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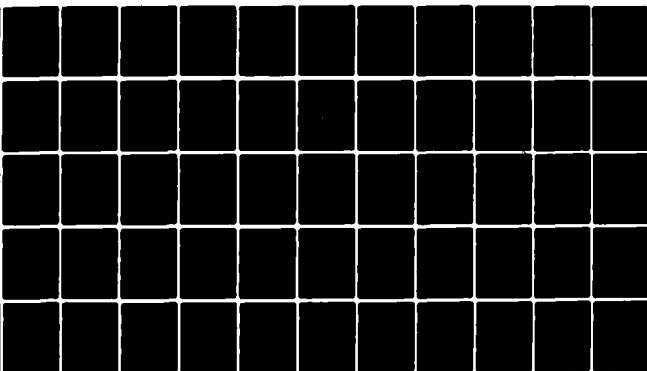
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This report is part of a research project conducted at the Woods Hole Oceanographic Institution to improve the flight characteristics of CTD* instrument packages. Improvement of these cable lowered instrument packages could allow their use in more severe weather conditions. It could improve the quality of the measurements.

This report presents the development of a simplified mathematical model of the CTD package flight characteristics. This computer model was exercised to perform a sensitivity analysis of different versions of CTD packages.

Part of the research project includes scale model testing. The second part of the report discusses pertinent flow similarity criteria and proposes a scheme for building a CTD half scale model.

Finally, recommendations to improve the hydrodynamic behavior of the present CTD configuration are summarized at the end of the report.

*CTD stands for Conductivity, Temperature and Depth.

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HYDRODYNAMICS OF CTD INSTRUMENT PACKAGES

by

Michael F. Cook

WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts 02543

September 1981

TECHNICAL REPORT

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1.0 ABSTRACT

This report is part of a research project conducted at the Woods Hole Oceanographic Institution to improve the flight characteristics of CTD* instrument packages. Improvement of these cable lowered instrument packages could allow their use in more severe weather conditions. It could improve the quality of the measurements.

This report presents the development of a simplified mathematical model of the CTD package flight characteristics. This computer model was exercised to perform a sensitivity analysis of different versions of CTD packages.

Part of the research project includes scale model testing. The second part of the report discusses pertinent flow similarity criteria and proposes a scheme for building a CTD half scale model.

Finally, recommendations to improve the hydrodynamic behaviour of the present CTD configuration are summarized at the end of the report.

*CTD stands for Conductivity, Temperature and Depth

2.0 BACKGROUND

The main users of CTD instruments are physical oceanographers who wish to obtain density gradients and acousticians who wish to obtain sound velocity profiles. The CTD measures conductivity, temperature and pressure from which the density and sound velocity can be determined. A typical CTD package contains three instruments; CTD, rosette and a pinger, all mounted within a protective cage. The CTD measures the conductivity (to derive salinity), temperature and depth of the package as it is lowered by an armored electrical cable. The rosette consists of either twelve or twenty-four water sampling bottles, each with a capacity of 1.2 to 4.0 liters. The acoustic pinger provides a measurement of the distance off the bottom in order to obtain samples close to the bottom and to prevent the CTD package from impacting the bottom.

Knowledge of the density structure obtained from measurements of salinity and temperature at a specific location allows the oceanographer to calculate the large-scale circulation of water masses in the ocean. Water samples permit a check on the accuracy of the CTD measurements. Samples are also used to study the biological and chemical properties of the ocean. The water must flow freely through the water bottles in order to prevent any entrapment of water as the package is lowered to the bottom. Only modifications which preserve or improve the accuracy of the measurement described above should be implemented.

The following scenario describes a typical CTD cast. The research vessel arrives at the location where the cast is to be made. The instrument is eased over the side as the ship heaves to. With present configurations, the CTD is lowered at 70 meters/minute in calm seas and at slower speeds in rougher seas. The CTD is lowered to just above the bottom and then raised. Water samples are collected on the way to the surface at predetermined depths. To take a water sample, the CTD is brought to the desired depth and allowed to equilibrate with the surrounding water for five minutes. A signal is then sent from the ship causing one bottle to close. The CTD is then raised to the next sample point and the sequence continued until the CTD package reaches the surface. The package is then placed back on board, the water samples transferred and the instruments readied as the ship steams to the next cast site.

As can be inferred from the above scenario, a significant length of time is required for one cast to be made, six to eight hours being typical. With the high cost of ship time, modifications which could reduce the amount of time per cast would be beneficial. The primary reason for limiting instrument lowering speed is to insure that the cable supporting the CTD never goes slack, which causes cable kinking and electrical failure, (Reference 2). Increase in the terminal velocity would permit a faster lowering speed and thereby reduce the time necessary for each cast.

One other characteristic of CTD flight concerns the stability of the motion. It is possible that CTD's in their present configurations go through a kiting or tumbling motion as they are lowered. The effects of such motion on the quality of scientific data is not presently known. One goal of this research project is to investigate the stability of CTD packages and to suggest modifications to improve the flight characteristics.

3.0 STATIC ANALYSIS

3.1 Static Stability

Static stability concerns the response of a CTD package when it is disturbed from its steady state vertical flight. The CTD package is statically stable if it has a tendency to return to its steady state path of flight after removal of the perturbation.

Dynamic stability involves the path the perturbed CTD follows after introducing the perturbation. The CTD is dynamically stable if the oscillations the CTD goes through after perturbation have a decaying amplitude. A short discussion of CTD dynamic stability is presented in Section 4.

Ideally a good CTD instrument package should be both statically and dynamically stable.

3.2 CTD Geometry

CTD instrument packages used by the oceanographic community differ widely in both the number of components used to make up the package and in the specifics of each individual component.

Components commonly encountered in CTD packages used at the Woods Hole Oceanographic Institution include:

1. Neil Brown Instrument Systems CTD with 24 inch pressure case.
2. General Oceanics (24)-1.2 liter water bottle rosette.
3. WHOI designed 3/4 inch diameter stainless steel protective frame. Typically the frame diameter is 32 inches and its height is 73 inches. The CTD is mounted below the rosette and both instruments are surrounded by the frame as can be seen in Figure 1.
4. An optional acoustic pinger, such as Benthos type 2216, which can be mounted next to the CTD instrument or strapped on the outside of the protective frame.

Mechanical properties of actual components such as weight, buoyancy, centers of gravity and buoyancy required for this analysis have been established either by measurements and/or computation.

3.3 Analytical Model

3.3.1 Assumptions

Many assumptions were necessary for developing a simplified mathematical model of the CTD package. First the complex geometry of the package had to be simplified. Components were assumed to be of simple shape with predictable hydrodynamic characteristics. For example the rosette has been modeled as a blunt cylinder 23 inches in diameter and 30 inches long. Figure 2 shows the simplified geometry of the package main components.

Next certain assumptions had to be made regarding drag coefficients. In the absence of experimental values, the selection of drag coefficients was based on the simplified shape of each component for both laminar and turbulent flow conditions. For the CTD, rosette, and pinger, the flow based

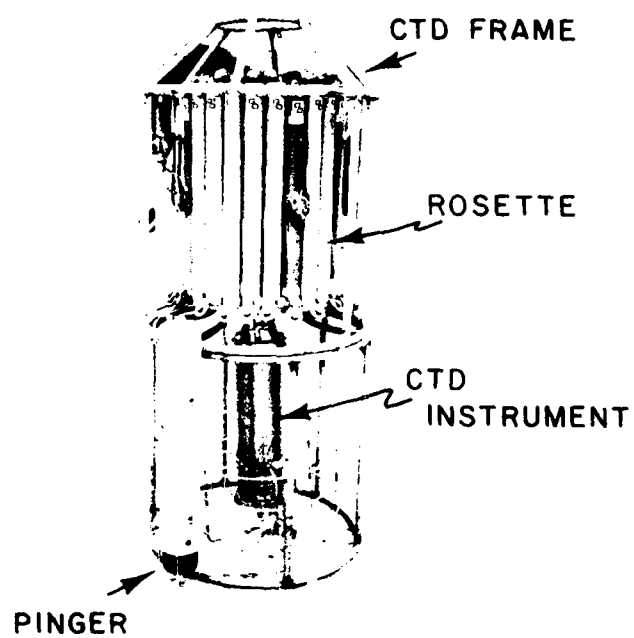
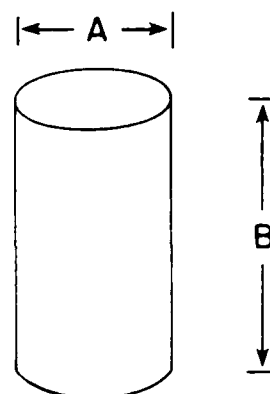
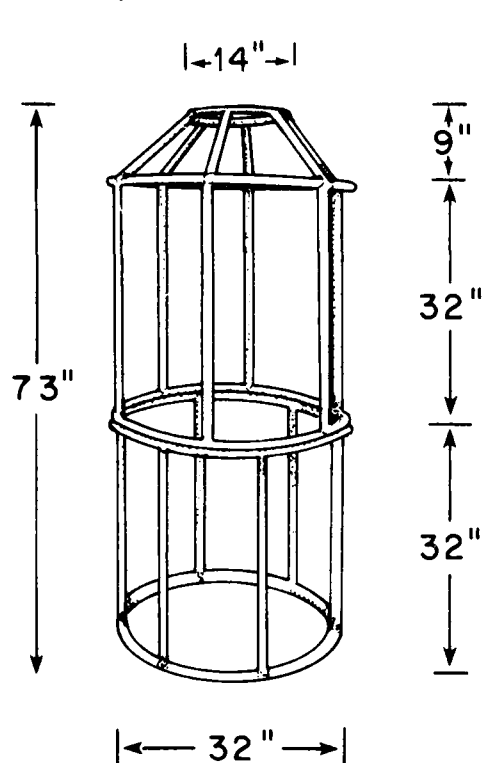


Figure: 1

SIMPLIFIED MODEL

CTD FRAME

Pipe diameter = 1.05 "



	A (in.)	B (in.)
ROSETTE	23	30
CASE	7	25
PINGER	5	26

COMPONENT	CENTER OF GRAVITY above ground (in.)	CENTER OF BUOYANCY (in.)	WEIGHT (lbs.)	BUOYANCY (lbs.)
CTD FRAME	37.3	37.3	82	28
ROSETTE	48.7	47.4	180	110
CTD CASE	18.1	18.6	138	39
PINGER	19.0	19.75	55	15
OVERALL	33.7	39.2	455	192

TENSION PT = 66.8 in.

WET WT. = 363 lbs.

Figure: 2

on Reynolds number was just below the transition region for smooth bodies. Turbulent values of C_D were used, however, to account for the many flow disturbing appendages of these components. For the CTD frame, the Reynolds number was much below transition and both laminar and turbulent values of C_D were used.

With these assumptions cross section areas and drag coefficients for normal and tangential flow could be determined for the different CTD components. Table 1 "Drag Coefficients and Frontal Areas of CTD Components" presents a summary of these values.

3.3.2 Forces at Play

The forces which act on the CTD package as it is steadily lowered in the ocean are: gravity, buoyancy, hydrodynamic drag and cable tension.

The gravity and buoyancy forces are easy to calculate from the geometry and weight distribution of the CTD package components.

Drag forces are more difficult to predict. They are resolved into normal and tangential components, using areas and drag coefficients of the CTD simplified model previously described.

The tension in the cable supporting the CTD package can be inferred from the cable angle, the package weight and inclination, and the drag forces for the prevailing lowering speed.

3.3.3 Mathematical Model

The steps that the mathematical model follows to investigate the static stability of a particular CTD package configuration include:

- o Assume an initial CTD package pitch angle.
- o Assume a lowering speed.
- o Resolve the resulting drag forces into normal and tangential components.
- o Compute the moment with respect to the CTD package center of gravity(c.g.) due to the hydrodynamic drag forces.
- o Assume a cable angle ϕ
- o Derive the cable tension. The formula used is:

$$T \cos \phi = W - B - \left(\sum_i D T_i \right) \cos \theta - \left(\sum_i D N_i \right) \sin \theta$$

DRAG COEFFICIENTS AND FRONTAL AREAS OF CTD COMPONENTS

TABLE 1

1. TANGENTIAL FLOW

COMPONENT	MODELED AS	FRONTAL AREA(ft) ²	REYNOLDS NUMBER	TURBULENT		LAMINAR	
				C _D	C _{DA}	C _D	C _{DA}
CTD case	7" diam.x 25"long blunt cylinder	.27	$v = 3.0 \text{ ft/sec}$ $\frac{1.2 \times 10^5}{v = 6.0 \text{ ft/sec}}$ 2.3×10^5	.82*	.22	-	-
Rosette	23" diam.x30"long blunt cylinder	2.9	$\frac{3.8 \times 10^5}{7.7 \times 10^5}$	.88*	2.552	-	-
CTD Frame	336 inches of 1" diam. 2D cylinder	2.33	$\frac{1.7 \times 10^4}{3.3 \times 10^4}$	0.5**	1.17	1.1**	2.56
Benthos Pinger	5" diam.x 26"long blunt cylinder	.136	$\frac{8.3 \times 10^4}{1.7 \times 10^5}$	.82*	.11	-	-

2. NORMAL FLOW

COMPONENT	MODELED AS	FRONTAL AREA(ft ²)	REYNOLDS NUMBER	TURBULENT		LAMINAR	
				C _D	C _{DA}	C _D	C _{DA}
CTD Fish	7" diam.x 25"long 2D cylinder in normal flow	1.22	$v = 3.0 \text{ ft/sec}$ $\frac{1.2 \times 10^5}{v = 6.0 \text{ ft/sec}}$ 2.3×10^5	0.5**	.61	1.1	1.34
Rosette	23"diam.x30"long 2D cylinder in normal flow	4.79	$\frac{3.8 \times 10^5}{7.7 \times 10^5}$	0.5**	2.40	1.1	5.27
CTD Frame	870" of 1"diam. 2D cylinder in normal flow	6.04	$\frac{1.7 \times 10^4}{3.4 \times 10^4}$	0.5**	3.02	1.1	6.65
Benthos Pinger	5" diam.x 26"long 2D cylinder in normal flow	.90	$\frac{8.3 \times 10^4}{1.7 \times 10^5}$	0.5**	.45	1.1	.99

* Reference #4, pages 3-12

** Reference #4, pages 3-9

where

T = Cable tension

ϕ = Angle between cable and the vertical

W = Package weight

B = Package Buoyancy

DT_i = Tangential drag of component " i "

DN_i = Normal drag of component " i "

Θ = Package inclination angle (pitch)

- o Compute the moment with respect to the CTD t.g. due to the tension force.
- o Compute the moment with respect to the CTD c.g. due to the package buoyancy forces.
- o Sum the moments.

By convention, if the sum is negative the overall moment is a righting moment. The package will have a tendency to return to the vertical thus decreasing its pitch angle. The configuration can be considered statically stable.

If the sum is positive the overall moment is a capsizing moment. The pitch angle will have a tendency to increase. The configuration is no longer statically stable.

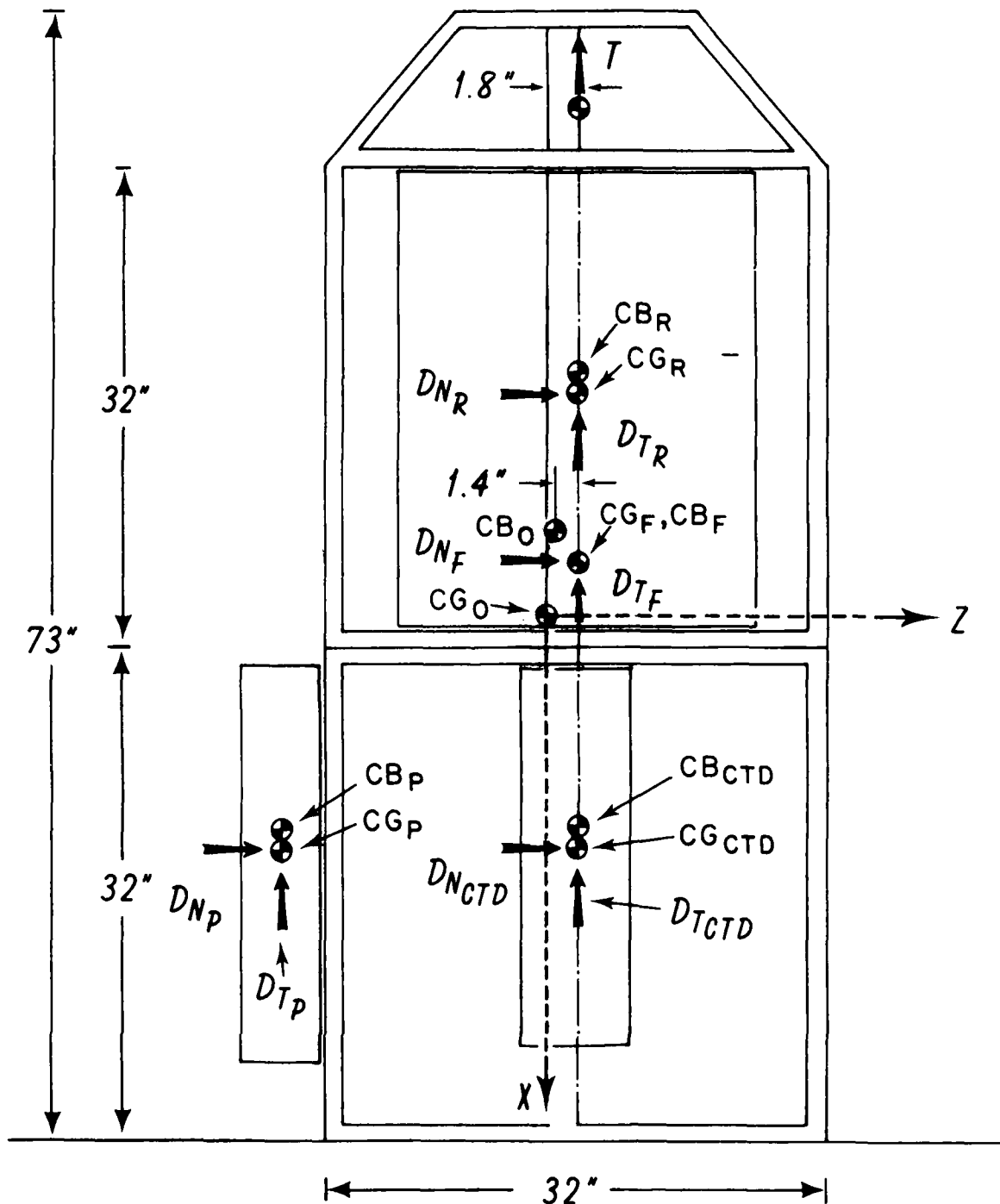
Figure 3 illustrates how a typical CTD package is modeled. Corresponding forces and sign conventions are depicted in Figure 4.

A computer program called CTDFLI has been written to calculate the resultant moment for various lowering speeds. Program inputs include the physical and geometrical characteristics of the CTD package components, the angle between the lowering cable and the vertical, and the package inclination. Program outputs include cable tension, tangential and normal drag forces and overall resultant moment. The lowering speed is increased until the tension in the cable vanishes. The package is then assumed to have reached terminal velocity. The speed at terminal velocity is also a program output. Appendix A is a description of CTDFLI.

3.4 Sensitivity Analysis

The program CTDFLI was exercised to study the static stability of typical and modified CTD instrument packages.

The stability of typical CTD packages was first established. Changes were then made to the base line configurations and the resulting effects were investigated. Changes included increased weight, reduced drag, and improved package symmetry. The sensitivity of the model to changes in tension and tension angle was also investigated using the standard CTD package. Finally several runs using combinations of the changes mentioned were made in an attempt at finding optimal configurations. Table 2 lists all the study cases investigated.



CG - Center of Gravity	O - Overall
CB - Center of Buoyancy	P - Pinger
DN - Normal Drag Force	F - Frame
DT - Tangential Drag Force	R - Rosette
T - Tension in cable	CTD - CTD Case

Figure: 3

Figure: 4

TABLE 2
LIST OF STUDY CASES

CASE NO.	DESCRIPTION	REMARKS
A.0	NBI 24 in CTD, G.O.(24)1.7 liter Rosette, WHOI standard protective frame.	Present basic configuration
B.0	Same as A.0 except Benthos pinger strapped to CTD	
C.0	Same as A.0 except pinger strapped to frame	
A.1	Same as A.0, cable angle = 10°	Varying the lowering cable angle on configurations
A.2	Same as A.0, cable angle = 20°	
A.3	Same as A.0, cable angle = 30°	
C.1	Same as C.0, cable angle = 10°	A & C
C.2	Same as C.0, cable angle = 20°	
C.3	Same as C.0 cable angle = 30°	
D.0	Same as B.0 except (2) Benthos pingers strapped to CTD.	Introducing symmetry on configurations B & C
E.0	Same as C.0 except (2) pingers strapped to frame	
A.0.W1	Same as A.0 except bottom ring of frame is solid steel.	Weight modifications
A.0.W2	Same as A.0, add 50 lbs to CTD	
A.0.W3	Add one inch lead ring attached to frame lower ring	
A.0.W4	Add two inch lead ring attached to frame lower ring	
C.0.W3	Same as C.0, except add 1 in. lead ring	
C.0.W4	Same as C.0, except add 2 in. lead ring	
C.0.D1	Same as C.0, except frame drag reduced $\frac{1}{2}$	Drag modification on C.0 configuration
C.0.D2	Same as C.0, except frame drag reduced to $\frac{1}{4}$	
C.0.D3	Same as C.0, except frame drag reduced to $\frac{1}{8}$	
C.0.D4	Same as C.0, except frame size reduced $\frac{1}{2}$	
F.0	Same as D.0, except drag reduced $\frac{1}{2}$ and 1 in. lead ring attached.	Optimum configurations
G.0	Same as above except small WHOI frame	

A description of the configurations studied and a review of the results of the computer analysis are hereafter presented.

3.4.1 Present Configurations

Three instrument packages, typical of those commonly encountered in practice were first modeled. These configurations were as follows:

- o Configuration A. Neil Brown 24 in. CTD, General Oceanics 24-1.2 liter rosette, WHOI standard protective frame.
- o Configuration B. Same as A except for Benthos pinger strapped to CTD.
- o Configuration C. Same as A except for Benthos pinger strapped to frame.

These three basic CTD package configurations were used to determine baseline data for the sensitivity analysis and to verify the validity of the model. The terminal velocity obtained for these three configurations ranged from 6.26 ft/sec to 6.95 ft/sec. An actual drop test conducted in July 1979 with a configuration similar to B yielded a terminal velocity of 6.85 ft/sec. Good agreement seems therefore to exist between the computed and the measured terminal velocities.

Righting and/or capsizing moments were computed for the three configurations assuming their pitch angle to vary from 0 to 45 degrees. A typical curve of moments as a function of package speed is presented in Figure 5.

To better understand this curve let us first consider what happens to configuration A as it changes inclination (pitch) and falling speed. The external forces acting on the package inclined at some angle θ are shown in Figure 6. Some of these forces, drag and tension for example, vary as a function of speed and their relative contribution to the overall moment needs some reflection.

Since configuration A.0 is axisymmetric no moment can exist at zero pitch angle, thus the zero moment value shown for the first moment curve. The first point on the second curve gives the value of righting moment at speed zero and five degrees of pitch angle. This static moment is simply the sum of two moments. The first moment is due to the normal component of the tension force. For this configuration, the tension acts vertically so at 5° of pitch this force creates a righting moment about the CG. Both these contributions increase as the pitch angle increases.

As the package acquires speed, drag force comes into play. Normal and tangential drag forces are computed for each CTD component based on its drag characteristics. These forces are then applied at the center of gravity of each of the CTD components. For configuration A there are three components as described previously. If only drag forces were present, the righting moment curve for each pitch angle would simple be a parabola (since drag $\propto V^2$) with a zero velocity value of zero. Adding the buoyancy force in the model just shifts these curves down by an amount equal to the static moment described above without tension. It is advisable to keep this parabolic

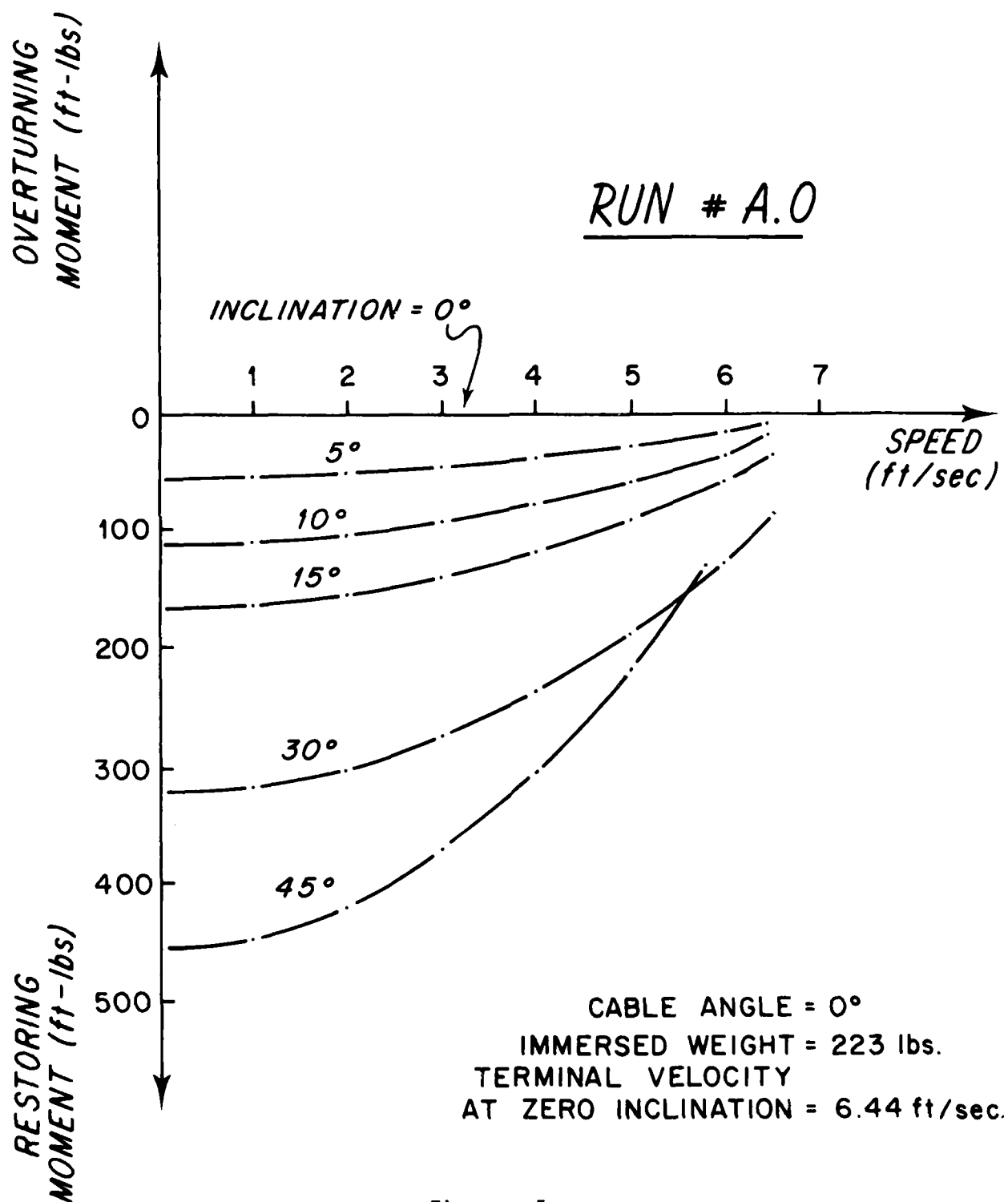
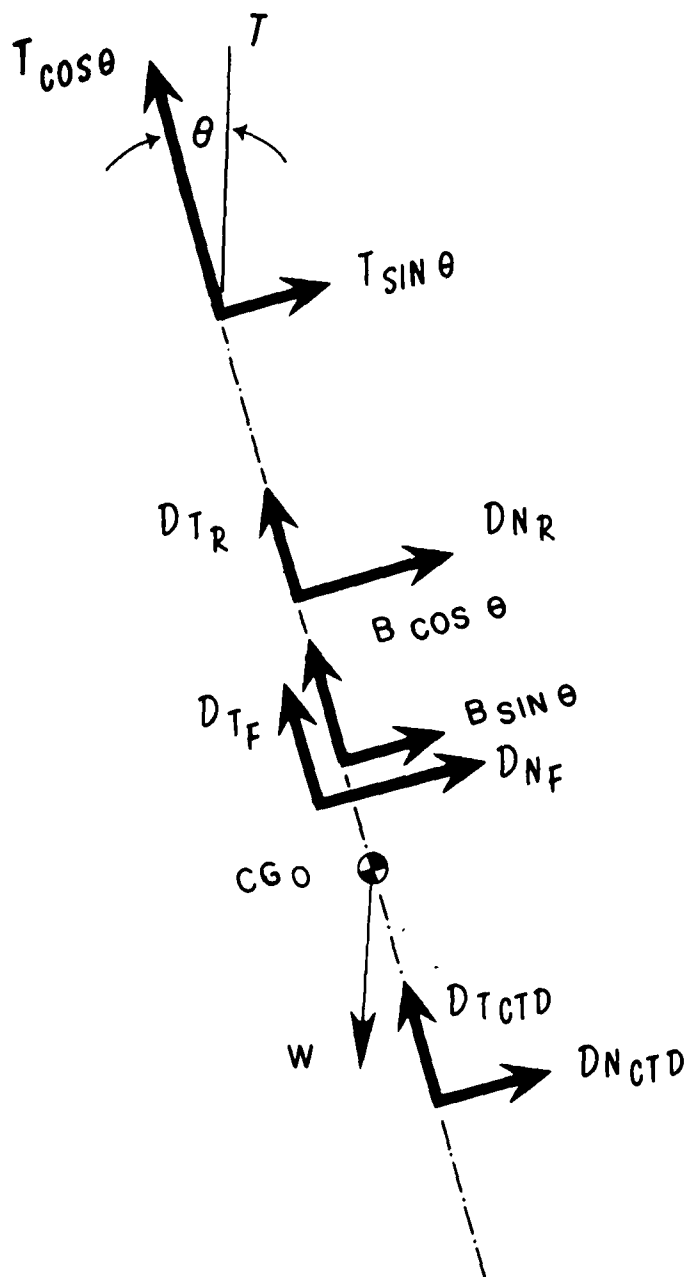


Figure: 5



T = Tension
 D_N = Normal Drag
 D_T = Tangential Drag
 B = Buoyancy
 W = Weight

R = Rosette
 F = Frame
 CTD = CTD Instrument
 CGO = Overall C.G.

Figure: 6

curve in mind when looking at the additional effect the cable tension has on stability.

As described earlier in the report the tension in the cable is determined by taking the difference between the submerged weight of the package and the vertical components of drag. At zero speed the magnitude of the tension force equals the submerged weight of the package. As the speed increases the drag forces increase with the velocity squared so that the tension decreases in a corresponding way. At terminal velocity the tension is zero and the righting moment reaches its smallest value. For all pitch angles greater than zero, the righting moment is a maximum at zero speed and decreases in a parabolic fashion as the speed increases (due to decreasing tension). Once terminal velocity is reached tension has no more effect. From the graph it is readily seen that at speeds below terminal velocity the tension force has the greatest effect on the righting moment.

Figures 7 and 8 show the stability curves for the next two basic configurations studied, B.0 and C.0. Both these configurations are not axisymmetrical, configuration C.0 with a pinger strapped on the outside of the frame being more asymmetrical than B.0.

It can be seen from these graphs that the static stability varies markedly with symmetry. Configuration A.0 is stable throughout a range of pitch angles of 0° to 45° , indicating that the CTD when perturbed would tend to right itself to zero pitch angle. On the other hand configurations B.0 and C.0 are both unstable at zero pitch angle with C.0 having the largest overturning moment as expected. The consequences of these instabilities in actual flight are unknown at present but several things are obvious. Configurations which are stable, fall with zero pitch angle, should have a higher terminal velocity since the projected area of the package is a minimum. Packages with overturning moments may tend to oscillate throughout the range of instability causing kiting or tumbling.

As part of the baseline case studies, the sensitivity of stability to cable angle was next investigated. The symmetrical A.0 and the asymmetrical C.0 configurations were subjected to cable pull angles of 10, 20 and 30 degrees respectively. Figures 9 to 14 show the stability curves thus obtained. These results indicate that increasing the pull angle causes a reduction in the righting moment, and thus enhances the potential of oscillations of a lowered CTD package. It is not known if fluctuations in tension angles occur at sea although it has been hypothesized (Reference 2).

3.4.2 Symmetry Modification

To test the sensitivity of the model to symmetry, configurations B.0 and C.0 were modified to make them axisymmetric. Configurations D.0 and E.0 were obtained by simply adding another pinger - or pinger casing - opposite the original one. The effect on stability was immediate, both configurations were stable throughout the range of pitch angles previously tested. Given the mathematical model used in CTDFCI, this result was to be expected. The stability curves of D.0 and E.0 are shown in Figures 15 and 16.

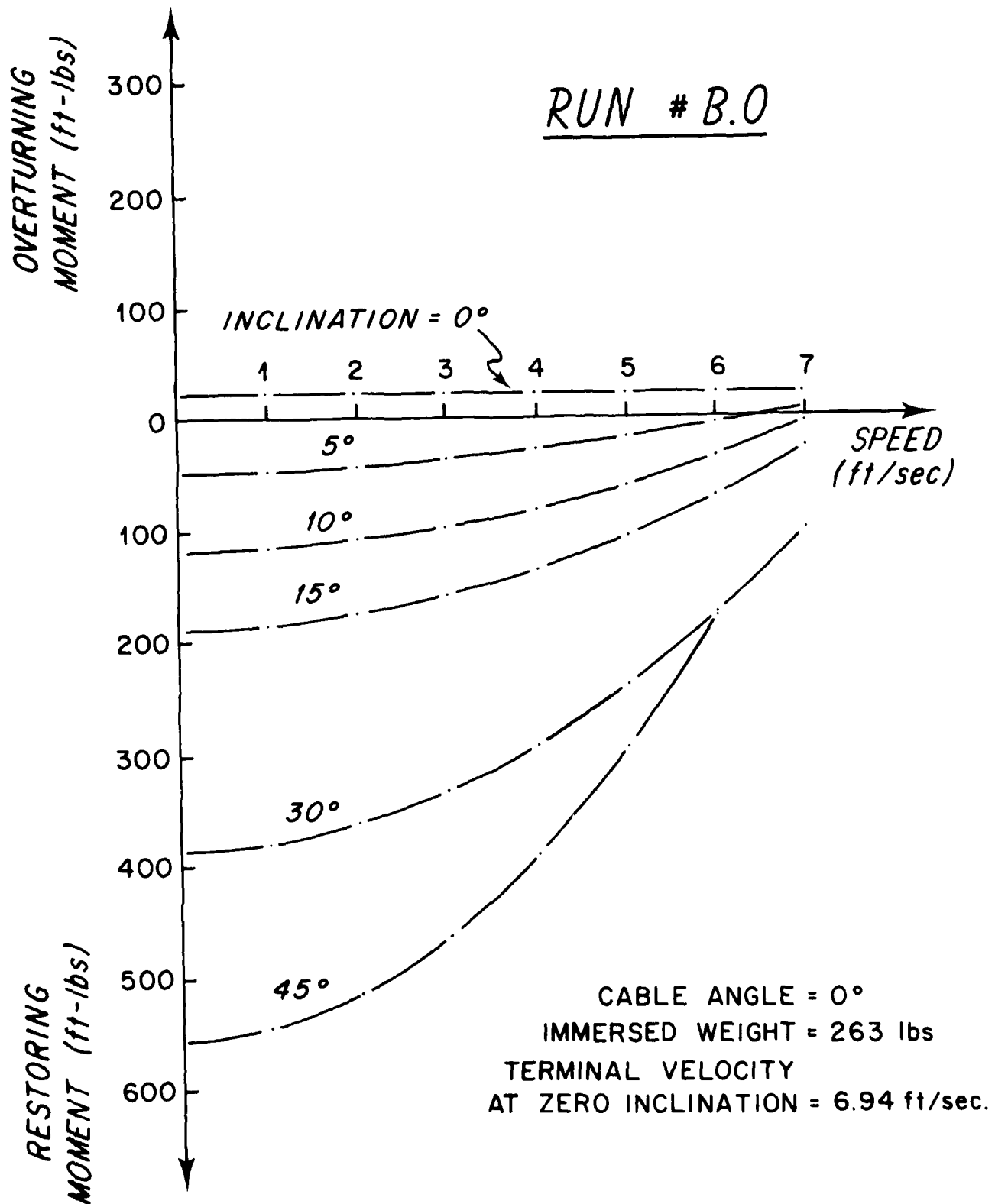


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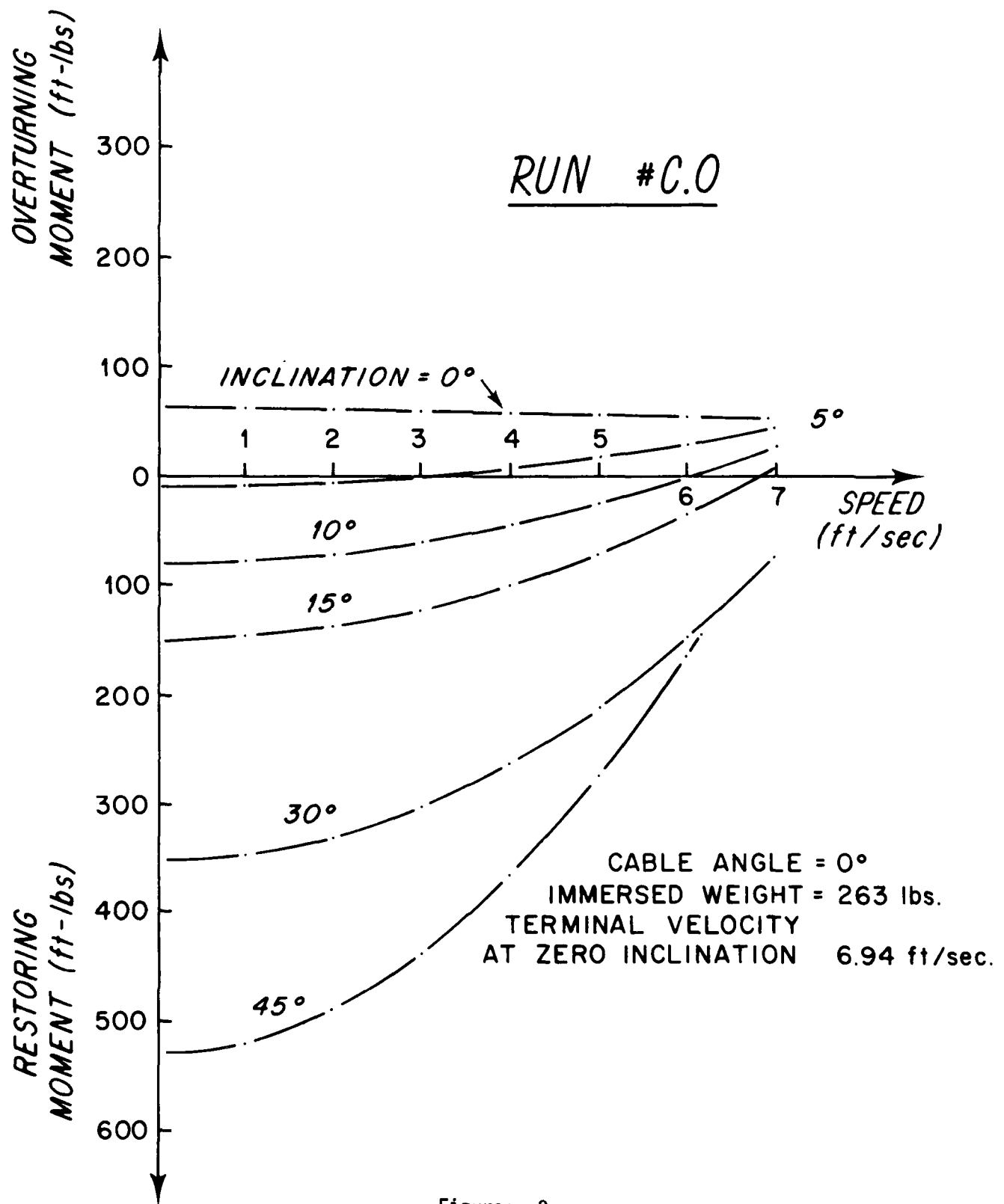


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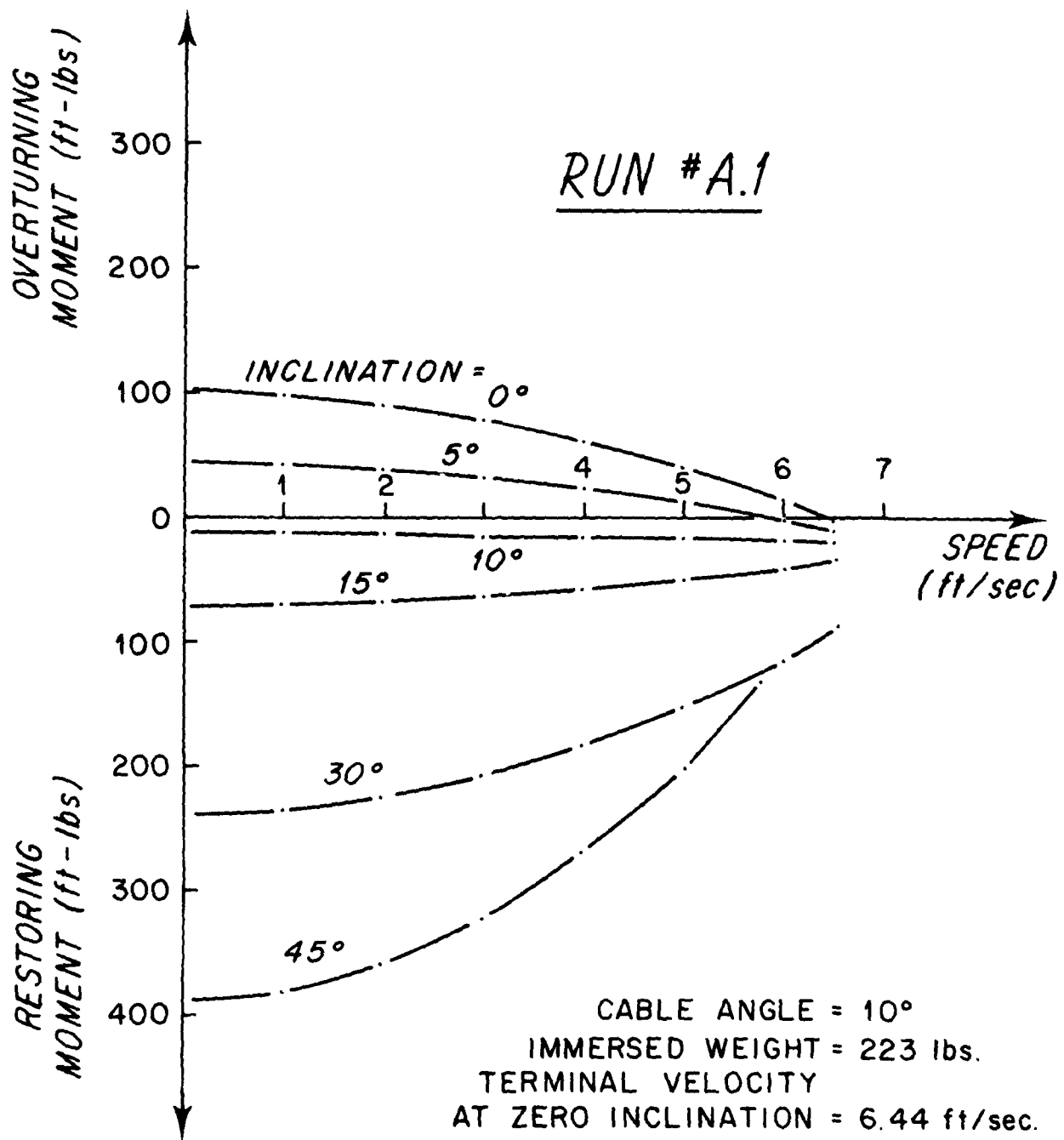


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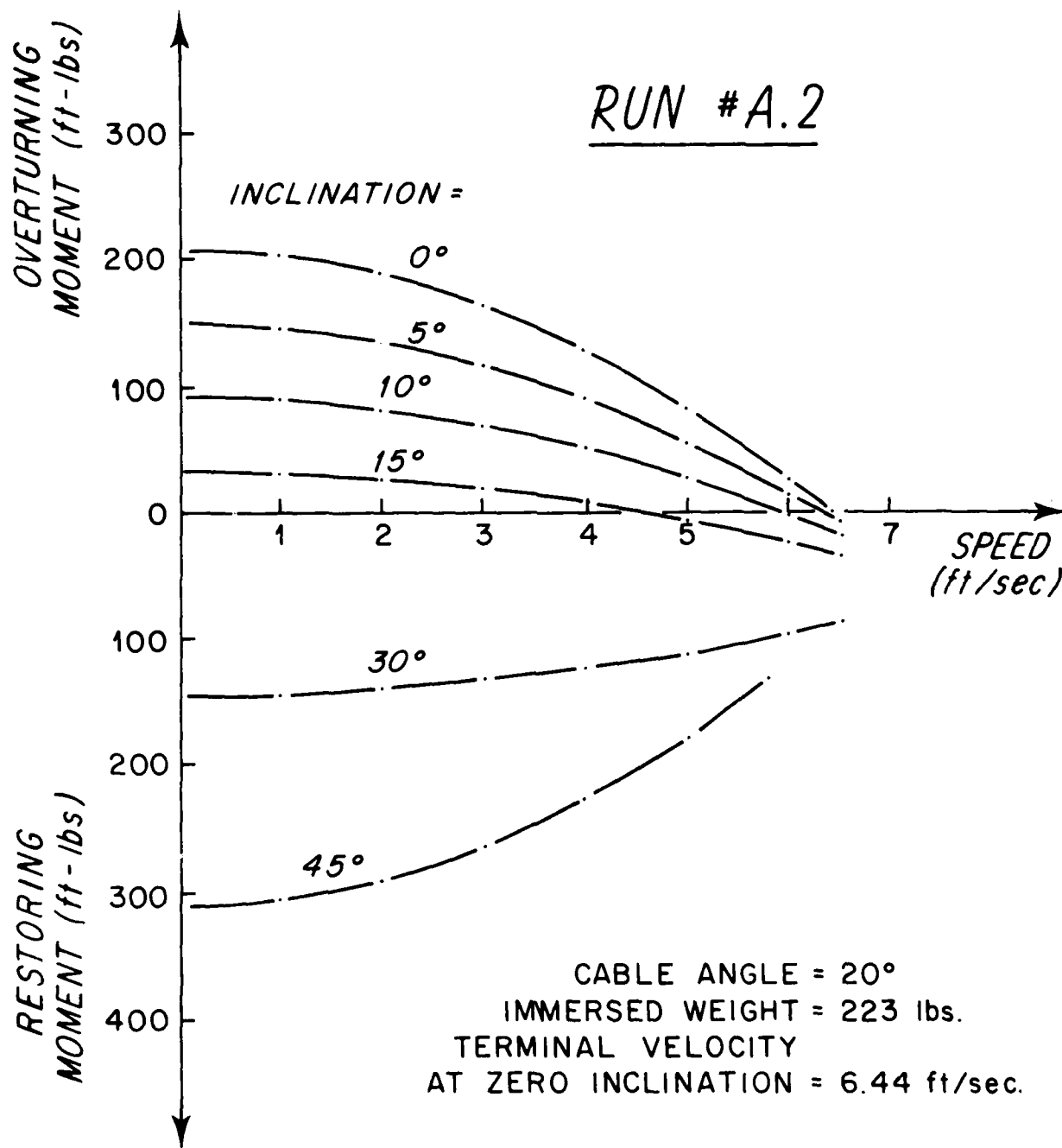


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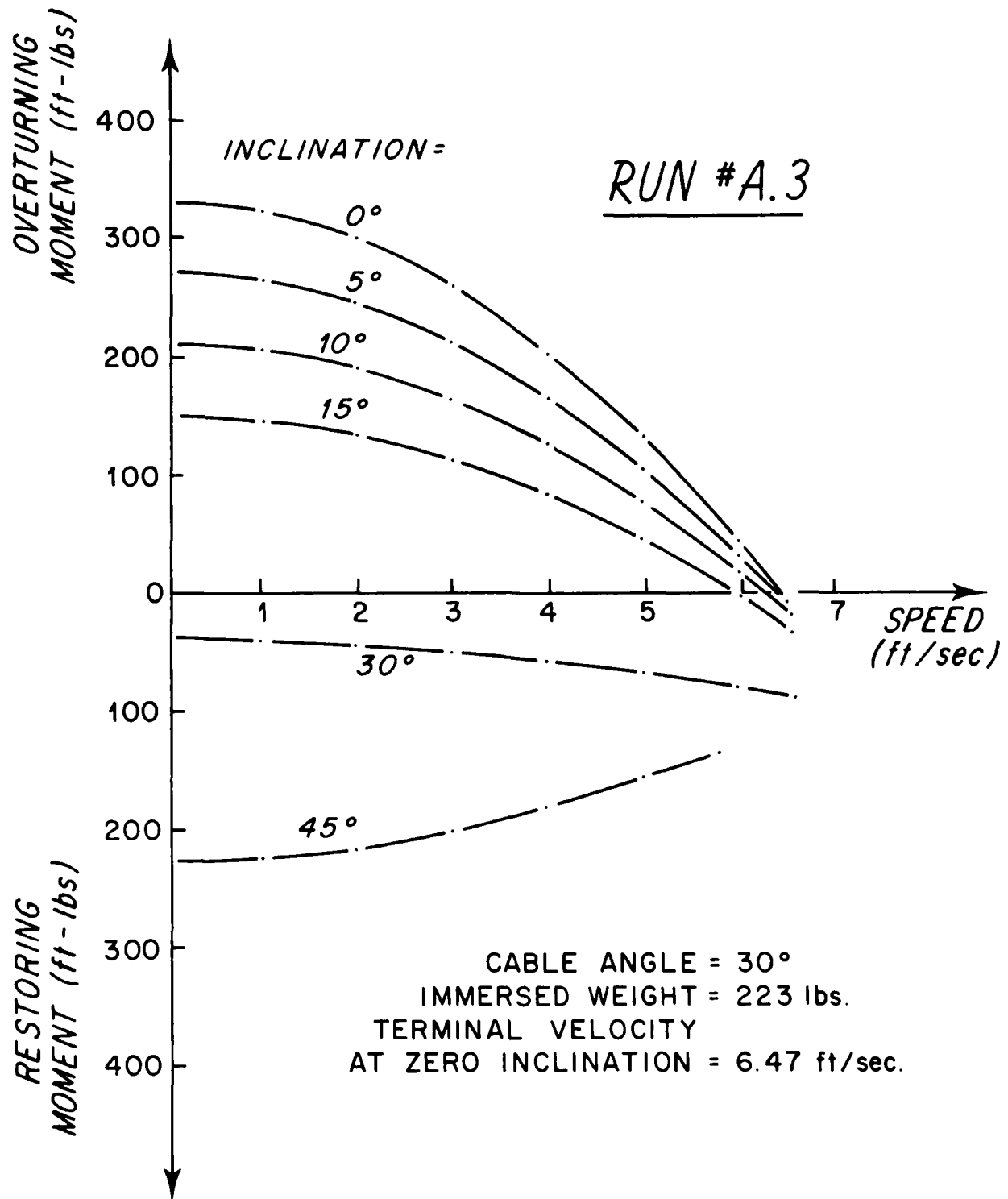


Figure: 11

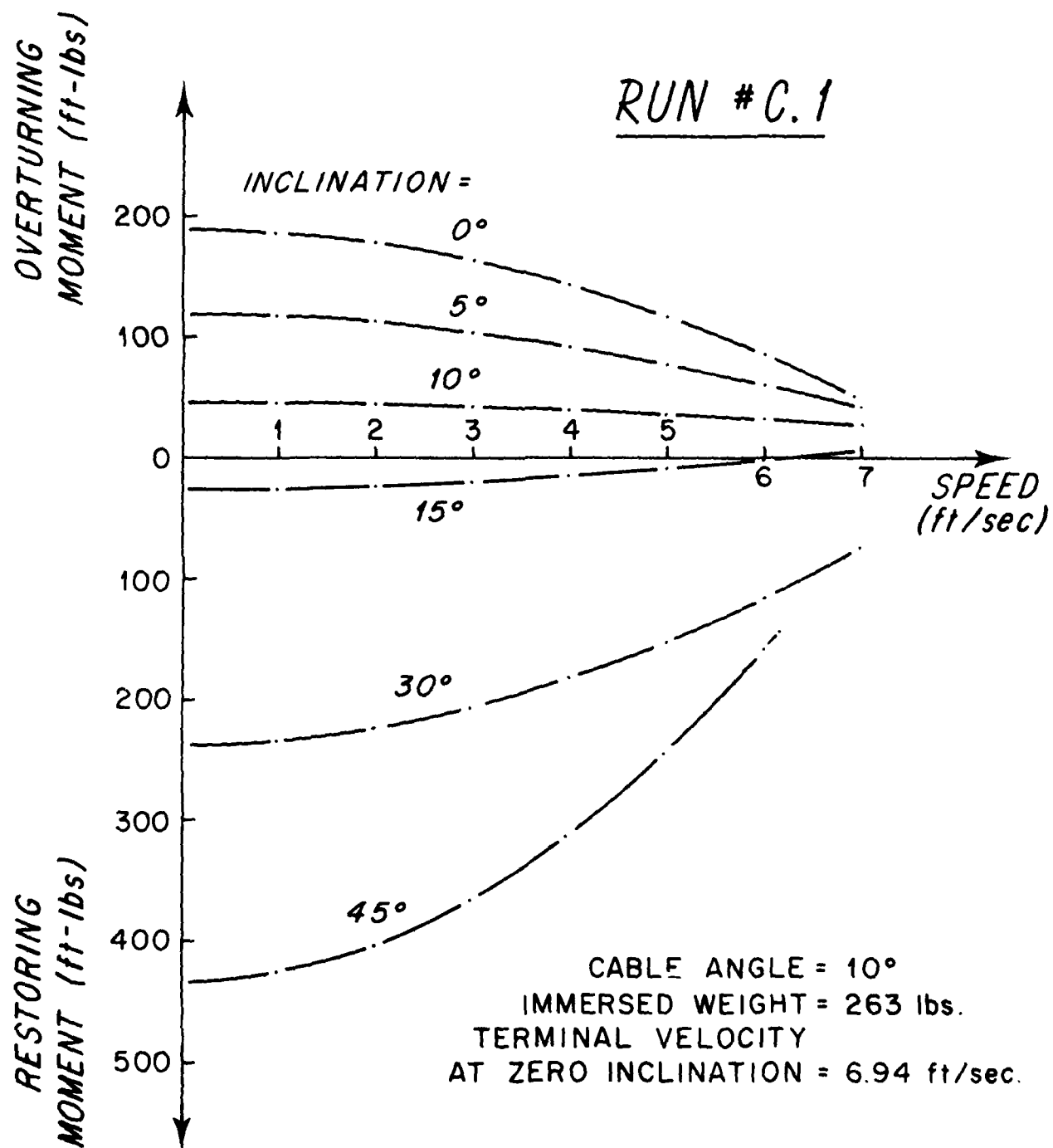


Figure: 12

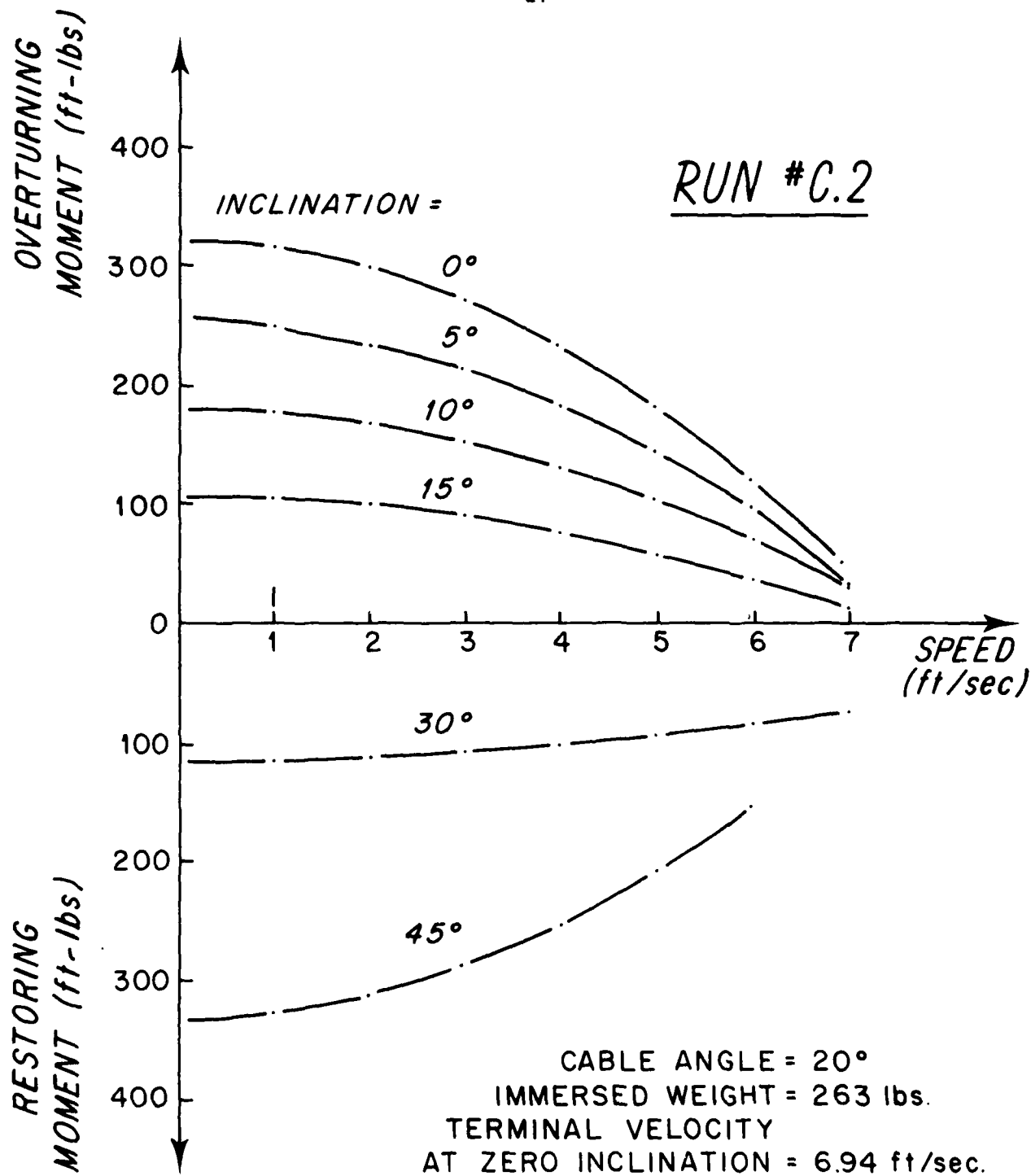


Figure: 13

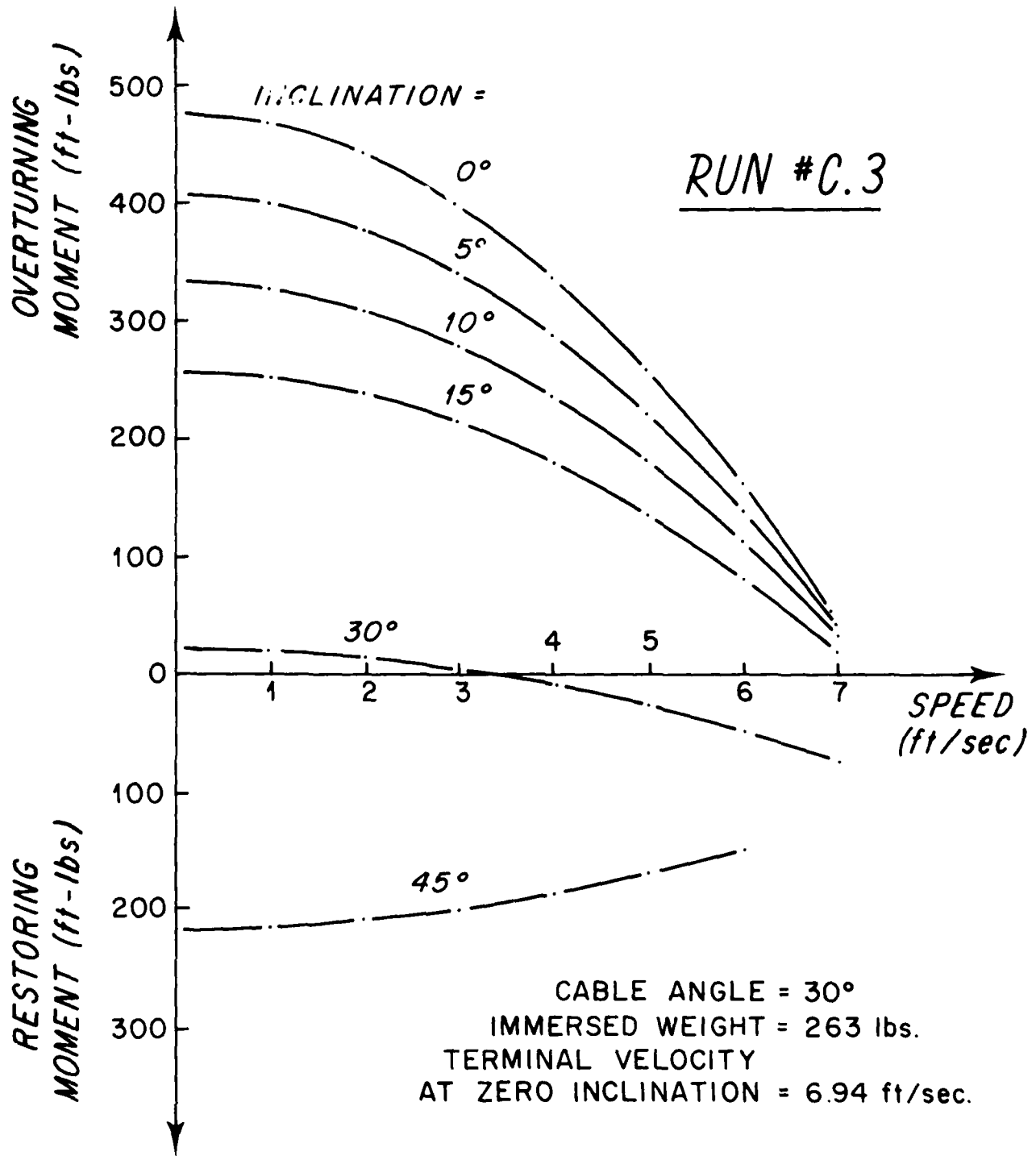


Figure: 14

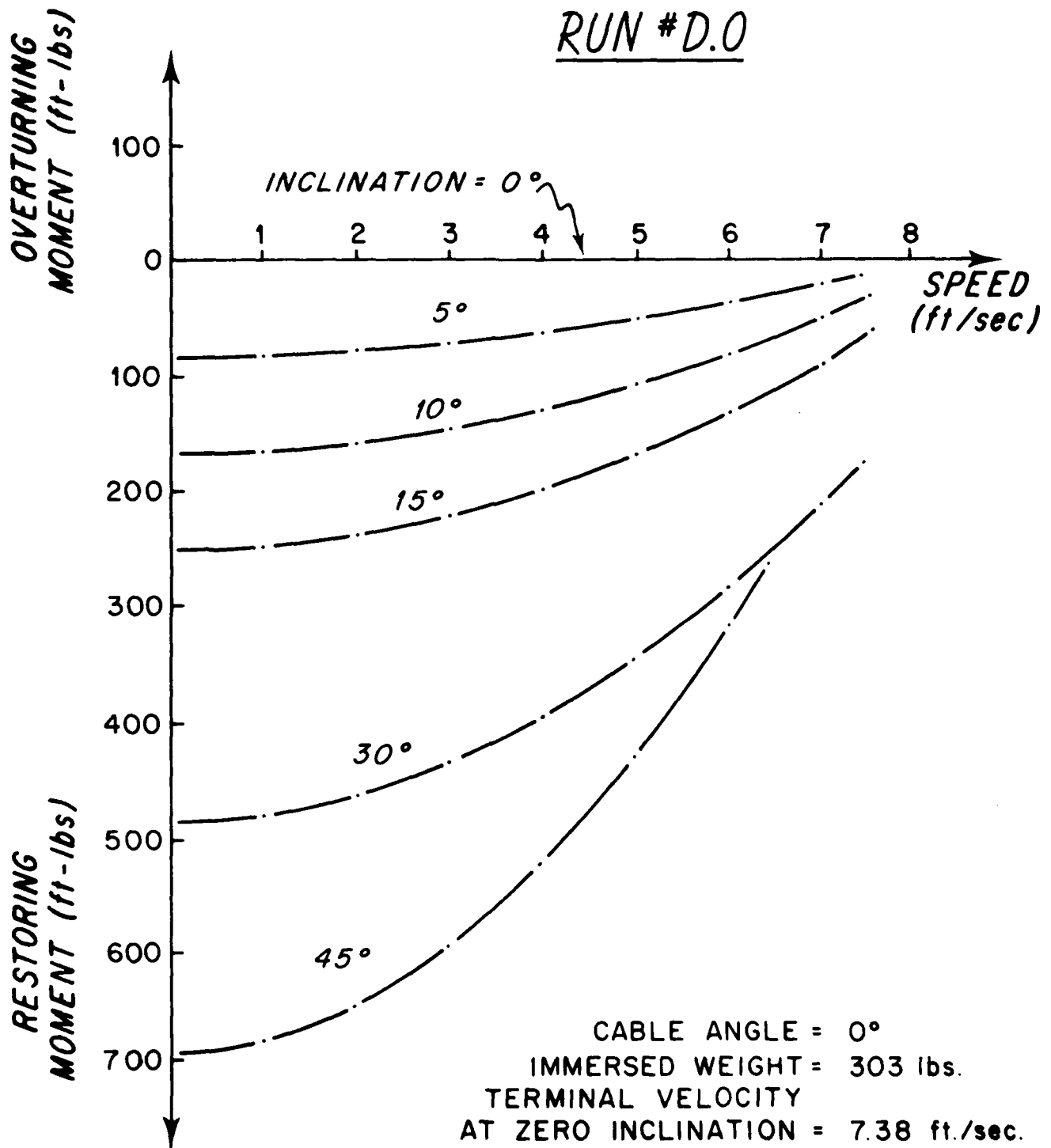


Figure: 15

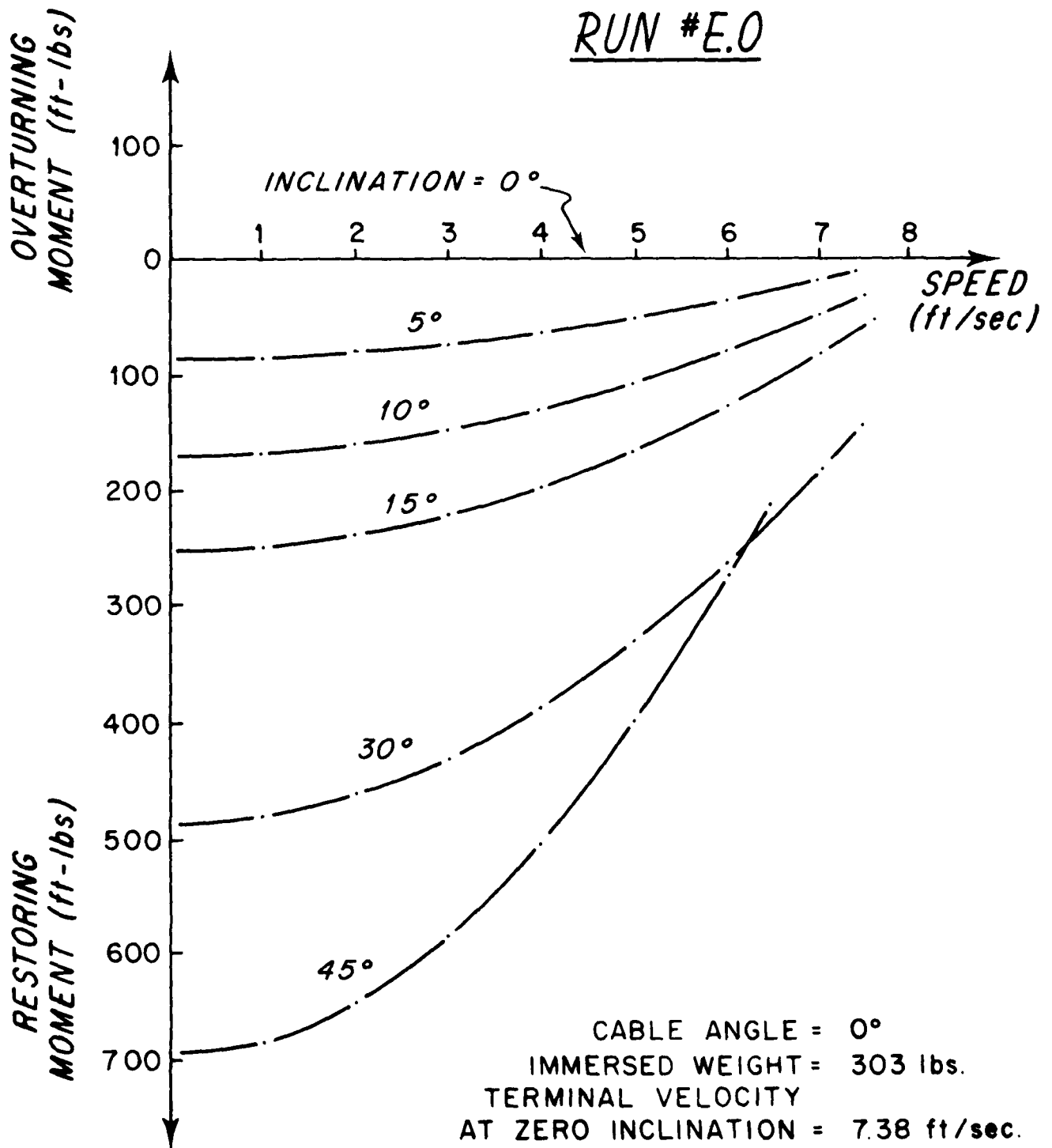


Figure: 16

The behavior of a real CTD package in the ocean, however, may not have the same response although it seems logical that a symmetric body would fall vertically. An added bonus to the flight characteristics of both configuration D and F was an increase in terminal velocity of .25 ft/sec. Modifying a package to make it symmetric should improve the stability greatly and it is recommended that in the future more concern be placed with making CTD packages as symmetric as possible.

3.4.3 Weight Modifications

The sensitivity of the model to the judicious addition of weight was studied next using again both the A(symmetric) and the C(asymmetric) configurations. Weight changes were introduced as follows: In configuration A.O.W1 the bottom ring of the standard WHOI frame is made of solid steel instead of tubing. In A.O.W2 50 lbs are arbitrarily added to the CTD instrument. In A.O.W3, W4 and C.O.W3, W4 lead rings of one and two inches in diameter are fastened to the frame lower ring. These changes could be easily implemented in practice. The increase in weight and terminal velocity that these changes caused are hereafter tabulated.

TABLE 3

Weight Modifications

Case #	Original Weight	Added Weight	Terminal Velocity	
			Ft/Sec	% Increase
A.O.W1	400	15	6.69	3.8
A.O.W2	400	50	7.16	11.2
A.O.W3	400	34.5	6.91	7.3
A.O.W4	400	125.0	7.94	23.3
C.O.W3	455	34.5	7.38	6.3
C.O.W4	455	125.0	8.31	19.7

Stability curves for these six configurations appear on Figures 17 to 22.

The major effect of weight addition appears to be a substantial increase in package terminal velocity. Stability improvements appear less obvious.

3.4.4 Drag Modifications

At present, CTD packages are anything but streamlined. Improvement in the drag characteristics of a CTD configuration by adding fairings, shrouds, varying dimensions, etc., should improve the terminal velocity substantially. To determine the sensitivity of the model-to-drag modifications four runs were made. Three of these investigate the improvement in terminal velocity due to reducing the drag on the WHOI CTD frame by 1/2, 1/4 and 1/8. At this stage, the exact mechanism for reducing the drag to these levels has not been determined although fairings would be a good candidate. The fourth modification involved substituting the standard WHOI CTD frame with one made of 3/8 in. pipe instead of 3/4 in. pipe. The increase in terminal velocities introduced by these changes are hereafter tabulated.

RUN #A.0 W1

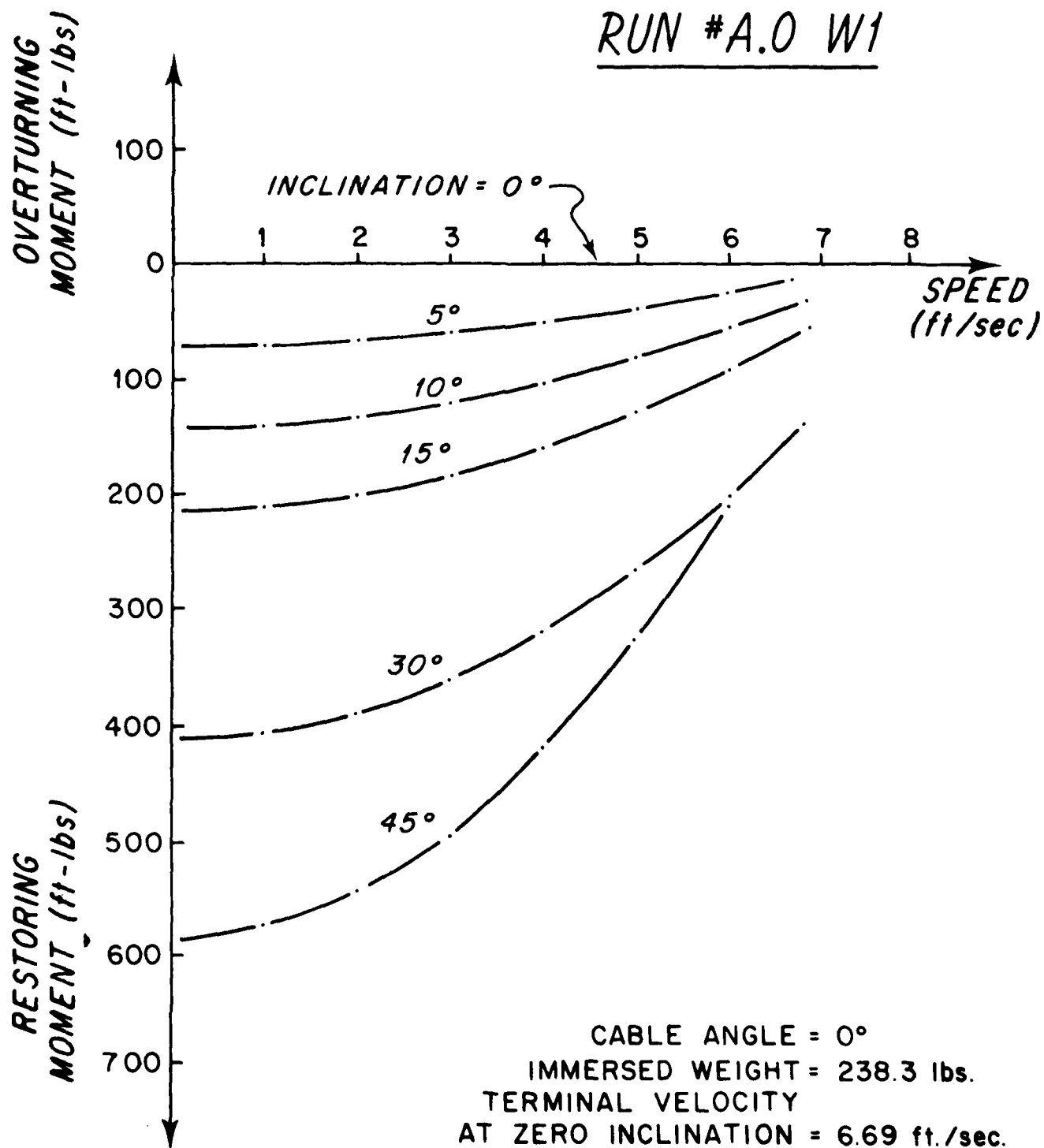


Figure: 17

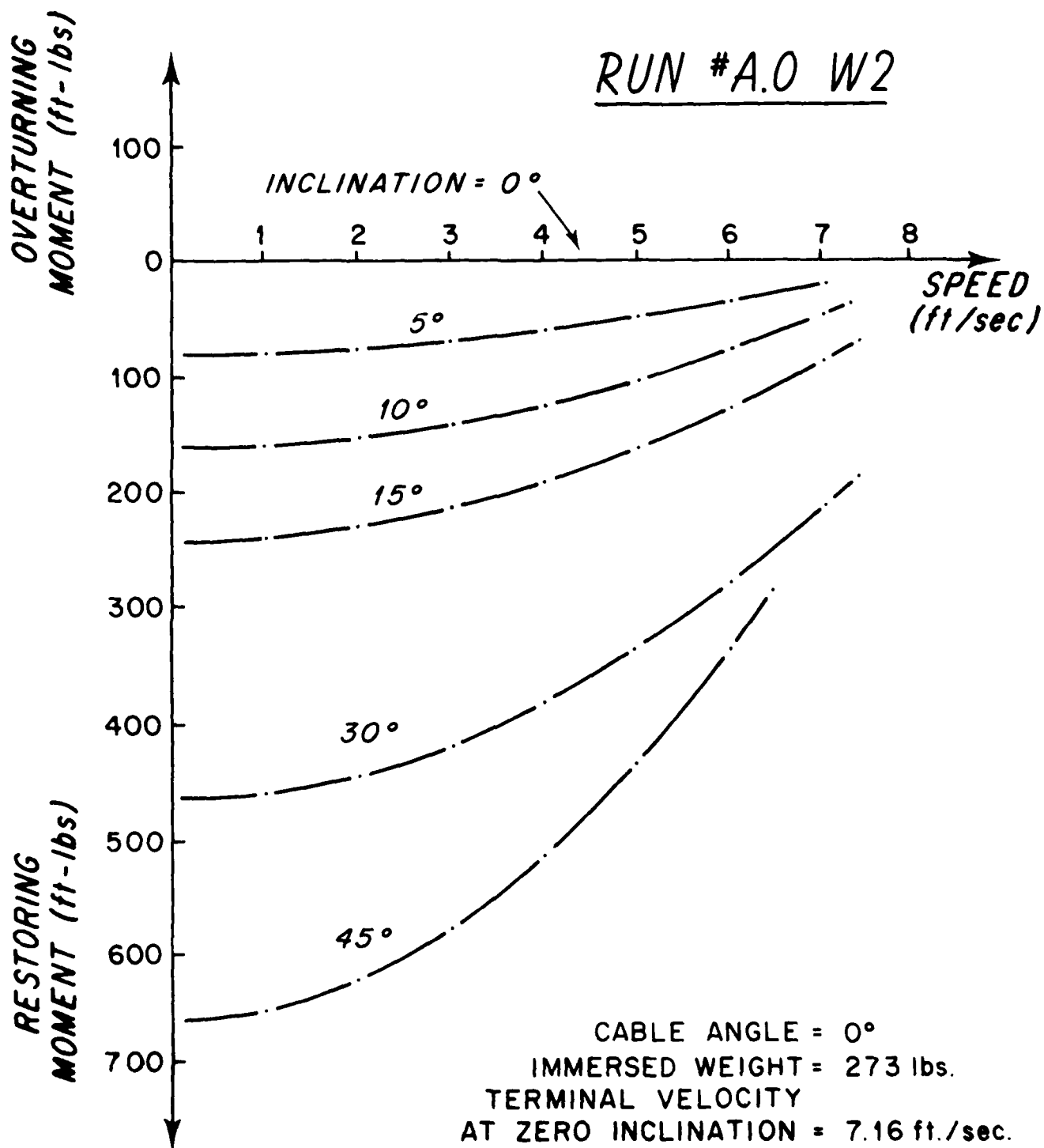


Figure: 18

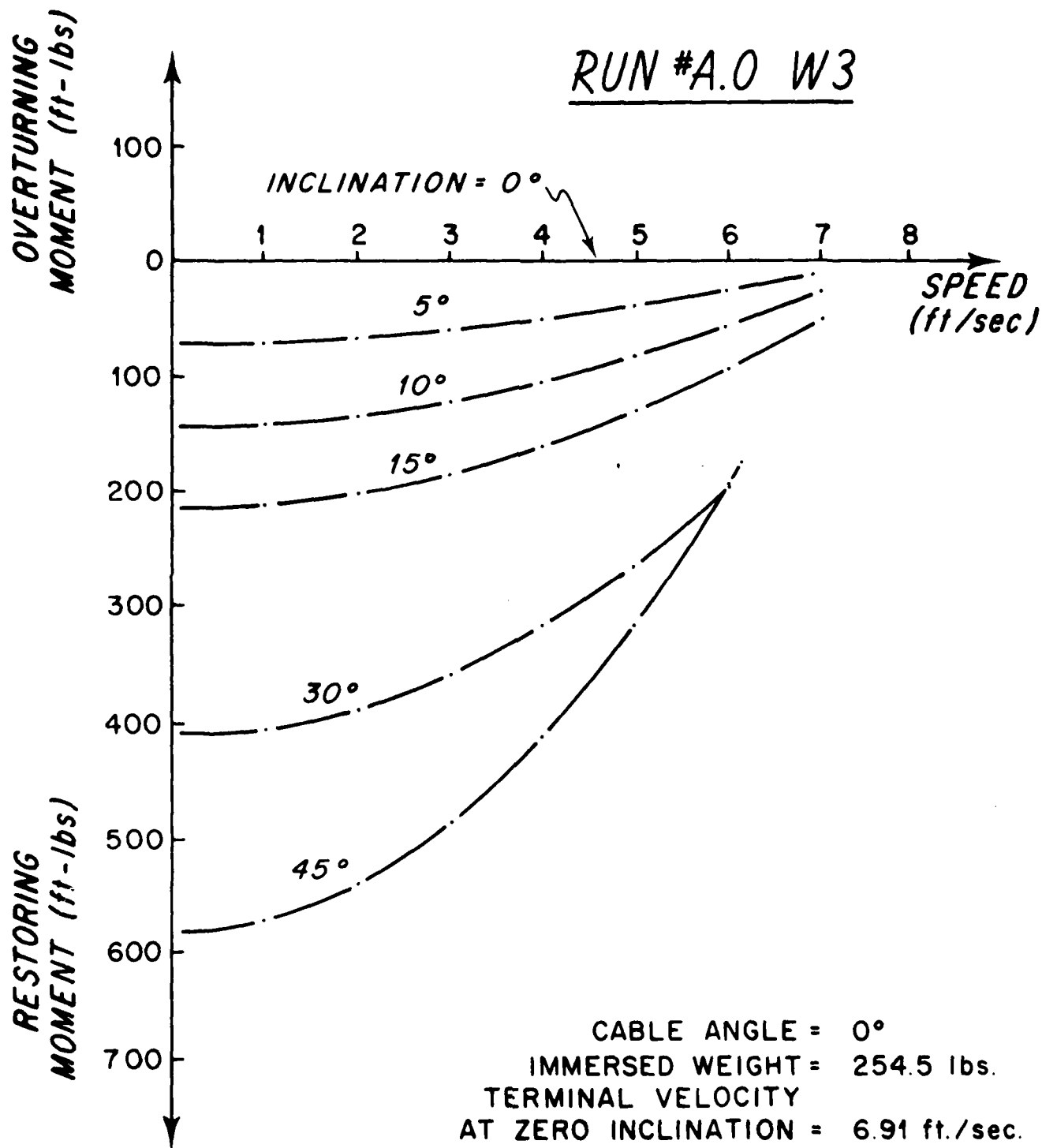


Figure: 19

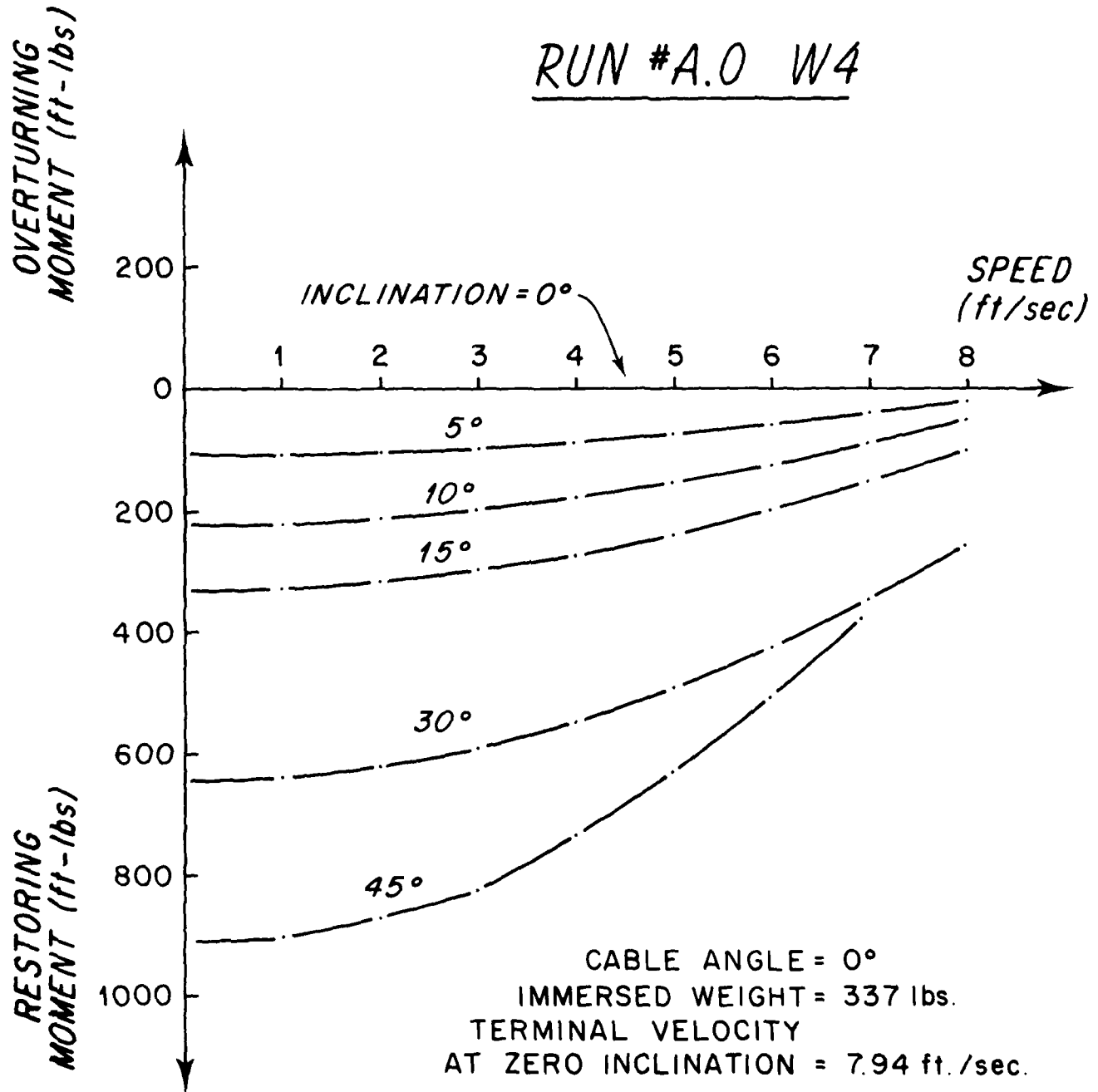


Figure: 20

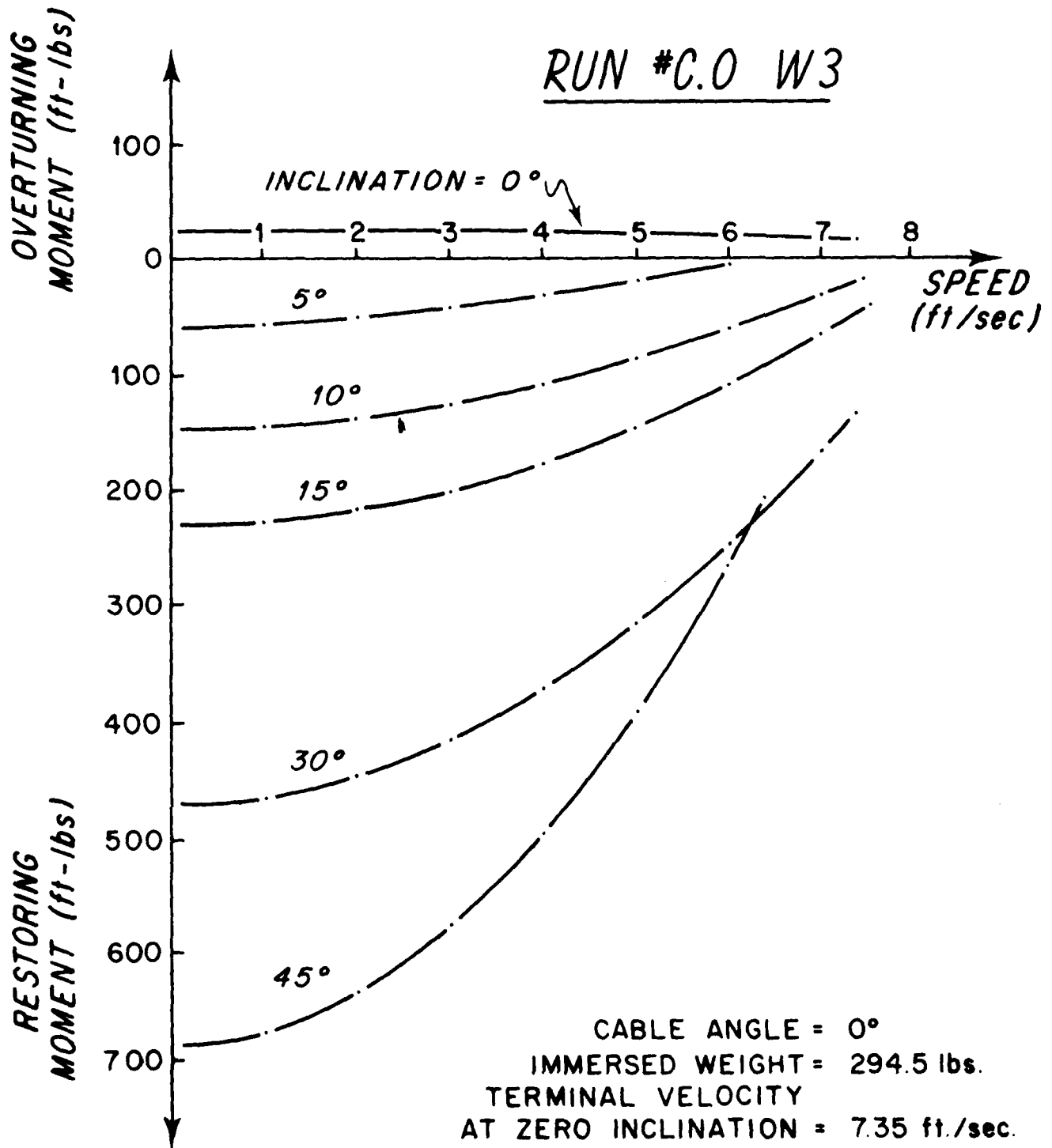


Figure: 21

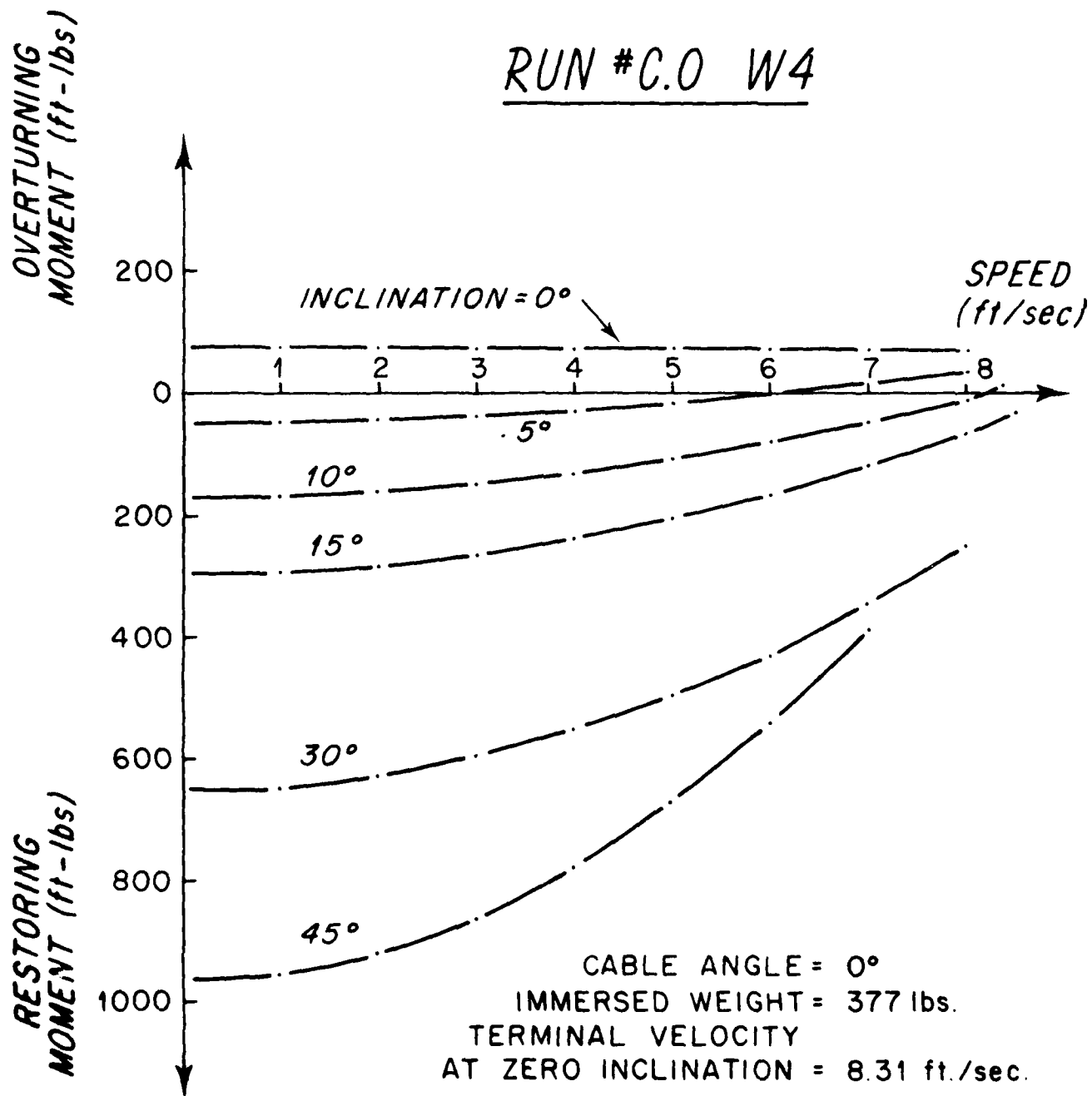


Figure: 22

TABLE 4
Drag Modifications

Case #	Drag Reduction	Terminal Velocity	
		Ft/Sec	% Increase
C.O.D1	1/2	7.94	14.4
C.O.D2	1/4	8.63	24.4
C.O.D3	1/8	9.06	30.5
C.O.D4	Small Frame	8.44	21.6

Figure 23 shows the stability curves for zero pitch angle of these four cases.

These results clearly indicate that drag reduction, even as little as $\frac{1}{2}$, greatly improves the package terminal velocity. A judicious combination of weight increase and drag reduction can only benefit the performance of future packages.

3.4.5 Optimal Configurations

Based on the results of the previous four sections, two runs (F.0 and G.0) were made in an attempt to optimize both stability and terminal velocity. Both configurations use configuration B.0 as a basis with the addition of another pinger to make it symmetric, a one inch lead ring to add weight, and a reduction in drag of the WHOI frame by $\frac{1}{2}$. Configuration G.0 differs from F.0 described above in that the small diameter WHOI frame is used. Stability curves for these two last runs are shown in Figures 24 and 25. These curves show a pronounced increase in stability. The improvement in terminal velocity, shown in the table hereafter, is even more impressive.

TABLE 5
"Optimal" Cases

Case #	Terminal Velocity Ft/Sec	% Increase
B.0	6.94	0
G.0	9.44	36.0
F.0	8.84	27.4

These values should not be thought of as final, however, as further study should investigate ways in improving these numbers even more.

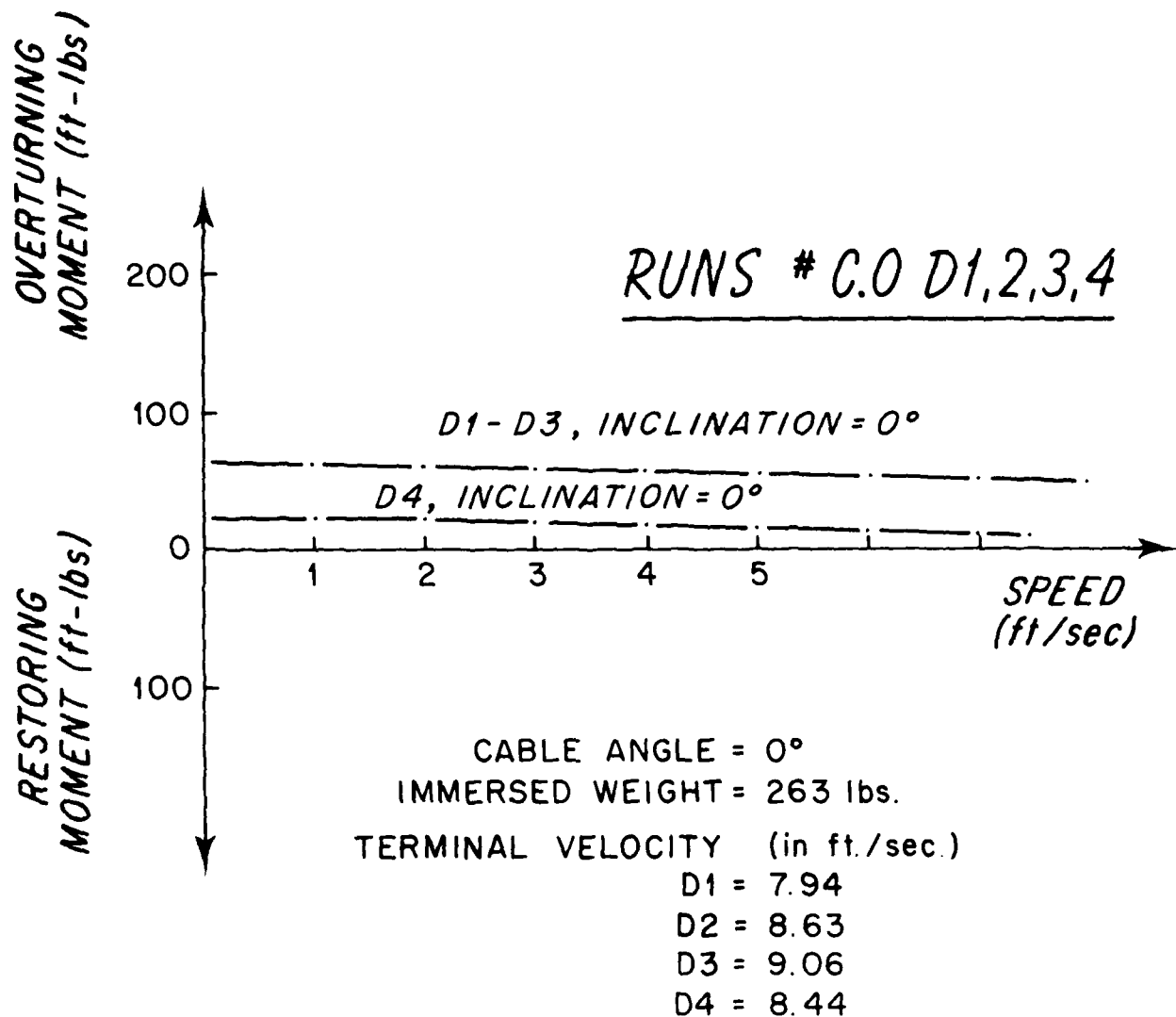


Figure: 23

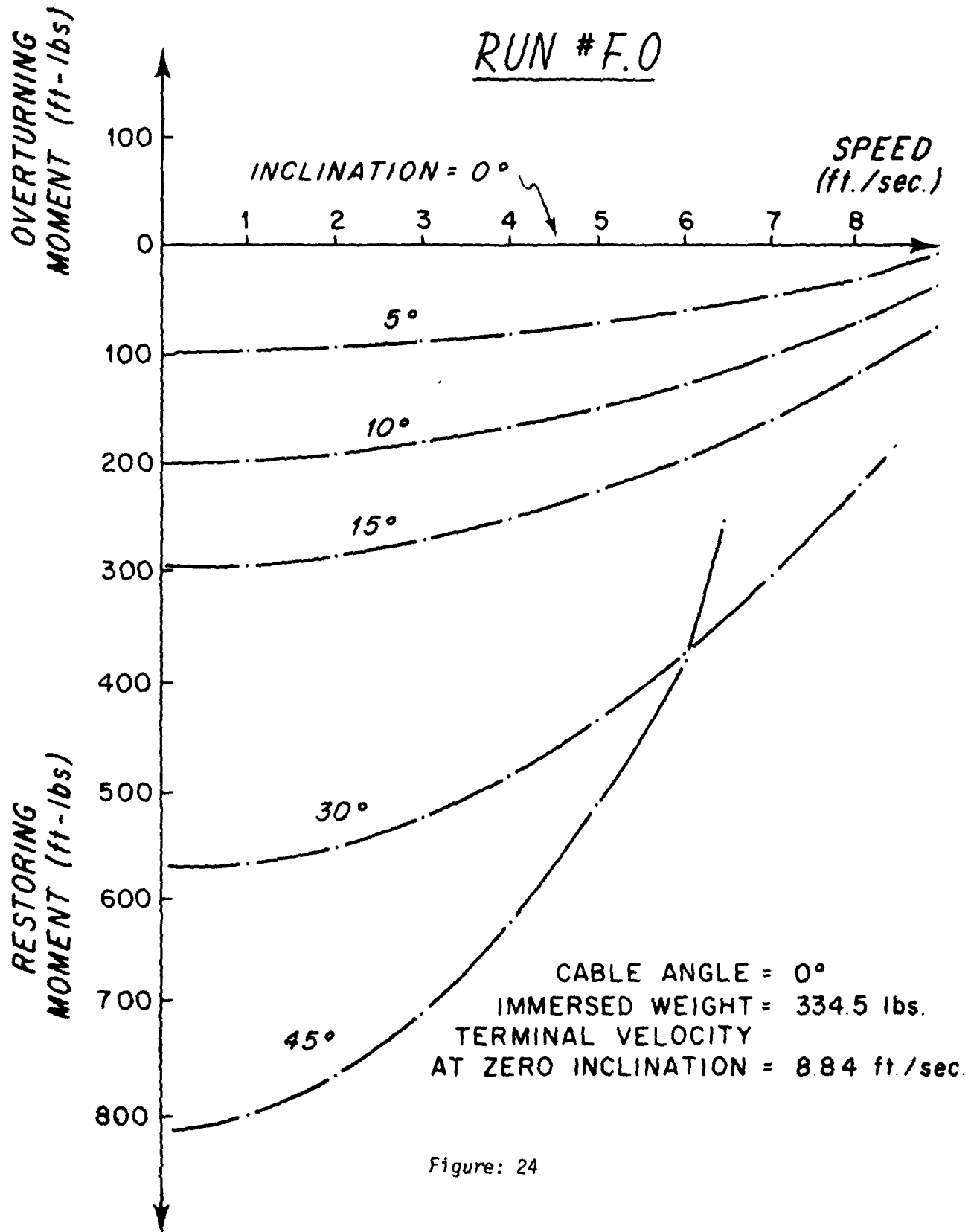


Figure: 24

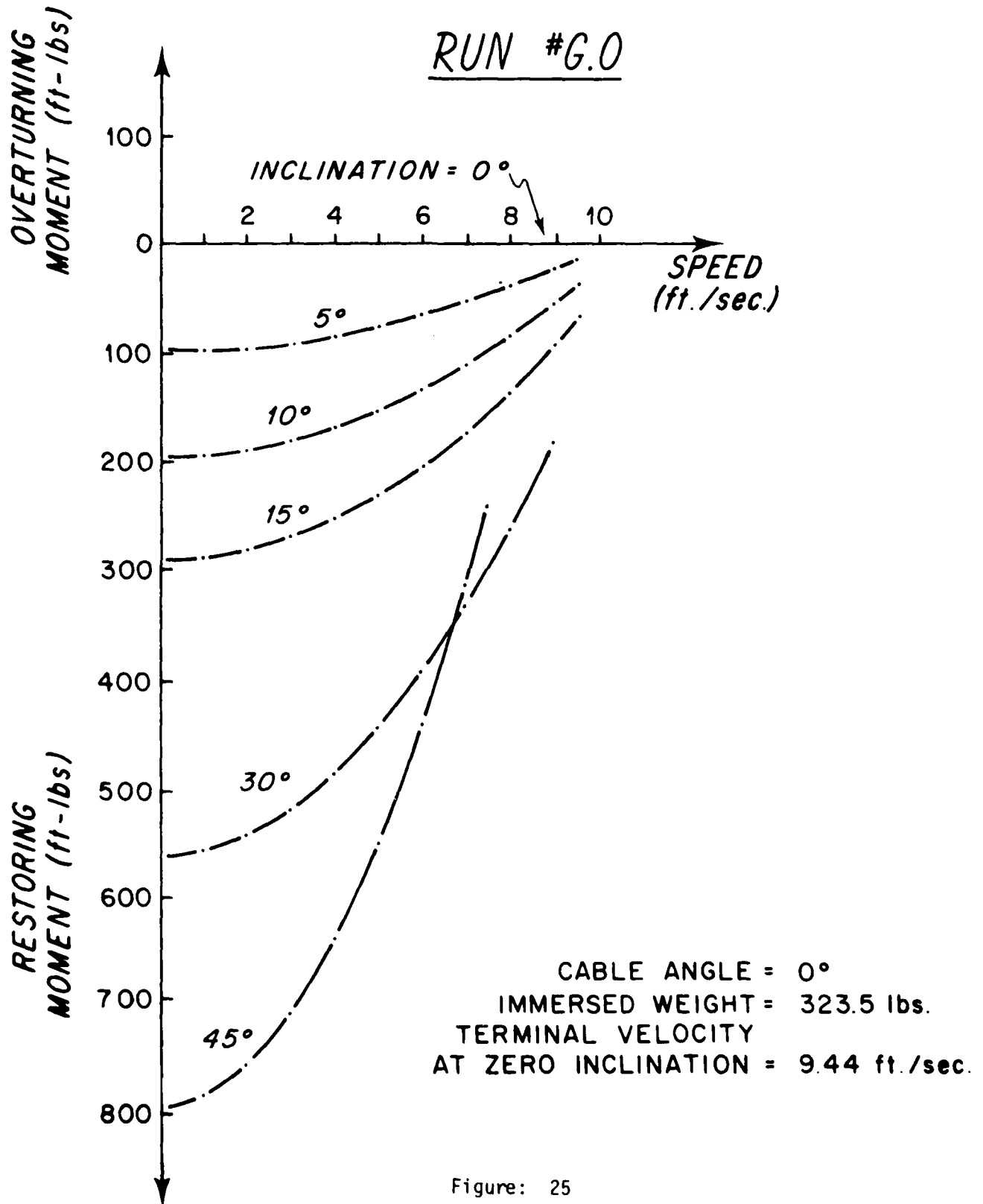


Figure: 25

4.0 DYNAMIC ANALYSIS

4.1 Dynamic Stability

The dynamic stability of an object moving at a constant velocity involves the path an object takes around the steady motion equilibrium position after a perturbation. At the outset of this study, it was thought that a dynamic stability analysis would be required to determine the flight characteristics of CTD packages. A literature survey was conducted and the preliminary equations of dynamic stability were derived, (Appendix B).

To conduct a meaningful dynamic stability analysis, the values of the stability derivatives are required. Stability derivatives are partial differentials which express how a force or moment changes with a differential change in position, velocity or acceleration from steady motion. A CTD package is a complicated body of several components and as such there is no analytical method to determine the true values of the stability derivatives. Values of stability derivatives can be inferred if enough simplifications are made but the hope that the resultant model replicates reality is remote.

The other method to determine the values of the stability derivatives would be to conduct a model test in a wave tank or water tunnel. The CTD model would have to be fully outfitted to measure the forces and moments in the principal directions and to be able to be perturbed from its steady motion. Such a test program is beyond the scope of this study.

4.2 Vortex Shedding

It has been inferred that alternate vortex shedding on either side of a horizontally mounted CTD (or nephelometer) may contribute to an instability in CTD flight and help cause large scale oscillations or kiting*. For a smooth cylinder vortex shedding would definitely be occurring. The effect of this small alternating hydrodynamic force should not be significant unless of course its frequency is close to the pendulum frequency of the CTD package. The natural frequency of oscillations of the CTD package about its point of attachment to the lowering cable has been estimated to be .54 (Hz) in air. The shedding frequency of the horizontally mounted CTD (7" diameter) is found from

$$f = .2 \frac{V}{D}$$

where V is the lowering speed (ft/sec)
and D is the CTD diameter (ft).

*Footnote. Verbal communication, R. Reiniger, Bedford Institute of Oceanography, Halifax, Nova Scotia, CANADA.

At a lowering speed of 1.5 ft/sec (27 meters/minute) the shedding frequency would be close to the CTD pendulum frequency and resonance would occur with possible side motion dependent on the damping in the system. However most lowerings are done at higher speeds, typically 60 to 70 meters/minute. At 70 m/min the frequency of the vortex shedding induced by the horizontally mounted CTD is found to be 1.3 Hz. As can be seen from the simple calculations presented in Appendix C, the package oscillations resulting from this vortex shedding would have a very small amplitude (less than a degree). Furthermore in actual practice the clamps which hold the horizontally mounted instruments cause turbulence which should reduce the likelihood of periodic vortex shedding substantially. It thus appears that vortex shedding is not a serious problem, if it exists at all.

5.0 MODEL TESTING

To actually determine the flight characteristics of existing and modified CTD packages two series of tests will be conducted as part of the current CTD hydrodynamics study.

Model testing will be first conducted in the 50 foot wide and 100 foot deep tank of the Naval Surface Weapons Center in Silver Spring, Maryland. Full scale tests will be later conducted at sea, using an actual CTD package specially instrumented to monitor the cable tension at the package and the package flight pattern.

The objectives of the scale model tests will be to observe and record the flight stability of different scaled down versions of CTD packages as they are cable lowered or free fall to the bottom of the tank. The rationale for the selection of the scaling factors and the resulting geometry and materials for model fabrication are hereafter explained.

5.1 Dimensional Analysis

The feasibility for constructing a smaller scale model of the CTD package is based on dimensional analysis. The use of a scale model is desired since the model would be smaller, easier to handle, less expensive to repair if damaged and easily modified. The liability of a model, however, is the uncertainty involved over whether the model duplicates the flight of the full-scale CTD. Proper hydrodynamic scaling and geometric similarity between model and full scale must minimize the scale effects between the two packages.

In a model test there are three kinds of similarity which must be satisfied:

1. Geometric similarity.
2. Kinematic similarity. Streamline pattern in the model must be the same for model and prototype.
3. Dynamic similarity. Force ratio must be the same between model and prototype.

Geometric similarity is relatively easy to obtain. It reproduces not only the shape of the prototype but also its mass and displacement distribution (center of gravity, center of buoyancy, moment of inertia, etc.).

In flow regimes where the drag coefficients are highly dependent on the Reynolds number, kinematic similarity will dictate that the Reynolds number be the same for both prototype and model. Inasmuch as the Reynolds number R_e is of the form

$$R_e = KV\eta$$

where K is the inverse of the fluid kinematic viscosity, V is the speed of the object and η its dimension, an equality of Reynolds numbers for model and prototype tested in the same fluid implies that

$$V_M D_M = V_P D_P$$

For this equality to be maintained the speed of a $\frac{1}{2}$ scale model must therefore be twice as large than the speed of prototype.

Furthermore, at terminal velocity the drag of a free falling object must equal its submerged weight.

The familiar equation expressing this fact is:

$$F_D = \frac{1}{2} \rho C_D A V^2 = \bar{W}$$

where F_D is the drag force

ρ is the fluid density

C_D is the drag coefficient

A is a representative area of the object

$A = g D^2$ where g is some geometry constant

V is the terminal velocity,

and $\bar{W}$ is the immersed weight, that is the difference between the object's actual weight and the weight of the water it displaces.

The corresponding equations for model and prototype falling at terminal velocity are:

$$\frac{1}{2} \rho C_{DM} g_M D_M^2 V_M^2 = W_M$$

$$\frac{1}{2} \rho C_{DP} g_P D_P^2 V_P^2 = W_P$$

Now for geometric and kinematic similarity to prevail,

$$C_{DM} = C_{DP}$$

$$\begin{aligned} g_M &= g_P \\ D_M^2 V_M^2 &= D_P^2 V_P^2 \end{aligned}$$

and therefore

$$W_M = W_P$$

One may note that if $W_M = W_P$ then the condition of dynamic similarity, namely

$$\frac{F_{DM}}{W_M} = \frac{F_{DP}}{W_P}$$

is automatically satisfied.

A half scale model which falls twice as fast and weighs in water as much as the prototype is not very desirable. Fortunately it has been established that the drag coefficient of blunt objects in turbulent flow regimes remains approximately constant over a large range of Reynolds numbers.

This being the case and provided that flow turbulence is maintained for the model, only the dynamic similarity will be used as our second criterion - geometric similarity being the first - for the design of the model.

5.2 Half Scale Model Design

Maintaining the drag-to-submerged weight-ratio equal between model and full-scale requires satisfaction of the following equations:

$$\frac{F_{DM}}{W_M} = \frac{F_{DP}}{W_P}$$

or

$$\frac{\frac{1}{2} \rho C_{DM} g_M D_M^2 V_M^2}{W_M} = \frac{\frac{1}{2} \rho C_{DP} g_P D_P^2 V_P^2}{W_P}$$

Assuming that $C_{DM} = C_{DP}$

and that $D_M = D_P/2$

and selecting a speed of model fall equal to the speed of prototype fall - which should be sufficient to maintain turbulent flow conditions - yields

$$W_M = W_P/4$$

In other words, a $\frac{1}{2}$ scale model which has the same terminal velocity as the full-scale CTD would have a submerged weight equal to $\frac{1}{4}$ of the full-scale value. This result is used next to develop specifications for a $\frac{1}{2}$ scale model.

The geometry of the scale model will be patterned after the simplified geometry used in the mathematical model. The different CTD components will be homogeneous cylinders with one-half the length and one-half the diameter of the cylinders they represent.

To maintain correct submerged weight distribution as well as correct total model weight, the material density of each cylinder must be calculated according to the following procedure:

1. Establish the immersed weight of the actual component " i ", $W_P(i)$
2. The immersed weight of the model component " i " is then

$$W_M(i) = W_P(i) / 4$$

3. Compute the volume $V_{D_M}(i)$ of the model component " i "
4. The density of the model component " i " is the

$$\rho_H(i) = \frac{1}{V_{D_M}(i)} [W_M(i) + V_{D_M}(i) \rho_w]$$

ρ_w being the density of water (lbs/cu.ft).

Results obtained with this simple computation procedure are summarized in Table 6.

TABLE 6

Specifications for $\frac{1}{2}$ Scale CTD Model

Component Modeled	Cylinder Dimensions (inches) (Diam x Length)	Weight (lbs)	Immersed Weight (lbs)	Specific Weight (lbs/cu.ft.)	Specific Gravity
CTD	3.5 x 12.5	29.26	24.75	415.63	6.66
Rosette	11.5 x 15.0	65.20	17.50	83.41	1.34
Frame	$\frac{1}{2}$ $\emptyset$ diam tubing Ring & Verticals to scale	16.90	13.50	310.0	4.97
Finger	2.5 x 13	12.24	10.0	349.71	5.60
Nephelo	3.0 x 16	22.87	18.68	349.71	5.60

The immersed weight of a CTD prototype package made of a CTD instrument, a rosette, a WHOI frame and one pinger is 263 lbs. The immersed weight of this package model is found to be 65.25 or 4.03 as small as the immersed weight of the prototype.

6.0 RECOMMENDATIONS AND CONCLUSIONS

The sensitivity analysis has shown that substantial improvement in CTD performance is possible. Symmetry was found to be very important to the stability of CTD packages and this result should be demonstrated in the NSWC tank. The reduction of drag was also determined to significantly increase the terminal velocity of CTD configurations and modifications to achieve this reduction should be much more thoroughly studied in the final phase of the project. A search for optimal configurations combining the beneficial effects of symmetry, drag reduction and weight addition should be concentrated on. Scale models should be constructed to use during the test phase which can be easily modified.

In this preliminary study a simple mathematical model was developed and used to study the hydrodynamic characteristics of CTD packages and the sensitivity of the package to various modifications. The form of the analytical model used above is adequate for this preliminary study. It is hoped that a much more detailed analysis be conducted to more accurately model the hydrodynamics of CTD and other oceanographic instrument packages. A fully instrumented model with which to obtain stability derivatives would be a logical first step.

Scale model tests and tests performed at sea with a full scale model should confirm the trends point out by relatively simple and more sophisticated analyses.

The ultimate recommendation will be to sensibly alter the existing configuration and to design a new package which would greatly improve the present performance.

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APPENDICES

APPENDIX "A"

"Description of Computer Program CTDFLI"

Appendix A

Description of Computer Program CTDFLI

7-28-80

Name: CTDFLI

Type: Main Program

Purpose: Calculates the fluid drag forces and moments acting on CTD packages to determine the stability of vertical motion as a function of velocity and angle of orientation.

Machine: Xerox Sigma 7

Source Language: Xerox Extended FORTRAN IV

Program Category: Numerical Model

Description:

The program computes the normal and tangential drag forces, the pitching moments these produce and the overall righting moment on CTD configurations as a function of vertical velocity and angle of orientation. A CTD configuration is made up of up to ten different components of known center of gravity and tangential and normal drag constants. The weight, buoyancy, center of buoyancy, cable tension angle and point of application of the cable tension must also be known for each CTD configuration. For each specific angle of orientation, the normal and tangential drag forces are calculated for each component at velocities from 0 to terminal velocity at 0.5 ft/sec increments. The pitching moment about the overall centers of gravity of a configuration due to the drag forces is then calculated as well as an overall righting moment. In addition to the pitching moment, the righting moment is made up of the moments caused by the buoyancy force and by the cable tension. The terminal velocity at each angle of orientation is also calculated and output.

The program has been written to run either on-line or as a batch job, with the primary use assumed to be on-line. The user must supply parameters defining the geometry of the configuration and the drag characteristics of each component. The center of buoyancy and centers of gravity of each component are measured relative to the overall center of gravity of each configuration. The overall center of gravity can be thought of as the origin of a body-fixed coordinate system with the x-axis positive (tangential direction) positive downward and the z-axis (normal direction) positive to the right. The user supplied parameters are:

BUOYF	Buoyancy force of overall package, lbs
XCB	Distance along x-axis to center of buoyancy (CB), inches
ZCB	Distance along z-axis to center of buoyancy, inches
WTAIR	Weight in air of CTD package, lbs
PHI	Angle tension acts measured from the vertical, degrees
XTEN	Distance along x-axis to pt. of application of tension, inches
ZTEN	Distance along z-axis to pt. of application of tension, inches

For each component:

XCGi Distance along x-axis to Center of Gravity (CG) of component i, inches

ZCGi Distance along z-axis to CG of component i, inches

CDANi Normal drag constant of component i

CDATi Tangential drag constant of component i

THETA Pitch angle; angle between body-fixed coordinates and the vertical, degrees (Up to 8 different pitch angles can be specified per run)

When all the parameters have been input the calculation sequence begins for the pitch angle specified. Forces and moments are calculated for 31 different velocities between 0 and 15 ft/sec at 0.5 ft/sec intervals. The calculation sequence for one velocity is as follows:

1. Break velocity into normal and tangential components

$$\begin{aligned} \text{VELN} &= \text{VEL} * \text{SIN}(\text{THETA}) \\ \text{VELT} &= \text{VEL} * \text{COS}(\text{THETA}) \end{aligned}$$

2. For each component, calculate tangential force:

$$\text{XI} = \text{CDAT}(\text{I}) * \text{VELT} * \text{VELT}$$

normal force:

$$\text{ZI} = \text{CDAN}(\text{I}) * \text{VELN} * \text{VELN}$$

and pitching moment:

$$\text{PMI} = \text{CDAN}(\text{I}) * \text{VELN} * \text{VELN} * \text{XCG}(\text{I}) + \text{CDAT}(\text{I}) * \text{VELT} * \text{VELT} * \text{ZCG}(\text{I})$$

3. Sum these up to get the total force and moments:

XF total tangential force, lbs

ZF total normal force, lbs

PMDYN pitching moment, ft/lbs

4. Calculate tension in the cable:

$$\text{TENSON}(\text{J}) = 1 / \text{COS}(\text{PHI}) * ((\text{SUBWT} - \text{XF} * \text{COS}(\text{THETA}) - \text{ZF} * \text{SIN}(\text{THETA})))$$

5. The program now checks to see if terminal velocity has been reached. Terminal velocity occurs when the tension in the cable is zero. If terminal velocity has been reached, which is determined when the tension goes from a positive to a negative value at the next velocity increment, the terminal velocity is calculated by interpolation using

- 48 -

the values of tension at the present and previous velocity values. The formula used is

$$VTERM = TENSION(J-1)/(TENSION(J-1) - TENSION(J)) * 0.5 + (VEL - .5)$$

Once terminal velocity has been reached no more moment calculations are performed for this pitch angle.

6. Calculate righting moment:

$$PMSTAT = PMDYN + BUOYF * SIN(THETA) * XCB + BUOYF * COS(THETA) * ZCB + \\ TENSION(J) * SIN(THETA - PHI) * XTEN + TENSION(J) * COS(THETA - PHI) * ZTEN$$

Following the calculation sequence, the results can be printed out. The program then asks if another run using a different pitch angle is wanted. If so, a new value of pitch angle is input and the calculation sequence is repeated. If no other runs are needed, the program asks the user if plots are desired. Plots of tangential drag force, normal drag force, pitching moment and righting moment versus velocity can be obtained. The user specifies which plot he wants drawn and the title of the plot. Up to four plots can be specified per run. At this point, the program stops. The details involved in having the plots printed are described in the Operating Instructions below.

Operating Instructions

I. On-line usage

1. To start the program respond to the ! prompt from the system by entering:

PLATEN_80

This command allows output to fit on paper. The computer should respond with another ! prompt, then type

SET F:95/Filename

This command creates a plotting file of the name specified which will contain the plotting information the user specifies while running the program. The computer should respond with another !prompt, then type.

S_CTDRUN

2. Program should respond

CTDFLI--VERSION 1.0 - JULY 1980

INPUT BUOYANCY FORCE (LBS)

?

Respond by entering this number. Input is free field: numbers can be specified in any normal way. Should a mistake be noticed after the return key has been hit, exit the program with a Control Y and restart the program.

Program asks:

INPUT X-CENTER OF BUOYANCY(IN)

Respond by entering the proper value. The program will continue to ask for all the variables described previously until after the value of CDAT for the last component has been entered. At this point the program asks:

TYPE THE NUMBER 3 TO HAVE HARD COPY OUTPUT

Respond by typing a 3 if paper tabular output is desired. If only plots are wanted then type any other character and return. The program responds by typing:

INPUT PITCH ANGLE(DEGREES)

?

After inputting an appropriate value, the program will commence typing the computed values of forces and moments described above if hard copy output was specified. The format is:

RUN NO. <u>1</u> THETA= <u> </u> DEGREES		TERMINAL VELOCITY = <u> </u> FT/SEC	
VELOCITY	VELOCITY	X-FORCE	Z-FORCE
		PITCH	RIGHTING
		MOMENT	MOMENT
(FT/SEC)	(M/MIN)	(LBS)	(LBS)
		(FT-LBS)	(FT-LBS)
			(LBS)

After all the results have been printed out, if the hard copy option was specified, or directly after inputting the pitch angle if no hard copy was specified, the program responds with:

TYPE THE NUMBER 1 TO MAKE ANOTHER RUN

?

If another run is wanted the program will ask for a new pitch angle and the above sequence will be repeated. If no more runs are desired the program will respond:

TYPE THE NUMBER 2 TO HAVE PLOTS MADE

?

Respond by typing a 2 if plots are needed. Any other character will end the program. If a 2 is typed, the program asks

TYPE:	1	TO PLOT TANGENTIAL FORCE
	2	TO PLOT NORMAL FORCE
	3	TO PLOT PITCHING MOMENT
	4	TO PLOT RIGHTING MOMENT

- 50 -

Respond by typing one of these four numbers corresponding to the desired plot. The program will then ask:

TYPE PLOT TITLE (40 CHAR.MAX)

Input an appropriate plot title. At this point the program returns with:

TYPE 5 TO HAVE ANOTHER PLOT MADE

Respond by typing in a 5 if more plots are wanted or any other character if no plots are desired. Program ends when no more plots are desired.

At this stage, no plot has been drawn if plotting was desired. What has been created is a deferred plotting file with the name given by the user in the SET command prior to running the CTDFLI program. To display the deferred plotting file requires the use of another program dependent on the plotter used. At WHOI there are three different plotters, Tektronix, Versatec and Calcomp, available to use. The CTDFLI program has been written primarily for use with the Versatec and this will be the only plotter discussed in the remainder of this report. The Sigma 7 computer group can answer any questions about the other two systems.

The steps required to get a Versatec plot of the run involve submitting a batch job. This can be done while on-line by writing a small disk file with the appropriate commands. A listing of the required commands is as follows:

```
!JOB out, user
!LIMIT (TIME,2) (CORE,20)
!MESSAGE USES VERSATEC
!SET F:95/Filename ; SAVE
!PLOTV
```

The filename in the SET F:95 command must be the same as specified prior to running CTDFLI. The SAVE option in the SET command prevents the file from being erased after the plot has been made. The above commands should be placed in a disk file under a filename such as PLOTVER. To have the Versatec plots made while on-line requires the following command:

BATCH_PLOTVER

This command instructs the computer to have a Versatec Plot drawn. The computer responds by typing:

```
ID= _ _ _ SUBMITTED 10:25 JUL 30, '80
WAITING: _ _ TO RUN.
```

The Versatec plot will be placed in the users bin upon completion.

RESTRICTIONS:

STORAGE REQUIREMENTS:

SUBROUTINES REQUIRED: INPUT, OUTPUT, CALCUL, IFPLOT, PLOTFOURS (User subroutines with main program)

AMITERM, PLOTDFER (from acct 3 library)

<u>Device</u>	<u>Function</u>	<u>Special Requirement</u>
Card Reader or Terminal	Input	F:105 DCB
Line Printer or Terminal	Output	F:108 DCB

TIMING: Fast

PROGRAMMER: Michael F. Cook
Mary M. Moffett (PLOTFOURS SUBROUTINE)

ORIGINATORS: Michael F. Cook
Michael S. Triantafyllou

DATE: July 1980

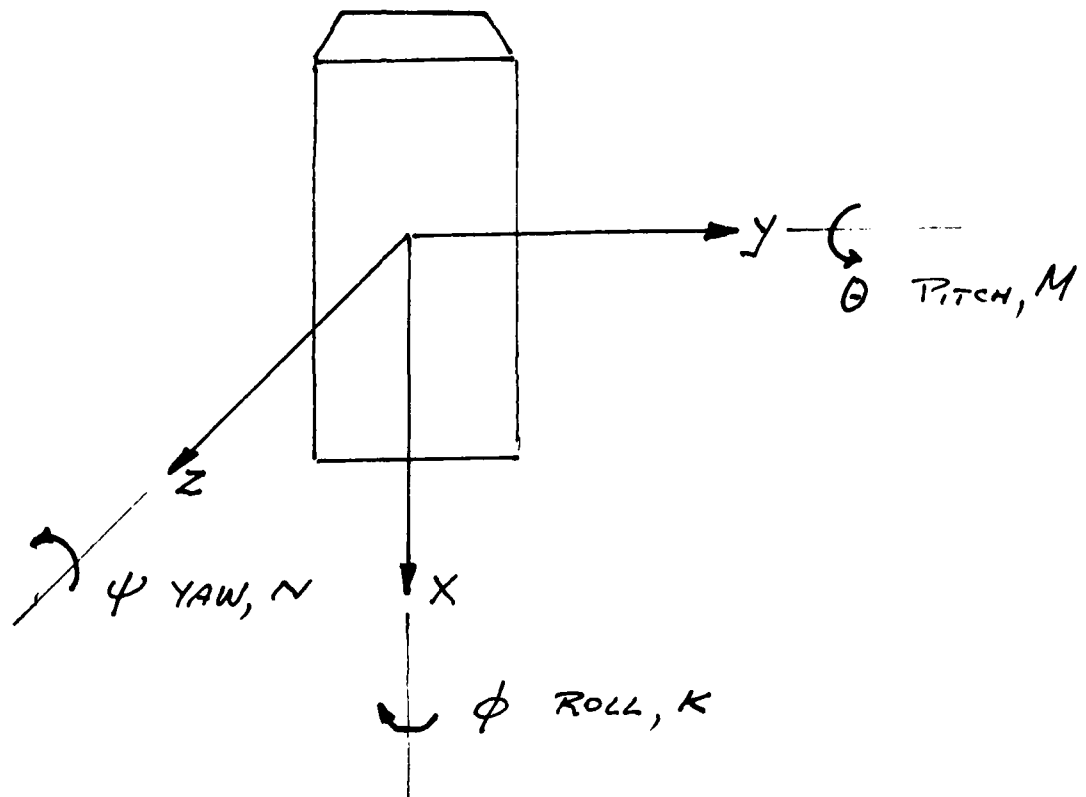
APPENDIX "B"

"Dynamic Stability Analysis"

"Dynamic Stability Analysis"

Definition of body-fixed coordinate system

Principal axes (all products of inertia are zero)



	Components	Vector	
unit vectors	$\hat{i}, \hat{j}, \hat{k}$		
displacements	x, y, z		roll angle ϕ
linear velocities	u, v, w	$\vec{U}$	pitch angle θ
angular velocities	p, q, r	$\vec{\Omega}$	yaw angle ψ
hydrodynamic forces	X, Y, Z	$\vec{F}$	
vector moments	K, M, N	$\vec{M}$	
moments of inertia	I_x, I_y, I_z		
Angular momentum	$\vec{H} = I_x p \hat{i} + I_y q \hat{j} + I_z r \hat{k}$		
subscript	o - initial condition		
	Δ - change in		

Derivation of Equations of Motion
(from Abkowitz, Appendix I)

Starting with Newton's laws of motion,

$$\vec{F} = \frac{d}{dt} (m \vec{U}) \quad (1)$$

$$\vec{M} = \frac{d}{dt} (H) \quad (2)$$

and expanding in terms of the variables on the previous page, six general equations of motions about the principal axes can be derived and the resulting equations are shown below.

$$X = m [\dot{u} + \omega q - v r - x_G (q^2 + r^2) + y_G (p q - \dot{r}) + z_G (p r + \dot{q})] \quad (3)$$

$$Y = m [\dot{v} + u r - \omega p - y_G (r^2 + p^2) + z_G (q r - \dot{p}) + x_G (p q + \dot{r})] \quad (4)$$

$$Z = m [\dot{w} + v p - u q - z_G (p^2 + q^2) + x_G (p r - \dot{q}) + y_G (q r + \dot{p})] \quad (5)$$

$$K = I_x \dot{p} + (I_z - I_y) q r + m [y_G (\dot{w} + v p - u q) - z_G (\dot{v} + u r - \omega p)] \quad (6)$$

$$M = I_y \dot{q} + (I_x - I_z) r p + m [z_G (\dot{u} + \omega q - v r) - x_G (\dot{w} + v p - u q)] \quad (7)$$

$$N = I_z \dot{r} + (I_y - I_x) p q + m [x_G (\dot{v} + u r - \omega p) - y_G (\dot{u} + \omega q - v r)] \quad (8)$$

To determine the forces and moments above, which are functions of geometry, velocity, etc., the standard practice is to expand these equations in a Taylor series expansion about a suitable initial condition. For our purposes, we will expand about steady vertical motion ($u = u_0$; $v_0 = \omega_0 = 0$; $v_0 = \dot{w}_0 = 0$; $p_0 = q_0 = r_0 = 0$)

Also, the six equations of motion are usually divided into two groups for stability purposes:

1. longitudinal (symmetric) stability X, Z, M
2. lateral (asymmetric) stability Y, K, N

In our case, the CTD is axisymmetric (with no pinger) so that only 4 equations need be solved. ($Z=Y$; $M=N$) The four chosen are X, Z, M, K .

Prior to linearizing equations 3,5,6 and 8, the following assumptions were made:

1. CG is on axis of symmetry along x - axis, i.e. $Y_G = Z_G = 0$
2. CTD has inertial symmetry, i.e. $I_y = I_z = I_1$ and $I_x = I_3$
3. Longitudinal equations (X, Z, M) assumed to be functions of only $X_0, Z_0, \theta, u, \omega, q, \dot{u}, \dot{\omega}, \dot{q}$ all other terms being zero.
4. K equation assumed to be function of $\phi, \theta, p, \dot{p}, u, \omega, q, \dot{u}, \dot{\omega}, \dot{q}$

Using the above assumptions equations 3,5,6 and 8 become:

$$X = m(\ddot{u} + \omega q - X_G q^2) \quad (9)$$

$$Z = m(\ddot{\omega} - uq - X_G \dot{q}) \quad (10)$$

$$M = I_1 \dot{q} - mX_G(\ddot{\omega} - uq) \quad (11)$$

$$K = I_3 \dot{p} \quad (12)$$

At this point, these equations must be linearized about steady vertical motion. In this process only the linear terms in the change of a variable from the steady position are kept. As an example of how this is done, consider the equation for X. As stated in assumption 3., X is assumed to be a function of the following:

$$X = X(X_0, Z_0, \theta, u, \omega, q, \dot{u}, \dot{\omega}, \dot{q})$$

Since all the variables have equilibrium values of 0, except u in steady vertical motion the change in a variable due to a perturbation from the steady motion can be written as

$$\Delta \text{ variable} = \text{variable} - (\text{variable})_0$$

for all variables except

Hence the linear terms in a Taylor expansion of X take the form

$$X = X_0 + \left(\frac{\partial X}{\partial X_0}\right)_0 \Delta X_0 + \left(\frac{\partial X}{\partial Z_0}\right)_0 \Delta Z_0 + \dots + \left(\frac{\partial X}{\partial \dot{q}}\right)_0 \Delta \dot{q}_0 \quad (14)$$

where $\left(\frac{\partial X}{\partial *}\right)_0 = \left(\frac{\partial X}{\partial *}\right)_{*=X_0} = X_*$ = Stability derivative of
with respect to *

Noting that X_0 is zero and using the stability derivative notation above, equation 14 can be written as

$$X = X_{X_0} X_0 + X_{Z_0} Z_0 + X_{\theta} \theta + X_u u + X_w w + \dots + X_{\dot{q}} \dot{q} \quad (15)$$

Similarly for the left hand sides of equations 10-12.

Now we note that the stability derivatives indicate the change in force or moment due to a differential change in displacement, angle, velocity or acceleration with all other variables in their equilibrium positions. For simple shapes, values of these stability derivatives can be derived. For complicated structures, such as a CTD, values of these derivatives can only be obtained by model testing.

At this point in the derivation, the right hand sides of equations 9-12 must be linearized about steady vertical motion. To do this we expand each variable to be the sum of the initial condition plus a perturbation (for example $u = u_0 + \Delta u$). Substituting these values into equations 9-12, neglecting higher order terms, and recognizing that in steady vertical motion only u_0 is non-zero, equations 9-12 become:

$$X = m \ddot{u} \quad (16)$$

$$Z = m(\dot{w} - u_0 \dot{q} - X_G \dot{q}) \quad (17)$$

$$M = I_1 \dot{q} - m X_G(\dot{w} - u_0 \dot{q}) \quad (18)$$

$$K = I_3 \dot{\phi} \quad (19)$$

Since $\ddot{u} = \ddot{u}_0 + \Delta \ddot{u}$ and $\ddot{u}_0 = 0$; $\ddot{u} = \Delta \ddot{u}$

In the expansions of X , Z , M and K , many of the stability derivatives are zero. Specifically, X_{x_0} , X_{z_0} , Z_{x_0} , Z_{z_0} , M_{x_0} , M_{z_0} are all zero since a translation in x or z will not change the equilibrium condition of steady vertical motion. Similarly, for symmetric bodies, Abkowitz has shown that $X_{\dot{\omega}}$, X_{ω} , $X_{\dot{q}}$, X_q and X_{θ} are zero when evaluated at condition of vertical motion equilibrium where $\dot{\omega} = \omega = \dot{q} = q = \theta = 0$

Expanding equations 16-19 with the above simplifications leaves the following 4 equations with 10 unknowns.

$$X_{\dot{u}} \dot{u} + X_u \Delta u = m \dot{u} \quad (20)$$

$$Z_{\dot{u}} \dot{u} + Z_u \Delta u + Z_{\dot{\omega}} \dot{\omega} + Z_{\omega} \omega + Z_{\dot{q}} \dot{q} + Z_q q + Z_{\theta} \theta = m (\dot{\omega} - u_g \dot{q} - \kappa_g \dot{q}) \quad (21)$$

$$M_{\dot{u}} \dot{u} + M_u \Delta u + M_{\dot{\omega}} \dot{\omega} + M_{\omega} \omega + M_{\dot{q}} \dot{q} + M_q q + M_{\theta} \theta = I_1 \dot{q} - m \kappa_g (\dot{\omega} - u_g \dot{q}) \quad (22)$$

$$K_{\dot{u}} \dot{u} + K_u \Delta u + K_{\dot{\omega}} \dot{\omega} + K_{\omega} \omega + K_{\dot{q}} \dot{q} + K_q q + K_{\theta} \theta = K_{\dot{\rho}} \dot{\rho} + K_{\rho} \rho + K_{\phi} \phi = I_3 \dot{\rho} \quad (23)$$

One more simplification is useful at this point to get the equations into their simplest forms. First we choose which four of the variables to be independent with the remaining 6 dependent. For the CTD in steady vertical motion, Δu , ω , θ and ϕ were chosen as independent.

Also, it should be noted, that all the above equations have considered only hydrodynamic forces. Forces due to weight and buoyancy must also be included. These equations can be written

$$X = (W - B) \cos \theta \quad (24)$$

$$Z = (W - B) \sin \theta \quad (25)$$

In steady vertical motion $\theta = 0$ and $X = W - B$ as it should be.

Substituting (24) and (25) into equations 20 and 21 and expanding in terms of the independent variables, the linearized dynamic stability equations of motion for an axisymmetric CTD perturbed from steady vertical motion are:

$$\left[(X_u - m) \frac{d}{dt} + X_u \right] \Delta U - (W-B) \cos \theta = 0 \quad (26)$$

$$\begin{aligned} & (Z_u \frac{d}{dt} + Z_u) \Delta U + \left[(Z_{\dot{w}} - m) \frac{d}{dt} + Z_{\dot{w}} \right] \dot{w} \\ & + \left[(Z_{\dot{q}} + m X_G) \frac{d^2}{dt^2} + (Z_q + m U_0) \frac{d}{dt} + Z_\theta \right] \theta - (W-B) \sin \theta = 0 \quad (27) \end{aligned}$$

$$\begin{aligned} & (M_u \frac{d}{dt} + M_u) \Delta U + \left[(M_{\dot{w}} + m X_G) \frac{d}{dt} + M_{\dot{w}} \right] \dot{w} \\ & + \left[(M_{\dot{q}} - I_1) \frac{d^2}{dt^2} + (M_q - m X_G U_0) \frac{d}{dt} + M_\theta \right] \theta = 0 \quad (28) \end{aligned}$$

$$\begin{aligned} & (K_u \frac{d}{dt} + K_u) \Delta U + (K_{\dot{w}} \frac{d}{dt} + K_{\dot{w}}) \dot{w} + (K_{\dot{q}} \frac{d^2}{dt^2} + K_q \frac{d}{dt} + K_\theta) \theta \\ & + \left[(K_{\dot{p}} - I_3) \frac{d^2}{dt^2} + K_p \frac{d}{dt} + K_\phi \right] \phi = 0 \quad (29) \end{aligned}$$

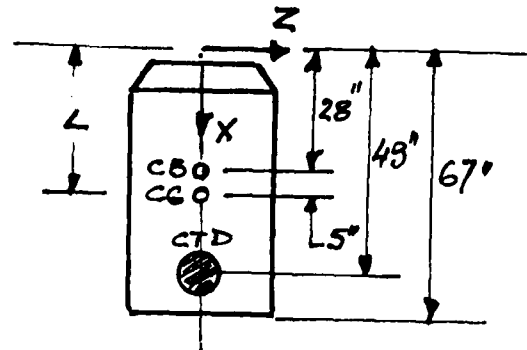
With proper values of stability derivatives these equations could be solved and the dynamic stability investigated.

APPENDIX "C"

"Analysis of Vortex Shedding"

Calculation of Pendulum Natural Frequency

Example: Configuration C.O
with horizontally mounted
CTD instrument (25"x7"Ø)



For this simple estimate of the pendulum frequency the following assumptions were made

1. CTD package is in air (for package in water natural frequency will be even lower)
2. All mass lumped at CG

Angular Equation of Motion about Y - axis (for small angles)

$$I\ddot{\theta} + mgL\theta = M \text{ where } I = mK^2, K = \text{radius of gyration}$$

$$\text{natural frequency} = \omega_n = \sqrt{\frac{K}{m}} = \sqrt{\frac{mgL}{I}} = \sqrt{\frac{gL}{K^2}}$$

Using assumption 2, $K=L=33$ inches $= 2.75$ ft

$$\text{and } \omega_n = \sqrt{\frac{g}{L}} = 3.42 \text{ rad/sec.} = .54 \text{ Hz}$$

Calculation of Moment due to vortex-shedding, M.

Assume lowering speed of 3.83 ft/sec (70 m/min)

Flow around CTD instrument is laminar
with a shedding frequency of 1.3 Hz $= 8.2$ rad/sec

Using a lift coefficient of 0.5 the maximum lift (side force) per unit length is found using

$$L_m = \frac{1}{2} \rho C_L V^2 d$$

$$= 4.3 \text{ lb/ft for the CTD instrument.}$$

The overall magnitude of this force is

$$L_T = 4.3 (85/12) = 8.9 \text{ lbs}$$

The moment about the top connection is therefore

$$M = 8.9 (49/12) \sin \omega_s t$$

or

$$M = 36.3 \sin 8.2 t$$

The equation of motion becomes

$$I \ddot{\theta} + mgL\theta = 36.3 \sin 8.2 t$$

Prior to solving this equation we note that the driving frequency of 8.2 rad/sec is more than twice as large as the natural frequency of 3.4 rad/sec. For a SDOF system with $\omega/\omega_n > 2$ we are in the mass-controlled region and to a first approximation the stiffness term can be neglected. Therefore, we are left with

$$I \ddot{\theta} = 36.3 \sin 8.2 t$$

with

$$I = m k^2 = \frac{455}{32.2} (2.75)^2 = 107 \text{ slug-ft}^2$$

we have

$$\ddot{\theta} = .34 \sin 8.2 t$$

solving this for θ yields

$$\theta = \frac{.34 \sin(8.2)t}{(8.2)^2} + C_1 t + C_2$$

$$\theta = .005 \text{ rad} = .29 \text{ degrees}$$

The possibility of significant vortex-shedding thus seems minimal.

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