencing primarily pressure drag. For reasons discussed above, V^2 has been expressed as Froude number $\frac{V^2}{DG}$, and cable tension, T, as a percentage of submerged buoyancy. The requirements of the solution routine have been fulfilled by incorporating these expressions into the program as an external function, THETO. This is discussed in Appendix (1-c).

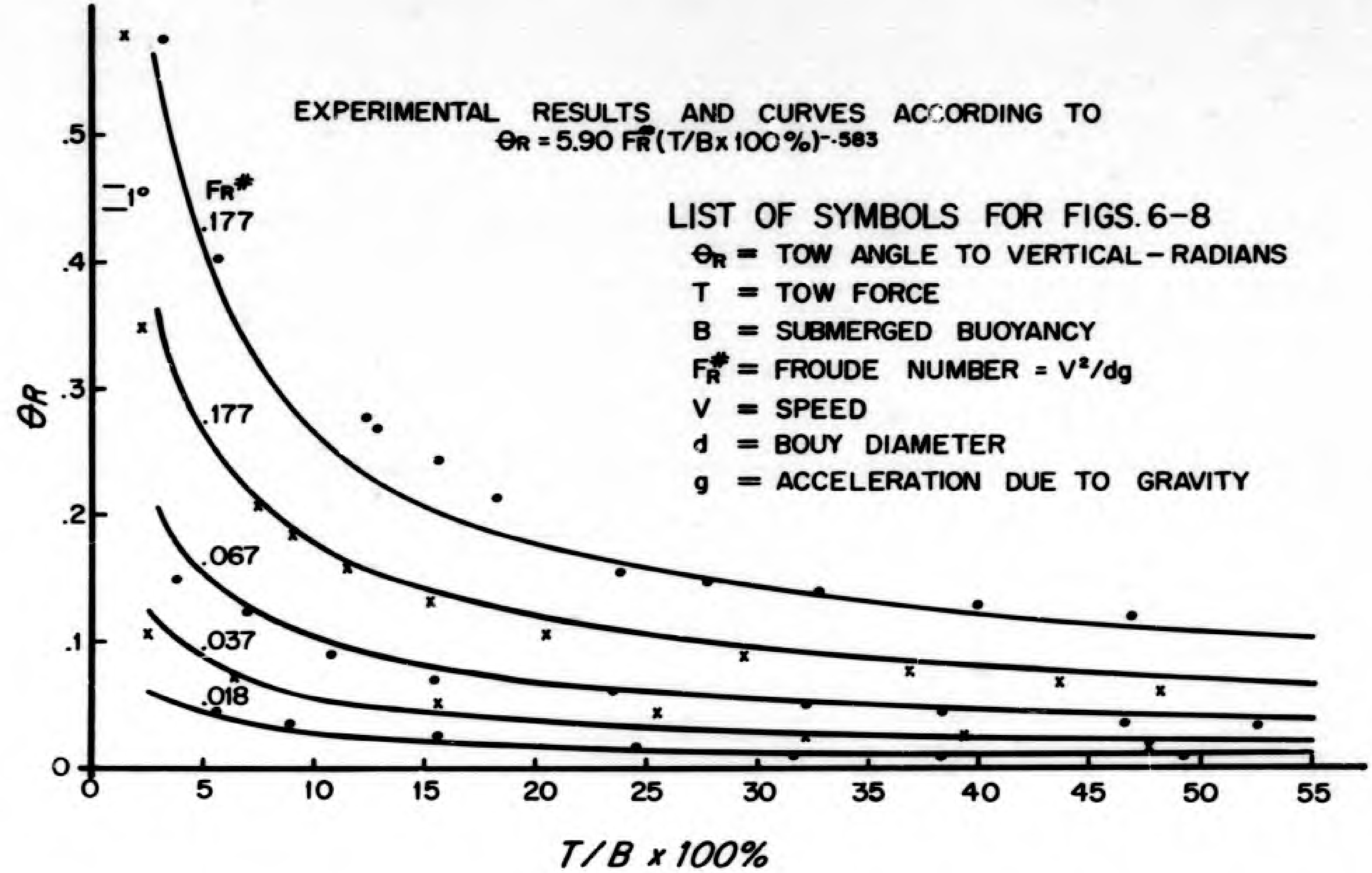


Figure 6. Disk-with-Feet, θ_R vs. T/B %

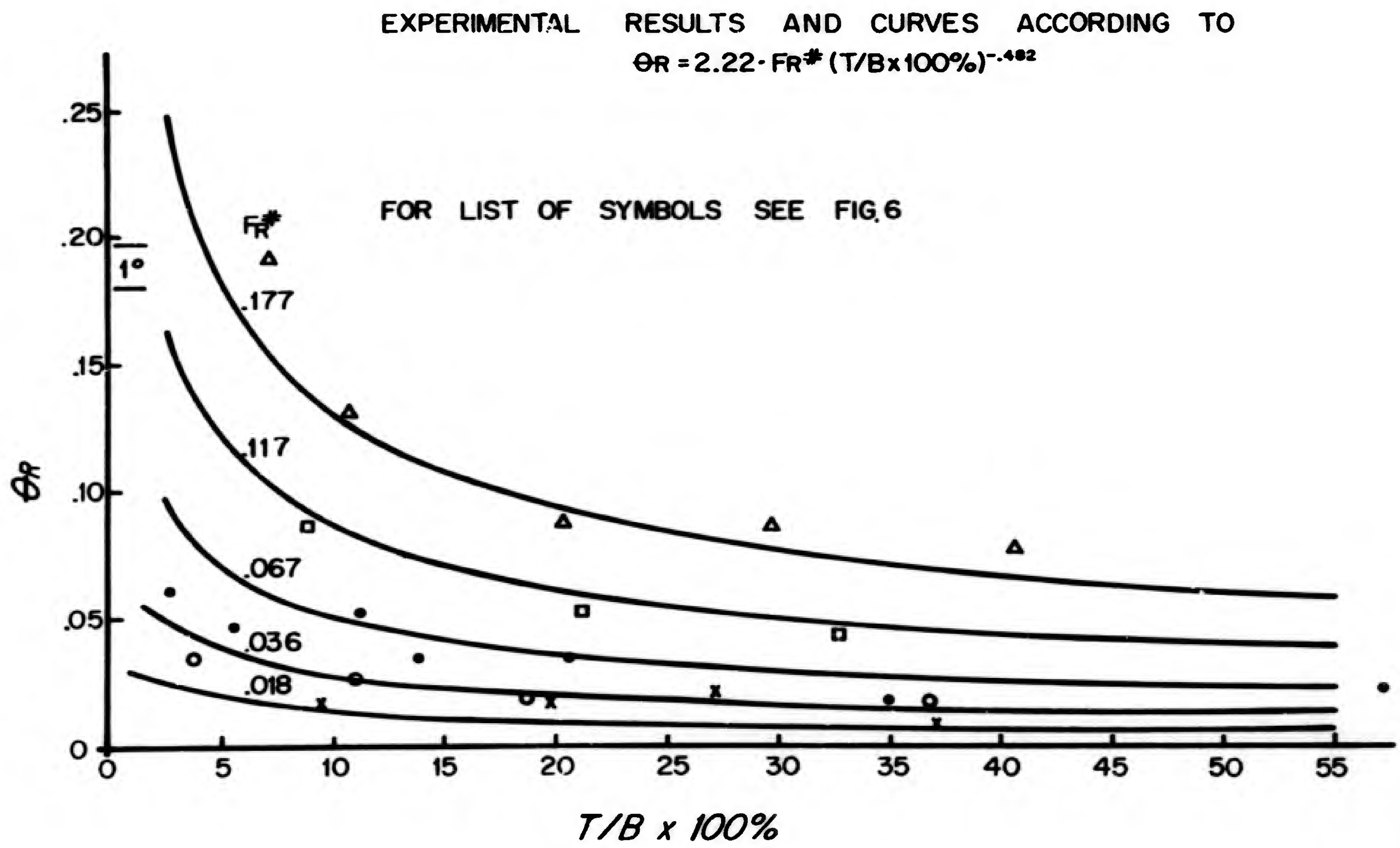


Figure 7. Disk-without-Feet θ_R vs. T/B %

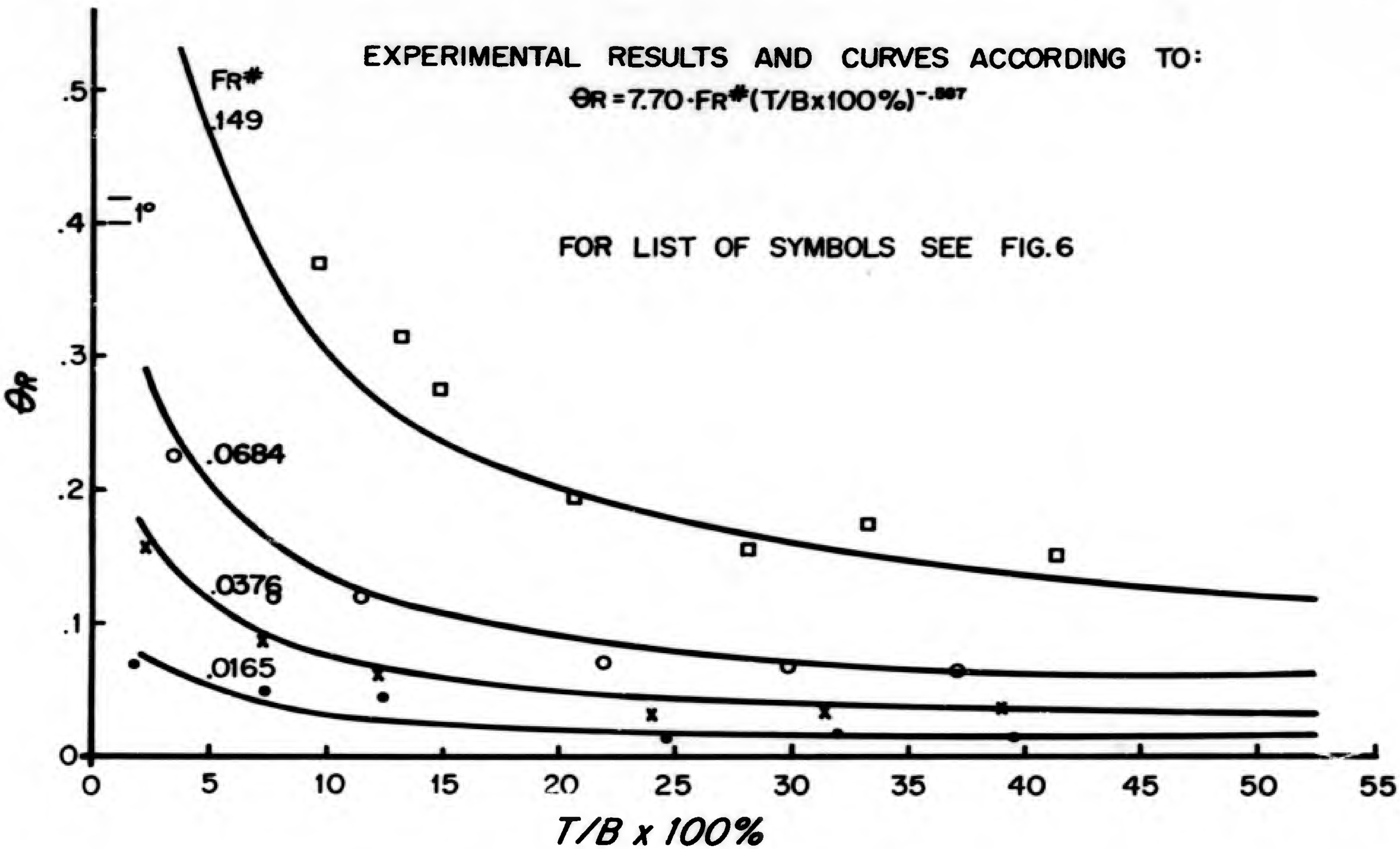


Figure 8. Toroid, θ_R vs. T/B %

CHAPTER IV - EXPERIMENTAL STUDY OF NYLON ROPE ELASTIC PROPERTIES

Although both the wire and nylon portions of the mooring are allowed to stretch in the solution program the elastic properties of nylon are predominant. Standard formulae are used to predict elongation of the wire rope and these are presented in Appendix (1-c).

A nylon rope in a deep sea mooring experiences a unique loading history and responds differently than ropes in more standard applications. In order to obtain an appropriate load-elongation relationship a specialized experiment which models this loading history has been performed.

At Woods Hole buoys are launched by the "anchor last" method. During this procedure, as the anchor is falling toward the bottom, the mooring line experiences a tension peak which is approximately equal to the anchor weight. This peak is known as the "launching transient". After the anchor bottoms, the tension and elongation decrease to that caused by nylon scope and currents. Further changes in cable tension, due to current fluctuation, normally occur very slowly. It is the final "steady-state" condition which is of interest in this study.

Several 50 cm. specimens of plaited nylon rope were tested in a standard tensile testing machine. The machine was used to: (1) reproduce the launching transient and, (2) hold the specimens at various tensions for arbitrary lengths of time. A typical experimental load-time curve is shown in fig. (9). Point B corresponds to the peak of the launch transient, and the curve from A to B, the period when the anchor is falling to the bottom. Specimens were tested with transient peak tensions of 20, 25 and 30% of rated breaking strength. Due to this variation in peak load, and other factors discussed below, a wide variety of peak elongations was obtained.

Load vs. percentage elongation curves obtained during this portion of the test (from A-B) are shown in fig. (10) for ropes experiencing their first usage and in fig. (11) for ropes being used for the second time. The scatter in fig. (10)

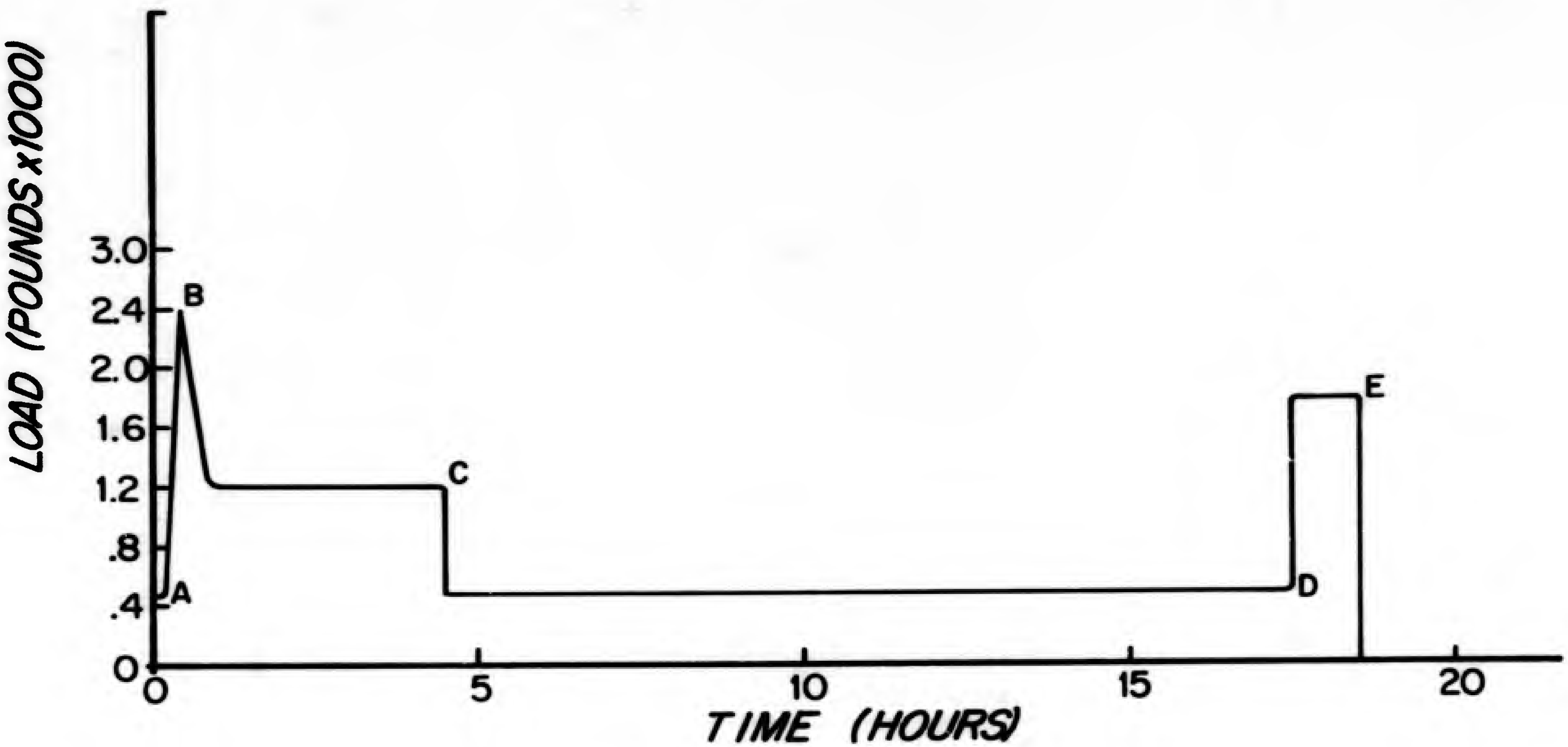


Figure 9. Typical Experimental Load Time Curve (nylon)

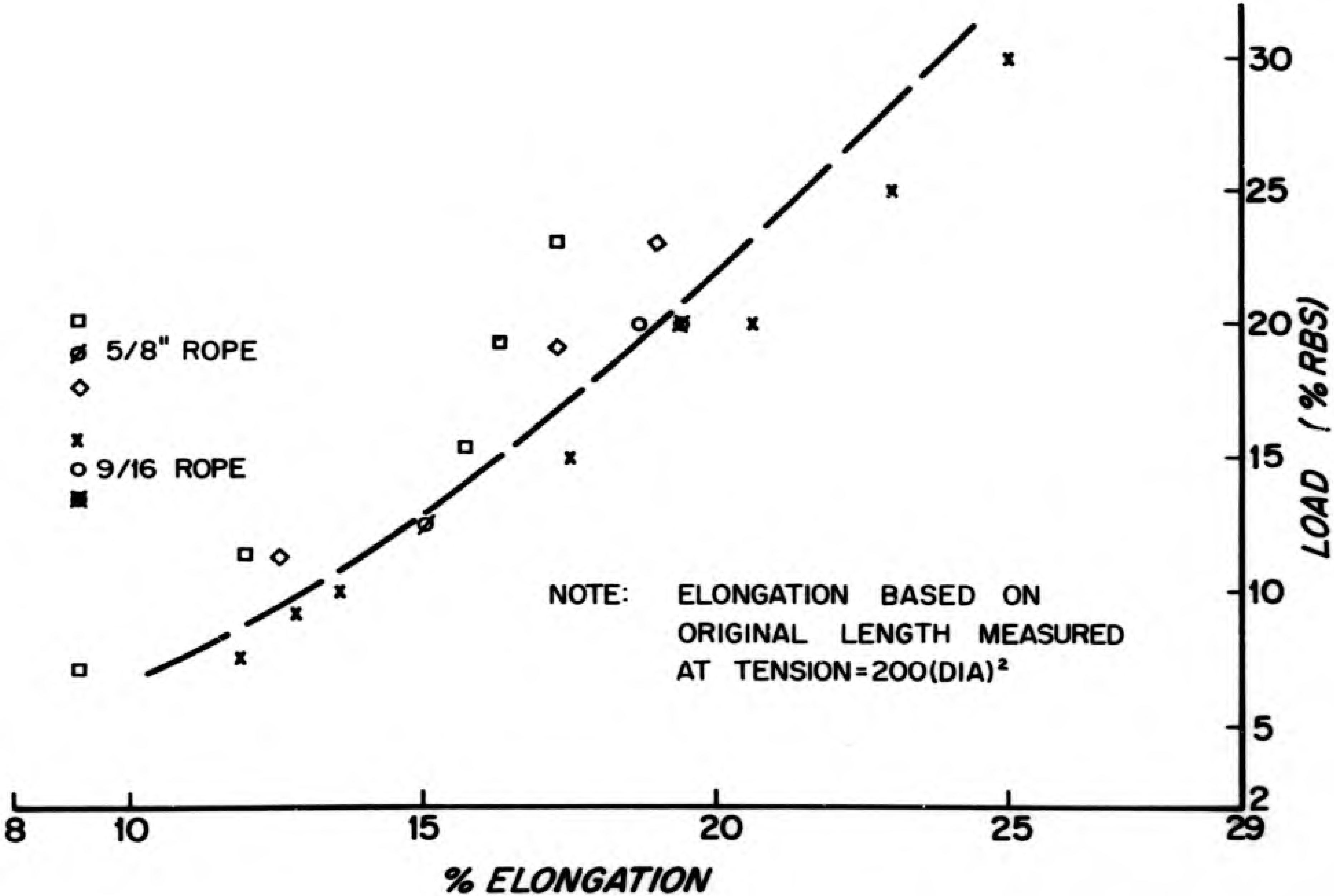


Figure 10. Plaited Nylon - Launching Load vs. % Elongation (first usage)

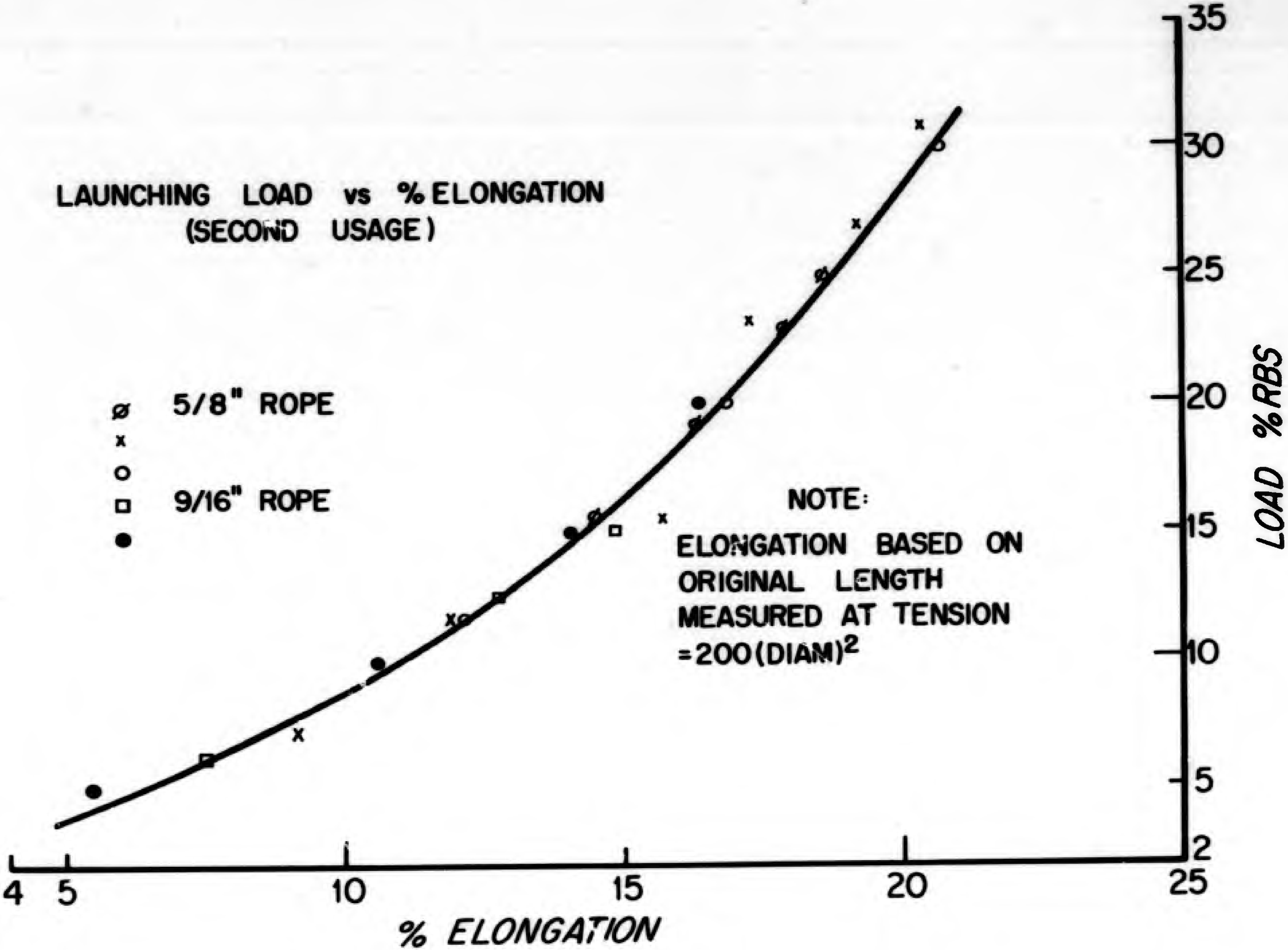


Figure 11. Plaited Nylon - Launching Load vs. % Elongation (second usage)

between different specimens is much greater than in fig. (11). This is probably due to manufacturing fluctuations which are more apparent the first time a rope is loaded. Nylon ropes also seem to expend an irrecoverable "construction" stretch in their first use and therefore experience less elongation in the second.

Points C, D, and E in fig. (9) are assumed to correspond to steady-state conditions experienced by the mooring. Plotting the load vs. elongation response at such points should yield a curve applicable to the solution program. It was found that such curves, for different specimens, though of similar shape, were displaced from one another according to the maximum elongation reached during the launch transient. In other words, the ropes experiencing greater launch transient peak elongation (due to greater anchor weight, manufacturing fluctuation, etc.) seem to display a proportionately greater elongation, when subjected to steady-state loads.

In order to obtain a general relationship, the steady-state results for each specimen have been reduced to fractions of the tension and elongation peak experienced by that specimen. The results from all the tests, reduced in this way, are presented in fig. (12), where:

$$\alpha = \frac{\text{steady state load}}{\text{launch transient peak load}} \qquad 12$$

$$\beta = \frac{\text{steady state elongation}}{\text{launch transient peak elongation}} \qquad 13$$

Using this diagram and reliable values of launch transient load and elongation, it is possible to predict steady-state elongation. Generalizing from these, as yet, relatively few tests it seems that predictions will be possible with errors normally less than 5% of the transient peak elongation. This is roughly the half width of the scatter band in fig. (12). As an example, if:

launch transient load = 2000 lbs.

launch transient peak elongation = 21.5%

and steady state load = 1000 lbs.

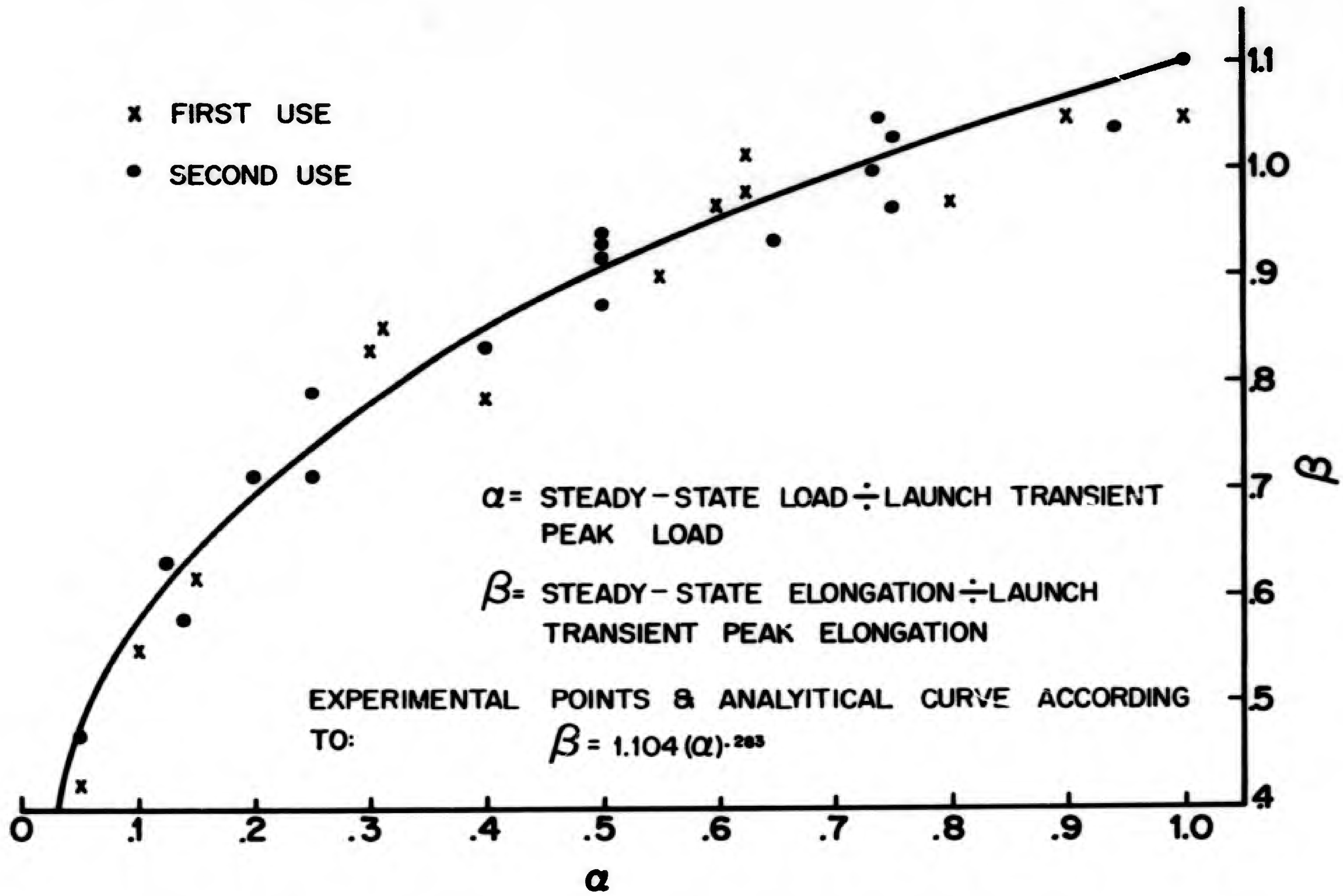


Figure 12. Plaited Nylon - Steady State Elongation Characteristics

then $\alpha = \frac{1000}{2000} = .5$

14

from fig. (12), $\beta = .905$

and steady state elongation = .905(21.5) = 19.5%

The analytical expression in α and β presented in fig. (12) has been incorporated into the program. It is necessary for the user to supply the launching load and elongation. These may be approximated by entering fig. (10) or (11) at the anchor weight, or preferably by performing an independent "launching test" on the rope under investigation. Performing such a test should take into account the manufacturing fluctuations. A more detailed discussion of the testing procedure and a discussion of nylon measurement at the standard tension of 200 D^2 are presented in Appendix (3).

PART II

CHAPTER V - PROGRAM CAPABILITIES AND LIMITATIONS

The major goal of this work has been to supply a practical tool for the realistic analysis of a specific type of mooring system. It is assumed that the user will know the type and approximate locations of the instruments which the mooring is to support. After the instrumentation has been established the program can be used to conveniently model a wide variety of mooring configurations. For each configuration a list of mooring parameters must be supplied (see Table 1). Any of these parameters may be varied independently, in order to determine its effect on mooring performance. Detailed instructions for programming are given in Appendix (1-d).

A few items deserve special note. Either an all-nylon or an all-wire mooring may be computed by entering zero wire length or zero nylon scope. Minimum tension (often an important design consideration) may be determined by setting the surface current equal to zero. The shape of the current profile may be changed internally. This is not a difficult process and is described in Appendix (1-c).

The principal outputs of the program are:

1) maximum wire tension and safety factor
2) maximum nylon tension and safety factor
3) buoy excursion where safety factor equals rope rated breaking strength divided by maximum tension.

If required, the length, depth, excursion and tension may be printed out at each segment, allowing a graphic presentation of mooring response.

In addition a slightly altered system with regard to surface angle, cable drag coefficient and nylon elongation is computed. These parameters are changed to the assumed limits of their uncertainty. The resulting changes in wire and nylon are taken as rough error bounds on the program outputs.

The program is presently limited to the three buoy shapes discussed in

TABLE (1) - MOORING PARAMETERS

1) buoy hull

   a) shape
   b) size

2) water depth

3) nylon scope

4) surface current (determines amplitude of entire profile)

5) launch transient effects

   a) peak nylon load
   b) peak nylon elongation

6) cable normal drag coefficient

7) wire rope characteristics

   a) slack length
   b) diameter
   c) weight per unit length
   d) rated breaking strength

8) nylon rope characteristics

   a) diameter
   b) weight per unit length
   c) rated breaking strength

Chapter III. Other shapes may be substituted by the user. It is limited to plaited nylon ropes, for which the experimental results discussed in Chapter IV are valid. Because the iterative solution depends on fixed water depth and variable buoy lift, it is not directly applicable to a subsurface mooring. No allowance is made for wave and wind drag on the buoy, or for non co-planar currents, any of which could have an appreciable effect. Furthermore it is purely a steady-state solution making no allowance for dynamic effects. The basic integration procedure (as outlined in fig. 4) is quite general, however, necessitating, itself, only the last two restrictions.

CHAPTER VI - MOORING ANALYSIS RESULTS

A number of representative mooring configurations have been computed to provide design information and demonstrate the program capabilities.

Figs. (15-25), as listed in Table (2), represent variations on a "standard" buoy system. The characteristics of the standard system are those listed in the example output, fig. (13). In all cases, parameters not specifically listed on the diagrams are those of the standard system. The instruments assumed in these studies are:

1) tensiometer, 10 meters chain and current meter; at segment 1
2) current meter; at segment 10
3) current meter; at segment 30
4) current meter; at segment 50

Following the figures there is a brief discussion of the results.

TABLE (2) - LIST OF RESULTS

Fig. No.	Title
13	Sample Output and Characteristics of Standard Mooring
14	Rope Characteristics
15	Mooring Shape vs. Surface Current
16	Safety Factor vs. Nylon Scope and Rope Size
17	Buoy Excursion vs. Nylon Scope and Rope Size
	Safety Factor vs. Surface Current and:
18	Rope Size
19	Buoy Type
20	Normal Drag Coefficient
21	Launch Transient Peak Elongation
	Buoy Excursion vs. Surface Current and:
22	Rope Size
23	Buoy Type
24	Normal Drag Coefficient
25	Launch Transient Peak Elongation

Fig. (13) - Sample Output and Characteristics of Standard Mooring

OCEANOGRAPHIC BUOY SYSTEM

Fig. (13)

RUN NUMBER 1
BUOY IS 8.00 FT DIA TOROID NO. 1
DEPTH = 2600.00 METERS
SURFACE CURRENT = 50.00 CM/SEC
LAUNCH TRANSIENT PEAK TENSION = 2000.00 LBS
LAUNCH TRANSIENT PEAK ELONGATION = 21.50 % 200 D SQ
NYLON SCOPE = 0.85
NORMAL DRAG COEF = 1.80
TANGENTIAL DRAG COEF = 0.036
1500.00 METERS OF 0.375 INCH WIRE ROPE
WIRE RBS = 10300.0 LBS; WEIGHT = 0.4100 LBS/M
918.93 METERS OF 0.562 INCH NYLON (SLACK)
NYLON RBS = 8000.0 LBS; WEIGHT = 0.0272 LBS/M

ITERATION PROCEDURE

TOP TENS	TOP ANGLE	DEPTH	DEPTH ERROR	
1163.99	1.5585	2579.04	20.9580	TRIAL RUN
1232.81	1.5589	2599.04	0.9553	CONVERGENT RUN

RESULTS

MAXIMUM WIRE TENSION = 1232.81; SAFETY FACTOR = 8.35
MAXIMUM NYLON TENSION = 397.43; SAFETY FACTOR =20.13
MAX NYLON ELONGATION = 15.02 % 200 D SQ
BUOY EXCURSION = 369.05 METERS

MOORING CONFIGURATION

	SLAC LENTH	STR LENTH	DEPTH	EXCURSION	TENSION	
T,CH,CM	AT	12.90 METERS				
1	37.09	37.11	37.10	0.88	1088.91	W
2	61.29	61.33	61.30	1.74	1079.00	W
3	85.48	85.54	85.49	2.68	1069.08	W
4	109.67	109.75	109.68	3.69	1059.17	W
5	133.87	133.96	133.87	4.75	1049.26	W
6	158.06	158.17	158.06	5.86	1039.35	W
7	182.25	182.39	182.24	7.01	1029.45	W
8	206.45	206.60	206.43	8.20	1019.54	W
9	230.64	230.81	230.61	9.43	1009.63	W
CUR METR	AT	232.60 METERS				
10	256.84	257.02	256.78	10.85	969.77	W
11	281.03	281.23	280.95	12.21	959.86	W

Fig. 13 cont.

12	305.22	305.44	305.12	13.60	949.96	W
13	329.42	329.65	329.29	15.02	940.06	W
14	353.61	353.86	353.46	16.48	930.16	W
15	377.80	378.07	377.62	17.97	920.26	W
16	402.00	402.28	401.78	19.50	910.36	W
17	426.19	426.49	425.94	21.06	900.46	W
18	450.38	450.70	450.10	22.65	890.56	W
19	474.58	474.91	474.25	24.28	880.66	W
20	498.77	499.12	498.40	25.93	870.77	W
21	522.96	523.33	522.55	27.63	860.87	W
22	547.16	547.53	546.70	29.35	850.98	W
23	571.35	571.74	570.84	31.11	841.08	W
24	595.54	595.95	594.99	32.91	831.19	W
25	619.74	620.16	619.12	34.73	821.30	W
26	643.93	644.37	643.26	36.60	811.41	W
27	668.12	668.57	667.39	38.49	801.52	W
28	692.32	692.78	691.52	40.43	791.63	W
29	716.51	716.99	715.65	42.40	781.75	W
CUR METR AT 717.64 METERS						
30	742.70	743.20	741.76	44.66	741.97	W
31	766.90	767.40	765.87	46.79	732.09	W
32	791.09	791.61	789.98	48.96	722.21	W
33	815.28	815.81	814.09	51.17	712.33	W
34	839.48	840.02	838.19	53.43	702.45	W
35	863.67	864.23	862.28	55.73	692.58	W
36	887.86	888.43	886.37	58.07	682.71	W
37	912.06	912.64	910.46	60.46	672.83	W
38	936.25	936.84	934.54	62.89	662.97	W
39	960.44	961.05	958.62	65.37	653.10	W
40	984.64	985.25	982.69	67.90	643.23	W
41	1008.83	1009.46	1006.76	70.48	633.37	W
42	1033.02	1033.66	1030.82	73.11	623.51	W
43	1057.22	1057.87	1054.88	75.79	613.65	W
44	1081.41	1082.07	1078.93	78.53	603.79	W
45	1105.60	1106.27	1102.97	81.32	593.94	W
46	1129.80	1130.48	1127.00	84.17	584.09	W
47	1153.99	1154.68	1151.03	87.07	574.24	W
48	1178.18	1178.88	1175.05	90.04	564.40	W
49	1202.38	1203.09	1199.07	93.07	554.56	W
CUR METR AT 1201.05 METERS						
50	1228.57	1229.29	1225.03	96.59	514.97	W
51	1252.76	1253.49	1249.00	99.92	505.15	W
52	1276.96	1277.70	1272.96	103.34	495.33	W
53	1301.15	1301.90	1296.91	106.83	485.51	W
54	1325.34	1326.10	1320.85	110.40	475.70	W
55	1349.54	1350.30	1344.77	114.05	465.90	W
56	1373.73	1374.50	1368.68	117.80	456.10	W
57	1397.92	1398.70	1392.58	121.63	446.30	W
58	1422.12	1422.91	1416.46	125.56	436.51	W
59	1446.31	1447.11	1440.32	129.58	426.73	W
60	1470.50	1471.31	1464.17	133.71	416.96	W
61	1494.70	1495.51	1488.00	137.95	407.19	W
62	1518.89	1519.71	1511.81	142.29	397.43	W

Fig. 13 cont.

63	1543•07	1548•97	1540•57	147•69	396•79	N
64	1567•25	1578•23	1569•32	153•12	396•14	N
65	1591•44	1607•49	1598•06	158•58	395•50	N
66	1615•62	1636•75	1626•80	164•08	394•85	N
67	1639•80	1666•00	1655•53	169•60	394•20	N
68	1663•98	1695•25	1684•25	175•16	393•56	N
69	1688•17	1724•51	1712•96	180•76	392•91	N
70	1712•35	1753•76	1741•66	186•38	392•27	N
71	1736•53	1783•00	1770•36	192•04	391•62	N
72	1760•71	1812•25	1799•05	197•72	390•98	N
73	1784•90	1841•49	1827•73	203•44	390•33	N
74	1809•08	1870•74	1856•40	209•19	389•68	N
75	1833•26	1899•98	1885•06	214•97	389•04	N
76	1857•44	1929•22	1913•72	220•78	388•40	N
77	1881•63	1958•45	1942•37	226•62	387•75	N
78	1905•81	1987•69	1971•01	232•49	387•11	N
79	1929•99	2016•92	1999•64	238•40	386•46	N
80	1954•17	2046•16	2028•26	244•33	385•82	N
81	1978•35	2075•39	2056•88	250•29	385•17	N
82	2002•54	2104•61	2085•48	256•28	384•53	N
83	2026•72	2133•84	2114•08	262•30	383•89	N
84	2050•90	2163•07	2142•68	268•35	383•24	N
85	2075•08	2192•29	2171•26	274•43	382•60	N
86	2099•27	2221•51	2199•84	280•54	381•96	N
87	2123•45	2250•73	2228•40	286•67	381•31	N
88	2147•63	2279•95	2256•96	292•84	380•67	N
89	2171•81	2309•16	2285•51	299•03	380•03	N
90	2196•00	2338•38	2314•06	305•26	379•38	N
91	2220•18	2367•59	2342•59	311•51	378•74	N
92	2244•36	2396•80	2371•12	317•79	378•10	N
93	2268•54	2426•01	2399•64	324•10	377•46	N
94	2292•73	2455•21	2428•15	330•44	376•81	N
95	2316•91	2484•42	2456•65	336•80	376•17	N
96	2341•09	2513•62	2485•15	343•19	375•53	N
97	2365•27	2542•82	2513•63	349•61	374•89	N
98	2389•46	2572•02	2542•11	356•06	374•25	N
99	2413•64	2601•22	2570•58	362•54	373•60	N
100	2437•82	2630•42	2599•04	369•05	372•96	N

MAXIMUM EXPECTED ERROR
(ASSUMING CURRENT PROFILE CORRECT)

IF: TOP ANGLE OFF 1 DEGREE; DRAG COEF OFF 0•2;
NYLON STRETCH OFF 10 PERCENT

WIRE TENSION   176•65 LBS
NYLON TENSION   177•45 LBS

Fig. (14) - Rope Characteristics

	1(STD)	2	3
wire diameter-inches (including jacket)	0.375	0.375	0.438
wire weight in water-lbs/meter	0.41	0.41	0.59
wire rated breaking strength-lbs.	10,300	10,300	14,800
nylon diameter-inches	0.562	0.625	.750
nylon weight in water-lbs/meter	0.0272	0.0344	.0475
nylon rated breaking strength-lbs.	8,000	10,400	14,200
launch transient peak tension	2,000	2,000	2,000
launch transient peak elongation	21.5	18.6	15.7

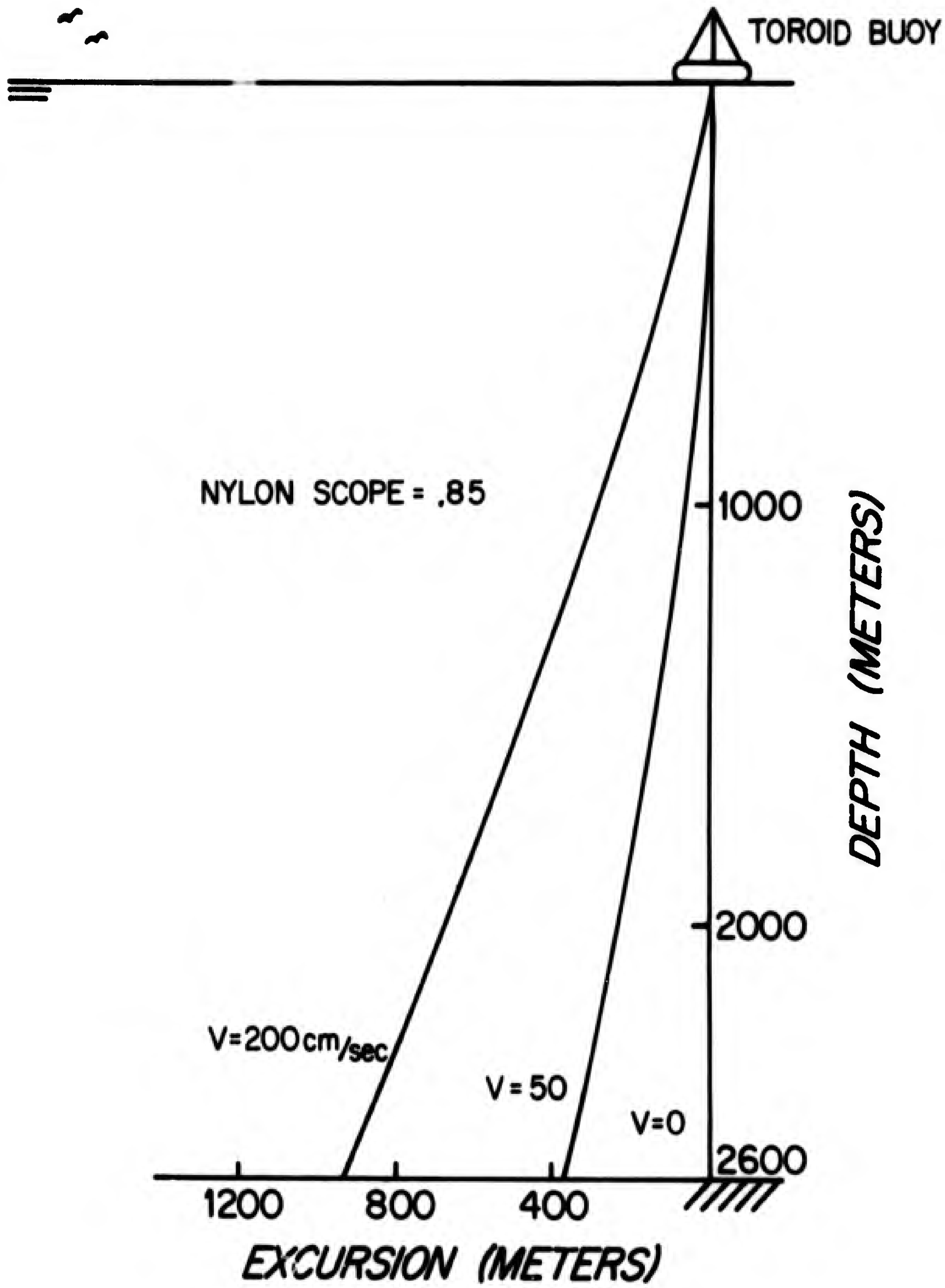


Figure 15. Mooring shape vs surface current.

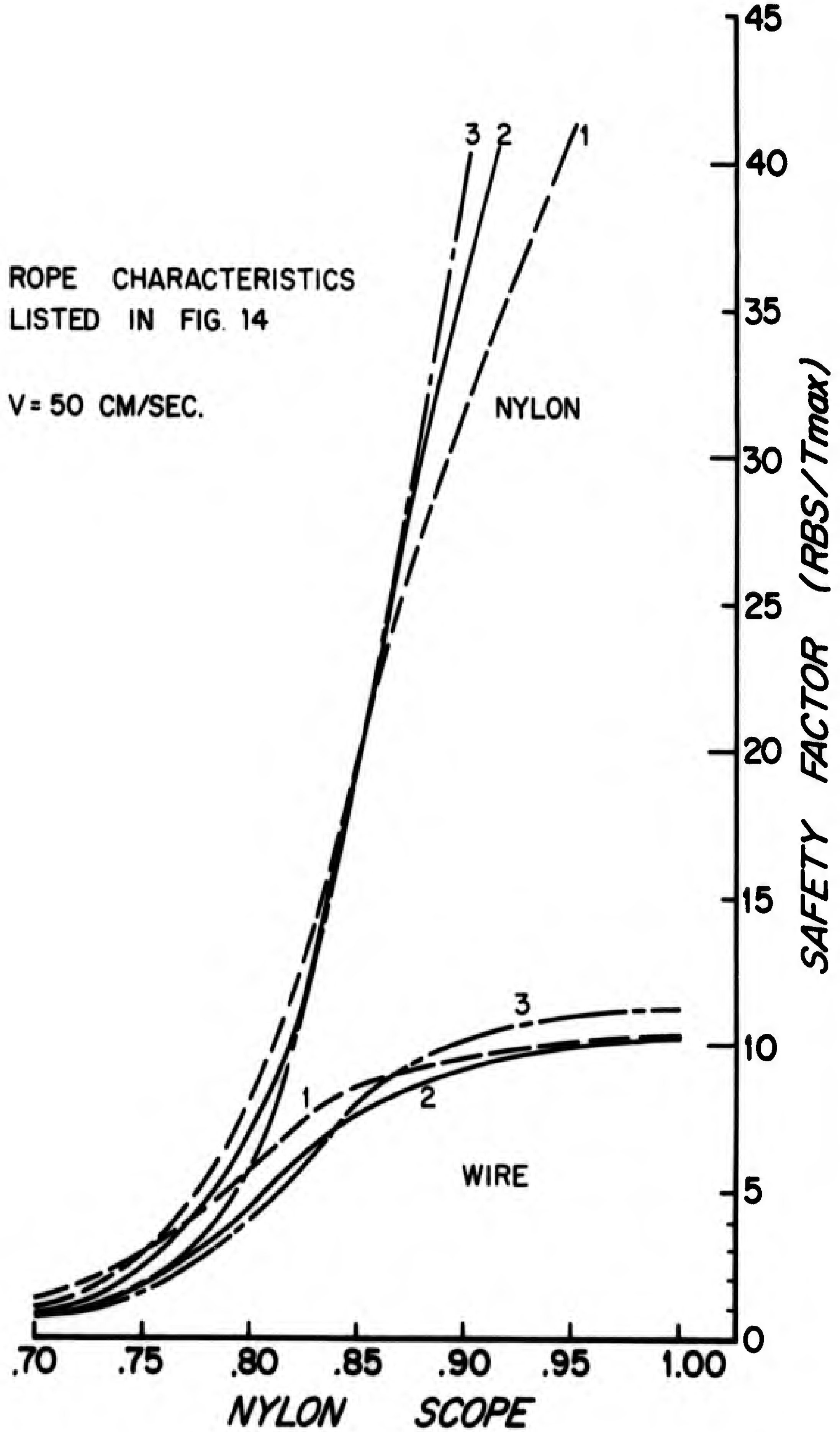


Figure 16. Safety factor vs nylon scope and rope size.

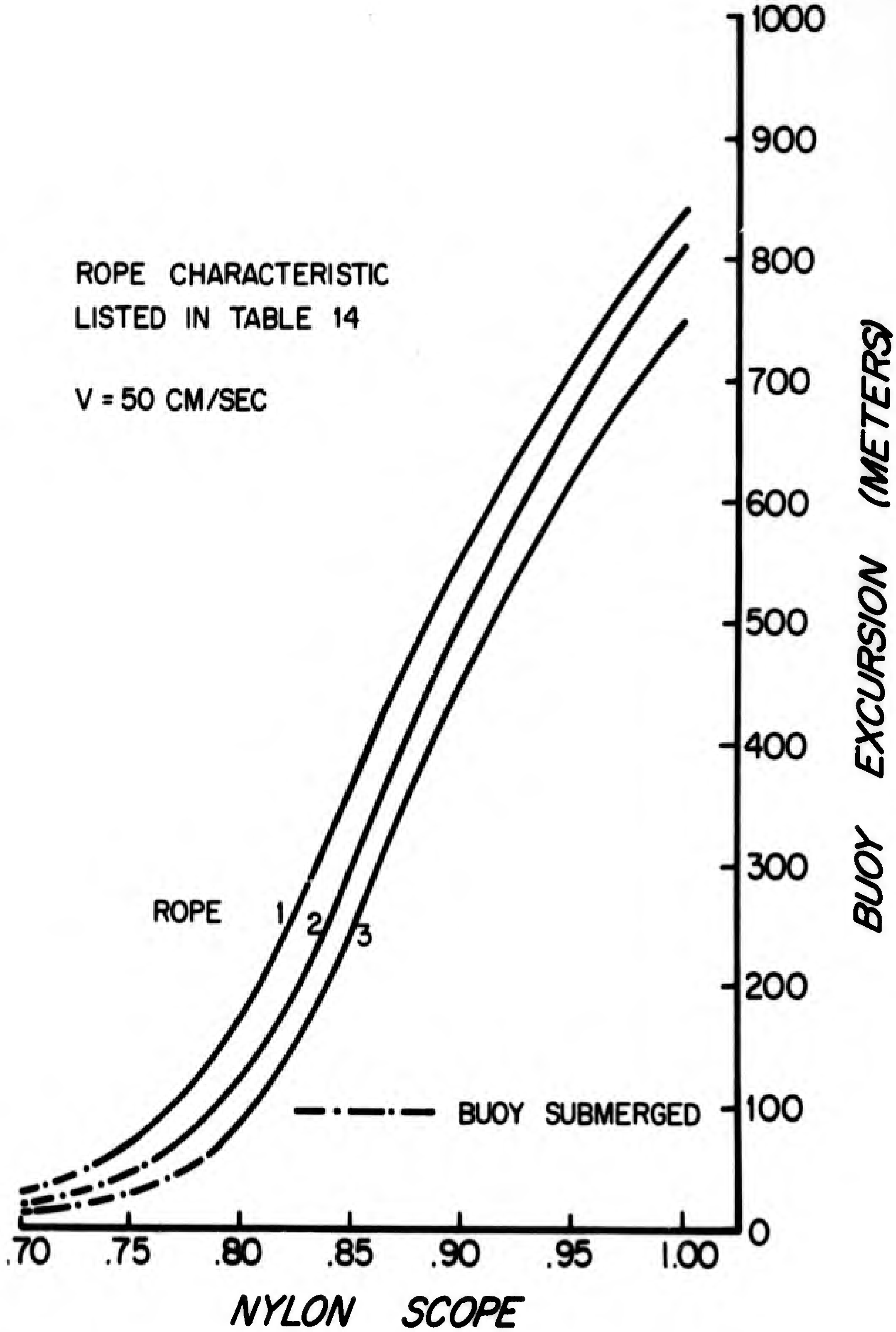


Figure 17. Excursion vs nylon scope and rope size.

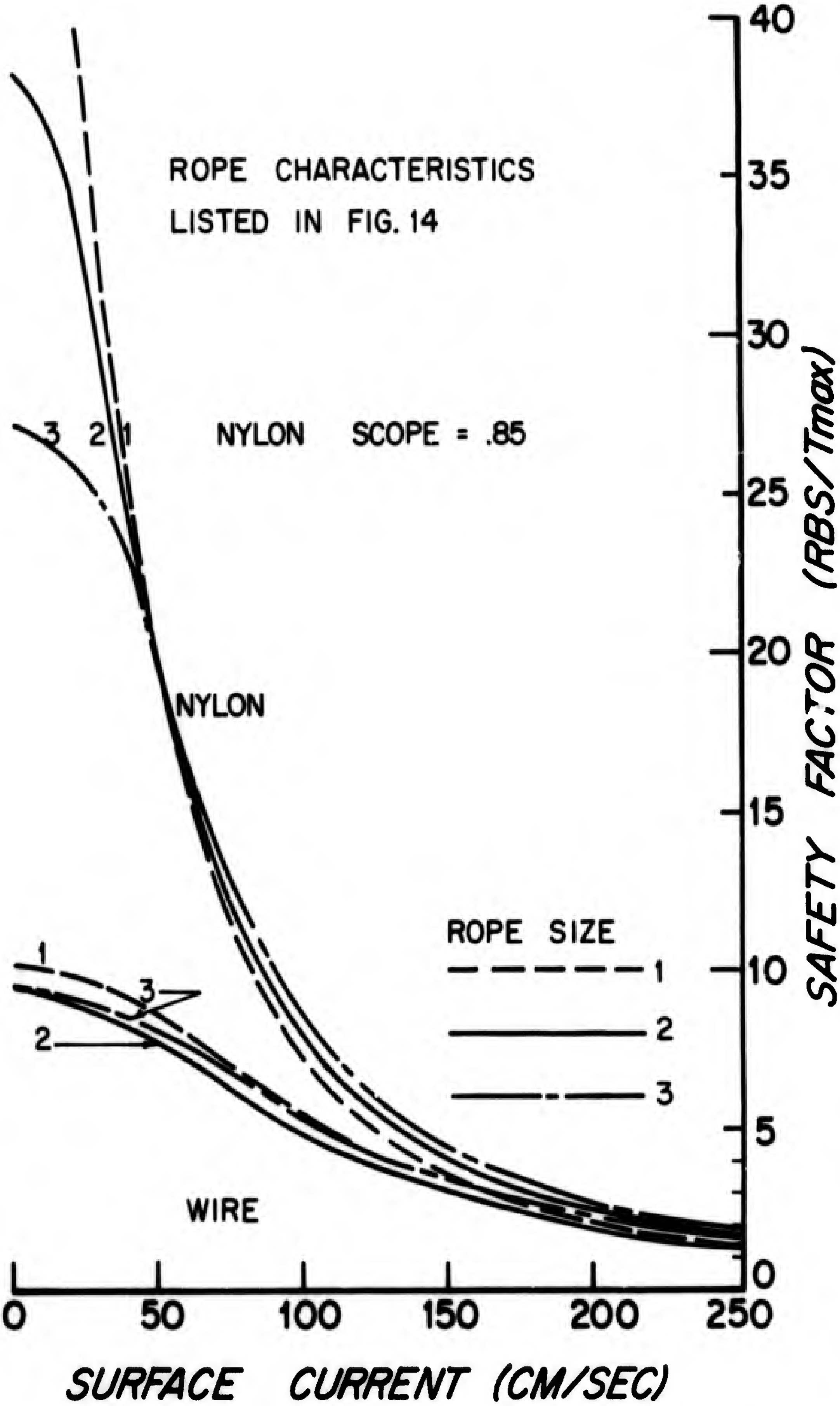


Figure 18. Safety factor vs current speed and rope size.

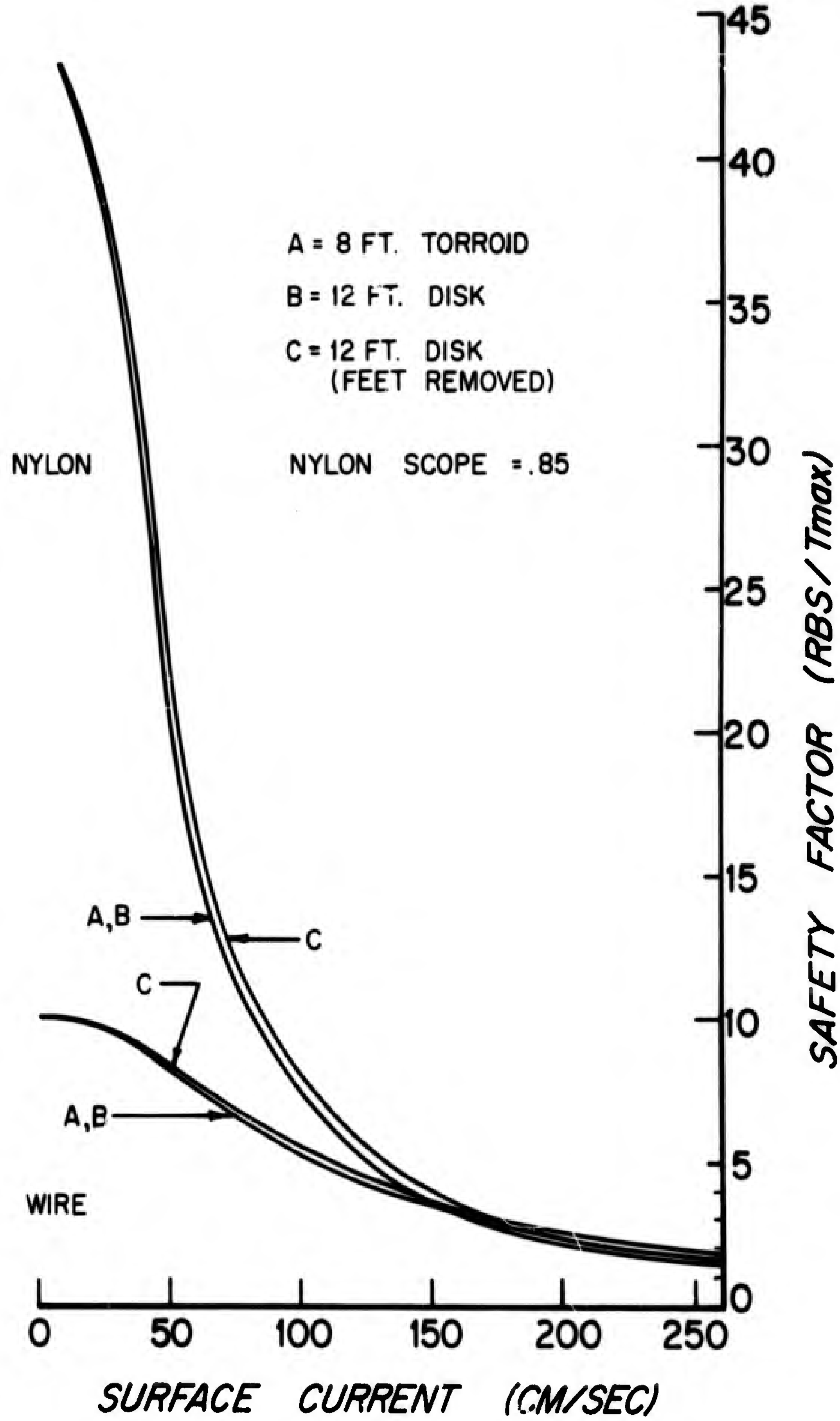


Figure 19. Safety factor vs current speed and buoy type.

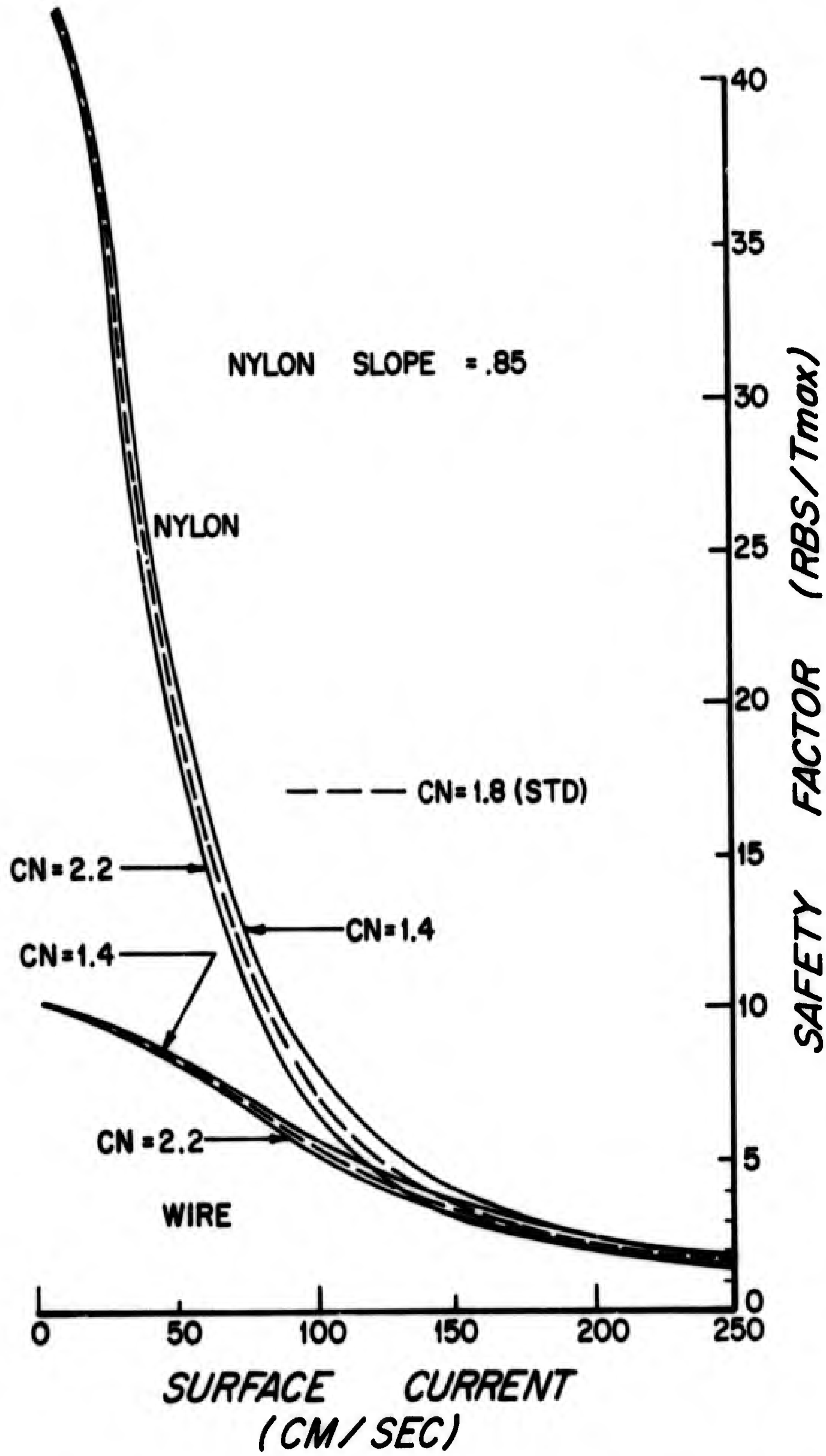


Figure 20. Safety factor vs current, speed and normal drag coefficient.

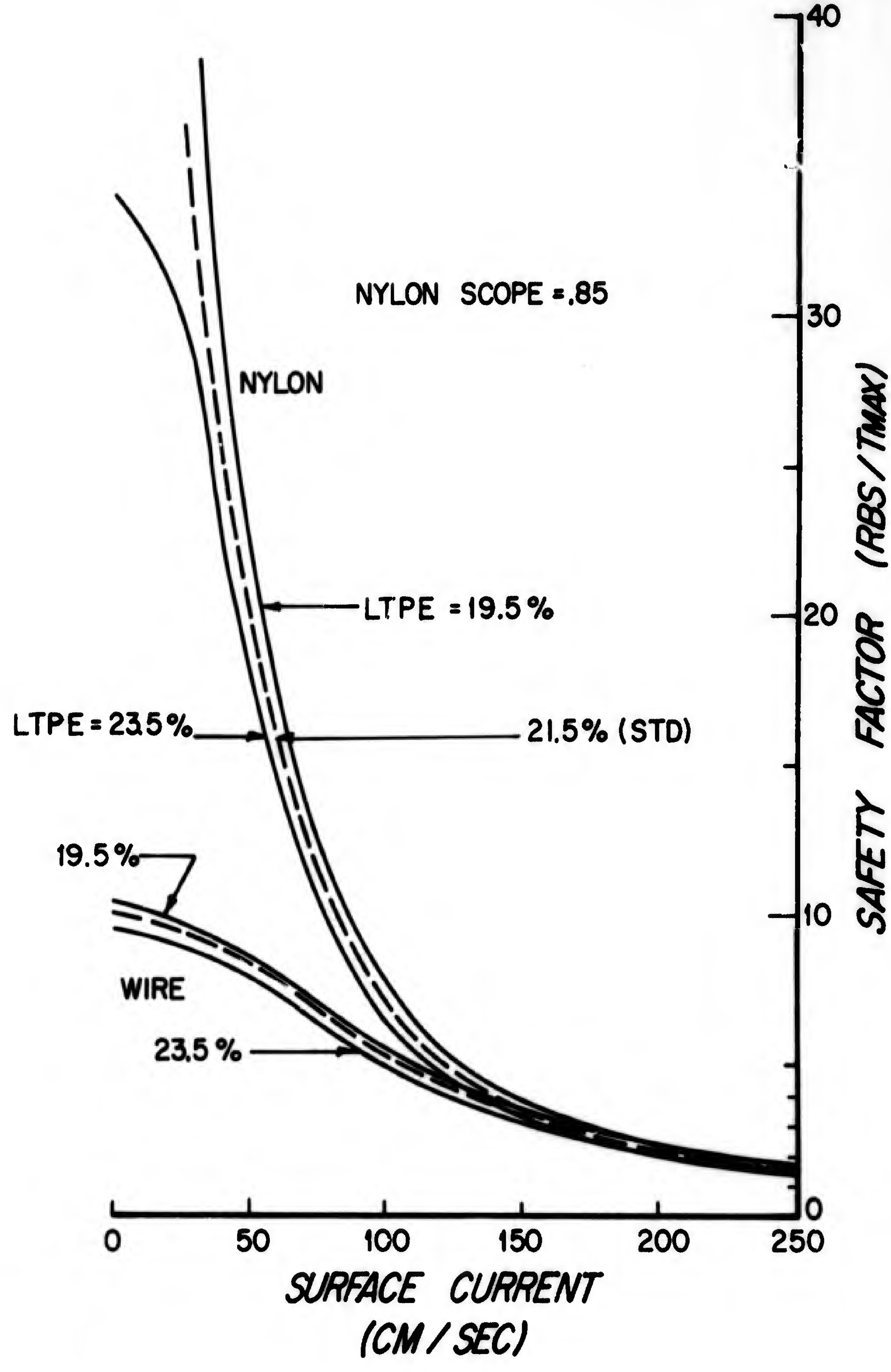


Figure 21. Safety factor vs current speed and launch transient peak elongation (LTPE).

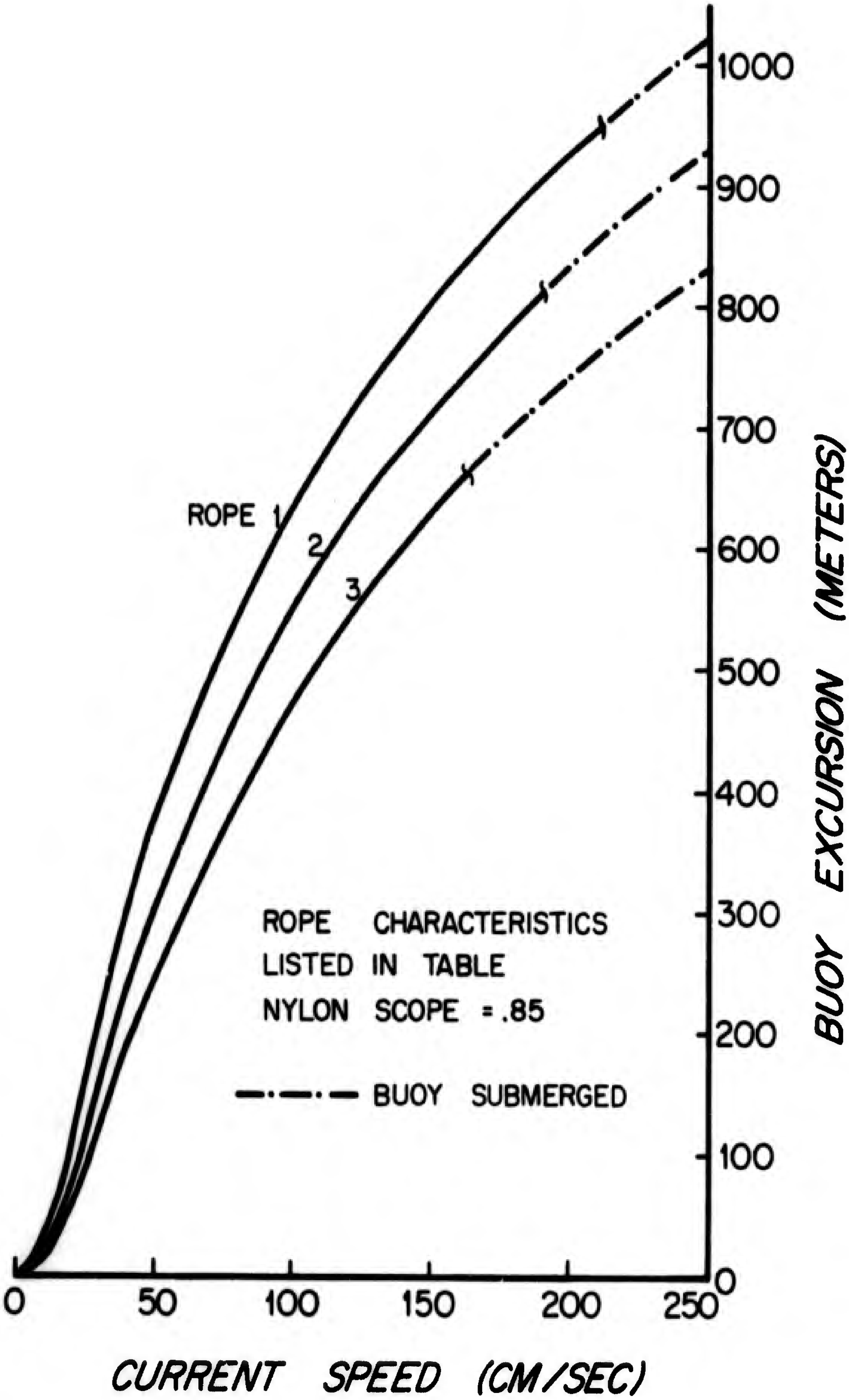


Figure 22. E·cursion vs current speed and rope size.

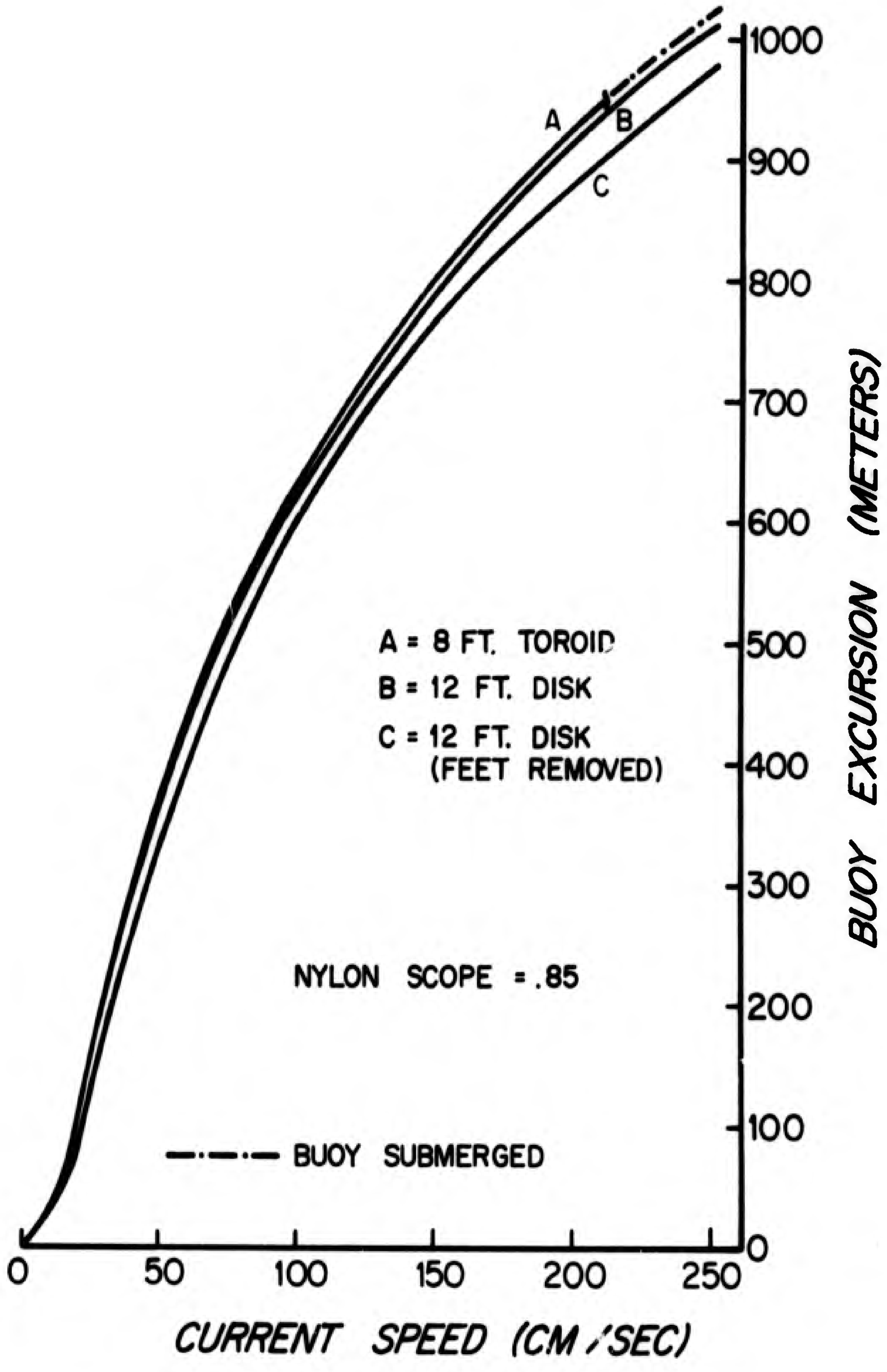


Figure 23. Excursion vs current speed and buoy type.

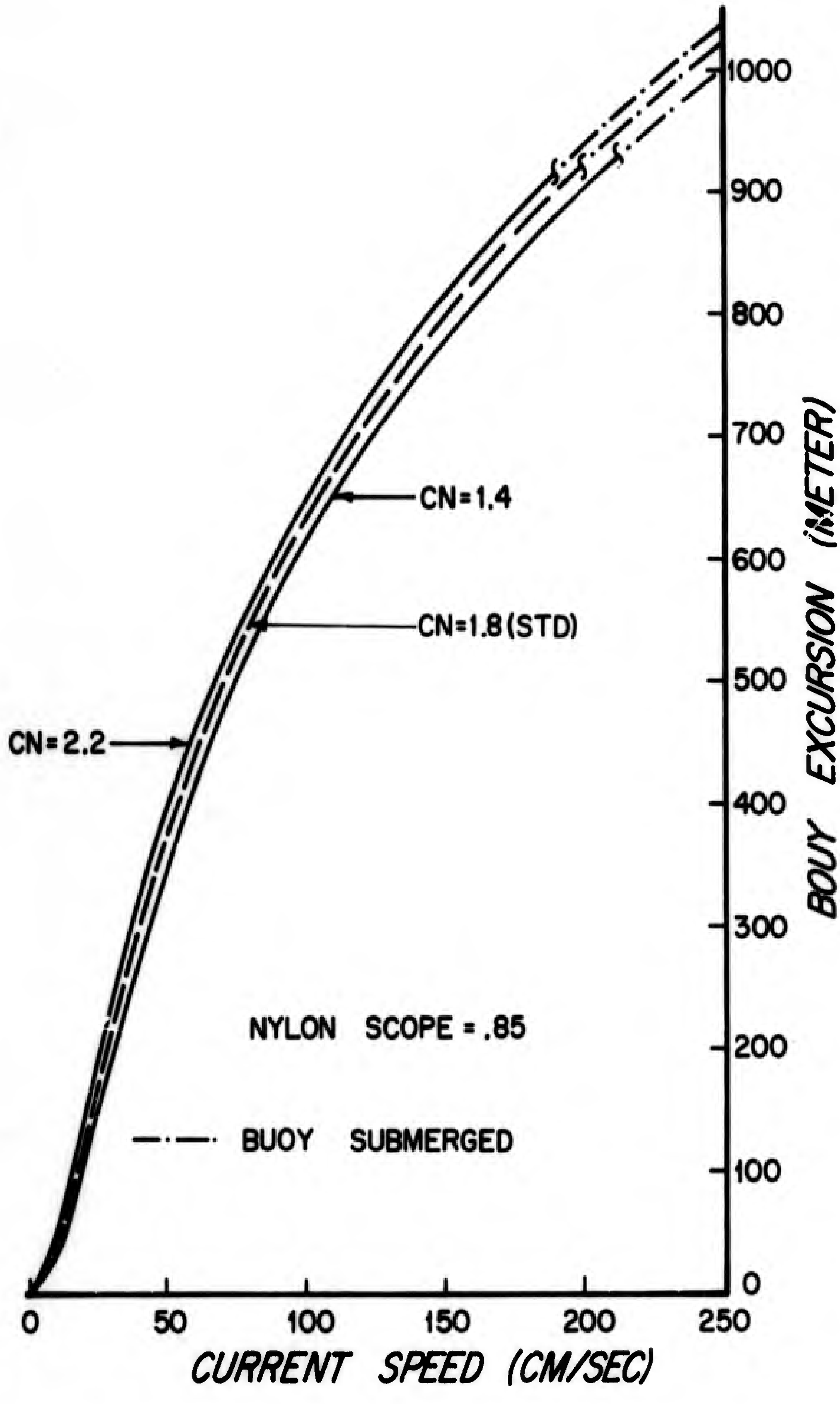


Figure 24. Excursion vs current speed and normal drag coefficient.

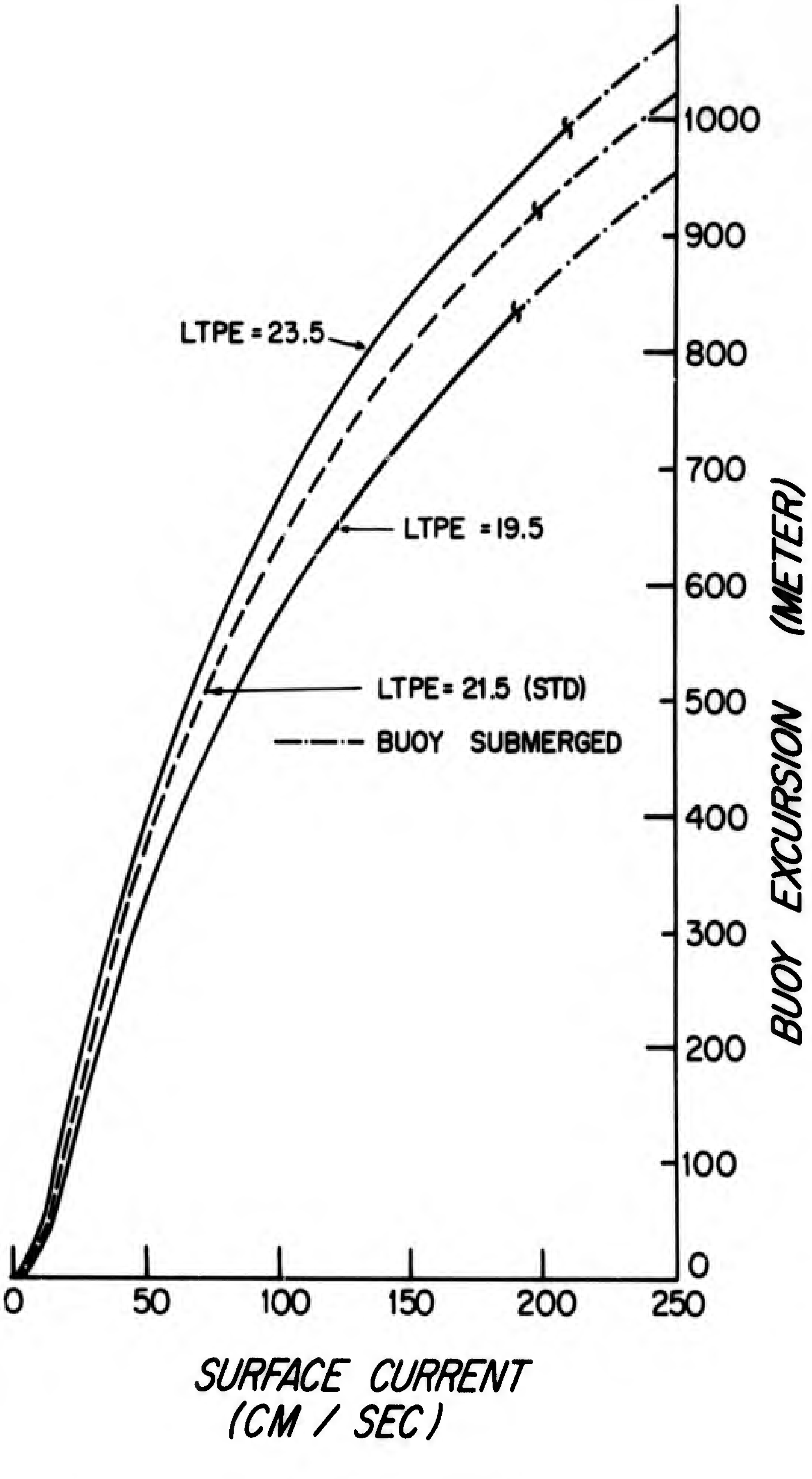


Figure 25. Excursion vs current speed and launch transient peak elongation (LTPE).

DISCUSSION OF RESULTS

Figs. (16-17) - Safety Factor and Excursion vs. Nylon Scope and Rope Size

Both safety factor and buoy excursion increase sharply with nylon scopes above 0.8. Below this value, as tension approaches cable strength and excrusion becomes small the curves level off. At high nylon scope, the safety factor of the wire, which must support its own weight, reaches a limiting value near ten. At low nylon scope, nylon elongation introduces the predominant contribution to tension. In that area smaller diameter ropes display lower tensions and higher safaty factors. Buoy excursion is less with larger ropes. As indicated the eight foot toroidal buoy will submerge at low nylon scope. In this situation the solution becomes invalid.

Figs. (18-21) - Safety Factor vs. Current Speed

Nylon and wire safety factors decrease with increasing current. This effect diminishes as tension approaches the cable strength. Tensions at zero current are due to nylon scope and component weight.

Fig. (18) - Safety Factor vs. Current Speed and Rope Size

At high currents the smaller, weaker ropes display lower safety factors. At currents below fifty cm/sec the tension due to nylon scope causes the larger diameter ropes to exhibit lower safety factors.

Fig. (19) - Safety Factor vs. Current Speed and Buoy Type

The disk-without-feet exhibits approximately half the drag of the other buoys. This results in lower tensions and greater safety factors throughout the system. The toroid and the disk-with-feet display almost identical characteristics. The disk buoys are larger than the toroid and do not submerge at high currents. If the toroid and the disk-with-feet were of similar size the toroid would cause larger tensions. The effect of buoy type on the entire system seems relatively small.

Fig. (20) - Safety Factor vs. Current Speed and Normal Drag Coefficient

Increased drag coefficient causes increased tensions and lower safety factors. Assuming that any realistic drag coefficient will lie between 1.4 and 2.2 these curves may represent, for this system, limits on errors due to this parameter.

Fig. (21) - Safety Factor vs. Current Speed and Launch Transient Peak Elongation (LTPE)

Changing the LTPE without changing the launch transient peak load has a direct multiplicative effect on the steady state elongation (see Chapter IV). Curves obtained in this way may be used to study the effect of varying elasticity independently of rope size and strength. Ropes with lower LTPE will be proportionately less compliant and therefore experience greater tensions and lower safety factors. The difference is greatest at low currents where tension is predominantly due to nylon scope.

Figs. (22-25) - Excursion vs. Current Speed

Excursion increases rapidly with current at low current speeds. The rate of increase is less at high excursions when there are greater cable angles and greater restoring forces. In many cases the toroidal buoy is submerged at high currents.

Fig. (22) - Excursion vs. Current Speed and Rope Size

Larger diameter, less compliant ropes permit less excursion. The larger lines cause the toroidal buoy to submerge at lower current speeds.

Fig. (23) - Excursion vs. Current Speed and Buoy Type

The effect of buoy type on excursion is somewhat greater than its effect on safety factor. Due to lower drag the disk-without-feet causes the least excursion. The disk-with-feet is just slightly better than the toroid. Again, if the buoys were of similar size the advantage of the disk would be increased. The larger disk does not allow the system to submerge at high current speeds.

Fig. (24) - Excursion vs. Current Speed and Normal Drag Coefficient

Increased drag coefficients cause increased excursions.

Fig. (25) - Excursion vs. Current Speed and Launch Transient Peak Elongation (LTPE)

The less compliant lines with lower LTPE's allow less excursion.

The elastic properties of nylon rope seem to have the greatest effect on taut-line mooring performance. This can be seen in the plots dealing with scope, line size and launch transient peak elongation.

SUGGESTIONS FOR FURTHER STUDY

The solution of this problem has necessitated study in several areas which might require more detailed investigation. It will be important to study the effects of wave and wind drag on the buoy hulls. The drag of various oceanographic instruments needs to be investigated. In some cases this seems as important as drag on the buoy. The drag coefficient for the mooring cable also needs further study.

As stated in the text, the nylon elongation experiments already performed are only a beginning. A detailed knowledge of nylon rope response, in mooring applications, will be essential to its successful use in buoy systems.

This program could be expanded to include other ropes, other buoys and subsurface moorings.

LIST OF REFERENCES

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2. Paquette, Robert G., and Henderson, Bion E. The Dynamics of Simple Deep-Sea Buoy Moorings. Technical Report, General Motors Defense Laboratories. Santa Barbara, November 1968, p. 7.

3. Pode, Leonard. Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream. R & D Report No. 687. Department of the Navy, March 1951.

4. Webster, Ferris. "Vertical Profiles of Horizontal Ocean Currents," Deep Sea Research, XV (in press), 1968.

5. Wilson, Basil W. Characteristics of Anchor Cables in Uniform Ocean Currents. Technical Report No. 204-1, Texas A&M Project 204 - Reference 60-51. April 1960.

APPENDIX (1) - SOLUTION PROGRAM

1a Variable Definitions

1b Program Listing

1c Program Details

1d Programming Instructions

1e Comparison of Results with Previous Solutions

APPENDIX (1-a) - VARIABLE DEFINITIONS

A	launch transient peak tension - lbs.
BUOY1 BUOY2	represent an eight character buoy name
CDI(10)	drag coefficient for each instrument - $\frac{\text{lbs}}{(\text{cm/sec})^2}$
CDIAS CDIAW	nylon and wire diameter coefficient = (length) x $(\text{diameter})^2$ - meters-inches^2
CDN CDT	normal and tangential cable drag coefficient
COST	COS(THETA)
DE	change in depth error - meters/50 lbs.
DEPTH	water depth - meters
DIA	cable diameter under tension - inches
DIAE	buoy diameter - feet
DIAS DIAW	nylon and wire original diameter - inches
DN DT	normal and tangential segment drag - lbs.
E	depth error - lbs.
E1	depth error after adding fifty lbs. - lbs.
ETS ETW	nylon and wire tension error - lbs.
H	depth to the end of a segment - meters
H2	depth of the mid-point of a segment - meters
I	instrument number
IB	buoy number
IE	controlling index for error calculation
INDEX	main program control index
INST	instrument subroutine

IW	number of systems with results printed at each segment
IZ	controlling index for Θ = zero check
J	index for parameter loop
JMAX	number of parameter cards
K	index for buoy loop
L	number of iterations
LTPE	launch transient peak elongation (nylon) - %200D^2
N	segment number
NI(10)	instrument position (number of segment below instrument)
NS	total number of nylon segments
NW	total number of wire segments
RBSS RBSW	nylon and wire rated breaking strength - lbs.
RNS RNW	number of nylon and wire segments (real mode)
S	accumulated stretched length - meters
S1	stretched segment length - meters
S2	accumulated slack length - meters
SCOPE	nylon scope, $\frac{\text{slack nylon length}}{\text{water depth-length of wire and instruments}}$
SFS SFW	nylon and wire safety factor (rated breaking strength/maximum tension)
SI(10)	instrument length - meters
SINT	SIN(THETA)
SIT	total length of instruments - meters
STRAIN	maximum nylon elongation- %200D^2
STRMAX	maximum nylon elongation - decimal based on 200D^2
STRS	nylon elongation under tension - decimal based on 200D^2
STRW	wire elongation under tension - decimal

SS	nylon slack segment length - meters
SST	total slack nylon length - meters
SW	wire slack segment length - meters
SWT	total slack wire length - meters
T	tension - lbs.
TENSON	tension at the first segment - lbs.
THETO	surface cable angle (external function) - radians
THETAT	surface cable angle - radians
THETA	segment orientation angle - radians
TMAXS TMAXW	maximum nylon and wire tension - lbs.
TSO TWO	maximum nylon and wire tension (storage positions) - lbs.
TYPE1(10) TYPE2(10)	an eight character instrument name
U	subsurface current speed - cm/sec
UN UT	normal and tangential current components - cm/sec
V	surface current speed - cm/sec
WI(10)	instrument weight in water - lbs.
WN WT	normal and tangential segment weight - lbs.
WS WW	nylon and wire segment weight in water - lbs.
WSUL WWUL	nylon and wire weight per unit length in water - lbs/meter
X	excursion to the end of a segment - meters

APPENDIX (1-b) - PROGRAM LISTING

```
15132 NOV 26,'68 ID=0000
 JOB 56,1080
FORTRANH LS,GO
              C  PROGRAM TO COMPUTE THE CONFIGURATION OF A BUOY SYSTEM
                    COMMON I,NI(10), SI(10), WI(10), CDI(10),V, INDEX,
                  1 TYPE1(10), TYPE2(10)
                    REAL  LTPE
              C INSTRUMENTATION
                    READ (105,101) (NI(I), SI(I), WI(I), CDI(I),
                  1 TYPE1(I), TYPE2(I), I = 1,10)
               101  FORMAT (I10, 3F10.3, 2A4)
                    WIT = 0.0
                    SIT = 0.0
                    DO 18 I = 1,10
                    WIT = WIT + WI(I)
               18   SIT = SIT + SI(I)
              C  LOOP FOR DIFFERENT BUOYS
                    DO 17 K = 1,3
                    READ (105,113,END = 19) JMAX, IW,BUOY1,BUOY2,IB,DIAB
               113  FORMAT (2I5, 2A4, I2, F10.2)
              C  LOOP FOR DIFFERENT MOORING PARAMETERS
                    DO 4 J = 1, JMAX
                   INDEX = 2
                    L = 0
                    IE = 1
                    IZ = 1
                    TMAXW = 0.0
                    TMAXS = 0.0
              C  MOORING PARAMETERS
                    READ (105,107, END = 19) DEPTH,V,A,LTPE,SCOPE,CDN,
                  1 DIAW, SWT, WWUL, RBSW, DIAS, WSUL, RBSS
               107  FORMAT (12F6.0, F8.0)
              C  NYLON LENGTH AND TANG. DRAG COEF.
                    SST = SCOPE * (DEPTH -(SWT + SIT))
                    CDT = 0.02 * CDN
                    WRITE (108,108)J,DIAB,BUOY1,BUOY2,IB,DEPTH,V,A,LTPE,
                  1 SCOPE,CDN,CDT,SWT,DIAW,RBSW,WWUL,SST,DIAS,RBSS,WSUL
               108  FORMAT (1H1,20X,'OCEANOGRAPHIC BUOY SYSTEM'//20X
                 1'RUN NUMBER  'I3/ 20X,'BUOY IS ',F5.2,' FT DIA ',
                 1 2A4,'  NO.',I5/
                 1 20X'DEPTH = 'F10.2,'  METERS'/20X'SURFACE CURRENT ='
                 1  F10.2,' CM/SEC'/20X'LAUNCH TRANSIENT PEAK TENSION = '
                 1 F8.2,'  LBS'/20X'LAUNCH TRANSIENT PEAK ELONGATION = '
                 1 F8.2,'  X 200 D SQ' /20X'NYLON SCOPE = 'F8.2,/20X
                 1'NORMAL DRAG COEF = 'F7.2/20X'TANGENTIAL DRAG COEF ='
                 1  F7.3 /20X,F10.2,' METERS OF 'F6.3,' INCH WIRE ROPE'/
                 120X'WIRE RBS = 'F10.1,' LBS;  WEIGHT = 'F6.4,' LBS/M'/
                 1 20X,F10.2,' METERS OF' F6.3,' INCH NYLON (SLACK)'/
                 120X'NYLON RBS = 'F10.1,' LBS;  WEIGHT = 'F6.4,' LBS/M')
               C  SEGMENTATION OF THE MOORING LINE
                    NW = (SWT/(SWT + SST))*100.0
                    NS = 100 - NW
```

```
          RNW = NW
          SW = SWT/RNW
          RNS = NS
          SS = SST/RNS
          WW = WWUL * SW
          WS = WSUL * SS
          CDIAW = SW*DIAW**2
          CDIAS = SS*DIAS**2
C  TENSION FIRST GUESS = STATIC WEIGHT
          TENSON = WIT +(WWUL * SWT) + ( WSUL * SST)
          WRITE (108,104)
 104      FORMAT (///33X,'ITERATION PROCEDURE'// 22X
     1 'TOP TENS  TOP ANGLE   DEPTH  DEPTH ERROR'/)
C  BEGINNING OF WIRE CABLE CALCULATIONS
  12      IF (IE .EQ. 2)CDN = CDN + 0.2
 7        S2 = 0.0
          N = 1
          S = 0.0
          X = 0.0
          H = 0.0
          I = 1
          T = TENSON
C  USE OF BUOY MODEL RESULTS
          THETAT = THETO (IB,V,TENSON,DIAB)
          IF (IE .EQ. 2)  THETAT = THETAT - .01745
          THETA = THETAT
          IF ( NW .EQ. 0 ) GO TO 15
          TMAXW = T
C  CHECK FOR INSTRUMENTATION
  1       IF (N .EQ. NI(I)) CALL INST (S2,S, X, H, THETA, T)
C WIRE ELONGATION
          STRW = T/((14.1E6) * (DIAW - .0625)**2)
          S1 = SW*(1.0 +STRW)
C  NUMERICAL INTERGRATION
          S2 = S2 + SW
          S = S + S1
          SINT = SIN(THETA)
          COST = COS(THETA)
          H = S1*SINT + H
          X = S1*COST + X
          DIA = SQRT(CDIAW/S1)
          WN = WW*COST
          WT = WW*SINT
          H2 = H - ((S1*SINT)/2.0)
          U = V * 2.52 * (H2**(-.4))
          IF (H2 .LE. 10.0) U = V
          UN = U*SINT
          DN = (2.94E-4)*CDN*S1*DIA*ABS(UN) * UN
          UT = U*COST
          DT = (2.94E-4)*CDT*S1*DIA* ABS(UT) * UT
          THETA = THETA - ((DN + WN)/T)
          IF (THETA .LE. 0.0) GO TO 3
          T = T - WT + DT
```

```
      IF(T .GT. TMAXW) TMAXW = T
      IF(INDEX .EQ. 3) WRITE (108,103) N, S2, S, H, X , T
C  CHECK FOR CABLE CHANGE
      IF (N .EQ. NW) GO TO 9
     N = N + 1
     GO TO 1
C  BEGINNING OF PLASTIC CABLE CALCULATIONS
 9    IF ( NS .EQ. 0 ) GO TO 11
      N = N + 1
 15   TMAXS = T
      STRMAX = 0.0
C  CHECK FOR INSTRUMENTATION
 10   IF (N .EQ. NI(I)) CALL INST (S2,S, X, H, THETA, T)
C  STRETCH OF THE NYLON
      STRS = (1.104* (T/A)**.283)* (LTPE/100.0)
      IF (STRS .GT. STRMAX) STRMAX = STRS
      IF (IE .EQ. 2)  STRS = .90 * STRS
       S1 = 1.052 * SS * (1.0 + STRS)
C  NUMERICAL INTERGRATION
     S2 = S2 + SS
     S = S + S1
     SINT = SIN(THETA)
     COST = COS(THETA)
     H = S1*SINT + H
     X = S1*COST + X
     DIA = SQRT(CDIAS/S1)
     WN = WS*COST
     WT = WS*SINT
     H2 = H - ((S1*SINT)/2.0)
      U = V * 2.52 * (H2**(-.4))
      IF (H2 .LE. 10.0) U = V
     UN = U*SINT
      DN = (2.94E-4)*CDN*S1*DIA*ABS(UN) * UN
     UT = U*COST
      DT = (2.94E-4)*CDT*S1*DIA* ABS(UT) * UT
     THETA = THETA - ((DN + WN)/T)
      IF (THETA .LE. 0.0) GO TO 3
     T = T - WT + DT
      IF(T .GT. TMAXS)  TMAXS = T
      IF(INDEX .EQ. 3) WRITE (108,105) N, S2, S, H, X , T
      IF (N .EQ. 100) GO TO 11
      N = N + 1
     GO TO 10
C  BEGINNING OF ITERATION PROCEDURE
 11  IF (INDEX .EQ. 1) GO TO 5
      IF (INDEX .EQ. 3) GO TO 13
C  CALC AND CHECK DEPTH ERROR
     E = DEPTH - H
     IF (ABS(E) .LT. 5.0) GO TO 6
      IF (IE .EQ. 1) WRITE (108,100) TENSON, THETAT, H, E
 100  FORMAT (20X,F10.2,F10.4,F10.2,F10.4,'   TRIAL RUN')
     L = L + 1
      IF (L .EQ. 10) GO TO 4
```

```
        INDEX = 1
C  ADD 50 LBS AND RECALCULATE
         TENSON = TENSON + 50.0
        GO TO 7
C  FIND DE/DT AND ADJUST TENSON
 5      E1 = DEPTH - H
        DE = E - E1
         TENSON = TENSON + 50.0*(E/DE)     - 50.0
        INDEX = 2
        GO TO 7
C  CALC. AND WRITE RESULTS
  6      IF (IE .EQ. 2) GO TO 14
         SFW = RBSW/TMAXW
         SFS = RBSS/TMAXS
         TWO = TMAXW
         TSO = TMAXS
         STRAIN = STRMAX * 100.0
         WRITE (108,102) TENSON, THETAT, H, E, TMAXW,SFW,
      1 TMAXS, SFS,STRAIN,X
 102  FORMAT(20X,F10.2,F10.4,F10.2,F10.4,'   CONVERGENT RUN'
     1////36X'RESULTS'
     1// 20X'MAXIMUM WIRE TENSION ='F8.2,
     1  ';   SAFETY FACTOR ='F5.2
     1 /20X'MAXIMUM NYLON TENSION ='F8.2,
     1  ';   SAFETY FACTOR ='F5.2
     1/20X'MAX NYLON ELONGATION =',F6.2,'  % 200 D SQ'/
     1 20X 'BUOY EXCURSION = 'F8.2,' METERS')
C  RECALC. AND WRITE OUT CONFIGURATION IF REQ'D
         IF (J .GT. IW) GO TO 13
         WRITE (108,109)
 109     FORMAT (///37X,'MOORING CONFIGURATION'//23X,
      1 'SLAC LENTH  STR LENTH    DEPTH  EXCURSION  TENSION'/)
        INDEX = 3
        GO TO 7
C  RECALC. TO DETERMINE POSSIBLE ERRORS
  13    IE = 2
         INDEX = 2
         GO TO 12
C  CALC. AND WRITE POSSIBLE ERRORS
 14      ETW = ABS(TWO - TMAXW)
         ETS = ABS(TSO - TMAXS)
         WRITE (108,112) ETW, ETS
 112     FORMAT (///20X'MAXIMUM EXPECTED ERROR'/ 20X
     1 '(ASSUMING CURRENT PROFILE CORRECT)' //20X
     1 'IF: TOP ANGLE OFF 1 DEGREE; DRAG COEF OFF 0.2;  '/
     120X'NYLON STRETCH OFF 10 PERCENT'//
     1 20X,'WIRE TENSION  ', F10.2, '  LBS'/ 20X
     1  'NYLON TENSION ',F10.2,'  LBS')
         GO TO 4
 103     FORMAT (20X,I3, 5F10.2,'  W')
 105     FORMAT (20X,I3, 5F10.2,'  N')
C  ADD 300 LBS TO TENSON IF THETA = ZERO
  3      IF (IZ .EQ. 11) GO TO 16
```

```
          IZ = IZ + 1
          TENSON = TENSON + 300.0
          GO TO 7
   16     WRITE (108,111) N
  111     FORMAT (20X,'THETA EQUALS ZERO AT SECTION',I3)
    4     CONTINUE
   17     CONTINUE
   19     CALL EXIT
          END
```

```
SUBPROGRAMS

  BF:PIN     BF:S3     BF:II     BF:FI     BF:SF     BF:S6     BF:FTI     BF:ITF
  THETO      INST      SIN       COS       SQRT      BF:FR     ABS        EXIT
  BF:SX

PROGRAM ALLOCATION

542.0   WIT      543.0   SIT      544.0   K       545.0   JMAX    546.0   IW
547.0   BUOY1    548.0   BUOY2    549.0   IB      54A.0   DIAB    54B.0   J
54C.0   L        54D.0   IE       54E.0   IZ      54F.0   TMAXW   550.0   TMAXS
551.0   DEPTH    552.0   A        553.0   LTPE    554.0   SCOPE   555.0   CDN
556.0   DIAW     557.0   SWT      558.0   WWUL    559.0   RBSW    55A.0   DIAS
55B.0   WSUL     55C.0   RBSS     55D.0   SST     55E.0   CDT     55F.0   NW
560.0   NS       561.0   RNW      562.0   SW      563.0   RNS     564.0   SS
565.0   WW       566.0   WS       567.0   CDIAW   568.0   CDIAS   569.0   TENSON
56A.0   S2       56B.0   N        56C.0   S       56D.0   X       56E.0   H
56F.0   T        570.0   THETAT   571.0   THETA   572.0   STRW    573.0   S1
574.0   SINT     575.0   COST     576.0   DIA     577.0   WN      578.0   WT
579.0   H2       57A.0   U        57B.0   UN      57C.0   DN      57D.0   UT
57E.0   DT       57F.0   STRMAX   580.0   STRS    581.0   E       582.0   E1
583.0   DE       584.0   SFW      585.0   SFS     586.0   TWO     587.0   TSO
588.0   STRAIN   589.0   ETW      58A.0   ETS


 PROGRAM SIZE 58B


/F4:COM  / ALLOCATION 3F     WORDS

0.0     I        1.0     NI       8.0     SI      15.0    WI      1F.0    CDI
29.0    V        2A.0    INDEX    2B.0    TYPE1   35.0    TYPE2


PROGRAM END
```

```
      SUBROUTINE INST (S2,S,X,H,THETA,T)
      COMMON I,NI(10), SI(10), WI(10), CDI(10),V, INDEX,
     1 TYPE1(10), TYPE2(10)
C  NUMERICAL INTEGRATION
      S2 = S2 + SI(I)
      S = S + SI(I)
      SINT = SIN(THETA)
      COST = COS(THETA)
      H = SI(I) *SINT + H
      X = SI(I) * COST + X
      WN = WI(I) * COST
      WT = WI(I) * SINT
      IF (NI(I) .EQ. 1) GO TO 301
      U = V * 2.52 * (H**(-.4))
  302 UN = U * SINT
      DN = CDI(I) * ABS(UN) * UN
      THETA = THETA - ((DN + WN)/T)
      T = T - WT
      IF (INDEX .EQ. 3) WRITE (108,303)TYPE1(I),TYPE2(I),H
  303 FORMAT( 20X,2A4,'  AT ' F8.2 ,' METERS' )
      I = I + 1
      RETURN
  301 U = V
      GO TO 302
      END
```

APPENDIX (1-c) - PROGRAM DETAILS

The program is described primarily by the comment statements in the program listing, Appendix (1-b), and the list of variable definitions in Appendix (1-a). Some portions are discussed below in more detail. They are:

1) program control (with abbreviated flow chart)
2) first tension assumption and theta equal zero check
3) wire rope elongation and diameter reduction
4) geometry of the integration procedure
5) current profile
6) cable drag calculations
7) nylon elongation and diameter reduction
8) calculation of error bounds
9) instrumentation subroutine - INST
10) surface angle function - THETO

The logic of the integrating and iterating procedures is explained in Chapter I.

1) Program Control

Several indices and indexing procedures are used to control the solution procedure. These are described briefly below.

a) INDEX - controls the iteration and printing procedures, when:

(1) INDEX = 2, normal computation is being carried out

(2) INDEX = 1, fifty pounds has been added to the surface tension and the system is being computed to obtain an improved surface cable tension

(3) INDEX = 3, a valid solution has been found and the system is being recomputed to write parameters at each segment.

b) IE - controls the error calculation procedure; when:

(1) IE = 1, normal computation is being carried out using input values of CDN, THETAT and STRS

(2) IE = 2, computation to determine error bounds is being carried out using altered values of CDN, THETAT, STRS.

c) IW and J - IW is the number of solutions which will have results printed at each segment. J is a dummy index for the inner control loop. It is indexed one unit for each complete solution. When J exceeds IW, control is no longer switched to the INDEX = 3 mode.

d) L = controls the number of iterative cycles for each solution. It is indexed once each cycle and will shift control to the next system if convergence is not achieved in ten attempts.

e) IEOD - if this card is read the run is terminated.

Fig. (26) is an abbreviated flow chart indicating these procedures.

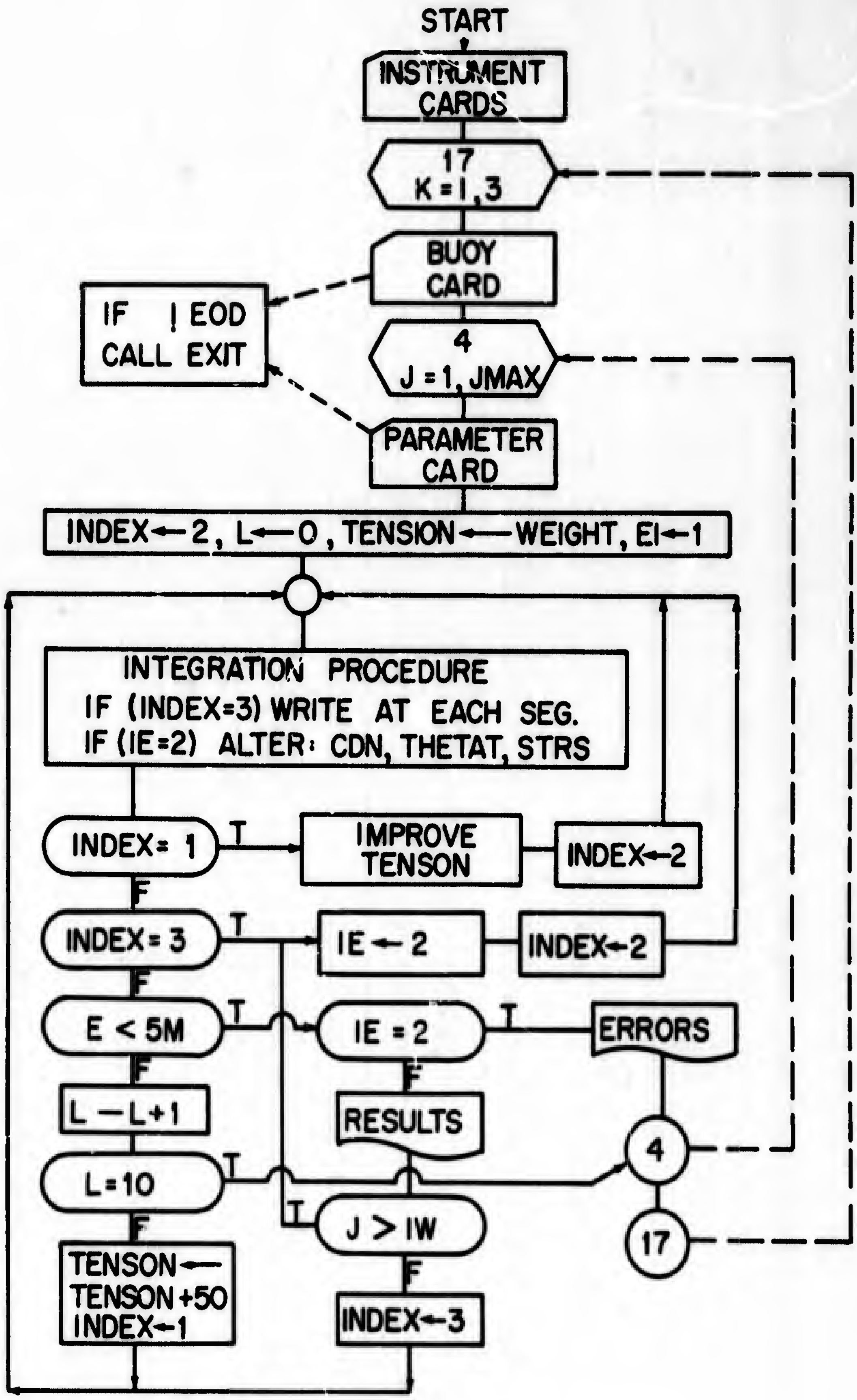

Figure 26. Program Control Procedures

2) First Tension Assumption and Theta Equal Zero Check

The first guess for surface cable tension is the weight in water of the entire mooring system. This is often very close to the required tension in cases of small currents with the scope near one.

In other cases this tension may not be great enough to obtain a valid solution. Employing the cable equation, $\Delta\Theta = -\frac{N}{T}$, at each segment, with small initial T, may cause Θ to go to zero and then become negative. This means that the cable has become horizontal and is returning to the surface. In this situation several of the integration procedures become invalid. To prevent this, Θ is checked each time it is recomputed. If it is zero or negative control is shifted to statement 3, where three hundred pounds is added to the initial tension assumption. This procedure may be repeated as many as ten times, allowing an increase of 3000 lbs. before a special error statement is printed and control is shifted to the next system.

3) Wire Rope Elongation and Diameter Reduction

For wire rope the standard formula is employed to determine the elongation, STRW:

$$STRW = \frac{\Delta L}{L} = \frac{T}{A_R E_R} \qquad 15$$

where L is length, T is the force or tension, A_R the area of the rope (not metallic area) and E_R is the modulus of elasticity based on rope area.

Values of E_R for wire ropes range from 12×10^6 to 24×10^6. A standard value of 18×10^6 is used. It is assumed that wire elongation will be small and that such a simplification will not reduce the validity of the program.

Most oceanographic cables are jacketed, which adds approximately 1/16 inch to the diameter. It is the total outside diameter which is read into the program as DIAW.

Therefore:

$$A_R = \frac{\pi}{4} (DIAW-.0625)^2 \qquad 16$$

Combining this result and equation (15)

$$STRW = \frac{T}{A_R \; E_R} = \frac{4.T}{(DIA-.0625)^2 \; . \; 18 \times 10^6} \qquad 17$$

$$= T/ \; (14.1 \times 10^6 \; . \; (DIAW-.0625)^2) \qquad 18$$

Stretched segment length, S1, is expressed as

$$S1 = SW.(1.0 + STRW) \qquad 19$$

where SW is the slack segment length.

The wire diameter is reduced such that the volume of each segment is held constant. For this purpose a diameter coefficient, CDIA, is computed for each cable type:

$$CDIA = (length) \; . \; (diameter)^2 \quad (unstretched) \qquad 20$$

This coefficient is proportional to volume and stretched diameter is adjusted to hold it constant, so that:

$$DIA^2 \; . \; S1 = CDIA \qquad 21$$

$$\text{and, } DIA = \sqrt{CDIA/S1} \qquad 22$$

where DIA is the stretched diameter.

4) Geometry of the Integration Procedure

The detailed geometry is presented in fig. (27) such that:

if $SINT = SIN\ \Theta_n$ 23

$COST = COS\ \Theta_n$

then

$S_n = S1 + S_{n-1}$

$H_n = S1 \cdot SINT + H_{n-1}$

$X_n = S1 \cdot COST + X_{n-1}$

$WN = W.COST$

$WT = W.SINT$

$H2 = H_n - (S1.SINT/2)$ 24

$UN = U.SINT$

$UT = U.COST$

$N = DN + WN$

$P = DT-WT$

$\Delta T = P = DT-WT$

$$\Delta\Theta = \frac{-N}{T_n} = -\frac{DN+WN}{T_n}$$

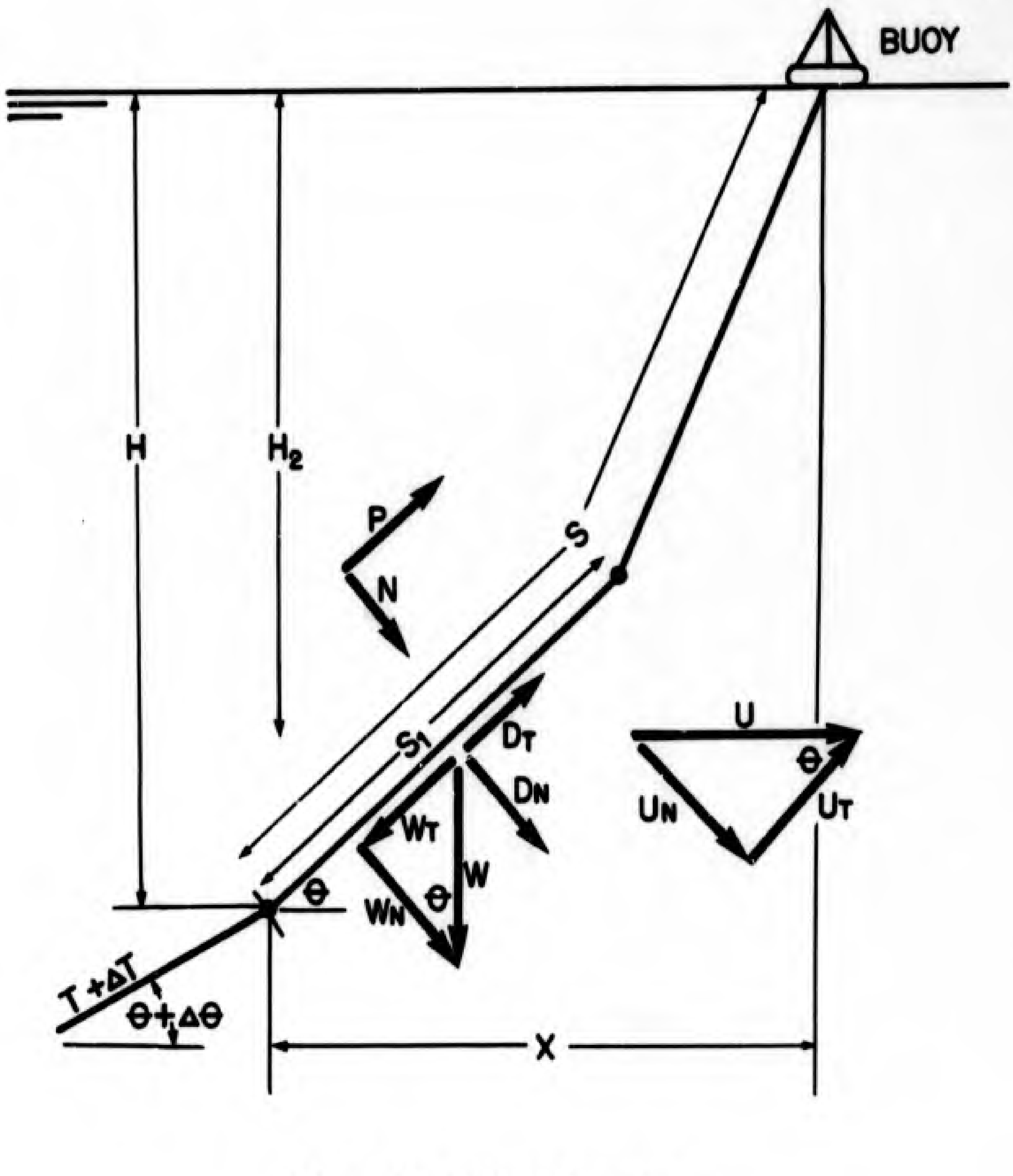

Figure 27. Program Geometry

5) Current Profile

The current profile expresses the current speed as a function of depth. As discussed in Chapter II a profile has been included in the program, but may be changed at the discretion of the user. The expression is listed in three statements within the program, once in each of the integration routines and once in the subroutine INST. It is of the form:

$$U = f\,(H2) \qquad 25$$

where U is current speed in cm/sec and H2 is the depth in meters.

The profile presently included is derived below. The surface current speed, V, is a program input and is used to determine the amplitude of the entire profile. Current speed is expected to decrease as $H2^{-.4}$. The relationship is therefore of the form:

$$U = T.V.H2^{-.4} \qquad 26$$

which becomes invalid at the surface, when H2 = 0. It is assumed that the first 10 meters of water will be moving at the surface current speed. Therefore, when:

$$H2 = 10, \quad U = V,$$

$$V = T.V.10^{-.4}$$ from equation (26), and therefore

$$T = 10^{.4} = 2.52 \qquad 27$$

This results in a profile which is valid from 10 meters below the surface down to any depth:

$$U = 2.52.V.H2^{-.4} \qquad 28$$

If H2 is less than 10 meters the surface current, V, is used.

To alter the profile the three cards containing the expression in U and H2 must be replaced. It is not necessary to include V in the relationship. Surface current must always be read into the program, however, to be used in determining buoy drag. Any continuous functional relationship, which can be interpreted by by the computer, may be used as a current profile. Reversing currents are permitted, and should be expressed by a sign change. The surface current should always be positive. If stepped currents are desired,statements of the form:

```
IF (H2 .GT. Z1 .AND. H2 .LE. Z2)  U = B
```
29

may be used, where Z1 and Z2 are water depths and B is the current speed between those depths. B may be a function of H2 and V.

6) Cable Drag Calculations

As discussed in Chapter 1 normal and tangential drag are computed separately using the normal and tangential components of the current. The standard formulae:

$$DN = \rho/2\ CDN.A.UN^2 \qquad 30$$

$$DT = \rho/2\ CDT.A.UT^2 \qquad 31$$

are employed, where $\rho/2$ for sea water = 1.0, drag is in pounds, A is in ft^2, and velocity in ft/sec. A is actually computed as stretched diameter times stretched length:

$$A = DIA.S1 \ \frac{3.281}{12} \qquad 32$$

where DIA is in inches and S1 in meters. The square of velocity is expressed as:

$$UN^2 = /UN/\ .UN = ABS(UN)\ .\ UN \qquad 33$$

$$UT^2 = /UT/\ .UT = ABS(UT)\ .\ UT \qquad 34$$

This allows negative drag forces in the case of reversing currents. To convert velocity from cm/sec to ft/sec the factor .03281 is used.

The result is then:

$$DN = CDN.DIA.S1./UN/.UN. \quad \frac{.03281^2\ .\ 3.28}{12} \qquad 35$$

or DN = (2.94E-4) * CDN * DIA * S1 * ABS(UN) * UN 36

and DT = (2.94E-4) * CDT * DIA * S1 * ABS(UT) * UT

in the Fortran language.

7) <u>Nylon Elongation and Diameter Reduction</u>

The expression in α and β discussed in Chapter IV has been included in the program. The launch transient peak load and peak elongation have been read in as, A and LTPE respectively. Therefore at tension, T:

$$\alpha = T/A$$ 38

$$STRS = \beta \ (LTPE/100)$$

where steady state elongation (decimal) = STRS. From Chapter IV, Fig.12

$$STRS = 1.104 \ . \ (T/A)^{.283} \ (LTPE/100.0)$$ 39

This is elongation based on an original length at a tension equal to $200D^2$ (see Appendix (3)). It has been determined that:

$$\text{length at } 200D^2 = 1.052 \ . \ (\text{slack length})$$ 40

therefore:

$$S1 = 1.052 \ . \ SS \ . \ (1.0 + STRS)$$ 41

where S1 is the stretched segment length and SS is the slack segment length. A procedure similar to that used for wire cable is used to calculate the stretched nylon diameter.

8) Calculation of Error Bounds

After the mooring configuration has been solved and the results printed, a slightly modified system is calculated to determine the combined effect of several possible input errors. Control of this function is held between statements 13-112. When control is shifted to statement 13, IE the controlling index is set equal to 2 and the system recomputed. When IE = 2, one degree is subtracted from the surface angle, 0.2 is added to the normal drag coefficient and the nylon stretch is reduced by 10%. The changes in wire and nylon tension due to these alterations are computed at statement 14 and are printed out as possible errors.

The tension change should represent a maximum error as the effect of the three adjustments will be additive. This would not be true for buoy excursion, when increased drag and reduced surface angle oppose decreased stretch. For this reason the change in buoy excursion is not computed. It is felt that for engineering purposes the tension figures are more critical.

9) Instrument Subroutine - INST

There are ten sets of instruments allowed in the mooring line. One card is read for instrument which lists its position, length, weight, drag coefficient, and name. This information is stored in six, ten-unit arrays.

The instrument position refers to the segment which the instrument will precede in the mooring line. When the segment index, N, reaches the instrument's position the instrument subroutine is called. The length, weight and drag of the instrument are integrated into the mooring as if it were a rope segment, except that no tangential drag is considered for instruments. The current profile is entered at the instruments' base, except for those directly below the buoy where the surface current is used.

The special drag coefficient, CDI, includes the instruments' cross-sectional area and the density of sea water, i.e.

$$CDI = \frac{DRAG}{U^2} = \rho/2 \; . \; A \; . \; C_D \; \frac{lbs}{(cm/sec)^2} \qquad 42$$

10) Surface Angle Function - THETO

The results of the buoy model tests have been incorporated into the program as the external function THETO. The test results as listed in figs. (6-8) of Chapter III are of the form:

$$\Theta_R = \zeta\,(T/B \times 100\%)^{-\gamma} \cdot (Fr\#) \qquad 43$$

Where Θ_R is towing angle to the vertical in radians, ζ and γ are constants, T the cable tension in pounds, B the total submerged buoyancy of the buoy and Fr# the Froude number.

For the toroid:

$$\Theta_R = 7.70\ (T/B \times 100\%)^{-.587} \cdot (Fr\#). \qquad 44$$

THETA, the cable orientation angle, is measured to the horizontal so that:

$$\Theta = \frac{\Pi}{2} - \Theta_R = 1.5708 - \Theta_R \qquad 45$$

Submerged buoyancy for a one foot diameter toroid equals 9.24 pounds, therefore,

$$B = 9.24\ (DIAB)^3 \qquad 46$$

for any geometrically similar buoy, where DIAB is the buoy diameter in feet, and

$$(T/B) \times 100\% = T/(.0924\ (DIAB)^3). \qquad 47$$

By definition

$$Fr\# = v^2/DIAB\ .\ g \qquad 48$$

where v is fluid velocity, and g the acceleration of gravity. Converting v^2 from $(cm/sec)^2$ to $(ft/sec)^2$ with the factor $(.03281)^2$ and using $g = 32.2\ ft/sec^2$

$$Fr\# = \frac{v^2}{DIAB}\ \frac{.03281^2}{32.2} = \frac{v^2}{DIAB}\ .\ (3.35 \times 10^{-5}) \qquad 49$$

Combining equations (44), (45), (47), and (49):

$$\Theta = THETO = 1.5708 - \left(2.58 \times 10^{-4}\ \frac{v^2}{DIAB}\ \ T/(.0924(DIAB)^3)\right)^{.587}$$

Derivations for the other buoys are similar.

APPENDIX (1-d) - PROGRAMMING INSTRUCTIONS

Four types of data cards are required by the solution program: (1) instrument cards, (2) buoy cards, (3) parameter cards, and (4) ! EOD card.

1) Instrument Cards

The first ten cards in the data deck must be instrument cards. If there are less than ten instruments then the deck must be filled out with "no-instrument" cards as described below. No more than ten instruments may be used. If more than one instrument is placed at a single location only one card is used. For that card lengths, weights and drag coefficients of the instruments in the group are added together. The instrument cards should be arranged in order of increasing depth.

Each instrument card should contain five pieces of information:

a) the segment of mooring cable above which the group is to appear (1-100) - integer mode - right justified in the first ten columns of the card

b) the length of the instrument group, meters-floating point mode - columns 11-20

c) the weight in water of the instrument group, pounds-floating point mode - columns 21-30

d) the special "instrument drag coefficient" $\frac{\text{pounds}}{(\text{cm/sec})^2}$ see Appendix (1-c) - floating point mode-columns 31-40

e) instrument or group name - may be any series of eight characters-columns 41-48

A listing of suggested values for several typical instruments is given at the end of this section. It is not possible to place an instrument directly above the anchor.

If "no-instrument" cards are required they should have the following form:

COLUMN	8	9	10	11	20	21	30	31	40	41	50
	1	0	1	0.0		0.0		0.0			

2) Buoy Card

Directly following the tenth instrument card there must be a single buoy card containing five pieces of information:

a) the number of systems which will be run using this buoy-integer mode, right justified - columns 1-5

b) the number of configurations using this buoy which will have results printed out at each segment - integer mode, right justified - columns 6-10

c) buoy type - any series of eight characters - columns 11-18

d) buoy number - (1) for toroid, (2) for disk-with-feet, (3) for disk-without-feet - integer mode, right justified - columns 19-20

e) buoy diameter, feet - floating point mode - columns 21-30

3) Parameter Cards

Following the buoy card should be the parameter cards describing the systems with which that buoy is to be used. The number of parameter cards must agree with the number listed in the first five columns of the preceding buoy card.

All of the information for the parameter card is in the floating point mode. Table (3) lists the information required, the columns in which it should appear and examples taken from the "standard" buoy system discussed in Chapter VI. Each parameter card initiates an independent computation. Following the first set of parameter cards may be a second buoy card and a second set of parameter cards. This second group will be calculated independently of the first, using a different buoy, but the same set of instruments. A third buoy card and set of parameter cards may be added if desired. If more than one buoy is used they need not be in any special order, but the correct buoy number must be entered on each buoy card.

(4) IEOD CARD

The last card in the data deck must have the form !EOD beginning in the first column and containing no spaces. This card will terminate the run.

TABLE (3) - PARAMETER CARDS

(all data in floating point mode)

Column	Item	Example
1-6	water depth - meters	2600.
7-12	surface current - cm/sec	50.
13-18	launch transient peak load - lbs.	2000.
19-24	launch transient peak elongation - % 2000D SQ	21.5
25-30	nylon scope	0.85
31-36	cable normal drag coefficient	1.8
37-42	wire diameter (incl. jacket) - inches	.375
43-48	slack wire length - meters	1500.
49-54	wire weight in water - lbs/m	.401
55-60	wire rated breaking strength - lbs.	10300.
61-66	nylon diameter - inches	.562
67-72	nylon weight in water - lbs/m	.0272
73-80	nylon rated breaking strength - lbs.	8000.

A typical data deck would be arranged as follows:

4 instrument cards

6 no-instrument cards

1 buoy card

10 parameter cards

1 buoy card

16 parameter cards

1 buoy card

3 parameter cards

1 !EOD card

TABLE (4) - ASSUMED INSTRUMENT CHARACTERISTICS

TYPE	WEIGHT- lbs.	LENGTH- m.	C_D'	C_D
1/2" chain	8.4 lb./m	1.0	.00066/m	1.0
acoustic beacon	30.0	0.8	.0073	2.0
AMF release	81.0	1.85	.0040	1.5
Geodyne current meter	30.0	2.0	.0042	1.5
tensiometer	20.0	.9	.0016	1.5
16" glass balls	-48.0	0	.00045	0.3

$C_D' = DRAG/U^2 \quad - \quad \frac{lbs}{(cm/sec)^2}$

$C_D = DRAG/\rho/2\ AV^2$

APPENDIX (1-e) - COMPARISON OF RESULTS WITH PREVIOUS SOLUTIONS

1) Comparison with Pode, ref. (3)

The integration procedure employing straight line segments and the incremental cable equations (4-5) has been used to solve Pode's example problem 1, "anchoring of a Buoy." The exercise was a preliminary check on the validity of the integration procedure and not a test of the entire solution program. Pode deals with non-elastic cables and constant currents. His treatment of the tangential drag forces is also different than that employed in the present solution. The procedure was modified in accordance with these restrictions. The following conditions are given:

cable weight in water	= .27 lbs/ft
cable drag (when normal to stream)	= 3.9 lbs/ft
buoy lift and buoyancy	= 9100 lbs.
buoy drag	= 5200 lbs.
water depth	= 3600 ft.
buoy just submerged	

The following results were obtained:

RESULTS	PODE	THIS STUDY	DIFFERENCE
cable length	8760 ft.	8750 ft.	0.1%
buoy excursion	7710 ft.	7696 ft.	0.2%
anchor tension	10220 lbs.	10210 lbs.	0.1%

2) Comparison with Wilson, ref. (5)

The complete solution program has been used to solve a special case for which Wilson's tables are applicable. These tables also deal with non-elastic cables and constant currents. No instruments are placed in the mooring line and the surface angle is assumed fixed at 90°. The following conditions are given:

depth	= 2600 meters
current	= 100 cm/sec
normal drag coefficient	= 1.8
tangential drag coefficient	= .018
cable length	= 3000 meters
cable diameter	= .25 inches
cable weight in water	= .663 lbs/meter

In order to use Wilson's tables, values of

$$\mu = \frac{W}{C_D\, dv^2} \quad \text{and} \qquad 51$$

$$\alpha = \frac{CD''}{CD'} \qquad 52$$

must be found, where V is current speed in ft/sec, W cable weight in lbs/ft, d cable diameter in ft., C_D' the normal drag coefficient and C_D'' the tangential drag coefficient.

Making the necessary conversions,

$$W = \frac{.663}{3.28} = .202 \text{ lbs/ft}$$

$$d = \frac{.25}{12} = .0208 \text{ ft.} \qquad 53$$

$$V^2 = 100.0^2 \, (.03281)^2 = 10.8 \text{ (ft/sec)}^2$$

then

$$\mu = \frac{.202}{1.8 \cdot .0205 \cdot 10.8} = 0.5 \qquad 54$$

and

$$\alpha = \frac{.018}{1.8} = .01 \qquad 55$$

Using these values, a surface cable angle of 90° and cable length of 3000 meters the following results are obtained:

RESULT	WILSON	THIS STUDY	DIFFERENCE
surface cable tension	5170 lbs.	5092 lbs.	1.5%
anchor cable tension	3450 lbs.	3379 lbs.	1.5%
buoy excursion	1255 m.	1260 m.	0.4%

Wilson has compared his results with various other solutions and obtained similar agreement.

This comparison provides a check on the integrating procedure (including the drag calculations) and the iterating procedure. Detailed examination of systems for which results were printed at each segment confirms that other portions of the program are working as expected. These include the cable elongation routines, the variation of current with depth, the instrumentation subroutine and the buoy drag function, THETO.

APPENDIX (2) - BUOY MODEL TESTS

The solution program requires knowledge of the surface wire angle as a function of the buoy type, the surface current and the surface cable tension. To obtain this relationship model tests were performed using two buoy hulls now in use at Woods Hole - the toroid and the disk. A third series of tests was run using the disk model with the supporting feet removed. Tests were run in the ship model basin at the Hydrodynamics Laboratory at the Massachusetts Institute of Technology. The basin is 110 feet long, about 4 feet deep and 8 1/2 feet wide. The towing carriage, running on rails above the tank, may be driven at any of a series of precisely calibrated speeds. The models, each two feet in diameter were towed from the end of an "L" shaped arm which was attached to the carriage (see fig. 28). The arm allowed the buoy to be towed forward of the carriage eliminating any disturbance of the water ahead of the model. The arm was constructed of five inch, heavy duty aluminum channel and showed no flexure or vibration during the tests.

The towing cable, a stranded picture hanging wire, was led around two pulleys and terminated at a tensiometer. This device was a Lebow, model 3345-100, four arm bonded strain gage bridge with a tension capacity of 100 lbs. Signals from the tensiometer were led into the tank control room and displayed on a Sanborne strip chart recorder. The tensiometer was hung from several turnbuckles which allowed adjustment of cable length. At each test speed the cable length was varied to obtain several values of tension and the corresponding angles. The tensiometer was calibrated, on the carriage, by hanging known weights directly below it. This was done before and after the tests. The two calibrations showed a maximum drift of 2%. A mean calibration curve was used to analyze the data. The maximum towing force was 30.5 lbs. and the minimum 0.9 lbs.

It is assumed that the force measured at the tensiometer is the same as

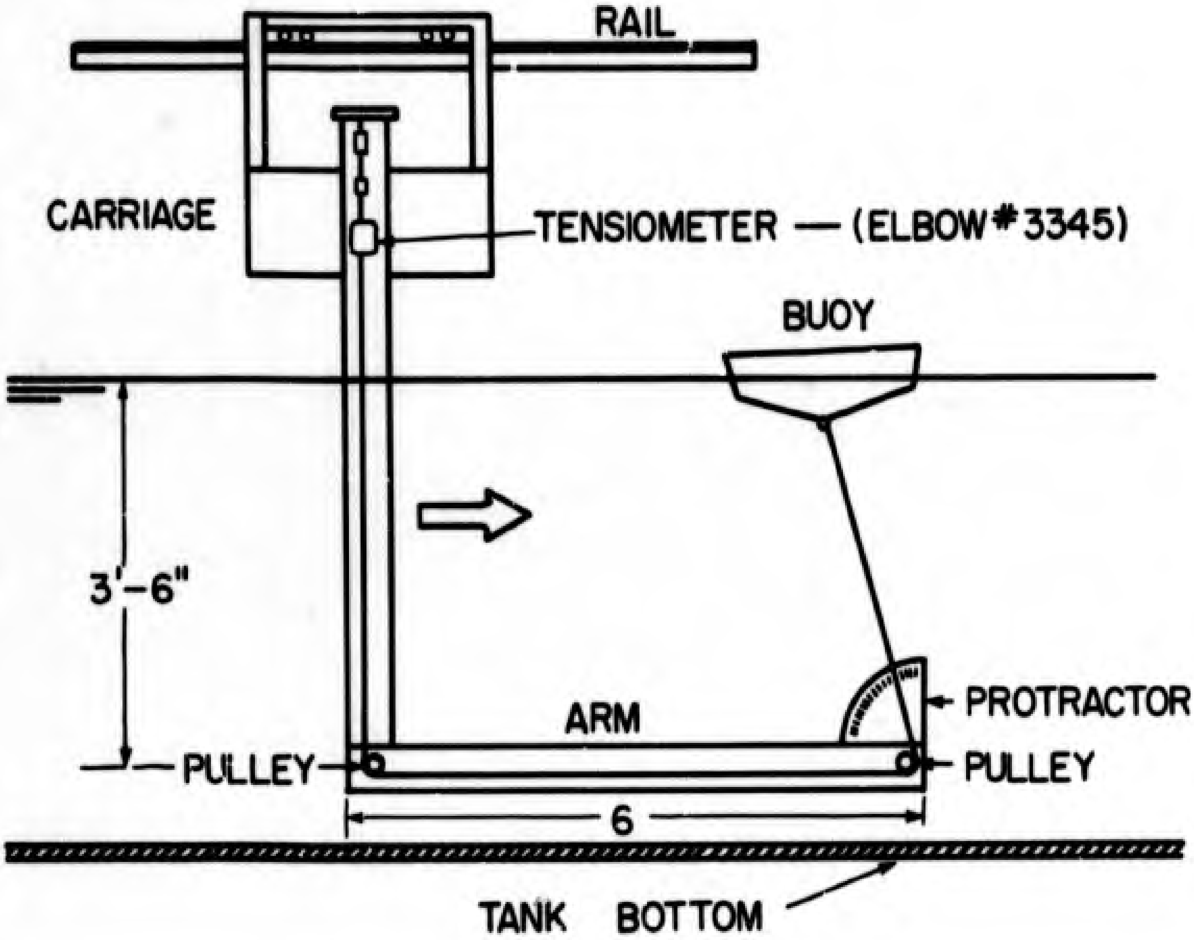

Figure 28. Model Test Apparatus

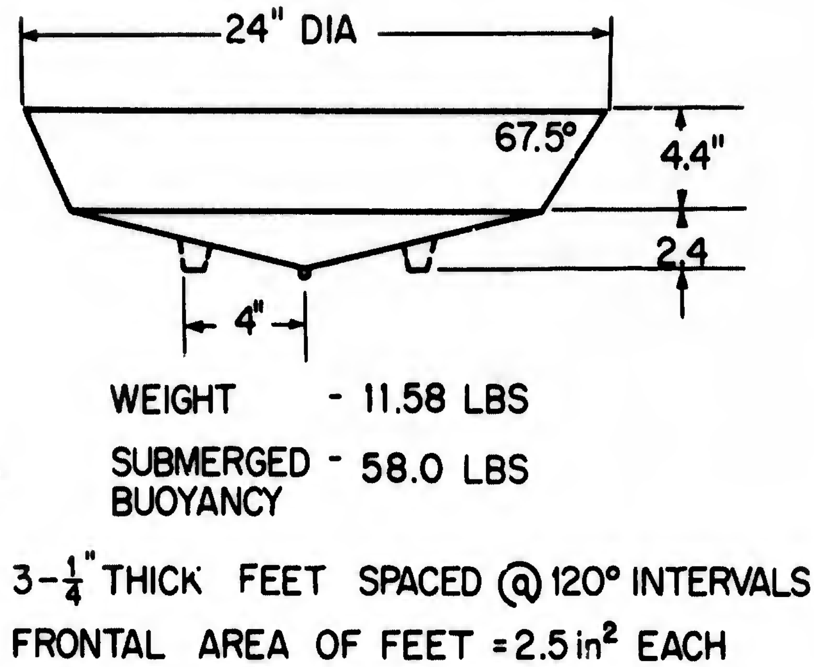

Figure 29. Disk Buoy Model

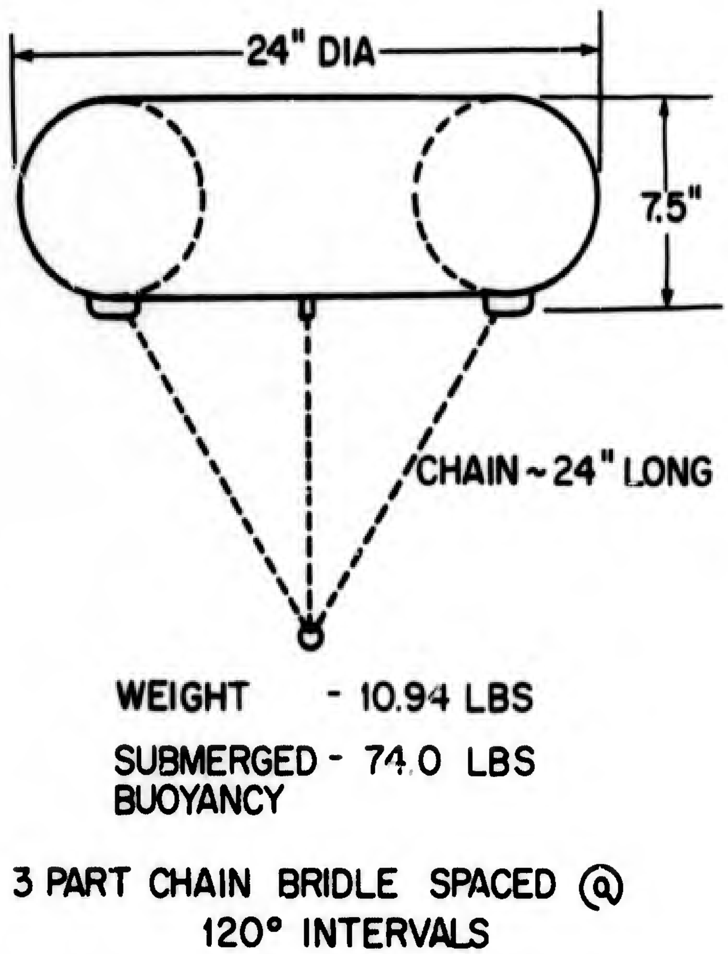

Figure 30. Toroid Buoy Model

that at the model. Tangential drag on the horizontal portion of the towing wire is negligible. The vertical portion is shielded from the flow by the channel. In all the tests there were continuous small fluctuations in tension, the mean value being taken as the towing force. This process should eliminate any contribution due to the pulleys.

The towing angle was read visually against a protractor attached to the forward end of the arm. The sides of the tank are transparent allowing the observer a direct and easy view. It was possible to read the protractor to approximately one degree. It was found that the disturbances due to carriage acceleration died out most rapidly for the disk with the feet attached. It is probably for this reason that there is less scatter in the results for this hull.

The models were constructed of polyurithane foam covered with fiberglass mat. The proper weight was achieved by ballasting with lead shot. Particulars are given in figs. (29), (30).

Scale Effects

It is assumed that the primary forces acting on the buoy are due to: buoyancy, form or pressure drag, wave making drag, and cable tension. Comparison of model total drag coefficients, based on surface area, with flat plate frictional drag coefficients confirmed that frictional effects were small, about 1% of the total. For this reason, and due to the difficulty in defining a characteristic length, no correction is made for frictional Reynolds number effects.

Since the cable angle is the result of several forces, it is important that they all be scaled in the same manner. Buoyancy is of course scaled in proportion to λ^3 where λ is the geometrical scale facto- Wave making drag is also proportioned to λ^3 so long as the Froude number V^2/D_g is maintained. This is according to standard naval architecture practice.

While maintaining Froude number, pressure drag due to separation of flow around the bluff body should be properly represented so long as the points of separation are geometrically similar in the full size and the model. This should occur if both experience the same type of separation. It is assumed that the full size buoy experience turbulent separation due to its relatively high Reynolds number, rough surface and the turbulence at sea. Typical full size Reynolds number, based on buoy diameter are 1-7 x 10^6.

For the model the lowest Reynolds number tested was 2.22 x 10^5 based on diameter. This probably lies below the critical range for smooth bodies of this shape. The surface of the models were kept rough in hopes that this would reduce the critical Reynolds number and induce the necessary turbulence in the boundary layer before separation. The consistent results over the entire range of model Reynolds' numbers which were as high as 7.25 x 10^5 yields some confidence that turbulence was attained. To maintain complete similitude the cable tension is also scaled according to λ^3.

APPENDIX (3) - NYLON ELONGATION EXPERIMENT

The purpose and a general description of the experiments are given in Chapter IV. A more detailed discussion of the procedure is presented below.

Six rope specimens were used, each being tested twice. Loops with metal thimbles were spliced into the specimens at each end, with a 50 cm. test section between the splices. Length measurements were made with a "strain rod" attached to the rope in the test section (see fig. 31). The two markers are fixed to the rope by small pins inserted into the weave. When tension is applied to the specimen the pins are gripped very firmly. The rod itself is calibrated in milimeters. It is attached to the upper mark, and passes through a slot in the lower mark. The figure read at the lower mark is the distance between the pins.

Each specimen was allowed to hang freely in the tensile machine in order to measure the "slack length". The load was then increased to 200 D^2 (explained below) and held for one minute. The length after one minute at 200 D^2 was used as the basis for calculating percentage elongation.

For two specimens, in their first use, a water tank which fully submerged the test section was employed. Salt water was used, and for one specimen ice was added to reduce the temperature. Any effects of moisture or temperature were not readily apparent amongst the experimental scatter. For these preliminary tests the use of the water tube was discontinued.

The tensile testing machine used in these tests was a Baldwin Model (CS-60,000) with a special six ft. long test space. Test specimens were 5/8" and 9/16" diameter plaited nylon.

ELONGATION BASED ON 200 D^2

There is an important problem encountered when performing these tests with a highly elastic material such as nylon. It is very difficult to measure the rope

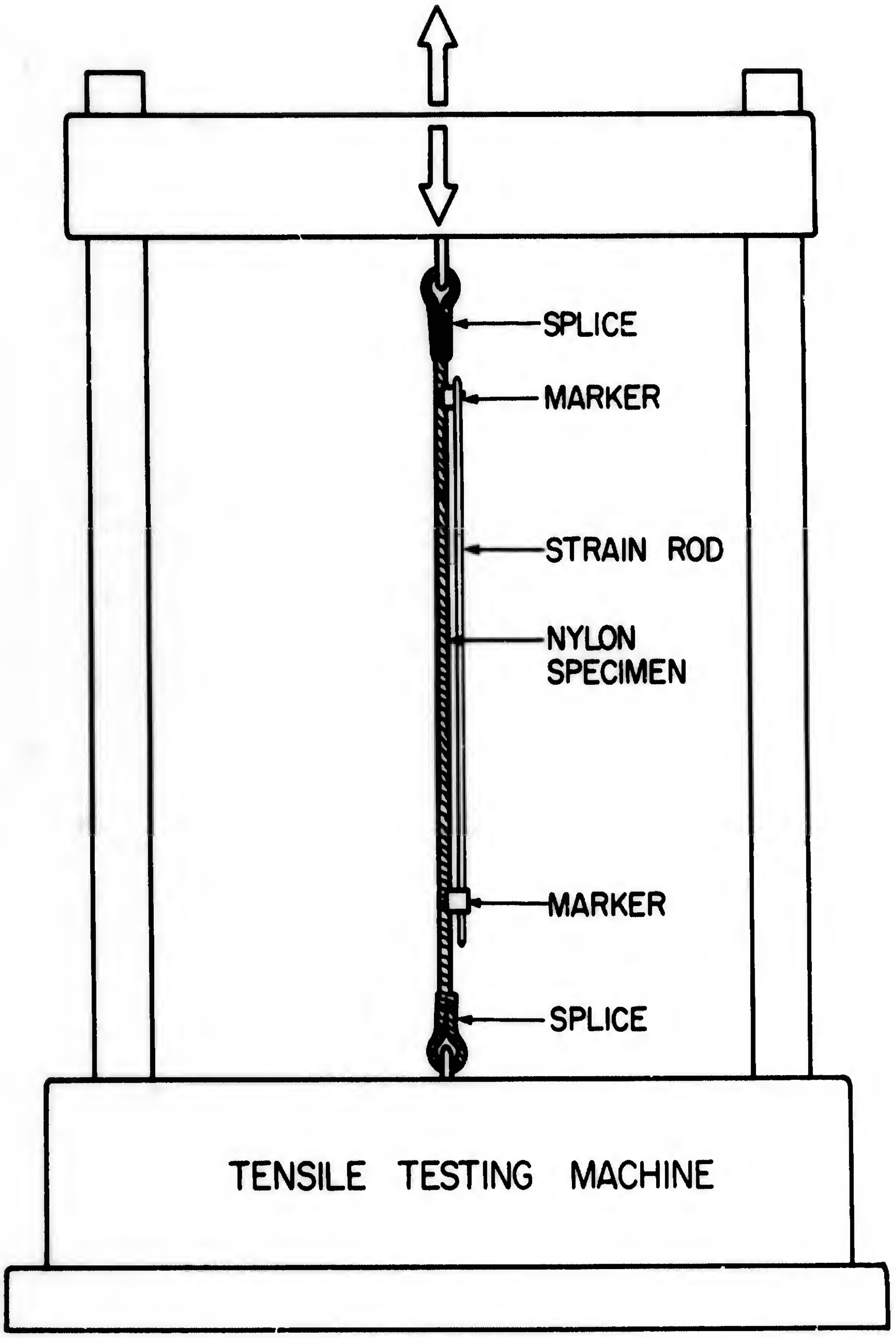

Figure 31. Nylon Elongation Test Apparatus

accurately and reproducibly in the slack condition. For this reason all percentage elongation figures are based on an original length measured under a tension

$$T = 200D^2 \qquad 56$$

where D is the diameter in inches and T the tension in pounds. For 5/8" rope this is 78 pounds and for 9/16" rope it is 63 pounds. Unfortunately no equipment is presently available to measure long lengths at these tensions, so that for practical purposes a load-strain curve based on the 200 D^2 length is of little value. To overcome this problem a correction factor has been determined by averaging the difference found in all the tests, between slack length and length at 200 D^2. On the average, slack length is 95% ($\pm$1.5%) of length at 200 D^2.

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13. ABSTRACT

A computer program is developed to study the steady-state geometry and cable tensions of the single-point, moored oceanographic buoy system as used by the Woods Hole Oceanographic Institution. This mooring is a combination of wire and nylon rope. The program numerically integrates the cable equations allowing for: elastic cables, variation of current speed with depth, drag and weight forces, instruments supported in the mooring line, and the effects of specific buoy shapes.

Model experiments performed to determine buoy drag as a function of hull shape, current speed and mooring dable tension are discussed. An experiment performed to determine the elastic properties of nylon ropes in a deep-sea mooring application is also described.

A series of representative mooring systems have been examined to determine the effect of nylon scope, current speed, rope size, buoy type, cable drag coefficient, and nylon elasticity on rope safety factor and buoy excursion. These results are presented and discussed.

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