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UNIVERSITY SEALAB

Model Tests for a Saturation Diving Facility for the National Oceanographic Community

Engineering Design and
Analysis Laboratory
University of New Hampshire

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March, 1969
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Engineering Design and Analysis Laboratory
University of New Hampshire
Durham, New Hampshire

UNIVERSITY SEALAB.

Model Tests for a Saturation Diving Facility for the National Oceanographic Community.

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UNIVERSITY SEALAB - MODEL TESTS

ABSTRACT

Model test programs to investigate certain dynamic performance characteristics of two saturation diving systems are described.

SEADOPOD employs a support barge which services a diving capsule or pod capable of delivering a four-man, diver-scientist team to and from depths of 300 feet. The pod elevator mechanism consists of a main winch and support cable, two constant-tension guy lines, and a trans-loader control which acts to decouple barge heave motion from the pod in order to maintain a more stable platform for the diver-scientists.

OSCILAB is a habitat-laboratory vehicle permitting four diver-scientists and two diver-crew members to live and work at depths of 300 feet for a period of two weeks under saturation diving conditions. The laboratory is capable of lowering and raising itself but relies on surface support for normal power, monitoring, and surface mobility.

ACKNOWLEDGMENTS

The work on this project was under the faculty supervision of Professor E. Eugene Allmendinger of the Department of Mechanical Engineering and Professor Fletcher A. Blanchard of the Department of Electrical Engineering. Major responsibilities were shared by Mr. Richard W. Curless, graduate student in Mechanical Engineering, Lt. John E. Howard, graduate student in Electrical Engineering, and Mr. Lloyd G. Nichols, Engineering Design and Analysis Laboratory staff engineer. Valuable assistance was provided to the program effort by Mr. Robert A. Blake, Engineering Design and Analysis Laboratory technician, Mr. Richard Griffin, student in Mechanical Engineering, and Mr. Frederick R. Hess, student in Geology.

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PART I - INTRODUCTION TO MODEL TEST PROGRAMS

University Sealab - A Saturation Diving Facility for the National Oceanographic Community,[1] a report submitted to the Office of Naval Research, by the University of New Hampshire's Engineering Design and Analysis Laboratory, describes complete conceptual designs for two proposed diving systems, which have been called OSCILAB and SEADOPOD. Based on recommendations in the above report and under contract to the Office of Naval Research, model test programs have been conducted for OSCILAB and SEADOPOD in order to obtain additional data to predict the performance of the prototype systems.

The model program for the SEADOPOD diving system is described in PART II of this report. The SEADOPOD concept and major components for the prototype and model systems are discussed. A summary of tests conducted at the Naval Ship Research and Development Center, analysis of the data obtained, and recommendations for SEADOPOD based on the model program are presented.

PART III of this report describes the model test program conducted for OSCILAB. The design concept, major system components, and operating phases of the diving system are reviewed. Recommendations are presented for OSCILAB based on analyses of data obtained from a series of tests conducted at the Naval Ship Research and Development Center.

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[1] UNIVERSITY SEALAB, Design and Analysis of a Saturation Diving Facility for the National Oceanographic Community, Engineering Design and Analysis Laboratory, University of New Hampshire, Report No. 100, January 1967.

PART II - SEADOPOD SYSTEM MODEL TESTS

A. BACKGROUND

The primary SEADOPOD modeling requirements were to obtain performance data for the mooring system and the elevator control system. As shown in Figure 1, SEADOPOD consists of a surface-support barge maintained over the diving site on a conventional 4-point moor. Operating through a center well in the barge is a submersible pod or elevator which is lowered to the desired depth by means of a support cable and winch. Guy lines, anchored to the bottom, reduce lateral motion and prevent twisting as the pod is raised and lowered. Analysis of the barge and pod acting as a coupled-mass system[1] has shown that the pod is closely coupled to the barge and will react to the barge heave motion with nearly unity amplitude response as long as the excitation does not approach the natural frequency of the barge-cable-pod system.

Requirements for SEADOPOD include operation in maximum water depth of 300 feet and in seas to State 5, characterized by average wave height of 8 feet and period T_{avg} of 8-seconds.[2] Divers, maintained at saturation pressure in the deck habitat, transfer to the pod and are then delivered to the working depth in the pod elevator. Once pressure in the pod has been equalized to the surrounding water pressure, the divers may pass freely between the pod and the diving site to conduct their research activities. For reasonable diver comfort and integrity of operational research equipment in the pod, some means is required for decoupling the pod from severe motion of the barge.

The SEADOPOD system employs a closed-loop elevator control as shown in Figure 2. A sense cable, anchored to the bottom, detects barge heave motion and controls a cable length adjusting device which takes up or pays out cable to maintain a relatively constant pod position above the

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[1] op. cit. pp. 234-249

[2] W. Marks, Sea State Chart, Geo-Marine Technology, Vol. 1, No. 1 November 1965, p. 2

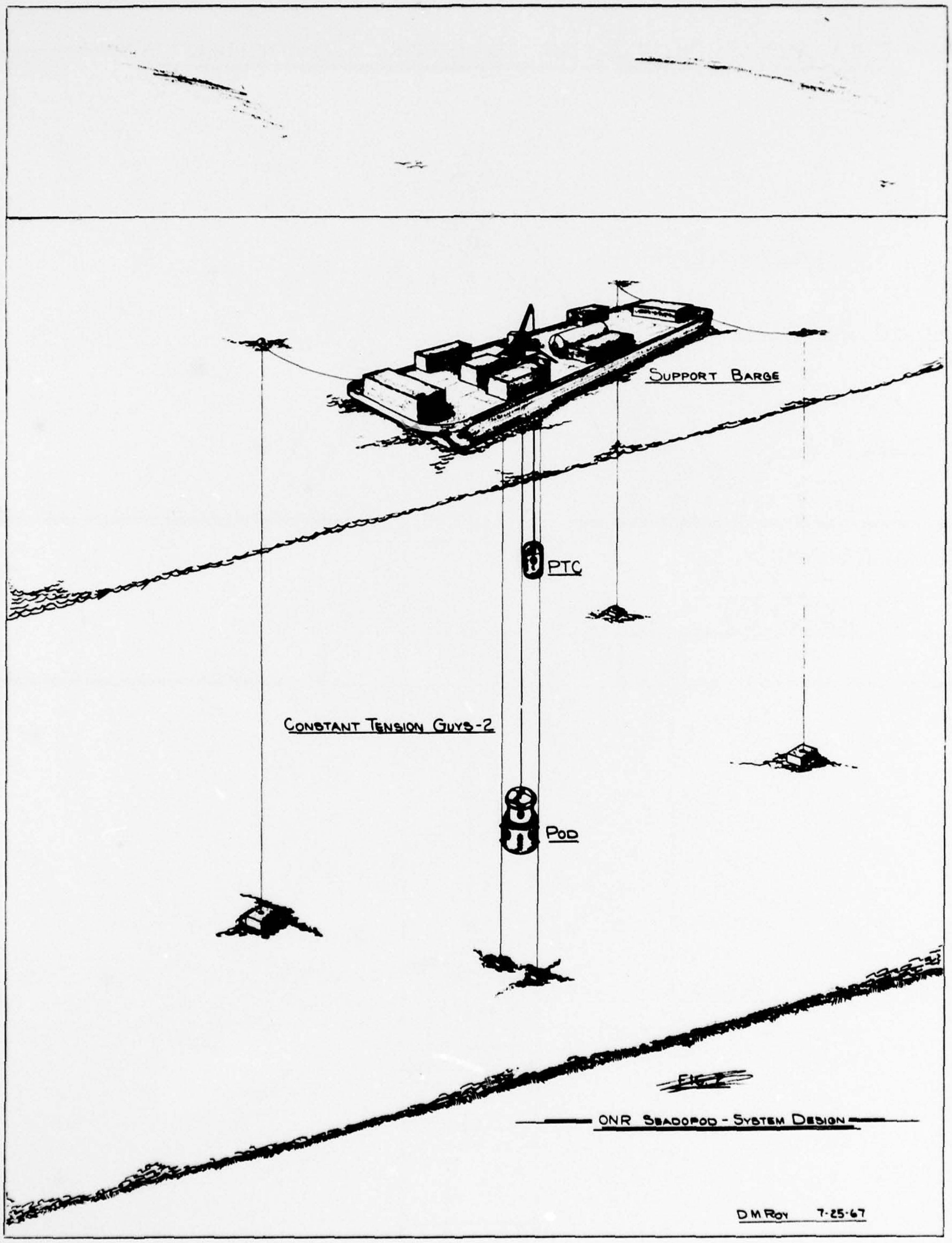

Figure 1

ONR SEADOPOD - SYSTEM DESIGN

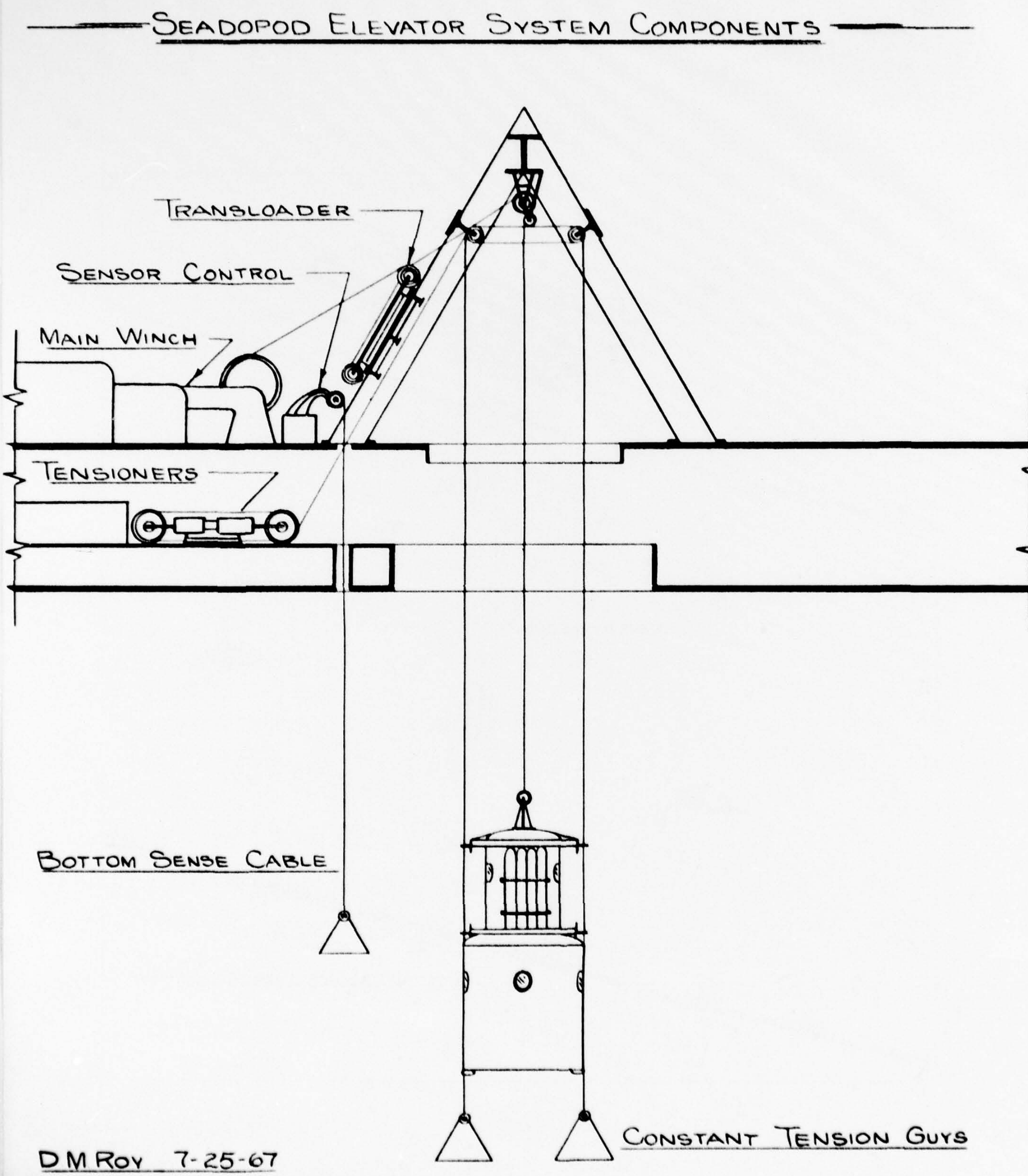

Figure 2 SEADOPOD ELEVATOR SYSTEM COMPONENTS

bottom. This control device is called a Transloader and consists of a set of fixed sheaves and a set of movable sheaves controlled by an electro-hydraulic actuator. The sensing device and actuator constitute a feedback system and are combined so that a tendency for the barge to rise on a wave crest produces a retraction of the transloader and a consequent lenghtening of the cable in order to hold the pod at nearly the same distance above the bottom. As the barge dips into a wave trough, the transloader is extended, thus taking up cable.

The 4-point moor is designed to maintain the barge over the research site under anticipated wind, wave, and current loading conditions. Typical requirements based on off-shore oil-drilling installations call for less than 10-feet horizontal displacement for each 100 feet of water depth.

B. Model Test Program - Summary

A scale model SEADOPOD system consisting of a support barge, pod, elevator-control, and 4-point moor was designed and constructed.

The pod elevator control as specified for SEADOPOD is based on the Rucker Transloader and wave cancellation system which has been operating in the Gulf of Mexico on an off-shore platform for several years. Limited data on the prototype transloader was available at the time of model design and prevented a more accurate simulation of such specifications as gain factor and time constants.

The moor design was based on specification for maximum static wind and current loading and allowable displacement of the support barge.

SEADOPOD model testing was conducted at the Naval Ship Research and Development Center, Maneuvering and Sea-Keeping Facility (MASK), Carderock, Maryland, during the period September 5 through 12, 1967. Performance data were obtained in the form of strip-chart recordings of system parameters and filmed record of the dynamic response of SEADOPOD to random waves with variable Sea State. Data were also obtained for simulated static wind and current loading to verify the moor system design.

This portion of the report UNIVERSITY SEALAB - MODEL TESTS, describes SEADOPOD model design and construction, testing procedures and data obtained, analysis of model test results, and recommendations for the proposed SEALAB system resulting from the modeling program.

C. SEADOPOD PROTOTYPE SYSTEM COMPONENTS

1. Barge

Recommendations for the surface-support barge made in University Sealab Report #100 called originally for a Navy YC barge with overall deck dimensions 34' x 110'. However, as noted in the report, the diving system requirements dictate a somewhat larger deck space and a barge approximately 50' x 120' was proposed as being adequate to house all the diving system components.

In order to establish acceptable dimensions for the barge, based on handling characteristics and sea-keeping behavior (and with the approval of the contract agency), a survey of typical coastwise-duty deck barges was made. The SEADOPOD proposal and cost analysis[1] called for conversion of an existing vessel for this application rather than construction of a specialized hull. Modification of a basic barge hull design then was in order.

Sources of information on coastwise-duty barges included:

a. Correspondence with several construction firms, notably Equitable Equipment Company, New Orleans, Louisiana
b. Barges in Ocean Service by J. L. Foley[2]
c. ABS Rules for Building and Classing Steel Vessels, 1967[3]
d. A summary of non-propelled craft constructed in the United States during 1966 prepared by the Marine Engineering/Log[4]

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[1] University SEALAB Cost Analysis, EDAL UNH Report #101, December 1967.

[2] J. L. Foley, Barges in Ocean Service, Society of Naval Architects and Marine Engineers, Spring Meeting, Seattle, Washington, May 1965.

[3] American Bureau of Shipping, Rules for Building and Classing Steel Vessels, 1967.

[4] Marine Engineering/Log, Yearbook Issue, June 15, 1967, pp. 130-134.

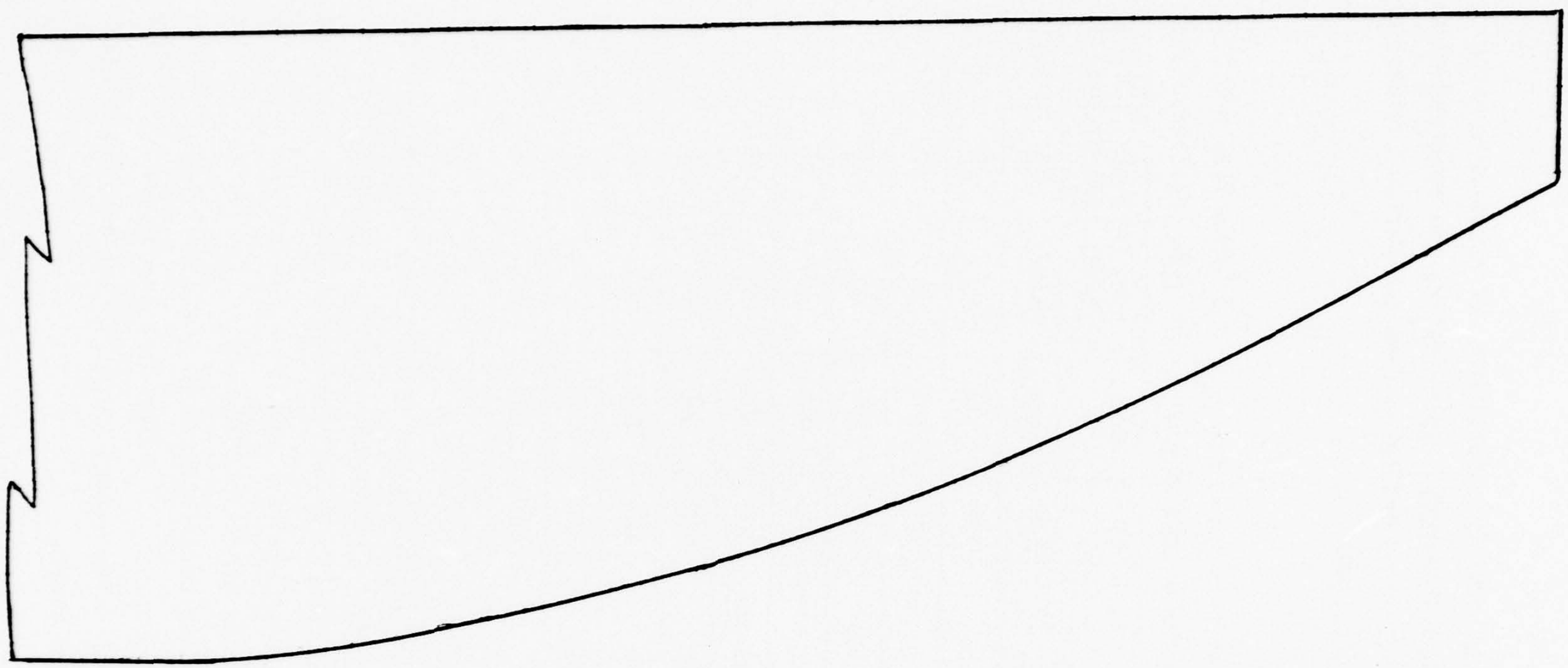
These sources proved helpful in establishing an acceptable barge design. Specification for ten deck-barges, approximating the required dimensions of the SEADOPOD support barge and taken from the Marine Engineering/Log Summary are presented in Table 1.

Table 1

Non-Propelled Craft (Barges, etc.) of 400 Gross Tons and Over Constructed in the United States During 1966 (Partial List)

Builder	GT	DWT	Length ft.-in.	Beam ft.-in.	Depth ft.-in.	Type
American Marine Corp.	400	800	140	38	8-5	Cargo
Conrad Industries	400	800	140	40	8-6	Cargo
Dravo Corporation	795	1400	160	40	12-6	Deck Cargo
Equitable Equipment Co.	400	800	140	36	8	Deck Cargo
Gulfport Shipbuilding Corp.	400	800	140	35	8-9	Cargo
Hillman Barge & Const. Co.	403	800	140	39	9	Deck Cargo
Intercoastal Shipyard	419	800	140	40	8-9	Cargo
Maxon Construction Co.	400	800	140	38	8-9	Deck Cargo
Tidewater Construction Co.	400	800	120	40	9	Cargo
Todd Shipyards	501	1000	150	39	9-6	Deck Cargo

A final prototype design was established for a rake-ended barge measuring 140' x 40' x 9' (length-beam-depth). Barge profile shown in Figure 3 was derived from Foley and Equitable Equipment Design No. 1471. Deck space requirements were reviewed and totaled 2566 square feet which is less than 50% of the approximately 5600 square feet of available deck space and was judged to be an acceptable space utilization factor. Figure 4 shows the proposed support barge deck layout for a 140' x 40' barge. The prototype barge loaded weight is set at approximately 600 LT which yields a 5-foot draft.



Scale: 0.4" = 1' - 0"

Barge Dimensions: 56" x 16" x 3.6"

Figure 3 MODEL BARGE BOW PROFILE

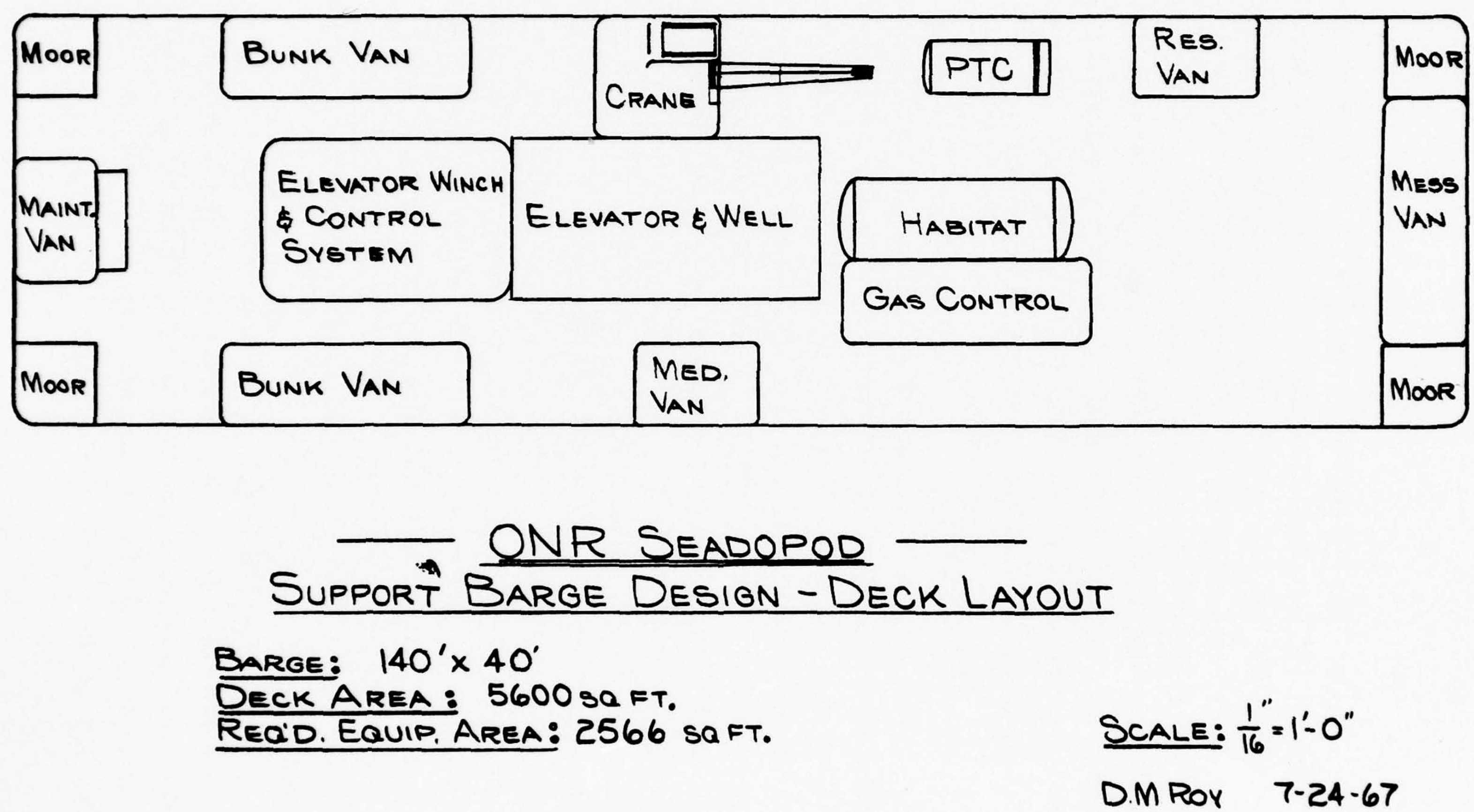


Figure 4 SUPPORT BARGE DECK LAYOUT

2. Pod

The final pod design as specified for University Sealab is a two-level 16' LOA chamber as shown in Figure 5. The lower section which serves as an exit-entry area, wet room, and diving equipment storage area, has an internal diameter of 9 feet and a 42" diameter entrance hatch. The upper section serves as a compact laboratory and work area and has a 7 1/2' internal diameter. The pod has a displacement of 60,000 lbs., and a dry weight of 48,000 lbs. The center of gravity is estimated to be approximately 6.27 feet from the bottom and the center of buoyancy is approximately 7.74 feet from the bottom of the pod.

3. Mooring System

As already described, the prototype diving system is designed to operate to a depth of 300 feet. Setting a maximum scope for anchoring of 10:1 and allowing for 45^{o} angles between anchoring cables and barge fore and aft and beam axes, the mooring system requires an area approximately 4000' x 4000'. Although sufficient data might be obtained by modeling the system under maximum depth conditions, it was judged advisable to run tests at intermediate depths as well, to verify the mooring system performance and the elevator control operation under these conditions. This would require some type of adjustable supports for the pod anchors and mooring anchors. In addition, platforms in the horizontal plane running beneath the anchor lines for a sufficient length are necessary for a proper simulation of "bottom conditions" particularly during static loading simulation producing slack in the two unloaded mooring cables. Support for the cables is required to assure that the cables assume their proper shape under both dynamic and static loading conditions.

Despite the fact that chain was determined to be preferable to cable for the mooring line members, it was judged more feasible to model these portions of the system using miniature wire rope. The required length of line was consequently larger and resulted in a considerably larger overall model system.

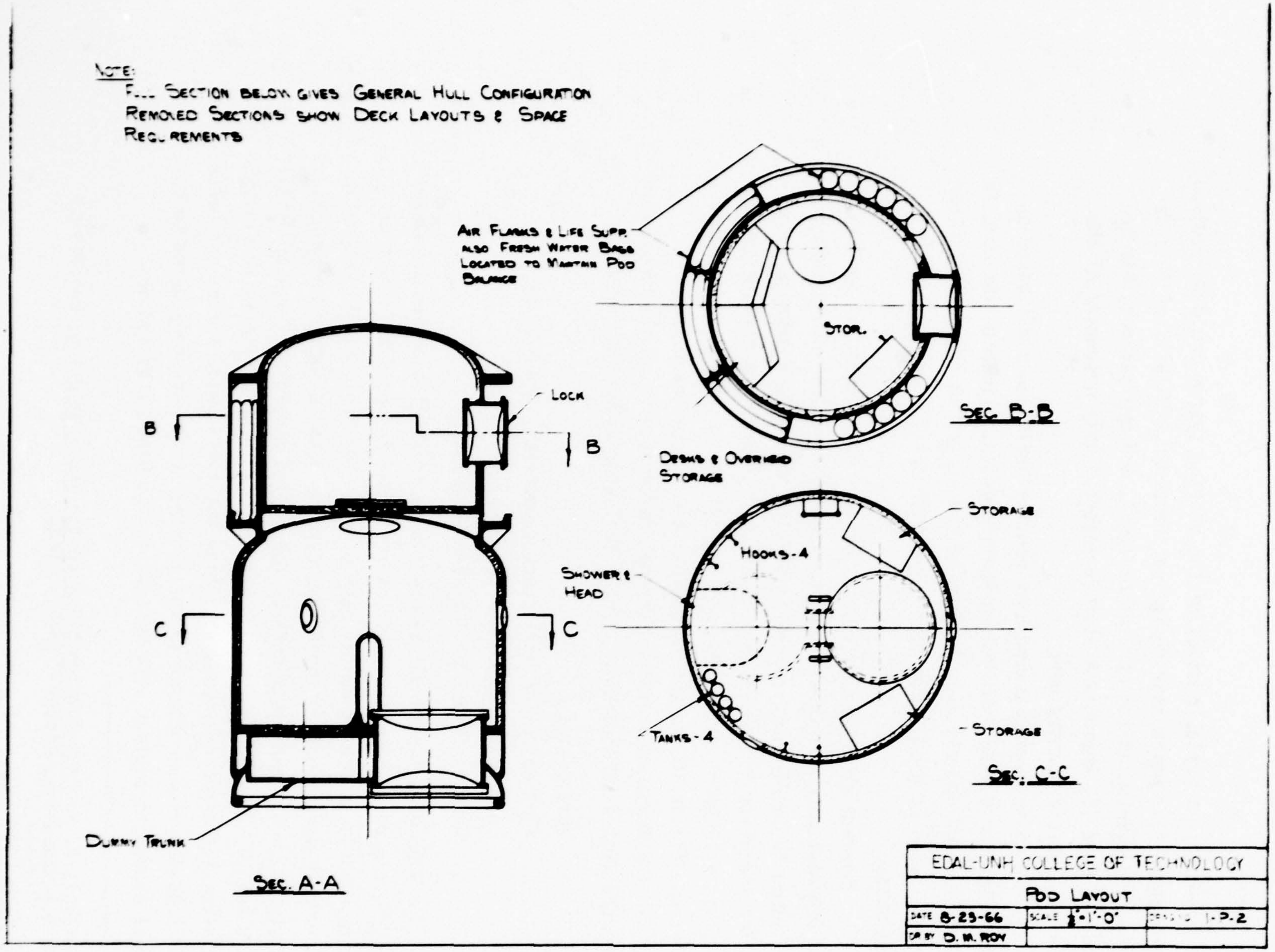


Figure 5 POD LAYOUT

Before a suitable model of the mooring system could be devised, a prototype four-point moor design was required. Details of this design are presented in the work of Curless[1], and typical data may be found in Part II, Appendix A of this report. Only a summary of the moor design is presented here.

It is to be emphasized that mooring performance was based on static loading due to wind and current; however, allowance was made in the design for dynamic wave loading of the barge. A "worst-case" loading was taken as wind, wave, and current forces all acting together from abeam.

Maximum allowable horizontal barge displacement for Sea State 5 and 300-feet water depth was set at a ten-foot radius. Wind velocity was taken to be 24 knots, corresponding to the highest average velocity for Sea State 5.[2] A one-knot current, uniform from surface to bottom, was assumed to act on the mooring cables, which in the unloaded position, lie at 45^{0} to the barge fore-and-aft and beam axes.

The magnitudes of the external forces acting on the barge were computed from a consideration of the following component forces:

a. Wave forces
b. Wind forces on hull, deck components, and A-frame
c. Current forces on the barge hull
d. Current forces on the anchor cables

When wave length of the ocean wave is small compared to vessel length, the waves simultaneously exert forces in opposite directions which tend to reduce or cancel each other. For Sea State 5, the ratio of average wave length to prototype barge length is 99/140 or approximately 0.7. Although this must be considered a marginal case of "small" wave length, the four-point moor was assumed to be sufficiently flexible to allow the anchored vessel to follow the cyclic wave forces and hence the transfer of wave energy to the mooring system was considered to be small enough to neglect with respect to the other load factors.

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[1] Curless, R. W. Four-Point Mooring Design and Simulation, University of New Hampshire, Master's Thesis, 1968.

[2] W. Marks, op. cit.

Wind and current forces were calculated using appropriate drag coefficients and projected areas. Cable current forces were based on using a full scale, one-inch diameter 6 x 24 galvanized mooring cable having a drag coefficient, C_D = 1.20, and a submerged weight per foot of 1.03 pounds.

The magnitude of the resultant external forces acting on the barge and mooring components was used to design a moor which would exert a restoring force equal to this resultant external force at the point of maximum allowable displacement. An iterative solution making use of computer generated catenary characteristics produced final moor geometries consistent with predicted barge motions at maximum loading as shown in the summary of Table 2, Prototype Moor Specifications.

TABLE 2 Prototype Moor Specifications

Water Depth	300 ft.	150 ft.
Cable length (1)	2438 ft.	1402 ft.
Mooring rectangle (1)	3446 x 3545 ft.	2004 x 2104 ft.
Total drag, beam seas, wind, current	6984.44 lbs.	4896.90 lbs.
Barge motion, beam	± 7 ft.	± 3.3 ft.
Total drag, head seas, wind, current	(2)	1687.31 lbs.
Barge motion, fore and aft	(2)	± 1.20 ft.

(1) Mooring rectangle dimensions include barge dimensions - 40' x 140'. All lengths rounded to nearest foot.

(2) Static moor simulation was conducted for 150 ft. depth only. No calculations were made for total drag and barge motion for 300 ft. depth and bow loading.

4. Winch, Elevator, and Tensioner Controls

The proposed elevator control system design specifies a Rucker electro-hydraulic Transloader to act as an effective "wave cancellation" device. Size, weight, and power supply considerations suggested that an electro-mechanical equivalent be investigated for this component. Similarly, the diesel-electric draw-works as proposed for the main winch system would likely be simulated with a geared electric motor driving an appropriately sized drum and coupled to the pod via the model Transloader and a suitable set of sheaves.

The Rucker Transloader includes a spring-loaded servo valve which acts as the sensor for the relative motion between the barge and the ocean floor. Figure 6, Transloader and Sensor Control, shows the bottom sense cable reeved over two auxiliary sets of sheaves, one fixed, the other movable, with the latter set coupled to the actuating mechanism of the servo valve. Slack cable is taken up on the sense drum. Relative barge-to-bottom motion causes the servo valve to be operated in such a way as to control flow of hydraulic fluid in the cylinder of the transloader to extend or retract so as to adjust the effective length of the support cable for the pod. Proper phasing of this corrective action provides an automatic adjustment of cable length and a corresponding nearly constant position of the pod above the bottom. Perfect compensation is not possible since some small error is required as an input for the control system. High gain in the control loop consistent with adequate stability is required for small errors.

Tensioners proposed for the pod guy lines were similar to Rucker pneumatic-hydraulic units and again suggested that alternate devices be used in the modeling.

D. SEADOPOD MODEL - SCALE FACTOR CONSIDERATIONS AND MODEL COMPONENTS.

1. General Considerations.

On the basis of the overall physical dimensions of the prototype diving system, it appeared that a major factor in selecting a suitable linear scale factor would be the dimensions of the available

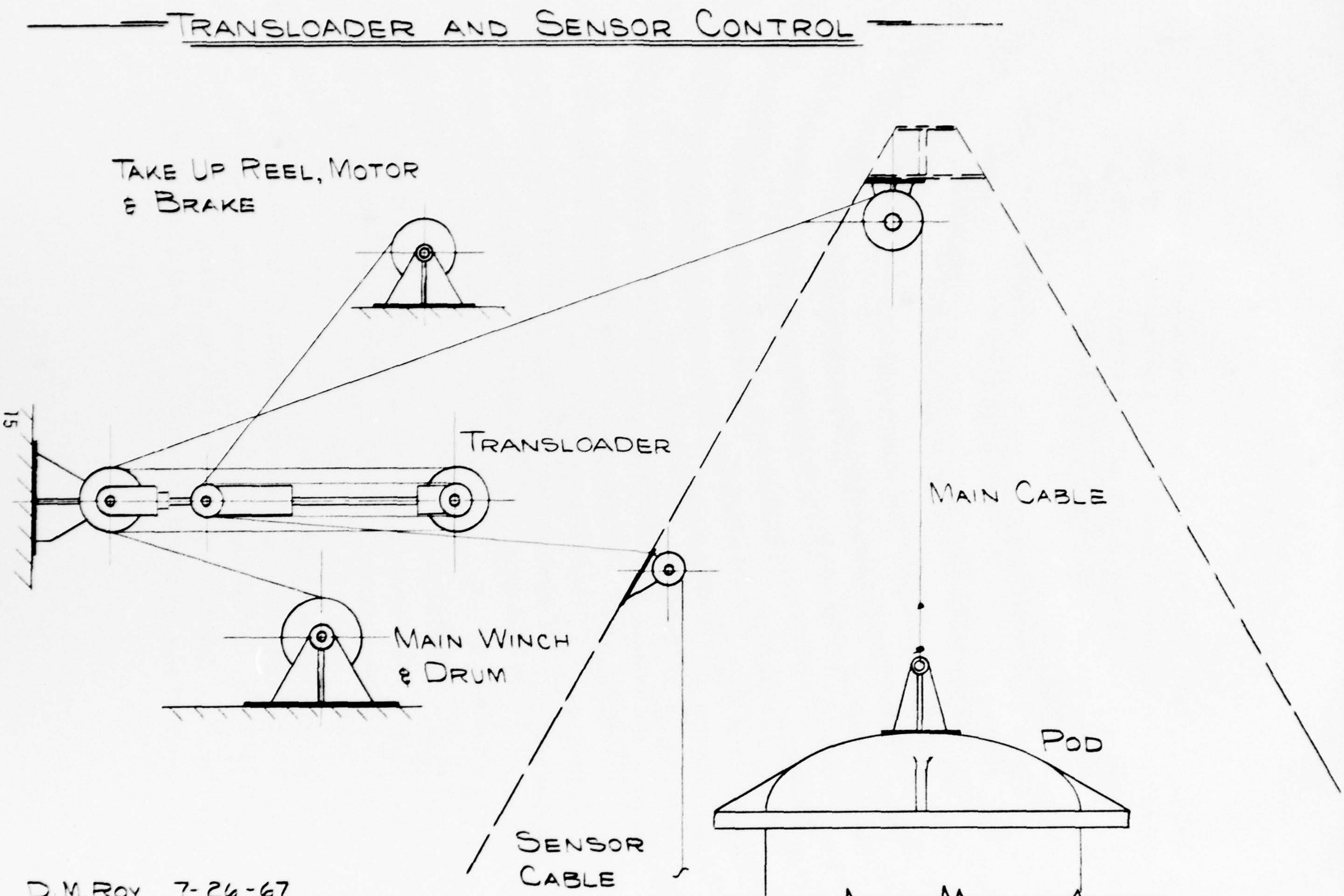


Figure 6 TRANSLOADER AND SENSOR CONTROL

test tank or basin. The Maneuvering and Seakeeping Basin (MASK) at the Naval Ship Research and Development Center, measures 360' x 240' and has a water depth of 20 feet in the main part of the basin (190' x 360'). A 50-foot wide "trench" with a depth of 35' runs the length of the basin (50' x 360').

Based on an overall prototype system area of 4000' x 4000', with a maximum anchor scope of 10:1, and assuming that it would be desirable to stay well within the 20-foot depth section of the MASK, a linear scale factor of $\lambda = 30$ was selected. In terms of model size, this yields a $\frac{140}{30}$ = 4 2/3' = 4'8" barge and would be entirely satisfactory from the standpoint of handling and portability. Having selected a linear scale factor, time becomes scaled by $\sqrt{\lambda} = \sqrt{30} = 5.48$, or 1 second of model time is equivalent to 5.48 seconds of prototype time.

Modeling water depth, however, with $\lambda = 30$, calls for maximum model depth of $\frac{300}{30}$ = 10 feet. It might be noted that a $\lambda = 15$ would allow using the 20-foot MASK water depth as the maximum model depth; however, the basin dimensions would be insufficient to model the barge mooring system unless a very restricted scope were used or unless a model chain anchor system were used. Having established the linear scale factor as $\lambda = 30$, some means for supporting the mooring and pod guy line anchors in mid-water is then required. If tests at intermediate operating depths are to be conducted, these anchor supports must also be adjustable.

2. Model Component Designs

Other portions of the system were judged to be compatible with a choice of $\lambda = 30$; therefore, the model component designs were undertaken.

a. Surface-support Barge

The 140' x 40' x 9' steel deck cargo barge was reduced to a 56" x 16" x 3.6" laminated mahogany model and was fabricated by Ocean Industries, Inc., Kennebunk, Maine. Deck vans were made of hollow mahogany blocks to give the general appearance of the working system and to maintain a more realistic c.g. The Model Barge Bow Profile shown to scale in Figure 3 was derived from Foley and Equitable Equipment as noted (Sect. C.1.). A raised head log of approximately 12 inches for the prototype was provided for towing. The hull had a slight deadrise (6 inches for the prototype) and a smooth bottom. The prototype barge, however, would most likely have a pair of keels on either side of the center well to improve its towing characteristics. The hull was partially hollow to reduce weight and to accommodate ballasting and trimming weights once all the model components had been installed. A final balanced model weight of 48.3 lbs. corresponded to a prototype system weight of 583 LT.

b. <u>Mooring System</u>

As described previously, a choice of miniature wire rope was made for the mooring lines primarily due to lack of sufficiently accurate scaled chain for the mooring system. Increased scope and hence rather long anchor lines were then dictated.

Bergen Wire, 1/32 inch diameter, 3 x 7 stainless steel wire rope served for anchor lines. Small electrical binding posts fastened to the four corner "mooring stations" of the barge were used to clamp the lines at the lengths determined in the mooring calculations.

The dimensions of the model moor and corresponding cable lengths are given in Table 3.

Prototype Water Depth	Model Water Depth	Model Moor Rectangle	Cable Length
300 ft.	10 ft.	108.51 x 105.18 ft.	74.42 ft.
150 ft.	5 ft.	71.63 x 68.30 ft.	47.79 ft.

Table 3 Model Moor Specifications

Selection of the scaled mooring cable was made on the basis of size and weight per unit length. As the cable lengths were great, cables were considered sufficiently flexible so that bending moment similarity was not of prime importance as long as the model cable was flexible also. Likewise, axial elongation was not taken into account in the model since the forces acting on the system were in the order of a few pounds which was not enough to perceptibly stretch the model cable. Strict geometric scaling of the mooring cable diameter was unnecessary since the Reynolds number in the model and prototype could not be made equal due to the use of water as the fluid in both systems. Therefore, the model cable was selected so that its submerged weight per unit length simulated the submerged weight per unit length of the prototype which for a 6 x 24, one-inch diameter cable, was taken as 1.03 lbs./ft. Using a linear scale factor of 30, 1000 feet of submerged model cable should weight $\frac{1000(1.03)}{(30)(30)} = 1.14$ lbs. This required weight is fulfilled very nearly by a standard 1/32 inch diameter aircraft cable which was calculated to have a submerged weight of 1.18 lbs. per thousand feet.

As noted previously, a system of platforms or "false bottoms" were required to allow the mooring cable to lie more or less "on the bottom" as the barge moved under the applied loading forces. These structures were fabricated by model basin personnel and consisted of a long, narrow platform made with a metal frame and covered with wire mesh, an adjustable support column, and a supporting base. The base could be located over a positioning pin set on the bottom of the basin according to the mooring rectangle geometry. Final angle adjustment of the platform position was required to position the platform below the mooring cable. The structures were more than adequate to support the mooring lines under the anticipated loading which was in the order of a few pounds. Each cable was attached at one end of the platform and allowed to extend along the platform for some distance before rising toward the barge. With load applied to the barge, more or less cable lay on the false bottom, thus simulating the actual conditions of the moor. A sketch of the model moor and "false bottom" structures is shown in Figure 7, Model Moor Arrangement.

c. Pod

The model pod was constructed of build-up mohagany sections and formed into a two-level cylindrical structure. The pod was then hollowed to reduce weight and to allow for weight and c.g. adjustment. This was accomplished by positioning a number of lead "washers" on a threaded brass shaft which passed through the axis of the pod. A threaded cap nut attached to the rod was provided with a swivel connector for attaching the model support cable.

d. Elevator Control System

The SEADOPOD Elevator Control System Schematic is shown in Figure 8. The following is a brief description of the function of the components as they are shown from left to right: the d-c Winch Motor is coupled to the Winch Drum on which the pod support cable is wound. The model cable is 3/64" d. 7 x 7 stainless steel wire rope. Also, mechanically connected to the shaft of the Winch Drum through a suitable gear ratio, is a depth indicating precision potentiometer which, assuming negligible slack or stretching of the support cable, provides a voltage output proportional to barge-to-pod distance or quiescent depth of the pod below the barge. Cable is reeved over the transloader sheaves - a set of three fixed sheaves at the left and two movable sheaves at the right, over a sheave at the peak of the supporting A-frame and is attached to the pod. The movable sheave set is driven by the Transloader Motor through a linear actuator device and is

Note: Length of cable lies on bottom.

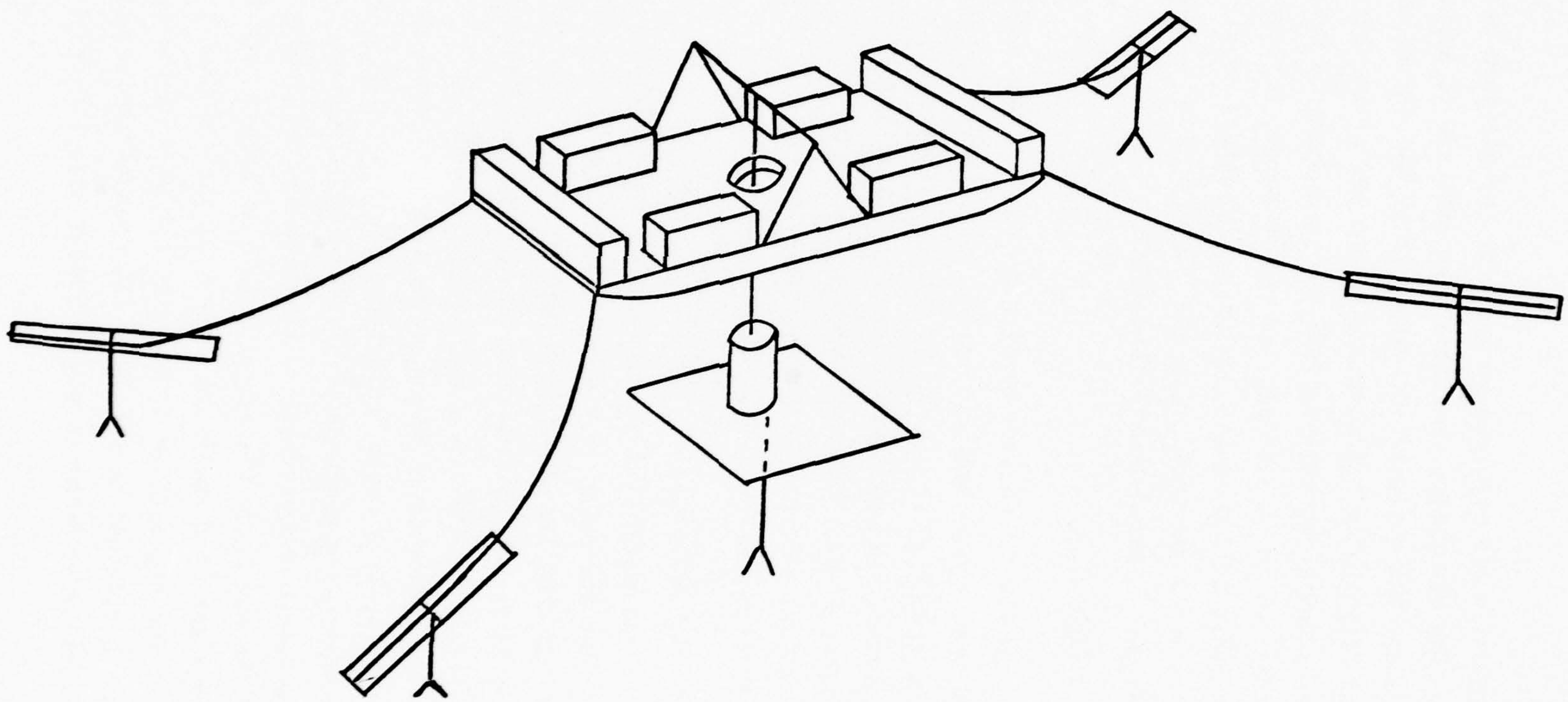


Figure 7 FOUR POINT MOOR

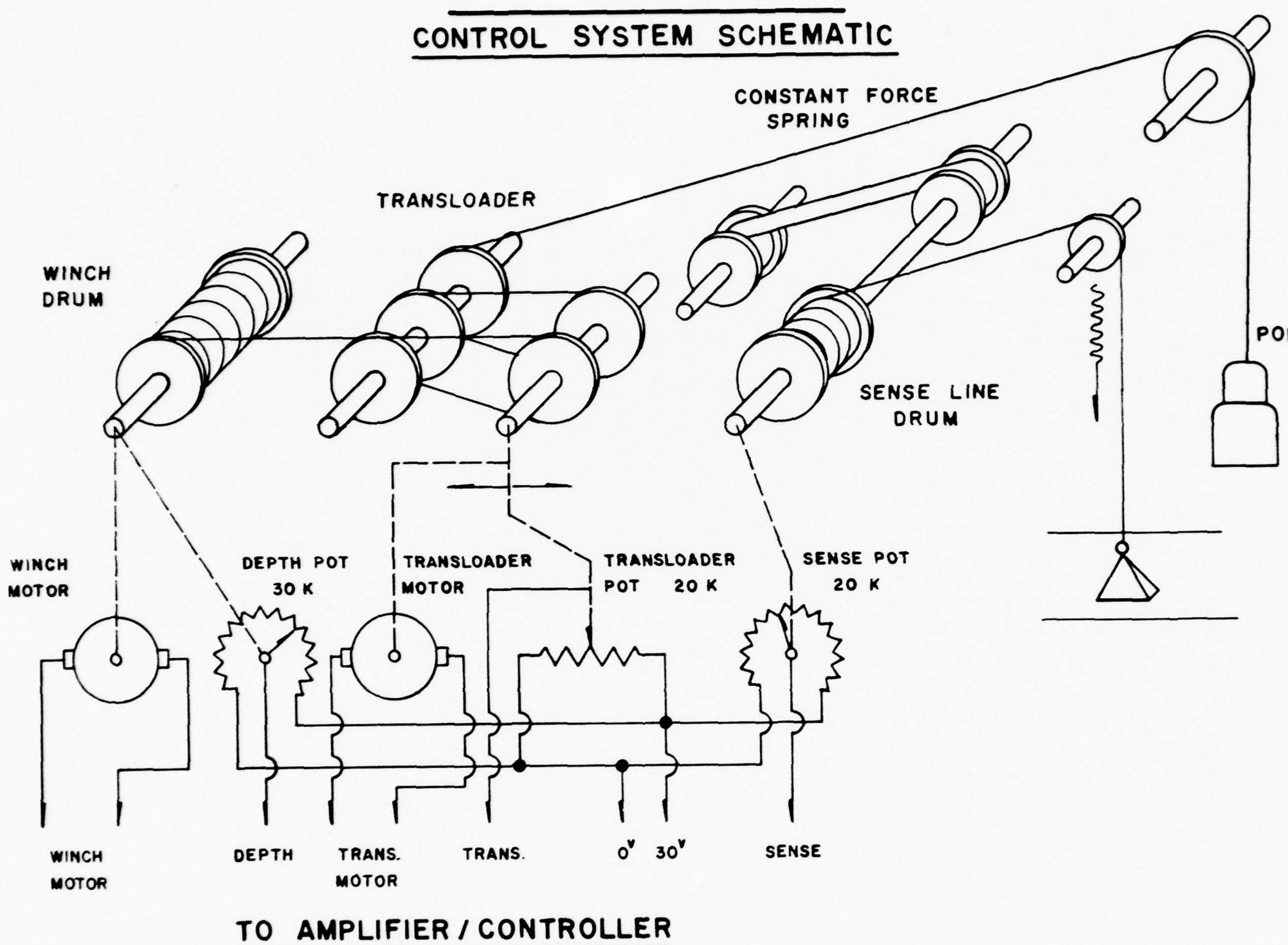


Figure 8 CONTROL SYSTEM SCHEMATIC

also mechanically coupled to a precision linear motion potentiometer. Again, assuming negligible cable stretch and slack, the output signal of the Transloader Potentiometer is proportional to the pod position. A Constant Force Spring maintains tension on the Sense Line Drum which is mechanically coupled to the precision rotary Sense Potentiometer. The sense cable, .0075" d. stainless steel wire rope, comes off its drum, over a sheave located on the A-frame and down to an anchoring point which is actually on the pod guy line anchor (not shown in the diagram). Electrical output ot the Sense Potentiometer can be seen to be proportional to the barge-to-bottom distance. Constant tension for the pod guy lines is provided by two drum tensioners similar to the sense line system but designed to operate with a scaled 6000 pounds of tension in each guy line. The lower ends of the guys are attached to the "pod anchor" which rest on the bottom directly below the barge center well. The guys are .018" d. stainless steel wire rope. Sheaves were modeled with appropriately sized gear blanks which were grooved to accept the miniature wire rope. Sheave diameters were selected primarily on the basis of recommended specifications for minimum bending radii to limit bending fatigue in marine service.

All components of the model control system are conventional electro-mechanical devices with the possible exception of the linear actuator which is used to simulate the hydraulic Transloader element of the prototype system. The actuator is required to produce a linear displacement of the movable set of sheaves in order to adjust the pod support cable length, thus compensating for barge heave motion. Since a d-c motor was selected as the power element, a conversion from rotary to linear motion is necessary. The Roh'lix linear actuator used in the model, manufactured by Barry Controls of Watertown, Massachusetts, might be described as a threadless lead screw. A stainless steel shaft is supported by two sets of three rollers, spaced on 120^{0} centers and attached to opposite sides of a spring-loaded split block through which the shaft passes. The rollers are inclined slightly to the axis of the shaft so that as the shaft is turned by the rotating motor, the rollers and hence the attached block advance. The effect of a small inclination of the rollers to the shaft axis is to produce a large effective "gear ratio". The unit selected has a lead drive of .015 which is interpreted as an advance of .015 inches for each revolution of the shaft. The Roh'lix unit has a built-in slip-clutch feature since when it is overpowered or driven against the mechanical stops, the shaft will slip in the rollers and prevent damage to the mechanism. Figure 9 is a photograph of the SEADOPOD Model Elevator Control.

From the description of components, it can be seen that Pod depth (barge at rest) is indicated by the Depth Potentiometer, pod motion (relative to bottom) is indicated by the Transloader Potentiometer, and barge motion (relative to bottom) is indicated by the Sense Potentiometer. These three voltages may be monitored to obtain a graphical record of the elevator control system performance. The measured motions are not true vertical displacements since they include horizontal motions of the pod relative to the barge and hence are resultant three dimensional displacements. Motion in the horizontal plane is limited by the restraining effects of the barge moor and the pod guy lines; however, this motion may be appreciable for certain Sea State conditions and pod operating depths.

All control and signal amplification functions are accomplished in the transistorized Amplifier/Controller which was designed for the model system. The schematic diagram of this unit is shown in Figure 10. Control functions consist of pod depth adjustment by means of the Winch Motor and selection of manual or automatic transloader operation. Automatic transloader operation is accomplished by feeding the error of the feedback control system (difference between Sense Potentiometer and Transloader Potentiometer signals) to the control amplifier, whose output then drives the Transloader Motor to correct the pod position. Manual adjustment of the transloader position is controlled by driving the Transloader motor from a separate source through a manually operated potentiometer.

Amplification and impedance matching is required to enable the low voltage error signal to be transformed to an appropriate voltage level with sufficient power capacity to drive the d-c Transloader

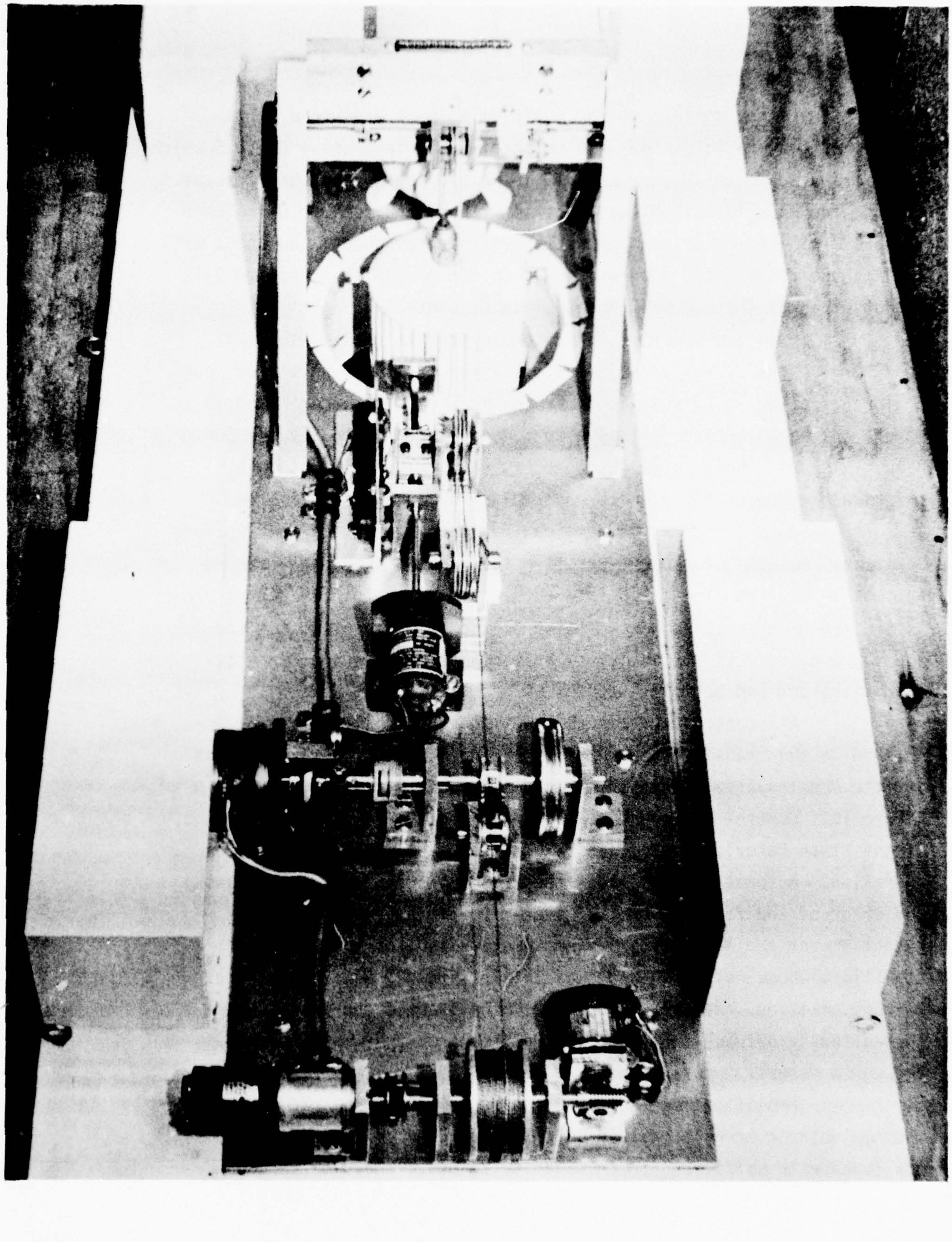
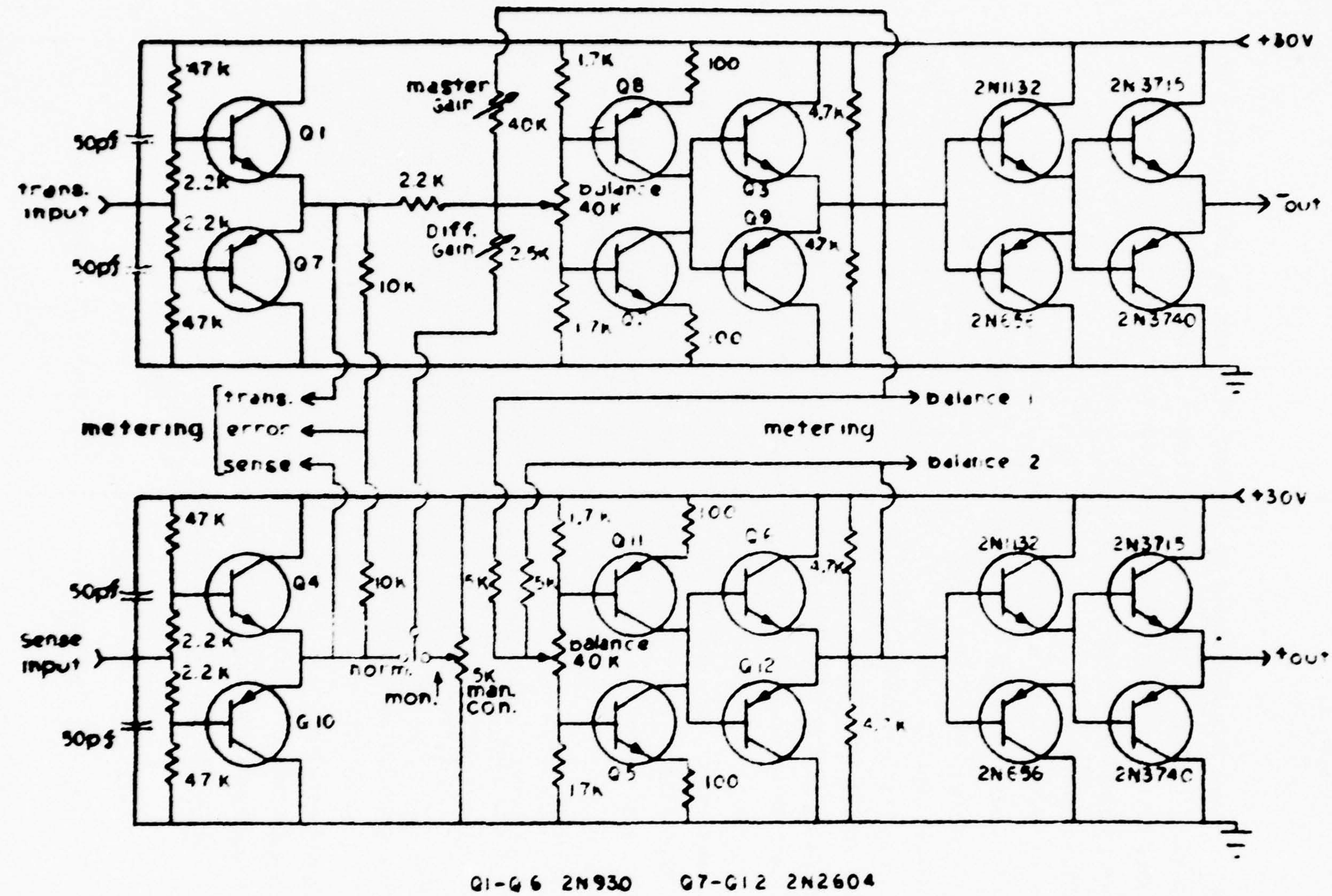


Figure 9 MODEL ELEVATOR CONTROL

SEADOPOD MODEL

SERVO AMPLIFIER CONTROLLER



Q1-Q6 2N930   Q7-Q12 2N2604

Figure 10 SERVO AMPLIFIER CONTROLLER

Motor. The input impedance of the amplifier must be sufficiently high to avoid loading of the input potentiometer source and the output impedance must correspondingly be low enough to drive the control motor. For simplicity, it was decided that the entire system be driven by a single power supply. In order to provide both positive and negative signal swings to drive the Transloader Motor to correct for positive and negative errors, as is required in a feedback controller, the amplifier operates in a balanced or symmetrical mode. Using a single 30-volt supply, a 15-volt "virtual" reference or neutral is established in each half of the amplifier. Operating about this virtual reference, the amplifier is basically two differential amplifiers with impedance matching at the input and output. The input stages are emitter followers which provide an input impedance of approximately 176 Kohms and hence only slight loading of the 20 Kohm Sense and Transloader Potentiometers occurs. The second amplifier stages consist of a push-pull common emitter amplifier followed by an emitter follower and provide the required voltage amplification. The third amplifier stages consist of two emitter followers in cascade and are designed for operation into the d-c motor load.

E. MODEL TEST CONDITIONS

The original proposal for SEADOPOD model testing was in some ways more ambitious and in other ways less ambitious than the tests that were actually performed in the MASK facility.

Test conditions underwent a series of modifications starting with the original proposal for the model program to the proposed testing schedule based on discussions with NSRDC personnel, and finally to the actual tests conducted within the limitations of time and budget.

Specifically, the following test procedures were originally proposed.

1. Original Test Proposal

a. All tests scheduled for 300' prototype water depth.

b. Series of tests for various pod depths.

c. Two sets of wave conditions - head seas and beam seas.

d. Tests were to be run 3 times for each condition to provide better average data.

e. Preliminary tests at MIT model basin were proposed.

f. Data collection only by moving picture record.

The results of planning with NSRDC personnel yielded the following proposed test plan.

2. NSRDC/UNH Test Plan

a. Tests to be conducted for prototype water depths of 50', 150', and 300'. Static moor load tests at 150' only.

b. Series of test for various pod depths and for pod raising and lowering.

c. Both head and beam seas to be generated.

d. Sufficient data time for each run to be adequately cover spectrum of wave characteristics at each condition. Duplication of conditions if time permitted.

e. No model tests priod to NSRDC.

f. Data collection with three synchronized moving picture cameras--two surface, one underwater. Strip chart data recording of pertinent system parameters.

Actual tests completed on the SEADOPOD model were as follows.

3. SEADOPOD Tests Conducted

a. Wave tests for prototype 150' and 300' depths. Static moor load test at 150'.

b. Pod tested at various depths, during raising and lowering, and for pod entry into water and retrieval of pod from water.

c. Head seas only.

d. Five-minute data runs for each condition. Some duplication of data with nearly constant generated wave conditions.

e. No preliminary wave tests before NSRDC. Ballasting and trim adjustments accomplished in small tank.

f. Data collection with two surface and one underwater cine cameras, not accurately synchronized. Six channels of strip chart data obtained.

F. MODEL TESTS - MANEUVERING AND SEA KEEPING BASIN (MASK) - NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

1. Rigging and Camera System

The SEADOPOD model test presented a unique problem for the MASK facility. The combination of a surface vehicle, a sub-surface vehicle, and a four-point moor provided a rather complex system which required the services of scuba divers, riggers operating from the carriage below the bridge which spans the basin, and personnel working from a small boat. Figure 11, SEADOPOD Model in MASK, is a photograph taken during testing in the model basin.

The first series of tests were conducted for the simulated 300-foot depth (10 feet of water in the MASK). Mooring cable supports and false bottoms, pod anchor support, and cable lengths were first adjusted then the barge and pod were positioned within the normal test area beneath the carriage. The bow camera was positioned in line with the model but slightly above the water surface to avoid contact with the waves. The beam camera was similarly located above the water and slightly ahead of the abeam position with respect to the model to allow the supporting and lowering pipe for the underwater camera housing to be positioned directly abeam of the submerged pod.

Camera speeds were to be 12 frames/second to provide a total running time of approximately 5 minutes with a 100-foot film load.

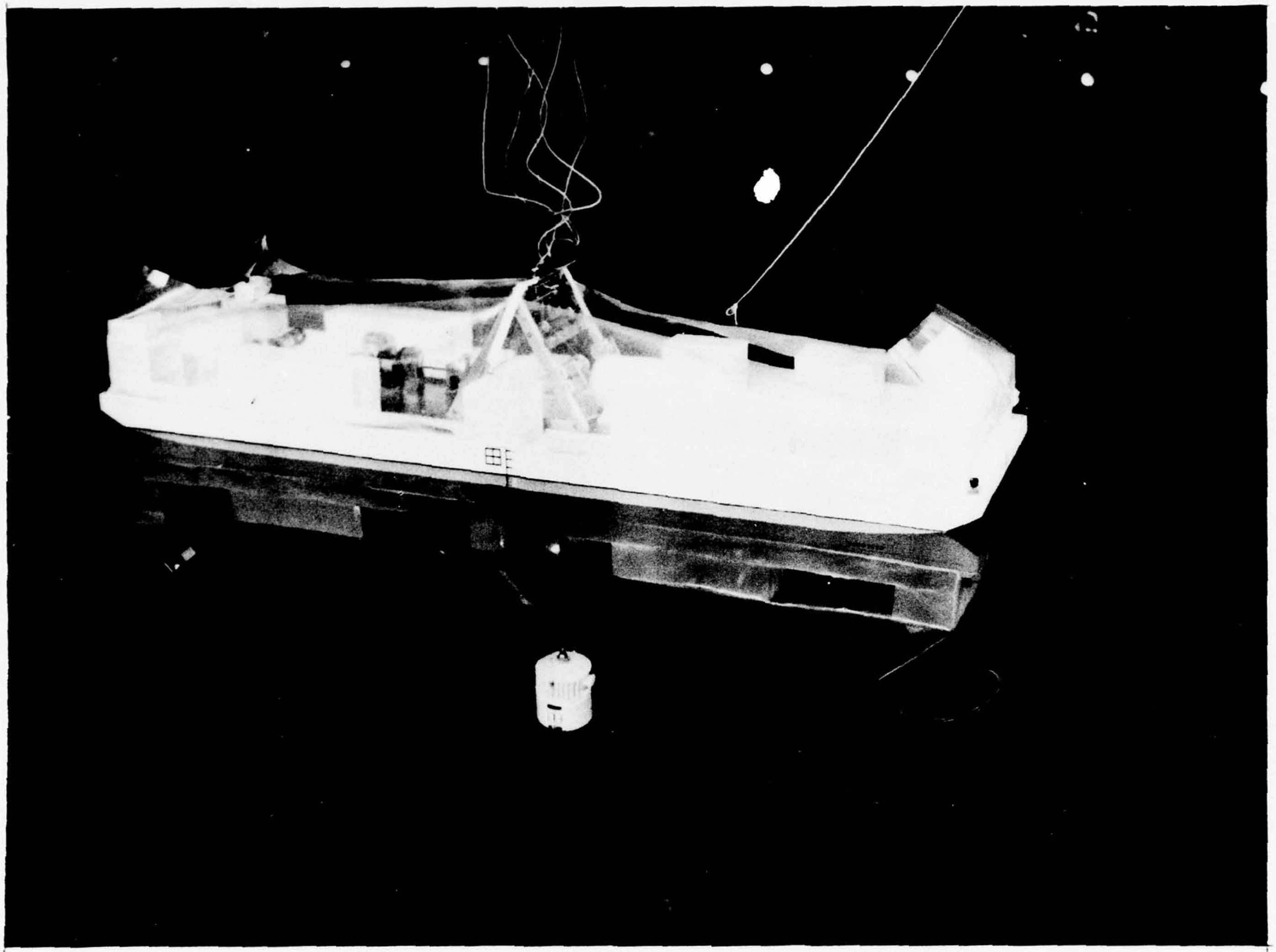


FIGURE 11

SEADOPOD MODEL IN MASK

One-tenth second time markers were recorded on each camera but were not supplied from a common source. No accurate synchronization of the three cameras was available. Camera film transports were strobed and d-c drive motor voltages adjusted after the first few camera runs showed that the three cameras had not been adjusted properly. All filmed data was recorded on Kodak PXN 449 black and white negative film with the exception of a single run which was recorded on Kodak EFB 430 color film. The underwater camera was fitted with a normal lens with a field of view of 2-3 feet for data runs with the pod at a fixed depth and a wide angle lens which had a field of approximately 6 feet for data runs with the pod raising and lowering. The full 10 feet of water from barge to bottom could not be viewed with this lens system. Surface lighting was provided by conventional photoflood lamps and underwater lighting consisted of two vertical light bars, each with six Model 91 Acme Photoflood assemblies.

2. Wave Generation

The MASK facility has two banks of pneumatic wave generators located along the west wall and north wall of the basin. These are referred to as the west bank and north bank wave generators and in terms of the SEADOPOD model test could provide respectively, scaled head seas and beam seas. Both regular and irregular waves can be generated in the MASK; however, it was decided that irregular waves would be used in order to subject the model system to waves which more nearly approximated actual sea conditions. The wave generators are tape controlled. Operating procedure consists of first selecting a tape containing a signal component most nearly approximating a desired Sea State. Wave height is then adjusted by controlling rpm's on the blowers which feed the pneumatic generators. Scaled wave heights are measured by means of a sonic wave height transducer mounted ahead of the model on an adjustable pipe frame platform. The output of this transducer is fed to an rms wave height computer to select the required blower rpm for a given model linear scale factor. Once the waves have been calibrated, the model system is ready for test. As mentioned previously, data runs of five minutes duration were considered an appropriate sample time to represent the statistical properties of the irregular waves, and were consistent with a 100 ft. film load and a 12 f.p.s. camera speed.

3. Model Instrumentation

Six channels of model data plus a camera ON-OFF pulse were recorded on an eight channel Sanborn strip chart recorder. Data signals were first passed through calibrated Dana preamplifiers to adjust voltage levels to be compatible with the recorder inputs. All signal sources were calibrated initially so that the chart records could be interpreted in terms of prototype parameters to provide consistency in referring to these records. The system variables measured are indicated in Table 4. Figure 12 is a Sample Strip Chart Record taken from Run 5.

Table 4 Strip Chart Channel Identification

Channel #	Variable	Description of Variable
1	Wave Height	Signal from calibrated sonic probe
2	Sense	Signal from sense line linear rotary potentiometer
3	Transloader	Signal from Transloader linear motion potentiometer - gives pod motion
4	Error	Differential control amplifier - proportional to difference betwee Sense and Transloader signals
5	Output	Signal derived from the control amplifier output - represents transloader motor drive voltage
6	Depth	Signal from winch drive linear rotary potentiometer
7	(Not Used)	
8	Camera	Positive pulse indicates cameras "on".

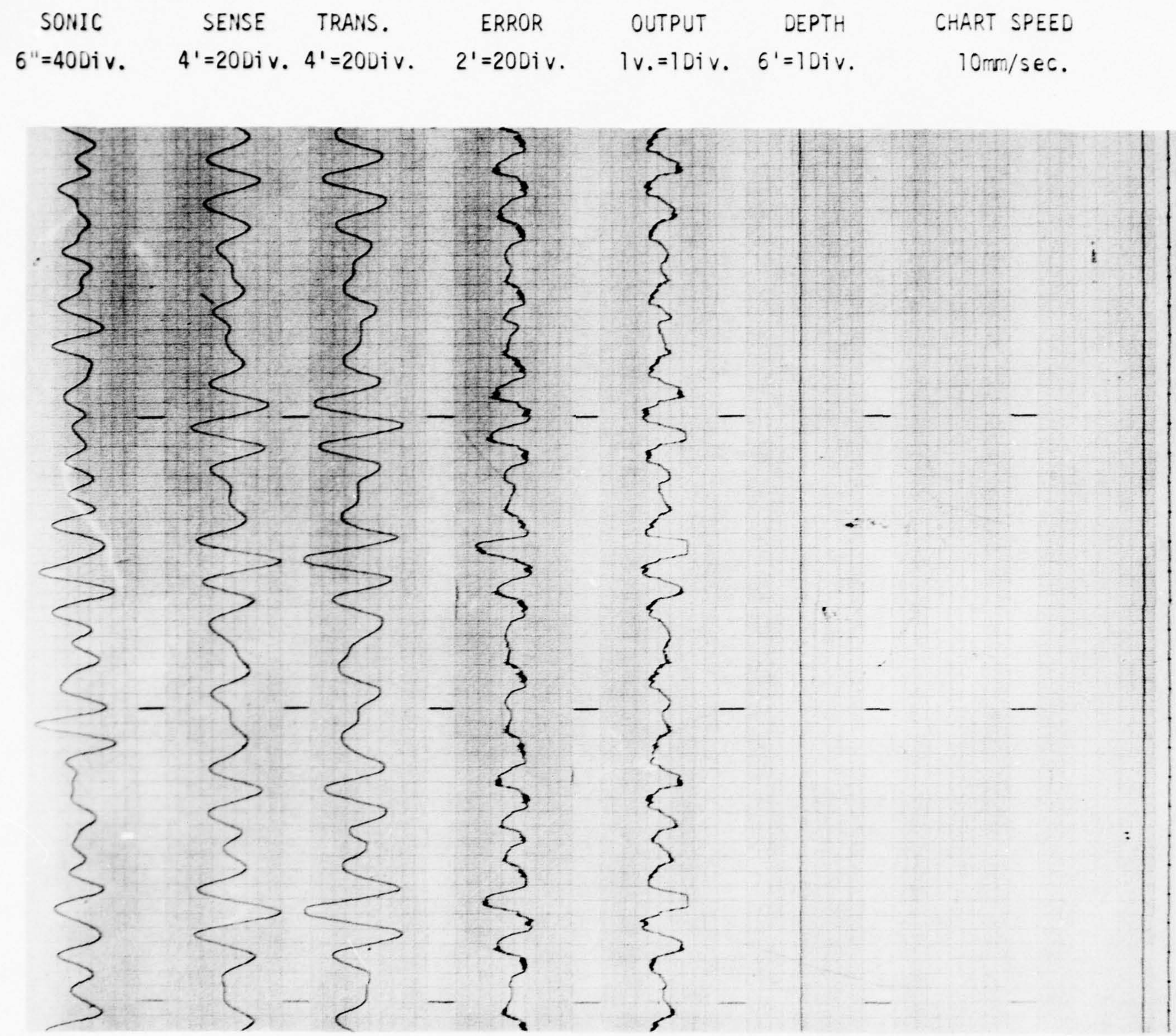


Figure 12 SAMPLE STRIP CHART RECORD

4. Data Runs

A total of 9 data runs were obtained for the maximum operating depth (300 ft.) of the system with the pod at various fixed depths and for raising and lowering the pod. Sea States were varied over the range of low 3 to mid 5. Only west bank generators (head seas) were available. Static moor loading tests were also conducted for the 150 ft. condition. The proposed data runs for the 50 ft. depth were not made due to the large amount of rigging time required to change operating depth and insufficient funds available for extension of the tests. Table 5, Wave Test Data Runs, gives a summary of the data runs and indicates the pertinent test conditions.

Table 5 Wave Test Data Runs

RUN	WATER DEPTH FT.	POD DEPTH FT.	SEA STATE	STD. DEV. FT.	BLOWER RPM.	REMARKS
1	300	250	3	.624	390	Gain adjust changed from 1 to 2 @ Mark. State 3 Tape, High 2 Ampl.
2	300	250	Low 3	.901	490	Transloader off @ Mark
3 A	300	250	5	1.24	500	2.5 min. No U/W Camera State 5 Tape, High 3 Ampl.
B	300	40-250	5	1.68	650	2.5 min. No U/W Camera State 5 Tape, High 4 Ampl.
4	300	250	Low 5	2.14	725	Replaced Defective Ch.#1 Preamp.
5	300	150	Mid 5	2.23	800	Gain at 3
6	300	40	Mid 5	2.20	800	
7	300	45-103	Mid 5	2.37	800	Gain to 4 @ Mark Pod Raised & Lowered
8	300	30-250	Low 3	0.65	300	Gain at 3 Pod Raised & Lowered
9	300	250	Mid 5	2.24	650	Color film all cameras
10	150	90	5	1.74	650	Wavemaker valves 2 & 4 not functioning properly High 4 Ampl.
11	150	90	Mid 5	2.27	800	
12	150	30	Low 5	2.09	800	
13 A	150	30-130	Mid 5	2.18	925	Approx. 2 min.
B	150	0- 20	Mid 5	2.39	925	Approx. 1 min.Pod removed from water
C	150	0-120	Mid 5	2.27	925	Approx. 1 min.Pod lowered into water
D	150	0	No Waves	-	-	Approx. 1 min.Static load test

5. Typical Data Run Procedure

The following outline indicates a typical data run for SEADOPOD testing.

a. Wave generator tape selected for Sea State wave spectrum.

b. Blower rpm adjusted for required scaled wave height.

c. Cameras loaded, model adjusted in moor, pod at required depth, wave generators off, U/W camera at surface; 10 seconds of data number card filmed on each camera.

d. U/W camera lowered to required depth, U/W lights on.

e. SEADOPOD Control energized and placed in Automatic.

f. 10 seconds of rest position of model recorded on all cameras.

g. Wave generators started - brief delay for seas to build up.

h. Sanborn recorder ON

i. Cameras ON

j. Rms. computer On (approximately 1 minute) for check of wave height.

k. After approximately 5 minutes, cameras OFF, Recorder OFF, Wave generators OFF (unless only Pod Mode to be changed).

l. U/W camera raised to surface. All cameras reloaded.

m. Set new conditions for next run.

G. DATA REDUCTION

SEADOPOD test results consisted of four basic types:

1. Visual evaluation of mooring system performance and pod elevator control system.

2. 16 mm photographic record of barge motion (bow and beam views) and submerged pod motion (beam view).

3. Strip chart recordings of six system variables plus camera ON-OFF mark.

4. 16 mm photographic record of static loading of mooring system consisting of a series of 5-second records of beam and bow views both at rest and for various loads applied to the barge as measured by a pulley and spring-scale system.

Considering the lack of camera synchronization due to non-uniform camera speeds and the three separate timing signal sources, interpretation of the filmed record could not provide a great deal of quantitative information. Without a common time base, a frame-to-frame analysis of relative barge-pod motion was not impossible. Strip chart data which was recorded simultaneously for the six model parameters was selected for more detailed analysis.

Reduction of the strip chart data was accomplished by first converting selected 40-second segments of data, samples at 0.1 second intervals, to punched tape using a Gerber Scientific GDDRS-3B-2 Digital Data Reduction System. A compromise was made in choosing 40-second samples between an attempt to obtain sufficient data time to cover representative wave action and a practical consideration of the time required to read six channels of data at each data point. Portions of data which appeared to give large errors, corresponding to severe wave conditions, were selected. A 0.1 second interval (corresponding to 1 mm. which was the smallest chart division) was selected to preserve the higher frequency components of the signals and still make data reading with the GDDRS convenient for the operator. Each segment of punched tape consisted then of 400 data points. Time (data point) and six amplitudes in hundredths of an inch in the form (Channel, Sign, Hundreds, Tens, Units) were converted by the GDDRS to Friden tape using a 6-channel ASKI code. Since this format was not compatible with an available IBM 047 printer, the Friden tape was converted to IBM cards using a teletype reader and a conversion program supplied by DIAL DATA of Newton, Massachusetts. This conversion did not yield true symbols for the model data but did provide a unique set of symbols which were then converted to the required signs and numerics by means of a simple conversion program on an IBM 360 computer.

Evaluation of the photographic record of model performance was accomplished by interpreting reference markings on the barge bow and topsides and the pod side. One-inch square markings divided in half vertically and horizontally to form a pattern of four half-inch squares were located at these points of the model. The brief filming of the "rest" position of the barge and pod before each data run, established the reference displacement since the one-inch reference square as shown by the projected image would correspond to 30 inches of displacement for the prototype system. An alternate interpretation would be to consider that each foot of displacement of the prototype system corresponds to $\frac{1 \times 12}{30} = 0.4$ inch model displacement. Projected images or photographic prints of the model views could thus be read to obtain displacement data. Camera mis-alignment as discussed in Part VIA was determined to produce less than 0.1% error in displacements scaled from the projected images.

H. <u>DATA ANALYSIS</u>

As discussed briefly in the preceding section, reduction of the strip chart data which was judged to be of more value for system error analysis than the unsynchronized cine record, required a selection of an appropriate data interval to convert from analog to digital form.

Magnetic tape inputs for the wave generators which were used in the model tests corresponded to the range of Sea State 3-5 and had frequencies of maximum energy of spectrum of 0.8 Hz to 0.675 Hz. Allowing for the higher frequencies and applying Shannon's Sampling Theorem, which requires a sampling rate at least twice the maximum frequency to be recovered, a 10 sample per second rate was selected. This yields frequencies up to 5 Hz, which is 7.4 times the frequency of maximum energy ($f_{max} = 1/T_{max}$) for Sea State 3 and 6.25 times the corresponding f_{max} for State 5.

Portions of five data runs were converted to punched cards for data analysis. These runs were judged representative of both high and low sea state and the several modes of model operation. Data runs 2, 5, 7, 11, and 12 from the thirteen total runs listed in Table 5 were used.

The first step in data analysis was to translate all magnitudes as read by the GDDRS to the form in which they appeared on the strip chart, i.e., as plus and minus readings about a zero signal level. This was accomplished by means of sets of readings for plus full scale, minus full scale, and zero point for each channel of data. This translation was required since all digital conversion magnitudes were referenced to zero inches located at some point near the bottom of the eight channel strip chart recording.

All data values were scaled to read directly in prototype feet. Print-outs of both translated and scaled values were provided for visual checking. The same information was punched on cards for use in the actual system performance and error analysis.

The computer program "Barge B-F/V" in Appendix B was used to analyze pod errors for each of the data runs selected. Initial information supplied by the program pertains to the run identification as follows:

NWM - number of wavemaker tape used

NRPM - wavemaker blower speed in revolutions per minute

NSS - simulated Sea State

NBD - bottom depth given in prototype feet

DTTIM - total run time in seconds and tenths

DTRMS - RMS surface height value for entire run

DTAVG - average or offset value of surface height for entire run

DTIN - scale factor, surface height inches/20 mm. on strip chart as measured by sonic probe

DT - date of data run

The second portion of the program reads in the digital data for the run as prepared from the strip chart conversions.

The format and description of the data input is as follows:

Variable	Columns	Description
Sonic	11-20	Surface height as measured by the sonic probe
Barge	21-30	Barge motion about its still water position
Transloader	31-40	Pod motion measured relative to the barge
Error	41-50	Pod change about its nominal depth
Amp. Out.	51-60	Servo motor correcting voltage
Pod Depth	61-70	Nominal pod depth

All values are given in prototype feet except amplifier output which is measured in d-c volts.

The first two cards in each data set give run number in columns 2-5 and time in columns 6-10 in addition to the above information.

Any number of digital data points between 2 and 600 may be used with this program. Approximately 400 data points were used in each of the five runs analyzed. Any comments to be printed with the output data should be entered on cards preceded by a card with a digit "1" in the first column, immediately following the digital information.

The third segment of the program searches through the data to find the maximum and minimum pod depths. If the pod varies during the run, both maximum and minimum depths will be printed. If, however, it remains fixed, then only a single value is given as output.

The next portion of the program locates the overall run information supplied by the MASK data analyzer (DTTIM, DTRMS, etc.). Following this step, the computer prints the necessary labels to set up the output pages. All values which have been computed up to this point are also printed. If no more than five digital data points are available, the program terminates at this point.

Pod error or deviation from a fixed position, was found in two ways. "Pod Deviation 1" refers to the error signal from the amplifier/controller differential amplifier. "Pod Deviation 2", obtained from the algebraic sum of the barge and pod positions as indicated by the Sense and Transloader recorded signals, was calculated in the next segment of the program.

Next, maximum and minimum values for each parameter for all points of the run are computed. This gives a spread of values.

The next two computations are the most significant as far as performance of the model system is concerned. Average values for each of the input parameters are computed from

$$\bar{F} = \frac{1}{T} \int_0^T f(t)dt$$

using appropriate subroutines.

Root mean square (RMS) values of the parameters are next calculated using the relations

$$F^2_{rms} = \frac{1}{T} \int_0^T f^2(t)dt$$

$$F_{rms} = \sqrt{F^2_{rms}}$$

The standard deviation or RMS value about the mean (average) is then calculated according to

$$F^2_{SD} = \frac{1}{T} \int_0^T (f(t) - \bar{F})^2 dt$$

$$= \frac{1}{T} \int_0^T (f^2(t) - 2\bar{F}f(t) + \bar{F}^2)dt$$

$$= \frac{1}{T} \int_0^T f^2(t)dt - 2\bar{F} \frac{1}{T} \int_0^T f(t)dt + \bar{F}^2 \frac{1}{T} \int_0^T dt$$

The first term in this expansion corresponds to F^2_{rms}, the second term is $2\bar{F}^2$, and the final integral is simply unity, thus

$$F_{SD}^2 = F_{rms}^2 - 2\,\bar{F}^2 + \bar{F}^2$$

$$= F_{rms}^2 - \bar{F}^2$$

$$F_{SD} = \sqrt{F_{SD}^2}$$

This indicates that the standard deviation can be computed without repeating the integration process.

The final computations are made to determine transloader effectiveness. This was evaluated in two ways. The first method is based on a comparison of the overall motion (difference between maximum displacement and minimum displacement) throughout the sampled portion of the data run, for both the barge and the pod. From these figures, the ratio of pod travel to barge travel is determined and this subtracted from unity gives the amount of pod motion removed by the transloader and is defined as transloader effectiveness.

The second measure of transloader effectiveness was determined from the standard deviation values (RMS about the mean) computed for barge and pod motions. As an example of the intepretation of this definition of effectiveness, an RMS barge travel of 1.5 feet and RMS pod travel of 0.5 feet would give (1.0 - 0.5/1.5) = 1.0 - .333 = .667 or an effectiveness of 66.7% for the transloader in eliminating barge motion at the pod. An effectiveness of 100% would of course indicate that complete wave cancellation had been accomplished.

A final portion of the program calls for the subroutine "FORSR". This calculates the Fourier Transform of data supplied, and if not required, a dummy subprogram can be used in its place. Although not used in this data analysis, calculation of the Fourier Transform could be used to provide a frequency spectrum of the sampled data points. Comparison of the barge and pod spectra would give frequency response data for the transloader and comparison of the spectra of the sonic wave height probe and the barge motion would yield a measure of the barge frequency response. Additionally, a comparison between the sonic wave height and the pod motion would give a frequency response of the complete system. Computer calculation of the Fourier Transform is very time consuming; however, a recently developed technique known as the "Fast Fourier Transform" shows promise in reducing computer time considerably.

I. MODEL SYSTEM PERFORMANCE EVALUATION

1. Elevator Control System

The stated objectives of the SEADOPOD model program were to investigate the dynamic performance of the barge-pod-elevator system and the static load response of the barge four-point moor.

In order to evaluate the performance of the elevator control and wave cancellation system, data from the instrumented model in the form of relative barge and pod motions were analyzed. Ideally, the sum of relative barge and pod motions should equate to zero, i.e., as the barge rises (relative to the bottom) on a wave crest, the transloader retracts, lowering the pod by the same amount (relative to the barge) so that the pod assumes a "fixed" position in the water. In reality, since a feedback control system requires some error to actuate the system, the transloader compensating action is incomplete and only a portion of the barge heave motion is removed from the pod. As has been previously noted, the measured displacements also include horizontal motions of the barge-pod system. Most of this motion is due to the surging action of the barge and pod. The model instrumentation measures net change in Sense cable length and displacement of the Transloader (net change in Winch cable length). For convenience, the elevator control action is described as acting only in the heave direction.

With regular near-sinusoidal waves, the transloader effectiveness could be evaluated in terms of relative frequency response of the barge and the pod to a constant amplitude, variable frequency wave excitation. The standard techniques of amplitude and phase response could then be employed to measure effectiveness of the elevator control. The choice of irregular waves for these tests, based on a desire to subject the model to more representative sea conditions, required a different measure of effectiveness. Since irregular waves and resultant model responses are statistically defined, root-mean-square values about the mean (standard deviations) over the sampled time periods were computed and used to define a per-cent transloader effectiveness as $(1 - \frac{POD_{rms}}{Barge_{rms}} \times 100.)$ This can be seen to approach 100% as POD_{rms} motion approaches zero, which corresponds to complete wave cancellation.

As an alternate measure, the range of motion (maximum to minimum positions) for both the barge and the pod were calculated for each sampled segment of the five runs analyzed and these values applied to a similar definition of % effectiveness as $(1 - \frac{POD_{range}}{Barge_{range}} \times 100.$ This might be described as a "worst case" measure since it would be exceedingly unlikely that an adjacent peak and dip of the motion curve would correspond to the range which was determined from the largest peak and the largest dip throughout the segment of data.

Table 6, Transloader Evaluation, summarizes the results of the motion analyses and transloader effectiveness calculations. As an example of the interpretation of these data, consider Run 5 which was conducted with Sea State 5 waves, a 300-foot water depth and with the pod at 150 feet. Using approximate values, maximum water surface change was 12.8 feet, maximum barge travel was 7.6 feet and maximum Pod travel was 2.7 feet. Consider these maximum changes or ranges of variables, the Pod travel was 21.5% of surface change and 36.1% of Barge travel. Thr transloader effectiveness on a maximum change or range basis was 63.9%.

In terms of RMS values, the water surface RMS height with respect to the mean height was 2.2 feet, the RMS Barge travel was 1.4 feet and the RMS Pod travel was 0.45.feet. Comparing these RMS values, pod travel was 20.9% of the surface height and 33.4% of Barge travel. Transloader effectiveness in terms of these RMS values, is 66.6% - i.e. the transloader eliminates approximately 67% of barge motion from the pod.

TABLE 6

TRANSLOADER EVALUATION

RUN NUMBER SEA STATE	2 3	5 5	7 5	11 5	12 5
MAXIMUM SURFACE CHANGE (FT)	5.288	12.788	12.883	11.658	12.342
MAXIMUM BARGE TRAVEL (FT)	2.923	7.580	8.471	7.885	7.389
MAXIMUM POD TRAVEL (FT)	1.477	2.739	2.944	3.129	2.382
POD / SURFACE (%)	27.00	21.45	22.90	26.79	19.31
POD / BARGE (%)	50.52	36.13	34.75	39.69	32.24
EFFECTIVENESS (%)	49.48	63.87	65.25	60.31	67.76
RMS SURFACE HEIGHT (FT)	1.090	2.229	2.449	2.000	2.125
RMS BARGE TRAVEL (FT)	0.533	1.367	1.440	1.442	1.278
RMS POD TRAVEL (FT)	0.309	0.457	0.461	0.554	0.378
POD / SURFACE (%)	28.38	20.91	18.82	27.83	17.74
POD / BARGE (%)	58.01	33.42	31.99	38.39	29.74
EFFECTIVENESS (%)	41.99	66.58	68.01	61.61	70.26

Note - RMS values are taken about the mean

Values for the other data runs are interpreted in similar fashion.

The validity of this Transloader analysis for a given Sea State specification is of course dependent on the soundness of the data sampling scheme. It will be recalled that approximately 40 seconds of data out of a total run time of 5 minutes was reduced from the strip chart records to digital form for the performance study.

Two questions are pertinent. If a 5-minute run was originally judged necessary to represent the statistical components of a given Sea State tape, then would a 40-second segment be a sufficiently representative sample? Secondly, did the wave height over the 40-second interval correspond to the required Sea State amplitudes?

It will be recalled that the RMS computer at the MASK analyzes the output of the sonic wave height probe and calculates both the d-c level and the RMS wave height from which the standard deviation (RMS about the mean) may be determined. To answer the first question, a comparison is made between the MASK standard deviation for the complete run and the calculated standard deviation for the partial run. These values are shown in Table 7, Comparison of Partial Run to Total Run. The indicated Difference (S.D.) values range from 0.0004 Ft. for Run 5, to 0.275 Ft. for Run 11, or less than 1% difference to approximately 12% difference. This agreement supports the validity of the partial run at least as far as the amplitude statistics are concerned. However, since no Fourier analysis of the data was performed, there is no assurance that the partial run has the proper distribution of frequency components to accurately represent a given Sea State. In Section G, it was noted that the sampling time selected for conversion of the analog strip chart data to digital form, was 0.1 second which allows the recovery of information with frequency components to 5 Hz. Since this is more than 7 times the $f_{max} = 1/T_{max}$ for State 3 and more than 6 times the f_{max} for State 5, all major wave components contained in the data should be accurately recovered.

Returning to the second question, a common measure of wave height is $\bar{H}_{(1/3)}$ which is the average of the 1/3 highest waves or commonly called the Significant Wave Height. From the Marks Sea State

TABLE 7

COMPARISON OF PARTIAL RUN TO TOTAL RUN

RUN NUMBER SEA STATE	2 3	5 5	7 5	11 5	12 5
TOTAL RUN					
TIME (SEC)	317.3	273.5	300.2	240.5	391.5
AVERAGE HEIGHT (FT)	0.390	0.102	0.594	0.315	0.581
RMS HEIGHT (FT)	0.982	2.237	2.449	2.296	2.174
STD DEVIATION (FT)	0.901	2.234	2.376	2.275	2.095
PARTIAL RUN					
TIME	37.9	40.0	40.0	39.9	40.0
AVERAGE HEIGHT (FT)	0.093	0.020	0.161	0.304	0.282
RMS HEIGHT (FT)	1.094	2.229	2.454	2.023	2.143
STD DEVIATION (FT)	1.090	2.229	2.449	2.000	2.125
DIFFERENCE (S.D.) (FT)	0.189	0.005	0.073	0.275	0.030

Chart, significant wave heights range from 3.3 to 4.6 feet for State 3 and from 8 to 12 feet for State 5. In order to relate these values to the standard deviation, we make use of the relations

$$S.D. = \sigma = .707 \sqrt{E}$$

and,

$$\overline{H}_{(1/3)} = 2.83 \sqrt{E}$$

or,

$$\overline{H}_{(1/3)} = \frac{2.83}{.707} \sigma = 4 \sigma$$

The corresponding values of standard deviation are accordingly one-fourth of the significant wave heights or 0.825 to 1.15 feet for State 3 and 2.0 to 3.0 feet for State 5.

From Table 6, Transloader Evaluation, we see that Run 2 is within State 3 range and Runs 5, 7, 11, and 12 are within the State 5 range.

We may conclude that the partial run data is valid with respect to RMS wave height (or Sea State specification of significant wave height) and sampling interval.

Although the photographic records of model behavior did not provide quantitative data for relative barge-pod displacements, they could be interpreted to give a better "feel" for total motions one would experience on the barge or in the pod. This is particularly true if barge and pod films for the same data run are viewed in sequence. In addition, the cine record includes horizontal displacements and would allow a two-dimensional analysis of the system. The filmed record of the submerged pod does give a good approximation of the total displacement, 2 axes only, experienced by the pod. A second underwater camera would have been required to observe lateral movement; however, this was judged to be relatively small.

Maximum values of vertical and horizontal travel of the barge and pod for all data runs, as derived from the films, are presented in Table 8, Transloader Evaluation - Film Analysis These maximum values are actually ranges or sums of the most positive swings and the most negative swings throughout the runs and are therefore a measure of the total excursions of the pod.

Table 8 Transloader Evaluation - Film Analysis

Run	Maximum Barge Travel - Ft.(1) (From BEAM Camera)		Maximum Pod Travel - Ft.(1) (From POD Camera)	
	Vertical	Horizontal	Vertical	Horizontal
1	2.87	2.60	2.55	1.80
2	3.25	3.62	2.30	1.90
3A (2)	4.65	5.30	-	-
3B (2)	5.15	4.55	-	-
4	8.50	8.20	5.17	4.42
5	9.05	8.70	3.60	5.82
6	9.15	8.45	3.85	14.70
7 (3)	9.80	7.95	2.40	6.00
8	3.35	3.90	3.50	4.75
9 (4)	8.75	9.00	-	-
10	6.45	7.50	5.20	5.55
11	9.20	11.90	4.42	9.42
12	8.25	10.70	2.68	10.45
13 (4)	8.70	11.80	-	-

(1) Range of sum of most positive and most negative travel from rest position.

(2) U/W camera inoperative.

(3) Pod Raise and Lower - only partial data for pod taken.

(4) Pod Raise and Lower - no data for pod taken.

2. Barge Moor System

Verification of the SEADOPOD moor design, summarized in Section C, Table 1, Prototype Moor Data, was conducted at the completion of wave testing with the barge set on the model moor and 150-foot phototype depth. Data were obtained from a series of photographic prints made from the 16 mm. cine record of the "at rest" and displaced positions of the barge with various scaled loads applied in both beam and bow directions. Displacements were read relative to the edge of the frame and scaled from the one-inch calibration markings on the model. Representative photographs used for the load analysis are shown in Fig. 13 A. Beam Static Loading, and Fig. 13 B, Bow Static Loading.

Table 9, Test Results - Static Barge Loading, summarizes the static load test results. All measured motions are within approximately 10% of the predicted motions with the exception of the lowest value bow force test. At this low value, measurement errors in the force application system and minor kinking of the moor cable may have contributed to the larger error of 20%.

Table 9 TEST RESULTS - Static Barge Loading

Direction	Applied Force	Predicted Motion	Actual Motion	Difference	Error
Beam	2.90 oz.	0.110 ft.	0.121 ft.	0.011 ft.	10.0%
Bow	1.75	0.067	0.073	0.006	8.9
Bow	1.25	0.048	0.050	0.002	4.2
Bow	1.00	0.040	0.040	0.000	0.0
Bow	0.50	0.019	0.021	0.002	10.5
Bow	0.25	0.010	0.008	0.002	20.0

A portion of Run 13 was devoted to an attempt to remove the pod from the water and then return it to the water. The Transloader specified for SEADOPOD has a 12,000 pound rating and is used with a one-part load cable. The Transloader can only handle the load of the submerged pod (weight in air less displacement = 12,000 pounds). During the out-of-water lowering and raising phases of the operation, the Transloader is blocked in the retracted position, thus providing direct winching of the 30-ton load without Transloader action.

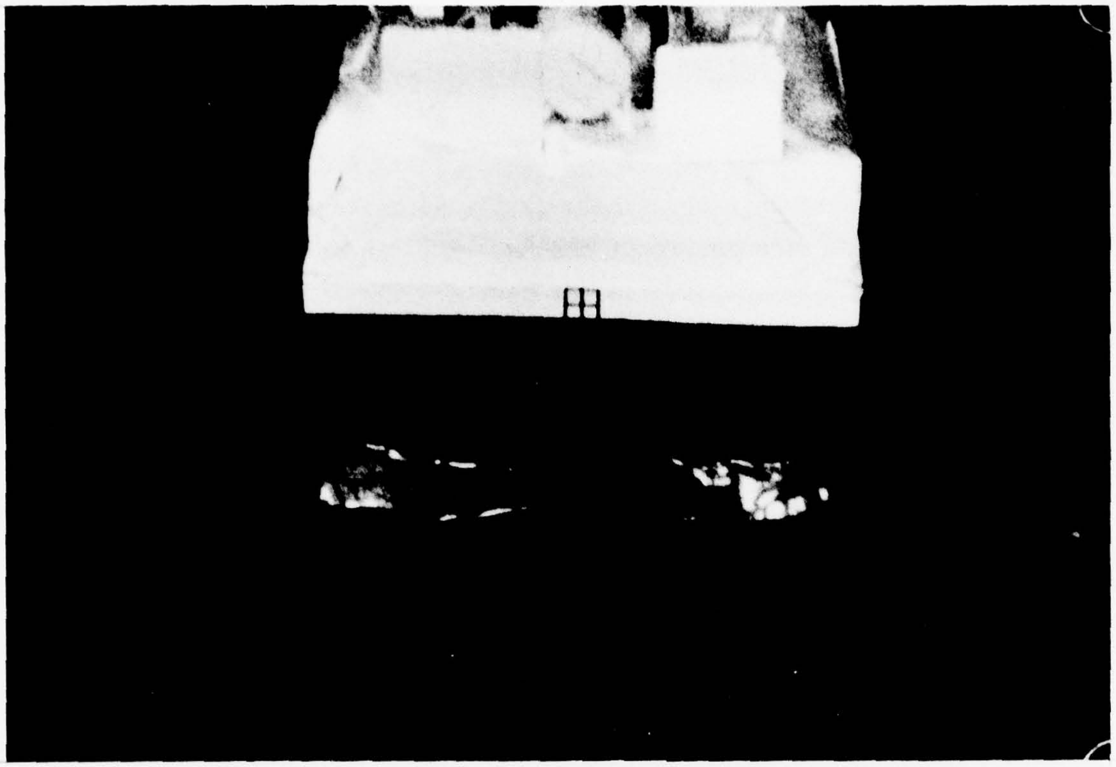


Figure 13-A BEAM STATIC LOADING

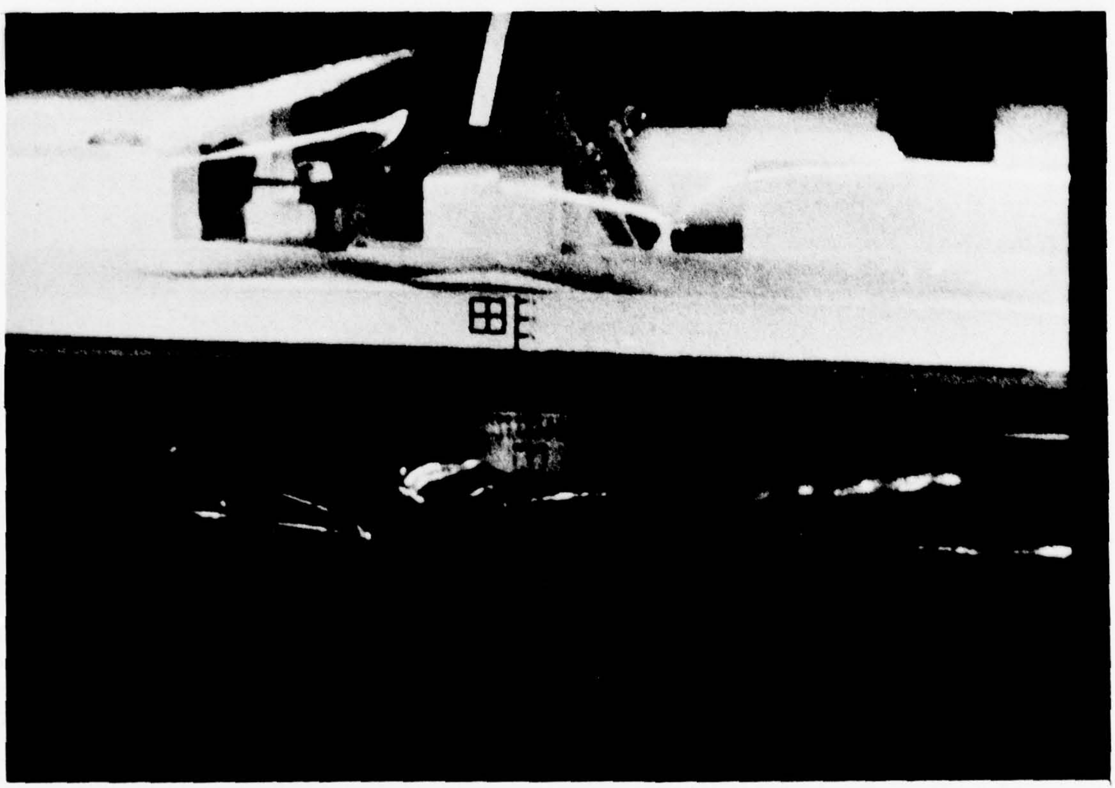


Figure 13-B BOW STATIC LOADING

Some operator experience is necessary to adjust the winching system controls while maneuvering the pod in and out of the water. For example, as shown in Figure 14, Typical Pod Lowering Operation, with the Transloader blocked, the operator waits until the barge begins to rise on a wave crest, then by manual control, causes the Transloader to be extended toward the mid-position as the pod is lowered quickly through the water surface. This is accomplished in a few seconds and, once the pod is submerged, the Transloader automatic control is put into operation and wave cancellation is in effect until the pod is to return to the surface.

Simulating a pod launch and retrieval is extremely difficult because $(\text{model time}) = \frac{(\text{real time})}{5.48}$. Using a T_{max} = 8 seconds for State 5, a model wave period is approximately 1.5 seconds. Less than a second is available to execute the model pod launch and this is hardly enough time for the operator to manipulate the elevator controls. The attempts were inconclusive in predicting prototype system performance. However, considering the time available in the actual system, smooth launch and retrieval should be possible with operator experience. An automatic system for synchronizing winch and Transloader controls with wave motion might be considered.

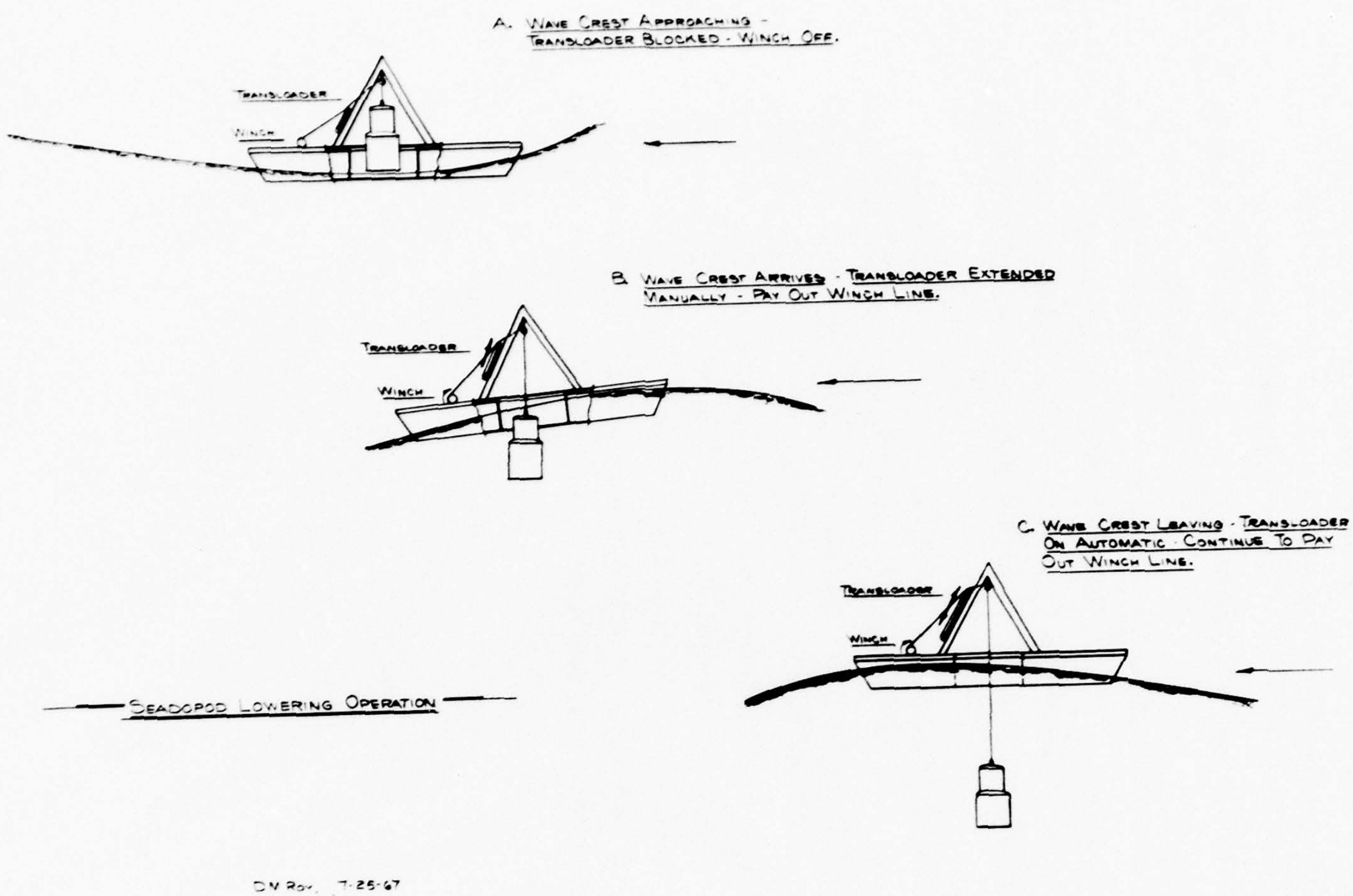


Figure 14 TYPICAL POD LOWERING OPERATION

J. CONCLUSIONS AND RECOMMENDATIONS

A model SEADOPOD diving system was designed, constructed and tested in the Maneuvering and Seakeeping Basin of the Naval Ship Research and Development Center. The system was subjected to irregular waves corresponding to Sea States 3 to 5 in simulated water depths of 300 feet and 150 feet and for several different pod depths. Performance of the pod elevator control was evaluated from strip chart recordings of pertinent model variables and from cine records of the barge and pod motions. Static loading of the barge was simulated in order to verify the performance of the model 4-point moor.

1. Elevator System Performance

Analysis of the strip chart recorded data for the instrumented SEADOPOD model yielded the performance data of Table 6, Transloader Evaluation, on page 44. When considered on an rms basis, the Transloader wave cancellation device was capable of eliminating up to 70% of barge travel from the pod. As discussed previously, the measured displacements are total displacements (in three dimensions) corresponding to the "lengths" of the SENSE cable and of the WINCH cable as determined by the TRANSLOADER position. Due to wave induced motion of the barge in the horizontal plane, largely fore-and-aft for head seas, the SENSE signal which actuates the elevator control is not a simple measure of the heave components and so the controller responds to a multi-dimensional input signal. This may be considered partial justification for evaluating performance from measured SENSE and TRANSLOADER signals.

Several improvements in model elevator control could increase Transloader effectiveness above 70%. Reduction of Transloader drive motor dead-band (region where applied voltage is insufficient to overcome static friction) could be accomplished by a better match of motor to load requirements. This effect is more pronounced for small amplitude wave inputs as can be seen in Table 6 for Run 2 which was conducted for State 3 seas. Increased controller amplifier gain consistent with closed loop system stability would reduce errors, i.e. improve wave cancellation. The elevator control as tested was judged to be an acceptable model of the prototype system despite the use of electromechanical components to simulate the electro-hydraulic components prescribed for SEADOPOD.

Analysis of the cine record of barge and pod motion as summarized in Table 8, page 48, reveals that under certain test conditions the pod may experience large horizontal motions. These might be thought of as pendulum effects generated by horizontal barge motion and accentuated by the pitch induced pivoting action of the A-frame structure which supports the main sheave for the pod winch cable and the pod guy line sheaves. With irregular wave inputs, these large pod excursions occur infrequently, and are quickly damped. However, for the system operating with waves of more uniform amplitude and frequency characteristics, any tendency toward oscillatory responses approaching possible resonance of the pod support-cable/guy-line system, must be avoided. As might be predicted, the pendulum effect is most pronounced when the pod is near the surface. Run 6 with a water depth of 300 feet and pod depth of 40 feet and Run 12 with a water depth of 150 feet and a pod depth of 30 feet, show the greatest horizontal pod travel - 14.70 feet and 10.45 feet respectively. These motions appear to be extreme but must be considered in terms of how they were measured. These values are ranges or sums of the most positive and most negative travel of the pod from the rest position during the complete data run. Very few displacements approaching these maximum positive and negative values occur and in all cases a maximum swing in one direction is not followed by a maximum swing in the opposite direction. For most other modes of system operation, pod horizontal motions are comparable to pod vertical motions.

2. Barge Moor Performance

Test results for the static barge loading were summarized in Table 9, page 49. Agreement between measured and predicted motions within approximately 10% for all loads except the lowest bow load, supports the validity of the 4-point mooring system design. Dynamic performance of the model barge on its mooring was satisfactory. This qualitative judgment was based on observations during wave tests and from viewing the cine records.

Although chain would most likely be used for the prototype moor components, miniature wire rope served as a suitable substitute in the model.

3. SEADOPOD Diving System

The proposed diving system consists of a personnel transfer capsule or pod operating through a center well of a surface support barge which is maintained over the diving site on a 4-point moor. To reduce the effect of barge heave motion on the pod, a wave cancellation device is incorporated in the pod elevator control. Results of scaled wave tests and simulated static wind and current load tests of the model system suggest the following recommendations for the prototype system:

a. Operation in seas approaching State 5 can be maintained; however, large horizontal motions may be experienced by the pod if it remains near the surface. Under these sea conditions, the pod should be lowered directly to its operating depth near the bottom.

b. An increase in tension above the 6000 pound design value in the pod guy lines might be considered to reduce pod travel and increase damping in the horizontal direction. A major refinement of the elevator control would be to employ a second closed-loop system to position the A-frame mounted sheaves for the pod winch cable and pod guy lines in order to compensate for horizontal barge motion and A-frame pivoting action. Consideration might also be given to a system which would allow mating of the pod with the decompression and living chamber below decks, although this might not be feasible with a shallow draft barge. This could improve pod entry and recovery operations and would allow cable supports to be placed nearer the center of gravity of the surface vessel.

c. Implantation and rigging of the pod anchor, guy lines and sense cable for SEADOPOD will require special care to avoid twisting and fouling, especially for operation in deep water. Modification of the bottom sensing system by replacing the sense line and spring-loaded servo valve of the Transloader with an electronic sensor and electrically operated servo valve, has been proposed by The Rucker Company. The elements of the system are a precision pressure transducer which senses the change in "head" in a hydraulic line at the ship relative to the bottom, a signal conditioning amplifier and the electric servo valve. The hydraulic line may be strung out so as not to interfere with the guy lines and pod support cable since the pressure signal depends on the vertical orientation of the line.

d. If operation of the SEADOPOD system must be carried out in severe sea conditions, personnel operating the pod elevator must have experience in coordinating the winch motor and Transloader controls with the wave induced barge motion in order to effect a smooth entry and recovery of the pod.

e. Satisfactory dynamic and static load performance of the prototype 4-point moor is predicted by the model results; however, a final design for SEADOPOD should include consideration of using chain components in the mooring members.

Appendix A

Typical Moor Calculation

Beam Sea - 150 Foot Depth

Wind speed assumed to be 19 knots for State 4 sea.

Current assumed 1 knot uniform from surface to bottom.

A-1.	Wind drag on hull	R_W = 2060.31 lbs.
	Wind drag error ($0.4R_W$)[1]	R_{WE} = 824.12 lbs.
	Current drag on hull	R_C = 1470.00 lbs.
	Wind drag on A-frame	R_{WA} = 304.32 lbs.
	Total drag	R = 4658.75 lbs.
A-2.	Component of drag in planes of windward catenaries	$F_C = 0.707\ R = 3293.74$ lbs.

A-3. At 150 foot depth, permissable barge motion is ± 5 feet. Design for maximum barge motion of ± 3 feet to stay within ± 5 feet for all other barge headings.

A-4. Iterative solution performed using computer generated catenary characteristics to determine cable length for which restoring force equals external drag force at maximum displacement of ± 3 feet. Approximate solution obtained after several iterations and used to calculate current drag, $\Delta F_C = 168.37$ lbs.

A-5. New total drag = $F_C + \Delta F_C = 3462.11$ lbs. used to calculate corrected cable length. Small difference in current drag = 1.03 lbs. is neglected.

Cable length = 1401.84 ft.

A-6. Mooring rectangle determined from barge dimensions and horizontal projection of equilibrium distance from barge to anchor = 1388.77 feet.

Width 2(0.707x1388.77) + 40 = 2003.72 feet

Length 2(0.707x1388.77) + 140 = 2103.72 feet

[1] H. E. Saunders, Hydrodynamics in Ship Design, II (1957), pp. 274-87.

Appendix B

Computer Program "Barge B-F/V"

```
                C       MAIN PROGRAM BARGE B-F/V
                C
 0001                   DIMENSION DP(600,6), A(600), B(600)
 0002                   DIMENSION DT(20), TIM(2), OUTA(6), OUTB(6)
 0003                   COMMON DP, A, B, H, N
 0004                   READ (1,700) NWM, NRPM, NSS, NBD
 0005                   READ (1,701) DTTIM, DTRMS, DTAVG, DTIN
 0006                   READ (1,708) (DT(I),I = 1,5)
                C
                C       LOAD DATA
                C
 0007                   DO 5 I = 1,2
 0008                 5 READ (1,705) NRUN,TIM(I),(DP(I,J),J = 1,4),DP(I,6),DP(I,5)
 0009                   N = 3
 0010                10 READ (1,707,END = 100) L,(DP(N,J),J = 1,4),DP(N,6), DP(N,5)
 0011                   IF (L.EQ.1)  GO TO 100
 0012                   N = N + 1
 0013                   GO TO 10
 0014               100 N = N - 1
                C
                C       MAXIMUM AND MINIMUM DEPTHS
                C
 0015                   MXPD = 0
 0016                   MNPD = 300
 0017                   DO 105 I = 1,N
 0018                   NPD = DP(I,5)
 0019                   IF (NPD.GT.MXPD)  MXPD = NPD
 0020                   IF (NPD.LT.MNPD)  MNPD = NPD
 0021               105 CONTINUE
 0022                   NPD = 0
 0023                   IF (MXPD.EQ.MNPD) NPD = MXPD
                C
                C       FIND NSRDC VALUES
                C
 0024                   DTD = SQRT(DTRMS/DTTIM)
 0025                   DTRMS = DTD * 2.5 * DTIN / 1.5
 0026                   DTD = DTAVG/DTTIM
 0027                   DTAVG = DTD * 2.5 * DTIN / 1.5
 0028                   DTSD = SQRT(DTRMS**2 - DTAVG**2)
                C
                C       PREPARE OUTPUT PAGE
                C
 0029                   NPAG = 2
 0030               125 WRITE (3,710)
 0031                   WRITE (3,711) NRUN
 0032                   WRITE (3,712) (DT(I),I = 1,5)
 0033                   WRITE (3,713) NWM
 0034                   WRITE (3,714) NRPM
```

```
0035            WRITE (3,715) NSS
0036            WRITE (3,716) NBD
0037            IF (NPD.EQ.0)  WRITE (3,718) MNPD, MXPD
0038            IF (NPD.GT.0) WRITE (3,717) NPD
0039            WRITE (3,740)
0040            WRITE (3,741) DTTIM
0041            WRITE (3,742) DTRMS
0042            WRITE (3,743) DTAVG
0043            WRITE (3,744) DTSD
0044            IF (L.NE.1)  GO TO 126
0045        127 READ (1,708,END = 126) (DT(J),J = 1,20)
0046            WRITE (3,737) (DT(J),J = 1,20)
0047            GO TO 127
0048        126 IF (N.LE.5)  GO TO 900
0049            WRITE (3,719) NRUN, NPAG
0050            WRITE (3,728)
0051            WRITE (3,720)
0052            WRITE (3,721)
0053            WRITE (3,722)
          C
          C     LOAD POD DEVIATION 2
          C
0054            DO 130 I = 1,N
0055        130 DP(I,5) = DP(I,2) + DP(I,3)
          C
          C     FIND MAXIMUM AND MINIMUM VALUES
          C
0056            DO 150 J = 1,6
0057            BMX = 0.0
0058            BMN = 0.0
0059            DO 140 I = 1,N
0060            VAL = DP(I,J)
0061            IF (VAL.GT.BMX)  BMX = VAL
0062            IF (VAL.LT.BMN)  BMN = VAL
0063        140 CONTINUE
0064            OUTA(J) = BMX
0065        150 OUTB(J) = BMN
0066            WRITE (3,723) (OUTA(J),J = 1,6)
0067            WRITE (3,724) (OUTB(J),J = 1,6)
0068            PDMX = OUTA(5) - OUTB(5)
0069            BGMX = OUTA(2) - OUTB(2)
          C
          C     FIND AVERAGE VALUES
          C
0070        200 H = TIM(2) - TIM(1)
0071            AN = N
0072            TTIM = AN * H
0073            DO 220 J = 1,6
```

```
0074             DO 210 I = 1,N
0075         210 A(I) = DP(I,J)
0076             CALL QSF (H,A,B,N)
0077         220 OUTA(J) = B(N) / TTIM
0078             WRITE (3,725) (OUTA(J),J = 1,6)
           C
           C     FIND RMS VALUES
           C
0079             DO 320 J = 1,6
0080             DO 310 I = 1,N
0081         310 A(I) = DP(I,J) * DP(I,J)
0082             CALL QSF (H,A,B,N)
0083             OUTB(J) = SQRT(B(N) / TTIM)
0084             OUTA(J) = SQRT(B(N)/TTIM - OUTA(J)**2)
0085         320 CONTINUE
0086             WRITE (3,726) (OUTB(J),J = 1,6)
0087             WRITE (3,727) (OUTA(J),J = 1,6)
0088             PDRM = OUTA(5)
0089             BGRM = OUTA(2)
0090         400 WRITE (3,730) TTIM
0091             WRITE (3,731) H
0092             WRITE (3,732) N
0093             WRITE (3,733)
0094             WRITE (3,734)
0095             WRITE (3,735)
0096             WRITE (3,736)
0097             WRITE (3,738)
0098             WRITE (3,739)
           C
           C     TRANSLOADER EFFECTIVENESS
           C
0099             EFMX = 100.0 - PDMX*100.0/BGMX
0100             EFRM = 100.0 - PDRM*100.0/BGRM
0101             NPAG = NPAG + 1
0102             WRITE (3,719) NRUN, NPAG
0103             WRITE (3,729)
0104             WRITE (3,750) BGMX
0105             WRITE (3,751) PDMX
0106             WRITE (3,752) EFMX
0107             WRITE (3,753) BGRM
0108             WRITE (3,754) PDRM
0109             WRITE (3,752) EFRM
0110             CALL FORSR
0111         900 CALL EXIT
           C
           C
           C
           C
```

```
             C      FORMAT STATEMENTS
             C
0112            700 FORMAT (5I5)
0113            701 FORMAT (4F10.5)
0114            705 FORMAT (I5,F5.1,6F10.5)
0115            707 FORMAT (I1,9X,6F10.5)
0116            708 FORMAT (20A4)
0117            710 FORMAT (1H1,52X,22HSEADOPOD TEST ANALYSIS,///)
0118            711 FORMAT (5X,10HRUN NUMBER,20X,I3/)
0119            712 FORMAT (5X,8HRUN DATE,23X,5A4/)
0120            713 FORMAT (5X,15HWAVE MAKER TAPE,15X,I3/)
0121            714 FORMAT (5X,12HBLOWER SPEED,18X,I3,4H RPM/)
0122            715 FORMAT (5X,20HSIMULATED SEA STATE ,10X,I3/)
0123            716 FORMAT (5X,12HBOTTOM DEPTH,18X,I3,3H FT/)
0124            717 FORMAT (5X,9HPOD DEPTH,21X,I3,3H FT,3X,5HFIXED///)
0125            718 FORMAT (5X,9HPOD DEPTH,24X,13HVARIABLE   -   ,I3,7H FT TO ,I3,
               13H FT///)
0126            719 FORMAT (1H1,52X,22HSEADOPOD TEST ANALYSIS,/,5X,3HRUN,I3,102X,
               14HPAGE,I3,///)
0127            720 FORMAT (25X,7HSURFACE,12X,5HBARGE,13X,3HPOD,13X,3HPOD,14X,3HPOD,
               111X,9HAMPLIFIER)
0128            721 FORMAT (26X,6HHEIGHT,10X,8HPOSITION,9X,8HPOSITION,7X,
               112HDEVIATION  1,5X,12HDEVIATION  2,8X,6HOUTPUT,/)
0129            722 FORMAT (28X,2HFT,15X,2HFT,15X,2HFT,15X,2HFT,15X,2HFT,14X,5HVOLTS
               1//)
0130            723 FORMAT (5X,13HMAXIMUM VALUE,5X,6(1PE12.5,5X)/)
0131            724 FORMAT (5X,13HMINIMUM VALUE,5X,6(1PE12.5,5X)/)
0132            725 FORMAT (5X,13HAVERAGE VALUE,5X,6(1PE12.5,5X)/)
0133            726 FORMAT (5X,13HRMS VALUE     ,5X,6(1PE12.5,5X)/)
0134            727 FORMAT (5X,13HSTD DEVIATION,5X,6(1PE12.5,5X)/)
0135            728 FORMAT (57X,14HOVERALL VALUES,////)
0136            729 FORMAT (53X,25HTRANSLOADER EFFECTIVENESS,////)
0137            730 FORMAT (//,5X,20HTOTAL TIME INTERVAL ,9X,F6.1,4H SEC/)
0138            731 FORMAT (5X,16HINCREMENTAL TIME,13X,F6.1,4H SEC/)
0139            732 FORMAT (5X,20HNUMBER OF INCREMENTS,9X,I4///)
0140            733 FORMAT (5X,7HNOTES -,/,14X,34HSURFACE HEIGHT AND BARGE POSITION
               149HARE MEASURED RELATIVE TO THE STILL WATER LOCATION,/)
0141            734 FORMAT (14X,41HPOD POSITION IS THE CHANGE IN POD HEIGHT ,
               121HRELATIVE TO THE BARGE,/)
0142            735 FORMAT (14X,44HPOD DEVIATION GIVES THE CHANGE IN POD DEPTH ,
               129HRELATIVE TO ITS NOMINAL DEPTH)
0143            736 FORMAT (19X,33HDEVIATION 1 IS MEASURED DIRECTLY ,
               119HFROM THE CONTROLLER)
0144            737 FORMAT (5X,20A4)
0145            738 FORMAT (19X,32HDEVIATION 2 IS THE SUM OF BARGE ,
               117HAND POD POSITIONS,/)
0146            739 FORMAT (14X,45HSTD DEVIATION IS THE RMS VALUE ABOUT THE MEAN,/)
0147            740 FORMAT (5X,25HNSRDC SURFACE HEIGHT DATA/)
```

```
0148      741 FORMAT (10X,14HTOTAL RUN TIME,10X,F6.1,5X,3HSEC/)
0149      742 FORMAT (10X,10HRMS HEIGHT,15X,F9.5,3H FT/)
0150      743 FORMAT (10X,14HAVERAGE HEIGHT,11X,F9.5,3H FT,/)
0151      744 FORMAT (10X,13HSTD DEVIATION,12X,F9.5,3H FT,///)
0152      750 FORMAT (10X,33HMAXIMUM PEAK TO PEAK BARGE TRAVEL,8X,F9.5,3H FT,/
0153      751 FORMAT (10X,31HMAXIMUM PEAK TO PEAK POD TRAVEL,10X,F9.5,3H FT,/)
0154      752 FORMAT (10X,28HREDUCTION DUE TO TRANSLOADER,13X,F6.2,4X,7HPERCEN
0155      753 FORMAT (//////,10X,16HRMS BARGE TRAVEL,25X,F9.5,3H FT,/)
0156      754 FORMAT (10X,14HRMS POD TRAVEL,27X,F9.5,3H FT,/)
0157          END
```

PART III - THE OSCILAB MODEL TESTS

A. BACKGROUND

The background information provided in this report is limited to a brief outline and discussion of the University Sealab's design specifications and criteria, the OSCILAB's design concept and basic reasons for proposing a model testing program for the OSCILAB system. A complete and detailed presentation of these subjects may be found on pages 12 to 15, 95 and 97 to 183 of the "University Sealab" Report (NONR 3710-04, Technical Report No. 100).

1. Design Specifications and Criteria - The "University Sealab" Report sets forth a listing of the "research users' specifications" and the "designer's technical criteria." Those which are pertinent to the OSCILAB model test program include:

a. Specifications

(1) Maximum depth for research activity - 300 feet

(2) Maximum sea-state for operation - 5

(3) Environmental conditions for research studies - currents:

(a) for research (divers outside lab) - 0 to 1 knot

(b) for system integrity - 0 to 5 knots

b. Criteria

(1) Habitat stability (with particular reference to stability when habitat is in that portion of the water column disturbed by surface waves) - that required for acceptable motion characteristics under specified operating conditions

(2) System component capacity and safety (with particular reference to the main and stream anchor systems) - adequate under specified operating conditions

2. The OSCILAB Design Concept - The OSCILAB (Ocean Science Laboratory), shown in Fig. 1, is one of two scientific sealab concepts proposed in the "University Sealab" Report to meet the above, and other, specifications set forth by a committee of prominent marine scientists representing the potential

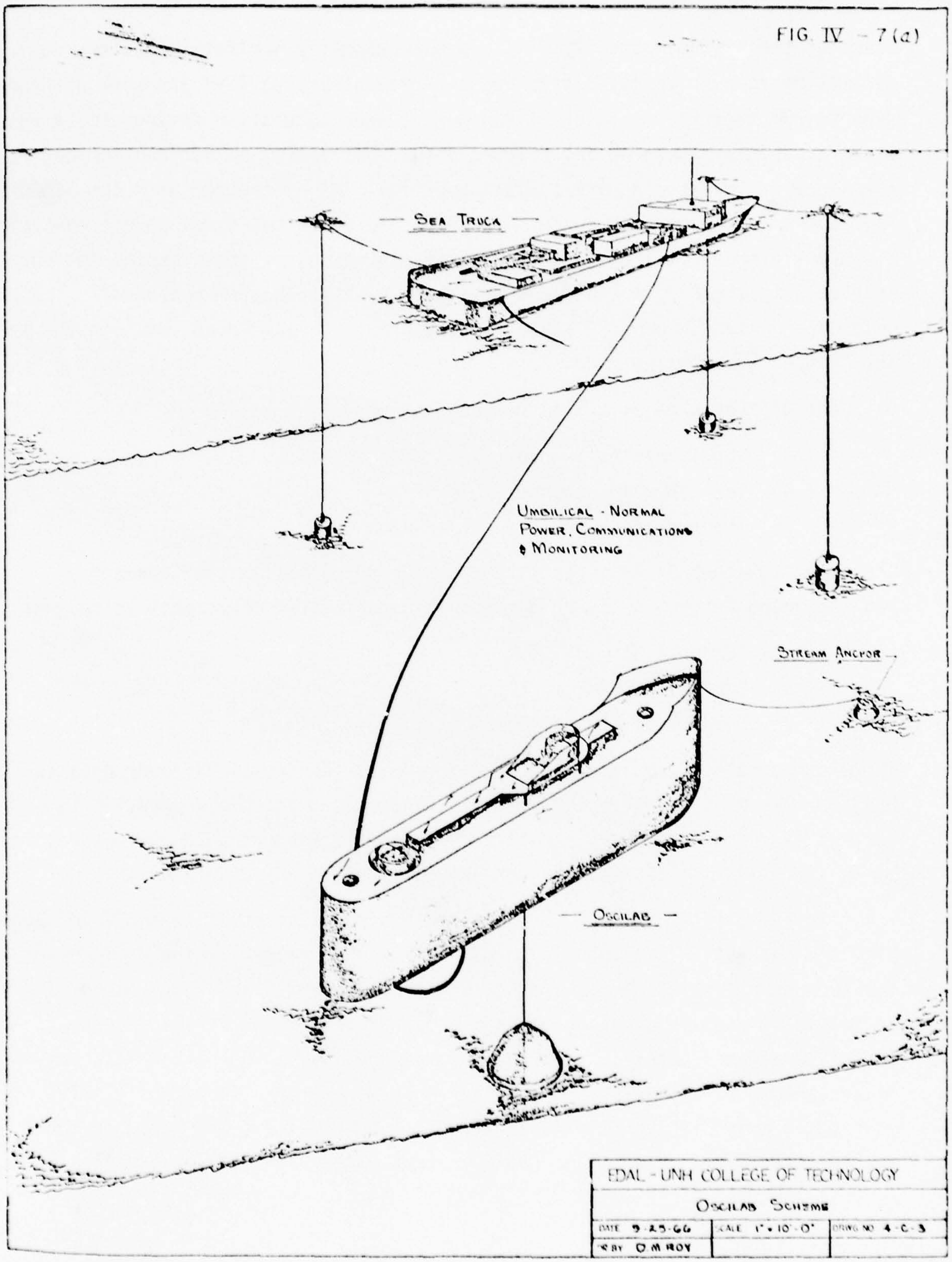


Figure 1
OSCILAB SYSTEM

users of the system. Briefly, it is a non-propelled habitat-laboratory vehicle permitting four scientist-divers and two crew-divers to live and work at depths down to 300 feet for a period of two weeks under saturation diving conditions. It is capable of lowering and raising itself but relies on surface support for normal power, monitoring and surface mobility. As contrasted with the SEADOPOD's "surface-oriented" design concept in which the scientist-diver spends most of his time in a pressurized surface facility invading the ocean depths for short intervals in the POD, the OSCILAB design concept is "bottom-oriented." The complete habitat-laboratory facility remains at its submerged location for the duration of the mission.

The OSCILAB's major system components are:

a. The laboratory - habitat
b. The surface - support ship
c. The surface - subsurface linkage

The investigations of this report are concerned only with the laboratory - habitat component which may be divided into sub-system components as follows:

a. The hull
b. The main anchor system
c. The stream anchor system

These three sub-systems are coupled, of course, insofar as the hydrodynamic behavior of the laboratory - habitat is concerned. In this regard, it is assumed that the laboratory - habitat and surface support ship are not coupled by the umbilical cable assembly forming the surface - subsurface linkage.

The hull, shown in Fig. 2, has overall dimensions of 71' x 18' x 10' beam with the main structure consisting of a 40' x 9' diameter cylinder closed at the ends by elliptical heads and housing the wet room, laboratory, control and living spaces. Three, double-hatched trunks serve as direct access and lock-type access routes to and from the main cylinder. One trunk also serves as an emergency decompression chamber. A personnel transfer capsule (PTC) is carried in a well just aft of the cylinder. Main ballast and buoyancy tanks are located at the ends of the craft. Fresh water bags, variable ballast

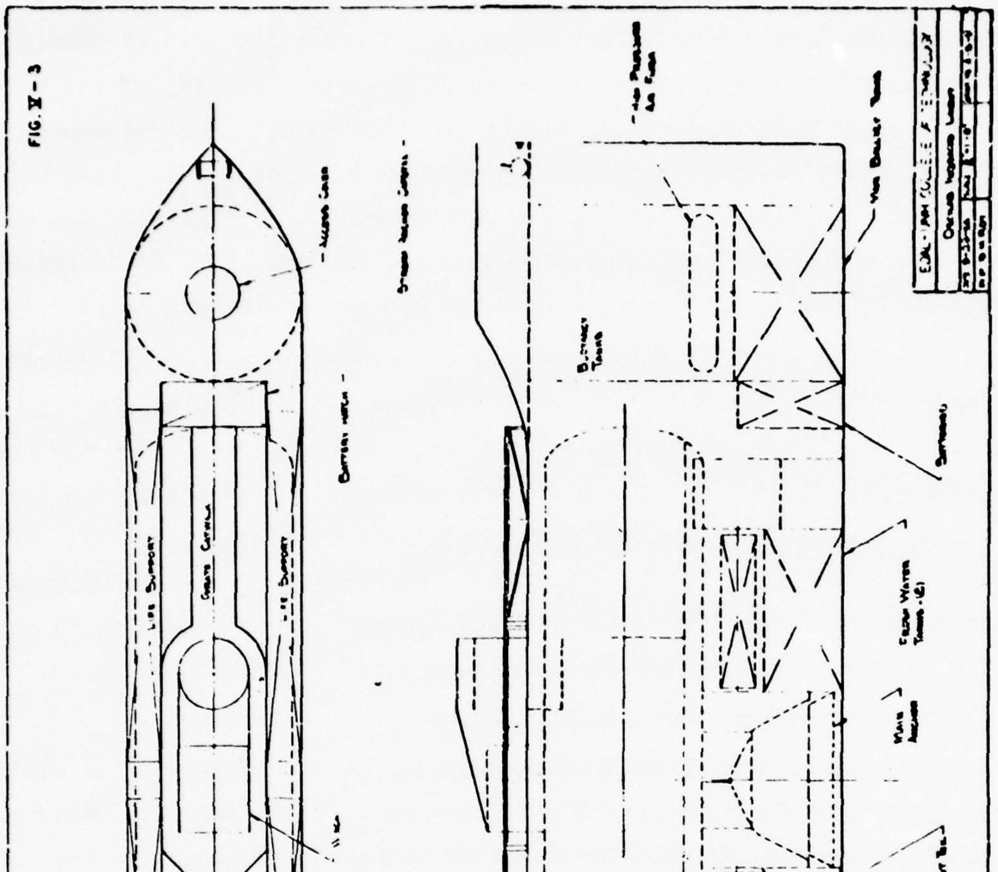


Figure 2
OSCILAB HULL

tanks and the main anchor recess are situated under the main cylinder. An emergency battery power pack is located on the keel just aft of the forward ballast tank. Life support gas flasks are located over the cylinder with compressed air flasks being stowed in the end buoyancy tanks. Lead ballast is located slightly above the hull's base line. Outer plating gives the hull a completely "wall-sided" shape curved at the bow and stern to decrease towing resistance and to provide for some measure of seakeeping ability.

The main anchor system consists of the winch and drive, the cable and the main anchor. The functions of this system are to provide a bottom mooring for winching OSCILAB down or up procedures, for tethering during the "decompression halt" procedure and for furnishing a secure mooring in the "on site" position. The main anchor consists essentially of two main ballast tanks which can be remotely flooded or blown. The smaller of the two tanks is flooded prior to lowering the anchor and assures adequate tension is developed in the cable. The larger of the two tanks is flooded when the anchor bottoms providing an adequate "holding down" force.

The stream anchor system consists of the winch and drive, the cable and the anchor. The functions of this system are to facilitate OSCILAB's making as nearly a vertical descent or ascent as is possible preventing horizontal drift by winching in or paying out cable and to aid in holding the vehicle in its bottom position in the presence of currents.

The OSCILAB's operating phases, diagrammed in Figs 3 and 4, are discussed briefly as follows:

a. Surface - In Transit - OSCILAB is towed in this operating phase. The main ballast tanks are dry thus providing the vehicle with about 3 1/2 feet of freeboard to improve seakeeping and handing characteristics. The main anchor is dry and housed.

b. Surface - Rig for submerging - The stream anchor is positioned on the bottom with its cable's scope such as to give the anchor proper holding power while permitting the vehicle to make a nearly vertical descent to the desired bottom location. The main anchor's lower ballast tank is flooded and it is lowered to a certain distance above

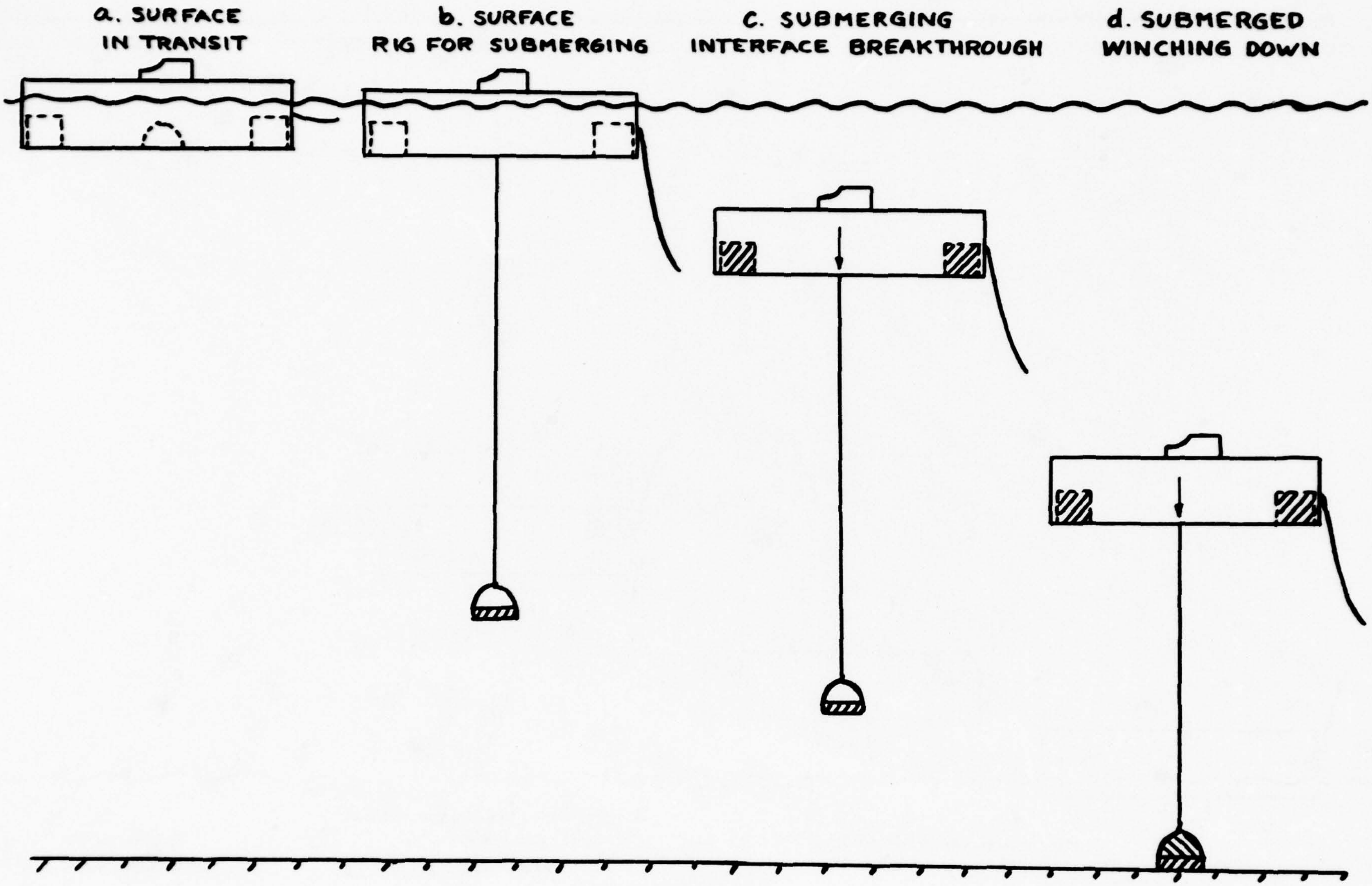


FIGURE 3
OPERATING PHASES

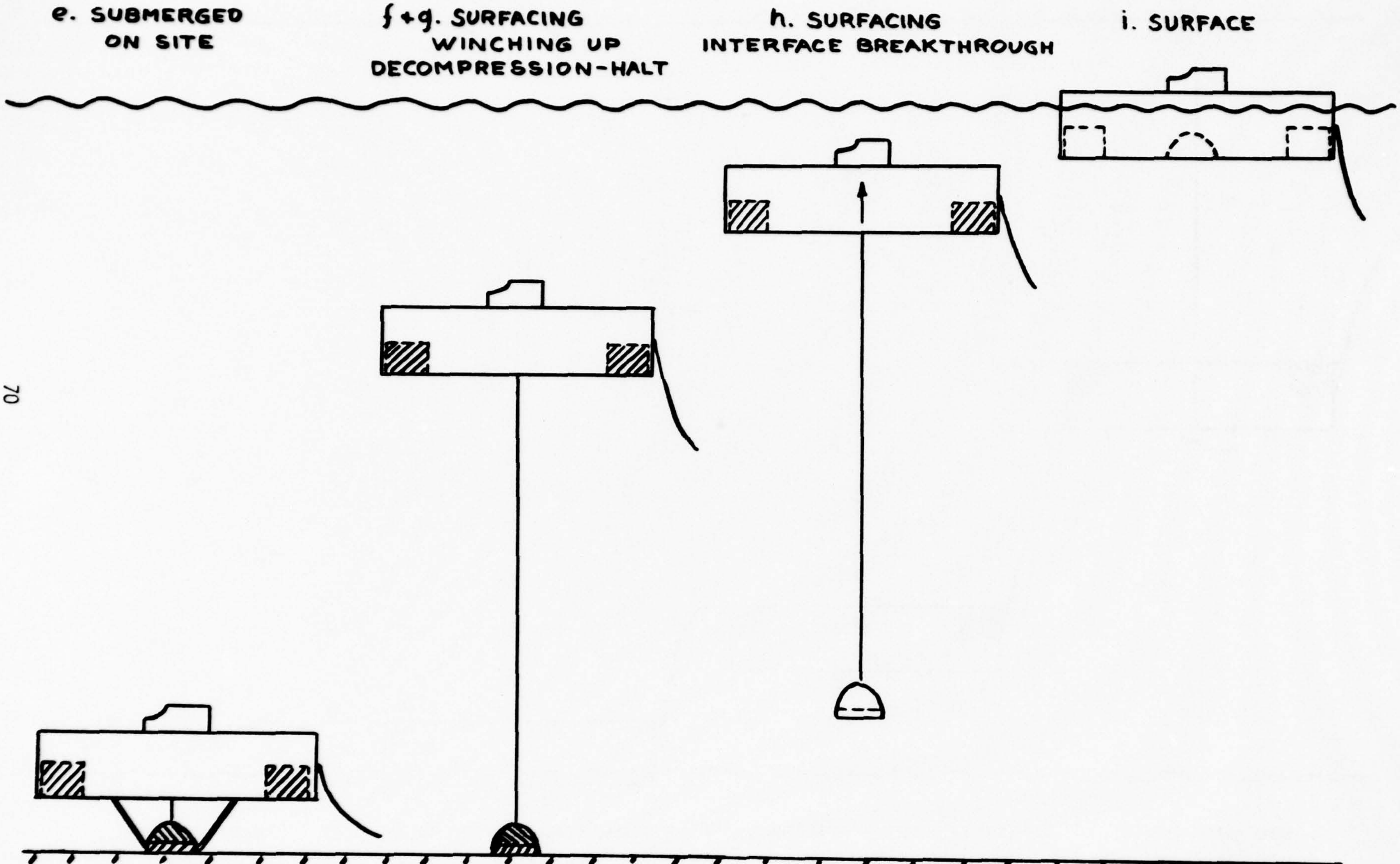


FIGURE 4
OPERATING PHASES

the bottom, this distance being such that the OSCILAB will have just penetrated the portion of the water column disturbed by surface waves when the anchor bottoms. The main ballast tanks are dry providing for a substantial degree of reserve buoyancy.

c. Submerging - Interface Breakthrough - The main ballast tanks are flooded which, together with the flooded lower ballast tank of the anchor, provide the slight negative buoyancy required for descent. The stream anchor cable is winched in to cause approximately a vertical descent. The main anchor's upper ballast tank vent is tripped when the anchor bottoms permitting the flooding of this tank and providing an adequate "hold-down" force.

d. Submerging - Winching Down - OSCILAB regains a slight positive buoyancy when the main anchor bottoms thereby placing it in a "tethered" condition. The vehicle is then "winched down" on the main anchor cable to its bottomed position. The scope of the stream anchor is continuously adjusted to obtain a nearly vertical descent.

e. Submerged - On Site - OSCILAB is positioned at its bottom working site. "Preventer-bars" are rigged between OSCILAB and the main anchor to back up the main anchor cable.

f. Surfacing - Winching Up - "Preventer-bars" are removed from the main anchor and the OSCILAB is "winched up" with slight positive buoyancy to the "decompression-halt" depth. Approximately vertical ascent is obtained by paying out the stream anchor cable.

g. Surfacing - Decompression Halt - A "Decompression-halt" in ascent is made at as shallow a depth as possible without subjecting OSCILAB to an undue amount of motion by surface waves and the main anchor cable to excessive dynamic loadings. This "halt" allows the occupants to carry on near-normal living and working routines, experiencing relatively little motion, while undergoing decompression procedures. The shallow depth facilitates help from the surface reaching OSCILAB or escape using oxygen purging techniques in event of emergencies encountered during the decompression period.

h. Surfacing - Interface Breakthrough - Both lower and upper main anchor ballast tanks are blown remotely, a jet system on the anchor being used to free it from the bottom if necessary. The anchor is raised off the bottom as the vehicle penetrates the interface and surfaces in an "awash" condition with the main ballast tanks flooded. The main anchor is winched up to its housed position.

i. Surface - The main ballast tanks are blown restoring full reserve buoyancy and freeboard. The stream anchor may or may not be retrieved depending on whether or not OSCILAB is to be towed to another site.

3. Basic Reason for Proposing Model Tests - The basic reason for proposing model tests is to acquire data and information, difficult to obtain by analytical means alone, which further investigates the feasibility of the OSCILAB's conceptual design. This design was developed sufficiently in the "University Sealab" Report to prove its general feasibility. However, the Report noted that this design concept should receive additional study through model testing to determine OSCILAB's dynamic responses to hydrodynamic forces and moments imposed by surface wave action and submerged currents - such tests being necessary to evaluate the design's safety and ability to operate successfully under conditions established by the user's specifications.

B. OBJECTIVES

The objectives of this model test program are stated as they pertain to the three normal and one emergency operating phases included in the scope of this program.

1. "Submerging - Interface Breakthrough" Test Objectives - To obtain qualitative data regarding:

a. Model response in pitching and heaving, in prescribed seas and with the main anchor at varying depths below model, while on the surface and descending through that portion of the water column disturbed by surface waves - for the purpose of obtaining maximum pitch, heave and acceleration data for motion and main anchor-cable system response studies.

b. The rate of descent, prior to the bottoming of the main anchor, in that portion of the water column not disturbed by surface waves - for the purpose of checking theoretical values of drag coefficients and ballasting calculations.

c. The "over-riding" of model after the main anchor bottoms - for the purpose of evaluating the necessity for a "constant-tension" winch and checking ballasting conditions.

2. "Surfacing - Winching Up" Test Objectives - To obtain qualitative and quantitative data regarding:

a. Model response in pitching and heaving, in prescribed seas and with the main anchor on the bottom, while being "winched up" into that portion of the water column disturbed by surface waves - for the purpose of determining practical "decompression-halt" depths insofar as limiting pitching and heaving motions and main anchor cable forces are concerned.

b. Model response and main anchor cable forces - for the purpose of checking analytical computations of these cable forces.

3. "Surfacing - Free Ascent" Test Objectives - To obtain qualitative data regarding:

a. Model response in pitching and heaving, in prescribed seas and free of the main anchor cable, while making a "free" ascent through the water column from its bottom moored position - for the purpose of obtaining maximum pitch, heave and acceleration data.

b. The rate of ascent - for the purpose of checking theoretical values of drag coefficients.

4. "Submerged - On Site" and "Surfacing - Winching Up" Test Objectives - To obtain qualitative and quantitative data regarding:

a. Forces developed in the main and stream anchor cables, the model in a bottom-moored position and in currents of prescribed magnitude and direction - for the purpose of evaluating the adequacy of the mooring system in this mode of operation.

b. Forces developed in the main and stream anchor cables and the general motion of the model, the model being "winched up" from its bottom-moored position in currents of prescribed magnitude and direction - for the purpose of evaluating the mooring system in this mode of operation.

C. THE OSCILAB SYSTEM AS MODELED

The geometry of the modeled system is based on a linear scale factor of 15, this value being chosen in order to model directly the 300 foot deep water column by the 20 foot depth of the Maneuvering and Seakeeping (MASK) basin at the Naval Ship Research and Development Center (NSRDC), Carderock, Maryland. Using this scale factor, the following hull model data is obtained:

TABLE 1

Characteristic	Prototype	Model
Length	71.0'	56.8"
Breadth	10.0'	8.0"
Depth	18.0'	14.4"
Displacement (Sur-Mn. Anchor Dry)	174.8 LT	112.9#
Displacement (Sub)	202.7 LT	130.9#
	(S.W.@64#/ft^3)	(F.W.@62.274#/ft^3)
Centers of Buoyancy (Sur)		
Vertical (Above Base Line)	9.3'	7.4"
Longitudinal (Amidships)	0.0'	0.0"
Centers of Buoyancy (Sub)		
Vertical (Above Base Line)	10.4'	8.3"
Longitudinal (Amidships)	0.1' aft	0.1" aft
Centers of Gravity (Sur)		
Vertical (Above Base Line)	6.7'	5.3"
Longitudinal (Amidships)	0.1'	0.1"
Centers of Gravity (Sub)		
Vertical (Above Base Line)	6.3'	5.0"
Longitudinal (Amidships)	0.1' aft	0.1" aft
Stability Data		
Surface (Mn. Anchor Dry)		
Trans. metacentric height (GM_t) (uncorrected for free surface)	3.0'	2.4"
Long. metacentric height (GM_l) (uncorrected for free surface)	32.3'	25.8"

Submerged (Tethered condition)		
BG (uncorrected for free surface)	4.1'	3.3"
Free surface correction assumed	0.1'	0.1"
Radii of Gyration (Sur)		
About roll axis (kx)	7.2'	5.8"
About pitch axis (ky)	18.4'	14.7"
Radii of Gyration (Sub)		
About roll axis (k'x)	6.8'	5.4"
About pitch axis (k'y)	20.0'	16.0"

The above data is based on a careful review and refinement of the weight and center data for the OSCILAB design as contained in the "University Sealab" Report.

The modeled hull is pictured in Fig. 5. Its dimensions, volume and volume distribution are such as to obtain the correct dimensions, volumes and centers of volume. The magnitude and position of lead weights placed on the hull are such as to obtain the correct weights, centers of gravity and distribution of mass. The hull itself is constructed essentially of laminated mahogany, its surface being prepared and painted in an effort to reduce water absorption to a minimum. Ballast tanks, modeled for those on the prototype, are located at the extreme ends of the hull being flooded by tripping vent valves and "blown" by lifting the hull out of the water.

The main anchor system is designed to model the prototype anchor as closely as possible. The dimensions and weight of the anchor are such as to obtain the correct weight dry and with its lower and upper ballast tanks flooded. As is the prototype, it is provided with a tripping mechanism which is activated on contact with the bottom causing the upper ballast tank to flood. The main anchor winch, together with its electric drive, is mounted on the hull and is operated by remote control.

The stream anchor system is designed to simulate the action of the prototype system but is not a model of it. The cable has a 5 to 1 (horizontal to vertical ratio) providing for a scope of 100' when the hull is on the surface in MASK facility tests. The dimensions of the Circulating Water Channel (CWC) facility, however, preclude the use of this scope. A 50 pound weight serves as the stream anchor clump. The anchor cable is led through a fairlead on this clump and attached to a "return line," this line being led to a surface station where it can be reeled in or out to simulate the action of the prototype's stream anchor winch.

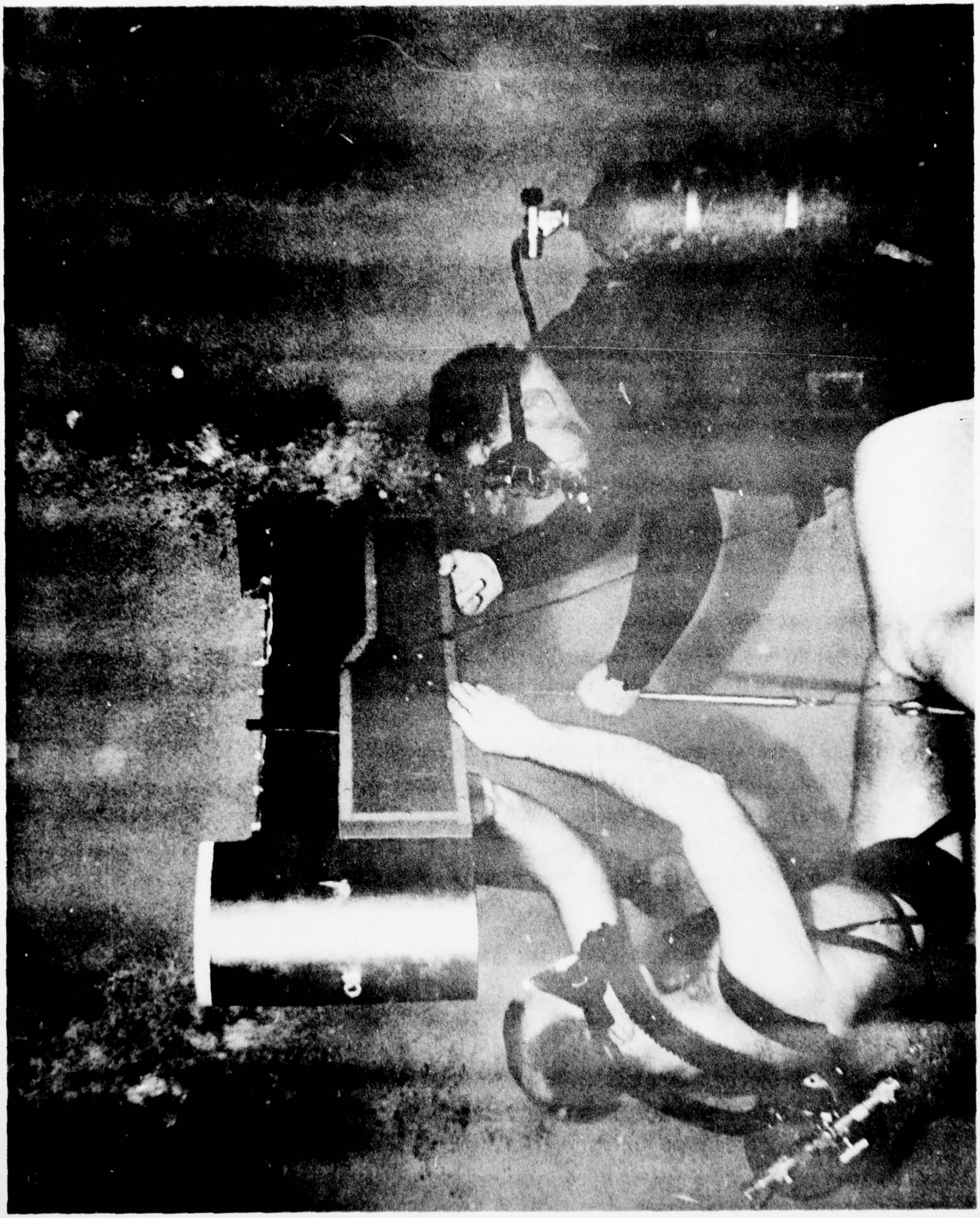


Figure 5 OSCILAB HULL UNDERGOING TEST

D. TEST PROCEDURES & FACILITIES

This presentation divides the test procedures and associated facilities into two categories; preliminary tests conducted at the University of New Hampshire and the scheduled tests at the facilities of the Naval Ship Research and Development Center, Carderock, Maryland. These procedures cover a period of time from 12 December 1967 to 17 April 1968.

1. Preliminary Tests

a. Tests to obtain calculated weight, displacement and centers (as listed in table of hull characteristics on page 11). The hull, as received from the vendor, was fitted with the "dynamic balance" weights located in their approximately correct positions. The assembly was then weighed, submerged in a "tethered" condition and balanced to obtain "first trial" weight, displacement and center data. An allowance was made in the design for a small addition of weight and displacement to facilitate obtaining the required centers of gravity and displacement if necessary. It was necessary and two additional trials were required to obtain the correct weight, displacement and centers within an accuracy range of $\pm$ 1.5%. It should be noted that this level of accuracy deteriorated to some extent as the tests progressed due primarily to water absorption by the hull in spite of its protective coating.

b. Dynamic balancing - Dynamic balancing required locating two, 24 pound lead weights on the hull so as to model the prototype's distribution of mass about the hull's centroidal pitch and roll axes while maintaining the center of gravity at its correct location. Conventional methods for ballasting models for seakeeping tests were used and the results checked by obtaining natural periods of pitch (submerged) and roll (surfaced). For pitching (submerged - for ease in timing the slower periods as compared to pitching periods on the surface):

(1) The calculated period for the model is:

$$T_P = 1.108 \sqrt{\frac{(k'y)^2(1 + Cp)}{BG_V}} = \sqrt{\frac{(1.33)^2(1 + 1.8)}{0.267}} = \underline{4.75 \text{ seconds}}$$

where:

$k'y$ = radius of gyration about pitch axis (sub) = 1.33'

Cp = Factor for virtual mass of hull associated with pitching motion = 1.8

BG_v = BG corrected for free surface = 0.267'

(2) The average observed period was 4.67 seconds

For rolling (surfaced):

(1) The calculated period for the model is:

$$T_R = 1.108 \sqrt{\frac{kx^2(1 + C_R)}{G_vM}} = 1.108 \sqrt{\frac{0.484^2(1 + 0.2)}{0.192}} = \underline{1.34 \text{ seconds}}$$

where:

kx = radius of gyration about roll axis (sur) = 0.484'

C_R = Factor for virtual mass of hull (wall-sided with square bilge) associated with rolling motion

G_vM = GM corrected for free surface = 0.191'

(2) The average observed period was 1.40 seconds

c. Watertightness and general operating tests - OSCILAB was tested extensively in the 15 foot depth section of the University's indoor swimming pool with the aid of scuba divers. Watertightness at the maximum depth was a primary consideration, and these tests revealed deficiencies which necessitated alterations in the hull construction. The final model's characteristics were checked in the 15 foot water column, including those relating to the "interface breakthrough," "winching down," winching up," and "free ascent" operating phases.

d. Equipment Tests - The major item of test equipment designed and built at the University was the "dumb waiter" - a device for lowering and raising the T.V. and movie cameras for tracking and recording the model's motion as it descended or ascended in the water column. The "dumb waiter," shown in Fig. 6, consisted of:

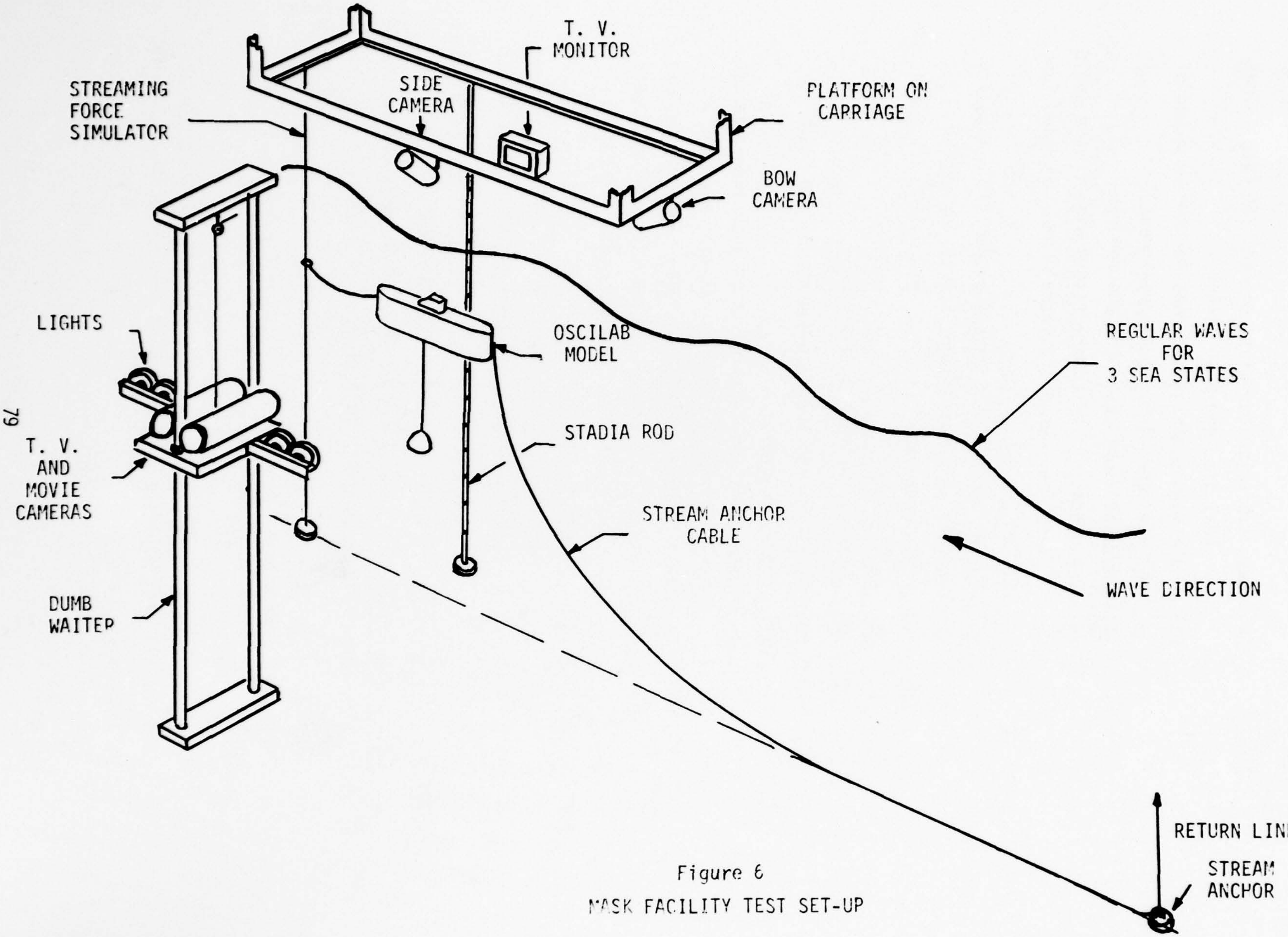


Figure 6
MASK FACILITY TEST SET-UP

(1) Two, 1.5" diameter aluminum rods 24' long joined by steel head and base plates

(2) A platform spanning the rods for the mounting of the T.V. and movie camera equipment

(3) Two watertight cases for the cameras

(4) One portable T.V. camera fitted with a wide angle 1" lens - a component of the GE Mobile Video Tape System

(5) One Milliken DBM-5C camera of 400' film capacity and set at a speed of 64 frames per second.

(6) Eight underwater lights of 650 watts, 120 volts and 5.6 amps

(7) Lowering and raising line

Test procedure for the above components of the "dumb waiter" were as follows:

(1) Watertightness Tests of Cases - prolonged immersion at 15 foot depth in swimming pool and at 20 foot depth in MASK facility with zero leakage.

(2) Tests of T.V. camera and associated video tape equipment, both on shore and with the camera operating under water.

(3) Operation tests of "dumb waiter" system, as assembled, in swimming pool (except for movie camera and lights).

2. Tests at the Naval Ship Research and Development Center

a. MASK Facility Tests - Three series of tests were conducted in the MASK facility being designated as follows:

Series A - "Submerging - Interface Breakthrough"
Series B - "Surfacing - Winching Up"
Series C - "Surfacing - Free Ascent"

The general test set-up, shown in Fig. 6, was essentially the same for all test series and is described briefly in the following paragraphs.

The MASK carriage and working platform positions were fixed, these positions locating the model in the 20 foot deep section of the basin with its longitudinal axis normal to the unidirectional wave train. The model was removed a sufficient distance from the basin's wave making end to permit a 100 foot scope of stream anchor "cable" and was well clear of the beach end of the basin to avoid reflected waves. The hull was constrained to move approximately vertically and in a fixed plane by the stream anchor and the "streaming force simulator" consisting of a "soft" coupling system of rubber bands attaching the stern of the model to a taut vertical wire. The plane of motion was 10 feet from the lenses of the "dumb waiter" cameras and 9 inches from the vertical references, or stadia, rod.

These test series were concerned primarily with the acquisition of the model's dynamic response to hydrodynamic forces and moments created by surface wave action in the "interface" - "interface" being defined as that portion of the water column significantly influenced by surface wave motion. For "deep water" waves, the depth of this interface layer from the surface is about one-half of the surface wave length. The scope of the study limited the tests to the use of unidirectional waves with crest-lines at right angles to the fore-and-aft axis of the model (bows-on waves). It was necessary to choose between unidirectional "regular" and "irregular" surface waves, the latter, of course, more closely representing actual sea conditions with wave heights and lengths varying in a random fashion. However, irregular waves could not be used throughout these tests as the time required for the model to penetrate the interface was so short that statistically meaningful data could not be obtained. Said another way, one could not be sure what segment of the irregular wave train record was "seen" by the model while in the interface. In certain phases of these tests, irregular waves could have been used, but the length of time involved in being certain that the model had "seen" the wave train sufficiently would have elevated the cost of response data acquisition by high speed motion pictures above the program's budget.

One set of regular waves were used approaching the severest conditions for the three sea-states involved - those generated by 12, 16 and 20 knot wind velocities representing Mid-2, High-3, and Low-5 sea states respectively. This set had wave periods equal to the periods of maximum spectral density for the three "seas" involved (using the "Newmann Spectra for Fully Developed Seas Generated by Wind Speeds of 12 to 20 knots"), Fig. 7, and wave heights equal to the average of the 1/10 highest for these same seas. The periods of these waves were quite close to the hull's natural heave and pitch periods which added to the severity of these tests. Reference is made to the Wilbur Marks "Wind and Sea Scale for Fully Arisen Seas" chart, Fig. 8, for the statistically derived wave parameters used in these tests. Table 2 summarizes the model wave data used:

TABLE 2

Wind Speed	Max Spectral Density			
	Period sec	L(wave) ft	LW/2 ft	Height* inches
12 k	1.24	7.9	3.9	2.2
16 k	1.68	14.4	7.2	4.7
20 k	2.09	22.4	11.2	8.0

* average 1/10 highest wave

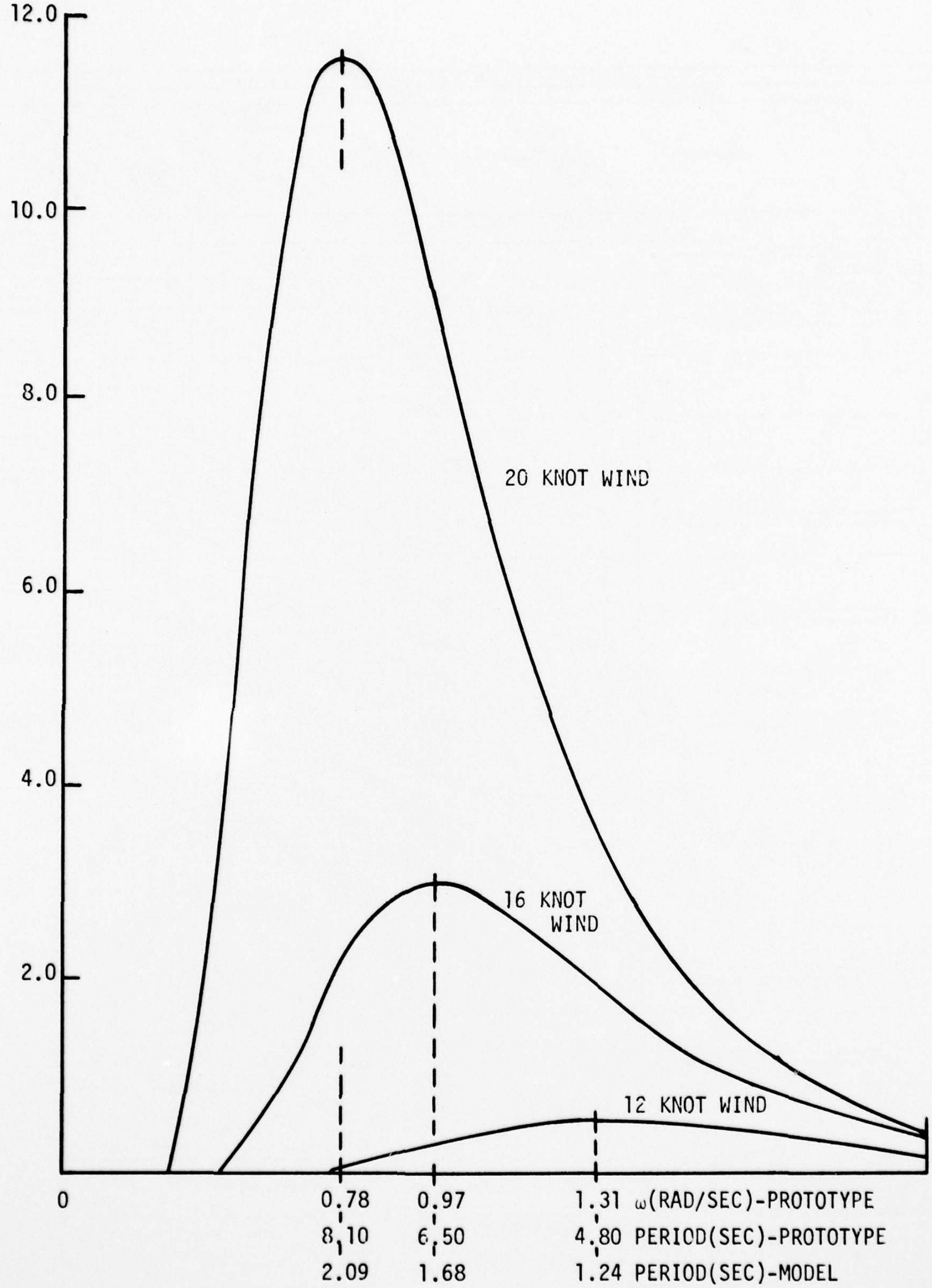


Figure 7

NEUMANN SPECTRA - FULLY DEVELOPED SEAS GENERATED BY WIND VELOCITIES OF 12, 16 & 20 KNOTS

WIND AND SEA SCALE FOR FULLY ARISEN SEA

Sea State[1]	Sea-General: Description[2]	Wind[3]: (Beaufort) Wind Force	Wind: Description	Wind: Range (Knots)	Wind: Wind Velocity (Knots)	Sea[3]: Wave Height Feet: Average	Sea: Wave Height Feet: Significant	Sea: Wave Height Feet: Average 1/10 Highest	Sea: Significant Range of Periods (Seconds)	Sea: T_{max} (Period of Maximum Energy of Spectrum)	Sea: $\bar{T}$ (Average Period)	Sea: $\bar{L}$ (Average Wave Length)	Sea: Minimum Fetch (Nautical Miles)	Sea: Minimum Duration (Hours)
0	Sea like a mirror.	0	Calm	Less than 1	[a] **0**	0	0	0	–	–	–	–	–	–
	Ripples with the appearance of scales are formed, but without foam crests.	1	Light Airs	1 - 3	2	0.05	0.08	0.10	up to 1.2 sec	0.7	0.5	10 in.	5	18 min
1	Small wavelets, still short but more pronounces; crests have a glassy appearance, but do not break.	2	Light Breeze	4 - 6	5	0.18	0.29	0.37	0.4-2.8	2.0	1.4	6.7 ft	8	39 min
	Large wavelets, crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	3	Gentle Breeze	7 -10	**8.5**	0.6	1.0	1.2	0.8-5.0	3.4	2.4	20	9.8	1.7 hrs
					10	0.88	1.4	1.8	1.0-6.0	4	2.9	27	10	2.4
2	Small waves, becoming larger; fairly frequent white horses.	4	Moderate Breeze	11-16	→ 12	1.4	2.2	2.8	1.0-7.0	4.8	3.4	40	18	3.8
					13.5	1.8	2.9	3.7	1.4-7.6	5.4	3.9	52	24	4.8
3					14	2.0	3.3	4.2	1.5-7.8	5.6	4.0	59	28	5.2
					→ 16	2.9	4.6	5.8	2.0-8.8	6.5	4.6	71	40	6.6
4	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray).	5	Fresh Breeze	17-21	18	3.8	6.1	7.8	2.5-10.0	7.2	5.1	90	55	8.3
					19	4.3	6.9	8.7	2.8-10.6	7.7	5.4	99	65	9.2
					→ 20	5.0	8.0	10	3.0-11.1	8.1	5.7	111	75	10
5	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray).	6	Strong Breeze	22-27	22	6.4	10	13	3.4-12.2	8.9	6.3	134	100	12
					24	7.9	12	16	3.7-13.5	9.7	6.8	160	130	14
					24.5	8.2	13	17	3.8-13.6	9.9	7.0	164	140	15
6					26	9.6	15	20	4.0-14.5	10.5	74	188	180	17
	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. (Spindrift begins to be seen).	7	Moderate Gale	28-33	28	11	18	23	4.5-15.5	11.3	7.9	212	230	20
					30	14	22	28	4.7-16.7	12.1	8.6	250	280	23
					30.5	14	23	29	4.8-17.0	12.4	8.7	258	290	24
					32	16	26	33	5.0-17.5	12.9	9.1	285	340	27
7	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh Gale	34-40	34	19	30	38	5.5-18.5	13.6	9.7	322	420	30
					36	21	35	44	5.8-19.7	14.5	10.3	363	500	34
					37	23	37	46.7	6-20.5	14.9	10.5	376	530	37
					38	25	40	50	6.2-20.8	15.4	10.7	392	600	38
					40	28	45	58	6.5-21.7	16.1	11.4	444	710	42
8	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Visibility affected.	9	Strong Gale	41-47	42	31	50	64	7-23	17.0	12.0	492	830	47
					44	36	58	73	7-24.2	17.7	12.5	534	960	52
					46	40	64	81	7-25	18.6	13.1	590	1110	57
	Very high waves with long overhanging crests. The resulting foam is in great patches and is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shocklike. Visibility is affected.	10	Whole Gale*	48-55	48	44	71	90	7.5-26	19.4	13.8	650	1250	63
					50	49	78	99	7.5-27	20.2	14.3	700	1420	69
					51.5	52	83	106	8-28.2	20.8	14.7	736	1560	73
9					52	54	87	110	8-28.5	21.0	14.8	750	1610	75
					54	59	95	121	8-29.5	21.8	15.4	810	1800	81
	Exceptionally high waves (Small and medium-sized ships might for a long time be lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	11	Storm*	56-63	56	64	103	130	8.5-31	22.6	16.3	910	2100	88
					59.5	73	116	148	10-32	24	17.0	985	2500	101
	Air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	12	Hurricane*	64-71	> 64	> 80[b]	> 128[b]	> 164[b]	10-(35)	(26)	(18)	~	~	~

*For hurricane winds (and often whole gale and storm winds) required durations and fetches are rarely attained. Seas are therefore not fully arisen.

a) A heavy box around this value means that the values tabulated are at the center of the Beaufort range.

b) For such high winds, the seas are confused. The wave crests blow off, and the water and the air mix.

1) Encyclopedia of Nautical Knowledge, W.A. McEwen and A.H. Lewis, Cornell Maritime Press, Cambridge, Maryland, 1953, p. 483

2) Manual of Seamanship, Volume II, Admiralty, London, H.M. Stationery Office, 1952, pp. 717-718

3) Practical Methods for observing and forecasting Ocean Waves, Pierson, Neumann, James, N.Y. Univ. College of Engin. 1953.

This table compiled by Wilbur Marks, David Taylor Model Basin

Figure 8

SEA-STATE CHART

These tests, as noted above, were limited to unidirectional, bows-on waves and hence the response motions of prime interest were those of pitch and heave. High speed motion picture techniques were used to obtain response data, the speed of the movie cameras being calculated as follows:

$$\text{Model Time} = \text{Prototype Time} \times (\text{scale factor})^{\frac{1}{2}}$$

or

$$\text{Camera Time (pauses/sec)} = \text{Projection time (frames/sec)} \times (\text{scale factor})^{\frac{1}{2}}$$

$$\text{Camera Time} = 16\ (15)^{\frac{1}{2}} = 16 \times 3.86 = 60$$

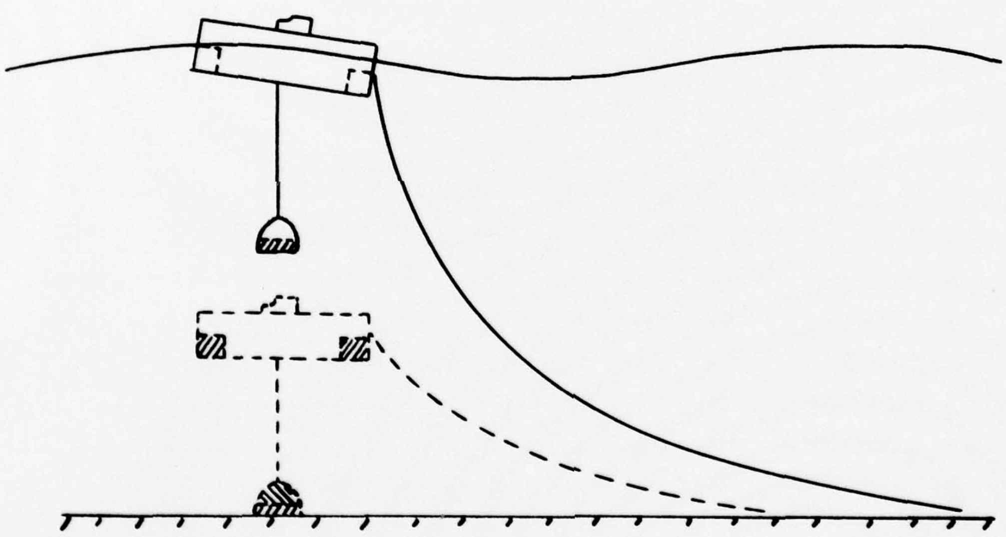
$$\text{Camera Time} \doteq 64 \text{ frames/second}$$

The horizontal reference line for measuring angular displacements in making a frame by frame analysis of the pitching response was the bottom edge of the frame, the underwater camera's base being in a horizontal plane at all times. The vertical reference for measuring displacements associated with heave was furnished by the stadia rod. While the primary response data was obtained by the "dumb waiter" camera, bow and beam oriented cameras recorded motion of the hull while on the surface.

The MASK facility tests required six men, three from the NSRDC and three from the University. NSRDC personnel were required to operate the wave generator, the Sanborn Recorder on the carriage and the movie cameras. University personnel operated the model's main ballast vents in submerging procedures the "dumb waiter" and controlled the stream anchor cable. The model's motion in the water column was tracked by T.V., this motion being recorded on video tape as well as on film. The video taping proved extremely useful for play-back purposes in checking on various aspects of the test run.

The following concerns procedures followed for the MASK series of tests:

(1) Series A - "Submerging - Interface Breakthrough" - A sketch of the A test series is shown below:



This series of tests began with the model on the surface, the stream anchor positioned on the bottom and the main anchor lowered to certain depths below the model with its lower ballast tank flooded. After the wave train was established, the model remained

AD-A071 403 NEW HAMPSHIRE UNIV DURHAM ENGINEERING DESIGN AND ANA--ETC F/G 13/10
UNIVERSITY SEALAB. MODEL TESTS FOR A SATURATION DIVING FACILITY--ETC(U)
MAR 69 E E ALLMENDINGER, F A BLANCHARD N00014-67-A-0158-0005
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on the surface for about 15 seconds for the purpose of acquiring maximum pitch and heave response data. The model's main ballast tanks were then vented giving the model - main anchor system a slight negative buoyancy and causing the system to sink. The "dumb waiter" cameras recorded pitch and heave response data and rate of descent data with the model in and below the interface. On bottoming, the main anchor's upper ballast tanks flooded. The model's downward momentum caused it to "override" the main anchor prior to finally reaching its "tethered condition" depth, this override data being recorded by the cameras.

The main anchor was lowered to three depths below the surface for each sea generated, the greatest depth being that required to first submerge the model below the interface. The effect of varying the length of the cable in the coupled model-main anchor system was thus observed. Instrumentation limitations precluded obtaining cable tension data as wiring leading from the anchor end of the cable to the surface would have influenced anchor motion.

The following table summarizes the A series tests, these tests being designated as illustrated by the example

A - 12 - 10

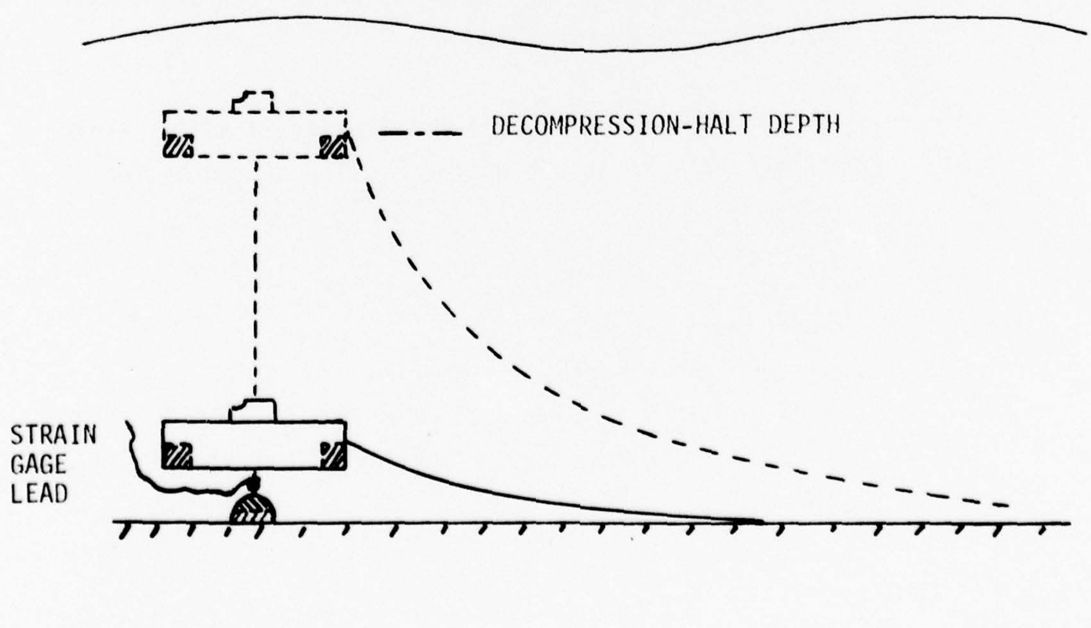
where

A = series designation
12 = 12 knot wind generated waves
10 = main anchor initially 10 ft from surface

TABLE 3

TEST	WAVE			
	Period sec	Length ft	L/2 ft	Height inches
A-12-10	1.24	7.9	3.9	2.2
A-12-13	1.24	7.9	3.9	2.2
A-12-16	1.24	7.9	3.9	2.2
A-16-6	1.68	14.4	7.2	4.
A-16-9	1.68	14.4	7.2	4.
A-16-12	1.68	14.4	7.2	4.
A-20-4	2.09	22.4	11.2	8.
A-20-6	2.09	22.4	11.2	8.
A-20-8	2.09	22.4	11.2	8.

(2) Series B - "Surfacing - Winching Up" - A sketch of the B series is shown below:



This series of tests began with the stream anchor and the fully flooded main anchor on the bottom. Initially, the model was in a "tethered" condition just below the interface zone. It was then gradually winched up to its "decompression halt" depth of 2.5 feet corresponding to a full scale depth of about 40 feet.

The "dumb waiter" camera recorded pitch and heave response during the ascent and "decompression halt" period. A U-type electric strain gage was affixed to main anchor cable just above the anchor and cable loadings were plotted on the Sanborn Recorder's strip chart.

The following table summarizes the B series tests, these tests being designated as illustrated by the example

B - 12 - 5

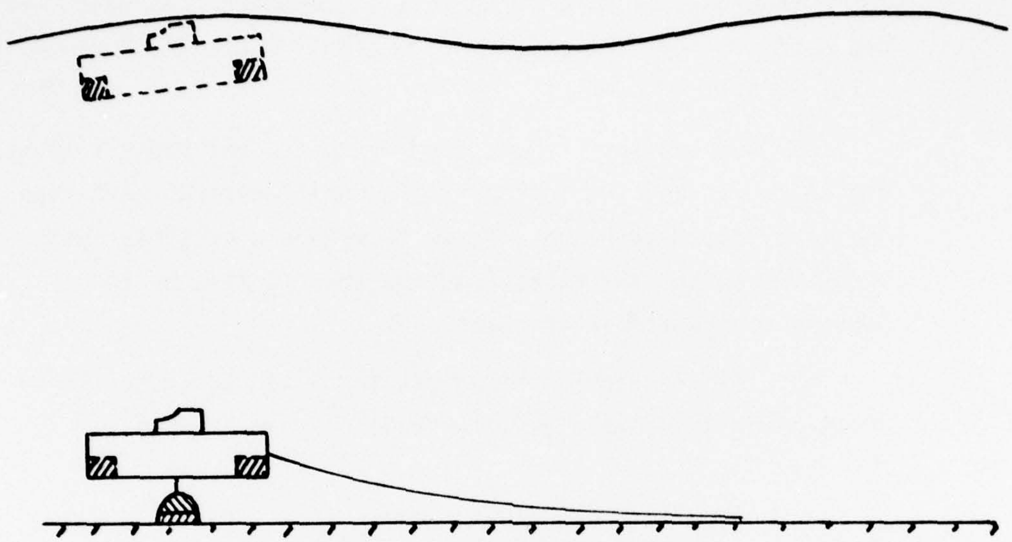
where

B = series designation
12 = 12 knot wind generated waves
5 = model initially 5 feet below "decompression-halt" depth

TABLE 4

TEST	WAVE			
	Period sec	Length ft	L/2 ft	Height inches
B-12-15	1.24	7.9	3.9	2.2
B-16-8	1.68	14.4	7.2	4.7
B-20-12	2.09	22.4	11.2	8.0

(3) Series C - "Surfacing - Free Ascent" - A sketch of the C test series is shown below



This series of tests began with the stream anchor and fully flooded main anchor on the bottom. Initially, the model was in a "tethered" condition just above the main anchor - its normal bottom position. It was then released from the main anchor and allowed to make essentially a "free" ascent. The stream anchor cable, allowed to "run free," remained attached as did the streaming force simulator for the purpose of keeping the model approximately in the correct vertical plane of ascent.

The "dumb waiter" camera recorded rate of rise data as well as pitch and heave response data as the model ascended through the interface.

The following table summarizes the C series tests, these tests being designated as illustrated by the example

C - 12 -20

where

C = series designation
12 = 12 knot wind generated waves
20 = model initially at 20 ft depth

TABLE 5

TEST	WAVE			
	Period sec	Length ft	L/2 ft	Height inches
C-12-20	1.24	7.9	3.9	2.2
C-16-20	1.68	14.4	7.2	4.7
C-20-20	2.09	22.4	11.2	8.0

b. Circulating Water Channel (CWC) Facility Tests - One test series, the D series, was conducted in this facility. The general test set up is shown in Fig. 9 and is briefly discussed in the following paragraphs.

The dimensions of the CWC, 30 feet long x 22 feet wide x 9 feet deep, necessitated placing the model near one wall of the tank and for shortening the scope of the stream anchor cable to 15 feet which was approximately the catenary curve's point of tangency with the bottom, the model being near the bottom. A 50 pound clump was placed at this point of tangency and the anchor cable led through a fair lead on the clump and secured to a "return line." As for tests in the MASK facility, this line was led to the surface and permitted simulation of the stream anchor winch action. The main anchor was located on a bottom

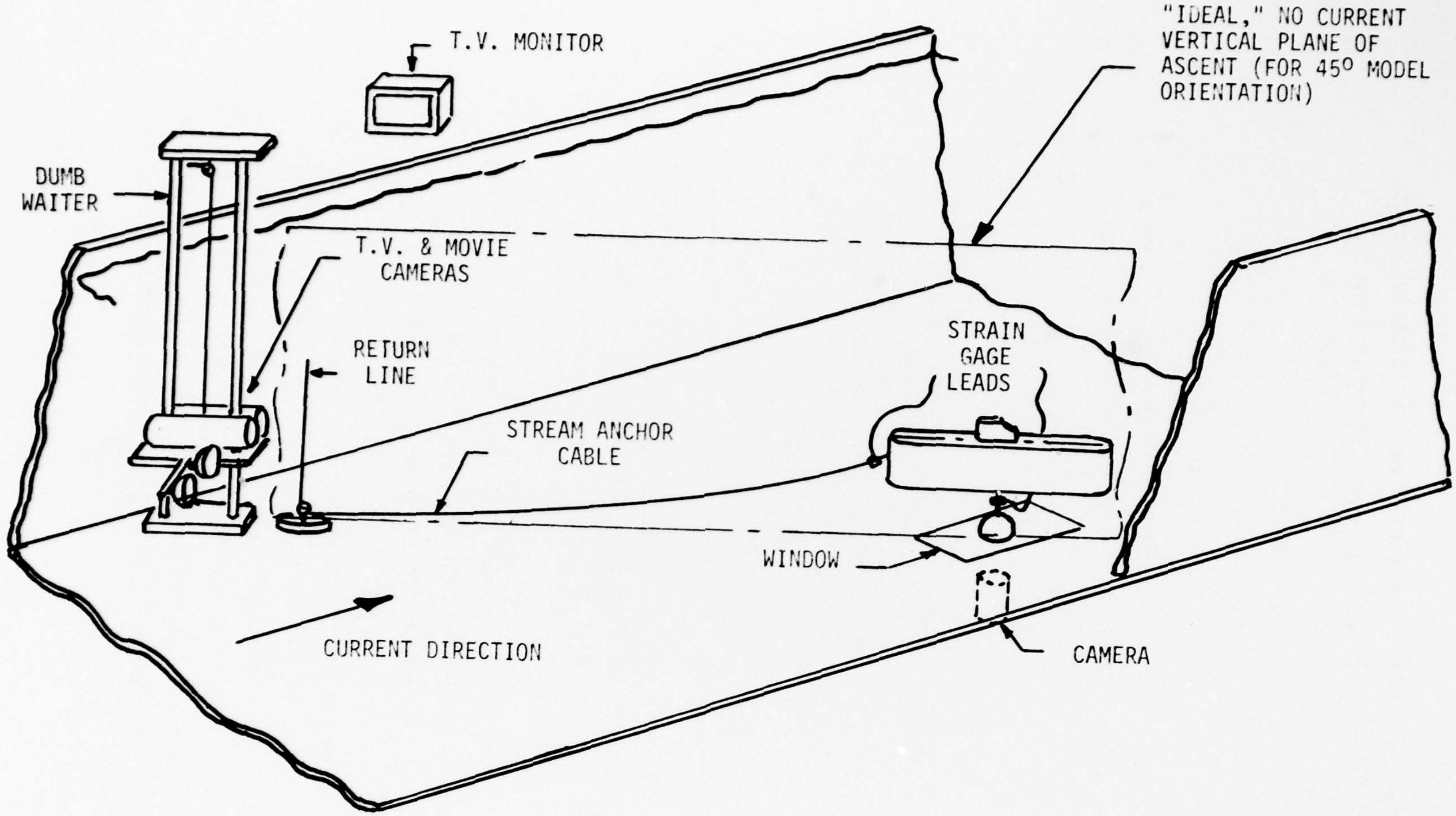


Figure 9

C.W.C. FACILITY TEST SET-UP

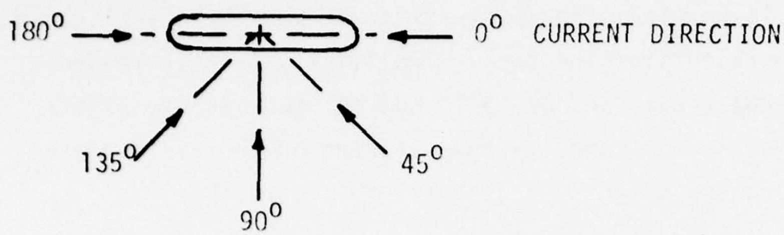
45° CURRENT DIRECTION SHOWN

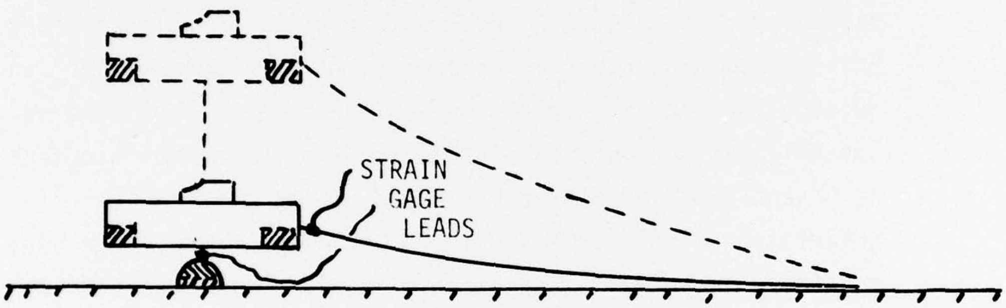
glass port to permit motion pictures to be made by a vertically mounted camera outside the tank. Preliminary tests revealed that the regular main anchor could not be used because of its inadequate hold-down capacity and slipping on the glass plate. Hence, a 50 pound weight was used for this purpose.

U-type electric strain gages were mounted on the main and stream anchor cables with tension data thus acquired being displayed on a Sanborn Recorder strip chart. Motion picture data was obtained by cameras mounted on the "dumb waiter" and outside the channel directly below the model. The "dumb waiter" assembly was located near the model's stern for model orientation of 0^o and 180^o and at the clump end of the stream anchor for orientation of 45^o, 90^o and 180^o. Motion pictures were used to record the model's action as it was winched upward from its bottom tethered position.

It was hoped that data could be obtained permitting investigations of the mooring system's adequacy in two ranges of current velocities; for divers working outside the lab (0 to 1 knot full scale) and for system integrity (0 to 5 knots full scale). However, the lowest reliable current velocity obtainable in the CWC facility was 0.5 knots (1.9 knots full scale). Hence, tests were limited to those investigating the system's mooring integrity.

A sketch of the D test series is shown on the following page.





Tests were conducted for three current velocities and five current directions, the model and mooring system being oriented with respect to the channel's axis so as to obtain the correct current direction. Initial tests revealed that a feasible range of current velocities was limited to 0.5 knots to 0.75 knots equivalent to a full scale velocity range of 1.9 to 2.9 knots. Beyond this range, the anchor weights dragged on the smooth bottom surface, despite the fact that they were increased from 50 to 100 pounds, and the anchor cables parted.

Initially, the model was located just above the main anchor in its bottom-moored position. This position was maintained until sufficient main and stream anchor cable tension data was recorded at which time the model was winched slowly upward, the cameras recording its motion in the current field.

The following Table summarizes the D series tests, these tests being designated as illustrated by the example

D - 0- 0.5

where

D = series designation

0 = a model angular orientation of 0^{o} with respect to the direction of current flow

0.5 = a modeled current velocity of 0.5 knots (actual CWC current velocity)

TABLE 6

D-0-0.5
D-0-0.625
D-0-0.75
D-45-0.5
D-45-0.625
D-45-0.75
D-90-0.5
D-90-0.625
D-90-0.75
D-135-0.5
D-135-0.625
D-135-0.75
D-180-0.5
D-180-0.625
D-180-0.75

E. TEST RESULTS AND DISCUSSION

1. Series A - "Submerging - Interface Breakthrough"

a. Results - Table 7 on the following page summarizes the results of the "A" test series with regard to amplitude of heave and pitch, average descent velocity and overshoot, that is, the distance the hull continues to descend after the main anchor has bottomed. The table also contains derived values of maximum heave and pitch velocities and accelerations. The latter values are derived from the simple expressions:

$$\text{Max velocity (heave or pitch)} = \omega A$$

where

ω = circular frequency of the motion

A = amplitude in heaving or pitching motion

and

$$\text{Max acceleration (heave or pitch)} = -\omega^2 A$$

b. Discussion - Table 8 compares pertinent wave and hull data, as based on full scale dimensions. All data are taken from the model tests except the periods which are calculated as follows for the hull on the surface:

$$T_p = 1.108 \sqrt{\frac{ky^2(1 + C_p)}{BM_L}}$$

$$T_p = 1.108 \sqrt{\frac{18.4^2(1.6)}{29.7}}$$

$$T_p = \underline{4.74 \text{ seconds}}$$

where

T_p = natural pitching period on surface (seconds)

C_p = added mass coefficient, assumed = 0.6

ky = longitudinal radius of gyration (ft)

BM_L = longitudinal metacentric radius (ft)

<u>"A" TEST SERIES</u>

Converted to Full Scale Data

Table 7

TEST	CIRCULAR FREQUENCY rad/sec	HEAVE			PITCH				DESCENT VEL AVERAGE ft/sec	OVER-SHOOT ft
		AMP. ft	MAX VEL ft/sec	MAX ACC ft/sec^2	AMP. deg.	AMP radians	ω(MAX) rad/sec	α(MAX) rad/sec^2		
A-12-10*	1.23	1.3	1.60	1.96	6.1	0.11	0.14	0.17	1.88	19
A-12-13	1.25	1.2	1.50	1.87	6.0	0.11	0.14	0.17	2.33	20
A-12-16	1.23	1.0	1.23	1.51	4.3	0.08	0.10	0.12	2.00	27
A-16-6	0.88	2.8	2.46	2.16	5.5	0.10	0.09	0.08	2.33	18
A-16-9	0.95	3.1	2.94	2.79	6.8	0.12	0.11	0.11	2.33	22
A-16-12	0.95	3.2	3.04	2.88	5.5	0.10	0.10	0.09	2.28	16
A-20-4	0.81	5.3	4.29	3.49	6.0	0.11	0.09	0.07	2.33	11
A-20-6	0.76	5.2	3.95	3.02	5.0	0.09	0.07	0.05	2.33	8
A-20-8	0.78	5.8	4.52	3.36	5.5	0.10	0.08	0.06	2.28	16

*A = test series designation

12 = 12 knot wind generated sea

10 = depth of anchor below hull (hull on surface) Note: this is <u>model</u>, not <u>full scale</u>, depth.

Also

$$T_H = 1.108 \sqrt{\frac{\tilde{V}(1 + C_H)}{A}}$$

$$T_H = 1.108 \sqrt{\frac{9720(1.9)}{680}}$$

$$T_H = \underline{5.75 \text{ seconds}}$$

where

T_H = natural heaving period on surface (seconds)

C_H = added mass coefficient, assumed = 0.9

$\tilde{V}$ = volume of displacement, excluding water in main ballast tanks but including entrained water (ft^3)

A = water plane area (ft^2)

TABLE 8

1	2	3	4	5	6	7	8	9
WIND	WAVE				HULL			
VEL knots	T_W sec	L_W ft.	AMP ft.	SLOPE degrees	T_p sec	T_H sec	HEAVE ft.	PITCH degrees
12	4.8	118	1.4	4.3	4.74	5.75	1.0-1.3	4.3-6.1
16	6.5	216	2.9	4.9	4.74	5.75	2.8-3.2	5.5-6.8
20	8.1	336	5.0	5.4	4.74	5.75	5.2-5.8	5.0-6.0

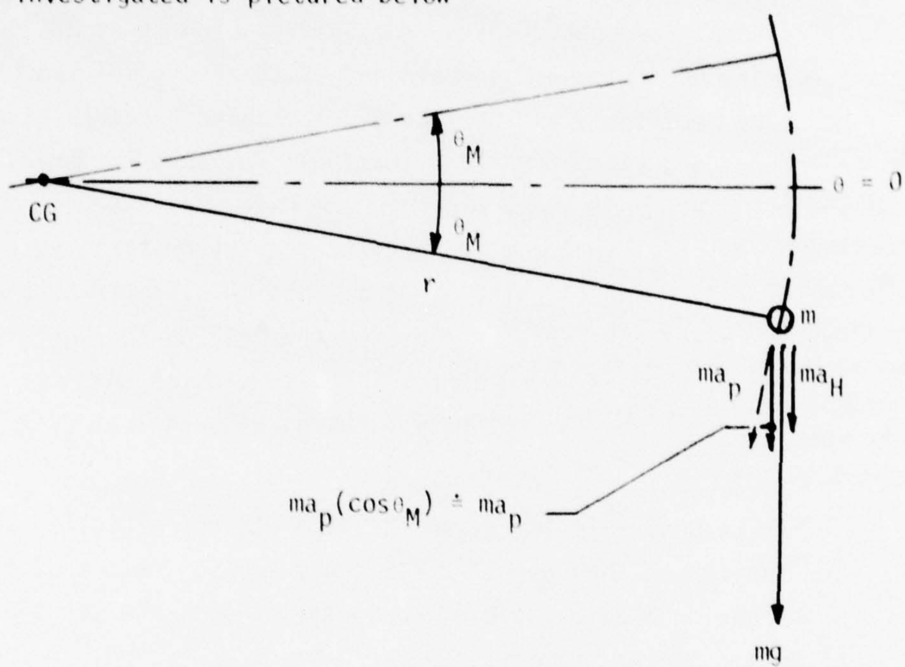
1. Sea states as designated by the wind velocity that generates them
4. Wave amplitude = 1/2 wave height
5. Wave slope = $\pi H_W/L_W$, expressed in degrees

6 & 7. Natural periods of pitch and heave

8. Hull response in heave (maximum) - range of test data
9. Hull response in pitch (maximum) - range of test data

It should be noted that the natural periods of heave and pitch are very close to the periods of the waves, the latter being the periods associated with the waves at the maximum spectral density of spectra describing the sea states. An important reason for choosing these waves with periods close to the hull's natural periods was to investigate the possibility of resonant responses. Data reduced from high-speed motion pictures produced sinusoidal heave and pitch records of reasonably constant amplitudes and periods displaying no evidence of a resonant condition. The fact that hull response in forced heave and pitch are relatively close to the wave amplitude and maximum slope indicates that damping approaching the critical value was present. Experimentally, it was not possible to obtain natural heave and pitch periods for the hull on the surface because of damping which supports the conclusion that the damping ratio approaches unity. Hence, resonant motion is not of concern.

It is desirable to review the data regarding acceleration and the forces they produce. In these tests, conducted in waves having a zero angle of encounter, two of the six types of motion are of primary interest - heave and pitch. Hence, a body of mass (m) will be subjected essentially to three sources of acceleration - from gravity, heaving and pitching. With respect to the center of mass moving along a curved path, gravity and heaving accelerations will be vertically directed while the pitching accelerations will be directed radially and tangentially to the path of motion. The total acceleration at any particular point on the path may be found by vector addition. Radial acceleration, involving the square of the angular velocity (ω^2) will have its maximum value when the pitch angle (θ) equals zero. The tangential acceleration will be zero at this point. Radial acceleration will add little to the vertical vector accelerations because the ω^2 term and the vertical component are very small. It is the tangential acceleration, having its maximum value at $\theta = \theta$ max, which will add materially to the vertical acceleration vectors. At $\theta = \theta$ max, the radial acceleration disappears. The situation to be investigated is pictured below



where

CG = the assumed pitching axis

θ_M = maximum pitch angle (radians)

a_H = maximum acceleration in heave

a_p = maximum acceleration in pitch

r = radial distance from body of mass (m) to axis of pitching

In picturing the highest value of total acceleration, the diagram assumes that the heave and pitch motions are in phase - that a_H and a_p have maximum values at the same time. The heave and pitch records reveal phase angles varying from zero to about 30 degrees, but zero phase angle is assumed for the purposes of maximizing the total acceleration. The expression for this total acceleration is

$$a_T = a_p \cos \theta_M + a_H + g$$

$$a_T \doteq a_p(1) + a_H + g$$

or

$$a_T \doteq r\alpha + a_H + g$$

Assuming r to have a maximum value of 38 feet (from CG to deck at the bow), Table 9 is generated.

TABLE 9

1	2	3	4	5	6	7
WIND VEL knots	MAX. ACC PITCH rad/sec^2	$r\alpha$ ft/sec^2	MAX. ACC HEAVE ft/sec^2	GRAV. ACC ft/sec^2	TOTAL ACC ft/sec^2	TOTAL ACC "gs"
12	0.15	5.7	1.4	32.2	39.3	1.22g
16	0.09	3.4	2.8	32.2	38.4	1.19g
20	0.06	2.3	4.3	32.2	38.8	1.20g

1. Sea states as designated by the wind velocities generating them

2 & 4. Average of three accelerations obtained for each sea condition (see Table 7)

Thus the inertia forces are only 20% of gravitational forces in under extreme conditions for motions considered in these tests. Undoubtedly, this percentage would increase somewhat if rolling were also considered in cases where the hull is subjected to oblique seas but it is doubted if the inertia forces would exceed 50% of the gravitational force as the radial distances from any of the axes of motion to objects on the OSCILAB are relatively small. It is common practice to allow an addition of 100%g to the gravitational force in the design of hull structure and foundations. Hence, the accelerations experienced in these tests are considered to be well within acceptable limits.

Men and most of the instruments and equipment will be subjected to even lower inertia forces. An appropriate maximum value of r to use for this group of "bodies" would be about 20 feet, presuming that they are housed within the mail hull. Hence, Table 10, similar to Table 9 can be completed as follows:

TABLE 10

WIND VEL knots	MAX ACC PITCH rad/sec^2	$r\alpha$ ft/sec^2	MAX ACC HEAVE ft/sec^2	GRAV. ACC ft/sec^2	TOTAL ACC ft/sec^2	TOTAL ACC "gs"
12	0.15	3.0	1.4	32.2	36.6	1.14g
16	0.09	1.8	2.8	32.2	36.8	1.14g
20	0.06	1.2	4.3	32.2	37.7	1.17g

These accelerations are considered to be well within the acceptable range of "g" values for humans, equipment and instrumentation.

The "rate of descent" and hull "overshoot," as experienced in the "A" test series, were considered to be excessive. A small reduction (0.5 pounds) was made in the ballast and the "descent" and "overshoot" tests were repeated for one condition in each of the three sea-states. The results are reported in Table 11.

TABLE 11

TEST	PRIOR TO BALLAST CHANGE		AFTER BALLAST CHANGE	
	DESCENT VEL AVERAGE ft/sec	OVERSHOOT ft	DESCENT VEL AVERAGE ft/sec	OVERSHOOT ft
A-12-16*	2.00	27	1.50	8
A-16-12	2.28	16	1.60	7
A-20-8	2.28	16	1.65	9

A = test series

12 = sea-state designated by 12 knot wind velocity generating it

16 = depth of main anchor below hull. Note: this is model depth, not full-scale depth

Average values of drag coefficients can now be obtained using the above full scale data in the equation

$$C_D = \frac{F_D}{\rho/2AV^2}$$

where

C_D = average drag coefficient

F_D = average force required to overcome drag at a given velocity (pounds)

A = bottom projected area - 682 ft^2

V = average descent velocity as found in tests (ft/sec^2)

Table 12 contains the results of these calculations.

TABLE 12

Full Scale Data

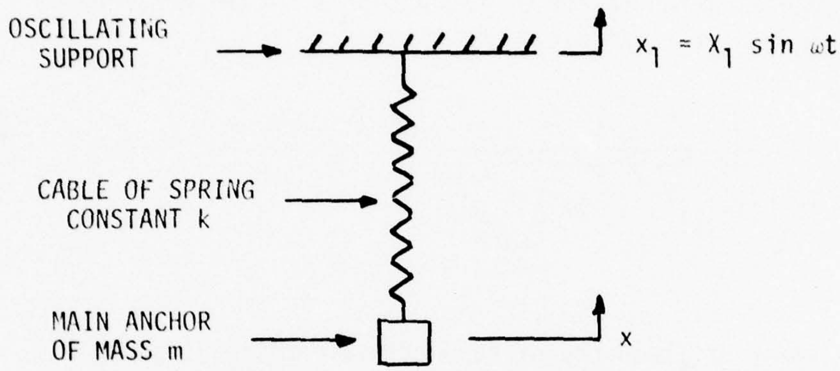
TEST	PRIOR TO BALLAST CHANGE			AFTER BALLAST CHANGE		
	DESCENT VEL ft/sec	F_D #	C_D	DESCENT VEL ft/sec	F_D	C_D
A-12-16	2.00	3700	1.36	1.50	1980	1.29
A-16-12	2.28	3700	1.05	1.60	1980	1.14
A-20-8	2.28	3700	1.05	1.65	1980	1.07

These C_D values seem to be within a reasonable range of values, as based on flat plate drag data, and serve as a rough check on the test data.

The rate of descent still appears high although the prototype would possess means of controlling descent (and ascent) velocity by adjusting variable ballast. It must also be noted that the change of water density with increase in depth cannot be modeled. An increase in density, due to the water's slight compressibility and other factors, cannot be offset by hull compressibility since pressures within and outside the hull are equalized. The increase in density will, of course, increase the displacement and will exert a stabilizing effect on OSCILAB as it descends through the water column. This effect will decrease rates of descent and overshoot.

Overshoot (the hull continuing to descend after the main anchor bottoms) is a serious matter as it can immediately cause the cable to go slack and loop with the danger of becoming kinked or snared on the main anchor or other objects on the bottom. Some overshoot must be accepted, but its effects should be countered by using a sensitive tension winching system which would assure a tension force in the cable at all times.

The "A" test series provides data regarding the heaving motion of the OSCILAB which facilitates studies of the main anchor's motion and forces developed in its cable. The following approach to these studies assumes that the main anchor cable will always be in tension and that the system can be modeled as indicated in the diagram.



The non-linear differential equation for damped, forced vibrations is

$$m\ddot{x} + c\dot{x}^2 + kx = kX_1 \sin \omega t$$

where

- m = virtual mass of anchor (pounds-seconds^2/ft)
- c = damping force per unit velocity^2(pounds-seconds^2/ft^2)
- k = linear spring constant for cable (pounds/ft)
- X_1 = amplitude of support motion (feet)
- ω = circular frequency (radians/second)

The solution of this equation will be facilitated if it is linearized by using an adjusted damping coefficient, c', which is found by equating areas (energies) under the Damping Force - Velocity curves. "Fundamentals of Vibration Analysis," by N. O. Myklestad, gives the following relationship between c' and c:

$$c' = \frac{8X\omega}{3\pi} c$$

The linearized equation thus becomes

$$m\ddot{x} + c'\dot{x} + kx = kX_1 \sin \omega t$$

The solution of this equation leads to the following formulation for the magnification factor of the anchor's motion relative to the OSCILAB's motion in heave:

$$\frac{X}{X_1} = \frac{1}{\sqrt{\left[1-\left(\frac{\omega}{p}\right)^2\right]^2 + \left[2\left(\frac{c'}{c_c}\right)\left(\frac{\omega}{p}\right)\right]^2}}$$

where

ω = circular frequency of support heave motion (rad/sec)

$p = \sqrt{\frac{k}{m}}$ = natural frequency of anchor-cable system (rad/sec)

c_c = critical damping coefficient (pounds-sec/ft)

The equation for the phase angle by which OSCILAB leads the main anchor in heaving motion is

$$\phi = \text{arc tan } \frac{2(c'/c_c)(\omega/p)}{1 - (\omega/p)^2}$$

The equation for the anchor cable force is

$$F_T = K[X_1 \sin \omega t - X \sin(\omega T - \phi) + \text{static elongation of cable})$$

The spring constant, k, used in the following calculations is based on a cable having the following characteristics::

Type - 3 x 19, Monitor AA Independent Wire Rope Center, Torque-balanced

Diameter - 3/4 in.

Metallic area - $0.2412 in^2$

Breaking load - 57,800#

Elastic limit load - 43,300#

Modulus of elasticity = 21.0×10^6 #/in^2

The basic equation for calculating the elongation of a Torque-balanced wire rope is

$$\text{Elongation (ft)} = \frac{\text{Load (\#)} \times \text{Length of rope (ft)}}{\text{Metallic area(in}^2) \times \text{Mod. Elasticity(\#/in}^2)}$$

An expression for k as a function of the cable length and properties is

$$k_L = \frac{X\text{(pounds)}}{1 \text{ (foot)}} = \frac{\text{Load (pounds)}}{\text{Elongation due to load(feet)}}$$

$$k_L = \frac{\text{Load}}{\text{Load} \times \text{length/metallic area} \times E}$$

$$k_L = \frac{\text{Metallic area} \times E}{\text{Length}}$$

For the particular cable being used

$$k_L = \frac{0.2412 \times 21.0 \times 10^6}{\text{Length}} = \frac{5.0652 \times 10^6}{\text{Length}}$$

Table 13 on the following page summarizes calculations leading to the determination of main anchor heave amplitudes and cable forces.

The table demonstrates that all main anchor-anchor cable systems investigated are satisfactory. The systems are all extremely compliant, the anchor's heave motion following that of the hull very closely and with negligible lag. The frequency ratios, with values ranging from 0.08 to 0.25, are well below the critical values of 1.00 and hence there is no danger of resonant motion developing. The cable is in tension for all systems studied and therefore no "snap" loadings or "kinking" possibilities are introduced due to cable slackness. The range of cable loads vary from 22% to 27% of the cable's elastic limit load of 43,300 pounds which is considered as providing an adequate loading allowance.

SERIES "A" TESTS - CABLE FORCE DATA

Full Scale

Table 13

1	2	3	4	5	6	7	8
TEST	CABLE LENGTH ft	K #/ft	ω rad/sec	p rad/sec	ω/p	$(\omega/p)^2$	c' $\frac{\# - sec}{ft}$
A-12-10	150	33,700	1.23	6.30	0.20	0.040	86.40
A-12-13	195	25,980	1.25	5.52	0.23	0.053	90.00
A-12-16	240	21,100	1.23	5.00	0.25	0.063	93.50
A-16-6	90	56,280	0.88	8.17	0.11	0.012	132.50
A-16-9	135	37,520	0.95	6.69	0.14	0.020	139.00
A-16-12	180	28,140	0.95	5.78	0.16	0.025	145.10
A-20-4	60	84,420	0.81	10.00	0.08	0.006	181.00
A-20-6	90	56,280	0.76	8.17	0.09	0.008	187.00
A-20-8	120	42,210	0.78	7.07	0.11	0.012	190.00

9	10	11	12	13	14	15	16	17
c_c $\frac{\# - sec}{ft}$	c'/c_c	X_1 ft	$\frac{X}{X_1}$	$\frac{X}{ft}$	ϕ degrees	STATIC ELONG. ft	MAX/MIN ELONG ft	MAX CABLE FORCE #
10,700	0.008	1.30	1.09	1.41	0.2	0.19	.30/.08	10,110
9,560	0.009	1.20	1.11	1.33	0.2	0.25	.38/.12	9,870
8,420	0.011	1.00	1.14	1.14	0.3	0.31	.45/.17	9,500
13,800	0.009	2.80	1.02	2.86	0.1	0.11	.17/.05	9,570
11,220	0.012	3.10	1.04	3.22	0.2	0.17	.29/.05	10,880
9,760	0.015	3.20	1.05	3.36	0.3	0.23	.39/.07	10,970
16,820	0.011	5.30	1.01	5.35	0.1	0.08	.13/.03	10,970
13,800	0.014	5.20	1.02	5.30	0.2	0.11	.21/.01	11,800
11,900	0.016	5.80	1.02	5.92	0.2	0.15	.27/.03	11,400

4. Driving frequency - from test data. $\omega = 2\pi/T$

5. Natural frequency anchor - cable system. $p = \sqrt{\frac{k}{m}}$

8. Equivalent damping coef. $c' = \frac{8X\omega}{3\pi} c$. $c = 54.0\# - \frac{sec^2}{ft^2}$. Repetitive trial values of X used until solution obtained.

9. Critical damping coef. $c_c = 2\sqrt{km}$

10. Heave amplitude of OSCILAB on surface - test data

12. Magnification Factor - calculated and checked by curves, pg. 4., TMB Report R-189

14. Phase angle

15. Static elongation of anchor cable - anchor (weight-displacement) for this condition = 6450#

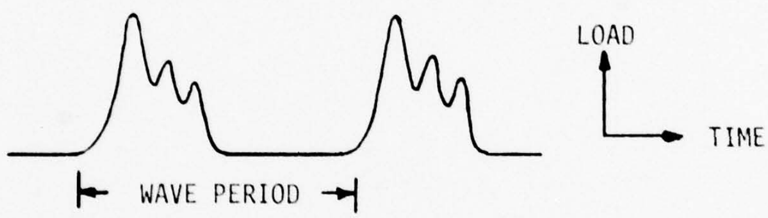
16. Max and Min cable extension in cycle - assume $\phi = 0$

17. Max cable force = k (max. elongation)

2. Series B - "Surfacing - Winching Up"

a. Results - Table 14 on the following page summarizes the results of the "B" test series with regard to amplitude of heave and pitch at the "lab decompression-halt depth," this depth being defined as the depth of the lab's axis below the surface when the lower hatches of the bottom access trunks are at the "diver's decompression-halt depth." Said more directly, "lab axis depth" equals "diver decompression-halt depth" minus 10 feet. The table also contains derived values of maximum heave and pitch velocities and accelerations at lab depth, these values being calculated by expressions used in the Series "A" tests.

Maximum main anchor cable loadings, recorded from strain gage data, are given in Table 14. All of the strain gage recordings are characterized by the sketch



indicating that the anchor was lifted off the bottom, oscillated and returned to the bottom in one wave period of time.

b. Discussion - The University Sealab Report established 40 feet as the "decompression-halt depth," herein referred to as the "diver's decompression-halt depth." Forty feet was chosen primarily on the bases that surface sources of help could reach that depth with relative ease or that occupants might escape from this depth using oxygen purging techniques in emergency situations. It is important to note that the 40 foot depth must be measured from the surface to the level of the lower hatches of the bottom escape trunks. The interior of the hull must be pressurized very nearly to this depth. The axis of the hull, establishing the "lab decompression-halt depth," is 10 feet above

"B" TEST SERIES

Converted to Full Scale Data

Table 14

1	2	3	4	5			6				7
TEST	HALT DEPTH (DIVER) ft	HALT DEPTH (LAB) ft	CIRCULAR FREQUENCY rad/sec	HEAVE			PITCH				MAXIMUM CABLE LOADINGS #
				AMP ft	MAX VEL ft/sec	MAX ACC ft/sec^2	AMP deg	AMP rad	ω(MAX) rad/sec	α(MAX) rad/sec^2	
B-12-5*	40	30	1.28	1.1	1.44	1.83	2.5	0.044	0.056	0.072	17,340
B-16-8	40	30	0.94	2.1	1.96	1.84	5.3	0.093	0.087	0.082	21,660
B-20-12	40	30	0.78	4.3	3.30	2.55	5.5	0.096	0.075	0.059	34,650

1. B = test series designation

   12 = 12 knot generated sea

   5 = start of test with hull 5 feet below "lab halt depth"

2. Decompression-halt depth for diver = depth to lower hatch of bottom access trunks.
3. Decompression-halt depth for lab = diver halt-depth - 10 ft. Axis of hull 10 ft. above lower hatches.
4. Circular frequency of heave and pitch sinusoidal motion.

5 & 6. *Pitch and heave motion data based on lab-halt depth.*

7. Maximum main anchor cable loadings - recorded by strain gage.

the lower hatch level and, hence, OSCILAB is assumed to be at a depth of 30 feet insofar as its response to surface wave action is concerned.

The primary consideration in determining suitable "diver's decompression-halt" depth is that the main anchor cable not fail through cyclic or "snap" overloadings thereby allowing OSCILAB to make an uncontrolled ascent during the decompression period. This criterion requires that the main anchor remain on the bottom at all times and that the cable be loaded continuously in tension at acceptable percentage levels of the elastic limit load. Another important consideration is the minimizing of motion to permit occupants to pursue living and working routines in relative comfort during the decompression period. Quite obviously, these tests indicate that excessive motion is experienced under all test conditions at a "lab decompression-halt" depth of 30 feet. The cable force situation is less conclusive due to difficulties in modeling the cable. It is proposed to determine satisfactory "decompression-halt" depths based on the above considerations and using the test data.

The "B" test series data is useful in observing the characteristics of the hull response to a pressure wave traversing its longitudinal profile when OSCILAB is moored at a certain "lab decompression-halt depth." Records of both heave and pitch motions were sinusoidal in nature and of fairly constant amplitudes. There was no indication of a tendency to develop resonant motion.

The data is also useful in estimating the hull response in heave to a pressure wave when moored at a distance, z, below the surface. Because of the great difference in masses of the hull and main anchor, it can be assumed that the hull motion is not influenced by the anchor. The gain of the transfer function of the hull can be calculated using the expression

$$H_z = A_z \text{ (gain of the transfer function)}$$

$$H_z/A_z = \text{(gain of the transfer function)}$$

where

H_z = heave amplitude of hull at depth z as recorded from tests (ft)

A_z = pressure wave amplitude at depth z(ft)

A_z can be calculated using the expression

$$A_z = Ae^{-kz}$$

where

A = amplitude of wave at surface (ft)

k = wave number = $2\pi/L$ wave (ft^{-1})

z = depth of lab axis from surface (ft)

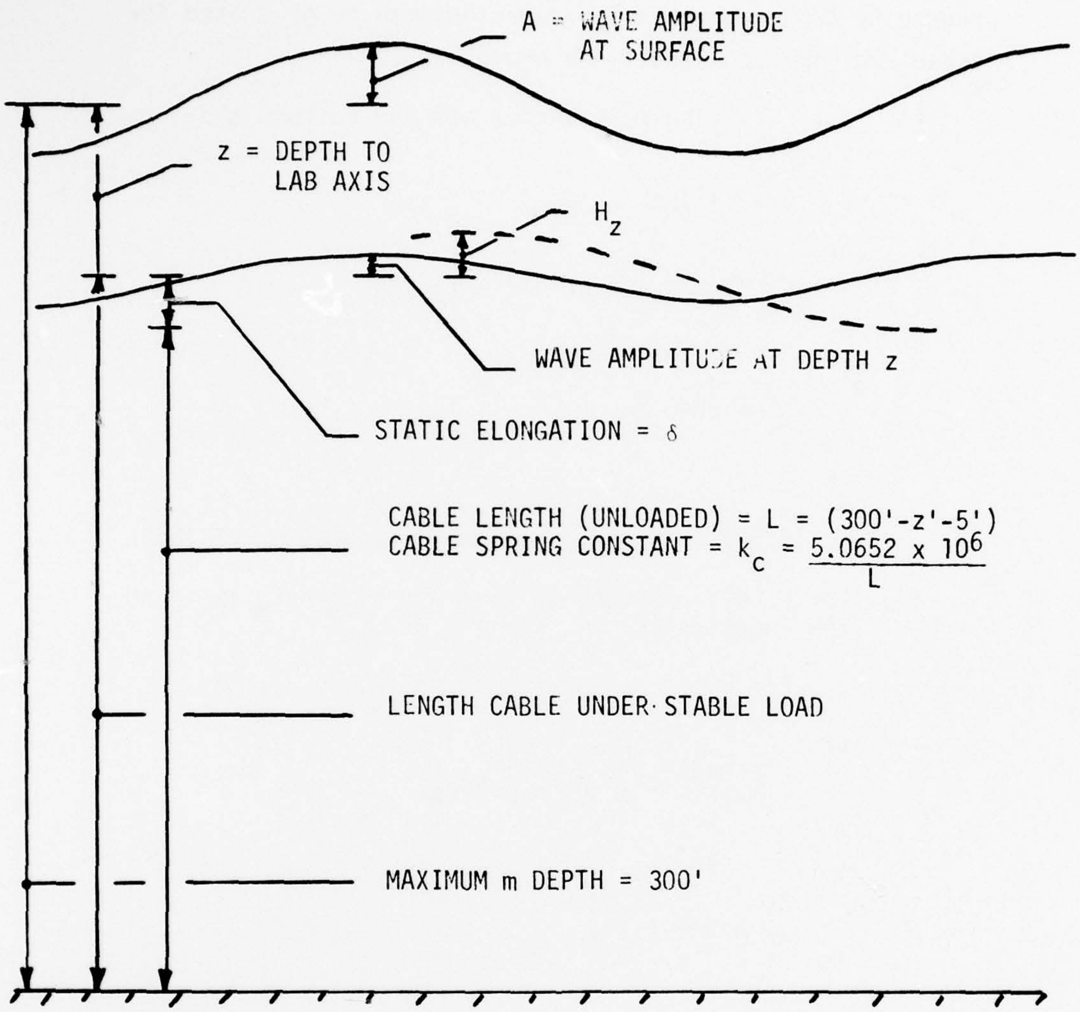
Table 15 summarizes calculations of the gain of the transfer function, H_z/A_z, using test data scaled up to full size. Actual test values of z, in the vicinity of 30 feet, are used.

TABLE 15

TEST	LW ft	k ft^{-1}	z ft	e^{-kz}	A ft	A_z ft	H_z ft	H_z/A_z
B-12-5	118	0.0532	28	0.225	1.40	0.32	1.10	3.44
B-16-8	216	0.0291	28	0.442	2.90	1.28	2.10	1.64
B-20-12	336	0.0187	32	0.548	5.00	2.74	4.25	1.55

These derived gains are intended to serve as general guides only in the analysis that follows.

This analysis is based on the diagram below.



The force exerted on the cable will be

$$F = k_c(\delta \pm H_z)$$

If

$F > 14{,}730$ pounds (fully flooded weight of main anchor in water) or if

$$F = -\text{ Force }(H_z \triangleright \delta \text{ causing cable to go slack})$$

the trail calculation is not valid as based on the criterion regarding cable forces. Two equations can be generated for these two limiting conditions as follows:

(1) for F lifting main anchor off the bottom, the equation is

$$F = 14{,}730 \text{ pounds}$$

or

$$k_c\left(\frac{5890\#}{k_c} + \frac{H_z}{A_z} Ae^{-kz}\right) = 14{,}730$$

$$\frac{H_z}{A_z} = 8840 \; \frac{e^{kz}}{k_c A}$$

where

5890# = static cable force exerted by OSCILAB

(2) for F being reduced to zero and slackness imminent, the equation is

$$F = 0$$

or

$$k_c\left(\frac{5890\#}{k_c} - \frac{H_z}{A_z} Ae^{-kz}\right) = 0$$

$$\frac{H_z}{A_z} = 5890\# \; \frac{e^{kz}}{k_c A}$$

Therefore, it is seen that for a given sea condition and "lab decompression-halt depth," the limiting value of H_z/A_z is governed by the consideration of avoiding slackness in the cable and not by lifting the cable off the bottom. Figure 10 on the following page are graphs of equation (2) for the three sea-states concerned and for "lab decompression-halt depths" down to 140 feet. The areas under and to the left of the

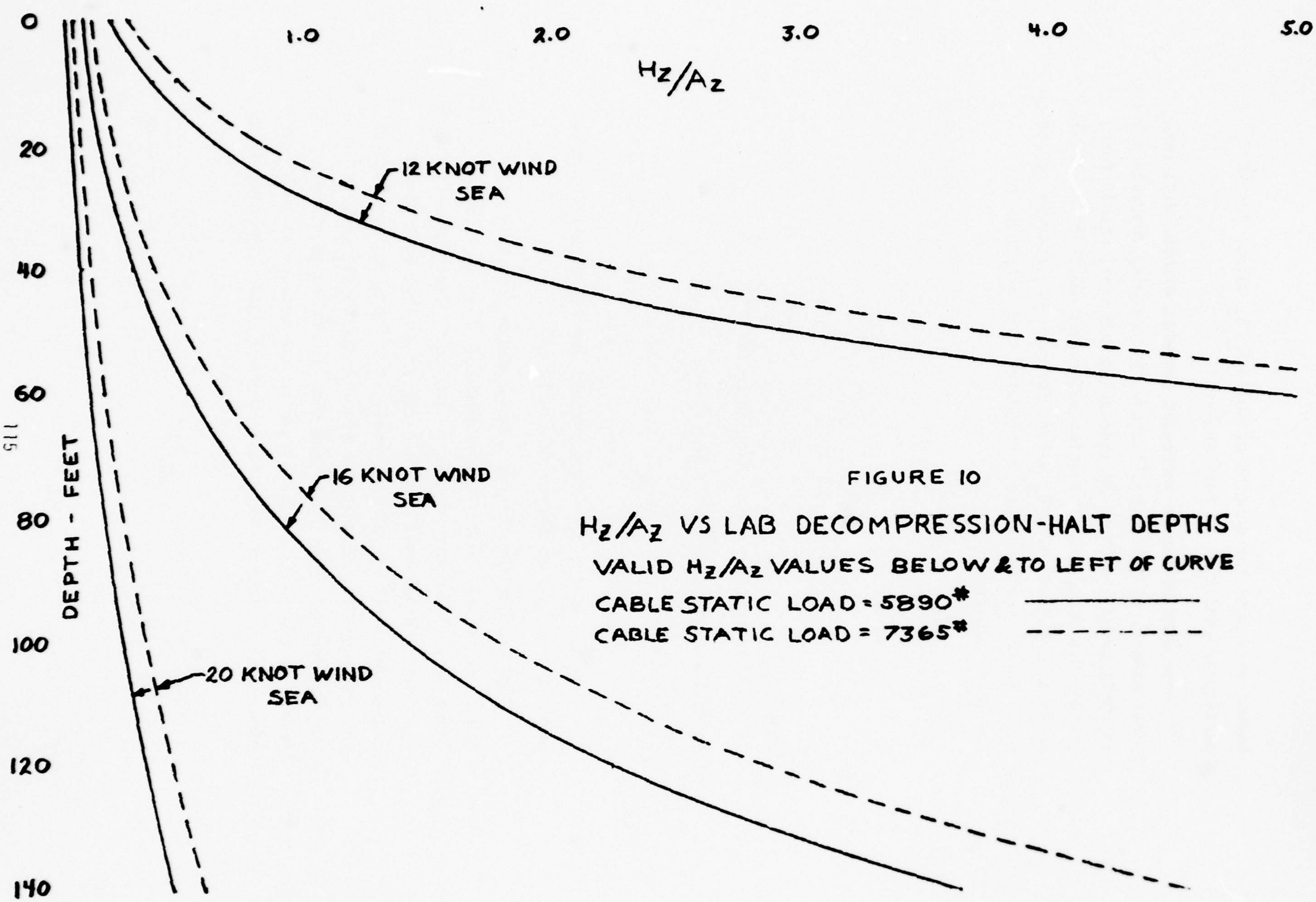


FIGURE 10

H_z/A_z VS LAB DECOMPRESSION-HALT DEPTHS curves represent the domains of valid H_z/A_z values for the particular condition of this analysis.

These domains can be increased somewhat without disturbing other aspects of this overall study (by changing characteristics of cable or main anchor) by increasing the static cable force during this procedure (releasing water from OSCILAB's variable ballast tanks) until H_z/A_z values for the two criteria regarding cable forces are equalized. Following this procedure by rewriting equation (1),

$$K_c\left(\frac{T}{k_c} + \frac{H_z}{A_z} Ae^{-kz}\right) = 14{,}730$$

$$(14{,}730 - T)\,\frac{e^{kz}}{k_c A} = \frac{H_z}{A_z}$$

where

T = static cable force exerted by OSCILAB.

Then, for equalization of H_z/A_z values

$$T = (14{,}730 - T)$$

$$T = 7365 \text{ pounds}$$

The domains, adjusted in this manner, are represented by areas under the dash-lined curves of Figure 10.

Singling out the 12 knot wind generated sea curves for study, it is seen that the experimental value of H_z/A_z of 3.4 (from Table 15) would require a "lab-halt" depth of about 48 feet and a "diver-halt" depth of about 58 feet to meet the cable force criteria of this analysis. The question concerns the applicability of this one experimental H_z/A_z value at varying depths. Thus, this and similar observations must remain in the realm of conjecture in the absence of much more experimental pressure wave-hull response data. The simplicity of the model for the force analysis, in which the cable is assumed to remain straight, must also be recognized.

One important conclusion can be reached, however, from the graphs of Figure 10. The experimental results of Table 15 suggest that all H_z/A_z values are greater than unity. Therefore, of the three sea-states studied, only the 12 knot wind generated sea permits reasonable "lab and diver decompression-halt" depths over a fairly wide range of H_z/A_z possibilities while satisfying cable-force requirements. The "decompression-halt" procedure is of first-order importance in the overall operational concept of the OSCILAB system. Figure 10 indicates that the system design regarding this phase of operation can and should be improved. The main anchor, with increased "hold down" capacity, and the cable, with possible insertion of spring buffers into the line, should be focal points of attention.

Motion for the three sea-states may be studied assuming that the experimentally determined values of the angular velocity of sinusoidal motion and H_z/A_z (Tables 14 and 15) remain essentially constant with change in depth. These assumptions may be conservative but their use will provide some appreciation for heave motion attenuation as the "lab decompression-halt" depth increases. Heave motion attenuation will serve as a guide to pitch motion attenuation. Figures 11 and 12 on the following pages contain graphs of heave motion data versus "lab decompression-halt" depth. Figure 12 and associated calculations assume that a range of "lab decompression-halt" depths from 40 to 60 feet is reasonable from the viewpoint of executing emergency procedures during decompression. Calculations are based on the formulations

$$H_z = H_z/A_z \, Ae^{-kz}$$

$$\text{Max velocity} = \omega H_z$$

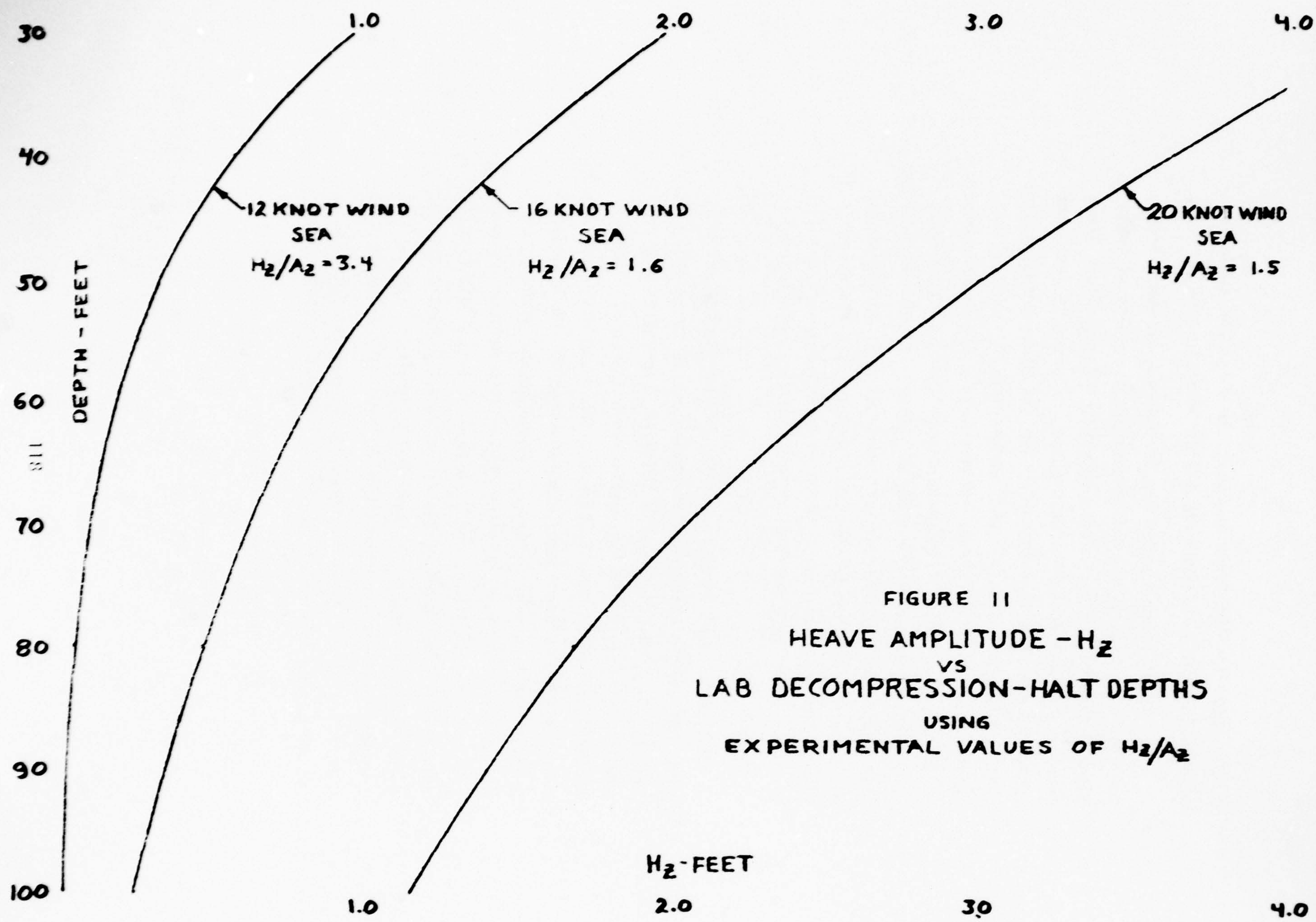
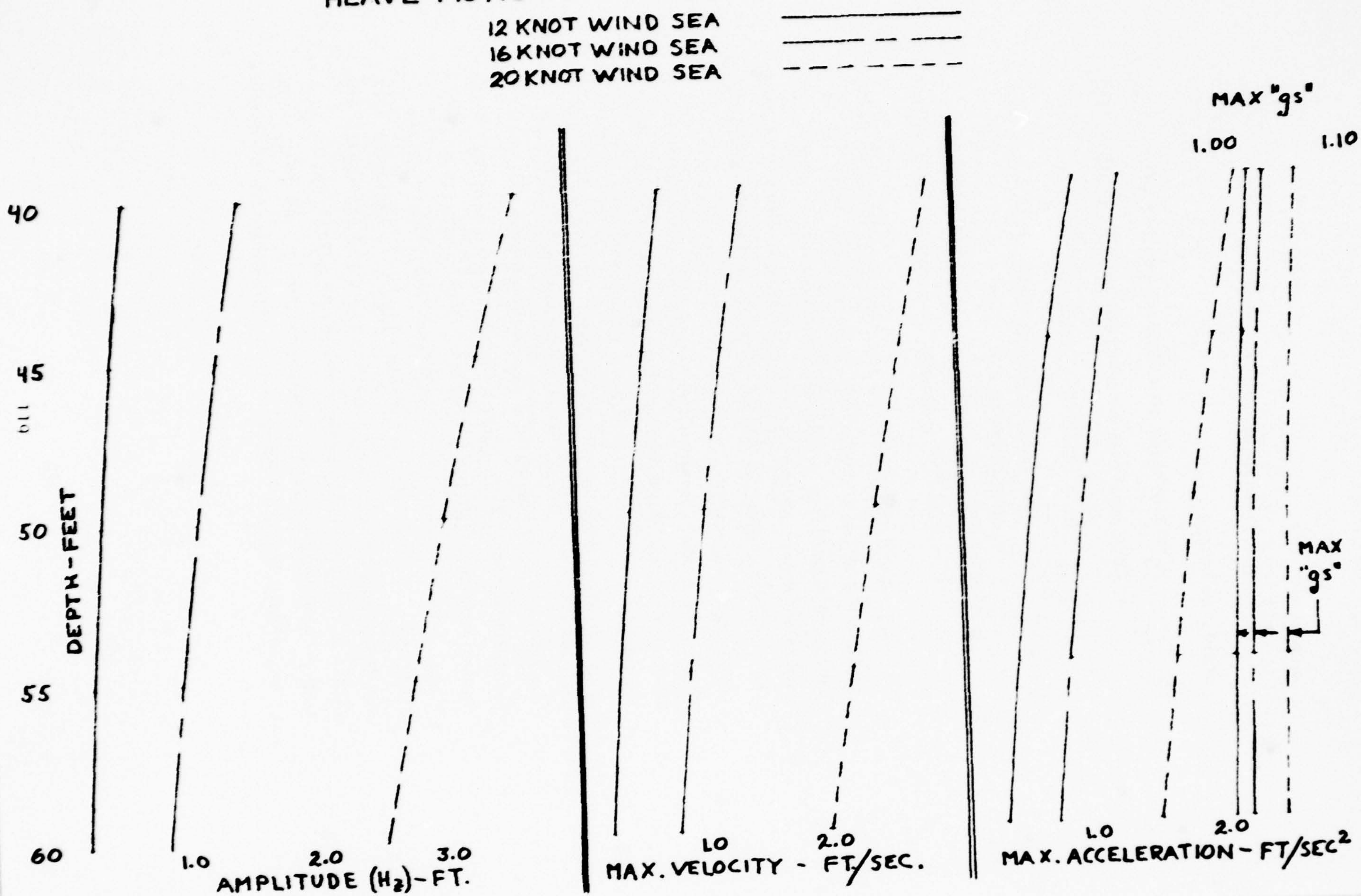


FIGURE 11

HEAVE AMPLITUDE - H_z VS LAB DECOMPRESSION-HALT DEPTHS USING EXPERIMENTAL VALUES OF H_z/A_z

FIGURE 12

HEAVE MOTION vs LAB DECOMPRESSION-HALT DEPTH



and

$$\text{Max Acceleration} = \omega^2 H_z$$

where, as before

H_z = lab heave amplitude at depth z (ft)

A_z = amplitude of pressure wave at depth z (ft)

H_z/A_z = gain in the hull transfer function

A = amplitude of surface wave (ft)

k = wave number = $2\pi/L$ wave

z = "lab"decompression-halt" depth (ft)

ω = circular frequency of heave motion (rad/sec)

OSCILAB will be moored at the "lab decompression-halt" depth for a maximum period of about two days while its occupants are undergoing decompression procedures. Hence, an important aspect of the OSCILAB operational concept is that its occupants enjoy "relative" comfort during this period, as compared to the comfort associated with the motions of a chamber on a small surface support vessel, thus permitting near-normal living and working routines to continue. What constitutes "relative" comfort in terms of motion is a moot question as, to the writer's knowledge, little or no work has been done on this subject involving long periods of time. Nonetheless, some conclusions can be drawn based on the following rationale. A person enclosed in an elevator loses his ability to establish a "horizon" and is sensitive to linear accelerations only. Amplitudes and velocities are unnoticed. In the case of OSCILAB, Figure 12 indicates that the total acceleration (a_H + g) for all three sea-states lies within a 1.01g to 1.07g range. While the writer admits to lack of knowledge regarding motion psychology and physiology, it would seem that "g" values within this range are acceptable over long periods of time. On this basis alone, mooring at "lab decompression-halt" depths of 40 to 60 feet appears to be feasible for all three sea-states considered. However, a person would notice pitching amplitudes as well as accelerations as evidenced by deck inclinations. The heave amplitudes for a 20 knot generated sea are considered to be relatively large and one might also expect commensurately large pitch amplitudes. Over a two-day period, cyclic deck inclinations of relatively large amplitudes might well impede living and working routines and become a source of severe psychological stress. In this regard, Figure 12 indicates that the 12 and 16 knot wind generated sea curves for heave amplitude are quite close together and it might be expected that their pitch amplitudes would also be reasonably close. In summary, then, Figure 12 leads to the conclusion that it probably will be feasible to moor OSCILAB at 40 to 60 feet "lab decompression-halt" depths for 12 to 16 knot wind generated seas. A similar conclusion might be reached regarding the effects of motion on equipment and instrumentation.

3. Series C - "Surfacing - Free Ascent"

a. Results - Table 18 on the following page summarizes the results of the "C" test series with regard to free ascent stability, depth at which oscillatory motion begins and terminal velocity.

b. Discussion - The dynamic stability characteristics of OSCILAB in making a free ascent are to be expected. At the low ascent velocities involved, the metacentric stability expressed by the hydrostatic moment

$$M = \overline{BG}W\theta$$

where

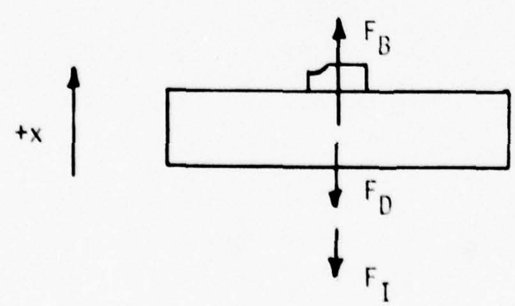
$\overline{BG}$ = submerged longitudinal metacentric height = 4.0 feet

W = weight of OSCILAB and water in main ballast tanks = 199.8 long tons

θ = pitch angle in radians

masks the effects of the hydrodynamic moment with the effect that motion can only be oscillatory and stable. The tests indicate that damping reduces oscillatory motion to an unnoticeable amount.

The experimental values of terminal velocity may readily be checked by the following analytical development. Consider the following free body diagram:



$$F_B - F_D - F_I = 0$$

"C" TEST SERIES

Converted to Full Scale Date

Table 18

1	2	3	4
TEST	FREE ASCENT STABILITY	DEPTH WHERE OSCILLATORY MOTION BEGINS ft	TERMINAL VELOCITY ft/sec
C-12-20*	Stable - no oscillatory motions - even keel ascent	27	2.03
C-16-20	Stable - no oscillatory motions - even keel ascent	35	2.02
C-20-20	Stable - no oscillatory motions - even keel ascent	69	2.10

1. B = test series designation

   12 = 12 knot generated sea

   20 = depth (in feet) at which model was released. This corresponds to 300 foot depth release for prototype.

2. Characteristics of motion in ascent through water column prior to reaching that portion of the column where motion due to surface wave action begins.

3. Depth at which oscillatory heave and pitch motion begins due to surface wave action.

4. Maximum ascent velocity attained.

where

F_B = positive buoyancy

F_D = drag force = $C_D\ \rho/2\ A\ \text{proj}\ V^2 = DV^2$

F_I = inertia force

The equation may be written

$$m\ddot{x} + D\dot{x}^2 - F_B = 0$$

or

$$\ddot{x} + \frac{D}{m}\dot{x}^2 - \frac{F_B}{m} = 0$$

To facilitate calculations, let

$$a = \frac{D}{m}$$

$$b = \frac{F_B}{m}$$

Then

$$\ddot{x} + a\dot{x}^2 - b = C$$

Further, let

$$z = \dot{x}$$

Then

$$\dot{z} + az^2 - b = 0$$

or

$$\frac{dz}{at} + az^2 - b = 0$$

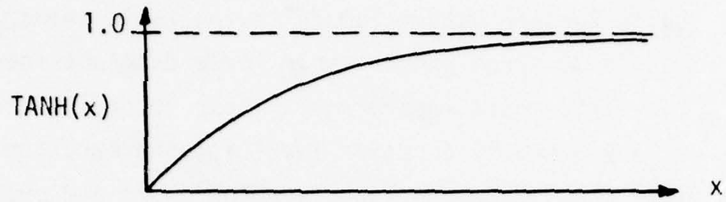
$$\frac{dz}{b - az^2} = dt$$

Integrating both sides

$$\frac{1}{a}\int \frac{dz}{\frac{b}{a} - z^2} = \int dt$$

$$z = \sqrt{b/a} \tan h \sqrt{ab}\, t$$

Recalling the properties of hyperbolic functions, the graph of tan h x vs x is



Therefore, the maximum, or terminal velocity is

$$z_m = \dot{x}_m = \sqrt{b/a} = \sqrt{F_B/D}$$

Substituting data into this expression

$$\dot{x}_m = \sqrt{\frac{4050}{857}} = 2.17 \text{ ft/sec}$$

where

F_B = positive buoyancy force of 4050#

$$D = C_D\, \rho/2\, A = 1.30 \times \frac{1.94}{2} \times 680 = 857 \frac{\# - \sec^2}{ft^2}$$

C_D is taken from flat plate data (b/h = 7 and Reynold's Number $> 10^3$) contained in "Hydrodynamics of Ship Design" - Saunders. "A" is the projected area of the deck. The experimental and analytical values of the maximum, or terminal, velocity agree reasonably well.

While the "Surfacing - Free Ascent" is not intended to be a normal operating procedure, these tests indicate that it can be successfully accomplished in emergency situations.

4. Series D - "Submerged - On Site" & "Winching Up"

a. Results

(1) "Submerged - On Site"

(a) Cable Tension Data - The following table summarizes main and stream anchor cable force data obtained from the strip-chart recordings. These recordings remained at a reasonably constant level for the duration of the test run. Cable force curves for model and prototype are shown in Figs 13, 14, and 15.

TESTS				
Series	Current Direction Degrees	Current Velocity Knots	STREAM ANCHOR CABLE Pounds	MAIN ANCHOR CABLE Pounds
D -	0 -	0.50	2.4	4.0
D -	0 -	0.625	2.9	5.5
D -	0 -	0.75	3.2	4.5
D -	45 -	0.50	2.8	5.0
D -	45 -	0.625	4.0	8.2
D -	45 -	0.75	5.0	9.5
D -	90 -	0.50	2.8	5.7
D -	90 -	0.625	4.0	9.0
D -	90 -	0.75	5.0	11.5
D -	135 -	0.50	2.8	6.0
D -	135 -	0.625	3.0	10.0
D -	135 -	0.75	3.3	12.5
D -	180 -	0.50	1.8	6.0
D -	180 -	0.625	2.5	7.5
D -	180 -	0.75	2.0	8.5

FIGURE 13

CABLE FORCES VS. CURRENT DIRECTION
FOR
MODEL IN 0.5 KNOT CURRENT FIELD
IN
SUBMERGED-ON SITE POSITION

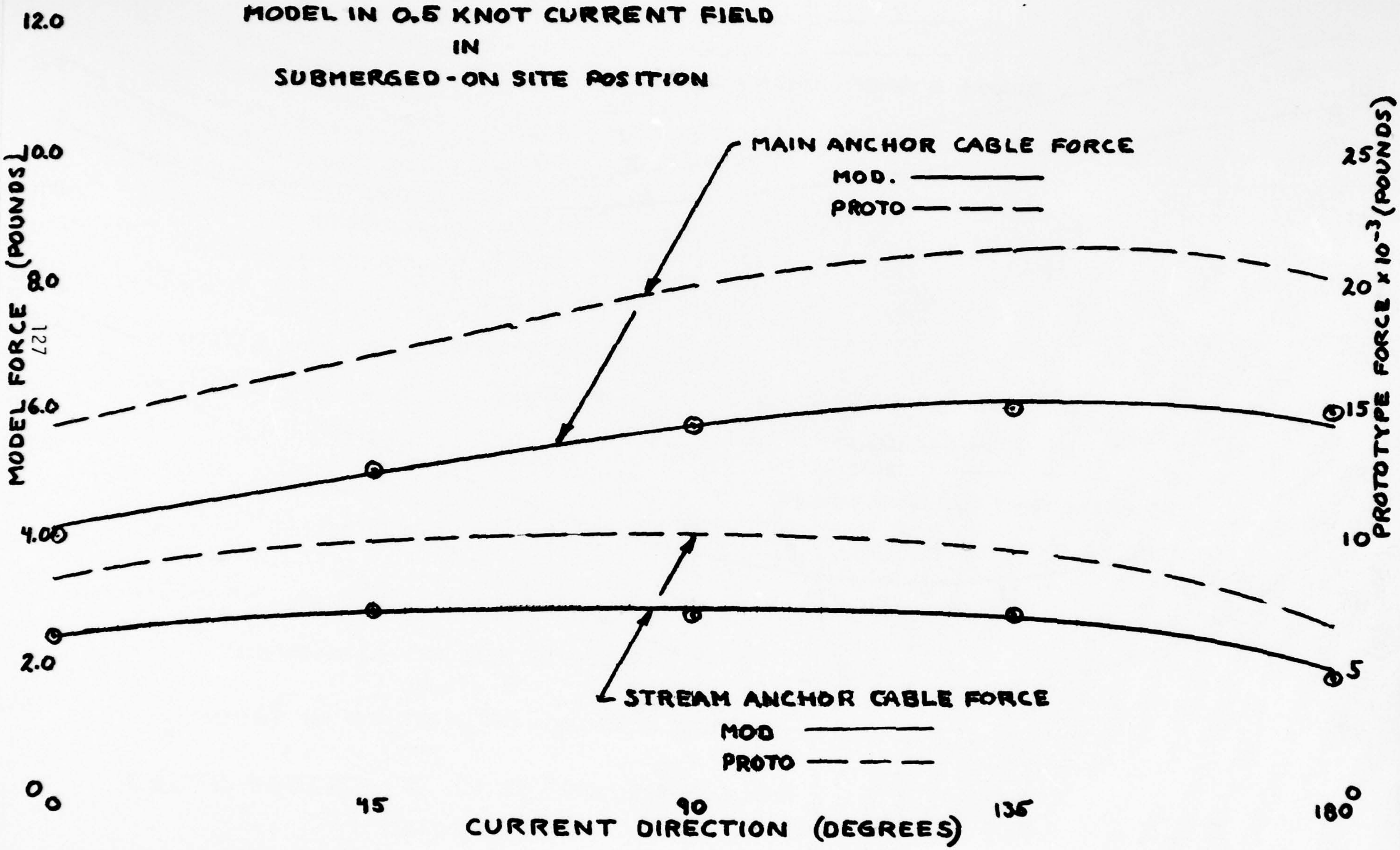


FIGURE 14

CABLE FORCES VS. CURRENT DIRECTION FOR MODEL IN 0.625 KNOT CURRENT FIELD IN SUBMERGED-ON SITE POSITION

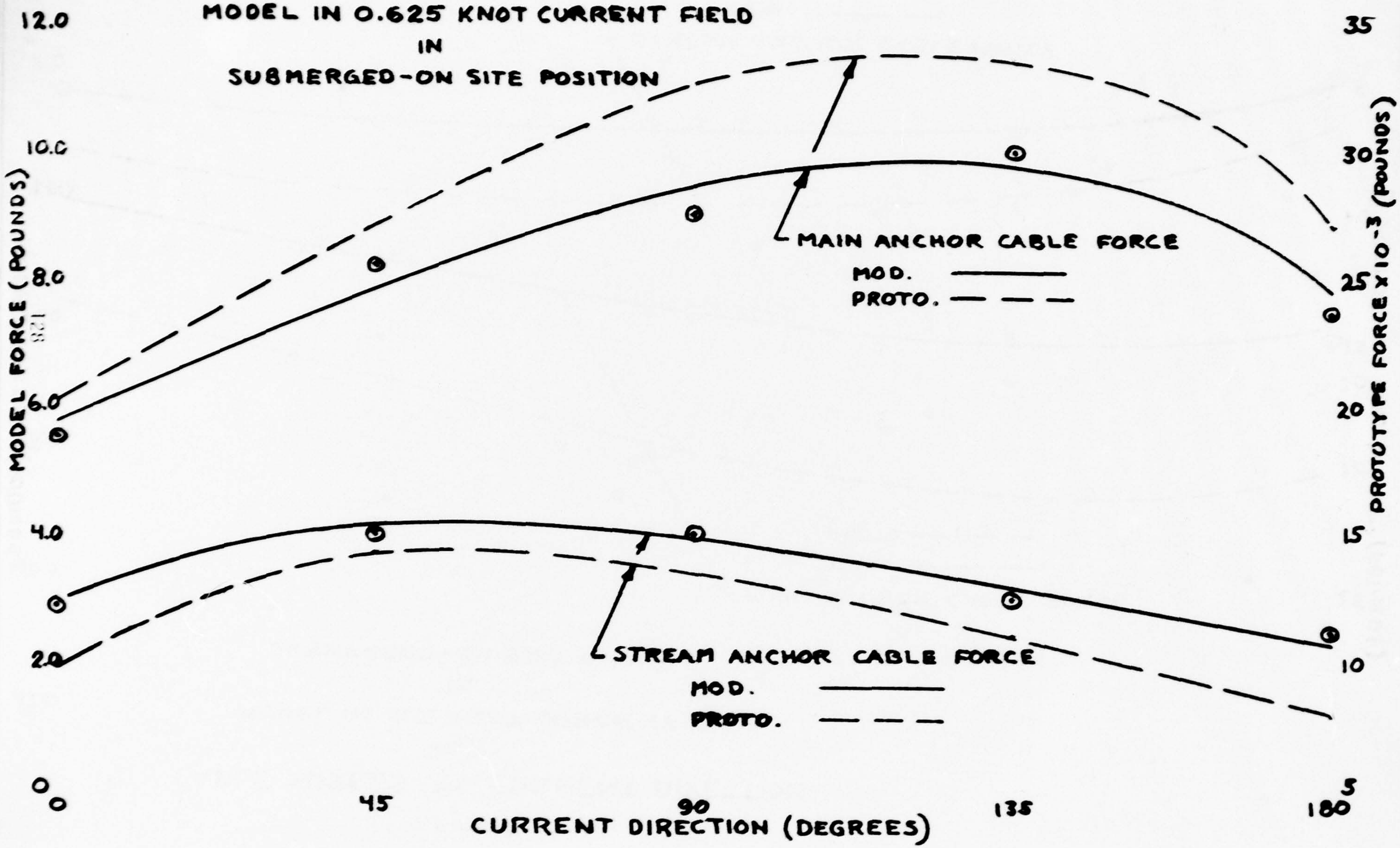
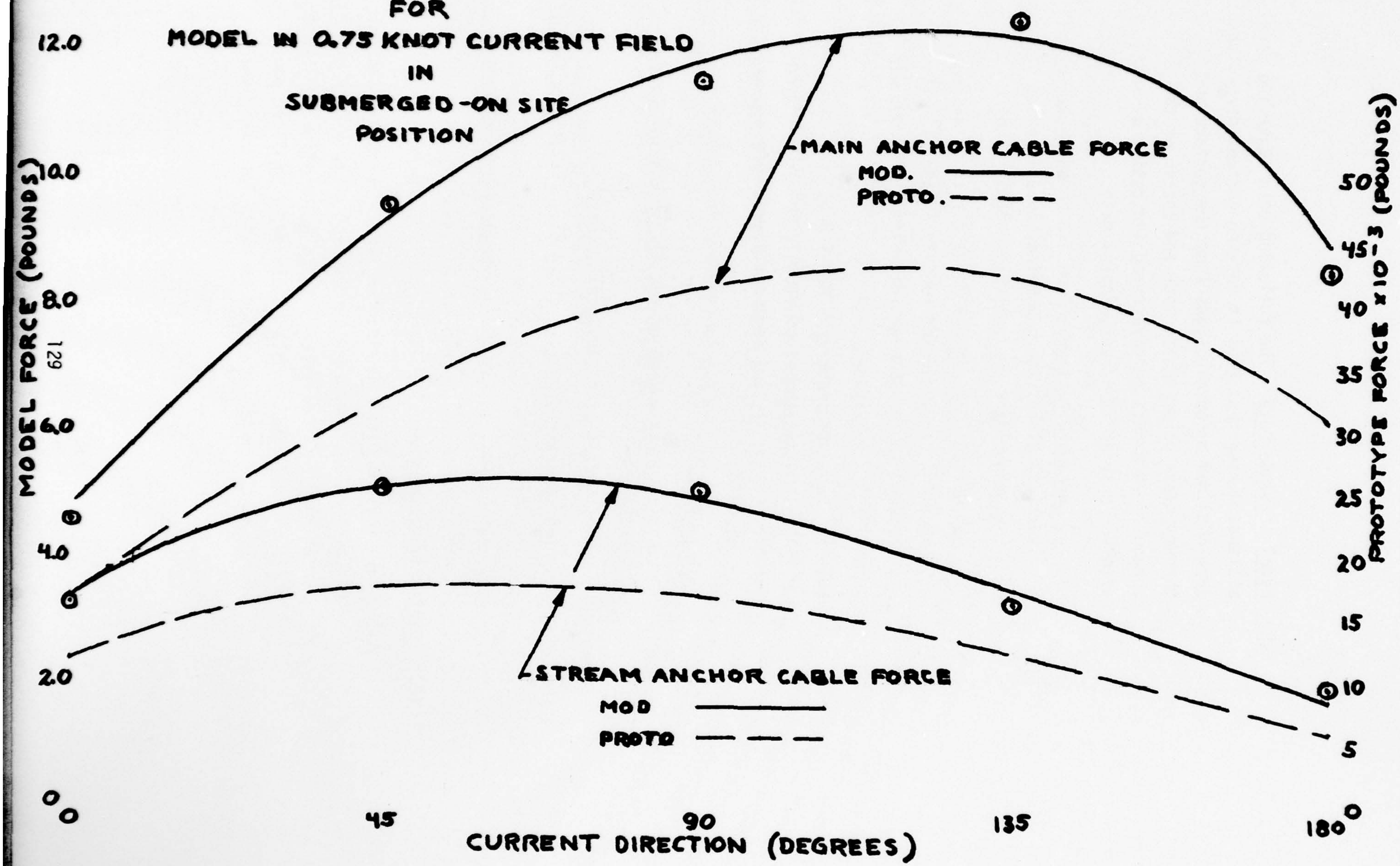


FIGURE 15

CABLE FORCES VS. CURRENT DIRECTION
FOR
MODEL IN 0.75 KNOT CURRENT FIELD
IN
SUBMERGED-ON SITE
POSITION



(b) Model Attitude Data - The following data regarding model attitude during test runs in varying current directions were obtained by observations from the surface and through glass ports in the side and bottom of the channel. This data is considered indicative of model attitude only as it is very approximate.

[1] 0° Current Direction - Model remained in its 0° vertical plane, the bow being elevated about 5°. (see Fig. 9 for vertical plane definition)

[2] 45° Current Direction - Model developed maximum heel and yaw angles of roughly 5° and 10° with respect to its 45° vertical plane. The bow was elevated about 5°.

[3] 90° Current Direction - Model developed maximum heel and yaw angles of roughly 10° and 15° with respect to its 90° vertical plane. The bow was elevated between 5° and 10°.

[4] 135° Current Direction - Model developed maximum heel and yaw angles of roughly 5° and 10° with respect to 135° vertical plane. The bow was depressed (stern elevated) about 5°.

[5] 180° Current Direction - Model essentially remained in its 180° vertical plane (slight instability in yaw noticed). The bow was depressed somewhat less than 5°.

(2) "Surfacing - Winching Up"

(a) Cable Tension Data - During the first few feet of ascent, strip-chart data recorded a reduction of both main and stream anchor forces for all tests below values obtained while the model was in its "Submerged - On Site" position. As the model continued to rise, the strip-chart cable force data became erratic for all but the "0^{o} Current Direction" tests indicating an inability of test procedures to winch-up the model smoothly as the current field caused it to depart radically from its "ideal - no current" vertical plane of ascent. This was particularly the situation for the 0.625 knots and 0.75 knot current velocities.

The following table compares the "0^{o} Current Direction" and "0.5 knot current velocity" tests for the "Submerged - On Site" and the "Surfacing - Winching Up" operating phases.

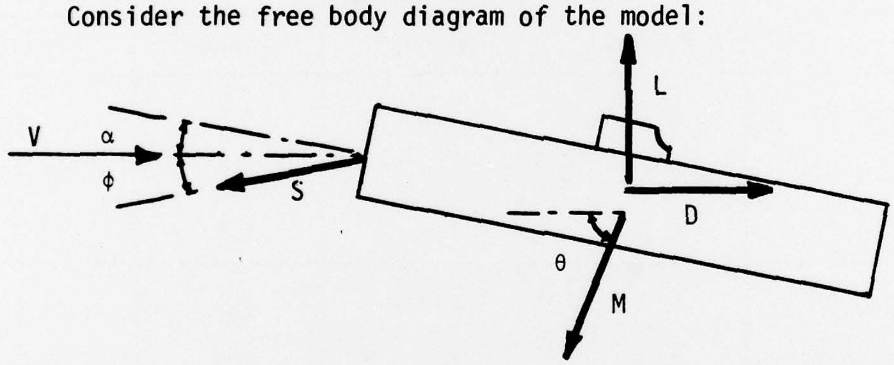
TEST	STREAM ANCHOR CABLE		MAIN ANCHOR CABLE	
Series Current Dir Current Vel	Submerged On Site	Surfacing Winching Up	Submerged On Site	Surfacing Winching Up
	Pounds	Pounds*	Pounds	Pounds*
D-0-0.50	2.4	1.2	4.0	1.5
D-0-0.625	2.9	1.2	5.5	1.5
D-0-0.75	3.2	1.5	4.5	2.0
D-0-0.50	2.4	1.2	4.0	1.5
D-45-0.50	2.8	1.5	5.0	3.0
D-90-0.50	2.8	2.0	5.7	3.0
D-135-0.50	2.8	2.0	6.0	3.5
D-180-0.50	1.8	1.0	6.0	2.5

* These force values remained fairly constant with change in depth

(b) Model Attitude Data - Model attitude data, obtained by cameras maintained on the "dumb waiter" and under the model, were of limited value revealing the model drifting out of the "ideal-no current" vertical plane of ascent. Drift associated with the 0.625 and 0.75 current velocities was so pronounced for all but the "0^{o} current direction" that the model was carried out of the cameras' frames after it had ascended a few feet.

b. Discussion - The lack of lift and drag information for shapes comparable to OSCILAB model presenting varying angles of attack in trim, heel and yaw preclude an analytical check of test data with the possible exception of the "0^{o} orientation" of the model, i.e. the model's bow facing directly into the current. As has been noted for this orientation, the model's centerline plane remained in the 0^{o} vertical plane, the angle of attack being composed entirely of about a 5^{o} bow up trim angle.

Consider the free body diagram of the model:



where:

L = Lift force - composed of a positive buoyancy force (2.2 lbs) and the dynamic lift force (lbs)

D = Drag force - dynamic drag (lbs)

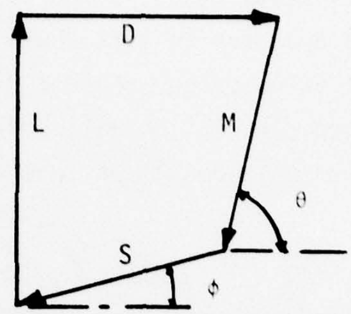
M = Main anchor cable tension force (lbs)

S = Stream anchor cable force (lbs)

V = Velocity of undisturbed current field (ft/sec)

α = Trim angle of attack

For static equilibrium, the force polygon must close thusly:



This polygon can be drawn to scale, using test data for M, S, θ and φ and values found for D and L. Inserting these D and L values into the well known equations

$$C_D = \frac{D}{\rho/2\ A_1 V^2} \qquad A_1 = \text{projected frontal area normal to flow - ft}^2$$

and

$$C_L = \frac{L}{\rho/2\ A_2 V^2} \qquad A_2 = \text{bottom area (approximately length x beam) - ft}^2$$

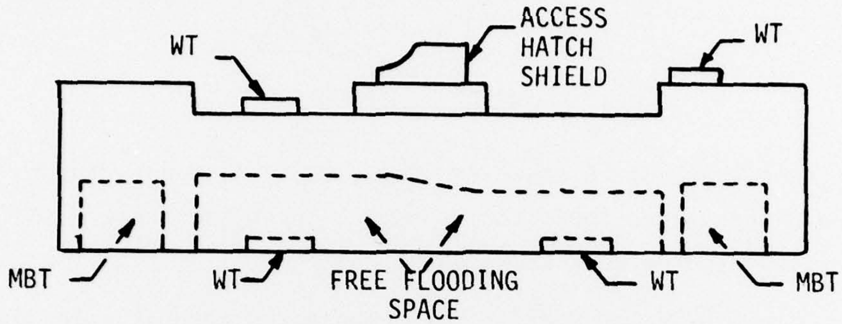
values for the drag and lift coefficients (C_D and C_L) may be found and compared with published values for these coefficients thus affording a check on test data.

Using the D-0-0.75 test data, the following computation is made for the drag coefficient:

$$C_D = \frac{3.6}{\frac{1.9384}{2} \times 1.2 \times 1.27^2} = \underline{1.9}$$

where D = 3.6 pounds is scaled from the polygon using values of M = 4.5 pounds, S = 3.2 pounds, $\theta = 85^0$ and $\phi = 5^0$ as recorded in the test. The OSCILAB's hull shape basically is composed of hemi-cylindrical ends with a parallel middle-body section in between. Data from "Hydrodynamics of Ship Design" (Saunders) gives C_D = <u>0.7</u> for a cylinder with comparable L/D ratio (2) and

Reynold's Number (4.85×10^5). Adding the parallel middle-body drag, primarily viscous drag, raises the drag coefficient to about 0.85. The drag due to lift would raise this to about 0.95. While the actual value of the model's drag coefficient cannot be closely checked, it will be well above 0.95 because of the irregular deck and open bottom as indicated in the sketch:



These irregularities approximate those found on the prototype and, hence, an experimental $C_D = 1.9$ appears within reason.

Following a similar procedure for computing the lift coefficient,

$$C_L = \frac{2.5}{\frac{1.9384}{2} \times 2.75 \times 1.27^2} = \underline{0.58}$$

where the hydrodynamic lift is L = 2.5 pounds which is the total lift scaled from the polygon (4.7 pounds) minus the positive buoyancy lift (2.2 pounds). The theoretical value of the lift coefficient for thin flat plates as given in "General Aerodynamic Theory - Perfect Fluids" (von Karman) is

$$C_L = 2\pi \sin \alpha = 2\pi \sin 5^o = \underline{0.58}$$

where $\alpha = 5^o$ is the angle of attack. Hence, the experimental value of C_L and the data from which it is derived seem reasonable.

The curves of forces in the main anchor cable all lie above those for the forces in the stream anchor cable. This is to be expected as a study of the polygon reveals that for θ and ϕ

angles in the vicinity of 75^0 to 85^0 and 5^0, as they were for these tests, a lift greater than drag must result in a "M" force greater than a "S" force. It is not surprising that the lift force, composed of both positive buoyancy and hydrodynamic lift, exceeded the hydrodynamic drag for all data recorded.

The general shape characteristics of the main and stream anchor force curves appear reasonable. Both can be expected to rise as the model departs from the "0^0 current direction" and the projected areas and angles of attack increase. The stream anchor curve reaches an approximate plateau between "45^0 and 90^0 current direction" and then falls off. This is to be expected as the mooring geometry requires the main anchor cable to carry an increasing portion of the load, including the drag, once the stern becomes the leading edge of the body in the current field with the stream anchor now attached to the trailing edge. This increase in main anchor cable loading is displayed in the curves, the maximum values being reached at about the "135^0 current direction."

Figures 13, 14 and 15 indicate that the main anchor and cable system is not adequate for any of the current velocities investigated with regard to both anchor "hold down capacity" and cable force. However, the curves for the 0.5 (model) current velocity reveal that this condition can be met if the main anchor "hold-down capacity" is increased to at least 23,000 pounds. The cable loading for this is about 50% of the elastic limit load which is considered adequate.

It has been noted that 0.5 knot current velocity (1.9 knots full scale) was the lowest reliably obtainable in the CWC facility. Hence, cable force data and model attitudes in current ranges for divers working outside the lab (0 to 1 knot full scale) could not be acquired. However, data for the 0.5

knot (1.9 knots full scale) can be considered as limiting data, including factors of safety, for this lower range of current velocities. A full scale mooring system adequate in a current field velocity of 1.9 knots will be adequate "plus" in a current field of 1 knot when the model is in a "Submerged - On Site" position and divers are working outside the lab.

Data obtained regarding the vertical ascent motion of the model in the current field is considered inadequate from a quantitative point of view principally because of main and stream anchor winching difficulties experienced during these tests. Qualitatively, the 0.625 and 0.75 currents velocity series of tests indicated the model making radical departures from its "ideal - no current" vertical plane of ascent almost as soon as ascent from its bottom-moored position began. The 0.5 knot tests produced better results with a maximum main anchor cable angle of about 45^{0} being developed with respect to the bottom, the cable being in a plane making an angle of about 70^{0} with the "ideal - no current" vertical plane.

Drift out of the ideal vertical plane must be accepted for a body ascending at an angle to the current direction and utilizing a two-point mooring system. The question is "How much drift is acceptable?" This is an extremely difficult question to answer but it would seem that a main anchor cable lead angle of 45^{0} might be considered an arbitrary limiting angle if one is willing to accept surfacing from a 300 foot depth somewhere within a 300 foot radius circle, the center of which is directly over the main anchor. However, such lead angles might overturn the main anchor. This should be investigated. In any event, the current field velocity and direction may vary with depth with the possibility of the cable going slack as OSCILAB ascends. This is yet another reason for using sensitive constant-tension winches.

The bottom of the channel was smooth (steel and glass) and afforded no opportunity to approximate the ocean bottom insofar as ground tackle holding power is concerned.

F. CONCLUSIONS AND RECOMMENDATIONS

Specific and general conclusions are drawn for each of the four test series comprising the overall test program. Recommendations are made regarding future activity as based on these conclusions.

1. Conclusions

a. Series A - "Submerging - Interface Breakthrough"

(1) Conclusions - Specific

(a) Hull Motion (Surface) - The tests indicate no danger of resonant motion developing despite proximity of wave periods and natural periods of hull heave and pitch. Inertia forces due to heave and pitch accelerations are within acceptable limits for structure and equipment as well as for occupants considering brevity of this phase of operation.

(b) Hull Motion (Submerging) - Hull descent rate appears relatively high, but the prototype descent velocity is controllable by means of the variable ballast system. Excessive "overshoot" is recorded, an undesirable characteristic that can be minimized by decreasing descent rate. A sensitive constant-tension winch will be required to protect cable and winching mechanisms from remaining "overshoot" effects.

(c) Main Anchor-Cable System - This system appears adequate for all cable lengths utilized and investigated under the most severe amplitudes of support motion (with hull on surface). No danger of anchor resonant motion is indicated. The cable is subjected to tension at all times and is loaded within acceptable limits as based on the elastic limit load.

(2) Conclusions - General

Experimentally and analytically derived data indicate that the OSCILAB system design is satisfactory for the "Submerging - Interface Breakthrough" phase of operation in all sea-states investigated and for test procedures employed.

b. Series B - "Surfacing - Winching Up & Decompression-Halt"

(1) Conclusions - Specific

(a) Hull Motion (at "lab decompression-halt depth") - Motion at "lab decompression-halt" depth of 30 feet (or "diver-decompression-halt" depth of 40 feet) is excessive for all sea-states investigated. A range of "lab-halt" depths from 40 to 60 feet appear feasible in 12 to 16 knot wind generated seas from the view-point of occupant comfort.

(b) Main Anchor - Cable System (with lab at "lab decompression-halt" depth). A 30 foot "lab-halt" depth fails to meet main anchor-cable system requirements in all sea-states investigated. A range of "lab-halt" depths of 48 to 60 feet appears feasible in a 12 knot wind generated sea for the main anchor-cable design as it exists.

(2) Conclusions - General

Experimentally and analytically derived data indicate that the OSCILAB system design is satisfactory for the "Surfacing-Winching Up and Decompression-Halt" phase of operation in 12 knot wind generated seas for "lab-halt" depths from 48 to 60 feet under test procedures employed.

c. Series C - "Surfacing - Free Ascent"

Experimentally derived data indicates that the OSCILAB system design is satisfactory in providing for a stable, non-oscillating ascent at resonable ascent velocities in all sea-states investigated and under test procedures employed.

d. Series D - "Submerged - On Site & Winching Up"

(1) Conclusions - Specific

(a) Mooring System (Lab on Site) - Test data indicates that the mooring system composed of the main and stream anchors is not adequate for all current directions and a velocity of 1.9 knots (the lowest current speed obtainable), the cable forces being acceptable but the main anchor's "hold-down" capacity being exceeded.

(b) Mooring System (Winching Up) - Test data indicates that the same conclusion can be drawn as for the "lab on site" tests.

(c) Hull Attitude (On Site) - Tests indicate that the hull attitude (in list, trim and yaw) are within acceptable limits for all current directions and speeds up to 2.4 knots.

(d) Hull Motion (Winching Up) - Tests indicate that hull motion characteristics may be satisfactory for all current directions and speeds up to 1.9 knots. Beyond this speed tests, while inconclusive, indicate that hull motion (principally in drift and oscillation) is excessive.

(2) Conclusions - General

Experimentally derived data indicate that the OSCILAB system design (with the main anchor "hold-down" capacity increased) is quite likely to be satisfactory for the "Submerged-On Site & Winching Up" phase of operation in currents of all directions and velocities up to 1.9 knots.

It is indicated that a two-point mooring system is not adequate for OSCILAB operation in submerged current fields exceeding a velocity of about 2 knots.

2. Recommendations

a. Regarding "Submerging - Interface Breakthrough" Phase of Operation

Hull motion characteristics and the response of the main anchor-cable system (as redesigned) should be studied with the hull on the surface and subjected to irregular waves associated with 12, 16 and 20 knot wind generated seas.

b. Regarding "Surfacing - Winching Up and Decompression-Halt" Phases of Operation"

The main anchor-cable system should be redesigned by analytical methods to increase its ability to satisfactorily moor the hull at "lab-halt" depths ranging from 40 to 60 feet in 12 to 16 knot wind generated seas.

The redesigned system should be model tested with the hull moored at "lab-halt" depths ranging from 40 to 60 feet (2.7 to 4.0 feet model depth) in irregular waves associated with 12 to 16 knot wind generated seas.

c. Regarding "Surfacing - Free Ascent" Emergency Phase of Operation

No recommendations are to be made regarding this emergency phase of operation.

d. Regarding "Submerged - On Site & Winching Up" Phase of Operation

The main anchor should be redesigned (in conjunction with the redesign recommended in "b") to increase its hold-down capacity in order to meet the requirements of bottom mooring and winching up associated with currents of all directions and velocities up to 1.9 knots.

The redesigned system should be model tested in currents of varying directions and speeds up to 1.9 knots (about 0.5 knots modeled) in a facility capable of generating current velocities lower than 0.5 knots if such a facility is available.

The possibility of OSCILAB system utilizing other than a two-point mooring system should be investigated if it is desired to operate OSCILAB in submerged current fields exceeding 2 knots.

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13. ABSTRACT

Model test programs to investigate certain dynamic performance characteristics of two saturation diving systems are described.

SEADOPOD employs a support barge which services a diving capsule or pod capable of delivering a four-man, diver-scientist team to and from depths of 300 feet. The pod elevator mechanism consists of a main winch and support cable, two constant-tension guy lines, and a transloader control which acts to decouple barge heave motion from the pod in order to maintain a more stable platform for the diver-scientists.

OSCILAB is a habitat-laboratory vehicle permitting four diver-scientists and two diver-crew members to live and work at depths of 300 feet for a period of two weeks under saturation diving conditions. The laboratory is capable of lowering and raising itself but relies on surface support for normal power, monitoring, and surface mobility.

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