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MOORING HANDBOOK

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NOAA Data Buoy Office
National Space Technology Laboratories
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MOORING HANDBOOK

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This handbook represents a summation of the NOAA Data Buoy Office experience to date. As such, it contains the work of all those people who have been involved with NDBO moorings in the past.

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CHAPTER I

INTRODUCTION

1.0 PURPOSE AND DESCRIPTION

This handbook is presented as a practical guide to the design, deployment, and recovery of data buoy moorings. It is based upon the experience of the NOAA Data Buoy Office (NDBO), primarily with large (10- or 12-meter diameter hull) discus buoys. Since many of the principles applied to large buoy moorings have been applied to smaller NDBO buoys and are applicable to most single-point surface buoy moorings, it is hoped that others in the field will find this handbook useful.

Every effort has been made to keep this handbook practical and restrict the text to what is known through firsthand experience. In addition, reprinting of material which can better be included by reference has been avoided. The handbook is an "in-house" effort since neither budget nor schedule has permitted solicitations of chapters from outside experts.

To apply today's experience to the ever-broadening demands for moorings, ocean engineers will need a handbook to guide their efforts that will range from small buoys to semi-submersible drilling rigs and offshore oil ports. Desirable as such a broad-based handbook may be, the goal of this effort is to record the procedures used in the design of moorings, the materials available, and the deployment and recovery techniques evolved by NDBO's contractors and engineers. Through this text, the future NDBO contractors and Government engineers may benefit from the problems and the successes of the past without resorting to hearsay; others may also benefit from this discussion of what we have learned.

Briefly, the contents are as follows: Chapter II is devoted to the mooring system design. It presents the important design considerations, a procedure for design, and an example of a mooring design. Chapter III covers the NDBO Hull/Mooring simulation which is the analytical design tool used to make the final component selection. Chapter IV describes the mooring components most commonly used by NDBO and the experience in avoiding or correcting materials problems. Chapter V discusses deployment and retrieval equipment and procedures in an effort to convey what has been learned about the hardware and the seamanship required. A brief closing chapter discusses ongoing and planned developments in mooring technology.

2.0 DESIGN PHILOSOPHY

NDBO has adopted a systems approach to buoy technology. Under this regime, the requirement to constrain the motion of a surface buoy within a specified area is met by the mooring. Alternative approaches include active subsystems such as the proven dynamic positioning used on deep-sea drill ships and the experimental wind-driven buoy positioning on which preliminary tests were conducted. However, data buoys will, for the foreseeable future, be moored by flexible mooring systems. The NDBO mooring material choice has been synthetic fiber lines, primarily nylon and polyester.

To meet the system requirements for the mooring, a conservative design philosophy has been adopted as reflected in the factors of safety discussed in Chapter II. The philosophy emphasizes simplicity of handling at sea and reliability to meet the design requirements which usually call for long-term deployments. The mooring is selected on the basis of the least expensive design which results from this philosophy and is fully capable of surviving the design environment.

Since the buoys, in most cases, are operational, there has been very limited opportunity to make the engineering measurements of mooring line tension, position, and motion needed to accurately predict mooring reliability. This is true since any instrumentation for such measurements would increase system size and power consumption and reduce reliability without improving the data, which is the buoy's operational output. To make the most of experience to date, histories of each mooring have been maintained to infer forces and performance from the meteorological data gathered by the buoy. Detailed analyses of any failures have been performed and necessary design modifications have been made. In addition, a mooring dynamics experiment to measure the motion and forces on a deep mooring is now in the final instrumentation assembly stage. Experience has generally shown that cost savings can be made as we apply the historical data of success and analyses of failures. Chapter II discusses factors of safety and the experience which, in many cases, has led to their gradual reduction.

The handling aspects of the design philosophy are the result of designing moorings for deployment, recovery, and servicing by ships-of-opportunity. While NDBO has one dedicated ship at its disposal, there are far too many buoys for it to service. The dedicated ship does, however, serve as the best vehicle to test new and simpler techniques. Chapter V presents the results of the efforts to meet the requirement of operating with crews which are not familiar with data buoys and their moorings.

3.0 DESCRIPTION OF MOORINGS

NDBO has restricted itself to single-point moorings for simplicity of design, deployment, and recovery. The moorings have ranged from taut with an unstretched scope of less than 1.0 to as slack as 3.0. The most taut moorings have been used for smaller buoys, while the large discus buoys have generally been deployed with a scope of 1.1 to 1.3. Scope as used herein is the ratio of total unstretched length of the mooring to depth of water.

The moorings have all had a nylon or polyester line as the predominant component because of their desirable elastic characteristics which serve to dampen the effect of wave action within a short distance of the surface. To avoid chafe problems, it has been common practice to use chain in the region of the mooring which comes in contact with the bottom. It is desirable to attach the mooring to large buoys under controlled conditions ashore. In these cases, chain is also used at the top of the mooring to prevent damage to the attached and exposed upper section during towing, deployment, and recovery operations.

Two configurations have evolved for mooring the large buoys. In the first, to meet the requirements to avoid chafing of the line on the bottom when the mooring is in a slack condition, syntactic foam floats have been used to support the line in a "lazy S." In the second design, the lower portion of the mooring is replaced with high strength alloy chain. This does not produce a major increase in maximum mooring tension. This "semi-taut" configuration lends itself to easy deployment and is less expensive than incorporating the foam floats. The length of line is generally chosen to avoid chafing and the length of chain is chosen to optimize the total mooring system cost. A more detailed discussion of this mooring is given in Chapter II.

Other moorings used have included an automatic, intermediate, subsurface float system combining wire rope and synthetic line, and another system which stored the synthetic line in an anchor box and payed it out as the box sank. These are described further in Chapter V. For the mooring of a buoy designed to be a drifting buoy, NDBO has utilized a surface float and tether arrangement. A sketch of these and other small buoy moorings is available in the NDBO document "Practical Experience with Buoys" (1973).

While the configuration for a particular purpose may vary, the design philosophy for ease of handling and reliable performance always applies.

4.0 EXPERIENCE

This handbook represents the experience gained in more than 25 mooring deployments. Buoys have been successfully deployed in the Gulf of Alaska and off the East Coast, and the moorings have survived severe winters in these environments. In addition, two moored in the Gulf of Mexico have survived a hurricane that passed directly over them. While these incidents, taken alone, do not fully validate the designs, they do indicate that a rational approach based on the NDBO Hull/Mooring simulation and the historical data gathered to date can be successful.

Although the procedures herein are proven, there is little doubt that changing requirements and new materials will evolve new designs to better serve buoy technology. Nothing in this handbook is intended to retard initiative; it is presented as a gateway, not a barricade.

Reference: NOAA Data Buoy Office, "Practical Experience with Buoys," Pub. NDBOM 0547-1, November 1973

CHAPTER II

MOORING SYSTEM DESIGN

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MOORING SYSTEM DESIGN

1.0 INTRODUCTION

This chapter outlines NDBO procedures for the design of moorings for large buoys in deep water. Most of the material is applicable to nearly all data buoy moorings. Included are an explanation of the procedures, an example of an actual design, and a list of references.

2.0 BASIC DESIGN CONSIDERATIONS

Factors that must be investigated and taken into account in the mooring design are:

- o Mooring Site (including depth, bottom conditions, environment and current profile)
- o Buoy/Mooring Interactions
- o Safety Factors
- o Deployment and Retrieval Methods

2.1 MOORING SITE SELECTION CRITERIA

The user of the data from the buoy specifies his most desirable mooring site. The mooring designer must then strive to find a site as close as possible to this site while avoiding, if he can, the following areas and hazards:

- o Shipping lanes
- o Submarine transit lanes
- o Restricted areas
- o Ocean dump sites
- o Areas where the ocean floor slopes steeply
- o Tops of submerged pinnacles
- o Strong currents such as the Gulf Stream
- o Icebergs and sea ice areas

Most of this information can be found on navigational charts, pilot charts, and atlases. U. S. Coast Guard District Aids to Navigation Offices can also provide helpful information.

Where it is imperative that a buoy be moored over a pinnacle or on a steep slope, special embedment anchoring devices may be considered.

2.1.1 Depth and Current Profiles

Chart depth and current profiles start the mooring selection design process. Larger scopes and line diameters increase safety factors, but at the same time increase costs. Therefore, tradeoffs are made to use the most economical combination of line diameter and scope to achieve a desired safety factor. Table II-1 gives examples of possible combinations. It should be noted that even though the largest scopes and diameters generally produce the greatest safety factors, they may also produce the greatest tensions, due to additional drag forces and weight of line.

2.1.2 Environmental Conditions

Once a general position has been chosen, the local environment is investigated. Data for many areas of the world are available through the National Climatic Center in Asheville, NC. Meteorological almanacs are also used to determine the worst-case environments for which the mooring will have to be designed. However, the validity of most of this data is limited by the fact that it has been gathered primarily by ships-of-opportunity, which tend to avoid extreme weather and sea conditions. Table II-2 lists the sources of environmental information used by NDBO.

The buoy system is designed to survive under a maximum environment consisting of a composite of the worst-case winds, current profile, and seas known for that area. NDBO has defined these maximum buoy environments for several areas from the East Coast to the Gulf of Mexico, and from northern California to the Gulf of Alaska (see Table II-3). The current drag constitutes a major load upon a deep mooring system and, unfortunately, a current profile is the most difficult parameter to obtain. Buoy systems designed to these criteria have successfully withstood the full force of at least one major hurricane. Extreme environmental conditions have not been a factor in mooring failures encountered to date, probably indicating conservatism in the selection of design, the design environment, and the safety factors. For high cost buoy and mooring systems, a conservative approach is realistic, since additional money spent in the mooring may greatly reduce the risk of loss of the entire system.

2.1.3 Bottom Conditions

In many cases, the most useful description of the bottom composition comes from navigational charts. There are also publications on the geology of some ocean areas. Knowing the soil characteristics in a given area aids in choosing an anchor and estimating how well it will hold, but they are seldom known for deep-water sites, and are generally assumed to be ooze or mud. Soil characteristics are also important because they define abrasive conditions to be encountered. The synthetic line generally used in deep-sea moorings--nylon or polyester (Dacron)--is subject to chafing damage from rock or sand bottoms. Our experience with two known cases of nylon in one location with a grey mud bottom, however, has been that no chafing occurred.

Knowledge of the bathymetry at the deployment site is of the utmost importance. It is very desirable to moor on a flat, broad plain rather than on a slope or a pinnacle where the possibility of dragging into deep water exists. A flat site is chosen from the charts and then rechecked by survey with a precision depth recorder prior to deployment to verify the depth and bottom contour. The depths at which NDBO deep-ocean buoys are normally moored range from 8,500 to 15,500 feet. A sufficient amount of excess line is included aboard the deployment ship as part of the original mooring design to accommodate the actual depth as determined by the final survey. The details of the deployment and retrieval operations are covered in Chapter VI.

2.2 BUOY/MOORING INTERACTIONS

The buoy and mooring must be a balanced combination; the forces exerted by each element must not exceed the other's capabilities.

The wind and surface current on the buoy impose a quasi-static (long time constant) horizontal drag loading which translates to a horizontal force at the top of the mooring line. The mooring system restrains the buoy horizontally, and produces opposing forces with vertical components at the attachment point. The magnitude of these forces depends on the angle of the mooring line at the buoy (which is a function of mooring length, material properties, and water depth), as well as the horizontal load. This vertical load, as well as the mooring weight, affects buoy draft and mooring tension, and must be acceptable to both system elements.

Dynamic response of the system to waves introduces motions and forces which are time-varying. The top of the mooring line must follow the motion of the buoy attachment point, and the tension must oppose the upward force of the buoy. These forces are functions of the wave height and period, the buoy size and shape, and water depth; as well as the mooring line size, length, and elasticity.

The design of the mooring system must include consideration of the steady state and dynamic mooring forces imposed by the buoy under normal and extreme environmental conditions. It must also consider those forces which the mooring imposes on the buoy. NDBO has developed a computer program which models the buoy mooring system. It is a two-dimensional, frequency domain model which first determines the steady state configuration of the buoy and mooring line under a specific wind and current environment. The results include horizontal excursion, depth, tension and cable angle along the mooring line, and anchor loads, as well as buoy draft and trim. Using this static solution, the program then simulates dynamic response to waves for desired frequencies and can predict spectral response by appropriately combining these frequencies. Dynamic response results include tension and velocities along the line.

Application of this model requires inputs which describe the buoy shape and mass properties, as well as the shape, mass, and mechanical properties of the mooring line, and mass and drag characteristics of objects attached to the line. The program can accommodate several generic buoy shape types: discus, boat, catamaran, spar, or hemispherical. This program is described in greater detail in Chapter III.

2.3 SAFETY FACTORS

Although the design method used is a quantified process which incorporates the most current information available, there are a significant number of unknowns and some of the assumptions may not be valid. These unknowns result from an inadequate definition of the ocean environment and forces imparted to the mooring system, assumptions involved in the prediction of mooring response, questions concerning in situ mooring material physical characteristics, and degradation in service. Because of this, safety factors greater than 3.25 are used for the worst-case design events. Recent sharp increases in the cost of mooring line are making it increasingly important that the magnitudes of these unknowns, and the safety factors necessitated by them, be reduced.

2.3.1 Environmental Conditions

The lack of well-defined in situ conditions contributes to the use of large safety factors. Most designs call for the use of an assumed current profile for a given area. When current profiles can be verified or revised through measurement, it is hoped that safety factors can be reduced. The analysis of known hurricane forces on a Gulf of Mexico-deployed buoy and full scale mooring dynamics experiments should supply some of the needed information.

2.3.2 Line Characteristics

Some safety factors are required because of unknown physical properties of synthetic line material. For example, the mooring line is described by a load-elongation curve for the given line size, but this is usually derived from measurements conducted in air, and does not take into account the long-term effects of water and pressure on the synthetic line. The in situ synthetic line behavior may be significantly different from the dry load-elongation behavior. The effects of water and pressure are largely unknown. Information on the actual properties of the mooring materials is given in Chapter IV, and also in the publication, "Review of Synthetic Fiber Ropes," by Dr. Walter Paul. Retrieved moorings have been tested and have shown up to 90%+ of their original strength; these have been reused.

The safety factor is defined as the ratio of the design mooring tension to the break strength of the weakest mooring component, usually the synthetic line. Since in some nylon line constructions significant creep (and a resultant degradation in line strength) can occur at loads as low as 40% of break strength, NDBO could design moorings to a minimum safety factor of 2.5 if this were the only unknown. While such new materials as Kevlar offer a higher threshold of creep and the hope of designing with smaller safety factors, the creep characteristics must be considered in sizing the line for any mooring.

2.3.3 Degradation and Hazards

The mooring system is susceptible to various hazards and forms of degradation. Rough deployment handling, chafing, and abrasion are sources of trouble. Poor splices about thimbles on a mooring attachment can cause wear on the line. Although no significant deterioration due to fouling has been found to date, fouling occurs on the mooring line in the upper water column where light promotes growth of marine organisms. The potential therefore exists for long-term degradation of deployed mooring line and components. Although NDBO has had may buoy-years of operation, most of the data acquired have been qualitative, and statistically significant degradation factors are not yet available.

2.3.4 Fishbite

Since the mid-1950's, fishbite has been recognized as a potential problem in moorings. To date, no system has been devised to completely eliminate fishbite damage to moorings. Woods Hole Oceanographic Institution has undertaken studies for NDBO to gather information on fishbite as a mooring problem, and to make recommendations defining the most practical approaches to pursue in guarding against fishbite. One approach has been the use of synthetic armors for mooring lines. Hard plastic jackets extruded about the synthetic line reduce the probability of damage. Two materials which offer some fishbite protection have been found to afford acceptable handling properties: nylon 6/6 and Celcon M25-04. Woods Hole field tests have been inconclusive, but laboratory tests have shown these materials to be superior to most other practical candidates. Armoring of the cables requires careful consideration of the loading anticipated and the stretch characteristics of the line.

Another approach to the elimination of fishbite damage is to eliminate whatever attracts fish and induces them to bite mooring line. There is some evidence to indicate that the attraction is acoustic and that suppression of strumming of the line may greatly reduce the problem. The present state-of-the-art is discussed in detail in the report by Prindle and Walden (1976).

2.4 DEPLOYMENT AND RETRIEVAL METHODS

The decision as to how a mooring system should be designed for deployment and recovery is a matter of economics and handling system requirements. The mooring line is expensive and, at least below the near-surface zone, deteriorates very little in normal use; thus it is generally suitable for reuse after testing. Safe deployment and recovery procedures must be considered during the selection of each component. The description of the components generally selected is contained in Chapter IV and the procedures for deployment and retrieval are covered in Chapter V.

The semi-taut, chain-tensioned mooring is usually used when conditions permit. This mooring consists of one continuous length of synthetic line equal in length to approximately 95% of the water depth. Below that line is a length of high strength alloy chain (typically 1,500 to 1,800 feet). This simple mooring is economical to deploy and retrieve because the line can be payed out from below deck, the chain can be stored on deck in a faking box, and the anchors deployed from gravity trays. For retrieval, a line-cutting device may be slipped around the line and sent down to sever it without fear of fouling the device. These items are discussed in detail in Chapter V.

When the environment dictates a mooring that has a large scope (see Table II-1), the chain length is usually reduced or eliminated, and floats are added to the mooring to keep the line from chafing on the bottom during slack conditions. These floats, or any sensors mounted on the line, preclude the use of the "slide-down-the-line" cutters, and an acoustic release is required to retrieve the line and the floats. This type of mooring and the acoustic release have several drawbacks:

- If the acoustic release fails to operate, much of the mooring may be virtually impossible to recover.
- The reliability of the acoustic release is limited to the life of the batteries--usually two years.
- The acoustic releases and the floats are expensive, particularly for the water depths involved in deep moors.

Large buoy mooring systems are nearly always retrieved with the use of a line cutter or acoustic release. Only under rare circumstances is it attempted to pull up the entire mooring (including the anchor and chain) because of the heavy, and possibly dangerous, loads encountered and the high probability that recovery forces may overstress the line or other mooring components, preventing their safe reuse.

3.0 MOORING COMPONENT SELECTION

Mooring components are selected on the basis of availability, compatibility, and engineering properties.

A basic design is synthesized, evaluated, and then the final details are completed on the basis of the specifications for available components. Properties are generally quantifiable for each component by a catalog or specification which defines nominal characteristics. Synthetic line materials are usually procured with a graph or table of the load-elongation response of the mooring line to the breaking point. For some applications, a general curve supplied by the factory is not satisfactory, and a curve for each production run must be generated. If the mooring components design loads are critical (as in most applications), the same kind of quality certification should be obtained for anchors, fittings, and chains. When these are purchased directly from a factory, it is common practice to obtain accompanying certificates. When obtained from marine surplus dealers or marine suppliers, a proof test is required. The test procedures are discussed in more detail in Chapter IV.

3.1 DESIGN REFERENCES

Design data on the physical properties and characteristics of mooring line components are derived from published handbooks and manuals, federal and military specifications and standards, and vendor data sheets. The most useful of these is the Handbook of Ocean and Underwater Engineering by Myers, et al. It has general information concerning ocean engineering, including several sections dealing with mooring components ranging from shackles and anchors to mooring line and chain. This book combines many different items into one convenient reference. The tablulations of components' physical properties are of principal benefit.

Vendor data bulletins itemize the physical properties of specific products and usually give the most complete tabulation of engineering values available. This information may not be sufficient for all purposes, but is the best available without conducting special tests.

The Naval Facilities Harbor and Coastal Systems Command Design Manual has extensive design data related to ship moorings. Of principal interest to mooring designers are the comparative data on anchor holding power for most of the commonly used anchor types. These data are tabulated to show the result of tests for anchors of different sizes where soil composition and shank angles were varied.

For attachment fitting properties of such mooring components as shackles, thimbles, connecting links, and swivels, the mooring designer must rely heavily upon vendor data. The Handbook of Ocean and Underwater Engineering also contains engineering data on many of these mooring fittings. Military and federal specifications and standards are helpful not only for fittings, but also for other mooring components from mooring lines to anchors. Some of the mooring components that NDBO uses most often are listed in Chapter IV.

3.2 COMPUTER SIMULATIONS AND DESIGN SYNTHESIS

The behavior of candidate configurations can be predicted by use of a hull/mooring simulation program which models each configuration. Many computer models of buoy and mooring systems have been developed and are available to the general public, so it is not necessary to try to develop a complete model. Each model has its advantages and disadvantages. There is at least one bibliography available which lists many such models and their principal features (Dillon, 1973).

The most important tool in the mooring design process is the hull/mooring simulation model whose frequent utilization for various mooring requirements since 1972 has resulted in a base of design data which enables NDBO to easily make a good first cut at bounding the primary design variables. This is particularly so when there is similarity between a new requirement and old ones for which computer runs have been made previously. This model has the capability to predict the static and dynamic response, in the frequency domain, of a buoy with a multi-component, single-leg mooring system. Thus, it can be used to predict the spectral response of the buoy and mooring system in a random sea. Features of this model are discussed in Chapter III. The model was formulated to apply to almost any single-leg mooring configuration, its output is reasonable, and it is inexpensive to use.

3.3 EXPERIENCE FACTORS

The mooring design data base at NDBO is comprised of the results of computer simulation runs for candidates of varied hull/mooring types and performance evaluations in situ, coupled with experience gained in assembly and deployment, retrieval, and analysis.

Mooring line constructions and materials and mooring system components are discussed in Chapter IV. Generally, there are many candidates for each element of the mooring and it is beyond the scope of this document to attempt to justify any "best" set, inasmuch as there are undoubtedly a number of satisfactory combinations. However, confidence in certain designs, components, and materials is gained by virtue of successful functioning of the hardware in situ. Thus, preferred configurations, components, and materials evolve on the basis of satisfactory performance. NDBO designs have evolved to meet the special conditions such as large buoys, long-term moorings, and the frequent use of ships-of-opportunity for deployment and retrieval. Confidence factors increase with the number of successful deployments. The feedback of actual performance data, whether favorable or not, into the design process is one of the most important elements in achieving and maintaining long-term objectives of reliability and acceptable life-cycle costs, and to this end NDBO maintains a history of each mooring.

4.0 MOORING SYSTEM DESIGN PROCESS

The order of the mooring design process at NDBO is as follows:

- o Mooring system requirements
- o Preliminary design
- o Basic design parameters
- o Final selection and detailed design

4.1 REQUIREMENTS

Buoy system requirements are reviewed and interpreted, then translated into as complete a set of mooring requirements as possible. This usually involves clarification of ambiguities and additional information concerning the end use and mandatory constraints. Necessary requirements must be clearly separated from desirable goals. A comprehensive understanding is needed of such items as:

- o Buoy hull configuration
- o Exact deployment locale and environment
- o Required mooring life
- o Deployment and retrieval plans
- o Definition of line attachments for payload elements or instrumentation packages
- o Assessment of risk factors vs. cost

4.2 PRELIMINARY DESIGN

In the mooring design process, preliminary design encompasses the definition of survival environment, selection of the basic approach to be pursued, and identification of candidate designs which can reasonably be expected to survive and operate within that environment.

This phase is mainly concerned with the selection of scope, line sizing, anchor loads, and the method of retrieval.

The survival environment is first defined by utilizing the information cataloged according to deployment locale (see paragraph 2.1.2). The next step is to review the specific requirement for similarity with previous requirements and mooring designs which met those needs. The preliminary design task is greatly simplified when there is closely-related experience applicable to the new requirements.

The type of mooring configuration is selected from one of these three classes: taut, semi-taut, or slack.

The line must have sufficient strength to withstand the maximum mooring tension, and the anchoring system must remain stationary.

If the mooring requirements are sufficiently similar, a previously-designed system can serve as an excellent first cut at bounding the basic design parameters. In that event, the line material and approximate size is quickly determined and the preliminary design task is abbreviated. If less similar, a few simulations may be required on the computer to achieve a preliminary design. Figure II-1 is used at NDBO as a basis for very rough estimates as a starting point, when necessary. The preliminary design phase is completed when there is a reasonable confidence that the mooring line selected is adequate in terms of safety factor for the chosen survival environment. Throughout this phase, the cost of the entire mooring is considered to trade off among acceptable preliminary designs.

4.3 BASIC DESIGN PARAMETERS

At this stage, after estimating the line size, the specific line size and material and the anchor requirements are determined. At NDBO the hull/mooring simulation model is used for this. The program is inexpensive to operate, requiring relatively little computer time per run, and is used on a daily basis (see Chapter III).

Inputs to the mooring line simulation include:

- o Physical properties of all line segments
  - Length
  - Weight in air
  - Weight in water
  - Diameter
  - Cross-sectional area
  - Modulus of elasticity
  - Creep characteristics
  - Drag coefficients

- o Drag and mass data for:
  - Subsurface floats
  - Sensors
  - Other attachments

- o Hull
    - Shape and pertinent dimensions
    - Weight
    - Center of gravity
    - Radius of gyration
    - Drag coefficients
- o Site and environmental input factors
    - Depth
    - Current
    - Wind
    - Seas

Since the model operates only in one plane, the design inputs are simulated by lining up maximum winds and current profiles for the static solution; then superposing of waves for the dynamic solution. The program will output tension, angle, and strain at any desired points throughout the mooring configuration, and can print out data identifying locations of highest tension and strain for each segment of different size and material in a composite mooring. The dynamic program can be run for a range of frequencies to bound the worst case of maximum loading in the cable for the anticipated range of wave height and period.

Generally, the safety factor for use in the mooring system has been determined during the preliminary design phase. The line size evaluation is based primarily on the maximum tension expected for the design environment. Depending on knowledge of the deployment area, the environmental parameters of wind and current profile may also be varied to determine the particular mooring's sensitivity to inaccuracies in estimating these parameters.

With the NDBO computer program, the anchor is not specified as an input, but the anchor requirements (in terms of horizontal and vertical loads) are determined as outputs of the program. If anchors of varying holding power are available, an engineering tradeoff evaluation may be in order to determine if a smaller anchor is practical as a means of lowering costs. If only one kind of anchor is readily available (e.g., standard fluke-type anchor), then the immediate interest is the holding power of that type of anchor. A stockless anchor can be considered to have a holding power in excess of 2-1/2 times its weight in a little known, but soft, bottom. Thus, for a 15,000-pound horizontal force, a 6,000-pound stockless anchor would be a reasonable choice. Anchors are discussed in more detail in Chapter IV.

If the design simulation runs indicate an excessive vertical load on the anchor (in excess of its weight), and the anchor is in danger of being pulled out of the bottom, the approach is to obtain more holding power--either by obtaining a larger (heavier) anchor, or by adding heavy chain. It has been determined that it is cheaper, easier, and more reliable to deploy a length of heavy chain than to handle multiple anchors or one huge anchor, and this is a major factor in the design approach. The addition of more chain will necessitate still further computer runs to begin to optimize the mooring system. This anchor vs. chain tradeoff is made on a cost basis because the moorings are generally in such deep water and the mooring loads are of such magnitude that the mooring and its incremental changes represent a significant part of the total system cost.

The iterative phase of the design process is complete when a sufficient number of simulation runs have been made to verify that the mooring line size and anchor are proper for the intended application and are consistent with the choice of safety factors.

4.4 FINAL SELECTION AND DETAILED DESIGN

The final phase is to completely define and lay out all elements of the mooring system. A complete definition of the mooring line includes the nominal length of synthetic material needed aboard ship for an anticipated deployment depth plus a recommendation of the final length as determined by the in situ depth survey. The anchor type and specification of interconnecting chain elements in size and length are included. All mooring line attachments (subsurface sensor fittings, buoyancy floats, thimbles, shackles, etc.) are specified both as to type and location in the line. Methods of deployment and retrieval are also stated.

5.0 MOORING EXAMPLE

EB-04, deployed in the Gulf of Mexico in August 1975, is used herein as an example of a 40-foot discus buoy mooring. The basic steps in the design of the mooring were performed as follows:

- The geographic area for buoy deployment was specified, based on a data-sparse area and the need for information on hurricanes approaching the Gulf Coast.
- 26°N, 90°W was selected as the specific location. A deployment site check sheet was prepared on this location, yielding the following information:
  - Bottom consists of brown and grey mud, red clay.
  - Depth (charted) is 9,570 feet, surrounding area flat, varying less than 500 feet within 30 miles.
  - Average current is WSW, .7 to 1.3 knots.
  - Lies in area of normal passage for commercial shipping between Brownsville, TX, and the Straits of Florida.

  This information was taken from C&GS Chart #1000, Notice to Mariners, and Bath.-152.1. Since no disturbing information was found, the location was technically approved.
- Since no ocean sensors or other special devices were included on EB-04, a chain-tensioned, semi-taut mooring was selected.
- Survival environment was defined as 155-knot winds, 2.1-knot surface current, and significant wave height of 50 feet. This environment is equivalent to a violent hurricane. The current was selected as less than the design current in Table II-3 due to the low average surface current.

- Hull previously selected, based on its survivability and availability, was a 40-foot-diameter thick discus buoy.

- Line size required was estimated at 1-7/8" diameter for 8-strand plaited nylon, based on experience with the hull and a feel for the tensions imposed by the survival environment.

- Line length was fixed at a length equal to corrected depth minus 500 feet, all multiplied by .95. This accounts for both line stretch under nominal load and accuracy of depth recorders, and still keeps the line off the bottom.

- Computer inputs (environmental, hull, and mooring) were compiled and given to the computer operator with instructions to run five cases, as follows (mooring described top to bottom):

  - 45', 1-5/8" stud link chain
  - 9,070', 1-7/8" diameter, 8-strand nylon
  - 1,400', to 1,800' in 100' increments, 7/8" alloy steel chain
  - 180', 1-5/8" stud link chain

- With 1,400 to 1,700 feet of chain, tensions in the mooring line and vertical loads placed on the anchor were excessively high. With 1,800 feet of chain, the mooring line safety factor reached 3.25, and the vertical force on the anchor was about 4,000 pounds.

- The 1-7/8" line was selected because of the cost and non-availability of larger line. An 8,400-pound stockless anchor was selected to handle the mooring loads at the anchor.

- Shackles and thimbles were selected for proper size and strength based on vendor data for inventory hardware (Newco coated bronze thimbles, Crosley-Laughlin shackles, and ACCO alloy hardware were used).

The resultant mooring configuration is shown in Figure II-2.

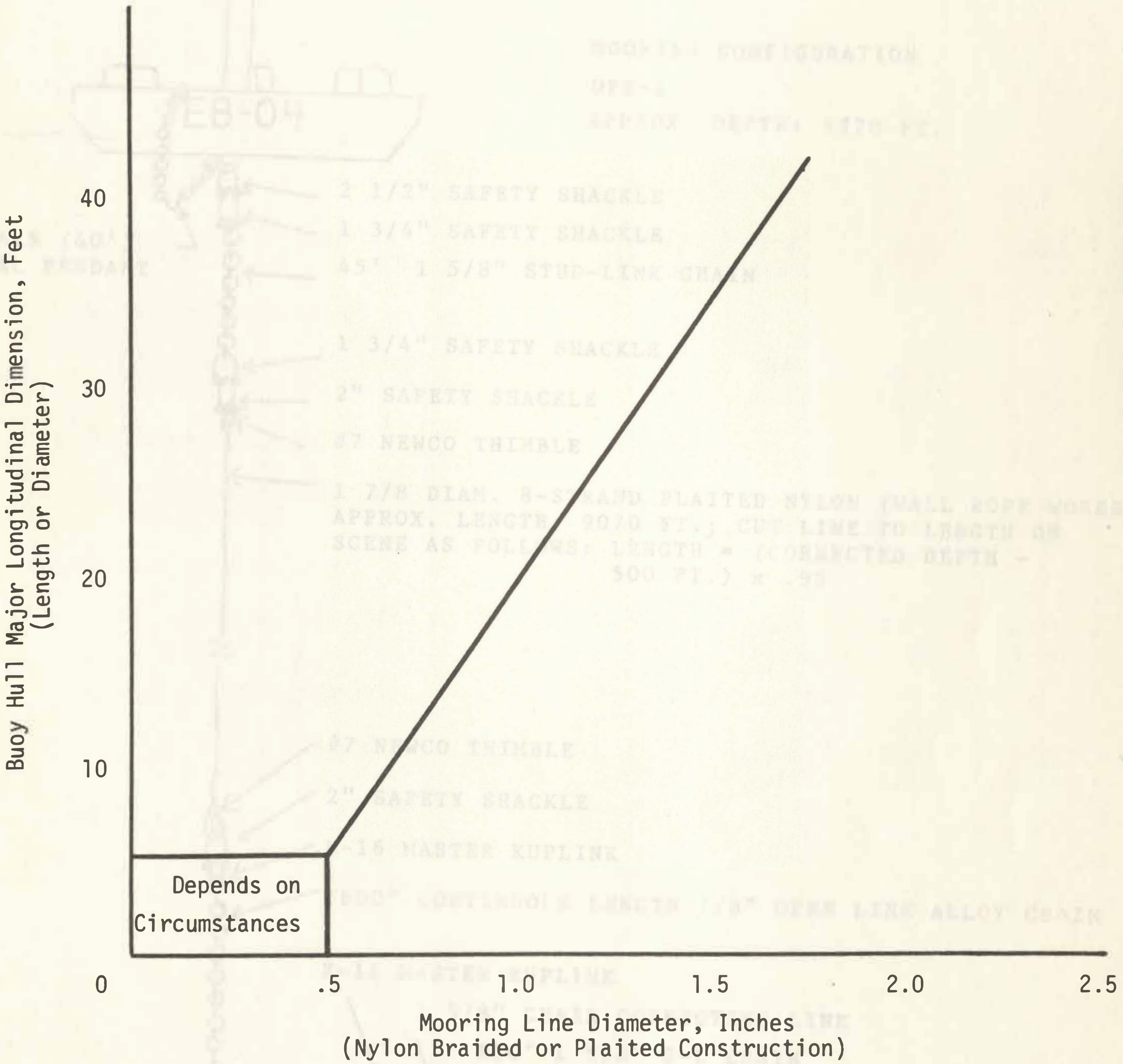
Reference: (1) Paul, Walter, "Review of Synthetic Fiber Ropes," United States Coast Guard and National Data Buoy Development Project, August 1970

(2) Prindle, Bryce, and Robert G. Walden, "Deep-Sea Lines Fishbite Manual," NOAA Data Buoy Office, 1976

(3) Dillon, D. B., "An Inventory of Current Mathematical Models of Scientific Data-Gathering Moors," Hydrospace-Challenger report HCI TR 4450 0001, February 1973

FIGURE II-1

GUIDE FOR ESTIMATING DEEP MOORING LINE SIZE
FOR A GIVEN BUOY SIZE



This represents a fair estimate for many applications. It is intended only as a starting point when modeling a mooring system; it will not serve all environmental or engineering design criteria.

If a non-standard line diameter is called for using the graph, select the next larger standard diameter which is manufactured.

EB-04

MOORING CONFIGURATION
OPS-1
APPROX. DEPTH: 9570 FT.

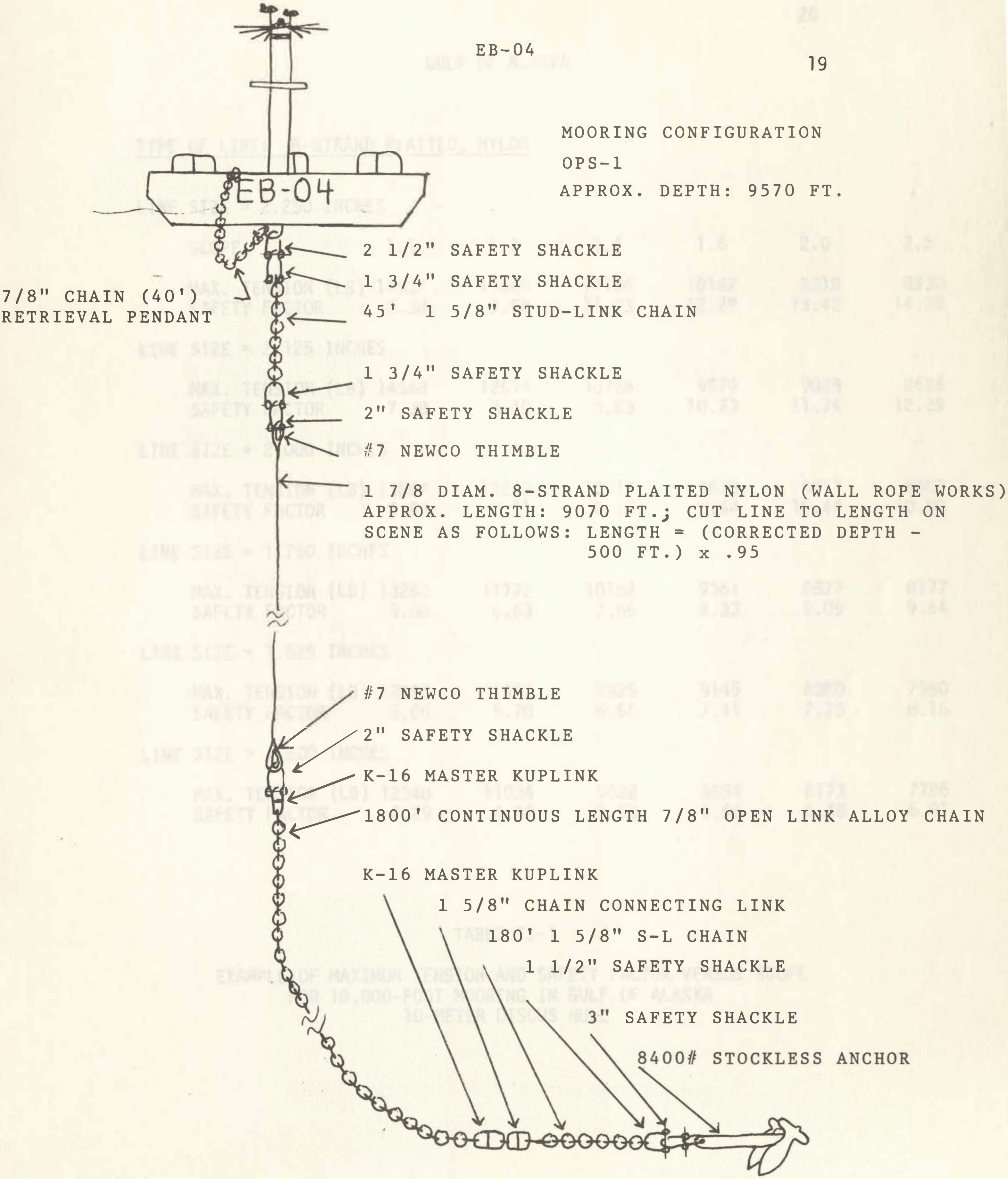


FIGURE II-2
EB-04 MOORING CONFIGURATION

GULF OF ALASKA

TYPE OF LINE: 8-STRAND PLAITED, NYLON

LINE SIZE = 2.250 INCHES

SCOPE	1.1	1.2	1.4	1.6	2.0	2.5
MAX. TENSION (LB)	14932	13045	11134	10182	9318	8930
SAFETY FACTOR	8.38	9.58	11.23	12.28	13.42	14.00
LINE SIZE = 2.125 INCHES						
MAX. TENSION (LB)	14368	12614	10786	9879	9029	8626
SAFETY FACTOR	7.38	8.40	9.83	10.73	11.74	12.29
LINE SIZE = 2.000 INCHES						
MAX. TENSION (LB)	13867	12243	10517	9639	8811	8403
SAFETY FACTOR	6.63	7.51	8.75	9.54	10.44	10.95
LINE SIZE = 1.750 INCHES						
MAX. TENSION (LB)	13262	11772	10182	9361	8577	8177
SAFETY FACTOR	5.88	6.63	7.66	8.33	9.09	9.54
LINE SIZE = 1.625 INCHES						
MAX. TENSION (LB)	12856	11412	9925	9145	8380	7980
SAFETY FACTOR	5.06	5.70	6.55	7.11	7.76	8.15
LINE SIZE = 1.500 INCHES						
MAX. TENSION (LB)	12348	11034	9628	8894	8173	7786
SAFETY FACTOR	4.29	4.80	5.50	5.96	6.48	6.81

TABLE II-1

EXAMPLE OF MAXIMUM TENSION AND SAFETY FACTOR VERSUS SCOPE
FOR 10,000-FOOT MOORING IN GULF OF ALASKA
10-METER DISCUS HULL

1. Marcus, S. O., ed., *Environmental Conditions within Specified Geographical Regions,* NODC, 1972
2. *Summary of Synoptic Meteorological Observations,* U. S. Weather Service Command, Washington, DC, Vol. 1-13, 1970.
3. *Oceanographic Atlas of the North Atlantic Ocean,* Pub. No. 700, Section I-V, USNOO, Washington, DC 1967.
4. Evans, M., R. A. Schwartzlose, and J. D. Isaacs, *Data from Deep Ocean Moored Instrument Stations,* SIO Ref. 1968-1972.
5. *Principal Tracking and Mean Frequencies of Cyclones and Anticyclones in the Northern Hemisphere,* U. S. Weather Bureau, Washington, DC, 1957.
6. MacDonald, W. J., *Atlas of Climatic Charts of the Oceans,* U. S. Weather Bureau, Government Printing Office, 1938.
7. Stidd, C. K., *Ship Drift Components, Means and Standard Deviation,* SIO Ref. Series 74-33, La Jolla, 1974.
8. Morevek, D., ed., *The Gulf Stream Monthly Summary,* U. S. Naval Oceanographic Office, Washington, DC.
9. Capurro, L. R. A., and J. L. Reid, *Contributions on the Physical Oceanography of the Gulf of Mexico,* Vol. 2, Gulf Publishing Co., Houston, 1972.
10. Quayle, R., *NCC Extremes from Buoy Measurements,* National Climatic Center, Asheville.

TABLE II-2

NDBO SOURCES OF ENVIRONMENTAL INFORMATION

Environment No. 1	Gulf of Mexico
Winds	155 knots
Significant Wave Height	40 feet
Current Profile	4.0 kt at surface 3.0 kt at 50 meters 1.0 kt at 500 meters 0.1 kt at bottom

Environment No. 2	Gulf Stream, Atlantic Coast
Winds	100 knots
Significant Wave Height	40 feet
Current Profile	5.0 kt at surface 5.0 kt at 500 meters 0.5 kt at 1300 meters 0.5 kt at bottom

Environment No. 3	Gulf of Alaska, North Pacific
Winds	100 knots
Significant Wave Height	50 feet
Current Profile	2.0 kt at surface 1.0 kt at 30 meters 0.1 kt at bottom

TABLE II-3

MAXIMUM BUOY ENVIRONMENTS

CHAPTER III

HULL/MOORING SIMULATION

CHAPTER III

HULL/MOORING SIMULATION

1.0 INTRODUCTION

The NDBO Hull/Mooring Dynamics Program was developed to provide a design tool for analyzing the complex buoy/mooring system. It provides a quantitative method for determining the response of critical parameters to a range of environments. Through its use, we can more confidently attempt to minimize costs by establishing reasonable sizes and lengths.

2.0 DESCRIPTION OF PROGRAM

This program provides a simulation of the buoy and a single-point mooring. Although the anchor itself is not modeled, the forces required at the bottom are determined so that a suitable anchor can be selected. A brief discussion of the theory and approach on which the program is based follows.

This is a two-dimensional, frequency-domain, linear model. The use of only two dimensions provides significant savings in program size, complexity, and computer time, with only a small sacrifice from a system design standpoint. In nearly all cases, maximum stresses will occur when the wind, current, and waves which comprise the forcing functions are coplanar. When this occurs, the buoy and mooring line will be contained in the same plane. By using the frequency domain, it is possible to predict the response at each frequency. The ratio of the response to the wave amplitude (forcing function) is called the "response amplitude operator" or "transfer function." Once the response has been computed for a unit wave amplitude, it may be used to predict response to any desired amplitudes. This transfer function may be used to predict the response to a broad range of wave spectra. The linearity assumption is required for the transfer function approach and also allows the dynamic response to be treated as a perturbation of the static or steady state configuration.

The simulation first determines the static solution. To do this, the forces exerted on the buoy are determined. The wind drag on the buoy hull and superstructure is computed with wind velocity, area, and drag coefficient specified as inputs. These quantities remain constant for a particular case. The drag coefficient must be selected by appropriately weighting individual drag coefficients of various areas which are exposed to the wind. Lift may also be included, and the moment caused by wind drag is computed using the drag and the lever arm between the center of pressure and the buoy center of gravity.

The current drag is computed using the specified surface current, buoy drag coefficient, water density, and a computed buoy surface area. The current moment is also computed, using a specified moment coefficient.

The procedure starts with an assumed buoy draft which allows the displacement to be determined. The difference between displacement and buoy weight must equal the vertical component of mooring tension at the attachment point. The sum of wind and current drag on the buoy becomes the horizontal component. Buoy trim is determined such that the sum of wind, current, buoyancy, and mooring tension moments about the buoy center of gravity is zero. Buoy draft and trim, in turn, establish the location of the attachment point and the top of the mooring line.

The mooring line is divided into as many steps as desired. For each step, a force balance is performed, including the current drag and the segment weight. Thus the changes in tension, angle, and elongation are determined, as well as the physical coordinates of the lower point. In this manner, an integration is performed from the cable top to the bottom. If the integration reaches the cable end with a physically satisfactory end condition, the static solution has been determined. If not, the buoy draft is altered and the calculation repeated until a satisfactory solution is found. The results of this process include the shape of the mooring line; the coordinates of desired points along its length; tension, elongation, and angle of these points; as well as the maximum tension and corresponding factor of safety in each cable segment. It also includes the required anchor load.

This procedure assumes a single-point moor, but the line need not be uniform. A number of different segments may be used, as long as the length and properties of each are properly described. Attachments are also permissible. They are treated as point loads where the effects of weight and current drag are introduced. Thus the equilibrium description of a rather complex system involving buoy, mooring line, attachments, surface environment, and subsurface current profile may be obtained.

The dynamic response of the system is treated as a perturbation of the steady state conditions. For most deep moorings, the amplitude of the motion caused by waves is quite small relative to the ocean depth and length of mooring line. The system is therefore assumed to be linear with respect to wave height.

The forcing function for the mooring line is provided by the buoy motion. Consequently, the buoy response is first determined. The coefficients of the buoy equations of motion, and the wave forces and moments, are computed for surge, heave, and pitch. These coefficients depend upon mass and shape parameters of the buoy. Subroutines are included in the program for the following standard or generic shapes: discus, boat, catamaran, spar, and hemisphere. The computations for each type of shape are based on an appropriate state-of-the-art approach.

Mooring line dynamics are based on a set of ordinary differential equations in four unknowns: tension, cable angle, and normal and tangential velocities. These are equations for dynamic perturbations about the steady state. These equations may be integrated from a known condition at the bottom to determine the condition at the top. The known boundary conditions are the two components of velocity which are taken as zero. This is equivalent to assuming that the touchdown point is pinned. Since four boundary conditions are required and only two are known, two sets of boundary conditions are assumed for the other variables and the cable equations are integrated for each set. The solution is then obtained by forming a linear combination of these two integrations which matches the known conditions at the top. The conditions at the top are the motions of the end of the line which must equal those of the buoy attachment point. The calculation also accounts for the interactive effect of buoy and mooring line on each other.

The result of the dynamic calculations is a set of solutions of buoy and mooring line dynamics for a set of frequencies. For each frequency, the solution represents the response to a wave of one-foot amplitude. The system is assumed to be linear with respect to wave amplitude so this response is equivalent to the ratio of response to wave amplitude and becomes the transfer function. The response spectral density is obtained by multiplying the square of the response by the input wave spectral density.

3.0 PROGRAM INPUTS AND OUTPUTS

3.1 INPUTS

To perform its function of simulating the steady state and dynamic response of the buoy-mooring system, the program requires descriptions of the buoy, the mooring, and the environment to which they are subjected. Following is a list of parameters which must be specified as inputs to convey these descriptions to the program:

o Buoy

- Type (generic category)
  - Discus
  - Boat
  - Catamaran
  - Spar
  - Hemisphere
- Length
- Weight
- Location of center of gravity
- Pitch radius of gyration
- Current drag and moment coefficients
- Wind drag coefficient
- Arm of wind center of pressure about center of gravity
- Location of mooring attachment point
- Appropriate shape dimensions

- o <u>Mooring</u>
  - Parameters of each cable segment
    - Length
    - Weight per foot
    - Diameter
    - Drag coefficient
    - Breaking strength
    - Modulus of elasticity
    - Constants for elastic strain equation (Maxwell Model)
  - Parameters of each attachment
    - Drag
    - Weight
    - Virtual mass in each direction
    - Location on line
  - Environment
    - Water depth
    - Current profile
    - Wind speed
    - Wave frequencies
    - Wave spectral parameters

These inputs, when provided in the required format, allow all of the necessary calculations to proceed. The buoy hydrostatic properties are computed; the static mooring line configuration is determined by integrating down the cable, applying the forces and determining tension, elongation, and angle; the buoy coefficients of motion and wave forces are computed; and the dynamic response of buoy and mooring line established.

3.2 OUTPUTS

The results are presented by tabulating values of the following parameters:

- o <u>Static Solution</u>
  - Buoy draft
  - Buoy trim
  - At selected intervals along the mooring cable
    - Depth
    - Horizontal displacement
    - Tension
    - Angle
    - Elongation
    - Unstretched length
    - Stretched length
  - For each cable segment
    - Maximum tension
    - Factor of safety
    - Anchor load
    - Length of cable on bottom

- o <u>Dynamic Solution - for unit wave amplitude</u>
  - Each frequency
    - Buoy coefficients of motion
    - Wave forces and moments
    - Mooring forces and moments on buoy
    - Buoy heave response amplitude and phase
    - Buoy surge response amplitude and phase
    - Buoy pitch response amplitude and phase
    - At selected intervals along the mooring cable
      - Dynamic mooring angle response amplitude and phase
      - Dynamic tension angle and phase
      - Normal velocity amplitude and phase
      - Tangential velocity amplitude and phase
  - Spectral response
    - Surge spectral density of each frequency
    - Heave spectral density at each frequency
    - Pitch spectral density at each frequency
    - Surge, heave, pitch rms values
    - Average of 1/3 and 1/10 highest responses

4.0 EXAMPLE

In Chapter II, the design of a typical discus buoy mooring was discussed, as an example. One of the simulation cases run in that design process will be described here, as an example of the application of the Hull/Mooring Dynamics Program.

A portion of the computer printout for this case is included as Figure III-1 at the end of this chapter. Figure III-1a summarizes the buoy and mooring descriptions used to define the system. The buoy description includes the physical parameters required to define the shape and mass properties, which are self-explanatory. It also includes hydrodynamic characteristics which must be properly determined. The current drag coefficient, in this case, is based on extensive model test data. The drag is a function of current velocity, or speed-length ratio, and may be varied for different cases. The moment coefficient provides a means for representing the moment due to the center of pressure not coinciding with the center of gravity. To permit calculation of wind drag and moment, appropriate values for area, arm, and coefficient are required. The coefficient represents an appropriately averaged drag coefficient multiplied by half the air density; the area is the effective exposed surface; and the arm represents the vertical separation of the center of pressure and center of gravity.

The description of the mooring line is also straightforward. The weight and strength of chain is obtained from catalogs or handbooks. The diameter, area, and drag coefficient must be consistent. The program treats the line as a long cylinder. If the diameter of the chain is used, the cross-sectional area per unit length of chain exposed to the current will be underestimated. This is offset by using a higher-than-normal value for the drag coefficient. In this example, elasticity is a function of the stress.

A table of strain versus tension, as a function of the breaking strength, is an input. The values used for nylon, in this table, were provided by the manufacturer. For chain, the table is based on an elongation of 1% when tension is equal to the breaking strength.

The other characteristics of the nylon were taken from a manufacturer's catalog, which lists weight, dimensions, and strength. The drag coefficient was assumed.

The environment is defined in Figure III-1b by the wind, current profile, and depth. The current at intermediate depths is obtained by linear interpolation. In Figure III-1c, five wave spectra are defined. These are two-parameter spectra which are defined by significant wave height and mean wave period.

The steady state or static solution is tabulated in Figures III-1d, e, f, and g. This is followed by a summary of significant data from the static solution.

The complete dynamic solution is not included. The solutions for two particular frequencies are tabulated, representing the response to a one-foot amplitude wave. Finally, the response spectra of the buoy are shown.

5.0 PROGRAM LIMITATIONS

Although the computer simulation program provides detailed and accurate answers for the responses of this complex system, it does, of necessity, have limitations. These are inherent in the assumptions used in its development. The principal limitations are discussed below.

5.1 GENERIC SHAPE SELECTION

Although five generic shapes are available for describing the buoy, there is no completely general subroutine applicable to other buoy shapes. It is necessary that the most appropriate generic shape be selected and the inputs tailored to make that shape represent the buoy design. This approach can be quite effective in many instances, particularly for hydrostatic properties. Sometimes more than one generic shape is used and the results compared.

5.2 USE OF CORRECTED VALUES

The static calculation considers wind and current effects on the buoy using various input quantities. The drag coefficient, area, and arm used for wind effects are all input quantities. Consequently, all are constant and do not vary as the buoy freeboard or trim changes in the course of the iterative approach to the static solution. However, if appropriate, an additional simulation can be made using corrected values. In computing current effects, the area and moment are functions of the draft, but the coefficients are fixed. Here again, it may be necessary to refine the solution using corrected values.

5.3 MOORING REPRESENTATION

The mooring representation has limited flexibility insofar as varying the normal and tangential drag coefficients as functions of the cable angle. Since attachments are treated as points, it is sometimes difficult to represent some particular objects. The normal form of the program treats elasticity as a constant, rather than as a function of tension. However, a form of the program is available which allows elasticity to be a function of load.

5.4 NON-LINEAR EFFECTS

The most significant limitation of the program is the inability to incorporate non-linear effects. Thus the program can accurately simulate responses only within the bounds in which non-linearities are small. Approximation of non-linearities through linearization must be used beyond these bounds. This problem is generally confined to buoy response at or near resonance for those shapes which exhibit a highly resonant response.

6.0 APPENDAGES AND NON-GENERIC SHAPES

The program, of necessity, cannot be completely general. As indicated earlier, subroutines are included to compute the hydrostatic characteristics and the coefficients of motion and wave forces for five generic buoy shapes. Obviously, these are not adequate to describe all possible shapes. However, with care and ingenuity, many buoy concepts can be closely approximated. Minor departures from the actual shape are not fatal if care is taken to preserve the most significant characteristics, such as water plane area and underwater volume and area of various cross-sections.

Care must be taken in selecting the proper generic shape. The analyses leading to the subroutines which provide the dynamic characteristics of the generic shapes make assumptions appropriate to each type. The discus, for instance, must have a large horizontal cross-section and low draft. The spar should have small water plane area and large draft. For static simulation, any subroutine which allows the buoy shape to be described is acceptable. But acceptable dynamic simulation requires that the shape be considered. The discus and spar representations will not produce the same answers.

The program does not include provisions for simulating the effects of appendages such as pitch or heave damping fins. To include these appendages, a separate analysis must be made and a modification to the appropriate coefficient or term made as a program modification. Within the limits of linearity, this approach can be very effective.

Free-flooding sections must also be treated correctly; weight and buoyancy must be consistent. For correct simulation of buoy dynamics, the other envelope should be used to describe the buoy shape and the mass of ballast water considered part of the buoy. Thus the input quantities for buoy weight, center of gravity, and radius of gyration should also include the water ballast.

7.0 VALIDATION

To establish confidence in the ability of this program to simulate the dynamic response of a buoy-mooring system, the calculated responses should be compared with measured response of an actual full-scale physical system. Unfortunately, adequate full-scale measured data is expensive and difficult to obtain. Operational moorings do not normally have the required instrumentation, nor is the forcing environment adequately measured. Special test programs require extensive planning and special instrumentation. Even then, although the environment can be measured, it cannot be controlled. A full-scale test of a 12-foot-diameter discus buoy moored in a 900-fathom depth is planned to provide validation of this and other simulation programs.

A smaller scale validation was performed in 1972. Since it is not practical to scale all the necessary parameters, preserving both Reynolds and Froude numbers, the test was treated as a full-scale, small mooring system. Moorings of several types of mooring lines were tested in the Circulating Water Channel at the Naval Ship Research and Development Center, Carderock, Maryland. The current could be controlled, and harmonic motion imposed on the upper end. The motion was observed and tension recorded. Results were compatible with simulations of the Hull/Mooring Dynamics Program. However, measurement precision was not good enough to validate the program completely.

Many series of scale models of buoys have been tested and the buoy dynamics subroutines have been shown to produce satisfactory simulations of these test results.

8.0 INTERPRETATION OF RESULTS

8.1 MOORING DESIGN PROCESS

The principal purpose of using this program is to support the mooring design process. Consequently, the results which contribute to pinpointing the design factors of critical interest are of major importance. The maximum tension in each line segment and the corresponding factor of safety are obviously important. These items are included in the summary table of the Static Solution. The anchor load, both vertical and horizontal, is also included in this summary. This, coupled with data on bottom conditions, allows selection of the proper anchor.

8.2 ENVIRONMENTAL CONDITIONS

Frequently it is desirable to run simulations for a range of environmental conditions. The extreme environment will impose the most severe tensions and anchor loads, of course, but the configuration under normal or subnormal environments may also be important. It may be necessary to assure that some portion of the line which is sensitive to chafing does not reach the bottom under slack conditions. There may also be limits on line angle or depth of the line at instrumentation attachment points under other conditions.

8.3 MOORING DYNAMIC RESPONSE

Interpretation of mooring dynamic response may be more difficult. The results of dynamic response are presented for each frequency, but not as spectra, as for the buoy. It is impractical to compute spectral response for all possible parameters of interest. However, the data required for such computations are available. By appropriately combining the input spectrum and the frequency response, or transfer function, for the parameter of interest, the response can be obtained. The extreme response may be estimated directly from the frequency response listing. The listed data represent response to a wave of one-foot amplitude. Assuming linearity, the response to the maximum expected wave of each frequency can be obtained by simple multiplication. The phase angle is also given for each response. The wave maxima should be available from the environmental investigations made in the design process.

8.4 LONG-TERM BEHAVIOR

To get some insight into the long-term behavior of buoy systems, NDBO developed a Long-Term Prediction Model. This program permits long-term buoy dynamic response predictions to be made as a function of environmental operating conditions. It requires data on spectral response from the hull/mooring simulation for a family of wave spectra covering the range of wave heights and wave periods that will be encountered by the buoy over the long term. The model also requires data on the probability of occurrence of the individual wave spectra. Statistical techniques are used to combine these data and to predict the probability of exceeding any given amplitude of buoy response. This model could also be used to predict long-term distributions of other mooring response parameters, such as tension.

9.0 <u>VARIATIONS</u>

The program was developed to model the static and dynamic response of moored buoy systems. However, it has been adapted to provide limited capability for two other types of systems.

9.1 DRIFTING BUOY-DROGUE

The drifting buoy-drogue system differs significantly from the moored buoy. The steady state response can be modeled quite well with a modified version of this program. It is also possible to simulate dynamic response to a limited extent. However, solutions frequently become unstable as the frequency is increased and the amplitude of the time-varying tension becomes greater than the static tension, indicating that the line becomes slack and the solution invalid.

9.2 SUBSURFACE MOORING

The program has also been adapted to a static simulation of a subsurface mooring. In this instance, a depth is assumed for the float. The net buoyancy and current drag determine the tension and angle of the line. The normal integration routine is applicable. If a satisfactory condition is not realized at the bottom, the float depth is iterated. The solution gives the depth of the float as well as the configuration and tension of the mooring line.

9.3 SHALLOW MOORINGS

The NDBO Hull/Mooring Dynamics Program will simulate either a taut or slack mooring. However, in the case of shallow water, effects which have little significance in deep water may become more important. One such effect is the behavior of the cable near the point at which it contacts the ground in the steady state configuration. The model considers the cable to be pinned at this point when it performs dynamic calculations. Actually, in response to waves, cable will alternately lift off the bottom and deposit on the bottom. Thus, for a slack mooring, the passing wave crest lifts the cable off the bottom rather than stretching it. The boundary conditons at the bottom of a shallow mooring require tangency and zero vertical velocity of a time-varying touchdown point rather than zero velocity of a fixed point.

Another effect which becomes more significant in shallow water is the hydrodynamic force on the cable due to wave orbital velocities. In shallow water, these velocities do not attenuate as rapidly with depth. Further, since the depth is less, these forces are significant over a greater portion of the mooring.

The NDBO Hull/Mooring Dynamics Program is being modified to include these effects. The new program will be available as an option where lift-off and wave forces on the mooring are significant.

10.0 OTHER HULL/MOORING MODELS

The NDBO program is a versatile tool, capable of simulating a broad range of buoy hull types, providing static and dynamic solutions for single-point moorings exposed to fairly complex environmental descriptions. However, it is not the only mooring simulation tool, nor necessarily always the best. Other approaches to mooring simulation include time-domain, three-dimensional, and multi-leg programs. Dillon (1973) contains a bibliography and summary of mooring simulation programs.

Closed-form frequency-domain models are available for one-dimensional analysis of longitudinal response and of natural frequency and model shape. These are economical programs to use, but of limited applicability near the surface.

Some of the limitations of linear, frequency-domain models, such as the NDBO Hull/Mooring Dynamics Program, may be overcome by a time-domain model. This approach allows non-linear effects to be included and provides greater flexibility in modeling some physical effects. However, time-domain models suffer from the general limitation of greater computer time requirements and the necessity to approximate the line as a series of lumped masses and springs or to use finite difference integration techniques.

One approach to modeling in the time domain is the lumped-mass model. In this approach, the system is represented by a number of lumped masses connected by springs. Each mass represents a segment of the system and all of the forces acting on that segment. Each mass is acted on by external forces as well as those transmitted from the adjacent masses. At the ends are the buoy and anchor, with appropriate end conditions. The program starts with some designated system configuration and determines response by performing an integration at each time interval. Each mass is acted on by environmental forces and effects of the adjacent masses.

This general approach is used by many investigators. By choosing a sufficiently large number of masses, errors may be minimized. The potential precision of simulation is limited, in principle, by our knowledge of the physical properties of components and the physical principles and effects. In practice, time and cost require compromises and approximations. This is a very flexible approach for many problems, particularly those in which there are significant non-linear effects. NDBO has a lumped-parameter, time-domain model under development which will be applicable to either moored or drogued buoy systems.

Another time-domain approach involves finite difference integration using the method of characteristics. It was developed by Nath for the thick discus buoy hull contractor, but has not been used by NDBO.

A three-dimensional time-domain program was developed for the U. S. Naval Underwater Systems Center by K. Patton. This program includes both finite difference and finite element versions for integration along the mooring line.

Time-domain, lumped-mass programs are also available for transient analysis of deployment dynamics. An example is the lumped-mass, anchor-last deployment model developed by Thresher and Nath.

11.0 MULTI-LEG MOORING MODELS

The use of multiple legs to secure a buoy to several anchor points presents a very difficult analysis. This would inherently be a three-dimensional problem involving a redundant structure. Multi-leg subsurface mooring models have been developed using an iterative procedure (method of imaginary reactions) to determine the steady state configuration. This approach could be extended to a surface mooring, but the complexity is even greater since buoy displacement and trim are added variables. A dynamic model would be considerably more complex.

Multi-leg moors are expensive because of the multiple components required and because the difficulties involved in setting a multi-leg moor make it a complex and expensive operation. Since NDBO has not had applications involving rigorous requirements for minimum watch circle, it has not used multi-leg moors to date. Due to this lack of near-term requirements, as well as limited development funds, development of a simulation program for multi-leg moors has not yet been undertaken.

Reference: Dillon, D. B., "An Inventory of Current Mathematical Models of Scientific Data-Gathering Moors," Hydrospace-Challenger report HCI TR 4450 0001, February 1973

```
                                        CASE NUMBER   1


                                      BUOY CHARACTERISTICS
                                  (ALL IN FOOT-POUND-SECOND UNITS)

LENGTH=            40.000          WEIGHT=      200000.000
L.C.G.=              .000          V.C.G.=           4.300          GYRADIUS=         11.300

X-CABLE=             .000          Z-CABLE=          -.500          MAX.DRAFT=         7.000

CUR.C(D)=           .47500         CUR.C(L)=           .00000       CUR.C(M)=           .00000
WIND.C(D)=          .00070         WIND.C(L)=          .00000       WIND.AREA=       292.000            WIND.ARM=           17.500

* * * * * D I S C   TYPE * * * * *

RAD(KEEL)=         13.000          RAD(KNUC)=         20.000         HT.(KNUC)=         4.000            K-SUB(I)=             .400

                                    TABLE OF CABLE PROPERTIES

CABLE      LENGTH   WT IN AIR    WT IN WATER  DIAMETER   AREA      ELASTICITY     BREAK TENSION    YO          TAU1      CN
             FT       LBS/FT       LBS/FT        IN      SQ.IN.    LBS/SQ IN          LBS          LBS          SEC

  1         45.00  26.05600      22.66000      1.625     2.074                     154000.0            .0         .0   3.320
  2       9070.00    .88000        .08500      1.875     2.760                      82500.0            .0         .0   1.200
  3       1800.00   7.20000       6.25000       .875      .567                     104000.0            .0         .0   3.320
  4        180.00  26.05600      22.66000      1.625     2.074                     154000.0            .0         .0   3.320

                          E = CABLE STRAIN , T/TB = CABLE LOAD AS FRACTION  OF BREAKING STRENGTH


  1   E   =         .00000          .01000          .00000          .00000          .00000          .00000          .00000
      T/TB=         .00000         1.00000          .00000          .00000          .00000          .00000          .00000

  2   E   =         .00000          .02000          .05000          .10900          .15100          .20100          .26300
      T/TB=         .00000          .00300          .03300          .10000          .16000          .28000          .50000

  3   E   =         .00000          .01000          .00000          .00000          .00000          .00000          .00000
      T/TB=         .00000         1.00000          .00000          .00000          .00000          .00000          .00000

  4   E   =         .00000          .01000          .00000          .00000          .00000          .00000          .00000
      T/TB=         .00000         1.00000          .00000          .00000          .00000          .00000          .00000

TOTAL LENGTH OF CABLE =11095.00 FT.
TOTAL SUBMERGED WEIGHT OF CABLE =17119.45 LBS.

INTEGRATION STEP SIZE    17.15 FT.

                                      *****NO ATTACHMENTS*****
```

Figure III-1a

```
                                        PHYSICAL DATA

   DEPTH OF WATER= 9570.00 FEET      WIND VELOCITY=155.00 KNOTS   MASS DENSITY OF WATER=  1.9905 SLUGS/CU.FT.


                                   TABLE OF CURRENT VELOCITIES

                                     DEPTH      CURRENT VELOCITY
                                       FT             KNOTS
                                        .00           2.100
                                    1640.00            .583
                                    2630.00            .486
                                    4930.00            .291
                                    9570.00            .194
```

Figure III-1b

```
         WAVE SPECTRAL DENSITY, TWO PARAMETER, ISSC 1967 SPECTRA

        SIG.HT.    6.000        8.000       12.000       15.000       25.000
        MN.PER.    5.000        6.000        7.000        8.000       10.000

      SPECTRA NO.      1            2            3            4            5
    WAVE FREQ.
         .314       .000         .000         .000         .000        2.803
         .550       .001         .483        8.735       29.674      101.045
         .785      1.805        7.017       16.292       20.437       30.243
        1.021      3.242        4.718        7.188        7.350        9.163
        1.257      2.043        2.206        2.957        2.841        3.365
        1.492      1.079        1.039        1.326        1.244        1.445
        1.728       .573         .524         .654         .607         .698
        1.964       .318         .283         .350         .323         .370
        2.200       .185         .163         .200         .184         .210
        2.435       .113         .099         .121         .111         .126
        2.671       .072         .062         .076         .070         .080
        2.907       .047         .041         .050         .046         .052
        3.142       .032         .028         .034         .031         .035
        3.378       .023         .019         .024         .022         .025
        3.614       .016         .014         .017         .015         .018
        3.849       .012         .010         .012         .011         .013
        4.085       .009         .008         .009         .008         .010
        4.321       .007         .006         .007         .006         .007
        4.557       .005         .004         .005         .005         .006

      MN.SQ.       2.258        3.941        8.969       14.845       34.960
      R.M.S.       1.503        1.985        2.995        3.853        5.913
      AVG.         1.878        2.481        3.744        4.816        7.391
      SIG.         3.005        3.970        5.990        7.706       11.825
      AV1/10       3.831        5.062        7.637        9.825       15.077
```

Figure III-1c

```
                                        ••••••••••••••••••••
                                        * STATIC SOLUTION *
                                        ••••••••••••••••••••

 RELAXED    STRETCHED     DEPTH      EXCURSION      CABLE      CABLE       CABLE   CABLE      MASS
  CABLE       CABLE       BELOW        FROM        TENSION     ANGLE      STRAIN  SECTION  ATTACHMENT
 LENGTH      LENGTH      SURFACE       BUOY         (LBS)      (DEG)              NUMBER     POINT
  (FT)        (FT)         (FT)        (FT)

     .00         .00        4.48          .20    26055.72      54.98      .00169     1                  (BUOY)
   34.30       34.35       32.39        20.23    25431.27      53.69      .20896     2
  137.19      158.75      132.36        94.25    25434.28      53.28      .20897     2
  274.37      324.60      264.88       193.98    25437.04      52.80      .20898     2
  411.56      490.46      396.61       294.76    25438.44      52.38      .20899     2
  548.75      656.32      527.65       396.43    25438.54      52.02      .20899     2
  685.94      822.17      658.09       498.87    25437.43      51.70      .20898     2
  823.12      988.03      788.01       601.96    25435.19      51.44      .20898     2
  960.31     1153.89      917.49       705.61    25431.89      51.21      .20897     2
 1097.50     1319.74     1046.60       809.73    25427.61      51.02      .20895     2
 1234.68     1485.59     1175.38       914.23    25422.46      50.87      .20893     2
 1371.87     1651.44     1303.92      1019.04    25416.51      50.74      .20891     2
 1509.06     1817.28     1432.24      1124.09    25409.86      50.64      .20889     2
 1646.24     1983.13     1560.40      1229.35    25402.60      50.57      .20887     2
 1783.43     2148.97     1688.43      1334.76    25394.85      50.51      .20884     2
 1920.62     2314.80     1816.36      1440.29    25386.97      50.45      .20881     2
 2057.81     2480.63     1944.18      1545.94    25379.05      50.40      .20879     2
 2194.99     2646.46     2071.90      1651.71    25371.09      50.35      .20876     2
 2332.18     2812.28     2199.52      1757.58    25363.09      50.29      .20873     2
 2469.37     2978.11     2327.05      1863.57    25355.06      50.25      .20870     2
 2606.55     3143.92     2454.48      1969.66    25346.98      50.20      .20868     2
 2743.74     3309.73     2581.83      2075.86    25338.87      50.15      .20865     2
```

Figure III-1d

2880.93	3475.54	2709.09	2182.15	25330.73	50.11	.20862	2
3018.11	3641.35	2836.26	2288.53	25322.56	50.06	.20859	2
3155.30	3807.15	2963.35	2395.01	25314.35	50.02	.20856	2
3292.49	3972.95	3090.36	2501.58	25306.12	49.98	.20854	2
3429.68	4138.74	3217.30	2608.24	25297.86	49.94	.20851	2
3566.86	4304.53	3344.15	2714.98	25289.58	49.90	.20848	2
3704.05	4470.32	3470.94	2821.80	25281.27	49.87	.20845	2
3841.24	4636.10	3597.65	2928.70	25272.93	49.83	.20842	2
3978.42	4801.88	3724.29	3035.68	25264.57	49.79	.20839	2
4115.61	4967.65	3850.86	3142.73	25256.18	49.76	.20837	2
4252.80	5133.42	3977.37	3249.86	25247.78	49.72	.20834	2
4389.98	5299.19	4103.81	3357.06	25239.34	49.69	.20831	2
4527.17	5464.95	4230.18	3464.32	25230.89	49.66	.20828	2
4664.36	5630.71	4356.50	3571.66	25222.41	49.63	.20825	2
4801.55	5796.46	4482.75	3679.06	25213.92	49.60	.20822	2
4938.73	5962.21	4608.95	3786.52	25205.40	49.57	.20819	2
5075.92	6127.96	4735.09	3894.04	25196.86	49.54	.20816	2
5213.11	6293.70	4861.17	4001.62	25188.31	49.51	.20813	2
5350.29	6459.44	4987.20	4109.26	25179.74	49.49	.20810	2
5487.48	6625.17	5113.17	4216.96	25171.16	49.46	.20808	2
5624.67	6790.90	5239.09	4324.71	25162.58	49.43	.20805	2
5761.85	6956.63	5364.96	4432.52	25154.00	49.41	.20802	2
5899.04	7122.35	5490.77	4540.38	25145.42	49.38	.20799	2
6036.23	7288.07	5616.53	4648.30	25136.84	49.35	.20796	2
6173.42	7453.79	5742.24	4756.27	25128.25	49.33	.20793	2
6310.60	7619.50	5867.90	4864.30	25119.67	49.30	.20790	2
6447.79	7785.20	5993.51	4972.38	25111.09	49.28	.20787	2
6584.98	7950.90	6119.06	5080.52	25102.50	49.25	.20784	2

Figure III-1e

6722.16	8116.60	6244.56	5188.71	25093.91	49.22	.20781	2
6859.35	8282.30	6370.01	5296.95	25085.32	49.20	.20778	2
6996.54	8447.99	6495.42	5405.25	25076.73	49.17	.20775	2
7133.72	8613.67	6620.77	5513.60	25068.13	49.15	.20772	2
7270.91	8779.36	6746.07	5622.00	25059.54	49.12	.20769	2
7408.10	8945.03	6871.32	5730.45	25050.94	49.10	.20766	2
7545.29	9110.71	6996.52	5838.95	25042.35	49.07	.20764	2
7682.47	9276.38	7121.67	5947.50	25033.75	49.05	.20761	2
7819.66	9442.04	7246.77	6056.11	25025.15	49.03	.20758	2
7956.85	9607.70	7371.82	6164.76	25016.55	49.00	.20755	2
8094.03	9773.36	7496.82	6273.47	25007.95	48.98	.20752	2
8231.22	9939.02	7621.78	6382.22	24999.35	48.95	.20749	2
8368.41	10104.67	7746.68	6491.02	24990.74	48.93	.20746	2
8505.59	10270.31	7871.54	6599.88	24982.14	48.91	.20743	2
8642.78	10435.95	7996.35	6708.78	24973.53	48.88	.20740	2
8779.97	10601.59	8121.11	6817.73	24964.93	48.86	.20737	2
8917.16	10767.23	8245.83	6926.73	24956.32	48.84	.20734	2
9054.34	10932.85	8370.50	7035.77	24947.71	48.81	.20731	2
9105.79	10994.96	8417.24	7076.68	24944.48	48.80	.00240	3
9191.53	11080.91	8481.50	7133.75	24543.91	47.98	.00236	3
9328.72	11218.42	8582.54	7227.01	23914.06	46.59	.00230	3
9465.90	11355.92	8681.23	7322.74	23298.79	45.14	.00224	3
9603.09	11493.41	8777.39	7421.00	22699.28	43.61	.00218	3
9740.28	11630.89	8870.82	7521.86	22116.81	41.99	.00213	3
9877.47	11768.37	8961.28	7625.37	21552.77	40.30	.00207	3
10014.65	11905.83	9048.55	7731.58	21008.62	38.51	.00202	3
10151.84	12043.29	9132.37	7840.52	20485.96	36.63	.00197	3
10289.03	12180.75	9212.47	7952.21	19986.47	34.65	.00192	3
10426.21	12318.20	9288.57	8066.66	19511.92	32.57	.00188	3

Figure III-1f

```
10563.40    12455.64    9360.37    8183.85    19064.17    30.40    .00183    3
10700.59    12593.07    9427.57    8303.73    18645.15    28.12    .00179    3
10837.77    12730.50    9489.83    8426.23    18256.83    25.75    .00176    3
10906.37    12799.22    9519.02    8488.44    18074.81    24.52    .00117    4
10974.96    12867.89    9544.99    8551.99    17487.13    19.88    .00114    4
11095.00    12988.06    9577.19    8667.65    16758.74    11.10    .00109    4              (BOTTOM)
```

Figure III-1g

```
                              ********************************
                              * SUMMARY OF STATIC SOLUTION *
                              ********************************


                                       **********
                                       * ANCHOR *
                                       **********

HORIZONTAL FORCE REQUIRED AT ANCHOR = 16445.14        VERTICAL FORCE REQUIRED AT ANCHOR =  3226.84


                                       *********
                                       * CABLE *
                                       *********
          CABLE        MAXIMUM       DISTANCE        CORRESPONDING       FACTOR
          SECTION      TENSION       FROM BUOY           STRAIN            OF
          NUMBER        (LBS)          (FT)                              SAFETY
            1         26055.72          .00              .00169           5.91
            2         25438.65        497.30             .20899           3.24
            3         24944.48       9105.79             .00240           4.17
            4         18074.81      10906.37             .00117           8.52


                                       ********
                                       * BUOY *
                                       ********

      BUOY EQUILIBRIUM DRAFT =    3.98 FEET         BUOY EQUILIBRIUM TRIM =    2.37 DEG.
```

Figure III-1h

```
                                        CABLE--BUOY DYNAMIC SOLUTION

                              WAVE FREQUENCY =        .550 RADIANS/SEC
                                             =        .087 HERTZ
                              WAVE LENGTH    =     669.552 FEET

                                               CABLE RESPONSES
DISTANCE (FT)            PHI (DEG)          TENSION (LBS)              U (FT/SEC)              V (FT/SEC)          CABLE    ATTACHMENT
                       AMP    PHASE         AMP    PHASE             AMP    PHASE            AMP    PHASE
      .01 BUOY       .3217  -64.20       58.2099 -133.24           .5841  151.38           .6072 -126.24          1
    34.31            .2562  -81.37       56.5785 -143.75           .5236  142.49           .6080 -127.33          2
   120.05            .1798 -101.85       53.8943 -144.18           .3755  122.16           .6051 -128.38          2
   257.24            .1045 -133.78       50.3934 -145.58           .2250   90.50           .6001 -129.81          2
   394.42            .0626 -164.33       47.3432 -147.75           .1382   60.02           .5955 -131.03          2
   531.61            .0386  166.99       44.5184 -150.47           .0871   30.88           .5912 -132.11          2
   668.80            .0242  140.58       41.8946 -153.55           .0562    3.28           .5872 -133.12          2
   805.98            .0154  116.56       39.5121 -156.87           .0371  -22.60           .5832 -134.05          2
   943.17            .0098   94.77       37.4155 -160.36           .0249  -46.65           .5791 -134.93          2
  1080.36            .0062   74.87       35.6353 -163.95           .0169  -68.86           .5749 -135.76          2
  1217.55            .0038   56.33       34.1849 -167.59           .0115  -89.35           .5705 -136.54          2
  1354.73            .0023   38.54       33.0636 -171.19           .0079 -108.44           .5658 -137.27          2
  1491.92            .0014   20.76       32.2600 -174.70           .0054 -126.66           .5610 -137.97          2
  1629.11            .0008    2.06       31.7553 -178.02           .0037 -144.70           .5559 -138.63          2
  1766.29            .0005  -19.00       31.5206  178.89           .0025 -163.22           .5506 -139.27          2
  1903.48            .0003  -49.29       31.4230  175.92           .0017  176.27           .5451 -139.69          2
  2040.67            .0002  -99.24       31.4109  173.00           .0011  151.33           .5393 -140.49          2
  2177.85            .0002 -145.96       31.4798  170.15           .0008  119.10           .5333 -141.08          2
  2315.04            .0002 -171.96       31.6246  167.38           .0007   81.48           .5271 -141.64          2
  2452.23            .0003  172.16       31.8397  164.71           .0007   48.67           .5207 -142.19          2
  2589.42            .0003  160.85       32.1194  162.15           .0007   25.00           .5140 -142.73          2
  2726.60            .0003  152.05       32.4578  159.69           .0008    8.05           .5071 -143.25          2
  2863.79            .0003  144.92       32.8485  157.35           .0009   -4.77           .5000 -143.76          2
```

Figure III-1i

3000.98	.0003	139.01	33.2846	155.12	.0009	-14.81	.4926	-144.25	2
3138.16	.0003	134.09	33.7605	153.01	.0009	-22.82	.4850	-144.73	2
3275.35	.0003	130.00	34.2710	151.02	.0009	-29.25	.4772	-145.21	2
3412.54	.0002	126.61	34.8110	149.14	.0009	-34.40	.4692	-145.67	2
3549.72	.0002	123.83	35.3758	147.36	.0009	-38.52	.4609	-146.13	2
3686.91	.0002	121.61	35.9610	145.70	.0009	-41.85	.4525	-146.57	2
3824.10	.0002	119.89	36.5624	144.14	.0009	-44.61	.4438	-147.02	2
3961.29	.0002	118.68	37.1764	142.67	.0008	-47.07	.4349	-147.45	2
4098.47	.0002	118.04	37.7993	141.31	.0008	-49.56	.4258	-147.88	2
4235.66	.0002	118.02	38.4279	140.03	.0008	-52.28	.4165	-148.31	2
4372.85	.0002	118.73	39.0592	138.83	.0008	-55.62	.4070	-148.74	2
4510.03	.0002	120.25	39.6905	137.72	.0007	-59.65	.3973	-149.17	2
4647.22	.0002	122.69	40.3193	136.68	.0008	-64.36	.3875	-149.60	2
4784.41	.0002	126.16	40.9434	135.72	.0008	-69.41	.3774	-150.03	2
4921.59	.0002	130.70	41.5607	134.82	.0008	-74.20	.3672	-150.47	2
5058.78	.0002	136.43	42.1693	133.98	.0009	-78.09	.3567	-150.91	2
5195.97	.0002	143.46	42.7677	133.21	.0010	-80.64	.3462	-151.37	2
5333.16	.0002	151.98	43.3540	132.49	.0012	-81.64	.3354	-151.83	2
5470.34	.0002	162.59	43.9253	131.81	.0013	-81.03	.3245	-152.31	2
5607.53	.0002	175.79	44.4799	131.16	.0015	-78.88	.3135	-152.81	2
5744.72	.0001	-167.98	45.0171	130.56	.0017	-75.35	.3023	-153.32	2
5881.90	.0002	-148.62	45.5361	129.98	.0019	-70.57	.2910	-153.86	2
6019.09	.0002	-127.21	46.0360	129.44	.0022	-64.59	.2795	-154.43	2
6156.28	.0002	-105.65	46.5162	128.93	.0024	-57.53	.2679	-155.03	2
6293.46	.0002	-85.77	46.9760	128.44	.0026	-49.37	.2563	-155.67	2
6430.65	.0003	-68.11	47.4148	127.99	.0029	-40.11	.2445	-156.35	2
6567.84	.0004	-52.43	47.8319	127.56	.0032	-23.77	.2326	-157.09	2
6705.03	.0004	-38.21	48.2267	127.15	.0034	-18.35	.2206	-157.89	2

Figure III-1j

```
 6842.21     .0005  -25.01    48.5987 126.77     .0038   -5.88     .2086 -158.76     2
 6979.40     .0007  -12.46    48.9472 126.42     .0042    7.54     .1965 -159.73     2
 7116.59     .0008    -.30    49.2717 126.08     .0047   21.73     .1844 -160.82     2
 7253.77     .0010   11.61    49.5715 125.77     .0053   36.40     .1722 -162.04     2
 7390.96     .0012   23.41    49.8461 125.47     .0061   51.26     .1601 -163.43     2
 7528.15     .0014   35.16    50.0951 125.20     .0072   66.02     .1479 -165.03     2
 7665.33     .0016   46.91    50.3179 124.94     .0085   80.46     .1359 -166.91     2
 7802.52     .0019   58.69    50.5140 124.70     .0101   94.46     .1239 -169.13     2
 7939.71     .0023   70.50    50.6832 124.47     .0121  107.98     .1121 -171.82     2
 8076.90     .0026   82.34    50.8253 124.26     .0145  121.05     .1005 -175.11     2
 8214.08     .0031   94.22    50.9400 124.07     .0173  133.70     .0893 -179.23     2
 8351.27     .0036  106.11    51.0275 123.88     .0207  146.02     .0787  175.52     2
 8488.46     .0042  118.01    51.0880 123.71     .0246  158.06     .0688  168.72     2
 8625.64     .0049  129.90    51.1221 123.55     .0293  169.88     .0602  159.84     2
 8762.83     .0057  141.77    51.1303 123.39     .0347 -178.46     .0535  148.41     2
 8900.02     .0067  153.60    51.1138 123.25     .0409 -166.92     .0494  134.44     2
 9037.20     .0078  165.40    51.0735 123.11     .0482 -155.48     .0486  119.05     2
 9105.80     .0084  171.01    51.0449 123.04     .0522 -149.76     .0495  111.46     3
 9174.39     .0096  174.41    50.9146 122.53     .0562 -144.37     .0494  111.96     3
 9311.58     .0116 -179.04    50.6793 121.48     .0662 -133.75     .0490  113.15     3
 9448.76     .0131 -171.99    50.4905 120.40     .0786 -124.00     .0482  114.62     3
 9585.95     .0140 -163.80    50.3643 119.30     .0928 -115.31     .0469  116.43     3
 9723.13     .0143 -153.83    50.3164 118.20     .1075 -107.51     .0450  118.60     3
 9860.32     .0141 -141.29    50.3588 117.13     .1215 -100.30     .0426  121.17     3
 9997.51     .0135 -125.16    50.4977 116.14     .1334  -93.40     .0395  124.18     3
10134.69     .0129 -104.46    50.7305 115.26     .1418  -86.60     .0358  127.64     3
10271.88     .0131  -79.49    51.0437 114.53     .1454  -79.68     .0315  131.57     3
10409.07     .0145  -53.24    51.4123 113.98     .1432  -72.47     .0269  135.98     3
10546.25     .0173  -29.31    51.8003 113.65     .1343  -64.74     .0220  140.78     3
```

Figure III-1k

```
10683.44          .0212   -8.89     52.1638  113.53      .1181  -56.09       .0173  145.72      3

10820.63          .0256    8.70     52.4551  113.62      .0947  -45.61       .0129  150.00      3

10906.37          .0285   19.49     52.5800  113.76      .0767  -37.04       .0103  151.62      4

10957.81          .0358   39.72     52.6390  114.25      .0629  -31.50       .0061  155.00      4

11095.00 ANCHOR   .0616   70.67     51.3620  116.46      .0000     .00       .0000     .00      4

                                COEFFICIENTS OF BUOY EQUATIONS OF MOTION


                         A(1,1) =    .8696+04   A(1,2) =    .5338+03   A(1,3) =    .0000
                         A(1,4) =    .0000      A(1,5) =    .0000      A(1,6) =    .0000
                         A(1,7) =    .5046+04   A(1,8) =    .0000      A(1,9) =    .0000



                         A(2,1) =    .0000      A(2,2) =    .0000      A(2,3) =    .0000
                         A(2,4) =    .2815+05   A(2,5) =    .4638+04   A(2,6) =    .8033+05
                         A(2,7) =    .0000      A(2,8) =    .0000      A(2,9) =    .0000



                         A(3,1) =    .5046+04   A(3,2) =    .0000      A(3,3) =    .0000
                         A(3,4) =    .0000      A(3,5) =    .0000      A(3,6) =    .0000
                         A(3,7) =    .1464+07   A(3,8) =    .1025-05   A(3,9) =    .7562+07



                                     WAVE FORCES AND MOMENT ON BUOY


                         SURGE FORCE =     .2991+04 LBS.     PHASE =  -90.00 DEG.
                         HEAVE FORCE =     .7343+05 LBS.     PHASE = -178.02 DEG.
                         PITCH MOMENT=     .6992+05 FT-LBS   PHASE =   91.53 DEG.

                                     MOORING FORCES AND MOMENT ON BUOY


                         SURGE FORCE =     .1123+03 LBS.     PHASE =  131.93 DEG.
                         HEAVE FORCE =     .1104+03 LBS.     PHASE =  -87.98 DEG.
                         PITCH MOMENT=     .5390+03 FT-LBS   PHASE =  131.93 DEG.

                                        BUOY RESPONSES


                         SURGE AMP =    .1094+01 FT.     PHASE =   94.88 DEG.
                         HEAVE AMP =    .1022+01 FT.     PHASE = -179.97 DEG.
                         PITCH AMP =    .5794+00 DEG.    PHASE =   91.84 DEG.
```

Figure III-11

```
PITCH/WAVE SLOPE =      .1078+01
```

Figure III-1m

```
                                         CABLE--BUOY DYNAMIC SOLUTION

                          WAVE FREQUENCY =      1.021 RADIANS/SEC
                                         =       .163 HERTZ
                          WAVE LENGTH    =    194.044 FEET


                                                CABLE RESPONSES
DISTANCE (FT)             PHI (DEG)         TENSION (LBS)           U (FT/SEC)          V (FT/SEC)          CABLE    ATTACHMENT
                         AMP   PHASE          AMP    PHASE          AMP   PHASE         AMP   PHASE

     .01 BUOY          .4794  -58.59     237.6831 -123.30       1.1472  150.67       1.1870 -128.77          1
   34.31               .3607  -84.50     230.1570 -131.63       1.0010  138.29       1.1886 -129.88          2
  120.05               .2251 -112.66     225.0161 -131.84        .6422  110.20       1.1874 -133.39          2
  257.24               .1096 -156.61     217.5185 -132.54        .3264   66.95       1.1919 -138.61          2
  394.42               .0560  161.65     209.7891 -133.45        .1714   26.61       1.2045 -143.47          2
  531.61               .0297  123.44     201.7320 -134.35        .0910  -10.25       1.2239 -148.00          2
  668.80               .0160   89.90     193.5895 -135.17        .0472  -43.94       1.2488 -152.22          2
  805.98               .0084   61.57     185.5574 -135.93        .0229  -76.02       1.2777 -156.11          2
  943.17               .0041   38.73     177.7339 -136.64        .0097 -111.15       1.3098 -159.69          2
 1080.36               .0016   22.86     170.1582 -137.35        .0035 -168.23       1.3441 -162.96          2
 1217.55               .0004   32.69     162.8470 -138.09        .0029  106.87       1.3800 -165.95          2
 1354.73               .0004  132.18     155.8143 -138.89        .0038   65.57       1.4167 -168.69          2
 1491.92               .0006  131.49     149.0780 -139.79        .0041   43.42       1.4539 -171.20          2
 1629.11               .0007  120.89     142.6617 -140.83        .0041   29.58       1.4909 -173.50          2
 1766.29               .0007  110.18     136.5788 -142.03        .0037   21.39       1.5275 -175.62          2
 1903.48               .0006  102.08     130.5103 -143.33        .0032   16.32       1.5631 -177.59          2
 2040.67               .0006   96.28     124.3343 -144.73        .0028   13.31       1.5977 -179.41          2
 2177.85               .0006   92.29     118.0701 -146.23        .0024   11.83       1.6308  178.90          2
 2315.04               .0006   89.72     111.7392 -147.86        .0022   11.19       1.6622  177.33          2
 2452.23               .0005   88.15     105.3664 -149.65        .0020   10.72       1.6917  175.87          2
 2589.42               .0005   87.18      98.9799 -151.65        .0018    9.82       1.7192  174.51          2
 2726.60               .0005   86.52      92.6130 -153.89        .0017    8.34       1.7444  173.24          2
 2863.79               .0005   85.97      86.3040 -156.43        .0016    6.07       1.7673  172.06          2
```

Figure III-1n

3000.98	.0005	85.44	80.0936	-159.35	.0015	3.05	1.7876	170.96	2
3138.16	.0005	84.85	74.0388	-162.72	.0014	-.89	1.8052	169.93	2
3275.35	.0005	84.25	68.2128	-166.66	.0013	-5.72	1.8201	168.96	2
3412.54	.0005	83.61	62.7079	-171.29	.0012	-11.55	1.8321	168.05	2
3549.72	.0005	82.97	57.6408	-176.75	.0011	-18.45	1.8412	167.20	2
3686.91	.0004	82.35	53.1564	176.83	.0010	-26.45	1.8473	166.40	2
3824.10	.0004	81.75	49.4268	169.38	.0010	-35.47	1.8504	165.65	2
3961.29	.0004	81.11	46.6389	160.91	.0010	-44.94	1.8504	164.94	2
4098.47	.0004	80.41	44.9653	151.64	.0010	-54.30	1.8473	164.27	2
4235.66	.0004	79.59	44.5201	141.99	.0010	-62.84	1.8410	163.64	2
4372.85	.0004	78.57	45.3198	132.50	.0010	-70.20	1.8315	163.04	2
4510.03	.0004	77.34	47.2744	123.64	.0011	-76.45	1.8189	162.47	2
4647.22	.0004	75.93	50.2168	115.74	.0011	-81.92	1.8032	161.92	2
4784.41	.0003	74.48	53.9490	108.91	.0011	-87.22	1.7843	161.41	2
4921.59	.0003	73.24	58.2801	103.11	.0011	-93.05	1.7622	160.91	2
5058.78	.0003	72.53	63.0453	98.24	.0011	-100.15	1.7371	160.44	2
5195.97	.0003	72.68	68.1107	94.16	.0012	-109.04	1.7089	159.99	2
5333.16	.0003	73.96	73.3700	90.73	.0012	-119.35	1.6776	159.55	2
5470.34	.0004	76.59	78.7295	87.81	.0014	-128.89	1.6434	159.12	2
5607.53	.0004	80.74	84.1260	85.30	.0017	-135.83	1.6063	158.70	2
5744.72	.0003	86.44	89.5126	83.13	.0020	-139.43	1.5663	158.30	2
5881.90	.0003	93.85	94.8512	81.24	.0025	-139.85	1.5235	157.90	2
6019.09	.0003	103.40	100.1098	79.59	.0029	-137.61	1.4780	157.51	2
6156.28	.0003	115.98	105.2617	78.13	.0034	-133.15	1.4298	157.12	2
6293.46	.0002	134.00	110.2838	76.85	.0039	-126.76	1.3791	156.74	2
6430.65	.0002	163.61	115.1559	75.71	.0044	-118.60	1.3260	156.35	2
6567.84	.0002	-148.25	119.8603	74.69	.0048	-108.59	1.2704	155.96	2
6705.03	.0002	-103.01	124.3810	73.78	.0051	-96.57	1.2126	155.57	2

Figure III-1o

6842.21	.0004	-74.45	128.7036	72.97	.0053	-82.07	1.1526	155.16	2
6979.40	.0005	-53.99	132.8150	72.24	.0054	-64.34	1.0906	154.73	2
7116.59	.0007	-36.59	136 7033	71.58	.0055	-42.63	1.0267	154.28	2
7253.77	.0010	-20.27	140.3576	70.99	.0059	-16.81	.9609	153.80	2
7390.96	.0013	-4.18	143.7679	70.46	.0068	11.30	.8934	153.27	2
7528.15	.0016	12.06	146.9252	69.98	.0085	38.41	.8244	152.69	2
7665.33	.0019	28.64	149.8217	69.54	.0112	62.56	.7540	152.03	2
7802.52	.0024	45.64	152.4505	69.15	.0149	83.76	.6823	151.25	2
7939.71	.0029	63.05	154.8060	68.80	.0196	102.86	.6095	150.32	2
8076.90	.0034	80.82	156.8837	68.49	.0254	120.66	.5359	149.17	2
8214.08	.0041	98.87	158.6804	68.20	.0322	137.73	.4615	147.67	2
8351.27	.0050	117.08	160.1941	67.95	.0404	154.45	.3867	145.63	2
8488.46	.0060	135.37	161.4238	67.72	.0498	171.06	.3119	142.64	2
8625.64	.0072	153.66	162.3691	67.52	.0609	-172.26	.2379	137.82	2
8762.83	.0087	171.90	163.0300	67.35	.0738	-155.43	.1666	128.80	2
8900.02	.0105	-169.95	163.4066	67.20	.0889	-138.40	.1048	108.00	2
9037.20	.0127	-151.91	163.4981	67.08	.1066	-121.16	.0798	60.21	2
9105.80	.0138	-143.28	163.4363	67.03	.1166	-112.48	.0929	35.50	3
9174.39	.0102	-126.11	162.7205	66.60	.1241	-106.54	.0924	34.42	3
9311.58	.0094	-50.78	161.2210	65.78	.1220	-98.39	.0914	31.96	3
9448.76	.0188	-11.96	159.5819	65.01	.0920	-93.45	.0910	29.45	3
9585.95	.0287	5.01	157.7582	64.29	.0351	-98.73	.0914	27.45	3
9723.13	.0356	19.27	155.7413	63.57	.0484	120.54	.0923	26.54	3
9860.32	.0382	35.73	153.5815	62.79	.1394	119.54	.0935	27.21	3
9997.51	.0374	57.51	151.4038	61.91	.2300	126.81	.0942	29.67	3
10134.69	.0359	87.00	149.4067	60.88	.3077	136.80	.0936	33.90	3
10271.88	.0378	121.79	147.8351	59.70	.3637	149.09	.0912	39.65	3
10409.07	.0439	154.73	146.9201	58.41	.3945	163.72	.0863	46.54	3
10546.25	.0511	-176.39	146.7959	57.14	.4011	-179.25	.0786	54.06	3

Figure III-1p

```
10683.44           .0566 -148.80    147.4216   56.03      .3865 -159.92       .0681   61.48       3
10820.63           .0601 -119.51    148.5470   55.21      .3516 -138.34       .0551   67.54       3
10906.37           .0614  -99.34    149.3217   54.89      .3190 -123.35       .0457   69.76       4
10957.81           .0766  -56.98    150.6238   54.67      .2803 -114.89       .0276   74.52       4
11095.00 ANCHOR    .1545   -7.43    150.0993   56.54      .0000     .00       .0000     .00       4

                                COEFFICIENTS OF BUOY EQUATIONS OF MOTION

                          A(1,1) =     .8696+04   A(1,2) =     .5338+03   A(1,3) =     .0000
                          A(1,4) =     .0000      A(1,5) =     .0000      A(1,6) =     .0000
                          A(1,7) =     .5046+04   A(1,8) =     .0000      A(1,9) =     .0000


                          A(2,1) =     .0000      A(2,2) =     .0000      A(2,3) =     .0000
                          A(2,4) =     .2493+05   A(2,5) =     .1642+05   A(2,6) =     .8033+05
                          A(2,7) =     .0000      A(2,8) =     .0000      A(2,9) =     .0000


                          A(3,1) =     .5046+04   A(3,2) =     .0000      A(3,3) =     .0000
                          A(3,4) =     .0000      A(3,5) =     .0000      A(3,6) =     .0000
                          A(3,7) =     .1497+07   A(3,8) =     .1747+06   A(3,9) =     .7562+07


                                     WAVE FORCES AND MOMENT ON BUOY

                          SURGE FORCE =     .9832+04 LBS.     PHASE =  -90.00 DEG.
                          HEAVE FORCE =     .6009+05 LBS.     PHASE = -164.93 DEG.
                          PITCH MOMENT=     .1995+06 FT-LBS   PHASE =  101.46 DEG.

                                     MOORING FORCES AND MOMENT ON BUOY

                          SURGE FORCE =     .1723+03 LBS.     PHASE =  167.13 DEG.
                          HEAVE FORCE =     .2727+03 LBS.     PHASE =  -98.79 DEG.
                          PITCH MOMENT=     .8268+03 FT-LBS   PHASE =  167.13 DEG.

                                             BUOY RESPONSES

                          SURGE AMP =    .1059+01 FT.     PHASE =   92.26 DEG.
                          HEAVE AMP =    .1059+01 FT.     PHASE =  178.16 DEG.
                          PITCH AMP =    .1960+01 DEG.    PHASE =   99.71 DEG.
```

Figure III-1q

```
PITCH/WAVE SLOPE =      .1056+01
```

Figure III-1r

```
IRREGULAR SEAS RESULTS

 RESPONSE (AMPLITUDE) SPECTRA          SIG. WAVE HT. =  6.00,  MEAN PERIOD =  5.00

   WAVE         WAVE
FREQUENCY     LENGTH        SURGE         HEAVE        PITCH
   .31400    2052.00        .000          .000         .000
   .54970     669.55        .124-02       .108-02      .347-03
   .78540     327.98        .216+01       .196+01      .247+01
  1.02110     194.04        .364+01       .363+01      .125+02
  1.25680     128.09        .193+01       .225+01      .176+02
  1.49250      90.83        .772+00       .103+01      .165+02
  1.72820      67.74        .258+00       .358+00      .111+02
  1.96390      52.46        .685-01       .828-01      .376+01
  2.19960      41.82        .120-01       .169-01      .282-01
  2.43530      34.11        .495-03       .670-02      .963+00
  2.67100      28.36        .490-03       .346-02      .139+01
  2.90670      23.95        .786-03       .775-03      .626+00
  3.14240      20.49        .230-03       .593-04      .716-01
  3.37810      17.73        .803-06       .248-03      .137-01
  3.61380      15.49        .578-04       .129-03      .488-01
  3.84950      13.65        .282-04       .211-05      .108-01
  4.08520      12.12        .561-06       .340-04      .125-02
  4.32090      10.84        .120-04       .939-05      .326-02
  4.55660       9.74        .142-05       .296-05      .601-04

              MN.SQ.        .208+01       .220+01      .158+02
              R.M.S.        .144+01       .148+01      .397+01
              AVG.          .180+01       .186+01      .497+01
              SIG.          .289+01       .297+01      .795+01
              AV1/10        .368+01       .378+01      .101+02


 RESPONSE (AMPLITUDE) SPECTRA          SIG. WAVE HT. =  8.00,  MEAN PERIOD =  6.00

   WAVE         WAVE
FREQUENCY     LENGTH        SURGE         HEAVE        PITCH
   .31400    2052.00        .353-20       .330-20      .119-21
   .54970     669.55        .578+00       .504+00      .162+00
   .78540     327.98        .839+01       .760+01      .959+01
  1.02110     194.04        .529+01       .529+01      .181+02
  1.25680     128.09        .209+01       .243+01      .190+02
  1.49250      90.83        .744+00       .993+00      .159+02
  1.72820      67.74        .236+00       .328+00      .101+02
  1.96390      52.46        .611-01       .738-01      .335+01
  2.19960      41.82        .106-01       .148-01      .248-01
  2.43530      34.11        .431-03       .584-02      .839+00
  2.67100      28.36        .424-03       .300-02      .120+01
  2.90670      23.95        .679-03       .670-03      .541+00
  3.14240      20.49        .199-03       .511-04      .618-01
  3.37810      17.73        .692-06       .213-03      .118-01
  3.61380      15.49        .498-04       .111-03      .419-01
  3.84950      13.65        .243-04       .181-05      .925-02
  4.08520      12.12        .482-06       .292-04      .109-02
  4.32090      10.84        .103-04       .807-05      .280-02
```

Figure III-1s

```
 1.55660       9.74      .122-05      .254-05      .516-04

              MN.SQ.     .410+01      .406+01      .186+02
              R.M.S.     .203+01      .202+01      .431+01
              AVG.       .253+01      .252+01      .539+01
              SIG.       .405+01      .403+01      .863+01
              AV1/10     .516+01      .514+01      .110+02


 RESPONSE (AMPLITUDE) SPECTRA             SIG. WAVE HT. = 12.00,  MEAN PERIOD =  7.00

  WAVE         WAVE
FREQUENCY     LENGTH      SURGE        HEAVE      PITCH
   .31400    2052.00     .446-09      .416-09      .150-10
   .54970     669.55     .105+02      .912+01      .293+01
   .78540     327.98     .195+02      .177+02      .223+02
  1.02110     194.04     .806+01      .806+01      .276+02
  1.25680     128.09     .280+01      .326+01      .255+02
  1.49250      90.83     .949+00      .127+01      .203+02
  1.72820      67.74     .295+00      .409+00      .126+02
  1.96390      52.46     .754-01      .911-01      .414+01
  2.19960      41.82     .130-01      .182-01      .304-01
  2.43530      34.11     .528-03      .715-02      .103+01
  2.67100      28.36     .518-03      .367-02      .147+01
  2.90670      23.95     .828-03      .816-03      .660+00
  3.14240      20.49     .242-03      .622-04      .752-01
  3.37810      17.73     .842-06      .260-03      .144-01
  3.61380      15.49     .605-04      .135-03      .510-01
  3.84950      13.65     .295-04      .220-05      .112-01
  4.08520      12.12     .586-06      .355-04      .131-02
  4.32090      10.84     .125-04      .981-05      .340-02
  4.55660       9.74     .148-05      .308-05      .627-04

              MN.SQ.     .993+01      .940+01      .280+02
              R.M.S.     .315+01      .307+01      .529+01
              AVG.       .394+01      .383+01      .661+01
              SIG.       .630+01      .613+01      .106+02
              AV1/10     .804+01      .782+01      .135+02


 RESPONSE (AMPLITUDE) SPECTRA             SIG. WAVE HT. = 15.00,  MEAN PERIOD =  8.00

  WAVE         WAVE
FREQUENCY     LENGTH      SURGE        HEAVE      PITCH
   .31400    2052.00     .907-04      .846-04      .306-05
   .54970     669.55     .355+02      .310+02      .996+01
   .78540     327.98     .244+02      .221+02      .279+02
  1.02110     194.04     .824+01      .824+01      .282+02
  1.25680     128.09     .269+01      .314+01      .245+02
  1.49250      90.83     .890+00      .119+01      .190+02
  1.72820      67.74     .274+00      .380+00      .117+02
  1.96390      52.46     .696-01      .841-01      .382+01
  2.19960      41.82     .119-01      .167-01      .280-01
  2.43530      34.11     .485-03      .657-02      .944+00
  2.67100      28.36     .476-03      .337-02      .135+01
```

Figure III-1t

```
   2.90670        23.95      .759-03      .749-03      .605+00
   3.14240        20.49      .222-03      .571-04      .690-01
   3.37810        17 73      .771-06      .238-03      .132-01
   3.61380        15.49      .555-04      .123-03      .468-01
   3.84950        13.65      .270-04      .202-05      .103-01
   4.08520        12.12      .537-06      .325-04      .120-02
   4.32090        10.84      .114-04      .898-05      .312-02
   4.55660         9.74      .135-05      .282-05      .574-04

               MN.SQ.        .170+02      .156+02      .302+02
               R.M.S.        .412+01      .395+01      .550+01
               AVG.          .515+01      .494+01      .687+01
               SIG.          .825+01      .790+01      .110+02
               AV1/10        .105+02      .101+02      .140+02


 RESPONSE (AMPLITUDE) SPECTRA          SIG. WAVE HT. = 25.00,  MEAN PERIOD = 10.00

   WAVE         WAVE
 FREQUENCY     LENGTH       SURGE        HEAVE        PITCH
    .31400     2052.00     .306+01      .285+01      .103+00
    .54970      669.55     .121+03      .105+03      .339+02
    .78540      327.98     .362+02      .328+02      .414+02
   1.02110      194.04     .103+02      .103+02      .352+02
   1.25680      128.09     .319+01      .371+01      .290+02
   1.49250       90.83     .103+01      .138+01      .221+02
   1.72820       67.74     .315+00      .437+00      .135+02
   1.96390       52.46     .798-01      .964-01      .438+01
   2.19960       41.82     .136-01      .191-01      .320-01
   2.43530       34.11     .553-03      .749-02      .108+01
   2.67100       28.36     .542-03      .364-02      .154+01
   2.90670       23.95     .865-03      .853-03      .689+00
   3.14240       20.49     .253-03      .650-04      .786-01
   3.37810       17.73     .878-06      .271-03      .150-01
   3.61380       15.49     .631-04      .140-03      .532-01
   3.84950       13.65     .308-04      .230-05      .117-01
   4.08520       12.12     .611-06      .370-04      .137-02
   4.32090       10.84     .130-04      .102-04      .355-02
   4.55660        9.74     .154-05      .321-05      .653-04

               MN.SQ.      .409+02      .367+02      .431+02
               R.M.S.      .640+01      .606+01      .657+01
               AVG.        .800+01      .757+01      .821+01
               SIG.        .128+02      .121+02      .131+02
               AV1/10      .163+02      .154+02      .167+02
```

Figure III-1u

CHAPTER IV

MOORING LINE AND MOORING SYSTEM COMPONENTS

CHAPTER IV

MOORING LINE AND MOORING SYSTEM COMPONENTS

1.0 INTRODUCTION

In the design of any buoy mooring, careful consideration must be given to each element of the mooring system. Potential problems have been identified with virtually every element of a mooring system, from the line itself down to every shackle, nut, and bolt. The myriad of unknowns involved with subjecting an unattended man-made structure to a hostile environment can only be addressed from experience and with extensive forethought.

2.0 MOORING LINE

The primary element of any mooring system is the mooring line itself. The capabilities and limitations of any particular type mooring line govern every aspect of a buoy's survivability. In the cordage industry, there are dozens of different line constructions available, and dozens more materials and blends of materials from which to choose.

2.1 LINE CONSTRUCTION

In line construction, the most common types for ocean usage are twisted, plaited, braided, double-braided, braided plaited (conductor carrying), parallel, and numerous wire rope cable lay constructions. A wealth of information is commercially available in the form of manufacturers' product data about each construction, and much independent study has been done on the subject. For a "typical" NDBO deep mooring, this mountain of study has been reduced to the need for a "zero torque" or "torque-balanced" construction. The random sea-keeping motion and loading by buoy hulls is a likely source of twisting in a non-torque-balanced construction which can result in knotting or hockling of lines. This limitation has eliminated the use of twisted ropes and wire rope or cable lay ropes on all surface buoys. Since NDBO has not, to date, been substantially involved with subsurface buoys, subsurface moorings and the use of wire rope and fiber ropes of similar construction for such moorings are not discussed here. Suffice it to say that these moorings have been well documented by such places as Woods Hole Oceanographic Institution (Heinmiller and Walden, 1973).

It should be noted, however, that special rope constructions do have specific uses. For example, parallel fiber constructions provide a mooring with virtually no elongation due to line construction. This limits line stretch almost entirely to the known, well-defined elastic characteristics of the fiber material used in the line. Where the mooring must carry electrical conductors or position instruments at a specific depth within close tolerance, parallel fiber lines have a great potential. As another example, NDBO has had successful experience with a conductor-carrying hybrid construction used on moorings equipped with inductively-coupled ocean sensors. This line had conductors in each of its eight plaited strands.

Each individual strand was of a parallel construction with a braid cover or jacket. This special construction yielded a fairly torque-free line, and did not overstress the wires in each strand. The greatest drawback to eight-strand plaited line is the large amount of undefined stretch allowed by the construction, thus making sensor positioning difficult. In service, the line was chafed by some sensor mounting bearing, a problem which can be corrected by bearing redesign. For reasons that do not involve the mooring line, these inductively coupled sensors may not be redeployed.

In all, however, torque-free lines are the mainstay of NDBO's mooring system, and the two most common types are plaited construction (MIL-R-24337) and double-braided construction (MIL-R-24050B). Where line stretch is not a primary consideration in selection of a line, NDBO uses these two constructions fairly interchangeably. Size for size, double-braided lines of a given fiber are slightly stronger than eight-strand plaited lines, but plaited lines equal in strength to double braid are usually cost-competitive due to their generally lower weight-per-unit-length characteristic. No significant difference in overall torque-free characteristics has been discerned between the two, and both lines appear to have adequate stretch to aid in attenuating buoy and wave dynamic loads. Both constructions are easily handled during buoy deployment or recovery operations, and both can be spliced without any great difficulty. Although there are significant differences in the two constructions, none are over-riding considerations in the selection of most NDBO deep ocean moorings.

2.2 LINE MATERIALS

Materials offer a second choice in line selection. The many natural and synthetic materials are too numerous to describe in detail; however, the most readily available materials include natural fibers (manila, hemp, etc.), synthetic fibers (nylon, polyester, polypropylene, Kevlar), and blends of these fibers. Of these materials, nylon, polyester, and certain blends are the most widely used. Kevlar, a new aramid fiber described as synthetic wire rope, is gaining acceptance because of its extremely high strength-to-weight ratio, but is still being widely studied and tested throughout the ocean science community prior to common operational usage.

Because of their low strength and susceptibility to chafe and to organic and chemical attack, natural fibers are not used in NDBO buoy moorings. Also, polypropylene and most fiber blends have been discarded due to chafe and embrittlement problems and low break strength relative to other fibers. Developmental fibers are generally not considered for operational buoy moorings by NDBO because of their unknown long-term reliability. Kevlar is being studied and holds a great deal of potential once long-term characteristics can be more adequately verified.

NDBO uses nylon and polyester almost exclusively for operational buoy moorings, with nylon being used in at least some portion of almost every mooring. Polyester is used where line stretch is undesirable, and has been used when nylon was not available. Polyester (often referred to as Dacron, a DuPont trade name) is slightly more expensive than nylon, but has proven to be a reliable substitute. Both fibers are durable, chafe resistant, strong (nylon is about 10% stronger for a given line size), resist marine chemical and organic attack, and are easy to work. NDBO has found nylon's competitive edge generally to be in cost, break strength, and availability.

3.0 ATTACHMENTS AND TERMINATIONS

Obviously, all mooring lines must be connected in one way or another to the buoy, the anchor, and (in many cases) to special instruments and sensors along its length. In all moorings, the line must be terminated, and rope manufacturers usually leave the method of termination up to the individual user.

3.1 THIMBLES

As a safety precaution, NDBO adopted early the policy of using captive thimbles on all synthetic line terminations. The captive thimble has two or more "ears" which surround the line and hold it in the thimble, even in the case of a loose eye splice. Other thimbles, such as wire rope thimbles with partial ears, have been tried but found unsuitable for long-term use, since a loose or stretched eye splice may ride up on the edge or completely work out of the thimble.

3.2 SPLICING AND POTTING

Wire rope is usually terminated using swaged lead-potted fittings or cable clamps. Kevlar is terminated using an epoxy mold on braided constructions or back braiding and whipping technique on parallel fiber constructions. When one length of line is to be connected to a second length of comparable size and construction, an in-line or "short" splice is usually used to eliminate unnecessary hardware in the mooring. Manufacturers' data indicate that such splices retain over 95% of the break strength of the line. Similar figures are given for the eye splices required to terminate the line in a thimble.

3.3 SHACKLES AND LINES

Between two thimbles or a thimble and end fitting, NDBO uses a galvanized mild steel safety shackle of either the anchor or chain shape. Several special-purpose links are also used. Detachable chain and anchor links are used where shackles are undesirable. Special alloy steel fittings are used when connections are made to alloy steel chain. Because of one previous failure and several near failures, all shackles, alloy coupling fittings, and detachable links, etc., are welded shut prior to deployment. This practice provides a large added margin of safety. With the emphasis on long-term reliability, the practice of welding all such fittings is less engineering overkill than it first appears. The failure cause is discussed later in the corrosion section of this chapter.

3.4 CHAIN

The most common mooring design now in use at NDBO also requires the use of a long length of chain at the lower end. This semi-taut design supersedes an earlier generation of moorings of a larger scope which used syntactic foam floats to suspend the "extra" synthetic line off the bottom when the mooring line was slack. The semi-taut chain design is cost-competitive to the use of floats, and is easier to deploy. The chain used in the present design consists of two segments: (1) a long length of small alloy steel chain, and (2) a short length of heavy studlink chain to provide damping of the dynamic cable forces and to reduce the vertical force on the anchor during storm conditions. The alloy chain possesses an extremely high strength-to-weight ratio. It is commonly made from AISI 8620 steel, and should perform well with respect to general corrosion. The heavier studlink chain is used primarily for its weight, and is far stronger than pure tensile load requirements would dictate. This chain is usually made of mild steel, and provides an adequate margin of corrosion and abrasion protection due to its massive size (usually 1-1/2" to 2-1/4").

4.0 COMPONENT TESTS

All load carrying members of a mooring system are procured by NDBO with accompanying certified load test results. Mooring line is tested in accordance with Method 6015 of Federal Standard No. 191, Textile Test Methods, except that modulus of elasticity is calculated at both 15% elongation and at 75% of rated break strength. This provides a minimum verification of load elongation characteristics up to break strength for each production lot procured. Chain is tested under proof load for verification of manufacturers' data, and break tests are performed to indicate ultimate strength. Since the ultimate strength of both line and chain is the failure point considered by NDBO in analyzing safety factors, this type of testing is required. Connecting links, when used, must be certified as equal to or greater than the break strength of the members being connected.

5.0 ANCHORS

At the bottom of all buoy moorings, NDBO prefers to use single anchors, although some contracted designs have used two anchors, either in-line or side-by-side. No evidence has ever been found, however, to indicate that the single-anchor design is inadequate.

The NDBO hull/mooring computer simulation resolves mooring forces at the anchor into vertical and horizontal components. The rule of thumb is to design the mooring conservatively (by varying line or chain length), so as to keep the vertical force less than the anchor weight and the horizontal force no more than three times the anchor weight. These maximums are not generally approached as mooring line tension usually becomes excessive before these conditions are met. After an extensive literature search on the holding power of various anchor types in various bottom conditions, almost nothing definitive can be said about these factors, particularly for deep water buoys. The holding power-to-weight ratio has been estimated as high as 5-to-1 on near-horizontal forces for anchors which are shaped for holding. In designing a deep ocean moor, this value can be used, but even this estimate is reduced where bottom conditions are known to offer poor holding and where mooring line forces on the anchor are likely to be high or poorly defined, such as for buoys moored in shallow water.

Of the many types of anchors available, NDBO uses primarily the stockless or Navy stockless types in the 7,000-pound range for large discus buoy deep moorings. These anchors have good holding power and are the most available and inexpensive. NDBO usually obtains anchors from surplus, considering any horizontal holding type (not clump) anchor acceptable. NDBO experience with mushroom anchors has been very good, but these anchors are not readily available from surplus sources. NDBO has no experience with exotic anchors such as explosive imbedment types, and has rarely used clump anchors or others not specially shaped for holding power.

6.0 MOORING ASSEMBLY

In all, a wide variety of factors determines the particular type, construction, and material of all elements of a mooring system. After selection, however, adequate quality control must be maintained during the assembly of the various system components. Most quality control checks are simple efforts, but their application is essential.

Synthetic mooring lines must be properly spooled or crated and protected during shipping and storage. Chafing and abrasion, handling damage, and--for nylon--exposure to sunlight, all must be guarded against. To insure deployment according to design, the line must also be accurately measured and marked. With the line under a nominal load (manufacturers often used $200D^2$ pounds where D = line diameter in inches), the line is marked with spray paint at fixed intervals as it is unreeled for deployment.

Once the correct lengths have been marked, the line must be properly terminated by splicing. Each rope manufacturer has developed specific splicing techniques for each construction of rope. These procedures must be followed exactly to insure retention of adequate line strength in the splice. The splice should be tight, neat, and extend the proper number of "tucks." Care must be taken in severing and tying off the strand ends so that they will not interfere with the passage of mooring recovery devices such as the explosive line cutter or saw.

7.0 CORROSION DESIGN

NDBO has had a great deal of field experience with many different types of connecting hardware for use in mooring systems. The problem which must be guarded against most closely is long-term corrosion in salt water; virtually every type of corrosion problem is encountered with connecting hardware.

General corrosion of metals in salt water is, of course, a considerable problem. The general corrosion is compensated for by the use of fittings of sufficient size to allow a constant corrosion rate for the expected lifetime of the deployment, and by use of protective coatings. The use of stainless steel chain and fittings exclusively is also a solution, but it is a very expensive proposition. Other corrosion problems, however, cause much greater concern and pose a high probability of mooring failure if left unaddressed.

Galvanic corrosion of dissimilar metals requires special attention. As an example, NDBO has long used thimbles specially designed for synthetic rope which are generally available only in bronze. When connected to a mild steel shackle underwater, the end result is highly accelerated corrosion (sacrificing) of the anode (in this case, the shackle). Some moorings were recovered intact with as much as one-third of the shackle pin diameter corroded and eroded away (a combined effect whereby corrosion oxidizes the base metal and allows it to rapidly abrade at the wear point.) On larger moorings, this problem does not become as critical because of the massive size of the hardware involved. On smaller moorings, however, the problem is accentuated. The small shackle is rapidly sacrificed and can reach the failure point in a short period of time.

The simplest solution is to use fittings of the same metal, but obviously this is not always possible. In the case of the thimble and shackle, NDBO has generally been unable to find a suitable replacement for the captive bronze thimble. The use of sacrificial anodes (such as zincs) has been tried. However, because they are subject to mechanical damage and not replaceable once deployed, they offer only limited protection. NDBO's solution to this problem is to coat the cathode (thimble) which provides a favorable area ratio even in the event of local coating breakdown. This is effective because the galvanic corrosion rate is governed not only by the electro-potential between metals, but also the ratio of surface areas--cathode to anode. The hybrid urethane being used to coat the bronze thimble is highly abrasion-resistant, adheres well, and reduces the cathode surface area only to points exposed by long-term wear.

A second corrosion problem is that of accelerated corrosion due to surface shape--crevice corrosion. This problem has also shown itself primarily on shackles, and specifically on the threads of the safety shackle pins. The crevice problem, accelerated by galvanic corrosion, has deteriorated some shackles sufficiently to allow the nut to fall off the pin. Nuts are now welded to the pins and all other connectors are welded to reduce the problem.

8.0 CONCLUSION

From design to deployment, then, the selection and proper use of mooring materials is critical to long-term survivability and reliability. NDBO's present design for deep water buoys is configured to survive the most severe environments anticipated and, hopefully, to remain in place for up to six years. With the benefits of in-house and external experience and good quality control, this goal does not appear to be at all unrealistic.

Reference: Heinmiller, R. H., and R. G. Walden, "Details of Woods Hole Moorings," Technical Report WHPO-73-71, October 1973

CHAPTER V

DEPLOYMENT AND RETRIEVAL

CHAPTER V

DEPLOYMENT AND RETRIEVAL

1.0 INTRODUCTION

This chapter documents some of the experience gained at sea in the deployment of the Deep Ocean Moored Buoys (DOMB), Continental Shelf Buoys (CONSHELF), and drifting buoys. The material relates to both at-sea operations and NDBO-designed hardware used for deployments and recoveries.

2.0 LARGE BUOY DEPLOYMENT

NDBO employs an anchor-last technique for the deployment of large buoy systems in the deep ocean. This technique is sometimes referred to as the "tow-away" method, and requires that the deployment vessel pay out the entire length of synthetic mooring line, sometimes up to 15,000 feet, while slowly steaming away from the buoy. The buoy is towed to a previously-surveyed deployment area where the anchor and ground tackle are released through the tripping of a single-point restraint when the ship and buoy are at predetermined locations.

2.1 AT-SEA PROCEDURE

2.1.1 The Tow

Prior to leaving port for the tow to station, the large discus buoy is ballasted with a slight bow-up attitude by shifting the water ballast from the forward to the aft tanks. Upon completion of the deployment, this water ballast is shifted back until the buoy rides on an even keel.

While leaving port and maneuvering out through channels, data buoys are towed at a nominal distance of 100 feet from the towing vessel. Upon reaching the open seas, the tow length is extended to over 500 feet. This length is adjusted for proper catenary so that the buoy and ship will remain in step, riding together over troughs and crests, thereby keeping a relatively constant tension in the towing line. If the length of the tow is such that the buoy is in the trough while the ship is on the crest, the tow line will slacken, and then go taut with a sudden jerk, producing heavy stresses in the towing line.

The following recommended maximum towing speeds have been established by NDBO based upon tow tank tests, computer model simulation, and practical experience:

Discus Hull Size	Maximum Tow Speed
12 m	9.0 kts
10 m	8.0 kts
5 m	5.5 kts

These recommended maximum speeds are the upper limits above which the deck of the buoy will tow under the bow wave and the deck will remain submerged. The speeds are reduced for increasing sea states. The tow speeds for the 10-meter discus buoys are reduced in accordance with the following table:

Approximate Wave Height	Maximum Tow Speed
<5 ft	8 kts
5 ft	6 kts
6 ft	5 kts
8 ft	4 kts
10 ft	3 kts

Since the wave steepness and direction are important, judgment and a good seaman's eye are still needed to avoid towing the deck under.

2.1.2 Site Survey

Upon arrival at the deployment location, a site survey is conducted. The primary navigation aid used by Coast Guard vessels is LORAN C. Satellite, LORAN A, or celestial methods are used for secondary means of navigation, depending upon availability. The ship is usually given liberty to deploy within a 20-mile radius of the originally-selected site. It is important that the bottom survey and the exact depth be known at the deployment site. With the semi-taut chain tension mooring configuration generally used by NDBO, there is a tolerance of approximatley 5% of the mooring site depth, typically allowing an average error in depth measurement of 500 feet in 10,000 feet of water.

2.1.3 Ship Handling for Proper Buoy Placement

The size of the deploying vessel, along with the 100-ton displacement associated with a 40-ft. (12 m) discus buoy, results in the development of very large forces during buoy handling operations. For this reason, ship handling and safety become of the utmost importance. There is little time for corrective adjustments; thus, alternative actions must be planned in advance to avoid disaster.

Two basic reminders for the planning of these operations generally assist in avoiding trouble. First is the recognition of Murphy's Laws, essentially assuming that anything that can go wrong, will go wrong. Second, "It's not nice (nor particularly smart) to fool Mother Nature." Wind, current, and wave forces are far stronger than man-made forces. If one out-foxes Murphy, respects the mass of the buoy and mooring, and is true to Mother Nature, there is generally little trouble.

The setup for the deployment operation involves positioning the ship and the buoy so that with all lines or attachments released, they will gradually drift apart. The drift of the buoy, because of the combined effect of the current and the wind, is determined prior to deployment. Upon arrival at the selected deployment site, the ship, with the buoy still in tow, goes downstream in the direction of the drift from the buoy deployment site. This means that upon turning back to the deployment site, the ship will be steaming as the buoy gradually drifts away, while the mooring line is payed out. In this manner, the mooring line is payed out gradually while approaching the drop site in a straight line. Originally, it was felt that the line should be deployed in a helix, or gradual curve, in order to avoid deployment loads based upon what was called the water sheave effect. This procedure was changed by NDBO in favor of the tow-away method. It has since been determined that this load was not of major concern because the deployment load approximates the static weight of the anchor (Thresher and Nath, 1975).

As the line streams out during the deployment, several last-minute checks are made, the first being to ensure that the line is of the length originally measured. There are three methods used by NDBO to verify proper length prior to drop. The line is marked every 500 feet prior to loading aboard ship, and these marks are accounted for during the payout. Second, a distance is measured from the capstan to the roller chock on the stern, and a paint mark is placed on a line as it leaves the capstan and tallied as it goes over the side. A third (and rather crude) check is available, based on radar ranging of the buoy just prior to deployment. When it is verified that the line payout is of proper length, and all equipment of the mooring is payed out with the exception of anchor and chain, the ship is ready for the drop.

As a general rule of thumb, NDBO estimates that the deployed (anchor) site of the buoy will be approximately half-way between the anchor drop position and the position of the buoy, with the line streamed out. A final check is made when the ship is just short of the drop position to endure that all components of the mooring system have a fair-lead for running upon release of the anchor. The end of the synthetic line is tied off alongside the vessel near the chain faking box by securing the shackle which connects it to the chain. This is accomplished with a piece of line sufficiently strong to restrain the tow from paying out, but weak enough so that the weight of the anchor and chain will have no difficulty in parting it. The ship then makes a slight turn to starboard (if the deployment is from the starboard side) in order to provide the best aspect for the drop. When all of the final checks are made, the fantail is cleared with the exception of one man. On command, he trips the pelican hook holding the anchor, thereby deploying the system.

2.1.4 Special Equipment

In order to carry out these deployments, some special equipment has been designed:

Anchor Release Devices - Three different varieties of anchor release mechanisms have been used. The first, called the "billboard" method, was outfitted only aboard the USCGC ACUSHNET. This billboard system was designed to accommodate the early moorings used by NDBO in which the ground tackle consisted of two 7,000-pound mushroom anchors shackled to a pipe A-frame. The billboard is illustrated in Figure V-1, and shows two mushroom anchors in position, starboard side aft, on the ACUSHNET.

A simpler method was designed to accommodate the same mooring system for a West Coast deployment by the USCGC YOCONA. This design, called the "gravity tray," is illustrated in Figure V-2 with two mushroom anchors and the A-frame in position ready for deployment. The gravity tray places the center of gravity of the anchor outboard of the ship's rail. With the center of gravity outboard, the anchor flips out of the tray upon release (see Figure V-3), clearing the side of the ship by a safe distance. The anchor does not slide down the tray, and therefore does not have to overcome any initial friction. No special angle of the tray or heel of the ship is required to deploy by this method. The gravity tray is the most effective method of anchor deployment used by NDBO because it is inexpensive, simple, safe, and readily adaptable to various types of anchors (as shown in Figures V-3 and V-4). Figure V-3 shows the deployment of a single 7,000-pound mushroom from a tray; Figure V-4 shows the same tray modified only by the addition of fluke supports to accommodate a 7,500-pound Navy stockless anchor. By using additional trays, with or without fluke supports, depending on the type of anchor, multiple anchors may be deployed simultaneously.

A third method of anchor release is used from a Coast Guard buoy tender using a mechanical chain stopper. This method of anchor release is peculiar to Coast Guard buoy tenders, and is described in the Coast Guard Aids to Navigation Manual, Seamanship, Publication CG 222-2. Basically, the mechanical chain stopper secures the anchor chain, while the center of gravity of the anchor is hung over the side through the buoy port. At deployment, a trip release frees the chain, allowing the anchor to drop. If the chain stopper is not sized for the chain designed in the mooring, a short pendant chain to fit the chain stopper may be shackled into the mooring chain.

Chain Faking Box - A chain faking box is used when a semi-taut mooring is selected. A typical semi-taut mooring consists of an anchor, a shot of 2-1/2" chain, 1,800 feet of 3/4" alloy chain, and a clear run of synthetic line attached to the upper mooring section containing ocean sensors or a thermistor string. This design has advantages in that it needs no floats or attachments, making it much easier for deployment and recovery with over-the-line cutters. It has a built-in design tolerance on deployment, permitting an error in depth of up to 5%.

The faking box is approximately 5 feet wide, 5 feet deep, and 4-1/2 feet high, and is used to accommodate over 1,800 feet of 3/4" or 7/8" alloy chain and up to two shots of 2-1/2" chain. The chain is faked in the box by alternating each layer, one going forward and aft, and the next layer going port and starboard, with each layer starting at the opposite diagonal from where the previous layer ended. The front of the box is approximately 9" lower than the back and has a flat-shaped frame constructed from large pipe, thus providing a smooth guide for the outflowing chain. The rate of chain spillout is not greater than the anchor descent rate. An anchor and chain being released using the faking box is shown in Figure V-5.

Fair-lead - Most of the synthetic mooring line is stowed below deck prior to steaming to the deployment site and must be passed up through a scuttle and hatch during the deployment operation. To guard against chafing and to ensure smooth operation during the payout of synthetic line, NDBO has designed a small roller that rests on the scuttle coaming. From this roller, the line is usually led around a vertical capstan and payed out in a controlled manner over a roller chock at the stern. Chafe protection must be provided for the entire length of the line paying out aboard the ship.

3.0 DECK BUOY DEPLOYMENT - CONSHELF

CONSHELF moored buoy systems and scientific drifting buoys are transported as deck cargo aboard ship to the various deployment sites. The only exceptions are the NOMAD and the 5-meter discus buoys, which may also be towed.

The five-buoy composite of Figure V-6 depicts the variety of configurations which have been evaluated for CONSHELF applications. Each of these can be handled on Coast Guard buoy tenders which were designed to service aids to navigation. The nominal physical characteristics for the five buoy configurations are described below. Whip antennas used in the HF communications systems for each configuration are quite long and extend well above the height values given here.

NOMAD:	Boat-shaped hull; 10 tons, 20' long x 7' high x 5' beam, plus 7' mast
5-METER DISCUS:	7-1/2 tons; 16' diameter x 3-1/2' thick, plus 14' mast
LIGHT BULB:	Spherical top; 3/4 ton; 4' diameter by 7' high
HORIZONTAL CYLINDER (with keel):	3 tons; 11' x 4-1/2' diameter, plus 7' mast
VERTICAL CYLINDER (with damping plate):	1-1/2 tons; 5-1/2' diameter x 8' high

Figures V-7 and V-8 are photographs of handling activity, deck storage, and deployment operations of the various buoys. The buoys are deployed in an anchor-last sequence. Slings, quick releases, tag lines, and fender poles are used in conjunction with the boom to hoist the buoys out over the side and into the water. Usually the buoy deployments have required the utilization of a Coast Guard small boat, as shown in Figure V-9. The workboat is stationed off the buoy port and used to pull the buoy away from the tender promptly upon release. Prior to release, the buoys are maintained in a vertical attitude, although some cant off the vertical has been required for the smaller CONSHELF systems to guard against damaging the relatively fragile, long HF whip antennas. The increased use of UHF communications is eliminating this problem.

In the anchor-last deployment scenario, the anchor is suspended over the edge of the buoy deck and held in place by the chain stopper. When the buoy is released and the entire mooring is fully payed out, the anchor is tripped by the chain stopper and the buoy is moored.

4.0 SEMI-AUTOMATIC MOORING OF LIMITED CAPABILITY BUOYS

Early in the NDBO program, an R&D effort was conducted to evaluate semi-automatic moorings of the light bulb and horizontal cylinder buoys to further increase their potential to meet a variety of user needs on or near the Continental Shelf.

Two deployments of the light bulb-shaped buoys were made in conjunction with the evaluation of a two-stage mooring system having a taut wire lower section moored to a subsurface float (the buoy itself does not have adequate reserve buoyancy to support an entire deep mooring system). A slack upper synthetic line segment was used between the buoy and subsurface float. The lower taut section of the mooring was deployed in a completely automatic fashion, which included the capability for the subsurface float to sense and stabilize at a predetermined depth, and to automatically pay out the taut wire section and anchor. A picture of the deployment operation is shown in Figure V-8. In these deployments, the surface buoy and 1,500 feet of upper line were deployed, as with the CONSHELF buoys. Then the automatic lower stage was deployed with the use of a quick release. Although these buoys are cumbersome to handle, the deployments worked quite well, demonstrating a special capability should the need arise.

Two semi-automatic deployments were also conducted for the horizontal cylinder buoy. Just as with the other CONSHELF systems, the buoy was first hoisted out over the side of the buoy tender and placed in the water. However, the line and anchor assembly were all contained within a dead-weight box assembly, a 5-foot cube weighing roughly 5,000 pounds. The box was designed for automatically paying out the line during descent. Two deployments were carried out with limited success utilizing this arrangement, but it is not considered operational.

5.0 DRIFTING BUOY DEPLOYMENT

Although some Limited Capability Buoys have been deployed without moorings as drifting buoys, the usual NDBO drifting buoy is much smaller and is expendable. It is normally made of aluminum or fiberglass pipe, and has a cone-shaped floatation section with a round top. The largest of this class of buoys is approximately 15 feet from the top of the anemometer to the attachment point for a drogue. The buoys range in weight between 260 and 360 pounds. The drogue attached to this class of buoy is a window-shade drogue approximately 5 feet wide and 50 feet long, and is made of Dacron sailcloth. It is attached with up to 100 meters of tetherline to adjust the drogue depth to track the flow at a specified depth.

The buoys are deployed either by sling or automatically. The sling method uses a bridle with a quick release that attaches about the cone. Prior to deployment, the drogue is accordioned and the drogue line is faked out on deck. The buoy is then hoisted over the side with a fish davit or a crane, and the quick release is tripped, deploying the buoy (see Figure V-9). The line is payed out, and finally the drogue is thrown over the side by hand. The sling method has been the most successful method thus far; however, for ships-of-opportunity, an automatic method has been designed.

Figures V-10 and V-11 show a deployment using the automatic technique. In this method, the buoy is deployed from the bottom half of its shipping crate. The buoy is held in the lower section of the crate with an 1/8" stainless steel wire. An explosive guillotine that is activated by the current of a seawater battery is attached to this wire. The buoy and crate are thrown over the side and the buoy drops out of the crate shortly after the package hits the water; upon activation of the seawater battery. This method allows the buoy to be deployed with inexperienced personnel. Also, the crate adds to the strength of the buoy for the larger distance free-fall drops from deploying vessels-of-opportunity.

6.0 BUOY RETRIEVAL

6.1 LARGE BUOY (DOMB) RETRIEVAL

The first step in the retrieval of a large buoy and mooring is to transfer the mooring to the ship and cast the buoy off. This is accomplished by using a retrieval chain that is attached to the buoy and to a point about 40 feet down the mooring. The rules of shiphandling are most important in a mooring retrieval operation for three reasons: first, the loads are much greater than during deployment by virtue of the mooring's being in place and subjected to current drag loads throughout its length; second, the ship, by being attached to the mooring, adds an additional load to the system due to the wind and current drag force on the ship; and third, the ship must sacrifice nearly all its maneuverability, since while attached to the buoy or mooring, the ship will turn with its stern into the predominant wind, sea, or current.

Because of the increased loads, the ship may be required to back slowly in order to relieve the load it imposes. Even with the ship backing, often two capstans are required to retrieve the upper mooring assembly. When two capstans are used, one does the primary pulling and the other assists by attaching to the mooring with a stopper and pulling bights.

6.2 RELEASE DEVICES

Once this mooring is transferred, the retrieval operation proceeds in recovery of the line. When acoustic release devices are utilized, they are used to free the line at the bottom. If there is no acoustic release device in the anchoring system, all sensors and attachments are first recovered, and then an over-the-line device, either explosive or saw, is used to sever the line as far down as practicable.

6.2.1 Acoustic Release

The primary advantage of an acoustic release is, of course, the ability to recover the mooring system intact. In some cases, recoverability is a basic requirement of a mooring system in order to retrieve self-contained recording instruments, other underwater sensors, or the mooring line itself for tests and evaluation. The principal disadvantage of acoustic releases arises out of the usable life of the device. In efforts to design deep-ocean mooring systems and components which will last for as much as six years without replacement, NDBO mooring configurations have been assembled which far exceed the usable lifetime and reliable operating period of acoustic releases (about two years). A failed release device in a long-term deployment adds to, instead of reducing, the cost of buoy moorings. A secondary disadvantage is the cost of floats frequently required above the release in slack or semi-taut moorings to keep the transponder off the ocean floor.

6.2.2 Explosive Line Cutter

There have been three variations of the explosive line cutters used by NDBO. All of the cutters are made of sheet metal and resemble an inverted funnel with a cylindrical ring about the stem. The cylindrical ring is pour-filled, usually with 25/75 cyclotol forming the cutting explosive. Two "Signals, Underwater Sound (SUS)" are bolted into the explosive container and are used as detonators (see Figure V-12).

One NDBO line cutter has a 10" inner diameter. It is filled with 60 pounds of Composition B (60 RDX 40 TNT) and is hinged such that it can be opened onto a mooring line and then bolted together again. NDBO has also used a hinged cutter with a 6.75" inner diameter carrying a nominal 40-pound charge, and a 10" inner diameter non-hinged cutter with the 60-pound charge.

The SUS detonator generally used with the line cutter is the MK59 MOD 3. This device arms at a water depth of 125 feet, at which point the water pressure exerts sufficient force on an arming piston to align the firing mechanism. Water also enters the SUS through flooding ports and the pressure is applied against a shear disc. When the shear disc ruptures with the firing mechanism aligned, the booster is fired, exploding the charge of 1.8 pounds of cyclotol. Shear discs can be used that rupture at pre-selected depths ranging from 1,000 to 18,000 feet.

A clock timer can be used to cover the flooding ports for a preset duration. Thus, by using one SUS with a timer and one SUS without a timer, the line cutter may be set to fire upon reaching the set maximum depth or (should it hang up on the line) to fire below a certain minimum depth after the preset duration.

Variations of the normal line cutter can be made by the Naval Weapons Station, Yorktown, Virginia, to suit special circumstances. Detonation at a depth of less than 1,000 feet can be accomplished using an MK57 MOD 0 or MK61 MOD 0 SUS. Both shape and charge may be varied. The 60-pound charge should not be detonated above a 1,000-foot depth.

The explosive line cutter comes under the classification of Class A Explosives, and must be shipped as such. Since it is an R&D device and is not certified, the system must be used only with a technician from the Naval Weapons Station, or a person designated by them. Certification is possible, but not yet cost-effective.

6.2.3 Model 32 Mooring Line Cutter

NDBO has procured a mooring line cutter which is battery driven and actually saws through the line when in position. The cutting is activated by a preset timer. To withstand pressure, the cutter is filled with diesel oil. This device has a disadvantage when compared to the explosive device in that it costs five times more than the explosive device, and therefore must be retrieved. To date, there has been no operational experience with this device.

6.3 CONSHELF BUOY RETRIEVAL

The buoys in this category have much smaller forces developed in the moorings due to the smaller buoy displacement, shallower depths, and smaller diameter line (drag). Some, if not all, of the line can be retrieved by positioning the recovery vessel over the anchor and pulling it up. Generally, line cutters or explosive devices have not been used to retrieve mooring line from these buoys since it is not cost-effective, and where there is little line involved, there is no significant savings from line retrieval.

One exception, however, was the automatically deployed subsurface stage of the light bulb buoy. A built-in line cutter was used successfully to retrieve the lower-stage subsurface float.

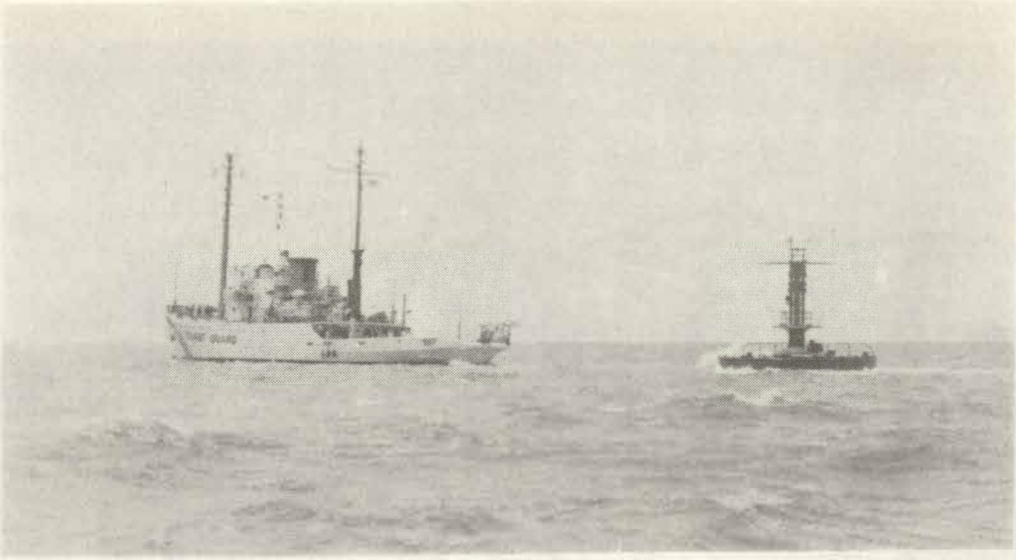
The retrieval of CONSHELF buoys is basically the inverse of the deployment operation. A workboat from the buoy tender must be placed into the water to secure slings and fittings, and to assist in the attachment to the boom. During the hoisting of the buoys onto the tender buoy deck, care must again be exercised to guard against damage to sensitive elements such as the HF antenna and meteorological sensor package. The ship's crew must also assist in the proper seating of the buoys in cradles and in the upright position for transport back to port.

7.0 CONCLUSIONS

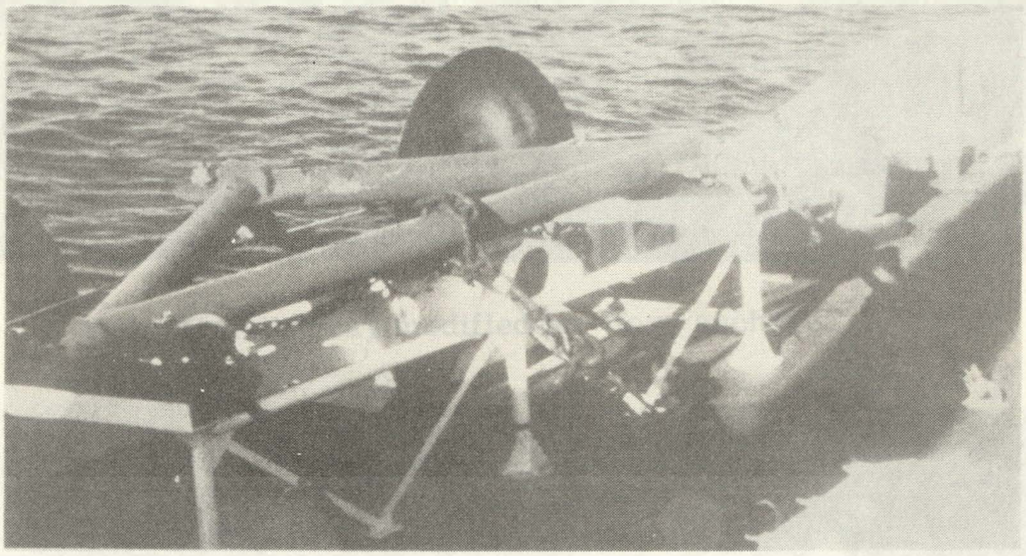
Deployment and retrieval operations for NDBO buoys have been conducted successfully at widespread sites with an effective utilization of US Coast Guard vessels and crews. Deployments have had greater than a 90% first-time success rate, and recoveries have returned in excess of 50,000 feet of reusable line without injuries to personnel.

Procedures and equipment designs have evolved from complicated line deployment patterns using costly and elaborate anchor release mechanisms to a straight-line payout with a simple gravity tray. Moorings like the semi-taut have been adopted with deployment and recovery in mind. These simpler and safer techniques have resulted in greater success, due both to less operator error and less equipment failure. New equipment and applied technology continually enhance this effort, but additional work is needed, particularly in the area of automatic mooring systems for both large and small buoys from ships-of-opportunity.

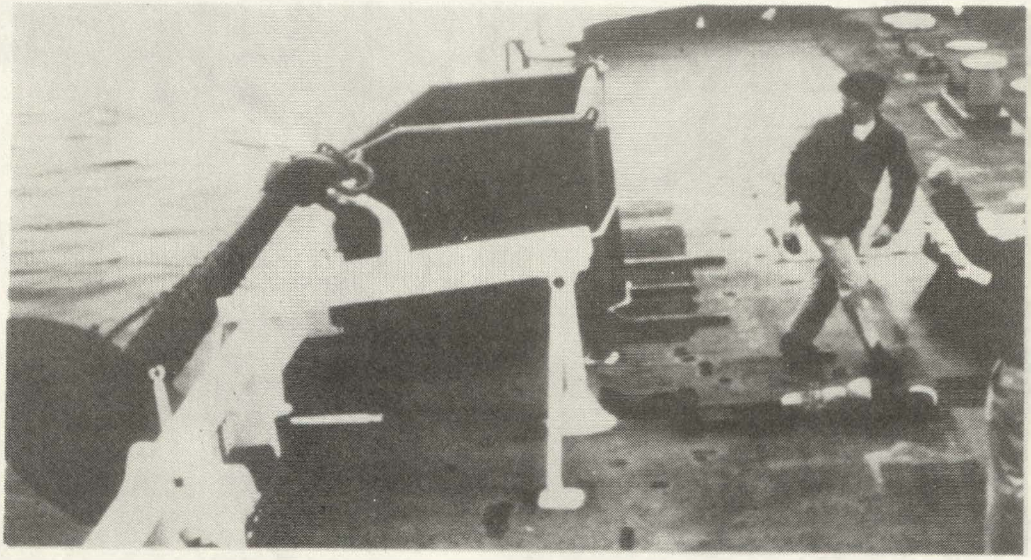
Reference: Thresher, R. W., and J. H. Nath, "Anchor-Last Deployment Simulation by Lumped Masses," Journal of the Waterways, Harbors and Coastal Engineering Division, ASCE, No. WW4, Proc. Paper 11709, November 1975, pp 419-433



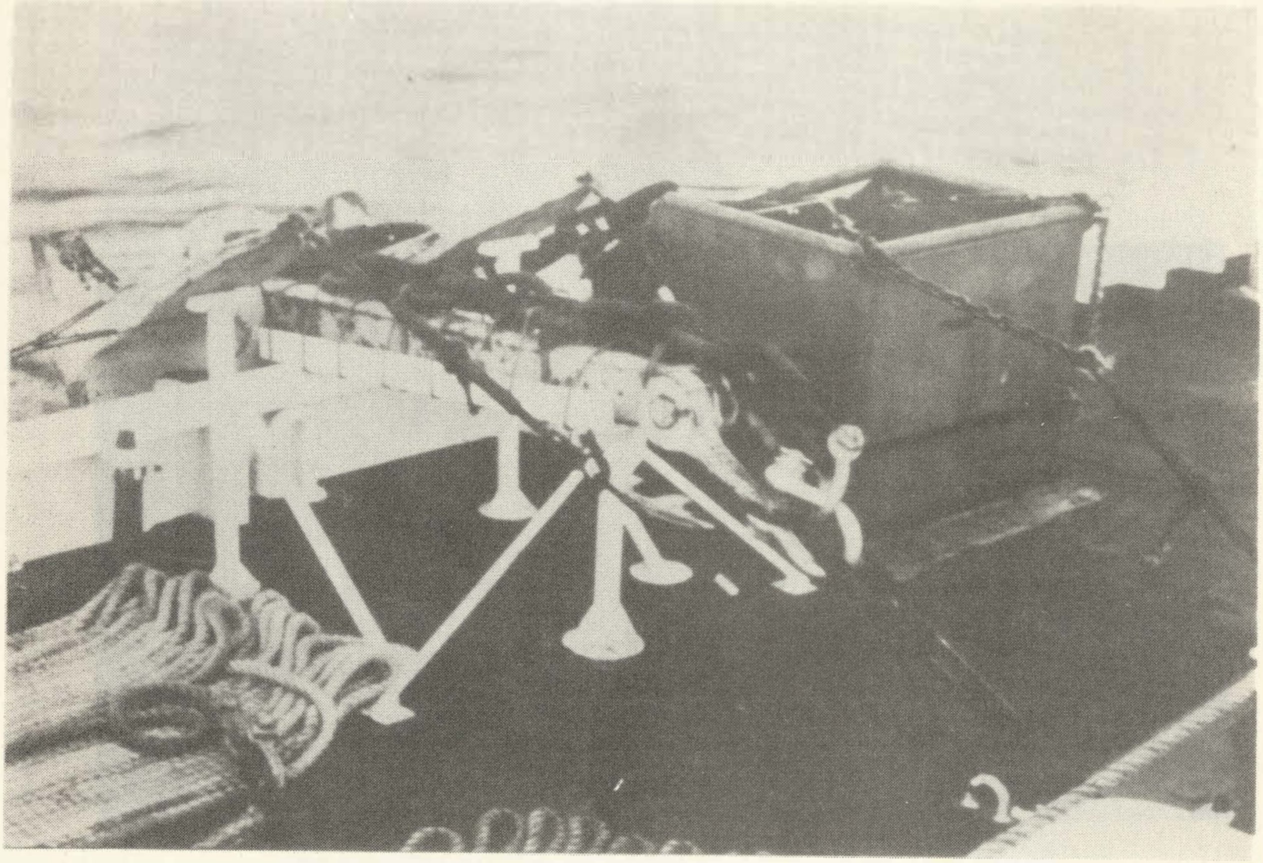
V-1. Acushnet with buoy in tow. Anchors in place on billboard.



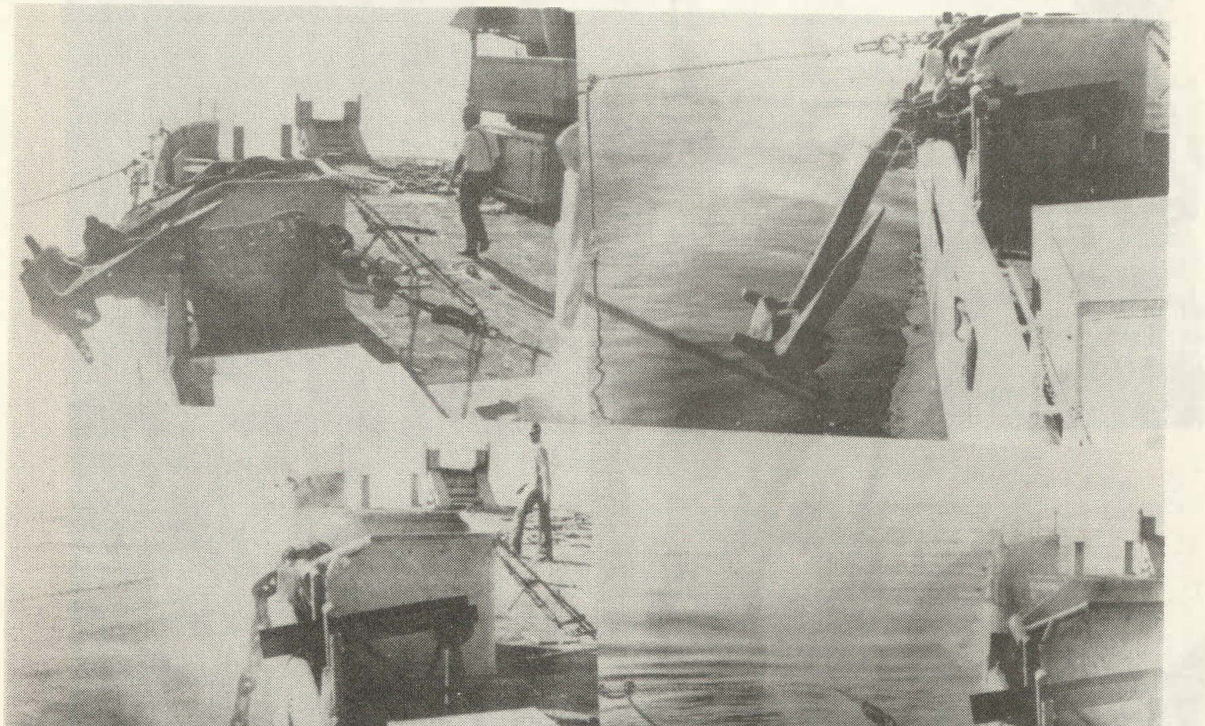
V-2. Two anchors in place on gravity tray.



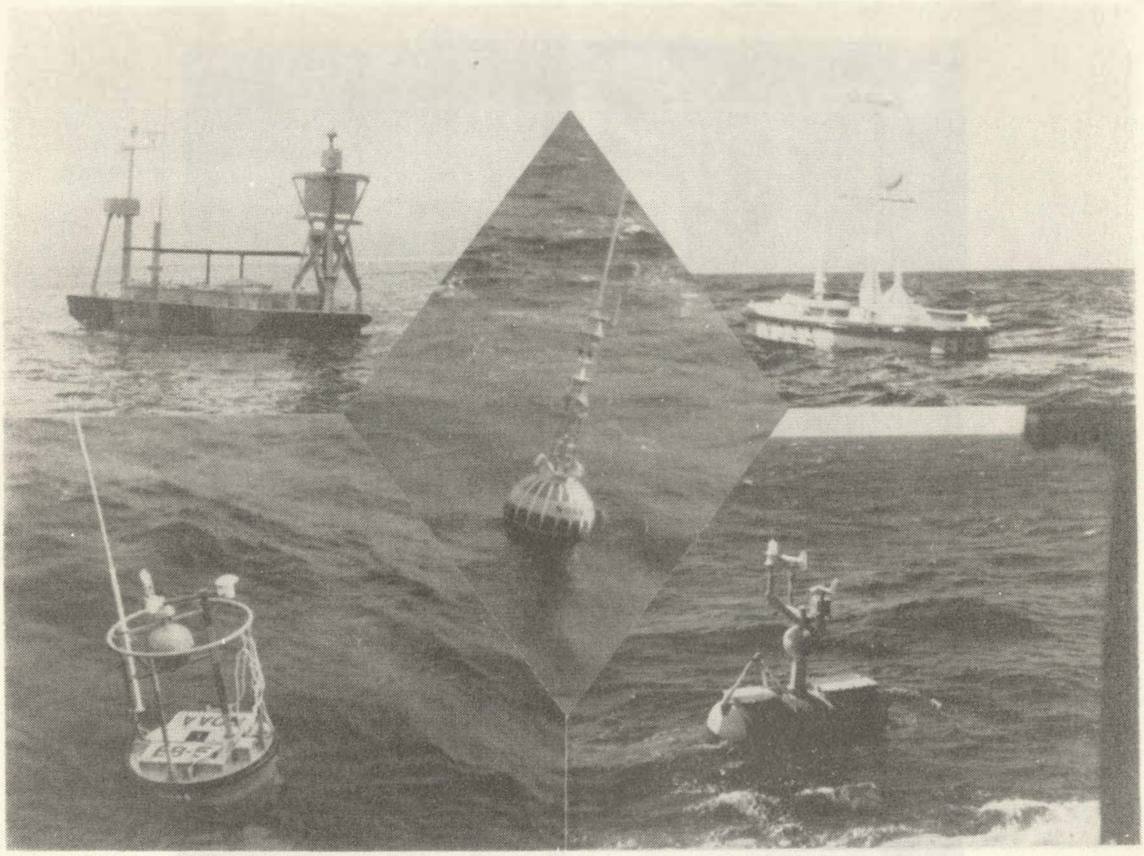
V-3. Single mushroom dropping from gravity tray.



V-4. Gravity tray modified for Navy anchor.

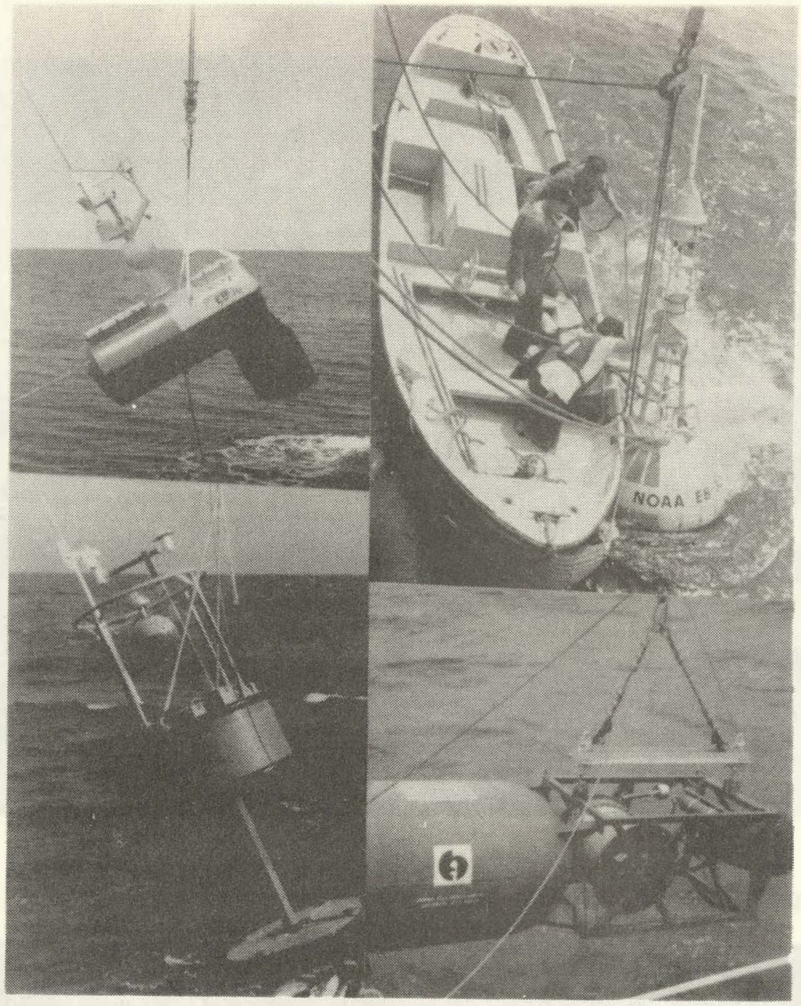


V-5. Anchor drop and chain payout.

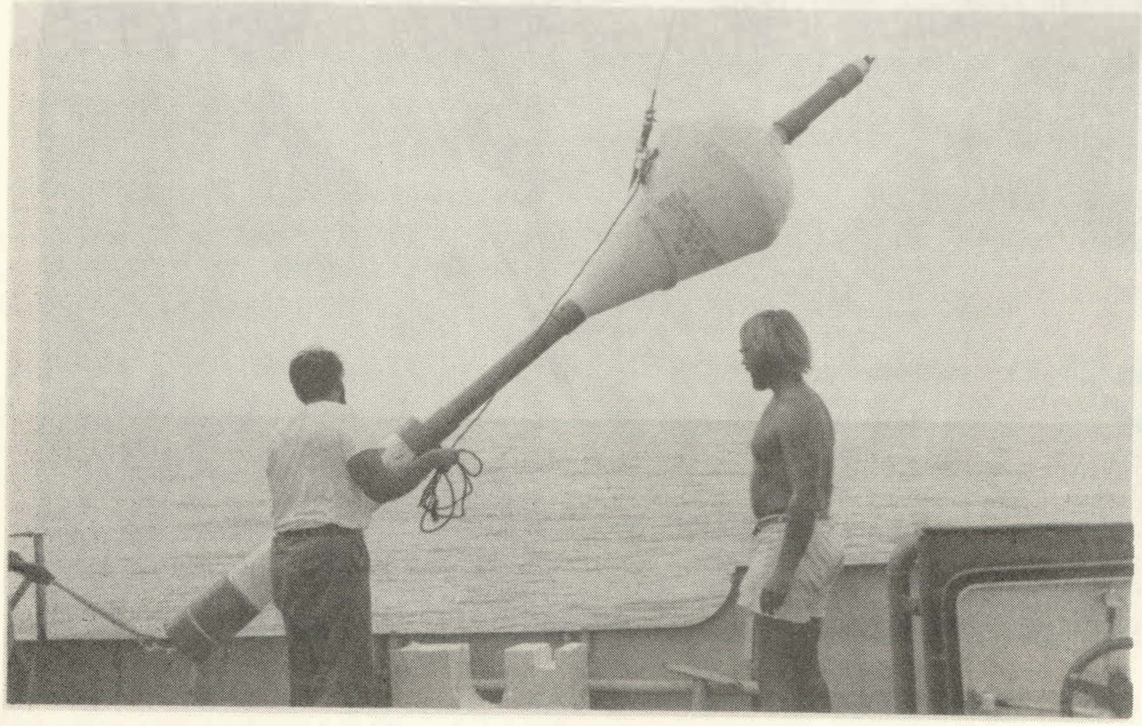


V-6. CONSHELF buoys.

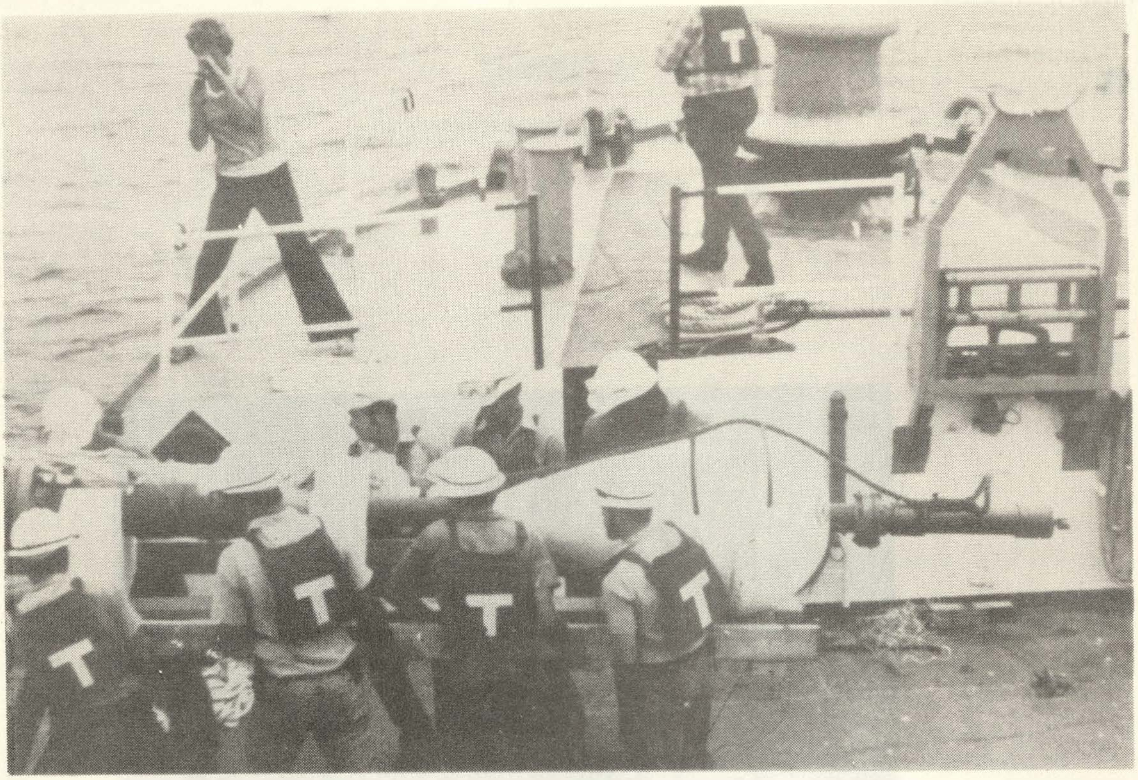
V-7. Transporting of CONSHELF buoys.



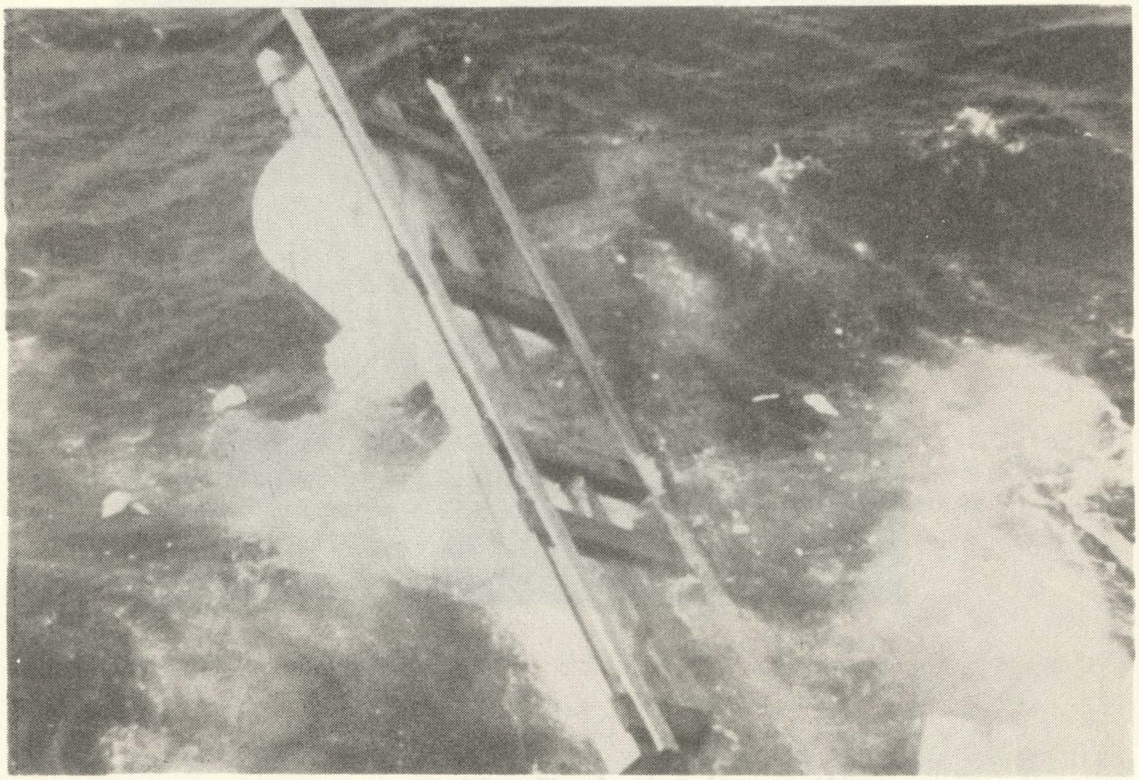
V-8. Deployment of CONSHELF buoys.



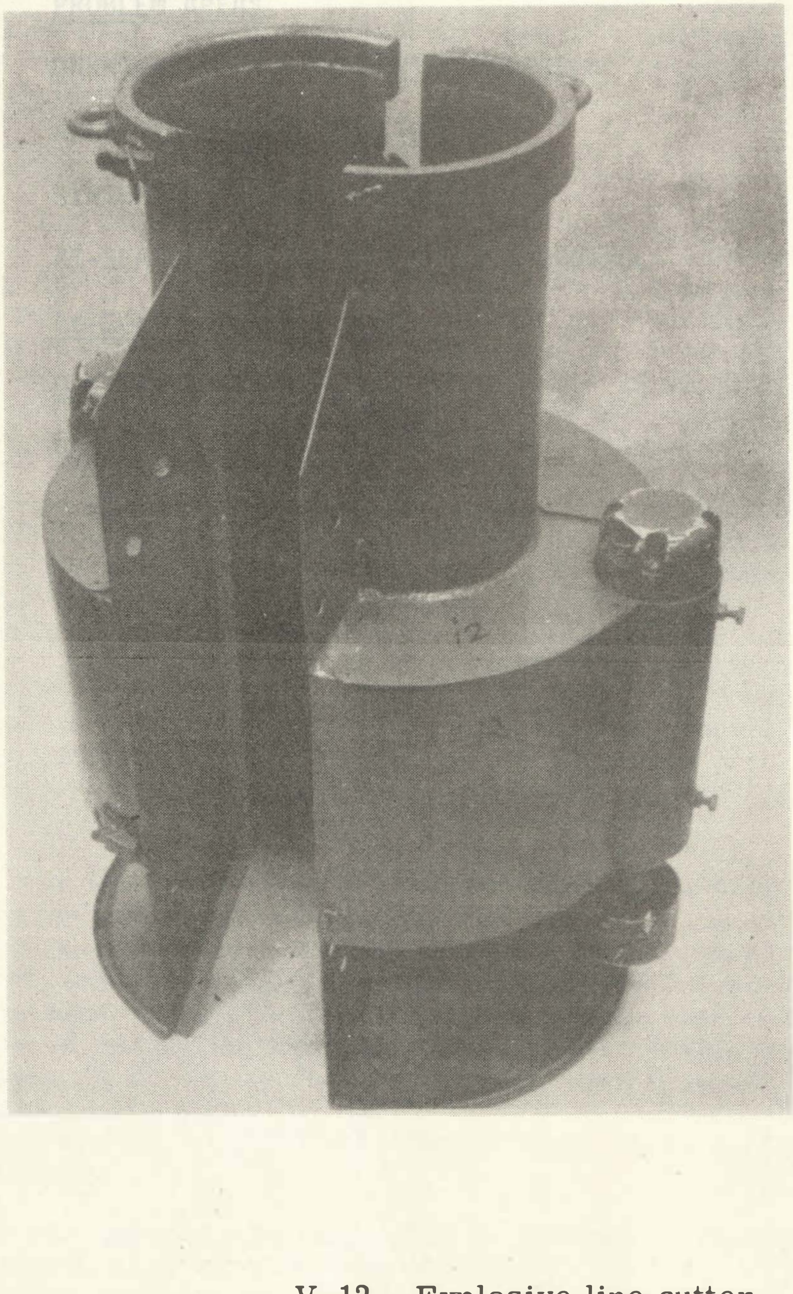
V-9. Sling deployment of drifting buoy.



V-10. Automatic deployment of drifting buoy.



V-11. Release from crate.



V-12. Explosive line cutter.

CHAPTER VI

FUTURE MOORING DESIGNS

CHAPTER VI

FUTURE MOORING DESIGNS

1.0 INTRODUCTION

From the previous chapters, some conclusions can be reached as to what can now be done in designing, deploying, and recovering data buoy moorings. This chapter is intended to tie these capabilities together. It discusses what new developments may lead to improved moorings and what problems remain to be overcome, and summarizes the present status of NDBO mooring design capability.

2.0 NEW MATERIALS

The best hope for major cost and performance improvements in moorings lies in the development of new materials. The synthetic materials which are the present preference of the NOAA Data Buoy Office were largely untested for ocean use as late as the 1960's. The improvements in rope construction which evolved through numerous tests, deployments, and failure analyses now permit the selection of at least three different constructions--plaited, double braided, and parallel fiber--all capable of reliable performance, each with its special mechanical properties.

Today, an aramid fiber, "Kevlar," is undergoing tests of first and second generation constructions. The fiber is similar in strength and elasticity to steel and holds promise as a replacement for wire rope. In ease of handling, it is superior to wire rope. Since it is more flexible, constructions utilizing Kevlar are free of the undesirable torque characteristic of wire rope and are, therefore, not subject to the slack line problems of "hockling" or "bird caging." NDBO tests of this material are scheduled for the near future. When all the properties of Kevlar ropes are understood, it will probably replace wire rope since the mass production now being implemented for the tire industry promises to drive the price down to a level competitive with steel.

In the class of more elastic ropes, a new material, N.F.X., offers a wide variety of elastic characteristics. It is now being fabricated into rope for ocean testing, since its ocean performance characteristics remain unknown. The elongation characteristics are available in a range from near those of rubber to those of the nylon used in rope construction. The choice of characteristics for this material makes it a candidate for the replacement of the synthetics NDBO now uses plus such applications as drogue tethers and shock- or motion-absorbing sections in surface moorings. Since the material is still untested in ocean service, its production costs remain unknown.

For mooring hardware, NDBO is attempting to reduce the corrosion problems associated with the ferrous items--shackles, link, and chain--which are now in use. New coatings, especially those which reduce galvanic corrosion by reduction of cathode area, offer promise of improvement, but corrosion remains the biggest question in the development of a six-year mooring. Materials less subject to corrosion than steel can be used in the production of mooring hardware, but presently these special products greatly increase the hardware costs. This area is a definite candidate for improvement through new materials and possibly new fastening and terminating techniques.

To improve mooring technology, it is essential in new materials that engineers remain informed of the latest product developments and the tests conducted by others in ocean engineering.

3.0 PROBLEM AREAS

It is apparent that problems remain in mooring technology from the high factors of safety which reflect the unknowns in the performance of the rope, the unknowns in the accuracy of the hull/mooring simulation, corrosion problems, unknown environmental forces, and the ever-present handling and quality control problems. Corrosion problems are discussed above and in Chapter IV. The other problems are discussed briefly below.

3.1 UNKNOWNS IN ENVIRONMENTAL FORCES

The lack of definition of the current profile in most mooring locations contributes directly to over-design of moorings. The accurate description of the maximum anticipated design event, which also includes wind and waves, is the governing factor in sizing the mooring line. The profile most frequently occurring at the site is also important, since it determines the typical mooring response and its effect upon the quality of data, especially data from subsurface sensors.

The normal current profile can be determined by more and better measurements. The need for a profile during a design event, such as a hurricane, can be resolved by measurement, but even an analytical method based on wind speed would be a useful tool. Future research in this area would be fruitful.

Waves, wind, and other forces play a role in sizing the mooring, but the degree of approximation of their values is not an important contribution to errors in calculating deep mooring tension. If the environmental forces for a deployment site can be given in the form of probabilities, NDBO can use its hull/mooring model to predict the long-term performance of a buoy and mooring.

3.2 ANALYTICAL APPROXIMATIONS

The problems caused by the approximations in mooring tension forces and motions are largely unknown. The simulation used by NDBO has been a valuable tool for mooring design and is described in detail in Chapter III. Its inaccuracies remain conjecture, since the few comparisons with other unvalidated models show only that there is fair agreement in the results.

The Mooring Dynamics Experiment scheduled for late 1976 should produce the first dynamic data on mooring forces and motions. Comparison of the experimental data with the simulation output should determine whether the accuracy is sufficient for the continued use of the simulation as a design tool. If inaccuracies are found, the data may point out the particular parts of the simulation needing revision.

Experience to date indicates that the simulation in its present deep water configuration may be conservative, since no tension failures or indications of over-tensioning of mooring lines have been found.

3.3 SYNTHETIC LINE PERFORMANCE

The performance of the nylon and polyester (Dacron) line usually chosen for moorings by NDBO has generally been more than adequate. Moorings in place for more than two years have been examined and the synthetic line has been found to have at least as much strength remaining as analysis predicted.

The major problem encountered has been an inability to predict the elongation of the line. This has been further complicated by the use of plaited line in many moorings. This line has a high elongation (as much as 10%) due solely to its construction. Most troublesome, however, is the fact that the elongation of plaited line is not predictable for a given production lot.

To eliminate the uncertainty of plaited line where elongation is of concern, as on instrumented moorings, testing each production run (as discussed in Chapters II and IV) and determining the repeatability of the results is a solution. The use of parallel fiber construction or even double braid will result in more predictable elongation, but even in these constructions, testing should be conducted for accurate prediction.

The elongation of the line may have been beneficial in the many moorings where stretching was not critical. The added length did reduce tension and angle at the anchor, thus adding to the factor of safety in tension and in anchor holding.

Solution of the elongation problem as discussed above is attainable and few other synthetic materials problems have been encountered. The fishbite problem is covered in Chapter IV and in the "Deep-Sea Lines Fishbite Manual," NDBO, 1976. The only other important problem, vulnerability of the line to chafe, is avoided by keeping the line off the bottom as discussed in Chapter II. Chafe within metal thimbles can be eliminated by proper splicing, as stated under quality control, below.

3.4 AT-SEA OPERATIONS AND QUALITY CONTROL

In the production and operation of any item, the human factor presents its own unique problem and moorings are no exception.

3.4.1 At-Sea Operations

Seamanship in the deployment and retrieval of the mooring is well covered in Chapter V. It is sufficient to say here that the practical aspects of handling the buoy cannot be neglected in any phase of the design. The basic consideration has been that the mooring will be handled by a ship-of-opportunity and the mooring designed accordingly. In those few cases where new techniques have had to be tested on the USCGC ACUSHNET, a dedicated vessel, every effort has been made to qualify these procedures for use by less experienced crews. In this respect, all engineers involved in mooring design must have mooring deployment and recovery experience. A system of design feedback should be maintained for those cases in which the designer is not present at sea. The real solution to the handling problem is the reduction or elimination of handling at sea. This should be done by completing all mooring assembly and adjustments under controlled conditions ashore. The effort in this direction should be continued so that the simpler and safer mooring system discussed in Chapter V can be achieved.

The deployment of a safe and simple mooring by a single lever is an achievable goal.

3.4.2 Quality Control

In general, the quality control in the assembly of moorings has been very good. Since a mooring may be deployed for up to six years, and since there is no opportunity for in-service adjustments, only the highest level of quality control is acceptable.

To date, there has been one mooring failure due to a loose eye-splice chafing on a thimble, one near-failure for the same reason, and one failure possibly attributable to this cause. These are definitely traceable to inadequate quality control. The solution to the quality control problem is to properly specify the desired job, train the personnel to perform the job, and adequately inspect the completed work. This is not unique to moorings. Attention to detail is important in all manufacturing, but in buoy moorings, any failure causes complete system failure.

4.0 CONCLUSIONS

This handbook represents the state-of-the-art at NDBO. A three-year deep-moored life for large buoys is a reality and a six-year mooring design is possible with good attention to design details and proper quality control.

With the mix of materials presently proven in moorings, it is possible to design for a variety of performance characteristics. The use of synthetic line, chain, and either wire rope or Kevlar can produce moorings which range from extremely taut (for minimal watch circle) to slack and elastic, which will attenuate wave forces over a minimal length and reduce tension.

Cost has not been discussed in detail, not because it is considered unimportant, but rather because both absolute cost and costs of one mooring component relative to another have varied greatly over the last three years. The oil crisis produced a peak in synthetic line prices which could recur. Sources of surplus anchors and chain have led to the use of Navy special anchors and large stud link chain primarily on a cost basis. Like all good designs, the mooring design represents the lowest-cost version which will safely do the job. When it has been necessary to make a tradeoff in mooring performance or safety, the additional costs of alternatives have been compared to total cost of the buoy system and not just to the mooring costs. Total cost is a more valid decision criterion when failure represents the loss of the entire system.

Achievements to date have taken large buoy moorings from the early uncertainties in all phases of design, performance, and handling to fully proven hardware. Thus, the accomplishments of the past can serve as a prelude to the needs of the future. It is the philosophy of simplicity of design and ease of handling that is important.