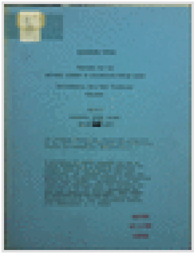


Background Papers: Prepared for the National Academy of Engineering Marine Board Environmental Data Buoy Technology Workshop (1973)

Pages
337

Size
8.5 x 10

ISBN
0309341795

Marine Board; National Academy of Engineering

BACKGROUND PAPERS

PREPARED FOR THE

NATIONAL ACADEMY OF ENGINEERING MARINE BOARD

ENVIRONMENTAL DATA BUOY TECHNOLOGY WORKSHOP

HELD AT

KINGSTON, RHODE ISLAND

26-29 [redacted] 1973

JUNE

The Workshop Session was financially supported by the Office of Naval Research and the National Oceanic and Atmospheric Administration

A collection of papers prepared for use as source documents in a workshop examining the present state of environmental data buoy technology. The workshop was held under the auspices of the National Academy of Engineering Marine Board (NAEMB). Recommendations and conclusions emanating from this workshop are contained in the NAE report Directions for Data Buoy Technology 1978-1983. This report is available from the NAS-NAE Printing and Publishing Office, 2101 Constitution Avenue, N.W., Washington, D. C. 20418

INTRODUCTION

This collection of background papers on environmental data buoy technology is available as a supplement to the NAE report, Directions for Data Buoy Technology 1978-1983. The report itself was prepared under the auspices of the National Academy of Engineering.

The background papers served as source documents in the workshop which led to the final report. Each paper is wholly the work and the responsibility of its author(s), who are all invited scientists and engineers with expertise in areas which the Steering Committee felt should be investigated at the workshop session. The papers are made available as reference information for those concerned with specific problems addressed in the report.

PANEL/WORKSHOP STEERING COMMITTEE

In April 1972, the Marine Board Panel on Buoy Technology Assessment was established for the purpose of developing and promulgating advice on environmental data buoy technology. The NOAA Data Buoy Office, the Office of Naval Research, the U. S. Coast Guard, and the National Science Foundation, were among the members of the marine community served by the Panel. Those involved in the direction of the Panel agreed that a workshop session was needed to synthesize and analyze the buoy technology base, identify deficiencies, and make recommendations for corrective action. Specifically, Panel members and workshop participants agreed to:

- Review and summarize the present state of data buoy technology
- Recommend programs to meet future requirements of users, with particular attention to increased reliability, stability of

measurement, reduction of self-noise, and reduced cost of operation

The Panel/Workshop Steering Committee established three basic ground rules for the Buoy Technology Workshop:

- Consideration of environmental data buoys in terms of shallow and deep application, moored or drifting mode, and synoptic or scientific data requirements
- Assumption of a need for environmental projection, military operations, and scientific project support
- Time-frame limitations: 1973 as reference year and 1978-1983 as projection years

Further, Workshop participants were to address several specific questions which simultaneously limited and gave direction to their mode of operation:

- What unknowns about the capabilities of current buoy systems must be documented in order to project corrective actions with regard to long-term reliability, as well as opportunities for reduced costs in construction, testing, operations, and maintenance?
- What identifications are presently lacking but requisite in order to understand specific relationships among system components, and between systems and the environment?
- What technical innovations exist now, or are within reach, that offer significant potential in areas of increased capability (i.e., duty cycle), increased reliability, and reduced costs?

- What steps should be taken to ensure specific goals? For example: credibility of data obtained, and interchangeability of data among users.

THE WORKSHOP

Participants arrived at the University of Rhode Island, Kingston, Rhode Island, on Monday evening, 25 June 1973. A brief meeting of all participants was held Tuesday morning, at which discussion centered on "Why Buoys are Necessary for the National Program." Following this general session, the participants adjourned to their assigned work groups; *viz.*:

- Systems (Test and Evaluation)
- Hydro/Mechanics
- Mechanical/Hydraulic Components (Hardware)
- Electronics/Sensors
- Implantation

Each work group was to complete a set of conclusions and recommendations, with priority assignments and cost estimates, by the end of the workshop.

Workshop participants also divided into three groups to discuss the MODE-1 Case Study, and came together as a unit to discuss the North Pacific Case Study. These case studies were prepared exclusively for this workshop.

During the Tuesday and Wednesday sessions, the five work groups met in individual sessions, endeavoring to reach agreement on the conclusions and recommendations to be submitted in their subject area for use in the final report. On Thursday, the work group members began their write-ups, and during an evening general session, the work group chairmen presented their groups' conclusions and recommendations.

During the final session of the workshop, held on Friday, 29 June 1973, the Chairman of the workshop presented the integrated conclusions and recommendations of the workshop, followed by discussion among the participants. The work group chairmen then finalized their write-ups.

The conclusions and recommendations of the individual work groups provided a primary input for the Panel's integrated Summary Conclusions, as delineated in the NAE Report.

PARTICIPANTS IN THE WORKSHOP ON ENVIRONMENTAL DATA BUOY TECHNOLOGY

Ledolph Baer *
Henri Berteaux
Kenneth Bitting
Thomas Blockwick *
J. E. Bowker *
Peter Branson
Hin Chiu
Ray Canada
Robert J. Cassis, Jr.
Robert Corell
J. M. Coudeville
Scott Daubin *
Robert Devereux *
Robert Dickenson
David Dillon
Melvin Folkert
Edward Geller
Theodore P. Goodman
John B. Gregory *
Peter Grose
Frank Haas
Dean P. Haugen
Dan Hoffman
Layne Livingston
W. A. Lucht
Edward MacCutcheon
Nicholas Marechal
Jerome Milgram *
Ronald Morey
Lawrence Murdock *
John Nath
C. S. Niederman
H. A. O'Neal *
Denzil Pauli
Robert A. Peloquin
David Price *
Dan Ross *
Godfrey Savage *
Herbert C. Schreiber, Jr.
Herman Sheets *
Dale Siegelin
Graham Smith
Bob Snyder
Paul B. Stimson
Wilton Sturges *
Richard Swenson
John Van Leer
Karl Vesper
James Winchester *
G. W. Withee
Roy Woodle
Hal E. Wyeth

* Steering Committee

CONTRIBUTORS

George Brown
Theodore P. Goodman
Edward Kolbe
Lester LeBlanc
Walter Lincoln
Clifford Petersen

GENERAL CONTENTS OF BACKGROUND PAPERS*

Part | Page

I. *Systems Technology Assessment*

Withee, G. W., and L. H. Clem. Programs to Evaluate Total Observational Error and Its Components in Environmental Data From Ocean Buoys 1

II. *Hydro/Mechanical Components*

Haugen, D. P. Power Systems for Buoys 17

Morey, R. L. Present and Future State of the Art, Materials and Design of Buoy Structures 25

__________., and H. O. Berteaux. Alleviation of Corrosion Problems in Deep Sea Moorings 75

Niederman, C. S. State of the Art and Future Projections in Buoy Mechanical Technology. 89

Ross, D. Buoy Power 99

Smith, G. Hardware Components of Automatic Mooring Devices 121

---

* Prepared by invited experts as a basis for discussion and development of recommendations by the participants at the workshop. These papers are available from the NAE Marine Board as supplements to this report.

Part | Page

III. *Hydro/Mechanical Modeling and Testing*

Nath, J. H. Basic Problems in Mathematical Analyses of Mooring Cable Hydrodynamics and Structural Dynamics........ 137

Snyder, R. M. Free-Fall Anchoring Systems.................................. 147

IV. *Electronics/Sensors*

Cassis, R. H. State of the Art of Data Buoy Sensor Systems Technology.......... 155

Folkert, M. B., and R. V. Woodle. Status of Environmental Sensing Systems for Unattended Ocean Buoys.................. 161

Livingston , T. L., and P. L. Grose. State of the Art in Data Handling, Communications and Processing for Environmental Data Buoys........................ 177

Siegelin, D. W. Present Capabilities to Determine Deployment Position, Operational Position and Reference Direction for Buoy Systems....................... 213

Van Leer, J. Buoy Deployed Profiles...... 231

V. *Deployment*

Flanders, W. M. NOAA Data Buoy Operations Support.................................. 237

Snyder, R. M. On the Problem of Implanting Complex Systems at Sea.................. 249

Part | Page

VI. *Data Buoy Capabilities*

A Graphic Inventory of Existing Environmental Data Buoy Capabilities, consisting of linear sketches and tabular materials; based on information received by the Panel on Buoy Technology Assessment, from the Office of Naval Research and the NOAA Data Buoy Office............ 295

VII. *Engineering Case Studies* (Available Separately)

Kolbe, Ed., under the direction of R. W. Corell and G. H. Savage, and in consultation with Karl H. Vesper. MODE-1, An Engineering Case Study of the Moored Ocean Systems. Parts 1 & 2. Prepared for the Marine Board of the National Academy of Engineering. Workshop on Buoy Technology Assessment. The University of Rhode Island. 1973.

Lincoln, W. B., and H. A. O'Neal, under the direction of G. H. Savage, and in consultation with Karl H. Vesper and H. A. O'Neal. The North Pacific Study, An Engineering Case Study of Ocean Environmental Data Buoys. Prepared for the Marine Board of the National Academy of Engineering. Workshop on Buoy Technology Assessment. The University of Rhode Island. 1973.

PROGRAMS TO EVALUATE TOTAL OBSERVATIONAL ERROR AND ITS COMPONENTS IN ENVIRONMENTAL DATA FROM OCEAN BUOYS

by

G. W. Withee and L. H. Clem

NOAA Data Buoy Office
Mississippi Test Facility
Bay St. Louis, Mississippi 39520

NOAA DATA BUOY OFFICE

PROGRAMS TO EVALUATE TOTAL OBSERVATIONAL ERROR AND ITS COMPONENTS IN ENVIRONMENTAL DATA FROM OCEAN DATA BUOYS*

G. W. Withee and L. H. Clem

1. INTRODUCTION

High quality marine atmospheric and oceanographic data are needed by environmental data users around the world. These data will be supplied in part by data buoys which automatically measure and report marine environmental data. The NOAA Data Buoy Office (NDBO) of the National Oceanic and Atmospheric Administration (NOAA) has the mission to design, develop, test, and evaluate these data buoys. In order to develop a buoy that will satisfy the data user's needs for high quality data, the NDBO has begun programs that will identify, evaluate, and, if necessary, reduce potential system errors in the data prior to the delivery of the data to the user. As used in this report, the system errors are defined in terms of a total observational error and its components.

The following sections present some of the effort that NDBO is making in this area. The definition and identification of the components of total observational are discussed in Section 2. The evaluation of these errors, particularly using a Measurement Comparison System (MCS) and a data error simulation program are specifically detailed in Section 3. Some applications of these error investigation programs are briefly summarized in Section 4.

2. DEFINITION OF OBSERVATIONAL ERROR AND ITS COMPONENTS

The total observational error** in the data for any environmental measurement platform has been defined. It is the difference between the reported value of the parameter as received

* In part, this paper is compiled from abstracted material from References 1, 2, and 3. In general, the detailed questions arising from this paper can be answered by referring to these references. This paper was prepared for the National Academy of Engineering Buoy Workshop, June 25-29, 1973.

** The above definition of the observational error is carefully defined for the data user as well as the engineer. From the user's point of view, this error can be evaluated by performing a sensitivity analysis to determine his maximum acceptable error and the desirable error value for his use. The maximum acceptable error in the input data should be the highest value at which his use or model still produces meaningful results. The desirable error is that low value at which the model outputs cease to become appreciably better, even if the value of the data error were reduced further. This is frequently considered to be the design goal. Of course, many other considerations can influence the data user's needs, such as cost, future requirements, and recognized state-of-the-art.

by the user, and the true value as it existed in the medium where the measurement was supposed to have been located in time and in space. The term "error," as defined in this way, can have multiple meanings. The preceding definition implies that the true value of an environmental parameter is known or can be measured. Since this is not the case, the definition of error includes a measure of uncertainty and is usually given in terms of some statistical measure (e.g., standard deviation).

The NDBO has attempted to evaluate the user's data needs in terms of the above definitions. for observational error, and is in the process of designing or redesigning ocean measurement systems to meet these user needs. This process requires the evaluation of the components of total error as discussed below.

For many applications -- particularly in the area of data measurement system design -- the individual components of the total observational error must be identified, defined and evaluated, and in addition, their contribution to the total error must be determined. The following component errors are particularly defined for an ocean measurement platform, but many can be applied to any environmental data measurement system.

Static Instrument Measurement Error: This is the residual error that remains after calibrating an instrument in a nonchanging environment. This error is determined in a laboratory under controlled conditions for all values of the parameter over the desired measurement range.

Dynamic Measurement Error: This error arises because the dynamics between the instrument and environment can cause instruments to read incorrectly. This includes that error resulting from the induced motion of the sensor due to buoy motion. Dynamic measurement error also includes the effect of the dynamic response of the instrument, or the inability of the instrument to respond completely within the required time period to all environmental changes.

Physical Disturbance Error: This error results when the superstructure of the buoy (or subsurface data line) distorts the true value of the continuous environmental parameter. Even if there were no environmental changes occurring, and all other component errors in the buoy system were zero, the possibility for a physical disturbance would still exist. Examples of this error include: vortex shedding about a buoy mast causing an artificial reinforcement or reduction in the value of the wind at the wind sensor; the buoy platform itself, because of its size and weight, interfering with the ability to measure short wave periods; the convected and radiated heat of the buoy hull causing errors in air temperature measurements.

Data Manipulation and Processing Error: Every time data are transferred, stored, retrieved or digitized, there is the possibility of data distortion. For example, during an analog-to-digital process, an error in time and/or a bit error can occur. Further, a limitation in the number of bits in each data word can reduce the accuracy of any measurement.

Transform Error: This error results if the user's parameter definition is different from the definition of the environmental parameter as measured. More explicitly, the device to translate the continuous environmental parameter into what the user desires is referred to as the transform. The difference between the value resulting from using the desired transform and the value resulting from an actual transform used aboard the buoy is the transform error. For example, suppose a user desires a sixty-minute average constructed from continuous air temperature measurements. The buoy system may be able to provide only a twenty-minute average based on 120, ten-second values of air temperature. Thus, there could be an error in the resulting buoy data due to the discretely sampled twenty-minute average (actual transform) being different from the continuously samples sixty-minute average (desired transform). The difference is a function of the natural variability of the environment, as discussed in Reference 4. An additional type of transform error occurs when conductivity is measured even though salinity is desired. The ability of a transform to translate conductivity, sea temperature, and depth into salinity is a measure of this type of transform error.

Dislocation Error: This error is composed of the errors resulting from: (1) The horizontal and vertical dislocation (due to ocean currents, waves, weather, and imprecise navigation) of the sensor from its intended geographical location; and (2) The temporal dislocation of the sensor measurement from the time of intended measurement (the synoptic time).

The errors identified above and possibly others, combine to form the total observational error. The values of the component errors that lead to the total error and their functional relationships to the total error must be considered if a reduction in the total error is required to meet user needs. Also, the determination of the functional relationship between the component errors and the total error can provide a basis for considering new buoy designs. Further applications will be discussed in Section 4. The next section discusses two NDBO programs that will assist in the identification and evaluation of the total observational error as well as its components.

3. EVALUATION OF THE TOTAL OBSERVATIONAL ERROR AND ITS COMPONENTS

The need to evaluate the total observational error and its components identified in Section 2 established the basis for NDBO data quality programs. A consolidation of NDBO data quality programs was compiled by the principle author and is discussed in Ref. 5. These programs also provide a rationale for improving data accuracy in the event it is unacceptable. The following two principle NDBO data quality programs, which attempt to evaluate errors in in the data from an oceanic measurement platform, will be discussed: The at-sea comparison or "ground truth" measurement program, and the data error simulation program.

3.1 At-Sea Measurement Comparison Program

An actual at-sea evaluation of buoy data is necessary in addition to the usual instrument calibration and checkout before and after buoy deployment. The basic premise of the need for environmental field comparison tests is that laboratory calibrations are inadequate. No matter how accurate and repeatable the buoy sensors prove to be during laboratory calibrations, the motions of the oceanic platform and the physical disturbance of the environment set up by the buoy itself may cause sensors to read differently from the values that would otherwise prevail in the laboratory or in an unobstructed environment. This at-sea evaluation can be done in part by comparing the buoy data to meteorological weather maps or other observations near the area. Eventually, however, if the buoy measurements are to be accepted by the data-using community, comparative data must be taken by high quality reference instruments very close to the platform at sea.

The instruments and equipment for the comparative measurement program at NDBO are: standard meteorological and oceanographic sensors that are typically used aboard a ship for research purposes; meteorological and oceanographic sensor comparators that are the exact buoy instruments packaged in a portable manner; and a stable Measurement Comparison System (MCS) capable of accurately measuring wind speed and direction, air temperature, air pressure, waves, and sea temperature. Figure 1 is a diagram of the MCS. Figure 2 is a picture of the MCS at sea. The MCS has been completed, tested, and delivered to NDBO by the Lockheed Ocean Laboratory, San Diego, California. The MCS has been subjected to a number of tests to date, and further testing and calibrations are planned during the next several months. Those tests which have been conducted so far, however, have satisfied us that the MCS performs up to the high in situ accuracy standards which were hoped for in most cases. A seeming paradox exists, of course, in the fact that it is virtually impossible to verify the in situ accuracy of the system -- the very job which the MCS is designed to accomplish for other systems. However, by identifying and minimizing all components, both within the system and environment that contribute to the total error, one can be confident that the system is providing accurate data. All information regarding the MCS is contained in the overview discussion in Reference 3 and the comprehensive discussion of its characteristics, performance, and application in Reference 4.

Using the above equipment, particularly the MCS, some of the error investigations that are planned include the following:

Physical Disturbance Error

- Determine structural effect on wind measurements.
- Determine effect of buoy radiation and convection on temperature readings.
- Determine effect of platform on wave measurements.

Dynamic Measurement Error

- Determine dynamic error on wind velocity measurements.

Transform Error

- Check transform calculations by independent instruments where possible. For example, use Nansen or properly calibrated STD casts in the evaluation of the salinity/conductivity transform.

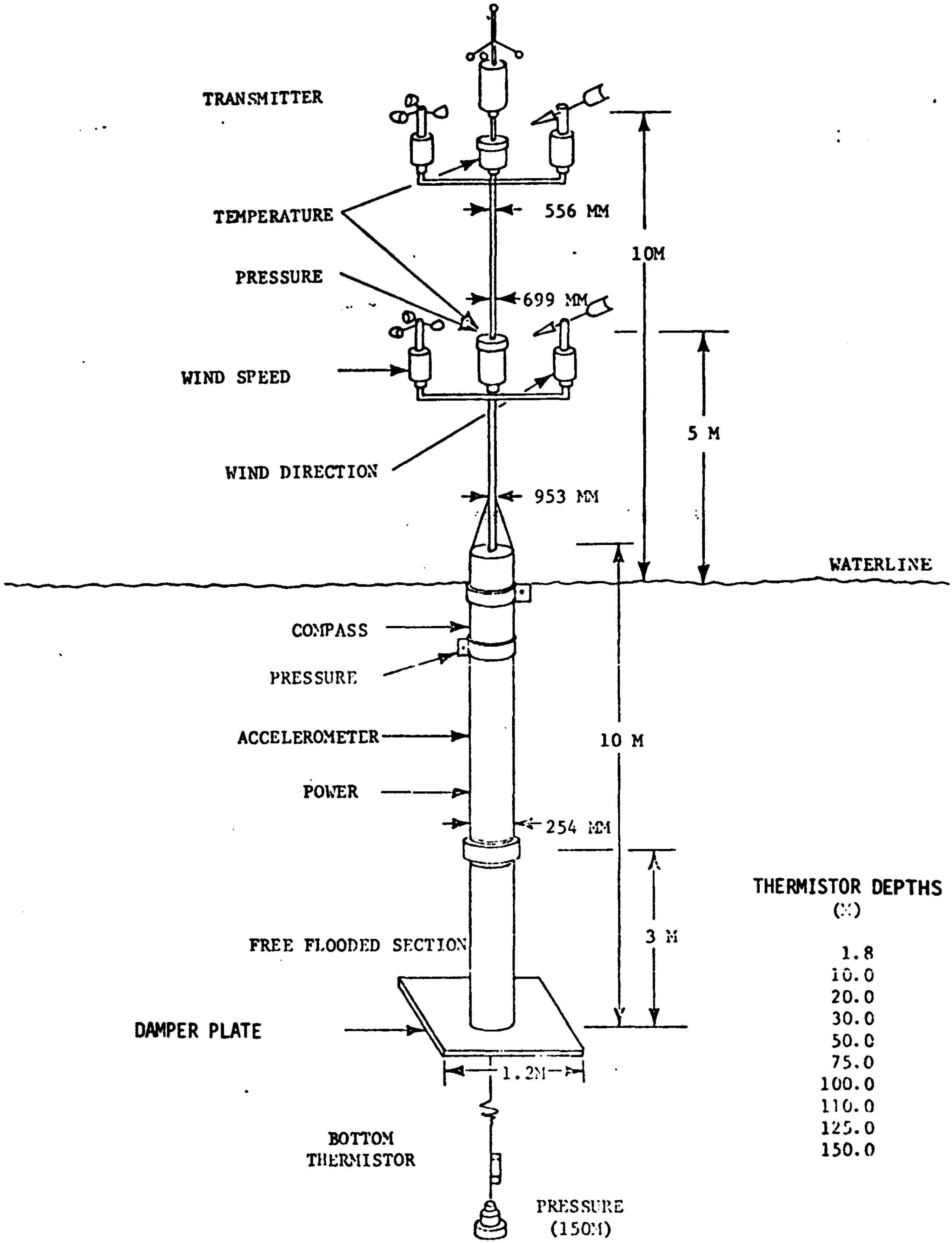


Figure 1. An Artist's Conception of the Measurement Comparison System Platform

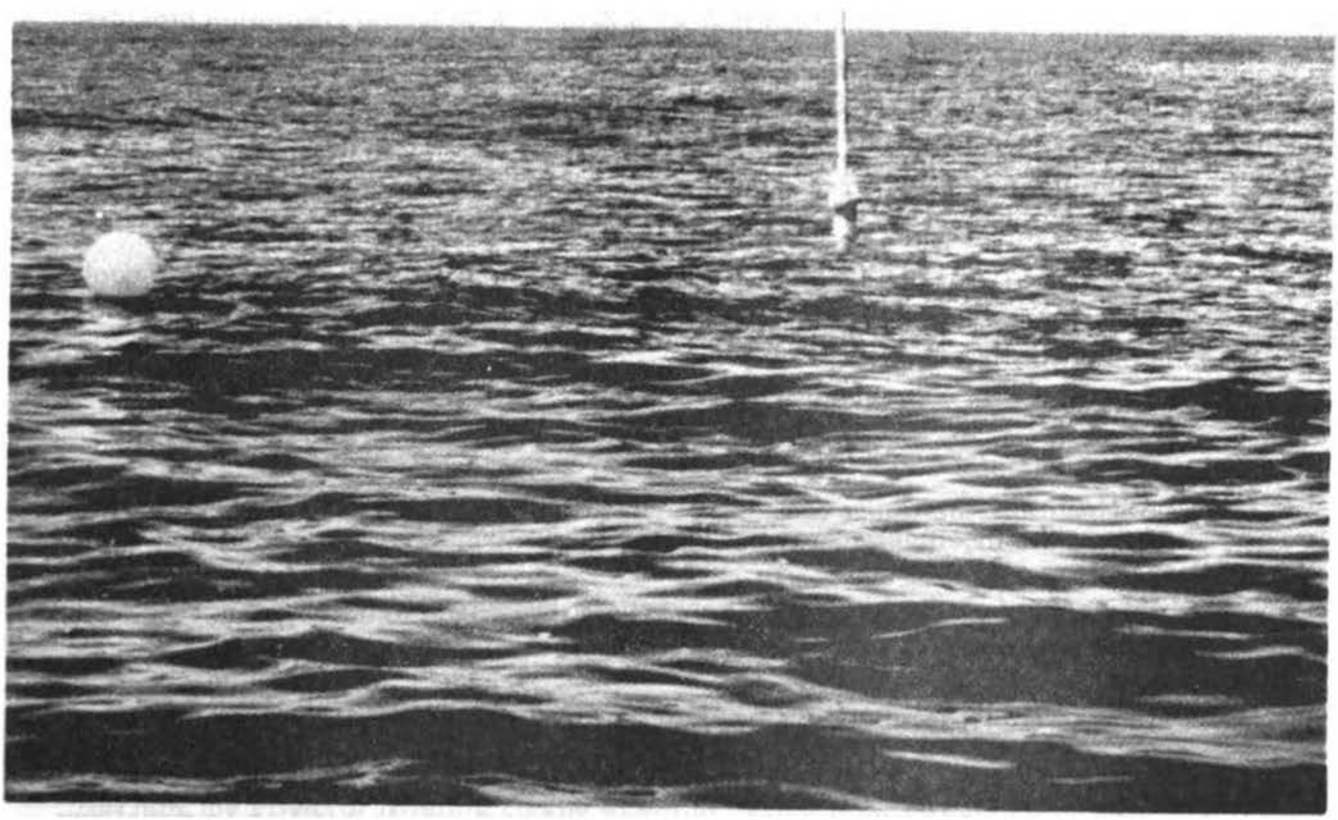


FIGURE 2. THE MEASUREMENT COMPARISON SYSTEM AT SEA

Dislocation Error

- Determine errors in vertical and horizontal space due to spatial gradients.

The need of the at-sea measurement comparison experiments is clear. However, these experiments are limited in that they cannot easily evaluate error values over the desired full range of environmental conditions. For this reason, and others to be discussed, it is necessary to have a computer program to simulate the error components and the total error for any desired environment. The error estimates of the simulation program can be validated by the limited environmental range of data from the measurement comparison experiments and hopefully extended for the full range of environmental conditions

2.2 Data Error Simulation Model

Estimates of error component values in the data from NDBO's forty-foot discus buoys have been estimated theoretically and to some extent, empirically (see referenced documents 7, 8, 9, 10, and 11. The results in these documents suffer from the fact that although one error component may be easy to evaluate, its effect on the total error may not be clear. In fact, the total error is most likely not the simple sum (or the square root of the sum of the squares) of the component errors. Thus, a mechanism had to be found to evaluate the total observational error and its relationship to its component errors.

Computer simulation technology provided that mechanism. A computer simulation provides a practical, useful solution to measurement error analysis and data quality evaluation, and easily handles static, dynamic, and correlated error sources. A simulation of this type can include the interactive effects on the data of all buoy subsystems. This interaction has been found to be crucial in modeling a buoy system. Thus, a Data Error Simulation Model was developed.

The Data Error Simulation Model developed provides a mechanism for evaluating data quality for both the data user and the system designer. To accomplish this, the error simulation must perform the following functions.

- Model the natural variability of the true environment.
- Represent the inherent accuracy of the sensing instrument.
- Simulate the dynamic interaction between the measurement system and the environment.
- Determine error contributions from data sampling and processing.

The error simulation developed accomplishes the above functions. In addition, a model was developed to simulate the long-term variability of buoy drift within the watch circle and the dislocation errors resulting from movement of the sensor through vertical and horizontal gradients. The error model has been structured as shown in Figure 3. The generation of dynamic variables, the error simulation, and the error analysis blocks represent separate generalized programs that can be exercised independently as required. The error models and measurement system parameters provide configuration data to simulate particular sensors and measurement systems. Design parameters represent instrument performance and buoy configuration. Control parameters represent sampling rate, sampling duration, and synoptic data reporting intervals.

The error components which form the total system error are simulated using individual error models for each component. These models are parameterized by dynamic variables which are a function of the environment and platform motion, design parameters, and control parameters. Because of the parameterization, the error models are generalized and can thus represent various environmental variability conditions and buoy configurations. Uncertainty in deterministic and in random error components are introduced into the total system error by the use of random numbers as error model parameters. Dynamic errors can be separated from static errors in analyzing the total system error. The error models are programs kept in a program library which can be updated or modified without affecting the main simulation program. Each can be called by the main program either separately or in any desired combination. A detailed description of the error models and the simulation program is contained in Reference 12. The error models and the simulation program were developed in FORTRAN IV and are accessed through an interactive time-share terminal. Data from these programs are retained as computer files and are available for various types of statistical analyses.

Various types of error analyses can be performed using the error simulation output statistics on variability of measurands, error components, and total system error. These include:

- Determination of dominant error components under particular environmental or operating conditions.
- Error budget analysis for allocation of allowable error to instrument errors, dynamic effects, or sampling error.
- Analysis of total error sensitivity to dynamic conditions, instrument parameters, buoy configuration and sampling method.
- Comparison of one sensor or buoy component against another.

Figures 4 and 5 illustrate outputs from the error analysis model and exemplify how the above analyses can be presented. Figure 4 exemplifies how clearly the error model output would display the dominant error sources as well as an error component budget. Figure 5 exemplifies how the effect of filtering can be shown to reduce total instantaneous error. In a real output, these filtering effects would reflect the frequency distribution of the variability of the natural environment. Error results from the error simulation model have been published for the meteorological measurements made from a forty-foot discus buoy. Although these results require too much explanation for this report, they can be found in Reference 12.

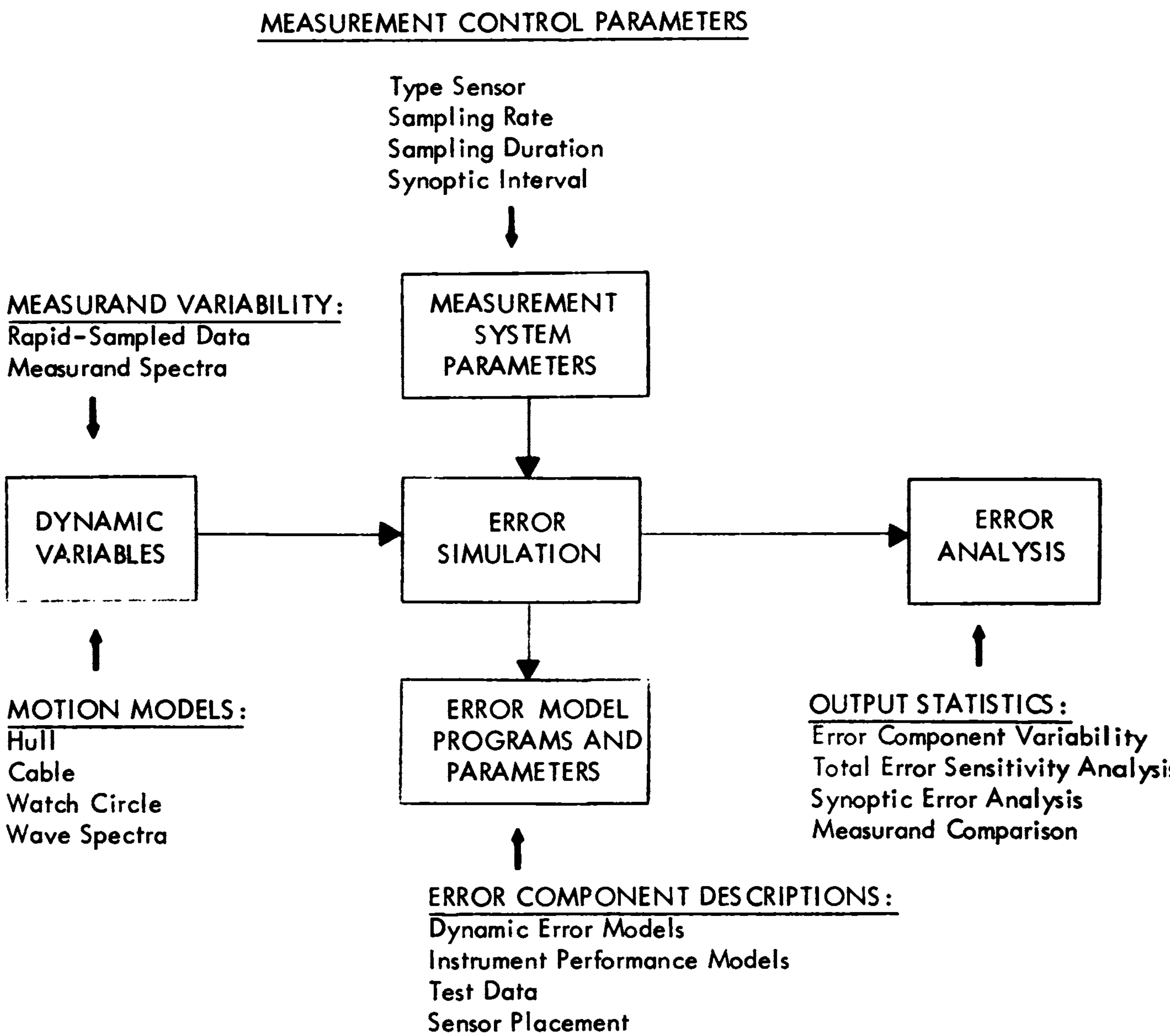


FIGURE 3. Data Error Simulation Program Structure

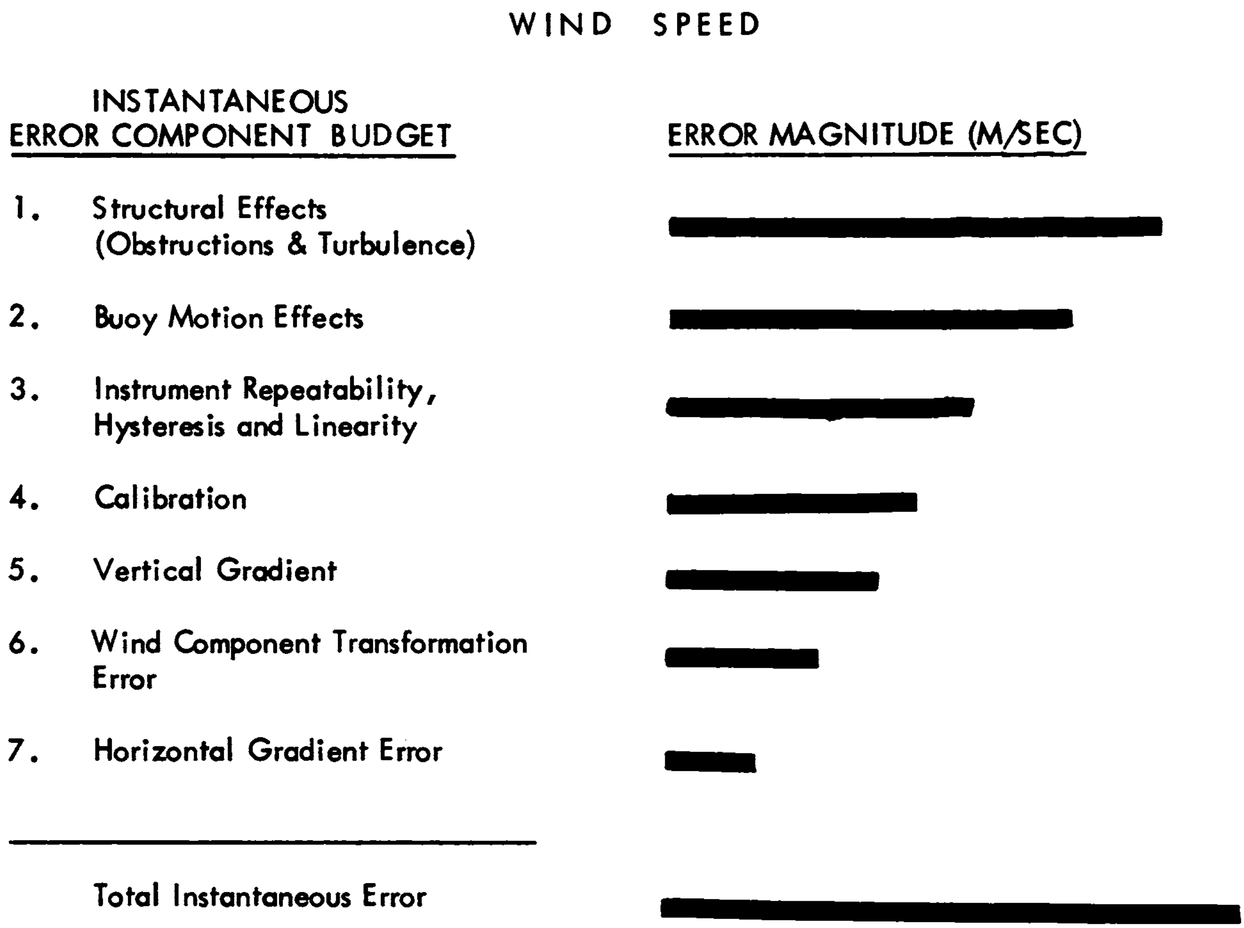


FIGURE 4. Diagrammatic Example of Instantaneous Error Budget for Wind Speed, Such as Would Be Calculated from the Data Error Simulation Model

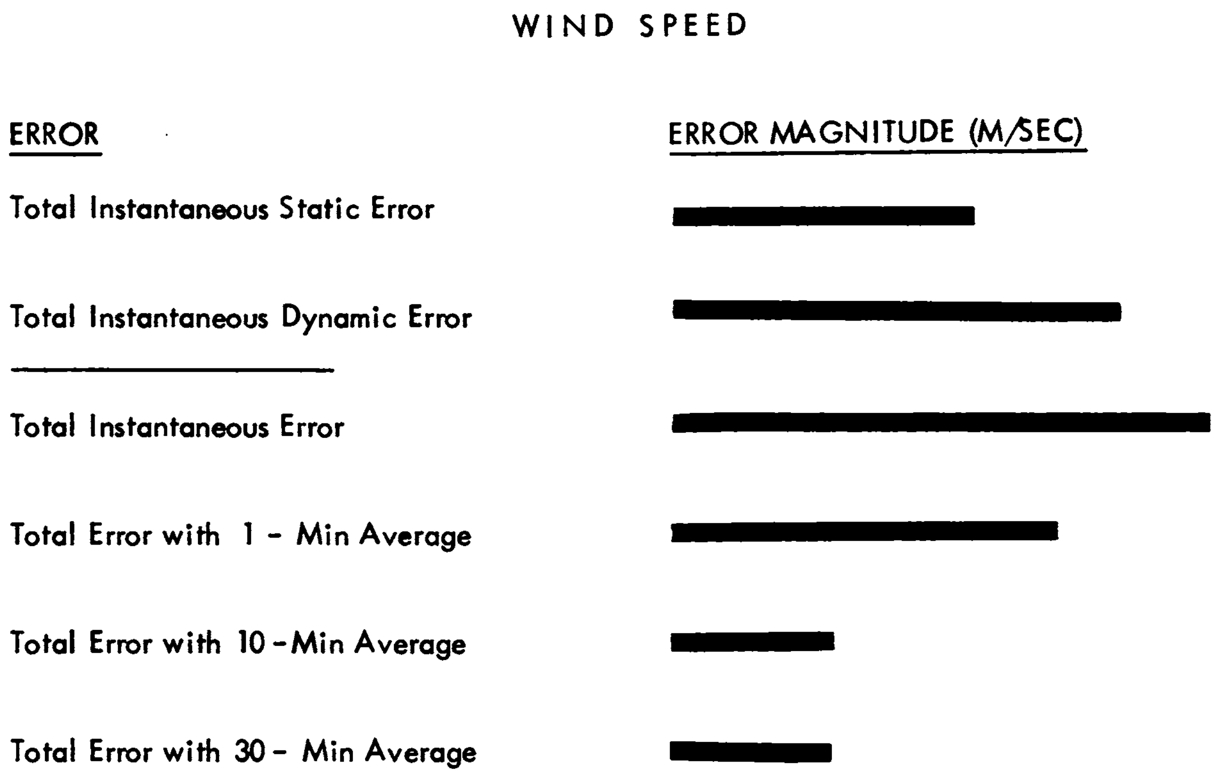


FIGURE 5. Diagrammatic Example of Total Error Budget Including Filtering for Wind Speed, Such as Would be Calculated from the Data Error Simulation Model

The error component statistics, as exemplified for Figures 4 and 5, can be inputted to a further analysis program. The outputs of this analysis are histograms of error component distributions, frequency spectra of error components, and total errors for various averaging and sampling periods. Measured distributions are also calculated.

4. APPLICATIONS

The determination of the total observational error in environmental data obtained from ocean measurement platforms has a direct use in itself. The determination will establish for the data user the confidence he may place on the data.

However, these programs for determining error components and total error have other significant applications. Suppose the total error is large and is not acceptable to the user. By having a simulation program which implicitly relates a component error to the total error, it is possible to establish which error component, or series of error components need to be reduced in order to achieve a certain acceptable total error. Consideration of cost or other program impacts can easily be introduced to the simulation program. This application will be of great value in refining designs to meet user's needs. Furthermore, putting the information needed to solve an entire data measurement problem in an easily accessible form would provide an invaluable tool to the designer. Combining the present interactive data error simulation model with interactive displays could present design information in such a condensed manner so that it can be reviewed rapidly. Using such techniques as this, one can make optimum design adjustments easily because the information needed to solve problems is available literally at his fingertips.

Another application of the simulation program is to use it to define the required measurement characteristics of a desired buoy system. The design of this buoy system, of course, could include any constraints the designer wishes to consider, such as user-desired accuracy, cost, or schedule. The trade-offs that can be examined by this approach could greatly enhance the utility of data acquisition systems in general. Not only will the users be more satisfied with the data received from such measurement systems, but this technique will benefit the system design, component supplier, and instrument designer as well.

A very intriguing application of the Data Error Simulation Model is to adapt it as a real time data quality check. Since the model can run on a time step basis, it is possible to compute the component errors on a time step basis. This will allow for a real-time troubleshooting capability. It seems feasible that if the total observational error seems to be large for a particular parameter at a particular time step, the simulation program could be set up to fit various realistic combinations of error components to this total error, and thereby tell the engineer where the trouble is most likely to be.

Eventual applications of the Measurement Comparison System (MCS) by itself include the possibility of the MCS concept being accepted by the scientific community as an international (or at least national) reference standard. The adoption of a universal reference standard such as the MCS for ocean platforms would provide a first major step toward optimizing national and international data exchange and scientific analysis.

Finally, although developed to investigate the observational error in the data from NDBO data buoys, both of these programs can be used to describe errors in data from many other environmental measurement platform configurations.

5. SUMMARY

Total observational error and its components have been defined. Two NDBO programs, the at-sea measurement comparison program and the data error simulation model, that will lead to the evaluation of these errors have been presented. The applications of these programs were discussed. As mentioned, these programs are a significant part of the total data quality effort at NDBO, as described in Reference 5.

ACKNOWLEDGEMENTS

This report describes, in part, two programs sponsored by the NOAA Data Buoy Office. The Measurement Comparison System was developed and completed by the Lockheed Missiles and Space Company, Contract NAS8-28918, under the direction of Dr. Hong Chin. The Data Error Simulation Model was completed and is being exercised by Operating Systems, Inc., under the direction of Dr. Richard M. Bird.

REFERENCES

1. Withee, G. W. and L. H. Clem (1972): Determination of Total Observational Error in Environmental Data from Ocean Measurement Platforms, The Proceedings of the WMO Technical Conference on the Means of Acquisition and Communication of Ocean Data.

2. Bird, R. M., J. R. Thompson, and G. W. Withee (1973): Oceanographic Measurement Platform Data Error Modeling by Computer Simulation, Published in the Proceedings of The Second International Conference on Marine Research and Marine Exploitation, IO-73-706.

3. Withee, G. W., R. F. Erickson, and H. Chin (1973): An In Situ Ocean Data Comparison System, Presented at the International Conference on Engineering in the Ocean Environment, September 1973.

4. Baer, L. and G. W. Withee (1971): A Methodology for Defining an Operational Synoptic Temporal Oceanic Sampling System, I. Stationary Conditions, J. Appl. Meteor., 10, pp. 1053-1060.

5. ______________ (1973): NDBO Data Quality Programs, NOAA Data Buoy Office Manuscripts, 0161-1.

6. Chin, H., et. al. (1973): Measurement Comparison System, Lockheed Report No. LMSC D241506, Prepared for NDBO under Contract No. NAS8-28918.

7. Mons, R. F. (1971): Data Buoy: Analysis of Structure Effects on Meteorological and Oceanographic Sensors, Westinghouse Electric Corporation, Engineering Note #130.

8. Rutledge, C., Jr. (1971): National Data Buoy Sensor System Error Analysis, Westinghouse Electric Corporation, Engineering Note #136.

9. Mons, R. F. (1971): Data Buoy:Calculation of Error in Air Temperature Measurement Due to Solar Flux and Power Dissipation of Internal Electronics, Westinghouse Electric Corporation, Engineering Note #129.

10. Vermeulen, J. C., et. al. (1972): Preliminary Estimates of Errors in EEP Data, Lockheed - California Company Report No. 25398.

11. ______________ (1973): An Analysis of Oceanographic and Meteorological Sensors for Ocean Data Stations, General Dynamics Electronics Division Report R-73-001.

12. Bird, R. M., R. L. Pickler, J. R. Thompson, and J. C. Tu (1973): Total Error Simulation Program for the EEP Buoy, Operating Systems, Inc., Report R-73-003.

13. Bird, R. M., R. L. Pickler, and J. R. Thompson (1973): Total System Error Analysis Results of the Large Discus High Capability Buoy -- Interim Report, Operating Systems, Inc., Report R-73-006.

Part II. HYDRO/MECHANICAL COMPONENTS

Haugen, D. P. Power Systems for Buoys.

Morey, R. L. Present and Future State of the Art, Materials and Design of Buoy Structures.

__________., and H. O. Berteaux. Alleviation of Corrosion Problems in Deep Sea Moorings.

Niederman, C. S. State of the Art and Future Projections in Buoy Mechanical Technology.

Ross, D. Buoy Power.

Smith, G. Hardware Components of Automatic Mooring Devices.

Prepared for:

National Academy of Engineering
Marine Board
Buoy Technology Workshop
26-29 June 1973

Introduction

This paper is intended to summarize the status of buoy power systems and serve as a starting point for consideration of future needs regarding power systems for automated data buoys. A brief outline is given of the power systems currently being used on several buoys ranging in size from the large High Capability Buoys (HCB) to the relatively small Arctic Data Buoy (ADB), both of which were developed by the NOAA Data Buoy Office (NDBO). Also included is a listing of the properties of several types of power sources, and an indication of some of the areas of current investigation which may result in improved power systems for future buoy application.

Important Criteria

A number of parameters are important in evaluating and selecting power systems. Depending upon the primary constraints and requirements involved, the order of importance of the various parameters will vary among different applications. Quite often, cost per energy unit and energy capacity per unit of weight are thoroughly considered after some minimum level of acceptance is exceeded regarding other parameters. Parameters of major importance include the following:

- Energy density (watt-hrs/lb)
- Energy density (watt-hrs/in^3)
- Cost ($/kilowatt-hr)
- Maximum power density (watts/lb)
- Reliability
- Conversion requirements
- Service cycle
- Storage life
- Temperature derating
- Safety
- Pollution

Power Sources

Power sources can be separated into the following broad categories:

Thermo-mechanical
Thermo-electric
Chemical
Environmental

Thermo-mechanical systems generally are cost-effective for relatively long-life and high total-energy applications, for instance where 50 watts or more average power is needed with one-year or longer service cycles. Thermo-electric systems are more applicable to intermediate requirements from a few watts to a few hundred watts. With the exception of fuel cells, chemical sources are not economically advantageous except for low power, limited capacity applications, for instance where less than 5 watts or 50 kw-hrs is needed. Fuel cells find application primarily in the intermediate power requirement range. Environmental systems can be used throughout the spectrum of power requirements, but have yet to be used to any great extent, probably because of the dependence upon the environment and an undemonstrated reliability of operation, particularly on buoy applications. Several studies have noted the potential of wind and wave driven energy sources and have encouraged additional development and evaluation of these extremely clean energy sources.

Most applications are characterized by variable load requirements where large surges of power are used for short periods such as during measurement and transmission operations, but otherwise relatively small amounts of power are used for standby operations. Except for certain low-power applications where a single type of primary battery can effectively satisfy both surge and standby requirements, most effective operation in these cases can be achieved by utilizing an inexpensive, high-surge-capacity secondary battery such as a lead-acid or nickel-cadmium cell for peak power loads, charged from a second power source selected on the basis of the total energy requirements.

Table 1 lists the more easily quantified properties of several types of power sources within these main categories. It should be noted that while convenient for gross comparison purposes, presentation of these data in such a concise format necessitates oversimplification and results in a tendency to "compare apples and oranges." The various properties actually depend upon many factors impossible to include in such a format, but which should be considered in the final selection of an energy source.

The table indicates the economic advantages of utilizing thermo-mechanical power sources (in conjunction with lead-acid secondary batteries for surge loads) in those applications where the total energy requirement is large enough to make the total cost primarily fuel-cost dependent. Radio-isotope sources are attractive for very long-life, high reliability requirements, but handling and accountability problems weigh against buoy applications.

Both the fuel cell and the lithium battery offer advantageous energy densities in the respective areas of application, but suffer from high costs. Perhaps additional development and increased use of these sources will result in improved cost figures for these cells.

Table 2 lists the power system characteristics for several currently operational buoys. These systems reflect considered engineering decisions for the particular applications involved, and may provide guidance for other applications.

Underway Development

Several areas of development known to the author are noted below. Undoubtedly others exist.

Lockheed is understood to be working on an improved seawater battery with a potential order-of-magnitude increase in energy density for long-life applications. Apparently this improvement will result from use of a consummable Lithium annode with controlled electrode separation and electrolyte concentration. Seawater batteries are, of course, of high interest for buoy application.

The NDBO is monitoring or conducting development efforts in several areas including liquid-fueled (diesel oil) TEG cells which will reduce fueling problems and thereby increase TEG utility, smaller motor-generator sets to bring the thermo-mechanical economies to the smaller power application, variable flux generators to improve operating efficiency of motor generators, improved seawater batteries, improved power conversion methods, the use of solar cells and others.

The Japanese and English are understood to be evaluating wave action generators for buoy use.

Recommendations

As can be seen, a wide and expanding variety of power sources are available for use on data buoys. The best source for a given application depends upon the requirements and limitations involved. Needless to say, achieving an effective power system for any application involves careful engineering of the entire power system including selection of the primary and secondary energy sources and design of power conversion and regulation electronics. Moreover, power reduction techniques in the other systems must be properly emphasized to reduce overall buoy costs.

There is no question that enormous benefits would result from significant advances in power source technology. The size, cost and lifetime impact of power systems are generally significant with respect to the overall buoy, and in some cases are critical limitations. Indeed, this will become even more so as improvements in other elements of the buoy make longer deployments feasible. More compact, higher energy, less costly and more reliable power systems optimized for buoy application are definitely needed.

There is a serious question, however, whether in view of the developments already underway as a result of normal market pressures and the needs of other, relatively affluent users such as the military and the transportation industry, funded development specifically for data buoy application would be justified. Active and competitive development of improved power sources is already underway and is providing essentially free, reasonably timely technological advances to the data buoy community. In view of this, the author believes that optimization of current and evolving power source technology specifically for the data buoy application is potentially more rewarding than attempting to effect development of new power sources.

References

1. USCG Oceanographic Sensor Study, Contract DOT-CG-90505-A, May 1970
2. Miscellaneous NDBO presentations and data
3. Power Sources Symposium Proceedings
4. D. Ross, Buoy Power, 1973

TABLE 1

SUMMARY, POWER SOURCE CHARACTERISTICS

			Energy Density (w-hr/lb)	Energy Density (w-hr/in^3)	Cost[1] ($/kw-hr)
Thermo-Mechanical		Propane Fuel	1000	35	0.15
		Diesel Fuel	1000	35	0.10
Thermo-Electric		Liquid Fuel	130	4	1
		Gas Fuel	130	4	1
		Radio-Iostope	250	25	50-200
Chemical	Primary	Fuel Cell	250	10	2
		Zinc Carbon	50	5	20
		Alkaline	75	5	50
		Air Cell	120	7	15
		Sea Water	100	6	15
		Mercury	75	7	150
		Lithium (inorgan)	250	10	600
	Secondary	Lead-Acid	25	2.5	.09(60)
		Nickel-Cadmium	15	1.0	.21(700)
		Silver-Cadmium	35	3.0	2.5(950)
		Silver-Zinc	80	5.6	8.4(800)
Environmental[2]		Wind	1000 +	20 +	0.5
		Wave	--	--	5
		Solar	--	--	10

(1) Secondary battery initial costs shown in brackets

(2) Properties are dependent upon the weather and area of use.

Buoy System		Power Source	Ave. Power (Watts)	Life (Mo)	Total Energy (kw-hr)	Weight (lb)	Size (ft^3)
HCB	EB-01	2 hp propane engine 2 kw dc generator (intermittent) Nickel-cad batteries supply loads	1500	12	15,000	13000	250
HCB	EB-02, -03, -10, -12, -14	6 hp diesel engine 3.5 kva generator (cont) Lead-acid battery for peak loads	1500	24	30,000	35000	600
HCB	LCKHD DKH EB-02	6 hp diesel engine (continuous) 3 kw 28 Vdc alternator Lead-acid batteries supply dc loads	1500	8	9,000	8000	150
LCB	GE MLCB & DLCB	Manganese Alk. primary battery Automatic series add. of cells to maintain voltage	2.7	4	10.9	230	2.13
LCB	LKHD MLCB	Air cell primary battery Nickel-cadmium secondary battery for peak loads	9.7	5	37.5	500	10
LCB	MGNVX DLCB	Zinc-carbon primary battery Nickel-cad. secondary for peak loads	3.9	4	13.5	466	6
IF YGL BUOY		Propane fueled TEG (20 Watt)	15	1.5	15	180	7.5
ADB		Mercury cell primary battery	0.3	12	3.5	100	0.75
AIDJEX HF BUOY		Air cell primary battery Lead-acid secondary for peak loads	6	8	36	320	6

SUMMARY, BUOY POWER SYSTEM CHARACTERISTICS

TABLE 2

PRESENT AND FUTURE STATE OF THE ART, MATERIALS AND DESIGN OF BUOY STRUCTURES

by

R. L. Morey

C. S. Draper Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02142

CONTENTS

	Page
Introduction	1
Environmental Effects	3
Buoy System Components	7
a) Buoys	8
b) Chain and Hardware	14
c) Wire Rope Terminations	21
d) Electromechanical Wire Table	22
e) Non Metallic Components	24
f) Instruments	33
Major Problem Areas	36
a) Corrosion Fatigue	36
b) Stress Corrosion Cracking	36
Mooring Results	41
Conclusions	42
References	44

etc., or can be compounded by tensile effects producing stress corrosion. Failure can be due to mechanical or environmental effects grafted onto tensile fatigue and corrosion factors.

There has been concern with the analysis of failure (3-6) and the results of such analyses has been fed back into mooring design thus improving the long term reliability of moorings(7).

Bivins (8) quotes the Stratton Commission Report of 1969 and the statement is oriented towards instrumentation but is equally applicable to ocean hardware in many aspects.

> "Most ocean programs have been limited in both staff and budget. As a result, specific program objectives are often compromised and only limited instrumentation is procured. Unlike conditions in many other non-oceanographic programs, such as the space program, ocean instrument specifications are often minimized, meaningful quality assurance programs are largely nonexistent, and service and maintenance manuals and other documentation are often inadequate to meet basic user need. In addition, statistical information defining conditions of use, maintenance and repair cycles, and modes of failure are seldom documented and made available to the manufacturer. This, in turn, slows down the correction of problem areas and prevents the upgrading of performance and reliability in a logical manner."

To paraphrase Bivins the ocean data collection system must be treated as a system. The cause of some of today's deficiencies can be attributed to bad compromises on the part of program managers when forced to live within certain budget constraints. Rather than reduce the total system certain critical considerations of the system engineering process are dropped. The adoption of the system concept will bring with it the total consideration of reliability, cost effectiveness, maintenance, testing and calibration.

Present and Future State of the Art - Materials and Design of Buoy Structures

I. Introduction

The selection of a material to be used in a buoy structure involves a consideration of the advantages and disadvantages of the alternatives. Selecting a material for a structure, whether for corrosion resistance, strength, reliability, etc., necessitates a decision and the problem can be complex. The question of corrosion characteristics may or may not even be the most important question to ask in selecting a material.

Back in 1964 Brown and Birnbaum (1)[1] stated, "with new materials and new geometries of components and structures for various deep ocean projects, the primary need for corrosion control has shifted from one of maintenance economy (though of course this is as desirable as ever) to one of survival of the component or structure." This problem is still with us and failures are still occurring.

As Masabuchi (2) has noted metals have been placed in the marine environment for centuries and performance has been observed and studied for over 200 years. There are countless numbers of papers published in technical journals. New materials have been developed, but despite all this knowledge corrosion is still one of the major problems facing ocean engineers. There are so many aspects of the performance of materials in marine applications, that it is all to easy to overlook one, or more of the controlling factors. Apart from corrosion other mechanisms of deterioration include tensile and shear loading effects, fatigue or material defects. There can be an interaction between the various failure mechanisms and any one failure may be a combination of one or many factors. A cable may fail by corrosion fatigue, corrosion cells may be set up between an instrument and associated hardware such as shackles, bridles, chains,

---

1. Figures in parentheses indicate the literature references at the end of this paper.

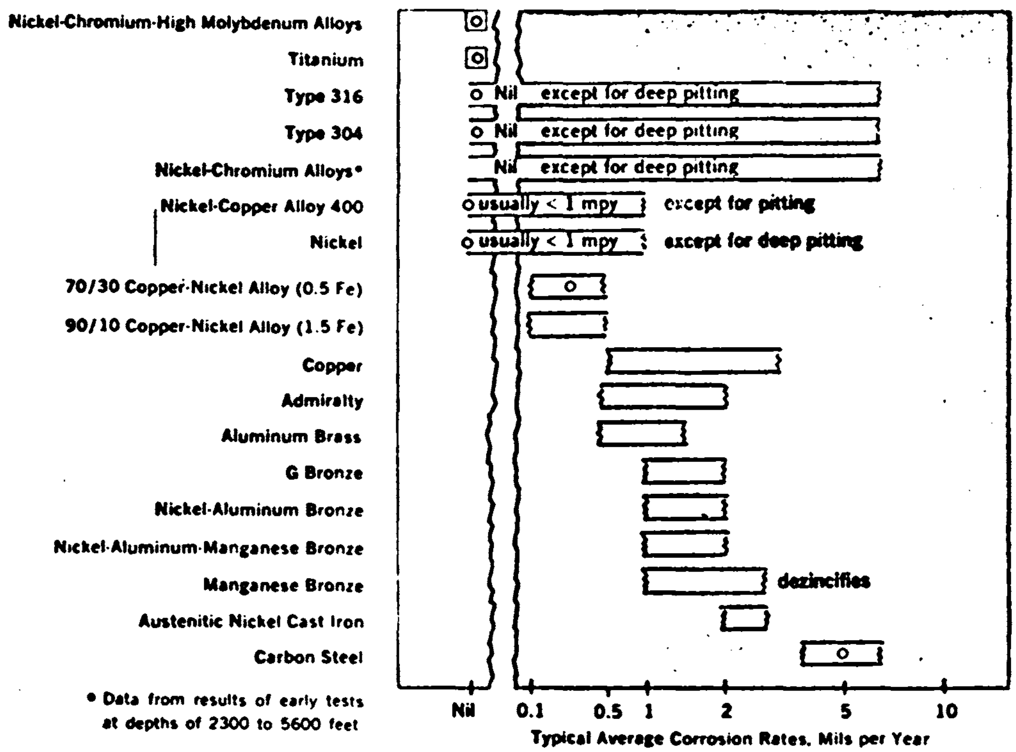
Instruments are an integral part of any mooring system and the problems alluded to here will be discussed later in this report. However, it should be borne in mind as Bivins insists that successful data collection does require a systems approach, that the total systems approach is expensive, but that is the only way that sequential progress can be made.

In the conclusions of the paper (5) given by the writer at the Materials in the Sea Program organized by NBS in October 1972 progress in improving reliability of long term moorings means that each new mooring or instrumented array be carefully examined for corrosion problems particularly at the design stage. The failure analysis of numerous mooring line components has been used to recommend design and material changes and this has resulted in an improved resistance to environmental deterioration.

2. Environmental Effects

Preponderant environmental effects resulting in accelerated deterioration of mooring components are corrosion: for long life, the corrosion behavior of a component can be the limiting factor. Figure 1 shows general corrosion rates based on weight loss immersed in quiet seawater for common marine materials. Note that stainless steel, nickel copper and nickel chromium alloys are rated inert except for localized attack. In quiet seawater, in the presence of marine organisms or other deposits, up to 90-99% of the surface of these relatively noble alloys can remain virtually unaffected. As Uhlig (9) notes the average corrosion rate as determined from Figure 1 are less than 3 mils per year if metal loss were uniform and not localized. Average corrosion rate data is meaningless if the weight loss occurs in a few pits.

The intrinsic corrosion resistance is not the only concern but also the often inadvertent coupling that can take place between different materials.



* Nickel chromium alloys designate a family of nickel base alloys with substantial chromium contents with or without other alloying elements all of which, except those with high molybdenum contents, have related seawater corrosion characteristics.

FIGURE 1 GENERAL WASTING OF VARIOUS MATERIALS IMMERSED IN QUIET SEAWATER[5]

The writer (10) examined the case where a taut stressed cable came in contact with a slack drifting cable and failure was due to galvanic action. The tendency to corrode can often be predicted but actual corrosion rates are difficult to predict. There is still a need for testing but the "dunk it in the sea" approach has been replaced by more realistic on land testing. Procedures are being developed as exemplified by Dull and Raymond (11) for stress corrosion cracking.

For simple corrosion one can make allowance for strength reduction due to loss of material but to overlook other factors such as stress corrosion cracking, hydrogen embrittlement, galvanic coupling, etc., could be disastrous. Fatigue: Surface buoy motion can induce repeated bending and torsion stresses in points of attachment of the mooring line as well as cyclic tension stresses in the line itself. Also in strong currents vortex shedding can create a strumming situation with high frequency lateral loading. The two following types of fracture are important.

a. High cycle, low stress fatigue

b. Low cycle, high stress fatigue.

In high cycle fatigue the endurance limit of a material after several million cycles is considered whereas in low cycle fatigue fracture after repeated loading is less than 10^5 cycles. In ocean engineering structures in which major loads are induced by waves, low cycle rather than high cycle fatigue is more of a problem. Figure 2 illustrates the effect of a corrosive environment on fatigue strength and corrosion is one of the most detrimental factors resulting in low fatigue strength. A solution to overcome the problem is to use a low strength alloy at a low working stress and make a bulky structure. An alternative is to use higher strength materials but then the effect of decreased corrosion fatigue strength cancels out any advantages.

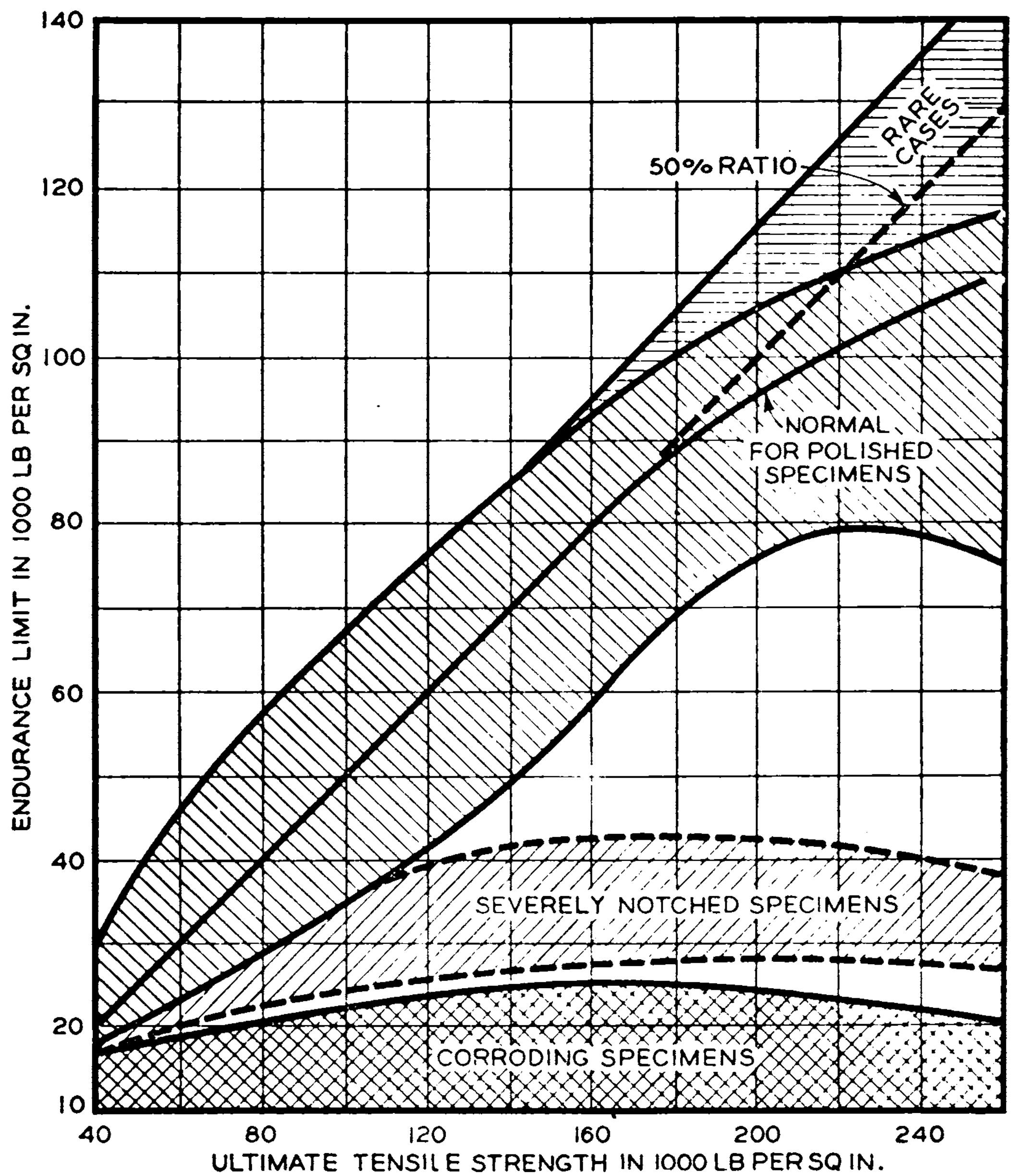


Figure 2 RELATIONSHIP BETWEEN THE ENDURANCE LIMIT AND ULTIMATE TENSILE STRENGTH OF VARIOUS STEELS(9)

Biological Attack: At the upper portion of any mooring line, fouling is present and can lead to initiation of attack. As Crisp (13) notes there has to be a systematic approach to the testing of proposed control measures, the analysis of the behaviour and the attachment mechanisms of naturally occurring organisms has to be determined and thereby there has to be a study made of the mode of application, release and penetration of various toxic substances dispensed in films of various types. Organisms can respond specifically to insoluble macromolecules present on a surface and the possibility thus exists of finding a durable anti-fouling material which does not depend on the leaching of toxic molecules from the surface. Substances which reduce or destroy the adhesion of marine organisms may be found as a result of investigations on the nature and mode of action of underwater cements produced by settling larvae. It will probably be necessary to promote accelerated testing methods as traditional testing methods are not geared for rapid evaluations.

Apart from anti-fouling, the other major biological problem is that the sharks and other benthic species attack mooring lines gashing the protective plastic jacket of wire ropes and exposing the underlying steel cable. Although corrosion has occurred at the cuts wire rope failures due to fish attacks have not yet been identified. Sessions and Brown (14) have reported instances where shark bite has penetrated into electrical conductors. As can be expected this problem is more acute on synthetic fibre ropes and this whole problem is discussed elsewhere in this program.

3. Buoy System Components

A number of structural components comprise any buoy system. Between the buoy and the achor are metallic and non metallic components as well as ancilliary equipment such as instrument casings, acoustic releases, flotation spheres, etc. Metallic components include chain, wire rope and connecting hardware and non metallic components include synthetic and

and glass fiber ropes.

Buoys

A number of buoys are made from steel and to inhibit corrosion they are then painted. Protective coatings are combinations of wash primer coats, primer coats, intermediate coats and top coats. In some instances the same material serves for both primer and top coats. Most paints consist essentially of a solvent, binder and pigment, however, there are some high polymer two component paints that may not be dependant upon a solvent. The binder is that part of the vehicle which cements the pigment to the substrate after the thinners (solvent) have dried out and can be either organic or inorganic. An organic binder can be linseed oil, alkyl, vinyl, chlorinated rubber, whereas an inorganic binder could be sodium silicate. Table 1 is a testing of the characteristics of paint binders. The U.S. Naval Civil Engineering Laboratory (36) has conducted some long period test programs on coatings for the protection of mooring buoys and Tables 2 and 3 show the results. It must be remembered that there are no ideal paints for any exposed surface. The best selection of a paint system is always a compromise involving the environment, metal, structure complexity, time, surface preparation, previous paint system, painting cycle, money and craftsmanship. A typical steel buoy is the Large Navigation Buoy developed by General Dynamics which has a 7.5 foot thick hull. Figure 3 gives an indication of the features of such large buoys.

Many buoys are also made from aluminum and Figure 4 gives a typical configuration.

A standard surface buoy is the foam filled fiberglass wrapped buoy which can be used as an instrument platform, a position marker or a navigation aid. It has good stability and net buoyancy of 5000 lbs. Towers can be erected for meteorological use.

Table 1 Characteristics of Paint Binders

1. LINSEED OIL	
a. The old classic binder obtained from flax seed b. Probably accepts more pigments than any other binder c. High wetting power d. High flexibility e. Short life in harsh environment[1], poor resistance to alkalis	f. Satisfactory application by spray or brush g. Easy to apply h. Readily available i. Dries by reacting with oxygen j. Cannot serve as a base for lacquers, vinyls, etc. The paints with solvents will lift the oil binder type paints.
2. ALKYD	
a. A synthetic binder b. Made from glycerine and phthalic anhydride usually modified by fatty acids or drying oils c. Dries by reacting with oxygen d. Available in pigmented form e. Gloss and color retention good	f. Easy to apply, easily maintained, tends to smudge easily g. Any surface coated with an alkyd paint must be alkali free h. Good performance in dry and normal environments i. Intercoat adhesion problems may result if straight alkyd is applied over vinyl; alkyd may not bite into the vinyl.
3. VINYL	
a. Resins are from copolymerized vinyl compounds b. Vinyl chloride and vinyl acetate are main constituents of vinyl resin c. High percentage of solvents, dries by evaporation of solvent d. Vinyl thinners are MIK (methyl isobutyl ketone), toluene and xylene. e. Resistant to most solvents except ketones and esters (the acetates and acetones) f. Resistant to water and alcohol g. Low percentage of solids requires many applications to build up system, difficult to achieve complete sealing of a surface with vinyl h. Vinyl cannot be used over any rust or dirt of any type or degree. i. Requires extensive surface preparation due to adhesion characteristics. Surface preparation of metal should be class IV. j. Difficult to apply properly because of lifting (good craftsmanship a must!)	k. Vinyl wash primers and paints may be diluted as much as 1-to-1 with thinner to prevent spattering and to get an even flow. Test to determine proper dilution. l. Cost is high due to many applications; vinyl systems should be built up of 0.5 to 1.0 mil layers. High-build vinyls, 2—3 mils per coat, are extremely difficult to achieve; some experts do not believe in high-build vinyls. m. Durable in harsh environments n. Not compatible with many aged paints. Use of a tie coat in between paint coats is possible at times; check manufacturer's recommendations. o. Vinyls have tendency to bridge peaks of substrate when applied by spray. Some experts feel that brushing vinyl is better than air spraying. p. Never use VR-3 directly on MIL-P-15328 or any polyvinyl butyral wash primer. q. VMCH, VYHH, and VAGH are Union Carbide classifications. VMCH and VYHH vinyls are not compatible with wash primers. VAGH vinyl is compatible with wash primers and to some extent other paints. VMCH is the only vinyl that has bare metal adhesion.
4. VINYL ALKYD	
a. Compromise between straight alkyd and vinyl, a combination of vinyl and alkyd resins b. Cost is lower than vinyl c. Easier application than vinyl	d. Requires pretreatment of surface; wash primer and zinc chromate e. Apply by brush or spray f. Durable top coat in dry and normal environments.
5. PHENOLIC	
a. Pheno-formaldehyde resin b. Available in pigmented colors or white c. Dries by reacting with oxygen	d. Tested extensively in very humid environments e. Primer for metal subject to fresh water immersion f. Good performance in normal and humid environments.
6. EPOXY (Catalyzed)	
a. Epoxy resin and polyamide type of hardener are good combination b. Two components, mix just before use c. Limited pot life, 4—8 hours; check manufacturer's labeling	d. Lifting problems on previously painted surfaces; compatibility[2] with other paint coats should be tested before general use e. Film layer is thick, one or two coats usually suffice f. May chalk rapidly when exposed to weather g. Very resistant to abrasion, alkalis, solvents, and corrosion.

Table 1 Characteristics of Paint Binders (cont.)

7. EPOXY (Ester)

a. One-component paint
b. Handles and dries similar to alkyds
c. Resistance is between that of alkyds and catalyzed epoxy
d. Cost is about the same as the alkyd group.

8. URETHANE (Uralkyd)

a. Oil modified urethane
b. Similar to alkyds in handling but more expensive
c. Poor color retention
d. Hard, tough film
e. Application critical for good adhesion
f. More resistant to harsh environment than alkyds.

9. URETHANE (Catalyzed)

a. Two-component finishes
b. Similar to, but more expensive than, catalyzed epoxies
c. Cures more rapidly at lower temperatures than catalyzed epoxies
d. Produces very hard films with good water and acid resistance
e. Less adhesion and alkali resistance than catalyzed epoxies.

10. URETHANE (Moisture Cured)

a. Reacts with air moisture to cure
b. Single component paint but has properties of two-component finish
c. Jelling of unused material begins in 2 hours
d. Only full cans can be stored
e. Durable and corrosion resistant
f. Adhesion is a problem
g. Before any overcoating or recoating, the existing paint coat should be tested with urethane to determine any degree of incompatibility.[2]

11. CHLORINATED RUBBER

a. Synthetic resin
b. Made by chlorinating natural rubber
c. Must be applied to a clean substrate, whiteblast
d. Poor wetting power
e. Serves for primer and top coats
f. Aromatic solvents will dissolve chlorinated rubber.

12. INORGANIC BINDERS
(Silicate, Phosphate, Silicone Zinc)

a. Good adhesion
b. Long life
c. Application by brush or spray
d. Thick coatings will mud crack
e. Abrasion resistant
f. Often requires "tie" coat between inorganic coat and other type paint coats; check manufacturer's recommendations
g. Inert binding agent
h. Comparatively low electrical resistance
i. Inorganic zinc-rich films have very high concentration of pigment content; 90 to 95 percent zinc in dry film is not uncommon
j. Silicones are high priced, used for painting high-temperature surfaces (up to 500°F).

Notes

[1] Refer to table 2-4.
[2] Refer to paragraph 4.20.

*Table 2 Ratings of Buoys With Test Coatings (Seacoast Atmosphere)**

<table>
<tr><th>Coating System</th><th>Months in Service</th><th>Color</th><th>Chalking</th><th>Blistering</th><th>Checking</th><th>Cracking</th><th>Scaling</th><th>Rusting without Blistering</th><th>Rusting with Blistering</th></tr>
<tr><td>Urethane</td><td>51</td><td rowspan="8">9</td><td>4</td><td>F</td><td>9</td><td rowspan="8">10</td><td rowspan="5">10</td><td rowspan="7">9</td><td rowspan="8">10</td></tr>
<tr><td>Epoxy</td><td rowspan="2">49</td><td rowspan="2">8</td><td rowspan="7">N</td><td rowspan="7">10</td></tr>
<tr><td>Epoxy Polyester</td></tr>
<tr><td>Phenolic</td><td rowspan="2">44</td><td>6</td></tr>
<tr><td>Phenolic Alkyd</td><td>4</td></tr>
<tr><td>Vinyl</td><td>45</td><td rowspan="3">10</td><td>N, 10</td></tr>
<tr><td>Inorganic Zinc Silicate Vinyl</td><td>51</td><td rowspan="2">10</td></tr>
<tr><td>Vinyl Saran (formula 113/54)</td><td>50</td><td>8</td></tr>
</table>

Notes

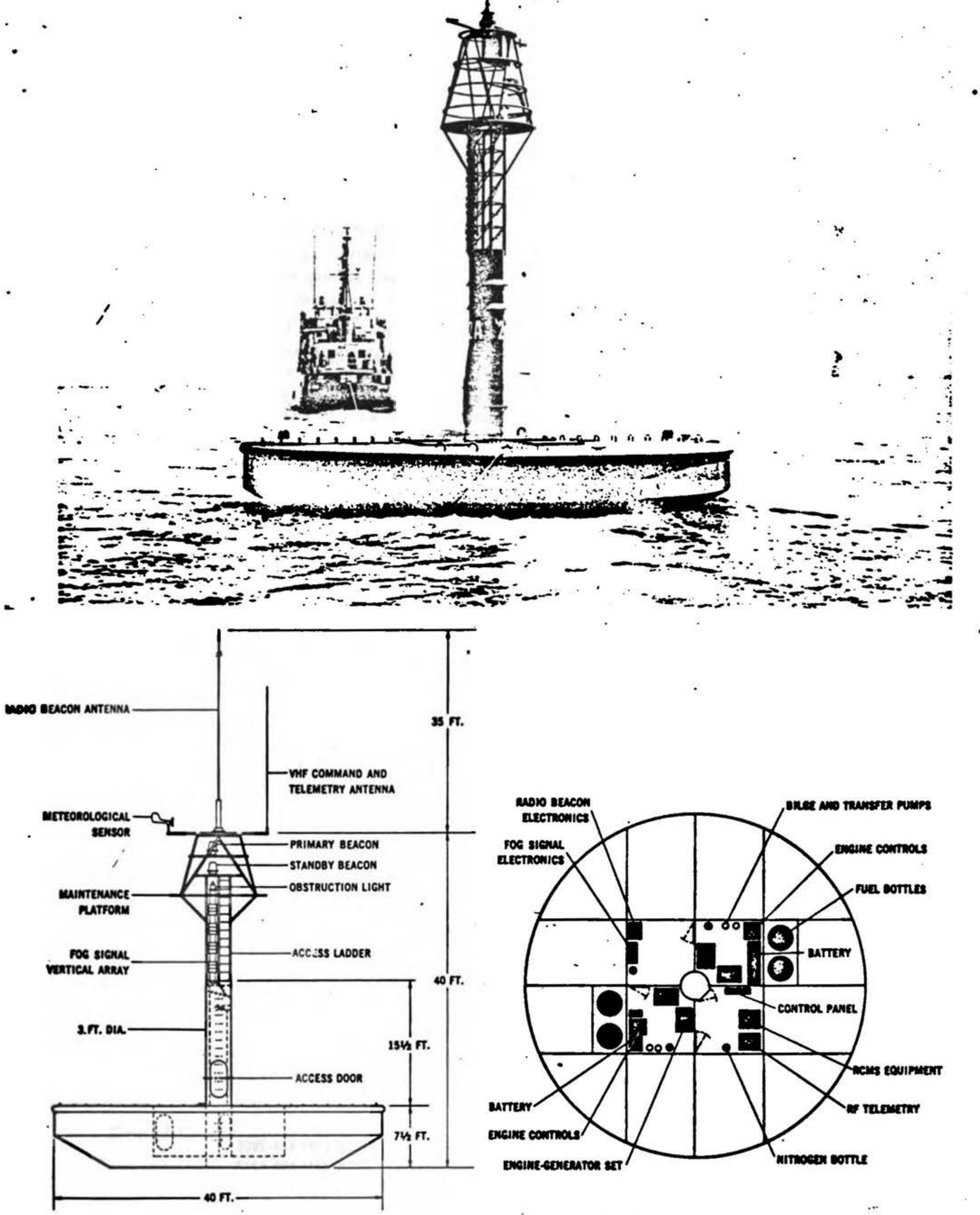
Rating Scale:
10—perfect condition
0—complete deteriortion

Blistering Frequency
N—none
F—few

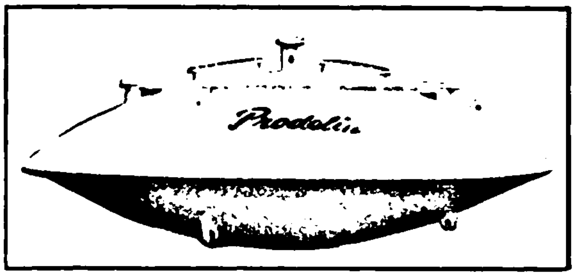
*Table 3 Ratings of Buoys With Test Coatings (Seacoast Atmosphere)**

<table>
<tr><th>Coating System</th><th>Months in Service</th><th>Color</th><th>Chalking</th><th>Blistering</th><th>Checking</th><th>Cracking</th><th>Scaling</th><th>Rusting without Blistering</th><th>Rusting with Blistering</th></tr>
<tr><td>Urethane</td><td>51</td><td rowspan="8">9</td><td>4</td><td>F</td><td>9</td><td rowspan="8">10</td><td rowspan="5">10</td><td rowspan="7">9</td><td rowspan="8">10</td></tr>
<tr><td>Epoxy</td><td rowspan="2">49</td><td rowspan="2">8</td><td rowspan="7">N</td><td rowspan="7">10</td></tr>
<tr><td>Epoxy Polyester</td></tr>
<tr><td>Phenolic</td><td rowspan="2">44</td><td>6</td></tr>
<tr><td>Phenolic Alkyd</td><td>4</td></tr>
<tr><td>Vinyl</td><td>45</td><td rowspan="3">10</td><td>N, 10</td></tr>
<tr><td>Inorganic Zinc Silicate Vinyl</td><td>51</td><td rowspan="2">10</td></tr>
<tr><td>Vinyl Saran (formula 113/54)</td><td>50</td><td>8</td></tr>
<tr><td colspan="10">Notes
Rating Scale:
10—perfect condition
0—complete deteriortion
Blistering Frequency
N—none
F—few</td></tr>
</table>

Figure 3


RADIO BEACON ANTENNA
35 FT.
VHF COMMAND AND TELEMETRY ANTENNA
METEOROLOGICAL SENSOR
PRIMARY BEACON
STANDBY BEACON
OBSTRUCTION LIGHT
MAINTENANCE PLATFORM
FOG SIGNAL VERTICAL ARRAY
ACCESS LADDER
40 FT.
3 FT. DIA.
15½ FT.
ACCESS DOOR
7½ FT.
40 FT.
RADIO BEACON ELECTRONICS
FOG SIGNAL ELECTRONICS
BILGE AND TRANSFER PUMPS
ENGINE CONTROLS
FUEL BOTTLES
BATTERY
CONTROL PANEL
RCMS EQUIPMENT
RF TELEMETRY
NITROGEN BOTTLE
ENGINE-GENERATOR SET
ENGINE CONTROLS
BATTERY

SURFACE

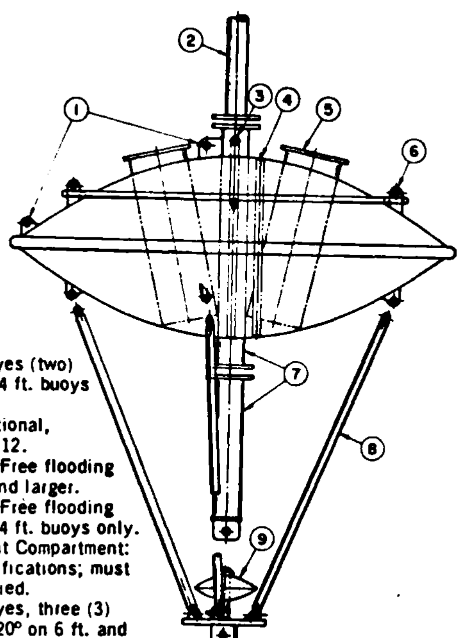


Para-Buoy in a horizontal attitude is designed for use as an active or passive RF marker for position finding from land, sea or air.

This Para-Buoy is available in sizes from 2 ft. to 20 ft. diameters. The standard mast provision is a monopole.

The standard construction is reinforced spun aluminum alloy. Compartments for instrumentation can be provided with or without the required instruments and battery racks. All buoys are polyurethane foam filled to provide permanent buoyancy.

This Para-Buoy is furnished with hoisting eyes. Recommended mooring for maximum stability is through a rigid tripod bridle. All aluminum is treated for corrosion resistance and finished with a high visibility epoxy paint. All steel parts are hot dip galvanized. Ballasting is not furnished as a part of the standard buoy.



1. Lifting eyes (two) on 2 and 4 ft. buoys only.
2. Mast: Optional, see page 12.
3. Conduit: Free flooding on 6 ft. and larger.
4. Conduit: Free flooding on 2 and 4 ft. buoys only.
5. Instrument Compartment: See specifications; must be specified.
6. Lifting eyes, three (3) spaced 120° on 6 ft. and larger, includes foot railing.
7. Post mooring column on 2 and 4 ft. only.
8. Tripod bridle on 6 ft. and larger, optional on smaller sizes.
9. Para Weight: Optional, see page 12.

SPECIFICATIONS
ORDERING INFORMATION

Cat. No.	Dia. Ft.	Average Net Weight (Lbs.)	Average Buoyancy Net (Lbs.)	Instrument Compartment Qty.	Size Dia.	Size Lgth.	Standard Mooring Pickup
2-200	2	15	80	0	0	0	Single eye in mooring post
4-200	4	120	500	0 to 2	8"	19"	Single eye in mooring post
6-200	6	370	2,000	0 to 4	10"	36"	Tripod Bridle
8-200	8	480	3,900	0 to 4	12"	32"	Tripod Bridle
10-200	10	600	10,000	0 to 4	12"	36"	Tripod Bridle

NOTE: When ordering specify –
1. Cat. No.
2. Number of instrument compartments
3. Ballasting required if any (At extra charge)
4. Type of mast required (See page 12)
5. Payload including weight of mooring line in CH_2O
6. Mooring depth
7. Operational and survival sea states

Prodelin
HIGHTSTOWN, NEW JERSEY
SAN CARLOS, CALIFORNIA
PHONE (AREA CODE 609) 448-2800
(AREA CODE 415) 593-8277

Spar buoys have advantages for certain applications and Figure 5 shows a typical configuration.

Initial prototypes of concrete buoys have been manufactured and these also offer advantages of minimum repair, corrosion resistance, etc.

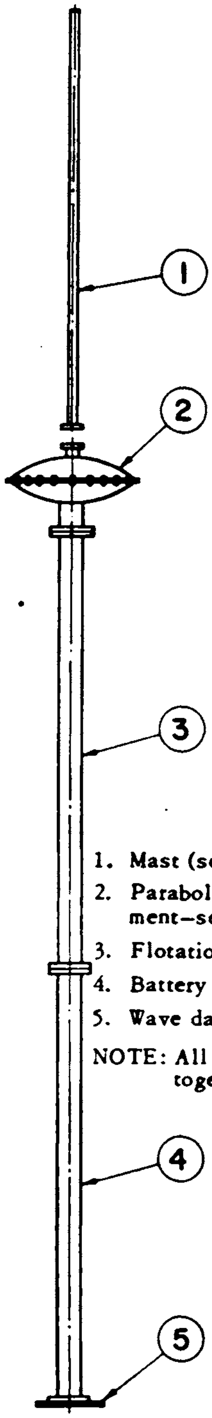
As LaQue and Tuthill (15) noted, the relative performance of materials in sea water have been difficult to estimate accurately due to variations in velocity,contamination,duration of exposure and so on. In this case although data has been generated over a number of years, in many cases the corrosion rate is highly dependant upon the surface preparation and coating applied. The foam filled toroid buoy uses a light weight foam and if inadvertently pulled under the surface by excessive currents it may collapse.

Chain and Hardware

Chain is used in short moorings as the only mooring line where its weight and drag can be tolerated. In deep sea moorings chain is used to provide damping during the deployment stage of implantment and also to reduce the vertical component of tension at the anchor.

The lower part of mooring lines may often drag on the sea floor and the use of chain reduces the effects of chafing.

Chain can be placed in the mooring line at critical points where higher strength and reliability are needed (between buoy and a series of instruments, between packages etc...). Chain is also used in bridles of surface buoys and as the first length of mooring line where it can damp out some of the wave action. Usually is galvanized and chain does not corrode appreciably over periods of months depending on amount of oxygen present in the sea water. Chain should be proof tested at the rated working load before its use at sea. Figure 6 shows some characteristics of Proof Coil Chain (McKay Company Data Sheet)



1. Mast (see page 12)
2. Parabolic instrument compartment—separates at mid-section.
3. Flotation section
4. Battery and Ballast section
5. Wave dampening plate

NOTE: All sections bolted together, water tight.

PARA-SPAR

Para-Spar buoy is used in satellite communication. Para-Spar is a trade off in performance between a Spar buoy and a Para-Buoy. Vertical stability is within plus or minus 10° motion of the buoy.

Para-Spar response to a wave contour is 50 percent higher than a Spar-Buoy. The center of rotation of the vertical angular motion is closer to the water line than a Spar Buoy by 50 percent. This results in a smaller translation of any mast mounted antenna system.

Para-Spar Buoys incorporate a modular design to facilitate handling, checkout and assembly. The buoy consists of four (4) separate sections: Antenna (or mast), instrumentation & communication, power supply and battery pack, and trim ballast. Each section is a moisture-proof container joined together by a flange. A minimum surface area is exposed above the water line. The instrument section configuration is two paraboloids of revolution, offering the minimum resistance to surface dynamics and enhances the performance of the buoy.

The Para-Spar buoy is constructed of aluminum alloy and supplied with a wave dampening plate and eye for mooring attachment. All materials are treated for maximum corrosion resistance and finished with high visibility epoxy paint.

SPECIFICATIONS ORDERING INFORMATION

Cat. No.	Diameter Parabolic Section (Ft.)	Buoyancy Net (lbs.) (Less Ballast)	Spar Length & Dia. (in.) x (feet)	Weight
2-215	2	190	6 x 12	Dependent upon number sections
4-215	4	700	8 x 30	

When ordering specify:
1. Catalog Number
2. Buoyancy, this can be varied per requirements
3. Diameter of spar when other than 6 or 8 inches is required.
4. Length of Spar section
5. Mast or Antenna size.

Metallic hardware is inserted in the line to connect and disconnect lengths of rope to the buoy, to the anchor, to instrument casings or to each other. The fittings mostly used are: shackles, links, rings, thimbles, and hooks. These fittings should have high strength , be protected from corrosion and be used at the safe working load recommended. Drop forged galvanized steel fittings perform over periods of months in seawater but care must be taken to obviate against galvanic action by coupling dissimilar metals together. In any galvanic cell the anode will be attacked and the cathode protected unless a third material is used to provide cathodic protection.

Vibrations and motion of the line may cause nuts to loosen, cotter pins to shear, and snap "safety" hooks to open. Loose splices of synthetic fibers can chafe over sharp edges. Steel shackles placed in aluminum bails will chew their way through in a matter of days.

Shackles should be of the safety type (safety anchor shackles with nut and cotter pin). Links should be of a larger nominal size than the shackles. An easy way to proof test shackles and links and to detect a defective part is to pull test to the expected working load a number of them connected in series. Loss of shackles due to corrosion of mild steel pins have been prevented by using stainless steel cotter pins (7).

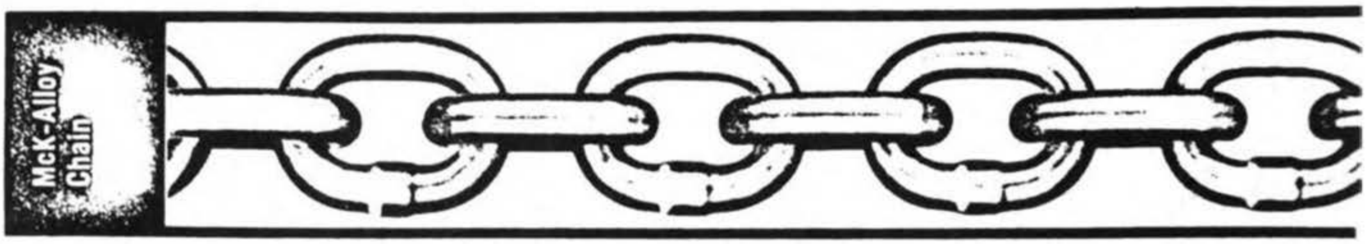
Swivels are sometimes placed in mooring lines. Swivels which can work for long periods under high tension and high hydrostatic pressure, and in the sea corrosive environment are few. Miller Swivels (Figure 7 have been used in a number of mooring lines.

Swivels permit preferential rotation of one of the two components they connect. Their usefulness is based on making certain that

1. The component that should freely turn really does so under working and environmental conditions.
2. The rotation of this component is not detrimental to either one of the connected components.

McK-Alloy Chain

McK-Alloy Chain is superior for all uses to which chain is normally put. It withstands more abuse, has increased abrasion resistance, handles greater loads per size, and is less tiring to workmen in applications where chain must be handled frequently. McK-Alloy Chain does not work harden and should never be annealed.



Description:
Manufactured from a special analysis alloy steel, McK-Alloy Chain has greater hardness, greater strength and greater strength-to-weight ratio making it superior to any other grade of steel chain. Proof-tested.

Applications:
Generally recommended for hazardous overhead lifting. It withstands more abuse, has increased abrasion resistance, handles greater loads per size than any other chain available.

Material:
The controlled analysis alloy steel chain is heat treated to develop a Brinell hardness of 240 to 280 and an average tensile strength of 125,000 lbs. per square inch.

Finish:

Standard — 3/4" size and under — Bright. Over 3/4" size—Self Colored.

Standard Packaging:

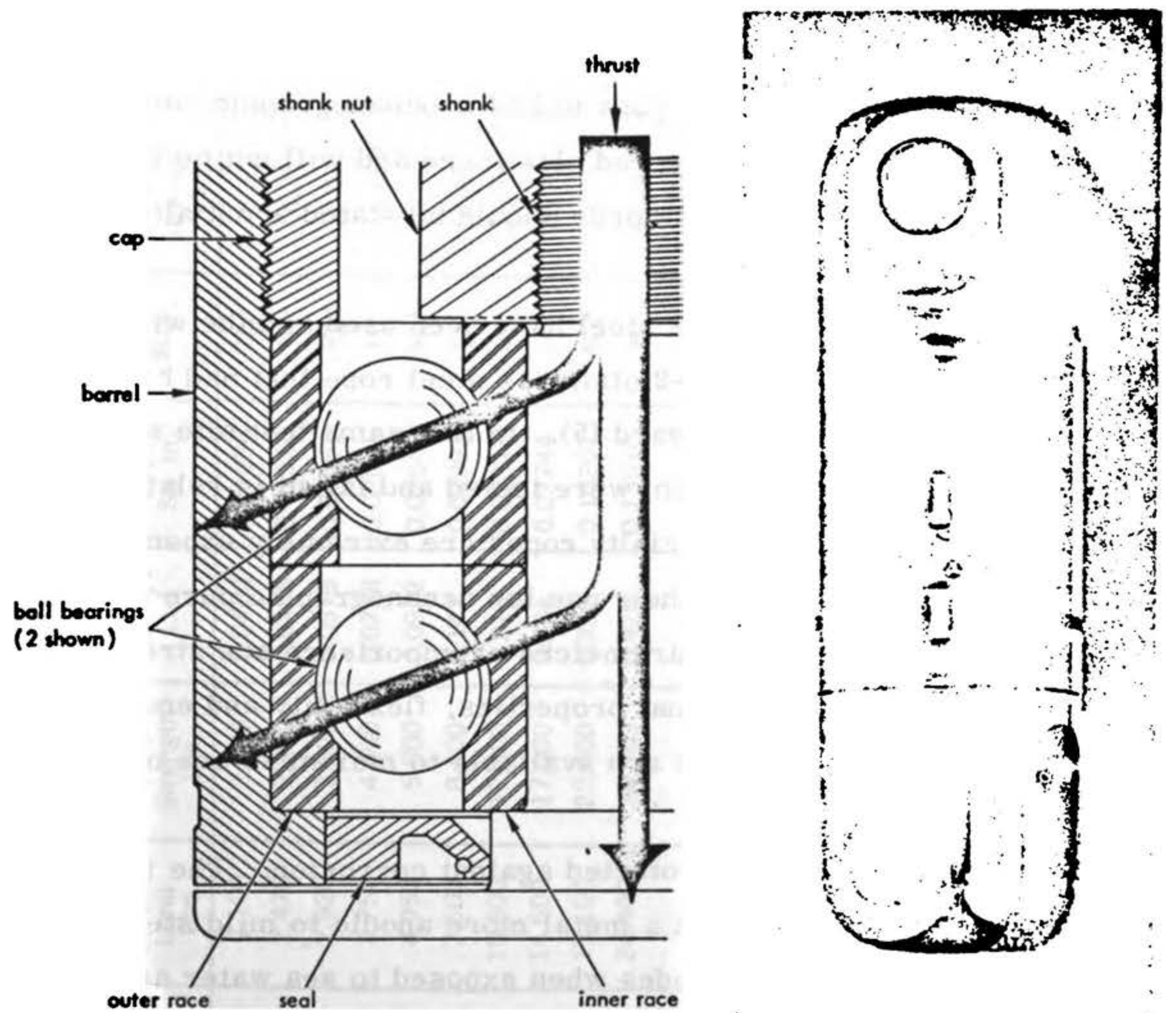
- 1,000 lb. Drums.
- 600 lb. Drums in continuous or cut lengths.

Also available as Assemblies and Sling Chains (See Bulletin A).
(All weights are approx.)

Specifications and Working Load Limits

Trade Size, Inches	Material Size, Inches	Inside Length Link, Inches	Inside Width Link, Inches	Links Per Foot, Number	Weight Per 100 Foot, Pounds	Working Load Limit, Pounds
1/4	9/32	.87	.43	13.5	70	3250
3/8	13/32	1.18	.56	10.2	170	6600
1/2	17/32	1.48	.76	8.1	280	11250
5/8	21/32	1.67	.90	7.2	428	16500
3/4	25/32	2.03	1.15	5.9	627	23000
7/8	29/32	2.25	1.25	5.3	800	28750
1	1	2.68	1.38	4.5	1020	38750
1 1/4	1 1/4	3.62	1.88	3.3	1552	57500
1 1/2	1 1/2	4.35	2.25	2.7	2152	79500
1 3/4	1 3/4	5.07	2.62	2.4	3030	94000
2	2	5.80	3.00	2.1	3960	130000

Figure 6



Patented Miller swivel.

Figure 7

A swivel placed below the surface buoy could for example avoid the transmission of the buoy circular motion in the mooring line, and thus reduce the torsion stresses in the wire rope.

Wire ropes are extensively used in ship and buoy mooring applications (16) and are usually constructed of galvanized carbon steel wire. Stainless steel has been used but with limited success (5, 17, 18, 19). Common cause of failure is by fatigue (7) and successful use at sea depends to a great extent on the knowledge of their properties and limits. Figure 8 lists typical properties of steel rope used for oceanographic purposes.

Steel wire and rope is covered elsewhere and will not be extensively discussed in this report. A few words should be stated about alternate materials of construction.

Various types of stainless steel have been used and the writer investigated the failure of an 18-18-2 stainless steel rope that had been used in a test site off Martha's Vineyard (5). In this same test site special ropes made of Inconel 625 and Titanium were tested and failed in relatively short periods of time (5). These specialty ropes are extremely expensive and the results to date do not warrant their use for oceanographic purposes.

In any mooring line the parameters of importance are strength, weight, size, drag, elongation, rotational properties, flexibility and endurance, and a variety of wire configurations are available to maximize one or more of the variables listed.

Carbon steel has to be protected against corrosion. The individual wires are generally coated with a metal more anodic to mild steel so that the coating preferentially corrodes when exposed to sea water and protects. Zinc is commonly applied (galvanizing) but aluminum also has been used (aluminizing).

A jacket of extruded plastic placed over the rope provides an additional barrier between the rope and the environment. Jacketed ropes have lesser drag and increased fatigue resistance. The plastic has to be tough,

3 x 7 Amgal-Monitor AA Rope

Size	Minimum Breaking Strength Lbs	Approx Elastic Limit Lbs	Min 0.2% Yield Strength Lbs	Wgt/Ft Lbs	Area Sq In.
5/32"	2,800	2,100	2,460	0.0402	0.01096
11/64"	3,300	2,470	2,900	0.0486	0.01326
3/16"	3,900	2,920	3,500	0.0573	0.01561
7/32"	5,000	3,750	4,500	0.0738	0.02011
1/4"	6,600	4,950	5,800	0.0972	0.02649
5/16"	10,000	7,500	8,800	0.147	0.03997
3/8"	14,500	10,800	12,800	0.213	0.05813
7/16"	19,300	14,500	17,000	0.284	0.07744
1/2"	25,500	19,100	22,400	0.375	0.10207
9/16"	32,500	24,400	28,600	0.478	0.13010

3 x 19 Amgal-Monitor AA Rope

Size	Minimum Breaking Strength Lbs	Approx Elastic Limit Lbs	Min 0.2% Yield Strength Lbs	Wgt/Ft Lbs	Area Sq In.
11/64"	3,500	2,620	3,100	0.0507	0.01394
3/16"	4,000	3,000	3,500	0.0586	0.01611
7/32"	5,400	4,050	4,750	0.0795	0.02184
1/4"	6,750	5,050	5,900	0.0997	0.02738
5/16"	10,300	7,700	9,100	0.153	0.04206
3/8"	14,800	11,100	13,000	0.220	0.06015
7/16"	20,000	15,000	17,600	0.304	0.08330
1/2"	25,700	19,200	22,600	0.392	0.10739
9/16"	32,500	24,400	28,600	0.492	0.13491
5/8"	40,300	30,200	35,500	0.602	0.16515
3/4"	57,800	43,300	50,900	0.879	0.24116
7/8"	78,000	58,500	68,600	1.21	0.33202
1"	100,600	75,400	88,500	1.56	0.42833
1 1/8"	124,000	93,000	109,000	1.96	0.53737

3 x 7 Type 304 Stainless Steel Rope

Size	Minimum Breaking Strength Lbs	Approx Elastic Limit Lbs	Min 0.2% Yield Strength Lbs	Wgt/Ft Lbs	Area Sq In.
5/32"	2,800	2,100	2,460	0.0406	0.01096
11/64"	3,300	2,470	2,900	0.0491	0.01326
3/16"	3,900	2,920	3,500	0.0578	0.01561
7/32"	5,000	3,750	4,500	0.0745	0.02011

3 x 19 Type 304 Stainless Steel Rope

Size	Minimum Breaking Strength Lbs	Approx. Elastic Limit Lbs	Min 0.2% Yield Strength Lbs	Wgt/Ft Lbs	Area Sq In.
11/64"	3,500	2,620	3,100	0.0512	0.01394
3/16"	4,000	3,000	3,500	0.0592	0.01611
7/32"	5,400	4,050	4,750	0.0803	0.02184

Figure 8

resist abrasion and pass over sheaves without damage. It should not absorb water under pressure and retain its properties over a reasonable temperature range and be resistant to fish bite. Various materials have been used, polyethylene, polypropylene-polyethylene copolymer, polyurethane and also polycarbonate.

Wire Rope Terminations

Mooring lines must be terminated at the buoy anchor ends and also at points of instruments and sensors. Wire rope terminations for deep sea applications should have the following characteristics:

1. Strength. The termination should not constitute a "weak" point of the line and should be capable to develop, as a minimum, the rated breaking strength of the wire rope itself.
2. Dimensions. Size and weight should remain as small as possible. Mass transition for vibration damping should be considered.
3. Material. The material of the termination should be the same as the material of the wire rope. For example, aluminized steel fittings over an aluminized rope. Copper alloy or cadmium plated fittings should not be used on bare or galvanized steel wire ropes.
4. Ease of fabrication and handling. Terminations should be easy to apply to the rope. Their configurations should be flexible to accommodate different field uses.

   The most commonly used wire rope terminations are:

   - Zinc filled sockets
   - Splices
   - Clamps or clips
   - Swaged fittings.

   Swaging gives the best strength and fatigue performance. It must be, however, critically controlled and performed with specialized equipment.

Electromechanical Wire Cable

Electromechanical wire ropes are used for suspending, towing, mooring and laying where an electrical path is required. There are a large number of types, materials and configurations of electromechanical wire rope consisting essentially of conductors, insulating materials and a cable component referred to as the strength member, whose primary function is to resist the mechanical loads imposed on the cable. Generally the strength member consists of a group of steel wire arranged in a specific manner, although other metals, glass, or synthetic filaments are occasionally used. Nowatzki (21) has compared the materials available for use and are compared in Figure 9.

The majority of underwater cable strength members are currently made of plow steel or improved plow steel. The other materials listed are generally used only when some particular property of a material is of sufficient importance to justify its higher cost or reduced strength relative to the plow steels. Examples of such uses are glass fibers in cables designed to be neutrally buoyant, beryllium copper in nonmagnetic minesweeping cables, aluminum coated steel in high current carrying deep suspension cables, Dacron in cables requiring extreme flexibility, and titanium or the multiphase alloys for long life, highly corrosion resistant cables. The multiphase alloys, which are composed of various proportions of cobalt, nickel, chromium, and molybdenum, also possess excellent fatigue resistance, but they are very expensive. Two such alloys are Elgiloy and Latrobe MP-35N. The use of Dacron, and to a lesser extent glass, as a strength member is limited by the low elastic modulus of the material. Particular care must be exercised in fabricating a low modulus strength member cable to insure that the conductors are wound with sufficient compliance that they do not take up the load before the strength member when the cable is strained.

MATERIAL	MAXIMUM STRENGTH, KSI	CORROSION RESISTANCE	COMMENTS
Low Carbon Steel	100	Basically poor but adequate for 1 to 2 years when galvanized	Easy to fabricate, low cost, readily available
Plow Steel	250		
Improved Plow Steel	275		
Extra Improved Plow Steel	300		
304 Stainless Steel	310	Good in moving water	Non-magnetic
355 Alloy Steel	425	Good in moving water	Poor fatigue resistance
Carbon Steel Rocket wire	450	Poor	Hard to fabricate
Copper Coated Steel	170	Used as insulated Conductors	30 to 40% conductivity
Aluminum Coated Steel	190		20% conductivity
Beryllium Copper	200	Good	Non-magnetic
B-III Titanium	180	Excellent	High Cost
Glass Fibers	500	Good	Subject to Abrasion
Dacron Fibers	120	Good	Low Modulus
Multiphase Alloys	300	Excellent	High Cost

Figure 9 Comparison of Materials

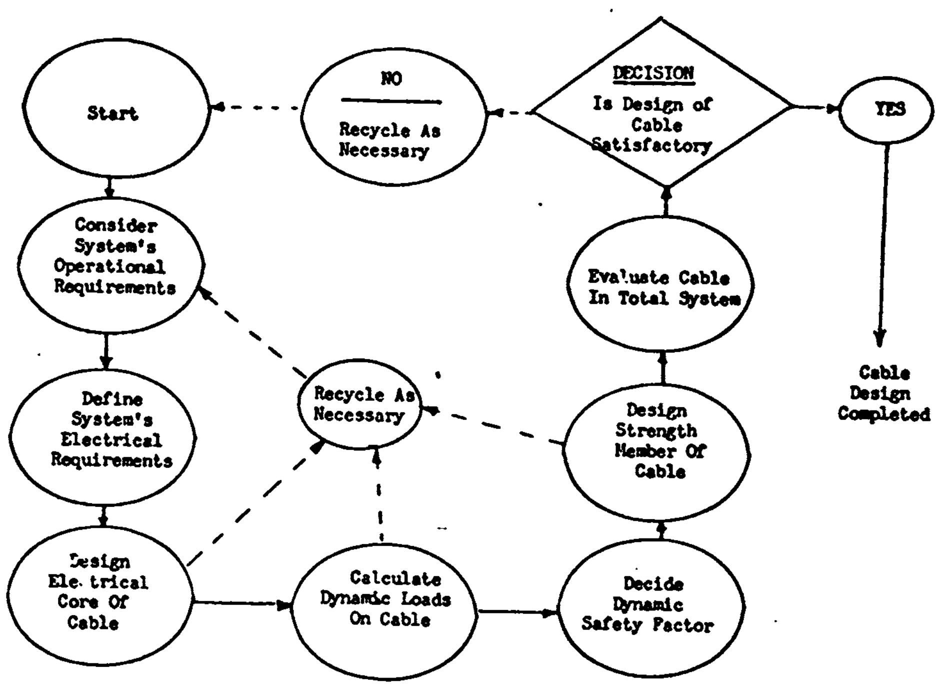


Figure 10 - Analysis sequence for an electromechanical cable.

Tan and Lui (22) strongly recommend a systems analysis and Figure 10 represents a suggested approach. They further state that to extend the usefulness of electromechanical cable two areas require careful attention. First is the identification of suitable materials for the strength elements with as high a free length as possible and with the reliability of steel. This free length is related to breaking strength, cable weight and safety factor. They determined that for aluminum, steel and fiberglass the free lengths would be 68,000 feet, 75,000 feet and 140,000 feet respectively. The second requirement is that dual function cable designs should be employed whenever possible. Dual function cables are cables in which one or more elements perform dual functions. Examples are conductor-strength and dielectric-strength.

Saunders (23) has investigated the use of pressure compensated cables consisting of a sheath with wires loosely coiled inside. The sheath serves three functions: it separates the compensating medium and the external environment, acts as the axial strength member of the cable assembly and pressure compensates the cable assembly.

Young (24) has also recently reviewed the design of electromechanical cables for undersea usage and is a summary of techniques that have been successfully employed in undersea cables.

The terminations of these cables must provide for continuity of current transmission, water insulation and strength integrity, a major problem being leakage at such points and at special break-outs, i.e. for sensors. McCartney and Wilson (25) have looked at the problem of high power transmission cables and connectors and recommend that a pressure balanced oil filled design is the most reliable approach for high power connectors.

Non-Metallic Components

Natural fiber ropes (manila, sisal) which are still in extensive use for on board marine applications suffer from the disadvantage of rotting under prolonged immersion and, they are heavier and, have less strength than synthetic rope.

Synthetic fiber ropes are often used as mooring line components (16). They probably would altogether replace the metallic ropes if they were immune to fish bites. This problem severely limits their use to geographical locations and depths where cuts due to fish bites are not likely to occur.

Synthetic fiber ropes do not corrode nor deteriorate appreciably in seawater, their specific gravity is near unity, they are easy to store and handle.

Synthetic fiber ropes cost approximately three to four times the price of steel ropes of the same working strength.

Synthetic fiber ropes can easily be terminated by standard eye splices over thimbles or by epoxy filled fittings. These terminations develop only 90% of the breaking strength. Haas (20) has reviewed the general characteristics of fiber ropes.

The mechanical characteristics of synthetic fibers are of prime importance. The length is necessary for this determines the scope of the surface buoy and tension for measuring length. This tension T is given by $T = 200\,d^2$ where T = Tension in lbs and d = diameter of fiber rope in inches. It is always necessary to know the past history and to experimentally determine the stretch and elastic characteristics of the rope. The response of the rope to stretch is important to know and Chabbra (26) has recently tested the characteristics of ropes under varying loads.

Common materials used for fiber ropes are nylon, dacron, polypropylene, polyethylene and a newer material Fiber B from Dupont.

A large percentage of synthetic ropes are made of nylon. They have high nominal strength but lose about 10% - 15% of strength when wet. Figure 11 lists the strength versus diameter of stranded nylon ropes. Nylon has the best endurance under repeated loading and the best absorption capacity (15,000 ft lb of energy per pound of rope).

NYLON ROPE SPECIFICATIONS

SIZE Diameter	Circumference	Tensile Strength	Lbs. per 100 Ft.
3/16"	5/8"	1,000	1.0
1/4"	3/4"	1,500	1.5
5/16"	1"	2,500	2.5
3/8"	1-1/8"	3,500	3.5
7/16"	1-1/4"	4,800	5.0
1/2"	1-1/2"	6,200	6.5
9/16"	1-3/4"	8,300	8.3
5/8"	2"	10,500	10.3
3/4"	2-1/4"	14,000	13.8
13/16"	2-1/2"	17,000	16.7
7/8"	2-3/4"	20,000	19.5
1"	3"	24,000	25.0
1-1/16"	3-1/4"	28,000	29.5
1-1/8"	3-1/2"	32,000	34.0
1-1/4"	3-3/4"	36,500	38.5
1-5/16"	4"	42,000	44.0
1-1/2"	4-1/2"	51,000	54.5
1-5/8"	5"	62,000	67.0
1-3/4"	5-1/2"	77,500	81.0
2"	6"	90,000	95.0
2-1/8"	6-1/2"	105,000	111.0
2-1/4"	7"	125,000	129.0
2-1/2"	7-1/2"	138,000	148.0
2-5/8"	8"	154,000	165.0
2-7/8"	8-1/2"	173,000	187.0
3"	9"	195,000	208.0
3-1/4"	10"	238,000	260.0
3-1/2"	11"	288,000	315.0
4"	12"	342,000	370.0

Note: Weights are subject to ±5% variation. Tensile strengths are approximate average. Tests have been made in accordance with Cordage Institute Standard Test Methods. Values shown above are for regular lay ropes.

Figure 11

Dacron ropes have 5 to 10% less nominal strength than nylon but do not lose much strength when wet and are as strong as nylon when immersed. Figure 12 lists the strength vs. diameter of stranded dacron ropes. Dacron is the heaviest of the synthetic fibers used in making ropes. Its specific gravity is 1.38. The initial stretch of dacron ropes is as large as for the nylon ropes (10%). The modulus of elasticity is much larger for dacron than that for nylon and this shows that dacron elongates less than nylon, and absorbs less energy than nylon (7000 ft lbs of energy per lb of rope), however, dacron has very good endurance under moderate repeated loading.

Polypropylene ropes have a shiny appearance. They are hard and stiff to the touch. The average nominal strength of dry polypropylene ropes is only 60% the dry strength of nylon ropes but is slightly larger wet than dry. Figure 13 lists the strength vs. diameter of polypropylene ropes Polypropylene is the lightest of the synthetic fibers used in ropes. Its specific gravity is 0.91, and it floats in water. Polypropylene does not absorb water at all and is an excellent insulator.

The initial stretch of polypropylene is much less than dacron or nylon (about 4%). The elastic elongation of polypropylene absorbs approximately 9000 ft/lbs of energy per pound of rope, and has excellent endurance, abrasion resistance, and good resistance to chemicals. Polypropylene ropes are used for buoyant mooring lines. Attention must be paid in their use to friction heat, polypropylene having a low melting point of 330°F and softening point of 300°F.

Polyethylene ropes are not extensively used in mooring applications. They are smooth in appearance and very slippery. Their average nominal strength is about 50% the strength of nylon and does not change when wet. Polyethylene is slightly buoyant with a specific gravity of 0.95. Polyethylene does not absorb water and is an excellent insulator. The initial and elastic stretch characteristics of polyethylene ropes are approximately the same as the characteristics of polypropylene, however, polyethylene creeps at a much faster rate than any other synthetic. It has comparatively

DACRON ROPE SPECIFICATIONS*

SIZE Diameter	Circumference	Tensile Strength	Lbs. per 100 ft.
3/16"	5/8"	900	1.1
1/4"	3/4"	1,580	1.9
5/16"	1"	2,540	3.1
3/8"	1-1/8"	3,520	4.3
7/16"	1-1/4"	4,900	6.0
1/2"	1-1/2"	6,200	7.6
9/16"	1-3/4"	8,300	10.3
5/8"	2"	10,700	13.3
3/4"	2-1/4"	14,000	17.5
13/16"	2-1/2"	16,800	21.3
7/8"	2-3/4"	19,600	25.0
1"	3"	23,000	29.4
1-1/16"	3-1/4"	26,500	34.2
1-1/8"	3-1/2"	30,300	39.0
1-1/4"	3-3/4"	34,800	45.0
1-5/16"	4"	39,500	51.0
1-1/2"	4-1/2"	50,500	65.5
1-5/8"	5"	61,000	79.0
1-3/4"	5-1/2"	74,000	96.0
2"	6"	86,000	115.0
2-1/8"	6-1/2"	97,500	130.0
2-1/4"	7"	112,000	150.0
2-1/2"	7-1/2"	130,000	175.0
2-5/8"	8"	147,000	197.0
2-7/8"	8-1/2"	162,000	218.0
3"	9"	178,000	245.0
3-1/4"	10"	217,000	300.0
3-1/2"	11"	253,000	355.0
4"	12"	300,000	425.0

Note: Weights are subject to ±5% variation. Tensile strengths are approximate average. Tests have been made in accordance with Cordage Institute Standard Test methods.

**These specifications for Dacron Ropes are based on the improved Type 67. Date of specification issuance 9/11/64. Values are for regular lay ropes.*

Figure 12

POLYPROPYLENE ROPE SPECIFICATIONS

SIZE Diameter	Circumference	Tensile strength	Lbs. per 100 ft.
3/16"	5/8"	800	.70
1/4"	3/4"	1,250	1.2
5/16"	1"	1,900	1.8
3/8"	1-1/8"	2,700	2.8
7/16"	1-1/4"	3,500	3.8
1/2"	1-1/2"	4,200	4.7
9/16"	1-3/4"	5,100	6.1
5/8"	2"	6,200	7.5
3/4"	2-1/4"	8,500	10.7
13/16"	2-1/2"	9,900	12.7
7/8"	2-3/4"	11,500	15.0
1"	3"	14,000	18.0
1-1/16"	3-1/4"	16,000	20.4
1-1/8"	3-1/2"	18,300	23.7
1-1/4"	3-3/4"	21,000	27.0
1-5/16"	4"	23,500	30.5
1-1/2"	4-1/2"	29,700	38.5
1-5/8"	5"	36,000	47.5
1-3/4"	5-1/2"	43,000	57.0
2"	6"	52,000	69.0
2-1/8"	6-1/2"	61,000	80.0
2-1/4"	7"	69,000	92.0
2-1/2"	7-1/2"	80,000	107.0
2-5/8"	8"	90,000	120.0
2-7/8"	8-1/2"	101,000	137.0
3"	9"	114,000	153.0
3-1/4"	10"	137,000	190.0
3-1/2"	11"	162,000	232.0
4"	12"	190,000	275.0

NOTE: *Weights are subject to 5% variation. Tensile strengths are approximate average. Tests have been made in accordance with Cordage Institute Standard Test Methods. Values shown above are for regular lay ropes.*

Figure 13

little energy absorption characteristics (4500 ft/lbs per pound) and does not perform well under repeated loading. Its resistance to abrasion is good. It has the lowest melting point (280°F).

Fibre B is a new polymer just becoming available. It has a very high breaking strength and limited test data indicates that it will be a very attractive material for mooring line applications.

Fiber Glass Ropes are made of glass filaments embedded in an epoxy solution and are possible materials for mooring line applications. Their performance in deep water is being evaluated.

The advantages of glass ropes are:

1. High tensile strength, comparable to mild plow steel (approx. 200,000 psi)
2. Small weight, especially in water (specific gravity of 2.0)
3. Low and predictable elongation
4. Non-corrosive and non-magnetic properties.

The drawbacks of these ropes are:

1. Low energy absorptions
2. Brittleness and poor resistance to alternate bending stresses
3. Some water absorption.

The characteristics of glass ropes can, however, be improved by the addition of urethane or polyethylene jackets. Laboratory tests seem to indicate that some special configurations could eventually compete with steel in mooring lines.

Glass fiber ropes are terminated by epoxy filled fittings. Figure 14 outlines some of the mechanical characteristics of "Glastran" fiber ropes.

Another type of fiber rod wheel was tested in the WHOI buoy site off Martha's Vineyard is a monofiliment rod. This material gave excellent service in this test array. Figure 15 gives a listing of properties of

glastran cable

urethane jacket — typical physical property ranges

urethane elastomers PROPERTIES	VALUES	ASTM TEST METHOD
Sp. vol., cu. in./lb. [cc/kg]	22.0-22.3 [795-810]	
Tensile strength, psi [kg/cm²]	5,000-10,000 [350-700]	D-638
Elongation, %	250-750	D-638
Mod. of elasticity in tension, 10 psi	0.1	D-747
Comp. strength, psi [kg/cm²]	>20,000 [>1400]	D-695
Flex. strength, psi at 50% defect. [kg/cm²]	600-1000 [40-70]	D-790
Impact strength (1/2 x 1/2 in. notched bar, Izod test)	Does not break	D-256
Hardness, Rockwell	M-28-R-60	D-785
Hardness, Shore D	30-55	
Thermal conductivity x 10^{-4} cal-cm/sec-cm²-°C.	5	C-177
Sp. heat, cal/°C-gm	0.42-0.44	
Thermal expansion 10^{-5}/°C	10-20	D-696
Resist. to heat, °F., continuous [°C.]	190 [88]	
Vol. resistivity	2 x 10^{11}	D-257
Dielectric strength, volts/mil		D-149
Short time, 1/8" thickness	450-500	
Step-by-step, 1/8" thickness	450-500	
Dielectric constant, 60 cycles	6.7-7.5	D-150
Dielectric constant, 10^3 cycles	6.7-7.5	D-150
Dielectric constant, 10^6 cycles	6.5-7.1	D-150
Dissipation factor, 60 cycles	0.015-0.017	D-150

abrasion ratings of jacket material

RELATIVE RATINGS FOR LOSS OF WEIGHT DUE TO ABRASION (TABER ABRASION TEST)

Urethane Elastomers	1
Polyester Film	5
High Density Polyethylene	7
Polytetrafluorethylene	10
Nitrile Rubber	11
Nylon 37	12
Low Density Polyethylene	17
Rigid PVC	40
Plasticizer PVC	47
Butyl Rubber	51

The weight loss of URETHANE was given a relative value of 1 (most abrasion resistant) for ease of comparison.

Figure 14

NUPLAGLAS PROPERTIES:

Dia. $^{+.062}_{-.000}$	Weight/foot Pounds	Min. Breaking Strength	Max. Elongation at working load
¼	.057	7,800	.7 of 1%
⅜	.10	12,000	.7 of 1%
½	.17	20,000	.7 of 1%
⅝	.27	30,000	.7 of 1%
¾	.36	40,000	.7 of 1%
1	.64	55,000	.7 of 1%

Larger diameters available; for specific data contact factory.

Physical Properties

Tensile Strength	100,000 to 200,000 psi
Modulus of Elasticity in Tension	6.34×10^6
Flexural Modulus of Elasticity	6.39×10^6
Flexural Strength	125,500 psi
Specific Gravity	1.85 to 2.05
IZOD Impact Strength	17.1 ft. lbs./in of notch

Thermal Properties

Coefficient Thermal Expansion	2.67×10^{-6} inch per inch per °F
Burning Rate (inches/min.)	Self extinguishing
Operating Temperature	250°F Maximum continuous

Chemical Properties

Water Absorption (weight change after 24 hours)	.02
Effect of Sunlight and Weathering	none to slight

Electrical Properties

Dielectric Constant (10^6 cycles)	4.80
Power Factor	
10^6 cycles	0.012
Volume Resistivity, OHMS/CM	
(50% Relative Humidity and 23°C)	$10^{12} - 10^{14}$

Figure 15

Certified laboratory test reports available upon request

NUPAGlass rod. It is susceptible to abrasion and apparently failed when a passing boat abraded and twisted the cable. Such material warrants further examination.

Instruments

Current usage is for alloys with high strength to weight ratio and a number of high strength aluminum alloys are being considered as possible candidates for structural applications in marine environments. High strength aluminum alloys of 7000 series-alloys 7075-T6 and 7079-T6 are comparable on a strength to weight basis to titanium alloys of 100-120 ksi yield strength and steels of 180-200 ksi yield strength. The general reluctance to use these alloys in aqueous marine environments is attributed largely to their susceptibility to catastrophic failure by stress corrosion cracking. New alloys have been developed and testing has been carried out by Walker and Chu (27). They tested 7002-T6, X7106-T63 and 7039-T64. They found:

1. 7002-T6 is susceptible to severe pitting attack in flowing sea water. X7106-T6 and 7039-T64 suffered only mild attack
2. All 3 alloys are subject to S. C. C. in sea water
3. Sensitivity to S. C. C. in all 3 alloys is dependant on microstructural variations with different plate orientations. Specimens having short transverse orientations were the most susceptible to S. C. C.
4. Both 7002-T6 and 7039-T64 alloys exhibited better toughness than X7106-T63 alloy.

Apart from the 7000 series the 5000 and 6000 series have been used where strength is not as critical but better corrosion resistance is required. Table 4 gives a listing of the mechanical properties of materials that have been used or contemplated for use.

Saroyan (28) has reported on the use of coatings on aluminum in sea water. Using the knowledge that the presence of chromate ion adjacent to the surface would inhibit corrosion tests were run by adding sodium chromate to the sea water. Complete protection was obtained during tests and an objective now is to derive the effective range of chromate ion concentration from bulk pigments or pigments incorporated in coatings. Tests with vinyl sealed coatings were variable.

Copper alloys have been used on board ship for sea water usage, but to a limited extent in buoy systems. May and Weldon (29) have reported on the use of copper-nickel alloys for service in sea water and recently Anderson and Efird (30) reported on the addition of chromium to copper-nickel alloys and its effect on the corrosion behaviour. The hardening due to the chromium enhances impingement and erosion resistance and apparently does not affect the corrosion resistance. Ferrara and Gudas (31) independently agreed on the results using 4 different test methods:

a. Multivelocity jet test
b. Rotating Disk Test
c. BNFMRA Impingement Test
d. Rotating Spindle Test.

Although the standard 90/10 and 70/30 copper-nickel alloys are highly resistant to sea water, the liabilities are density, cost and availability.

Standard naval brass and similar alloys suffer from dezincification and great care must be taken to ensure that inhibited grades are utilized.

Monel, although not quite as resistant as the copper-nickel alloys, does have high strength and could be utilized where such properties are necessary. Hastelloy C and Ineonel 625 are also essentially inert.

Stainless steels have been used for instrument cases but the standard 300 series stainless steels are susceptible to cold work and may lose their non-magnetic properties. 316 is the most resistant to pitting and crevice corrosion, but is not immune and cathodic protection schemes are essential. Fiberglass also offers many desirable properties and is used to package glass balls for flotation devices. Prolong exposure has not apparently affected the material.

Lexan is another plastic that has attractive marine properties. However it has a low modulus of elasticity and fabrication may present difficulties.

Titanium is being extensively used. There are problems with stress corrosion cracking with some of the higher strength alloys. Its use is likely to be in the following areas:

a. A structure in which strength to weight ratio is critical
b. A corrosion free material which does not need to be painted or further coated
c. A part which must have high corrosion fatigue strength.

Many investigators have investigated the problem of stress corrosion cracking in titanium alloys and testing schemes will be discussed briefly in the next section.

Mumford and Rock (32) investigated the influence of cold work on the stress corrosion susceptibility of Ti-13V-11Cr-3Al alloy. They noted that although most titanium alloys require the presence of a notch or stress concentration in order to exhibit S. C. C. some titanium alloys do not. This alloy is severely embrittled in the presence of aqueous salt solutions and premature failure of smooth specimens is dependant upon strain rate, applied potential and microstructure but one can reduce the susceptibility by careful control of processing history. By decreasing grain size and avoiding skip plane deformation and by inducing a 110 wire texture will increase the critical stress necessary to initiate a (100) microcrack over that which would have been observed in a random microstructure.

Green and Sedriks (33) have run corrosion tests using a Ti-8Al-1Mo-1V alloy in an endeavor to determine if chloride ions or hydrogen are the critical failure inducing species in the transgranular S.C.C. of high strength titanium alloys. Their technique indicated that hydrogen is responsible for the propagation of stress corrosion cracks.

4. Major Problem Areas

a. Corrosion Fatigue

The prediction and prevention of fatigue failures is a complex subject and the present state of the art leaves much to be desired on the numerous factors influencing fatigue behaviour. It is possible, at least in principle, to overdesign a part by overestimating the expected loads and by keeping the design stresses at low levels. In order to prevent fatigue failure there are three approaches that can be utilized. An analytical approach, an experimental approach and planned inspection of the component during their life. As Masabuchi (2) notes because of the prohibitive cost of experimentation with fatigue in field situations most experimental work is done in the laboratory. Laboratory efforts in the next few years should study the fatigue behaviour of a wide variety of materials and strength levels. More information is needed relative to the effects of notches,environment, crack propagation and stress history with respect to the evaluation of materials. The long range objective should be directed toward incorporating laboratory test data into design criteria.

b. Stress Corrosion Cracking (S.C.C.)

In this area as was previously mentioned only selected topics will be discussed.

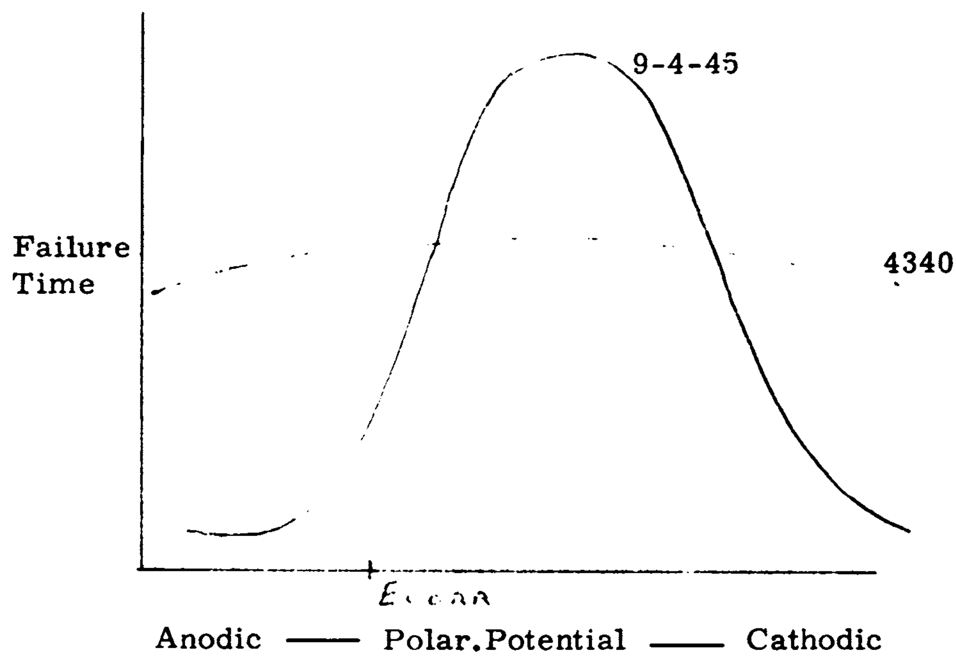
Barth and Troiano (34) have investigated the relationship between cathodic protection and stress corrosion cracking. The brittle delayed failure of high strength steels resulted in the proposal of several different mechanisms:

a) Preferred path anodic dissolution concept

b) Adsorption Theory

c) Hydrogen Embrittlement (HE) mechanism

The failure phenomena is generally characterized as SCC with some tendency to rule out HE as a mechanism of SCC. They used the procedure of polarizing the specimen during the exposure period.



Both alloys are embrittled at strong cathodic polarization but only the 9-4-45 steel is embrittled at anodic polarization. Low and intermediate cathodic polarization resulted in optimum resistance to failure.

There was agreement that H_2 is responsible for failure induced by strong cathodic polarization. High strength martensitic steels are susceptible to HE, some but not all are also embrittled by anodic potentials. It has been argued that under anodic potentials direct deposition of H_2 is electrochemically impossible and as a result other mechanisms of crack initiation and growth have been proposed to account for observed cases of failure. Most involve a form of stress induced dissolution of metal along an active path or the sorption of a damaging specie at the tip of an advancing crack which in turn lowers the fracture energy of the metallic bond. The latter mechanism has been considered particularly for the Cl^- ion. The sorption process is favored by anodic polarization and should be inhibited by application of moderate cathodic potentials (cathodic protection phenomena).

Metal-environment systems exhibiting SCC behaviour under cathodic polarization become less susceptible to delayed failure when moderate cathodic potentials are applied. The explanation given is that the damaging ion is inhibited from being adsorbed by the action of the cathodic potential.

Anions such as O_2, Cl^- may cause shifts in the corrosion potential E_{corr}. Resultant shift in $\underline{I}_{corr}$ can give rise to an even higher rate of hydrogen reduction under cathodic polarization when these ions are present. The apparent increase in H_2 evaluation has been attributed to the presence of the adsorbed species on the surface and substantial cathodic potentials are necessary to bias the competitive adsorption process in favor of hydrogen to cause the anions to be desorbed. Eventually hydrogen adsorption rates become appreciable at increasing cathodic potentials and only then can absorption presumably occur on a scale sufficient to cause delayed failure by a HE mechanism.

This type of reasoning has constituted one of the major objections to a generalized HE mechanism for SCC. The argument is simply that hydrogen cannot be responsible because mild cathodic potentials minimize propensity for SCC but increase the evolution of H_2 and presumably its absorption. It has been shown recently that:

a) H_2 can enter a steel during anodic polarization

b) Enter a steel during free corrosion

c) Be evolved from cracks during anodic polarization of the metal surfaces.

They do not account for the phenomenon of cathodic protection in terms of a HE mechanism.

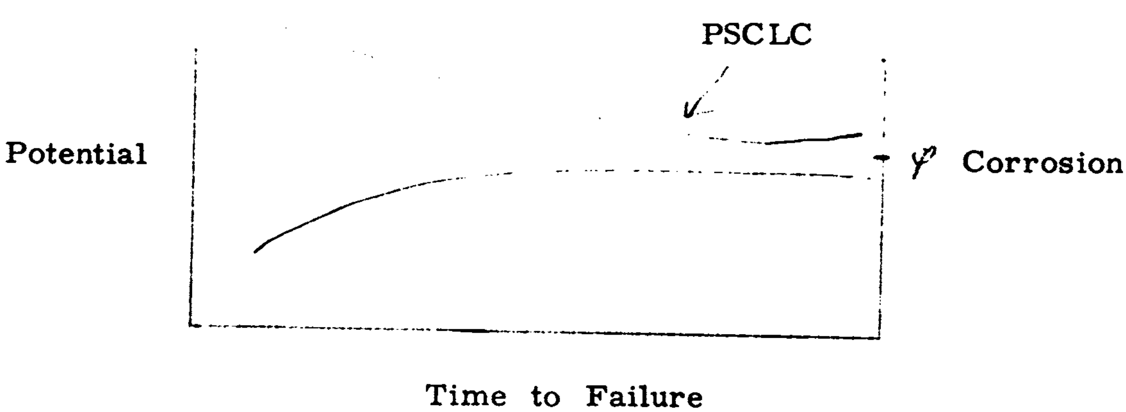
The relationship between brittle delayed failure under stress, hydrogen permeation and applied potential has been examined for a high strength steel in an aerated and dearated 3 N sodium chloride environment. In the presence of O_2 at low cathodic potentials, no H_2 permeation was detected and the brittle delayed failure characteristics were minimized, thus exhibiting the usual behaviour associated with cathodic protection. However, in the absence of O_2, substantial H_2 permeation and brittle delayed fracture were observed at precisely the same cathodic potentials as employed in the aerated solution. Thus a definite 1:1 correlation exists between H_2 availability for embrittlement and SCC. It is concluded by the authors that the phenomenon of cathodic protection does not rule out a H_2 embrittlement mechanism for SCC. Under anodic potentials the relation between H_2 permeation with pitting and brittle delayed failure was confirmed.

Dull and Raymond (11) have looked at the testing procedures to evaluate the relative susceptibility of materials to stress corrosion cracking. They accept the standard definition that SCC is a cracking process that requires simultaneous action of a corrosive environment and a sustained stress. They also note that hydrogen embrittlement is a particular SCC mechanism that is characteristically found in steel and titanium alloys. Two methods are generally used for testing. One method is typified by MIL-STD-1312 Fasteners, Test Methods and Federal Spec QQ-A-337

Aluminum Alloy forgings. This determines the SCC susceptibility of a material to a particular environment. The test specimen is sustained at 75% of U.T.S. in a test cylinder and alternately immersed in dry air and 3.5% Na Cl for a given time.

A second method typified by MIL-S-5002 Surface Treatments QQ-P-416-Cadmium (Electrodeposited) and MIL-R-81294 Remover Paint Epoxy Systems is directed at determining whether or not a manufacturing processing sequence has caused the material to absorb Hydrogen to the extent that H.E. could later be induced. Typical procedure is to statically load the part to greater than its design yield stress for a minimum period of 200 hours.

Another type of method is the cantilever beam test developed by Brown (35) essentially a fracture mechanics test. Here the usual procedure is to establish the so called threshold stress intensity below which stress corrosion cracks will not propagate. It is generally accomplished by testing several precracked cantilever specimens until failure. If specimens do not fail within an arbitrarily selected time interval these data are considered as runout points and are used for establishment of the threshold values. An alternate test being developed is the potentiostatic stress corrosion life curve



Tests have been run and noted that in the 7000 series alloys tested SCC is anisotropic, i.e., dependant upon grain boundary orientation.

The galvanic couple potential is dependant upon the coupling materials, ratio, condition of exposed areas, kinetics of the reactants and the environment. Thus in couples the best materials for resistance to SCC can be determined by superimposing the PSCLC for each specific material and then partitioning the specific potential range.

5. Mooring Results

Deep moored instrument stations have been under development at Scripps Institution of Oceanography and Woods Hole Oceanographic Institute, toname but two for over a decade and it is worthwhile considering the results obtained.

The writer has been involved in mooring failure analyses for WHOI and has followed the implementation of specific design recommendations.

The major corrections recommended were:

- Elimination of galvanic incompatability
- Extensive use of cathodic protection
- Redesign of instrument housings to obviate crevice corrosion
- Use of sealants where redesign impracticable
- Quality control procedures for checking wire rope, chain, shackles, etc.
- Precautions in welding to eliminate weld decay by using inhibited alloys
- Precautions in surface finishing and selection of coatings for instruments and metal structures
- Material changes where required
- Machining precautions for effect on surface finish
- Design for problems of corrosion fatigue and stress corrosion cracking

The results of the improvements in the reliability of such moorings have been substantial.

Sessions and Brown (14) reviewed the results of their experience. They have had problems with fatigue failures of attachment fittings and caution that great care in designing fittings and particularly electrical connections is still required. Careful design was needed for the electrical cable and care has to be taken to avoid salt water shorting out components such as thermistors.

Weldments have to be smooth and O-ring seal seats need care in design. They have had corrosion in crevices, screw threads, as well as O-ring seal areas, but noted that results are better from areas with rougher sea conditions than from smooth seas. This is probably due to water movement flushing out crevices preventing differential cell corrosion to take place. Three moorings have failed due to fatigue failure of the mooring strap on the buoy hull and this is somewhat similar to straps which failed on a buoy from W. H. O. I. Problems have also been encountered with antifouling coatings.. The depth sensor circuits have not operated satisfactorily but the reason has not been determined. In general the performance of their buoy systems has shown improvement.

6. Conclusions

It is possible to maintain buoys operating for periods of one year. Subsurface moorings would show higher reliability than surface moorings as one decouples wave effects. If meteorological data is also required then surface buoys are essential.

Standard wire rope material is still a plain carbon steel. Ropes made of more corrosion resistant material such as titanium, stainless steel, Inconel 625 have failed in relatively short periods of time. More careful care in manufacture could eliminate some of these problems. A titanium wire rope could be made of a material less susceptible to stress corrosion cracking.

Corrosion Fatigue and S. C. C. are still major problems to be resolved in the next decade. The development of accelerated testing methods to verify material selections is a necessity particularly for periods of greater than 1 year. The relationship between dissolved oxygen content in sea water and corrosion susceptibility needs greater definition. This becomes important as greater interest is focussed on the coastal zone and then other contamination factors which could influence material selection need to be evaluated.

Installation of instruments introduces problems of galvanic incompatability and cathodic protection schemes need to be quantitatively analyzed. Some of the newer alloys, particularly stainless steels, which are claimed to be more pit and crevice corrosion resistant need to be extensively evaluated.

The past few years have shown intense effort in the theoretical aspects of failure mechanisms and these now have to be incorporated into the practical aspects of materials surviving in an ocean environment.

REFERENCES

1. B. F. Brown and L. S. Birnbaum, "Corrosion Control for Structural Metals in the Marine Environment, N. R. L. Report 6167 (1964).
2. K. Masabuchi, "Materials for Ocean Engineering," MIT Press (1970).
3. H. O. Berteaux, E. A. Capadona, R. Mitchell and R. L. Morey, Trans. Marine Tech. Soc., p. 671 (1968).
4. H. O. Berteaux and R. L. Morey, "Experimental Analyses of the Failed Wire Ropes of the Submersible Alvin System," W. H. O. I. Tech. Memo 2-70 (1970).
5. R. L. Morey and H. O. Berteaux, Proc. 3rd Int. Congress on Marine Corrosion and Fouling (In Press).
6. H. O. Berteaux and R. G. Walden, 6th Annual Preprints, M. T. S. (1970).
7. R. L. Morey, "Evaluation of Long Term Deep Sea Effects on Mooring Line Components," MIT/C. S. Draper Lab Report E-2748 (1972).
8. L. E. Bivins, 8th Annual Preprints M. T. S., p. 621 (1972).
9. H. H. Uhlig, "Corrosion and Corrosion Control," Published John Wiley, New York (1963).
10. J. M. Dahlen, "Oceanic Telescope Engineering Program," MIT/C. S. Draper Lab Report E-2367 (1970).
11. D. Dull and L. Raymond, Corrosion 29, 205 (1973).
12. W. H. Munse, "Fatigue of Welded Steel Structures," Welding Research Council (1964).

13. D. Crisp, Proc. 3rd Int. Congress on Marine Corrosion and Fouling (In Press).

14. M.H. Sessions and D.M. Brown, 7th Annual Preprints, M.T.S. p. 93 (1971).

15. F. LaQue and A. Tuthill, Trans. of Soc. of Naval Arch and Marine Engineers, 69 (1962).

16. J.E. Smith, "Structures in Deep Ocean Engineering," Eng. Manual for Underwater Construction, U.S. Naval Civil Eng. Lab. (1965).

17. M. Peterson and T. Lennox, "The Corrosion Behaviour of Stainless Steels in Sea Water," N.R.L. Mem. Report 1795 (1967).

18. T.J. Lennox, "Corrosion Analyses of 304 Stainless Steel Wire Rope and Fittings from a NOMAD Buoy Mooring System," N.R.L. Memo. Report 2045 (1969).

19. H.T. Wood, "A Survey of Publications Dealing with Corrosion in Wire Rope," Inst. of Ocean Science and Eng. The Catholic University of America Report 71-3 (1971).

20. F.T. Haas, Handbook of Ocean and Underwater Engineering, 4-42, Publ. McGraw Hill, New York, (1969).

21. J.A. Nowatzki, 7th Annual Preprints, M.T.S., p. 147 (1971).

22. F.C. Tan and C.L. Liu, Paper given at Offshore Technology Conference (OTC 1636), (1972).

23. W. Saunders, 8th Annual Preprints, M.T.S., p. 23 (1972).

24. R.E. Young, 8th Annual Preprints, M.T.S., p. 39 (1972).

25. J. McCartney and J. Wilson, 8th Annual Preprints, M.T.S., p. 467, (1972).

26. H.O. Berteaux and N.K. Chhabra, "Computer Programs for the Static Analysis of Single Point Moored Surface and Subsurface Buoy Systems, Tech. Report 73-22 (1973).

27. G. Walker and H. Chu, Corrosion 28, p. 233 (1972).

28. J. Saroyan, Proc. of 3rd Int. Congress on Marine Corrosion and Fouling (In Press).

29. T.P. May and B. Weldon, Proc. of Int. Congress on Marine Corrosion and Fouling (1964).

30. D. B. Anderson and K.D. Efird, Proc. of 3rd Int. Congress on Marine Corrosion and Fouling (In Press).

31. R.J. Ferrara and J. P. Gudas, Proc. of 3rd Int. Congress on Marine Corrosion and Fouling (In Press).

32. Mumford and Rock, Corrosion 29, 146 (1973).

33. J. Green and A. Sedriks, Corrosion 28, p. 226 (1972).

34. C.F. Barth and A.R. Troiano, Corrosion 28, p. 259 (1972).

35. B.F. Brown, Materials Research and Standards, p. 129 (1966).

36. U.S. Naval Civil Engineering Laboratory Report R531 (1967)

ALLEVIATION OF CORROSION PROBLEMS IN DEEP SEA MOORINGS

by

R. L. Morey and H. O. Berteaux

C. S. Draper Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02412

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

Alleviation of Corrosion Problems in Deep Sea Moorings

R. L. Morey[1] and H.O. Berteaux[2]

A number of single point taut moorings have been lost necessitating an analysis of all components in the mooring line. Systematic examination of retrieved components has indicated the presence of corrosion at all stages in the mooring from the surface buoy to the anchor. This includes the various instrument housings and attachments, the mooring line and its terminations, and the interconnecting hardware such as shackles, links and chain. Pitting type corrosion, crevice corrosion, galvanic incompatibility, corrosion fatigue and stress corrosion cracking have been identified and design changes made.

Failure analysis of mooring line specimens exposed in a shallow water experimental array to long term environmental effects has helped the systematic identification and classification of failure modes. Rope specimens which have been tested in this shallow water (120 feet) evaluation program included jacketed and unjacketed carbon steel, modified stainless steel (18-18-2), titanium, Inconel 625, and fiberglass. The characteristics of such materials are evaluated and a comparison made for the newer materials with the standard carbon steels.

The diagnostic capability obtained from this continual analysis has been used to advantage to recommend design and material changes resulting in an improved resistance to environmental deterioration.

Key Word Moorings

---

1. Introduction

Single point taut-moored systems are used for the placement of instruments of oceanographic and meteorological data. Such buoy systems are deployed each year in the Atlantic Ocean by the Woods Hole Oceanographic Institution for the Office of Naval Research and are retrieved on a regular basis.

These systems sense and record the velocity fields of winds and ocean currents in situ and over long periods of time. Long-term series measurements thus obtained enable the physical oceanographers to establish a correlation between experimental data and the theoretical concepts of oceanic flow.

The type of mooring consists either of a single surface or subsurface float and a taut mooring line. (Fig. 1) Recording instrumentation is placed on the float and inserted in the line at various depths.

C.S. Draper Laboratory[1]
Massachusetts Institute of Technology
Cambridge, MA 02142

Ocean Engineering Department[2]
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

The mooring line is generally part wire rope and part synthetic fibre rope but can be all fibre rope depending on the prevalence of fish bite in a particular area.

The compound mooring line configuration has the advantage of low cost, ease of handling at sea, prevention of possible failures due to fish bites in the upper part of the line, reduced excursion and consequently low noise level on the scientific data.

The reliability of single point moored buoy systems depends on the performance of each of the mechanical components in series in the mooring line - wire rope, chain, hardware, nylon rope, instrumentation casings, etc.

In order to improve this reliability one must positively identify defective parts prior to use and also eventually establish the modes and causes of failure of components while in use. If failure of a component results in failure of the entire mooring a back-up recovery system (1) can be used to recover the remaining part of the failed mooring lying on the ocean floor. The failed component thus retrieved can then be subjected to macro and micro examination to determine the failure mode.

Reliability improvement results in greater mooring life expectancy. This will tend to minimize expensive ship time to retrieve, service and re-implant the systems. Furthermore as the capability for long term data storage increases the demand for longer life of the components that make up the total system is also increasing.

A major cause of mooring failure is corrosion. Other mechanisms of deterioration such as tensile or shear loading effects, fatigue and material defects are often present and must also be considered. Furthermore there is always an interaction between the various failure mechanisms and any one failure may be a combination of one or many factors. For example, a cable may fail by corrosion fatigue, corrosion cells may be set up between an instrument and associated hardware such as shackles, bridles, chains, etc., or can be compounded by tensile effects producing stress corrosion. Failure can be due to mechanical or environmental effects grafted onto tensile fatigue and corrosion factors.

In September 1967 a buoy with a fractured wire rope was found 250 miles off station. This buoy was recovered and an analysis made of the failed cable (2). In this case the conclusion was that deformation had occurred at the point of fracture probably caused by a kink and that subsequent fatigue compounded by corrosion caused the failure of a number of wires in this area. Due to a reduction in the ultimate strength of the wire rope it broke with the balance of the wires failing in tension.

As part of the engineering effort to improve the reliability of deep sea moorings, a continuing program of metallurgical analysis was then inaugurated (3). This paper presents a number of typical case studies, and reviews briefly the theoretical aspects common to most of the failures considered, and outlines the corrective means of prevention resulting in increased reliability of deep sea moorings.

2. Environmental Effects

Preponderant environmental effects resulting in accelerated deterioration of mooring components are:

Corrosion: for long life, the corrosion behaviour of a component can be the limiting factor. The intrinsic corrosion resistance is not th only concern but also the often inadvertent coupling that can take place between differ materials, e.g. a taut stressed cable in contact with a slack drifting cable has caused failure by galvanic action (4). Corrosion

[1] Figures in parentheses indicate the literature references at the end of this paper.

tendencies are difficult to predict and there is still a need for testing in the ocean prior to use. For simple corrosion one can make allowance for strength reduction due to loss of material but to overlook other factors such as stress corrosion cracking, hydrogen embrittlement, pitting corrosion, galvanic coupling, etc., could be disastorous.

Fatigue: As has been pointed out (5) surface buoy motion can induce repeated bending and torsion stresses in points of attachment of the mooring line as well as cyclic tension stresses in the line itself. Furthermore, in strong currents, vortex shedding can create a strumming situation with high frequency lateral loading. Being in a corrosive medium, the problem is compounded and the effects of corrosion fatigue are greater than the effects produced by either corrosion or fatigue acting singly. Such failures can generally be traced to stress raisers such as sharp edges, pits, nicks, etc.

Biological attack: At the upper portion of the line, fouling is present and can lead to the initiation of pits on surfaces. This problem is actively being studied at W.H.O.I. to determine the mechanism of corrosive attack.

Sharks and several benthic species attack mooring lines, gashing the protective plastic jacket of wire ropes and exposing the underlying steel cable. (Fig. 2) Although some corrosion has occurred at the cuts, wire rope failures due to fish attacks have not yet been identified. As can be expected on synthetic fibre ropes, the problem is more acute and losses of moorings due to fish bites have occurred.

3. Analysis of Retrieved Components

Metallurgical and mechanical analysis was performed on buoy systems components which had been exposed to the environment either as part of regular deep sea moorings or as part of special test moorings deployed in shallow waters. The shallow water test array of the Woods Hole Oceanographic Institution which was implanted seven miles off Cuttyhunk, Massachusetts from 1969 to 1972, enabled specimens of different materials and configurations to be submitted to prolonged environmental exposure. A typical test buoy is depicted in Figure 3. The response of the components evaluated in this way differs from that of components inserted in deep sea moorings of finite duration in that the effects of the environmental exposure extend over a longer period, with a greater prevalence of marine fouling, and with smaller temperature gradients along the line length. This evaluation serves a valuable purpose in that the effects of mechanical loading and corrosive media can be studied, problem areas identified, new materials appraised and modifications incorporated to improve the reliability of deep sea moorings.

Upon recovery of these moorings the components or specimens were examined to determine the degree of deterioration and when applicable establish the mode of their failure. This systematic analysis was performed primarily at the C.S. Draper Laboratory of the Massachusetts Institute of Technology and at the Ocean Structures, Moorings and Materials Section of the Woods Hole Oceanographic Institution.

Components or specimens were visually examined immediately after retrieval to detect gross features of deterioration (corrosion, fish bites, kinks, wire breaks, etc.). The ultimate tensile strength of representative samples were often determined to establish the percentage of strength loss. The bitter ends and/or the fracture faces of components were also subjected to exhaustive macro and micro examination and metallurgical testing in order to understand the mode and ascertain the cause of the failure. In broken wire rope, for example, the strands are carefully disassembled and the fracture face of each wire is examined to determine nature of the break. Samples are photographed in the raw state and after solvent cleaning are inspected by a 100X stereo microscope. Stainless steel specimens are often cleaned in dilute nitric acid.

When necessary, cross-sections of specimens are prepared metallographically for study. A scanning electron microscope has been found useful in determining the fracture path in those instances where subsequent corrosion has not damaged the fracture face.

The following, outlines in the form of a series of case studies, some of the typical and more interesting modes of deterioration and failure so far encountered.

4. Case Studies

1. Wire Rope Assemblies. Wire rope is extensively used in deep sea moorings as it is easy to store and handle, is moderate in cost, has low elongation characteristics and resists fish attack. It is, however, susceptible to mechanical damage (kinks), fatigue and corrosion of the wires. The success of mooring lines using wire rope depend to a great extent on the type of wire rope selected and on the means of protection from the environment (6). Furthermore, wire rope terminations are critical and often are an additional cause of wire rope assembly failure. Deterioration and failure due partly or entirely to corrosion effects has been noted:

a. Deep Sea Moorings: The initial moorings used Nicopress fittings for terminations and bare steel wire rope with a relatively high failure rate. A change to a better termination (Fig. 4), an improved type of rope (torque balanced), and larger size with zinc coated wires, has resulted in a very low failure rate within the limits of present life expectancy (6 months). As an additional protection against corrosion and for better hydrodynamic characteristics, the rope is covered with a plastic jacket. Usually, this is a polyethylene/polypropylene copolymer but other coatings can be used, such as urethane and polycarbonate. Fish bite is still a problem and Fig. 2 shows a severely slashed wire rope jacket retrieved from mooring 314. Fish bite has not as yet caused a cable failure although the inside is flooded. The construction of any wire rope causes the presence of a multitude of crevices which should permit crevice corrosion to occur. This, being like pitting corrosion, an autocatalytic type of corrosion. As noted by Fontana (7), the driving force for the reaction to continue is the need to maintain electroneutrality. The overall reaction involving the dissolution of metal M and the reduction of oxygen to hydroxide is as follows:

$$\text{Oxidation} \quad M \longrightarrow M^{+} + e$$

$$\text{Reduction} \quad O_2 + 2H_2O + 4e \longrightarrow 4OH^{-}$$

Initially these reactions occur uniformly both within and outside the crevice. Charge conservation must be maintained and a hydroxyl ion is produced for every metal ion in solution. After a short time the oxygen within the crevice is depleted and as dissolution of metal produces an excess of positive charge in the solution, this must be balanced by the diffusion of chloride ions into the crevice to maintain electroneutrality.

For metals commonly used in underwater applications, hydrolysis takes place.

$$M + Cl^{-} + H_2O \longrightarrow MOH + H^{+}Cl^{-}$$

Chloride and hydrogen ions accelerate the dissolution rate and consequently the rate of oxygen reduction on adjacent surfaces also increases. However, as these gashes are generally narrow, it is postulated that there is a limiting exchange of water within the jacket and outside. Corrosion does occur but generally at a very low rate due to the non-availability of replacement ions. On occasions damage to the jacket has occurred during deployment and if severe enough the corrosion can also be severe. The results from the shallow water test site does show that for the same type of rope, jacketed samples outlast bare samples by a factor of approximately 4:1.

Fatigue failure have occurred with the termination fitting. Until recently they were manufactured from a 1017 carbon steel eyebolt with a drilled hole in the shank. The shank is swaged over the wire rope and the resultant strength of such a bond should exceed the rated strength of the wire rope. Station 374 was set in April 1971 and failed within 7 days at a depth of 500 meters below the surface under generally calm conditions. The individual wires were examined and most had failed in shear leading to the conclusion that an improper swaging operation had taken place. This was not a corrosion problem but only indicates the need for careful examination of each failure. A number of moorings are set at W.H.O.I. site D approximately 100 miles south from Woods Hole with few recent failures in wire rope. Stations 403 and 405 set October 1971 failed at the termination with the shank failing in fatigue, after 14 and 60 days respectively. Occasionally, the Gulf Stream shifts and these particular moorings were subjected to higher currents and consequently greater stress than for which they were designed. The endurance limit was exceeded and the failures were due primarily to fatigue but also compounded by the environmental effects of the ocean. To overcome the fatigue problem in the termination itself, the end fitting had to be redesigned. It is now made of 1040 steel with a heavier wall thickness to increase the endurance limit of the steel. Such fittings are now routinely being used.

b. Shallow Water Array Moorings: Wire rope evaluation has so far been the principal objective of the shallow water tests. For such rope flexibility, resistance to impact loading and resistance to hydrodynamic drag are important features. The latter factor can be reduced somewhat by using a swaged wire rope which has a smaller diameter for a given number of wires. The swaging operation does indent wires and tests in the shallow water array in this configuration showed that fatigue cracks had propagated from such areas.

For long life, the corrosion behaviour of a wire rope can be the limiting factor and this has prompted an evaluation of newer materials.

Two samples of Inconel 625 1/4" - 7 x 19 aircraft construction wire ropes were tested and retrieved after 279 and 294 days on station. Broken wires were noted and part of the rope had "bird caged." This can happen with a sudden load release or with cyclic loading the rope can rotate and separate the strands. The wires that were broken were not the core wires and examination showed that these wires had broken with brittle type fracture. It appears that this configuration rather than corrosion has caused the failures noted. It would be desirable to test this material in a more standard type of configuration such as a 3 x 19 torque balanced rope.

Three samples of an 18/18/2 (Cr, Ni, Mo) modified stainless steel have been tested at the shallow water site and failed after approximately 12, 60, and 75 days respectively. All three samples were 3/16" 3 x 19 torque balanced cable and the first two samples failed at the termination which was a standard swaged steel eye bolt. A defective swaging operation had caused shearing of the wires and premature failure of the first rope tested. The second rope failed at the termination due to fatigue. The third rope utilized stainless steel aircraft type swaged terminations and specialized grips to transfer bending motion away from the termination. The wires failed in brittle fracture and metallographic examination shows cracks in the wire both at the point of failure and away from this zone. It was thus concluded that the problem belonged more to the actual wire drawing process than environmental effects.

A titanium wire rope 1/4" 7 x 7 configuration consisting of 6 Al 4V wires was tested and failed after 27 days. Each individual wire was resin coated and the end terminations consisted of epoxy filled socket grips. The rope failed completely approximately 1" from one termination in a brittle fracture and partly failed at the other termination. Micro hardness tests indicated that work hardening was not a factor. As has been shown (8) such alloys are susceptible to stress corrosion cracking which can be related to microstructure and the effect of alloying elements such as aluminum. The local embrittlement is generally associated with propagation of stress corrosion cracks and further tests are planned with this rope to more fully identify cause of failure.

A sample of 1/4" 1x7 jacketed glass fibre rope with epoxy filled end fittings was tested and failed at the end fitting after 146 days. Two samples of Nupaglass monostrand fibre rope were tested and failed after 370 days and 618 days respectively. As this rope shatters on failure, it is difficult to determine the cause but may be due to hydrolytic effects. In comparison, it should be noted that a torque balanced 3 x 19 jacketed mild steel cable set in May 1970 is still on location whereas another sample with deep gashes to simulate fish bite failed after 367 days. Also two samples of 1 x 42 G. A. C. jacketed cable failed after 533 and 581 days respectively by fatigue at the termination.

2. Mooring Line Points of Attachment

a. Attachment to Buoy: Mooring 228 was set in the North Atlantic on December 19th, 1968. The surface buoy had disappeared when time came for recovery on April 17, 1969. Recovery was achieved by use of a back-up recovery system. This compound mooring used 1 x 42 UHS steel cable and 5/8" nylon rope. Failure occurred at a 1" diameter stainless steel bolt on the rigid bridle under the surface buoy which is used as a connection point from the mooring line to the buoy (Fig. 5). The tension record on a tensiometer close to the surface showed the highest recorded tension to be 4,000 lbs. This bolt has been previously used and the actual immersion time is difficult to ascertain.

The fractured face showed a relatively smooth surface, covering approximately seventy percent of the area while the balance had a rough crystalline appearance. The smooth surface was marked with "beach marks" more pronounced at the edge but extended across the surface. Micro examination at 500X showed no signs of ductility in the smooth area but was evident in the region that broke with a crystalline appearance.

It was concluded that the bolt had failed in fatigue and that it had followed the three stages of the fatigue process:-

1. Initial fatigue damage leading to a crack initiation.
2. Crack propagation until the remaining uncracked cross-section of the part became too weak to carry the load imposed upon it.
3. Final sudden fracture of the remaining cross-section.

As this failure occurred in sea water, the failure could more properly be called corrosion fatigue. Microscopic examination was carried out to determine the cause of the initial crack. The presence of sulfide/selenide stringers indicated that this material was a free machining grade steel and was verified by analysis to be Type 303. Surface examination in the vicinity where the crack originated showed the presence of deep pits, often as an extension of the sulfide/selenide stringers. It was concluded that the fatigue crack started at a pit site caused by corrosion due to the inhomogeneities present in the form of the stringers. In corrosion fatigue the rate of crack propagation is enhanced due to the effect of cyclic stresses and corrosion, and also the rate of corrosion is affected by the properties of the surface film. The film on stainless steel once broken in sea water cannot be reformed. The pitting type of corrosion is one form of electrochemical corrosion being an autocatalytic type of anodic reaction. This type of failure being due to corrosion fatigue, step 2 of the classical fatigue process outlined above, could be modified in that the combined action of corrosion and cyclic stresses damages the steel to such an extent that the fatigue process is accelerated and that even if the corrosive environment were entirely removed, fracture would still result.

Unfortunately, the prediction and prevention of fatigue failure is a complex subject and the present state of the art leaves much to be desired on the numerous factors, influencing fatigue behaviour. It is possible, at least in principle, to overdesign a part by overestimating the expected loads and by keeping the design stresses at very low levels. In order to prevent fatigue failure there are three approaches that can be utilized. An analytical approach, an experimental approach and planned inspection of the component during their life. Due to insufficient data, a purely analytical approach has severe limitations. An experimental approach is expensive and time consuming but an inspection and monitoring method can be beneficial. In this application, the material was changed to a 316 type stainless steel which eliminates the presence of stringers and although they are susceptible to a pitting type corrosion, they are less susceptible than the steels they replaced. The components are routinely inspected after each retrieval.

b. Attachment ot Instruments Inserted in the Line: Another example of a problem with stainless steel is the failure of a bail of a tension meter housing on Station 323. This mooring was set January 4, 1970 and failed March 9, 1970. This bail had previously been used for 4 months. The mooring was on the ocean bottom which caused also the collapse of the instrument housing not being designed to withstand high pressure. As noted in Fig. 7 the bail is in the shape of a U-bolt passing through the end plate of the case and is held in place by nuts on top and bottom of the plate. To prevent nut rotation, they were tackwelded onto the bolt. The fracture face of this bail was examined using a scanning electron microscope which showed that failure had occurred by stress corrosion cracking. The requirements in this case are a tensile stress and a corrosive medium. Different materials are attached by different media and stainless steels are subject to cracking in a chloride environment. Analysis showed that the material was also a free machining grade type 303 stainless steel which after welding is susceptible to intergranular corrosion. This attack is localized at and adjacent to grain boundaries with relatively little corrosion of the grains. Unless stabilized steels are used, welding causes chromium depletion at the grain boundaries. Metallographic sectioning showed that this was the case and that intergranular corrosion was present. Pits were noted at the surface and apparently at least one was deep and sharp enough to initiate a stress corrosion crack. This is generally a very rapid mode of deterioration. Brown has pointed out the problems in quantifying the index of resistance to stress corrosion cracking, an index comparable to the arbitrary 0.2% offset yield strength index of resistance to plastic deformation. It is possible that cathodic protection measures may help in coping with stress corrosion cracking but not enough data is available to generalize.

Another failure occurred in Station 322 and examination of retrieval hardware showed failure was at a current meter utilizing same type of bail. The problem of intergranular corrosion can be overcome and in this case, new bails were made of 316 stainless steel and the nuts were epoxied onto the threaded portion. All instruments were so modified but on station 373 a current meter failed. This bail was also examined by a scanning electron microscope and showed also that the bolt had failed by stress corrosion cracking. In this case, the initial crack had occurred at the root of the thread. These threads are machined, not rolled, and the root in this case was rough and sharp. This was sufficient to form a crevice and a pit had formed and again a stress crack had propagated causing failure. The solution in this case was to redesign the bail and one typical modification was to use a threaded eyebolt and another was to cathodically protect the bail with an expendable block of zinc.

3. Mooring Hardware

a. Shackles: 1/2" round pin anchor shackles with galvanized steel cotter pins were originally used to connect the mooring components. The pin of the shackle is held in place by the cotter pin, but tests run in the shallow water test site showed that the cotter pin could corrode away, allowing the shackle pin to fall out. Corroded and abraded cotter pins were found on the moorings, corrosion being accelerated by motion. Tests were run on alternate materials for cotter pins in both deep and shallow water moorings and a change was made to use type 316 stainless steel. A further modification was made in that the shackle pin was initially replaced by a bolt held by a "stop nut" with a nylon insert. However, the nylon insert created a further problem of crevice corrosion so that the final configuration is now to use stop-nut without a nylon insert, backed up by a 316 stainless steel cotter pin.

b. Toroid Bånds: These bands are used to hold the supporting structure on the syntactic foam surface buoy. Mooring 379 had a band that was completely broken and a second band that had partly fractured. These bands are made of 304 stainless steel and although the cracking had occurred near the welds there was no evidence of improper welding techniques. There is a fibreglass coating over the band and the welded area was rought. It was concluded from the nature of the crack and the presence of further cracks away from the fracture zone that cracking had occurred due to crevice corrosion and failure was due to corrosion fatigue. It was recommended to the manufacturer to smooth the welded areas, by polishing if necessary to reduce the presence of roughened areas.

c. Brummel Hooks: These hooks are used for attaching glass balls to a mooring line having a quick connect/disconnect facility. In this way, glass balls in nylon nets can be quickly attached to a line as it is being paid out from the ship, such balls being essential for buoyancy purposes. These hooks are only available in manganese bronze in a composition that is susceptible to dezincification or selective corrosion. In this type of corrosion, which is noted in brasses and bronzes containing more than 15% zinc, the zinc is corroded away, leaving behind a porous copper mass of little strength. The slow disappearance of zinc from the alloy can be disastrous, as apart from a change in color which can be attributed to tarnishing, there is no marked change indicating that corrosion is taking place. The loss in tensile strength caused the hooks to fracture with the loss of balls. As these hooks are not available in alternate materials, a time limit is now placed on the time of exposure. They are used once on 4 month moorings and if a mooring is expected to remain on station for more than this period, alternate means of attachment of glass balls to the line are used. Such a method is to place the glass balls in polyethylene containers which are then bolted onto chain.

4. Instrument Hardware

The connecting hardware on the instrument cases is usually stainless steel whereas the terminations of the wire rope are mild steel which has led to problems with galvanic corrosion. This problem has generally been alleviated by careful consideration of the general rules:-

a) Use a combination of materials as close together as possible in the galvanic series.
b) If dissimilar metals are to be used, ensure that a large anode is coupled to a small cathode.
c) Coat cathode only and not the anode.
d) If possible, install a third non structural metal, e. g. zinc, anodic to both materials in galvanic contact.

The instrument cases are generally extruded aluminum alloys 7075-T6 or 6061-T6 which are hard coat anodized and then coated with an epoxy paint. Care must always be taken to ensure that this coating is not ruptured as otherwise serious pitting can occur. The fasteners used on such cases are usually 316 stainless steel. For cathodic protection, two methods can be utilized:-

a) All cathodic metal grounded. In this case, all material is electrically at the same potential with a common anode to protect both metals.
b) All cathodic metals electrically isolated from each other and protected by individual anodes.

Both methods are being used and under evaluation for life and cost effectiveness.

5. Review of Corrective Measures

Typical corrections recommended and implemented for increased reliability of moorings were:

- Cathodic protection
- Elimination of galvanic incompatibility
- Precautions in welding
- Precautions in machining (elemination of roughened surfaces)
- Material changes (i.e. 316 S.S. in lieu of 303 S.S. , etc.)
- Coatings (care taken in surface preparation)
- Elimination of crevice corrosion (use of sealants)
- Design for corrosion fatigue and stress corrosion cracking

6. Conclusions

A program instituted by the Ocean Engineering Department of the Woods Hole Oceanographic Institution and carried out primarily at the C.S. Draper Laboratory of M.I.T. has involved the failure analysis of numerous mooring line components. This continual analysis has been used to advantage to recommend design and material changes resulting in an improved resistance to environmental deterioration.

The improved reliability is evidenced by longer moorings and the major causes of problems now are mainly mechanical. This can be due to too much tension in strong currents, vibration, or isolated events such as a weak component. It is imperative that each new mooring or instrumented array be carefully examined for corrosion problems, particularly at the design stage for the various instruments used in line.

The work reported in this paper was supported by the Office of Naval Research under Contract Number N ooo14 - C0241 - NR083 - 004.

References

1. H.O. Berteaux, R. Heinmiller, "Back Up Recovery Systems of Deep Sea Moorings," W.H.O.I., Tech. Memo. 69-7.

2. H.O. Berteaux, E.A. Capadona, R. Mitchell and R. L. Morey, "Experimental Evidence on the Modes and Probable Causes of a Deep Sea Buoy Mooring Failure," P. 671 Trans. Marine Tech. Soc. 1968.

3. R. Morey, "Evaluation of Long Term Deep Sea Effects on Mooring Line Components," M.I.T., C.S. Draper Lab Report (In Press).

4. J. M. Dahlen, "Oceanic Telescope Engineering Program," M.I.T. C.S. Draper Lab Report E-2367 (1970).

5. H.O. Berteaux and R.G. Walden., "An Engineering Program to Improve the Reliability of Deep Sea Moorings," 6th Annual Preprints, M.T.S. (1970).

6. H.O. Berteaux, "A Review of W.H.O.I. Buoy Programs," Collcque Internationale sur L'Exploitation des Oceans," Theme V, Tome II, Bordeaux (1971).

7. H.G. Fontana and N.D. Greene, "Corrosion Engineering," McGraw Hill, New York (1967)

8. T. L. Mackay and N.A. Tiner, "Stress Corrosion Susceptibility of Titanium Alloys in Aqueous Environment," P. 61, Met. Eng. Qtly. (1969).

Summarized Discussion

Discussion from the floor pointed out that stress corrosion cracking, such as might be inferred from the reported cracking failure in the 18% Cr, 8% Ni stainless steel, would not be expected to occur in unheated sea water unless the steel had been severely cold worked.

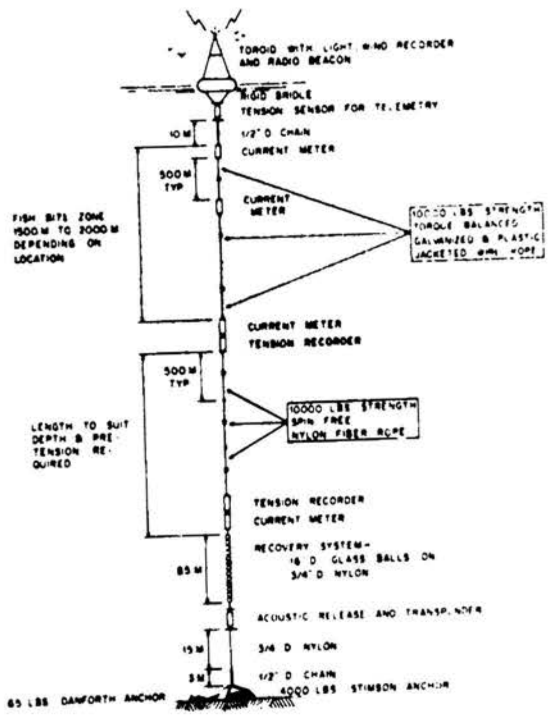


Figure 1. Typical W. H. O. I. Surface Buoy System

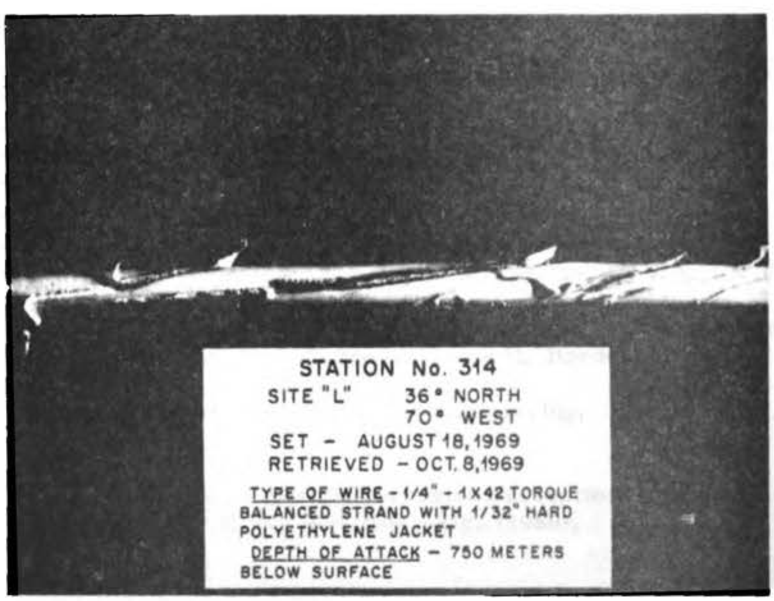


Figure 2. Fishbite on Jacketed Wire Rope

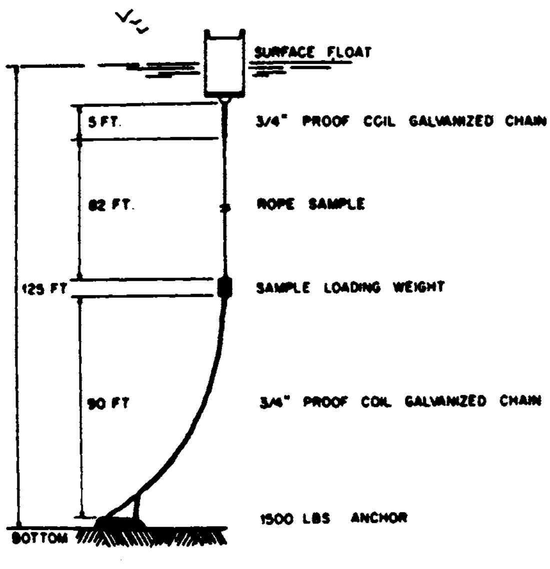


Figure 3. Shallow Water Test Array

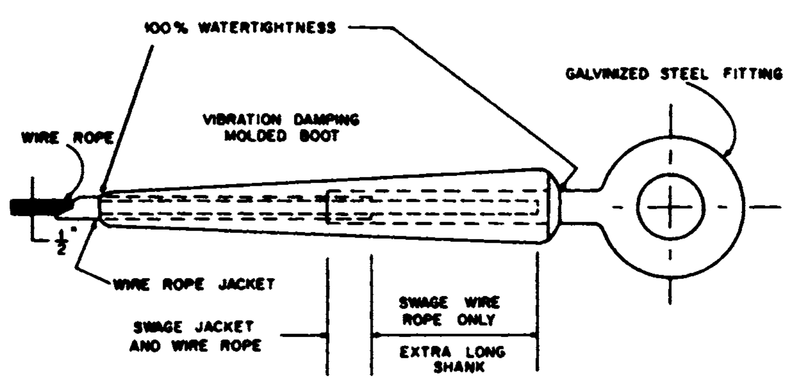


Figure 4. Typical W. H. O. I. Termination

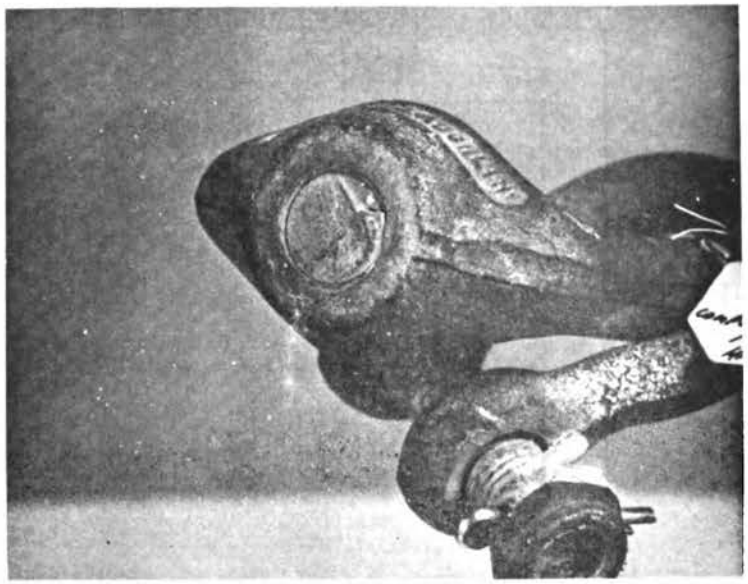


Figure 5. 1" Bolt Failure at Buoy Bridle Connection

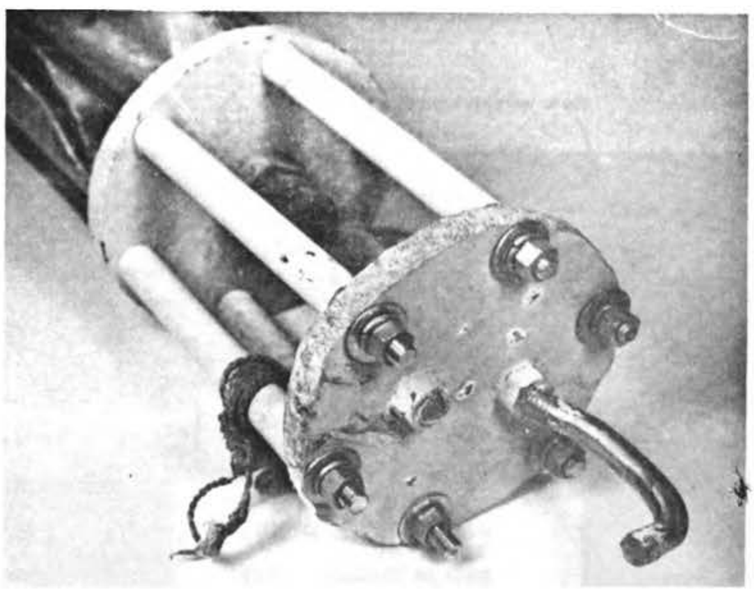


Figure 6. Failed U-Bolt from Tensiometer

STATE OF THE ART
AND FUTURE PROJECTIONS IN BUOY MECHANICAL TECHNOLOGY

by

C. S. Niederman

NOAA Data Buoy Office
Mississippi Test Facility
Bay St. Louis, Mississippi 39520

STATE OF THE ART AND FUTURE PROJECTIONS IN BUOY MECHANICAL TECHNOLOGY

INTRODUCTION

The intention of this paper is to cover the state of the art and future projections in buoy mechanical technology based on the practice and plans of the NOAA Data Buoy Office. This includes discussions of hull design, moorings, and buoy construction materials. Included in the hull design discussion are comments on analytical capabilities in design, the choice of the basic buoy shapes, and discussions, both for large versus small buoys and moored versus drifting buoys. The mooring discussion includes sections on present and near-future selections of line materials and the associated hardware, methods of deployment, and reliability versus cost tradeoffs. The materials section includes a discussion of the general materials used in the marine environments and some tradeoffs.

HULL/MOORING SIMULATION AND TESTING

Present hull design practice, in addition to the use of the basic tools of the Naval Architect, includes the use of the NDBO hull/mooring simulation program, model tests, and full-scale experience in the field. The hull/mooring simulation has the capability to predict the static and dynamic performance of the buoy hull, and to predict the statics and dynamics of single-leg, multiple component moorings and attachments. It predicts mooring line angle, tension, and velocity down the mooring line in both regular and irregular waves.

Model tests are used to check input coefficients, to validate the hull/mooring simulation outputs, and to assess survivability in spilling waves. Full-scale experience from five large and six small hulls presently deployed on the East Coast, Gulf of Alaska, and the Gulf of Mexico also improves our design capability.

Future plans include a full-scale testing program to validate the hull/mooring simulation and model tests. Additional model tests will be undertaken as necessary for regular wave tests on new hull forms and spilling wave tests on all promising candidate hulls. A statistical approach to the prediction of long-term buoy performance has been developed and will be utilized with the results of model tests to assess survivability.

HULL

Present technology can supply buoys for nearly all long-term user needs. Several tradeoffs must be made in the selection of these buoys. Large buoys, although requiring a higher initial cost, have several advantages by virtue of their size. They have generally greater survivability, they are easier to maintain at sea (in that a small support ship may come alongside and board them), and they, of course, have greater payload capacity, permitting redundancy in sensors or the provision for many experiments that may be conducted aboard the buoy. Small buoys are much less expensive for the initial investment; however, the payload capacity may reduce the ability to maintain redundant systems. Survivability may be a problem, and they generally must be maintained with larger support ships, in that the buoys are too small and often too lively in themselves to be boarded; the general procedure being to pull a small buoy aboard the deck of the support ship. Tradeoffs must be made in the area of moored versus drifting small buoys for short-term buoy users who are usually constrained by funds. Table 1 compares these buoys.

MOORING

Mooring systems can be made of steel or stainless steel wire rope, steel chain, or synthetic lines. The variety of synthetics available includes dacron polyester, polypropylene, polyethylene, blends of the above-mentioned lines, rubber cord, and a new material, Kevlar (formerly called Fiber "B"). Construction may be twisted, plaited, braided, double-braided, braided and plaited, or jacketed parallel fiber.

TABLE 1

CONSIDERATIONS FOR MOORED VS DRIFTING BUOYS

CHARACTERISTIC	MOORED	DRIFTING
POSITION	FIXED MAINTAINED BY MOORING	VARIABLE MUST BE TRACKED BY REMOTE POSITION FIXING SYSTEM
COST OF POSITIONING	$.50 - $1.00 + PER FOOT OF DEPTH	$1000 RAMS POSITION FIXING SYSTEM
CURRENT MEASURING CAPABILITY	RELY ON EXPENSIVE CURRENT METERS OF QUESTIONABLE RELIABILITY	TRACKS CURRENT AT ONE LEVEL ONLY SUBJECT TO WIND & SURFACE CURRENT EFFECTS
PAYLOAD CAPACITY	BUOY IS LARGE TO SURVIVE & SUPPORT MOORING CAPABLE OF SUPPORTING LARGE PAYLOAD	BUOY IS SMALL TO MINIMIZE SURFACE INTERFERENCE LIMITED PAYLOAD LIMITED RESERVE BUOYANCY
MET. PARAMETER MEASURING CAPABILITY	CAN SUPPORT SUITE OF MET SENSORS @ 5 M. LEVEL AND ABOVE	MINIMUM CAPABILITY SUPERSTRUCTURE HEIGHT & AREA MINIMIZED TO REDUCE WIND INTERFERENCE ON CURRENT FOLLOWER

CHARACTERISTIC	MOORED	DRIFTING
SURVIVABILITY	MUST BE LARGE ENOUGH TO SUPPORT MOORING IN EXTREME SEAS MOORING MUST BE STRONG ENOUGH NOT TO PART IN HEAVY SEAS	REQUIRES ONLY THAT IT BE STRONG ENOUGH TO REMAIN INTACT MUST HAVE 180° STABILITY
DEPLOYABILITY	BUOY & MOORING BOTH LARGE - REQUIRE HEAVY CRANE AND/OR EQPT. TO DEPLOY BUOY AND/OR MOORING	BUOY IS PROBABLY SMALL (<1000#). MAY BE DEPLOYED BY SHIP OF OPPORTUNITY - NO SPECIAL EQPT. REQUIRED
MAINTAINABILITY	MAY BE MAINTAINED ON STATION OR RETURNED TO SHORE FOR MAINTENANCE	MAY BE SMALL ENOUGH & CHEAP ENOUGH TO BE EXPENDABLE

CHARACTERISTIC	MOORED	DRIFTING
ENDURANCE	MAY REMAIN ON STATION FOR SEVERAL YEARS WITH PERIODIC MAINTENANCE	3-6 MONTH MAXIMUM MISSION ENDURANCE - POWER LIMITED
COMMUNICATIONS	MAY SUPPORT HF AS WELL AS SAT. COMMS.	SIZE REQUIRES DEPENDENCE ON SAT. COMMS.
SENSORS	MAY SUPPORT MULTIPLE SETS OF REDUNDANT SENSORS	WILL SUPPORT A LIMITED NUMBER OF SENSORS AND DATA CHANNELS

Any of the above materials may be used in combination. Attachments to the mooring system include floats, shackles, swivels, sensors on the line, and acoustic releases for retrievals. Terminations include splices above thimbles, clamps, and plastic molds. All types of anchors may be used: mushroom anchors, stockless anchors, clump anchors, lightweight Danforth-type anchors, Stimson anchors, explosive embedment, and combinations of the above.

The reliability of these mooring systems must be compared with the cost. For example, the 40-foot discus buoy moored 120 miles east of Norfolk, Virginia, in 10,000 feet of water, was at one time moored with 3" diameter nylon line, as detailed in Table 2. That mooring has since been replaced, and the buoy is presently moored with 2½" nylon, and a shorter scope. The present mooring represents a 45% cost savings over the original mooring, and represents no sacrifice in reliability. The maximum observed mooring line tension over a six-month period has been 6,250 pounds. This is well below the recommended working load range of 10-15% of break strength for nylon line. Due to the high current regime in the area of this mooring, much of the mooring load is due to the drag of the mooring line itself. Thus, it has been proposed that a smaller diameter mooring line may result in a corresponding decrease in mooring line tension. This would permit a further decrease in the mooring scope. A possible proposed mooring, shown in Table 2, illustrates how a mooring may be designed to yield a cost savings of more than 75% without a significant sacrifice in reliability.

In general, moors may be single-point, either taut or slack, or multi-point. The moorings may be deployed in a number of different ways. In one case, the buoy is deployed first and the anchor is deployed last. The ship steams away, trailing out the anchor line, and when the bitter end is reached, the anchor is then deployed. Another method of deploying the buoy first and the anchor last is with a self-mooring system, with a fully automatic subsurface winch system or

TABLE 2

RELIABILITY VS COST

EXAMPLE - 40 FOOT DISK MOORED 120 MILES EAST OF NORFOLK IN 10,000 FT. OF WATER

- o ORIGINAL MOORING WAS 3 INCH DIA. NYLON, BREAKING STRENGTH 200,000 LBS.
  - SCOPE OF 2 TO 1
  - COST OF 20,000 FT. (3" DIA.) $63,000
- o PRESENT MOORING IS 2 1/2 INCH DIA. NYLON, BREAKING STRENGTH 140,000 LBS.
  - SCOPE OF 1.6 TO 1
  - COST OF 16,000 FT. (2 1/2" DIA.) $35,000

    THE MAXIMUM OBSERVED MOORING LINE TENSION OVER A SIX MONTH PERIOD WAS 6,250 LBS. FOR THIS MOORING. THIS REPRESENTS 4.5% BREAKING STRENGTH.
- o POSSIBLE FUTURE MOORING IS 1 3/4 INCH DIA. NYLON, BREAKING STRENGTH 78,000 LBS.
  - SCOPE OF 1.2 TO 1
  - COST OF 12,000 FT. (1 3/4" DIA.) $15,000

    THE EXPECTED MOORING LINE TENSION WOULD BE LESS WITH A SMALLER DIAMETER LINE, THEREFORE, LOAD WOULD BE LESS THAN 10% OF THE BREAKING STRENGTH OF THE LINE.

a semi-automatic system (requires cutting to length), using a faking box to hold the line as the anchor is deployed. In other cases, the anchor may first be deployed and the mooring set up, and then the buoy attached. Variations of all these above methods may be used for multi-point moors.

The techniques of implantment include self-mooring with a faking box on the ship, a faking box below the buoy, and automatic mooring devices. Other systems include streaming the mooring aft and then dropping the anchor, as mentioned before, and to winch the anchor down with the mooring line. Future mooring designs will utilize the favorable qualities of synthetics, steel cable and chain combinations for individual mooring applications, continued investigation in new materials, validation of mooring simulations, and more economical moorings and mooring simulation models..

MATERIALS

A number of tradeoffs may be made in the materials used in buoy fabrication. General properties sought include a high strength-to-weight ratio; high fatigue strength; high corrosion resistance, including resistance to stress corrosion cracking; ease of fabrication, including weldability, long life, low maintenance, and material availability at low cost.

In buoy construction as well as in ship construction, steel still maintains its lead as the choice of hull material. It is readily available, at a relatively low cost. Fatigue strengths are well documented, and there is a wide range of tensile strengths available. Fabrication and weldability are particularly good, and there are many standard corrosion treatments available. In addition to the mild steel that is protected by protective coatings, stainless steel offers corrosion resistance without treatment, and when used as a railing for sensors, such as a compass, stainless steel can offer the advantage of being non-magnetic, depending on the type of stainless used.

Aluminum is the second most popular material for buoy construction. It is a common structural material and its characteristics are well documented. Weldability is good even though slightly more difficult than for mild steels. The strength of aluminum is less than steel, but its strength-to-weight ratio (aluminum being 1/3 the density of steel) makes it a very efficient choice in some cases. It also offers particularly good resistance to corrosion. Like steel, aluminum is also available in a wide range of strengths. However, aluminum is slightly more costly than steel per pound.

Titanium, from an engineering point of view, is a desirable material in buoy construction. It has high strength and low density, and extremely high corrosion resistance, although there has been some evidence of stress corrosion. It has good fatigue characteristics, and it is non-magnetic. The greatest drawback to titanium is that it is extremely expensive when compared to steel, i.e., fabrication is considerably more difficult than that of steel. As a result, titanium has only been used in the construction of Data Buoy sensors, and not hulls or masts.

Other metals are used as called for in normal marine practices. Copper-nickel is used mostly for piping systems, due to its excellent corrosion resistance and its resistance to fouling. Bronze has also been used in mooring systems.

In non-metallic material applications, concrete has been used as a hull material. It has the advantages of resistance to corrosion, easy formability, easy maintenance repairs. It is readily available, and it has a relatively low cost. It has disadvantages, however, low tensile strength and low impact strength. It is also more limited as to modifications and additions to a hull than a metallic hull would be. Ferro-cement, or tensioned concrete, somewhat enhances concrete's tensile and impact characteristics.

Synthetic materials make up the remainder of materials used in data buoy technology. Many come with high strength-to-weight ratios, and they come in a wide range of densities. Many synthetics with relatively low density are available. They generally have good impact characteristics and they are corrosion-resistant, only having to take care to insure resistance to common marine and shipboard chemicals and fuels. Fabrication of synthetics (depending on craftsmanship) is easier than metals for both cutting and shaping. The materials are versatile in forming complex forms. Bonding is usually accomplished chemically using epoxy. Synthetic materials have relatively low cost and they are avialable with a wide range of material characteristics, although the characteristics are not well documented. The materials can be designed to meet desired specifications. Also in the group of synthetics are the buoyant materials, or foams. These desirable properties include low densities, impact absorption, resistance to chemicals and fuels common in the shipboard environment, resistance to water absorption and sunlight, non-corrosive, non-toxic, non-flammable, and low cost. The synthetic foams are available in a wide range, offering most of the desired characteristics. Closed cell is preferable to open cell in resistance to water absorption. If material flexibility is not a criterion, then a foam-in-place foam is desirable for most shapes.

CONCLUSION

In summary, it should be emphasized that broad hull choices are now avialable, both for long- and short-term user needs. Hull and mooring responses can be predicted; however, we need a better description of the environments. Moorings are available to meet all needs; choices are available for the required characteristics. Many materials can be used to broaden buoy applications. The major concerns still remain the method of fabrication and cost.

In hull/mooring simulation work, we can use the programs we have now with gradual improvement. Hull design techniques are improved by the simulations and through advances in buoy technology. Most mooring improvements must come from buoy technology. The improvements required for most overall advancement in the state of the art are in materials. For the basic development, we must rely on other technologies and adapt them to buoys, since buoy technology does not offer sufficient market to basic materials producers to induce them to change their products. We must therefore closely check materials advances in associated technologies.

BUOY POWER

by

D. Ross

Ocean Systems Program
General Electric Company
Philadelphia, Pennsylvania 19101

Introduction

One of the major constraints on unattended buoy operating life is the endurance of the power supply. In general, the evaluation of buoy power subsystems is based on some of the criteria given in Table 1. In some cases, such as for the LCB, the average power requirements are only a couple of watts, while for the EEP class of buoys, requirements range in the hundreds of watts. However, even for the buoys requiring one or two watts, surge powers of one or two hundred of watts are required for data transmission. In evaluating any power supply, the major consideration is its effect on total station cost per year in which both power supply energy density and initial cost play a role. (See Reference 1).

Many different types of power supplies can and have been used on buoys. The various combinations of energy source and energy conversion systems that can be used for the buoy power range in question are shown in Figure 1. The potential uses of these different power supplies for present and future buoy applications are discussed in the following sections.

Batteries

Batteries are used for prime and/or peak power for almost all data buoy applications. The state of the art of batteries is outlined in Table 2. The most favorable power sources for present buoy designs are the alkaline maganese dioxide batteries and the zinc-air cell/nickel-cadmium hybrid. One LCB design which uses the zinc-carbon/nickel-cadmium hybrid is limited by the poor low-temperature performance of the zinc-carbon cells and has to revert to manganese-alkaline batteries for these environments. The alkaline manganese cells offer an added advantage, as compared to the silver/zinc or magnesium corrosion cells. Gas evolution is negligible and, hence, these cells are hermetically sealed.

For longer operating life, savings in cost and weight would result from the use of oxygen depolarized zinc-air cells. Zinc-air cells have been successfully

FIGURE 1

POWER/ENERGY SOURCES

ENERGY CONVERSION / ENERGY SOURCE	CHEMICAL	ENVIRONMENTAL: WAVES & CURRENTS	ENVIRONMENTAL: WINDS & TIDES	ENVIRONMENTAL: SOLAR	NUCLEAR RADIOISOTOPE
BATTERIES	LCB				
FUEL CELLS	●				
THERMOELECTRIC	EEP LFTEG			●	RTG NAVY
PHOTOVOLTAIC				●	
ROTATING MACHINERY					
TURBINES	●	●	●		
RANKINE CYCLES	EEP DIESEL			●	●
COMBUSTION ENGINES					
ADVANCED					
THERMIONIC	●				●
MHD	●				

TABLE 1

BUOY POWER

• POWER RANGE	1 to 500 watts
• POWER SURGES	several hundred watts
• DURATION	> 1 year unmaintained as objective in some applications
• EVALUATION CRITERIA	$/kw-hour watt-hrs/lb watt-hrs/cu ft lbs/watt environmental constraints state of the art

TABLE 2

BATTERIES

Present Applications (LCB)

Zinc-Air/Ni Cad for Surge Power

Zinc-Carbon/Ni Cad for Surge Power

Alkaline-Manganese Dioxide Batteries

Improved Present Designs

Oxygen depolarized Zinc/Ni Cad for Surge Power

Sea Water Batteries

Advanced Designs -- Significant Improvement

Lithium-Sulfur

Sodium Sulfur

used at sea, but such air-breathing systems are vulnerable to sea water flooding. This can be avoided by use of an oxygen cylinder attached to a water-tight unit. Such a battery, including oxygen bottle, will deliver to a small steady load 70 watt-hours per pound as compared to 35 watt-hours per pound for the alkaline manganese battery.

The sea water battery is another intermediate possibility with the surrounding sea water as the battery. The basic metal plates (magnesium) can be stored indefinitely until ready for immersion into the electrolyte. The sea water battery can be used for short-term applications requiring large powers. However, for buoys the problems of fouling prevent long-term use. Another difficult problem is that the surrounding common electrolyte (sea water) prevents series connections of the battery cells and, hence, a voltage converter is required.

In considering major potential improvements in batteries, the material costs, power and energy densities of different electrode combinations are shown in Figure 2. One of the greatest potential improvements can be exhibited by the sodium-sulfur battery shown schematically in Figure 3. This battery utilizes a solid beta-alumina electrolyte whose ion conductivity at 350°C is about the same as the conductivity of a gaseous electrolyte at room temperature. On one side of this ceramic electrolyte is molten sodium and on the other side a molten mixture of sulfur and sodium polysulfides. The molten salt is immobilized in a porous ceramic disk, while the beta-alumina electrolyte is a single-phase, nonporous solid. However, the applicability of this battery is far off with problems such as cracking of the ceramic on continous electrical cycling, the sealing of the ceramic to metal or glass, the development of suitable ceramic processing procedures to improve the uniformity and quality of the material, the development of reliable and safe cell filling and activation techniques, and the development of a safe, reliable high-temperature battery system design.

Fuel Cells

A fuel cell is an electrochemical device that continuously converts chemical energy by the oxidation

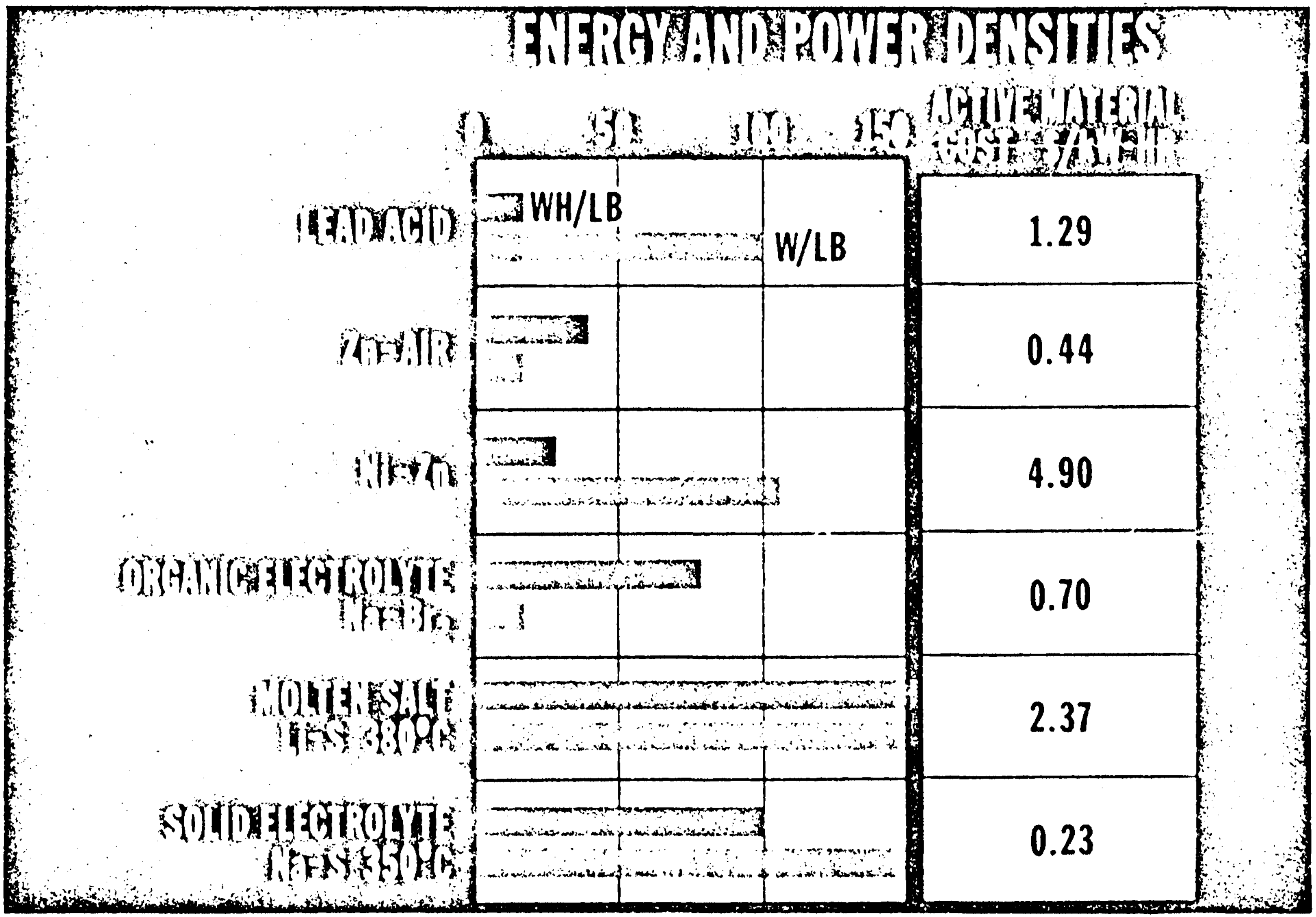


Figure 2: Energy and power densities.

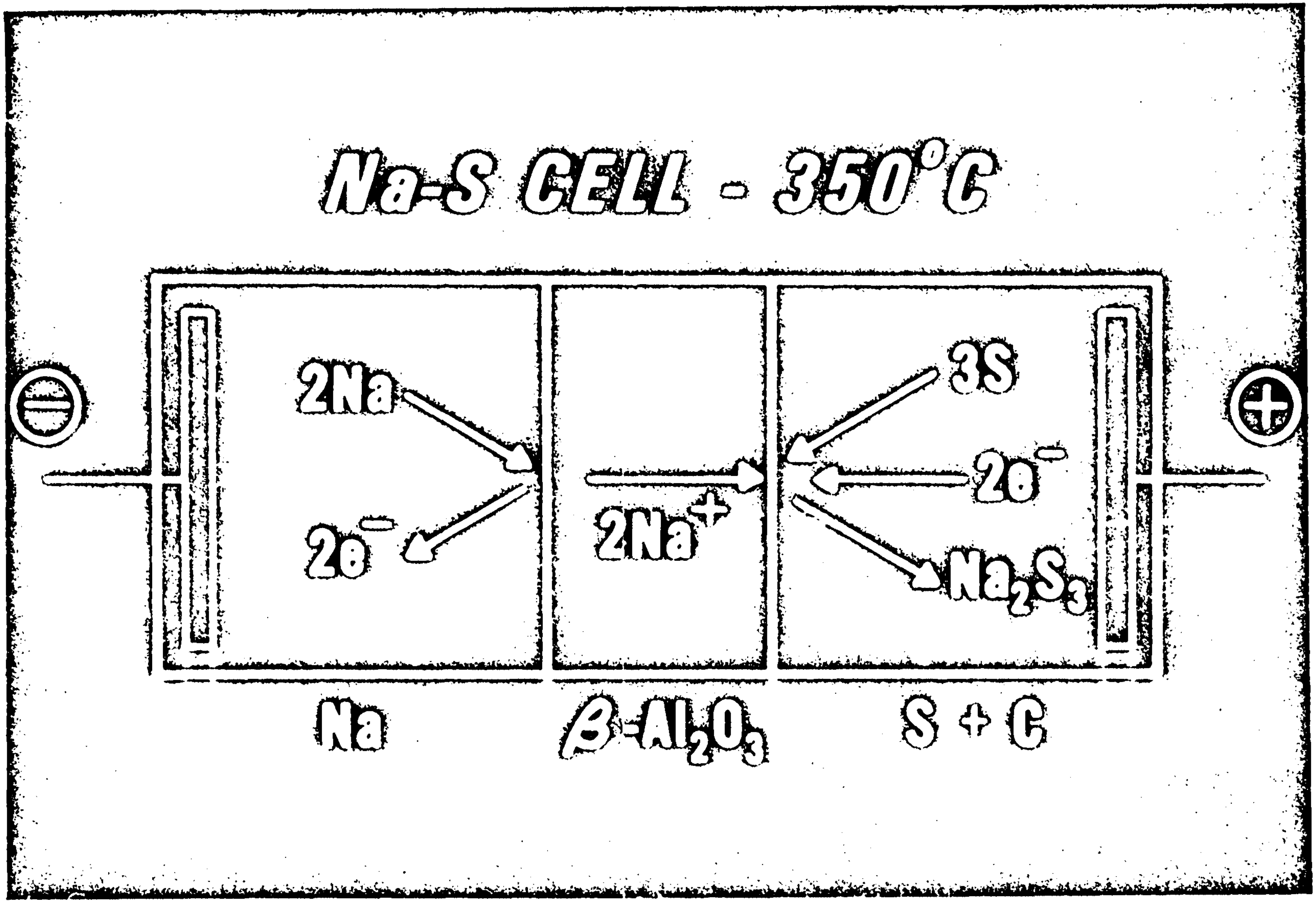


Figure 3: Sodium-sulfur battery schematic diagram.

TABLE 3

FUEL CELLS

Characteristics

- High Efficiencies
- High Peak Power Capabilities
- Long Life Capability (Fuel Supply Determines Life)
- High Energy Density
- High $/kw-hr
- Silent Operation

BUOY FUEL CELLS

Fuels

- Lithium - Aluminum Hydride
- Sodium - Aluminum Hydride
- Liquid Methanol
- Liquid Ammonia
- Hydrazine
- Hydrocarbon Fuels + Reformer

Oxygen Sources

- Air
- Cyrogenic or Gaseous Oxygen
- Sodium Chlorate Candles
- Potassium Superoxide

of a conventional fuel to electric power in an essentially invariant electrode-electrolyte system. A fuel cell operates as long as fuel and oxidant are supplied, and the byproducts removed. The characteristics of fuel cells are outlined in Table 3.

Fuel cells offer the prospect of performance for exceeding that of chemical batteries. The basic reactants weigh about one pound per KWH.

For the present hydrogen-oxygen fuel cells, cyrogenically stored reactants have been utilized. For long-term operation, cyrogenically storing reactants brings a system weight penalty of about six to nine pounds per kilowatt-hour, which is several times that of the basic reactants. The use of solid storable fuels such as listed in Table 3 for hydrogen production can reduce this weight to the order of a pound per KWH, especially when air is used, or not much greater when an oxidant is also provided. These fuels, typically Na AL H_4 or LiH, release hydrogen upon reaction with the fuel cells' product water. These reactants can cost about $20 per KWH.

In addition to hydrogen, various other fuels can be utilized including liquid methanol, ammonia, and hydrazine. In the ultimate attempt to use low-cost hydrocarbon fuels, a fuel cell system would consist of a reformer to convert fuel and air into hydrogen, which would then be fed with additional air to the fuel cell stacks to produce electricity.

Thermoelectric Power

The use of thermoelectric power conversion elements gives the potential of providing very long term uninterrupted power; i.e., five to 10 years. Table 4 gives a listing of the various electric alternates. The most widely used thermoelectric elements for power conversion consist of lead telluride alloys and bismuth telluride alloys. The former is used for higher temperatures. For higher efficiency, the thermoelectric elements are segmented with the bismuth telluride alloys. Overall efficiencies of five to 10 per cent are attained. These elements are hermetically sealed with a surrounding low conductivity inert atmosphere to minimize vaporization of the elements. Silicon-germanium elements which require higher temperatures for efficient operation also are in use.

Liquid fueled thermoelectric generators have been used with various fuels: J-P4, propane, etc. At present, a liquid fueled thermoelectric generator is being developed to provide 300 watts for the EEP buoys. This design utilizes a diesel fuel which is fed into the combustion chamber via an ultrasonic atomizer with the air being supplied by a blower. The combustion chamber is lined with carborundum. One of the principal difficulties is the deposition of carbon inside and about the combustion chamber. To prevent this, the linear must be kept at a high temperature to ensure complete combustion.

TABLE 4

THERMOELECTRIC POWER

Liquid Fueled Thermoelectric Generators

Diesel Oil, Propane, JP-4, etc.

Lead-Bismuth Telluride Elements (in hermetically sealed container)

Silicon - germanium Elements

Life Limited by Combustion Chamber

Radioisotope (RTG's)

Strontium - 90 Fuel

5-10 years life

High initial costs

Submerged operation

The most extensively used thermoelectric generators for buoys are the radioisotope thermoelectric generators (RTG). The principal RTG's now in service producing at least five watts are listed in Table 5. All of these RTG's listed in the table use strontium-90 as the fuel.

Table 5

RTG'S IN SERVICE

RTG	POWER (w) END OF LIFE	LIFE (yrs)	WEIGHT (lbs)	SIZE	COST ($)	APPLICATION HISTORY
Sentinel-25-D	25	5	3000	26"Dx27"H	-	Shallow-water applications NOMAD buoy
Sentinel-25-C3	25	5	1400	24"Dx30"H	-	To 1000-ft depth NUC location marker project ESSA COSMOS stable platform array
Sentinel-25-E	25	5	4100	26"Dx25"H	-	To 20,000-ft depth Pacific Sea Spider Project abandoned RTG's produce over 40w
SNAP 21	10	5 to 10	640	15.85"Dx 25.1"H	-	To 23,000-ft depth Ocean-tested for more than 2 1/2 yrs by NUC
SNAP 7A & 7C	10	2	1700	-	$75,000	7A - navigation buoy 7C - weather station
LCG-25B	25	5	3000	-	$63,230 (5yr warranty)	Anchored at 5,000-ft depth Now in NUC Acoustic Range Program
SNAP 7B & 7D	60	10	4600	-	$120,000	7B - fixed navigation light 7D - terrestrial weather station
SNAP 7E	7	5	6000	-	$75,000 to 100,000	To 15,000-ft depths Acoustic power beacon
TRACS-25A	25	3	1400	24"Dx42"H	-	To 13,000-ft depths Poor performance; not used

One of the most advanced designs from a technological standpoint is SNAP-21. This RTG utilizes a high-temperature shield of depleted uranium - 8% molybdenum alloy directly in line with its strontium titanate heat source, resulting in a much lighter overall system than other RTG's of comparable power. The heat source is insulated by vacuum multi-foil insulation. The thermoelectric generator utilizes improved segmented lead-tin-telluride/ bismuth-antimony-telluride thermoelectric elements hermetically sealed in an enclosure containing a xenon atmosphere. Heat is transferred to the generator's hot frame by radiation across a gap. Berylco 165 is used as the pressure vessel. After two and a half years of testing three RTG's in the ocean, no degradation in performance has been exhibited except by radioisotope decay. This unit has capabilities of being used for 10 years unmaintained life.

Even though the initial cost of the RTG is high, the energy cost is quite modest, being of the order of one to five cents per watt-hour. The weights of the RTG's are quite high, being of the order of 50 to 100 pounds per watt; but, because of the very long life, the energy density of the RTG can attain 1,000 watt-hours per pound.

Solar concentrators can be used to power a low-temperature bismuth telluride thermoelectric generator but have seen little or no applications.

Rotating Machinery

Internal combustion engines are now being used for the high capability buoys (see Table 6). Different buoys use six HP diesel engines to produce 3.5 KVA AC and battery for peak loads on the alternate two HP propane engine and two KW DC generator.

All of these designs utilize larger engines than necessary because of the lack of availability of a small diesel engine; the result is inefficient operations. In addition, diesel engines require periodic maintenance which prevents very long operation. These factors are the impetus for the 300-watt LFTEG program.

Organic or steam Rankine engines can produce powers of the order of 100 watts, or even watts with efficiencies in the range of 10 to 20 per cent, at least twice those of thermoelectric devices. In addition, these engines have the capability of unattended lifetimes for over one year, using the working fluid as the lubricant. Rankine cycle components have been developed for a cycle utilizing biphenyl vapor as the working fluid. These, which consist of boiler, turbine-alternator, regenerator and condenser, operate at maximum pressures of less 100 psia, temperatures less than 700°F, at efficiencies of 15 per cent in the power range under 500 watts. These can be adapted to radioisotope, solar and chemical heat sources.

TABLE 6

ROTATING MACHINERY

Present Applications

Internal Combustion Engines

Diesel (HCB)

Propane Engine (HCB)

Advanced

Organic or Steam Rankine Engines
(Use chemical, solar or radioisotope energy)

Stirling Engines

Wave or Wind Energy - Turbogenerator/Batteries

A reciprocating steam engine has been developed for circulatory assist devices which can produce power as low as 10 watts at cycle efficiencies (thermal to shaft) of 20 per cent. An alternate engine, the Stirling, has the capability of obtaining efficiencies of 30 per cent, but has problems of attaining long life.

Environmental energy -- waves or wind coupled to a prime mover -- offers a good, present state-of-the-art capability to provide buoy power. The wave-activated generator is in active use by the Japanese for buoy light stations. The preferable type of buoy for this type of power source is a spar-type buoy or a buoy with a relatively low heave response. This power source consists of a submerged vertical pipe. The wave motion compresses the air in this pipe which flows undirectionally to an air turbine connected to the pipe. The electric energy is produced by a generator which is used to charge a battery. These units have to be overhauled about every two years to remove seaweed and marine growth from the pipe.

A 60-watt, 12-volt unit is available from the Japanese Maritime Safety Agency at about $2,500. This turbine unit is about two feet in diameter and utilizes 500 AH of lead acid batteries.

Other forms of environmental energy have been evaluated for various applications, such as wind energy. This type is less adaptable to buoys because of the requirement of a propeller several feet in diameter which would drive a generator. To get any reasonable performance, wind velocities of 10 to 15 knots would be required. Hence, there would be a more severe energy storage requirement than for the wave generator.

Miscellaneous Power Sources

Other sources which can be used for buoy power are listed in Table 7. The only one of these which is being considered for buoy power is solar cells with secondary batteries for energy storage. Solar cells have been successfully used both in satellites and for providing power for emergency communication stations on remote highways. Silicon solar cells are about 10 per cent efficient at present, and cost in the hundred dollar per watt range. Work has been under way for several years to increase efficiency and reduce costs. Other approaches, such as thin film CdS cells, have had difficulty in matching the efficiency of the silicon cells.

Solar cells, however, can be attractive in extending the unmaintained life of batteries for buoys requiring only a couple of watts in certain regions where there is a minimum of cloud cover. The major problem with the use of these cells is the loss of light transmission due to the salt spray. More work is required to overcome this problem by location or by use of a non-fouling window.

TABLE 7

MISCELLANEOUS POWER SOURCES

Solar Photovoltaic/Batteries

Chemical - MHD

Chemical - Thermionic

Radioisotope Thermionics

System Considerations

At present, major constraints on unattended buoy operating life are power supply endurance and life of the sensors and instrumentation. The power supply, however, does affect the overall buoy system competitiveness with other data platforms in the following areas:

- System size and weight
- Deployment and maintenance cost
- Initial cost
- Unattended operating lifetime

As the data platform networks become better utilized over a wider scale, there will be a much greater emphasis toward data platforms, and, hence, buoy system optimization.

In the present applications, little emphasis has been given to buoy system size and weight, mainly because we have encountered the expensive 40-foot discus buoy, where weight isn't a problem, or the LCB, where only a less than six-month lifetime constraint has been placed. In the future, especially where large buoy networks are required, there will be a greater economic necessity to reduce buoy weight and cost.

Deployment cost reduction is one area which has to be considered. Figure 4 gives examples of the deployment costs of a buoy network (Reference 1). Both the C.G. cutter and the C-130 are restricted by payload weight. For sparse buoy fields, there is a great incentive to reduce buoy system and consequently power supply weight to permit air deployment for most economic operation.

The power supply initial cost, of course, enters into the system economics. However, a system evaluation should consider some size-weight factor in the initial cost to account for the system expense due to increased power supply weight. An example of this is given in Figure 5 (Reference 1).

One of the most significant factors affecting buoy data platform cost is unattended station operating life. In Figure 6, buoy station cost, normalized with respect to data output, is given as a function of operating life (Reference 1). This cost includes both the deployment, refurbishment and initial buoy costs. It is noted that there are large reductions in overall buoy station cost for operating lives of one to two years, especially when no maintenance is required.

The buoy system will be a highly cost-competitive data gathering system, especially if buoy unattended operating life is increased to one or two years. Here, increasing power supply energy density is significant.

Summary

From the economic standpoint, there is great incentive to develop both low-cost and high energy density power supplies permitting unattended operating times in the range of at least one to two years. The development of high-energy power supplies is necessary to contribute to economic data platform operation considering all the system factors -- deployment, unattended lifetime, and initial cost. Hence, there is a great impetus to develop and utilize improved power supplies: advanced batteries, fuel cells, RTG's, Rankine engines, etc.

DEPLOYMENT VEHICLE CHARACTERISTICS

CHAR. \ VEHICLE	DEDICATED SHIP	U.S. C.G. 180 FT. BUOY TENDER	C-130 AIRCRAFT
INITIAL COST	$16.4M	LEASE	LEASE
CRUISE SPEED (KTS)	18	15	350
CRUISE ENDURANCE LIMIT	30 DAYS	30 DAYS	10 HOURS
OPERATION & MAINT. COSTS	$5600/SEA DAY +$7/n.m. + $4700/ PORT DAY		$570/FLT. HR. $35/GRND. HR.
P/L CAPABILITY	2000 TONS 8800 FT²	113 TONS 24600 FT³	45300 LBS. 5400 FT³
AVAILABILITY	BUILD	>23 (37 MAX.)	>500

TABLE 6

C.G. CUTTER COSTS AND CHARACTERISTICS

	180' CLASS SEAGOING TENDER			311' CLASS SEAPLANE TENDER HIGH END.			213 CLASS SEAGOING TUG MEDIUM END.			210' CLASS MEDIUM END.		
AVG. COST/YR ($K)	'69	'68	'67	'69	'68	'67	'69	'68	'67	'69	'68	'67
CREW	263.4			678.3			351.2					
FUEL	72.6			59.4			50.1					
VESSEL	14.4			208.1			187.6					
MISC.	8.7			8.9			8.9					
TOTAL	373.1	357.9	339.4	946.7	881.3	904.4	583.6	636.8	435.4	517.7	523.9	489.6
N.M. LOGGED	11,711	11,980	13,642	25,456	37,279	28,538	32,334	18,070	15,109	17,694	20,019	22,980
OPER. HRS. (OUT)	2,193	2,291	2,423	3,966	4,653	3,938	3,360	2,976	3,260	2,616	2,738	3,237
NO. COMMISSIONED	37			8			2			11		
STORAGE	VOLUME LIMIT 24500 FT³			VOLUME LIMIT 5000 FT³			AREA OF AFTERDECK 12000 FT²			ZERO CUE TO TOPSIDE STABILITY		
ENDURANCE*	32000 N.M. @ 7.5 KTS 10500 N.M. @ 15 KTS			22000 N.M. @ 11 KTS 8000 N.M. @ 18 KTS			20000 N.M. @ 7 KTS 5000 N.M. @ 15.5 KTS			6100 N.M. @ 14 KTS 2700 N.M. @ 18 KTS		
NOTES:	45 MAN CREW $6M NEW $1M SURPLUS			150 MAN CREW $12M NEW			"ACUSNET"					

*ADDITIONAL TANKAGE MAY BE SUPPLIED FOR RANGE EXTENSION

TABLE 7

DEPLOYMENT CONSTRAINTS MAX. BUOYS DEPLOYED- CRUISE

DEPLOYMENT VEHICLE	
DEDICATED SHIP	86[1]
C.G. CUTTER 180 FT. TENDER	18[2]
C-130	3[2]

NOTES:

1. CRUISE ENDURANCE LIMITED.
2. P/L WEIGHT CAPACITY LIMITED.

TABLE 8

DEPLOYMENT VEHICLE COST COMPARISON

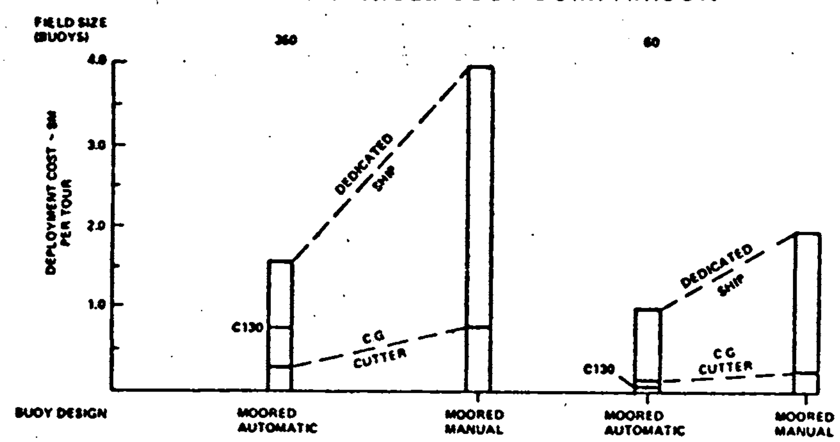


FIGURE 9

Fig 4

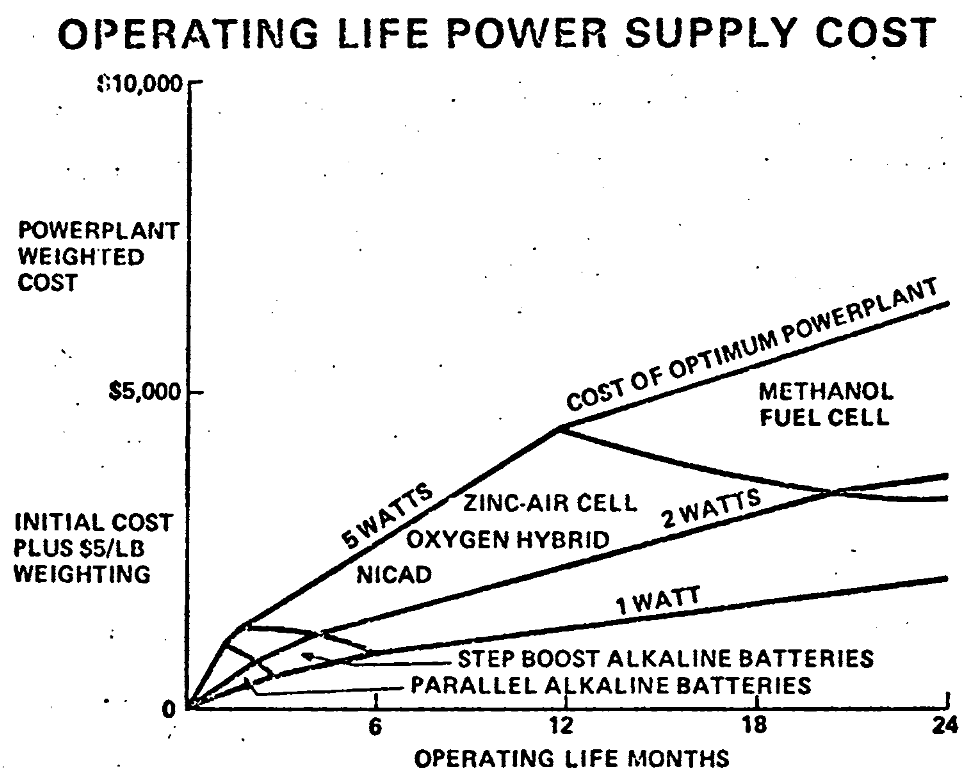

OPERATING LIFE POWER SUPPLY COST
$10,000
POWERPLANT
WEIGHTED
COST
$5,000
INITIAL COST
PLUS $5/LB
WEIGHTING
0
COST OF OPTIMUM POWERPLANT
METHANOL
FUEL CELL
5 WATTS
ZINC-AIR CELL
2 WATTS
OXYGEN HYBRID
NICAD
1 WATT
STEP BOOST ALKALINE BATTERIES
PARALLEL ALKALINE BATTERIES
6
12
18
24
OPERATING LIFE MONTHS

FIGURE 5

ANNUAL COST PER SENSOR BIT VS. LIFE

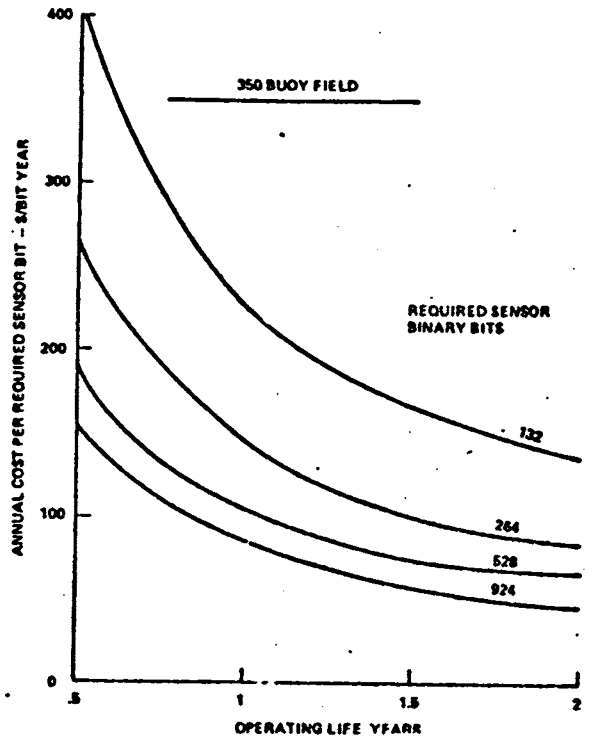


FIGURE 17

ANNUAL COST PER SENSOR BIT VS. SENSOR BITS

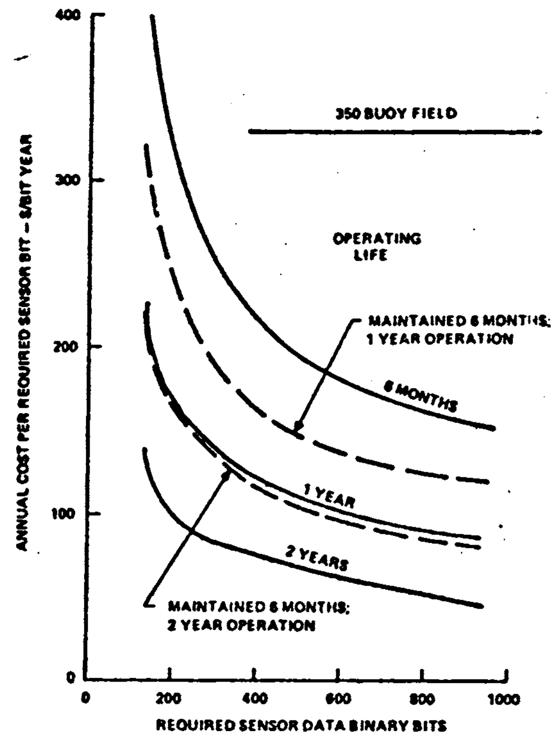


FIGURE 18

ANNUAL COST PER SENSOR BIT VS. FIELD SIZE

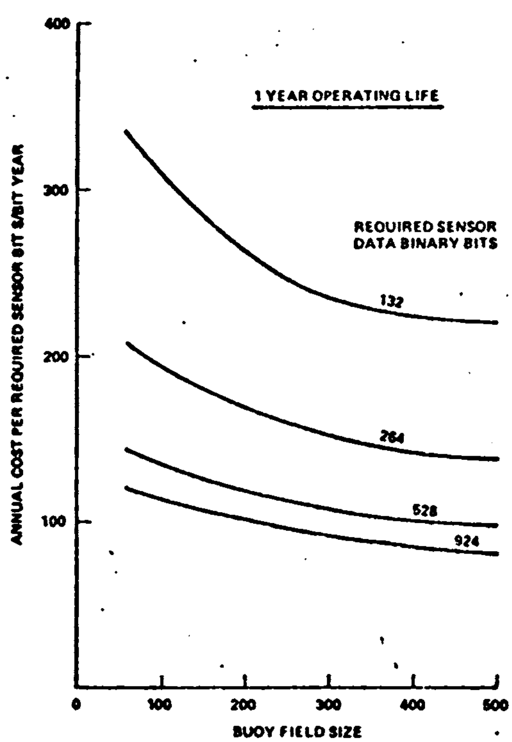


FIGURE 19

LIST OF REFERENCES

1. E. Ray, G.F. Sullivan, and D.P. Ross, "Data Buoys" Paper presented to Panel on Ocean Exploration and Surveying Systems at Workshop held at Airlie, Va. 30 Jan-3 Feb 1972

2. Buoy Power System; NDBC Presentation to National Academy of Engineering, October 26, 1972

3. H.A. Christopher, R.P. Hamlen, and E.L. Simons, "Batteries and Fuel Cells in Future Energy Handling - General Electric Co. Report No. 72CRD255, Technical Information Series.

4. E. Ray and D.P. Ross, "Power Systems - Advances and Levels" Astronautics and Aeronautics, Jan 1965

5. R.N. Edwards, M.E. Cohen and J.A. Hill, "Economic Selection of Undersea Powerplants" - Proceedings of the Fourth Intersociety Energy Conversion Engineering Conference, Sept 22-26, 1969, Washington, D.C.

6. SNAP-21 Program, Phase II - Deep Sea Radioisotope-Fueled Thermoelectric Generator Power Supply System - Final Summary Report, 10 Watt System, May 1970, Space and Defense Products, 3-M Company.

7. F.A. Shirland, A.F. Forestieri and A.E. Spakowski, "Status of the Cadmium Sulfide Thin - Film Solar Cell". Paper No. 689016, 3rd IECEC 168 Record (Intersociety Energy Conversion Engineering Conference)

8. A.E. Potter, Jr.;"Conventional and Thin-Film Solar Cells" - Space Power Systems Advanced Technology Conference - at Lewis Research Center, Cleveland, Ohio, August 23-24, 1966, NASA-SP-131

9. I. Yogo and T. Yoshida, "Wave-Activated Generator lighted Buoy" Paper given by Maritime Safety Agency, Japan and by President of Ryokuseisha Corp.

10. Letter to D.P. Ross by Maritime Safety Agency, 27 August 1970, Giving quote on TG-1 type Wave-Activated Generator Buoy; also descriptive disclosure on Type TG-1 Wave-Activated Generator Buoy

11. GE-Direct Energy Conversion Operation Brochure "Fuel Cells as Buoy Power Supplies", July, 1970

12. C.E. Leach and B.G. Fryer, "The Radioisotope Energized Stirling Engine for Spacecraft Auxiliary Electric Power in the 250 to 500 W(e) Power Range - 4th IECEC, 1969 Paper 699081

13. Energy Systems of Extended Endurance in the 1-100 KW Range for NAVAL Undersea Applications - A report by the panel on Energy Sources of the Committee on Undersea Warfare; National Academy of Sciences - National Research Council - Washington, D.C., September 1968 NRC: CUW: 0348

14. O.J. Adlhart and P.L. Terry, "Ammonia Air Fuel Cell System" 4th IECEC, 1969, Paper No. 699130

15. J. Perry, Jr., "The Hydrazine- Air Bicell, "A Simplified Fuel Cell System - 4th IECEC, 1969, Paper No. 699131.

16. R. Ramakumar, H.J. Allison, W.L. Hughes, and K.A. McCollom, "A Wind Energy Storage and Conversion System for Use in Underdeveloped Countries, 4th IECEC, 1969, Paper No. 699074

17. Technical Seminar, Sundstrand-Denver, August 31 - September 1, 1965, Organic/Rankine Cycle Auxillary Power Systems

18. T.P. Fleming and M.P. Starr - "NAVFAC RPD Underwater Power Systems - Marine Technology-1970, Volume 2

HARDWARE COMPONENTS OF AUTOMATIC MOORING DEVICES

by

G. Smith

Hermes Electronics Ltd.
Dartmouth, Nova Scotia, Canada

The following treatment discusses components of mooring systems which are automatic or self-implanting, in that they perform certain functions without attendance after release over the side.

Automatic elements in mooring systems can serve several very important purposes. One advantage is in minimizing the extent of handling required to place a buoy system in the sea. A second feature of automatic components is their ability to perform, during or after implantment, certain functions which cannot be attained otherwise.

The reduction in handling complexity can provide obvious savings in ship time. The risk of damage to the equipment or of injury to personnel may also be greatly reduced by use of appropriate automatic devices. An automatic mooring system, for example, can allow the launch sequence to be controlled entirely by one man, which is significant in view of the long history of aborted moorings and damage or injury caused by excessive confusion on deck prior to launch. Such confusion is characteristic of "manually" laid moorings.

Once in the sea, an automatic system can be used to advantage for such tasks as the deployment of a sensor unit at a prescribed depth. The automatic device assures protection of the sensor before deployment by allowing it to be retained in a non-vulnerable position. Generally, the placement can be performed more accurately than by use of hand-tailored moorings because there is no need to take depth soundings, and such problems as the ship drifting during preparation of the mooring do not occur with the automatic device.

Without automatic features, the mooring system must be made up to suit a specific depth of water, whereas the automatic device can accommodate a broad range of depths by paying out cable from a storage drum or winch. It is obvious that all buoy systems deployed from aircraft must be automatically moored.

The broad topics of interest, then, are winch locking, depth setting, cable payout, sequential releases, and pressure-sensitive release mechanisms.

The winch locking devices are used to stop further cable payout after the desired length has been deployed.

The depth-setting technique is used to place a buoy or sensor unit automatically at a predetermined depth without the need to manually select lengths of cable before launch.

Cable payout may be performed by several configurations of the winch drum. The axis of the spool may be horizontal or vertical; the latter is of interest because inertia may be minimized to reduce shock loads.

Sequential releases are used where one event must not occur until after another event; e.g., deployment of a sensor from beneath a subsurface buoy may be delayed until the winch drum has been immobilized.

Pressure-sensitive devices wherein a piston is driven by sea pressure are very useful in controlling the sequence of "breakup" in the sea. For example, an anchor can be released from a buoy system at a certain depth, whereafter a servo-brake is actuated to maintain the submerged buoy at some greater depth until the anchor reaches the bottom.

The four winch locking methods which are explored in detail are the direct impact, rotation sensing, tension sensing, and depth bracketing types.

The depth setting function, whereby a buoy is automatically placed at a predetermined depth, may be accomplished by a variety of methods. Those discussed are the pressure-controlled winch down device, the servo-brake, and the anchor leader.

The section on cable payout concentrates on three vertical-axis spool configurations, which are free of inertial problems.

Sequential releases are discussed, wherein one event triggers another, by means of a control cable or other mechanism.

Pressure-sensitive devices generally employ a piston driven by sea pressure against a spring in a cylinder. Devices are presented which utilize the piston motion to draw a pin or plunger which in turn may release a buoy, anchor, or other object.

Automatic Deployment Hardware

A. *Winch-Locking*

- Impact
  - -distortion
  - -explosive crimp
  - -pin
  - -cone
- Rotation Sensing
  - -centrifugal
  - -hydraulic
- Tension
  - -anchor leader
- Depth Bracketing
  - -swaged balls/gates

B. *Depth-Setting*

- Pressure-Controlled Winch
- Servo-Brake
- Anchor Leader

C. *Cable Payout*

- Basket
- (Figure 8) Bollards
- Vertical Axis Spool
  - -internal
  - -external

D. *Sequential Releases*

- Control Cable
- Messenger Release

E. *Pressure-Sensing Releases*

- Timed
- Pressure Increase

A. *Winch Locking*

1. Impact

Distortion (Figure 1)

As the anchor bottoms, the distortion straps yield. Two functions are accomplished: (a) energy absorption to reduce shock loads, and (b) the drum is locked by insertion of the pin into the ribs. The cone contains a moving water mass, the inertia of which provides the force to distort the straps.

Explosive Crimp (Figure 2)

Impact at the seabed triggers an explosive charge which crimps a metal ball to the cable. The ball diameter is greater than the throat of the fairlead, so that further cable payout cannot occur.

Pin (Figures 3 and 4)

The distortion technique above uses a pin lock, with a horizontal axis spool. This may also be used without distortion, whereby the bearing blocks move downward at impact to insert the pin (see Figure 3). A pin with a vertical axis spool is seen in Figure 4, whereby a rotating cable guide is immobilized by the pin.

Cone (Figure 5)

Impact causes a spring-loaded cone of compliant material (e.g. lead) to be thrust into the fairlead throat, thereby preventing further cable payout. This method has also been adapted to explosive anchors.

2. Rotation-Sensing

Centrifugal (Figure 6)

Centrifugal force prevents locking of the drum until its rotation stops as the anchor bottoms. The arms then move in to engage cutouts in the disc. The spring-loaded blocks allow the device to be cocked open before launch.

Hydraulic (Figure 7)

A reciprocating pump works off a can on the drum shaft. The pump pressurizes a reservoir which has a timed bleed orifice. The piston in this reservoir cylinder is acted upon by sea pressure on one face, and by pump pressure on the other. When the anchor bottoms and rotation stops, the pressure in the reservoir bleeds away (in two to three minutes) and the withdrawal of the piston rod releases a spring-loaded pin to lock the drum.

Tension-Sensing

The tension decrease due to anchor bottoming may be sensed to lock the wind drum by various mechanical means. This method may utilize the anchor leader.

Depth-Braketing (Figure 8)

A series of various diameter swaged balls along the cable are used to control the amount of cable which can be released from the drum. A series of gates atop the fairlead allows passage of only the balls below a certain diameter. Since the gate is moved by a pressure device as the unit descends in the sea, successively more cable can be paid out. A second winch is needed elsewhere to control lengths of cable for intermediate depths between the swaged balls.

B. *Depth-Setting*

- Pressure controlled winch (Figure 9)

  Figure 9 shows two configurations of "tide" winches, which are controlled by pressure to maintain a buoy some fixed distance below the surface. The wind also drains the buoy below the surface during deployment.

- Servo-Brake (Figure 10)

  A servo-signal is generated by the difference between sea pressure and a preset reference pressure, to actuate a band brake. This unit provides accurate placement of a buoy at any chosen depth, as determined by the reference pressure.

- Anchor Leader (Figure 1)

  A weight suspended below the anchor impacts the seabed, and the tension relief in the leader cable locks the payout drum at the anchor. The anchor weight then draws the buoy down to the chosen depth, as selected by the length of leader cable.

C. *Cable Payout*

Basket (Figure 12)

Cable can be drawn as needed from the device shown. When all the cable is drawn off (slack movings) the base plate and vertical rods are discarded.

Figure 8 and Bollards (Figure 13)

Cable can be drawn as needed from the device shown. When all the cable is drawn off (slack movings) the base plate and vertical rods are discarded.

Vertical Axis Spool (Figure 14)

Vertical spools may be used for both internal and external payout. The drum is fixed for internal payout; for external, either the drum or guide tube rotates. In either case, the cable is wound with a cement which maintains the packing, but which allows the cable to be drawn away under some tension.

D. *Sequential Releases*

Control Cable

A push-pull control cable may be used to trigger an event following an earlier event. Usually a spring-loaded device at the end of the cable is used, such that the cable prevents actuation until the earlier event occurs.

Messenger Releases

Commercially available devices allow a sequence of events, e.g. the opening and closing of a plankton net, by sliding weights down the cable to actuate mechanical linkages. The first weight actuates one event and cocks the actuator for the second event.

E. *Pressure-Sensing Releases*

A cylinder/piston unit may be used to actuate release of a buoy anchor, or other object.

Timed (Figure 15)

The device may be cocked at the time of launch, such that a spring forces motion of the piston as air bleeds through an orifice. This constitutes a timed device, whereby such objects as flotation collars may be released, some time after launch, by the piston rod motion.

Pressure Increase (Figure 16)

The dashpot without bleed orifice may be used to trigger an event at some chosen depth in the sea. Pressure compresses air in the cylinder, and the piston rod motion provides the actuation (e.g., the opening of manacles holding an anchor to a buoy).

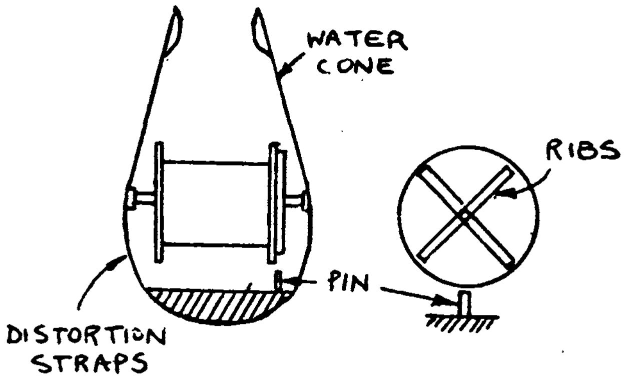


FIGURE 1
DISTORTION LOCK

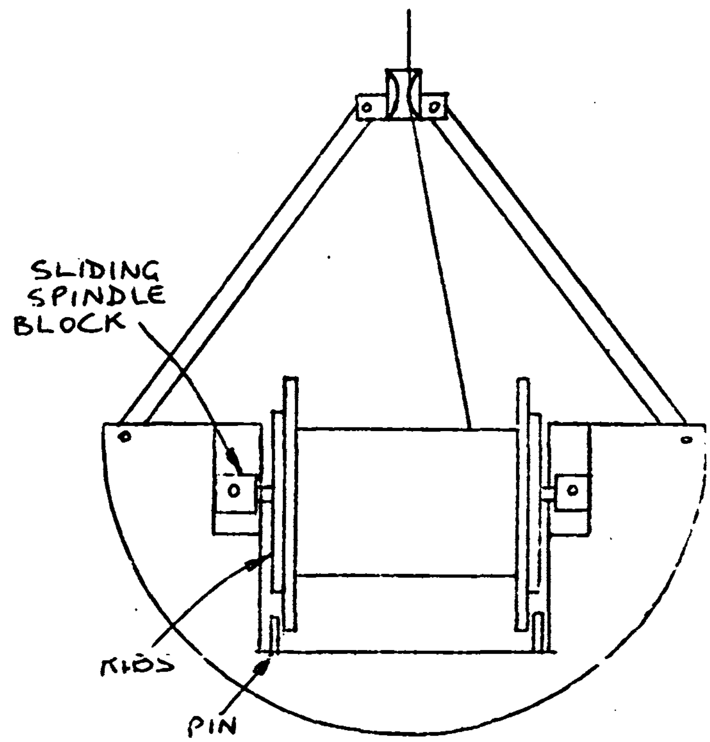


FIGURE 3
PIN IMPACT LOCK
(HORIZONTAL SPOOL)

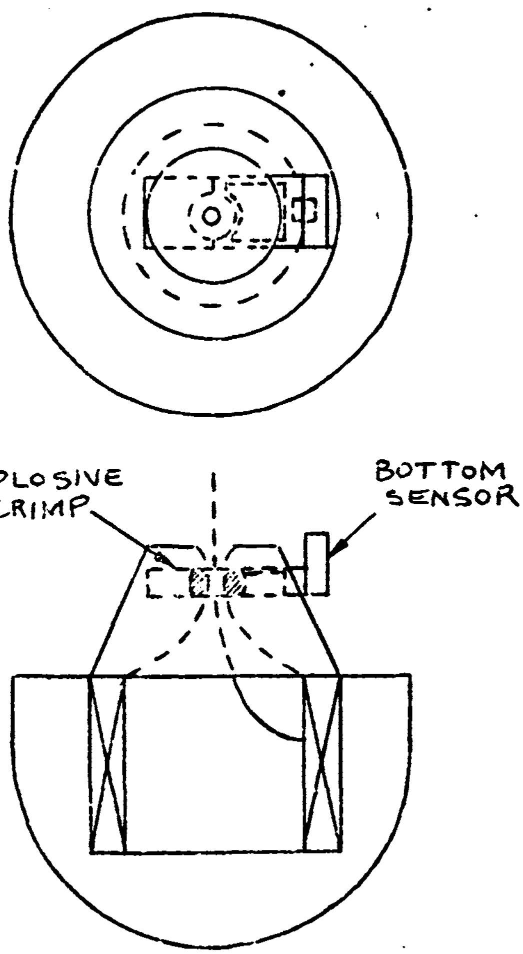


FIGURE 2
CRIMP LOCK

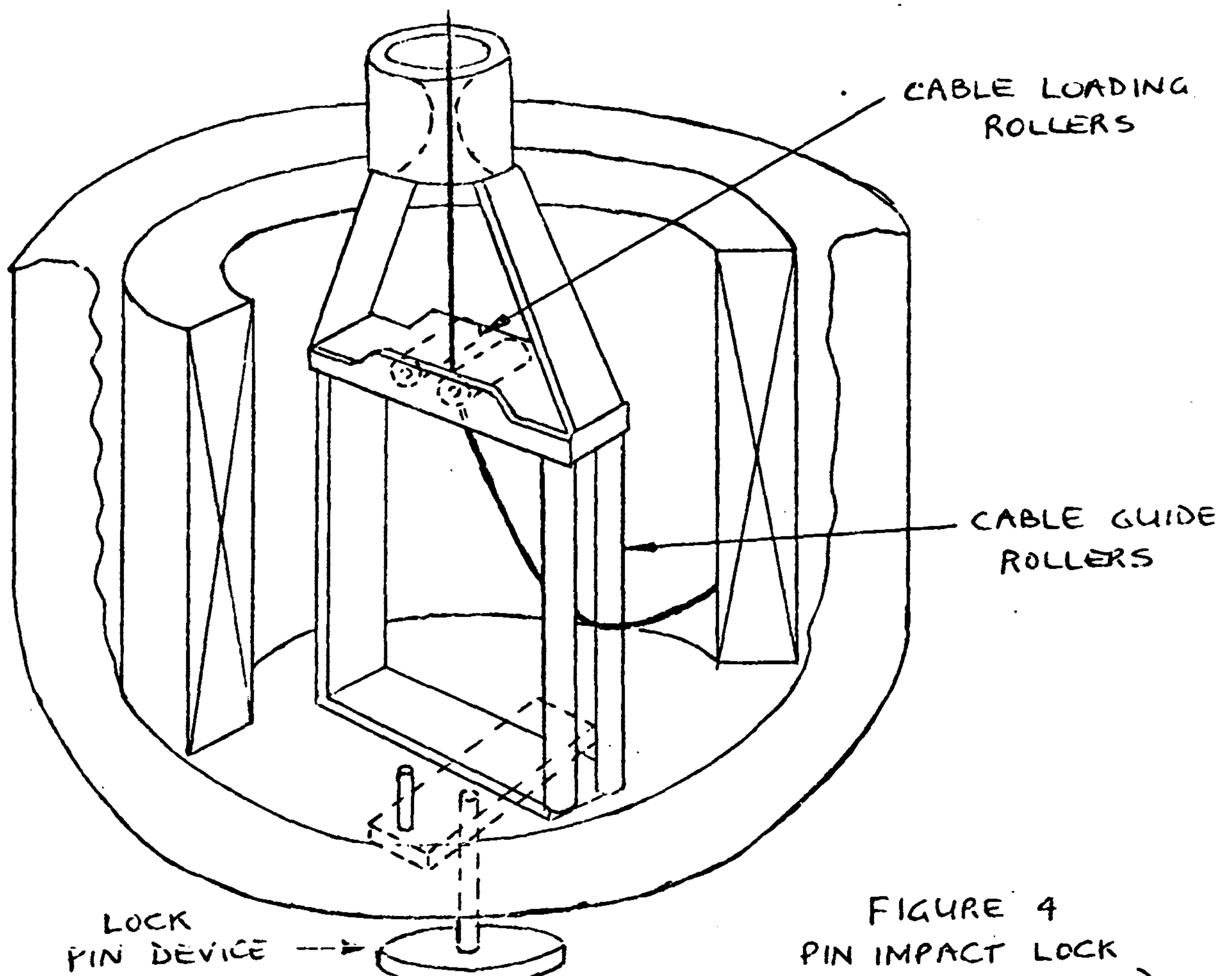


FIGURE 4
PIN IMPACT LOCK
(VERTICAL SPOOL)

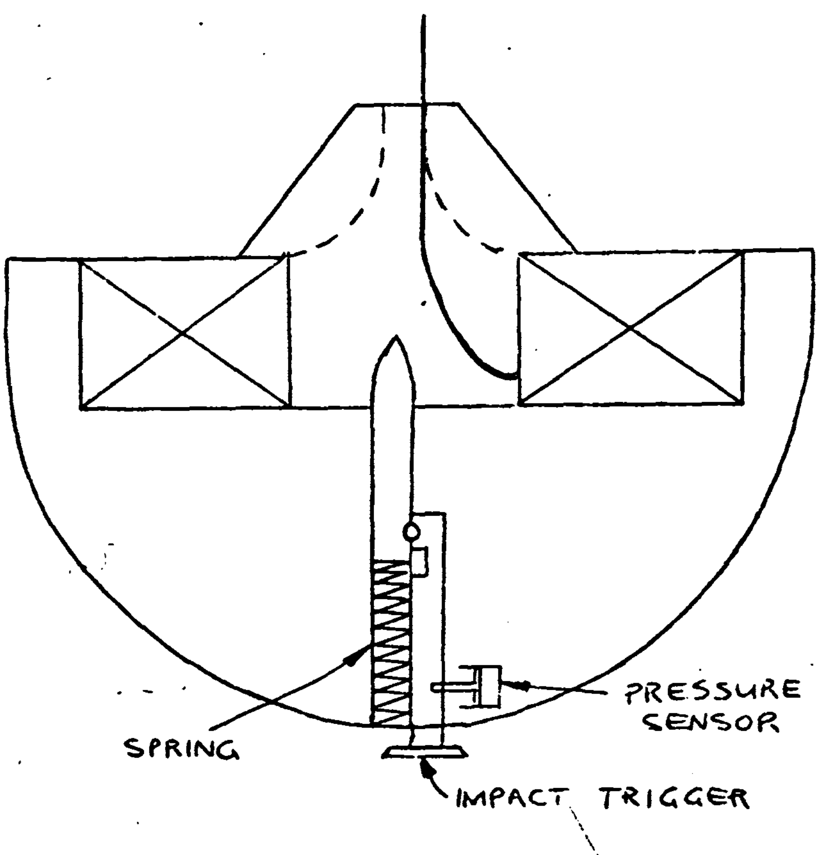


FIGURE 5
CONE IMPACT
LOCK

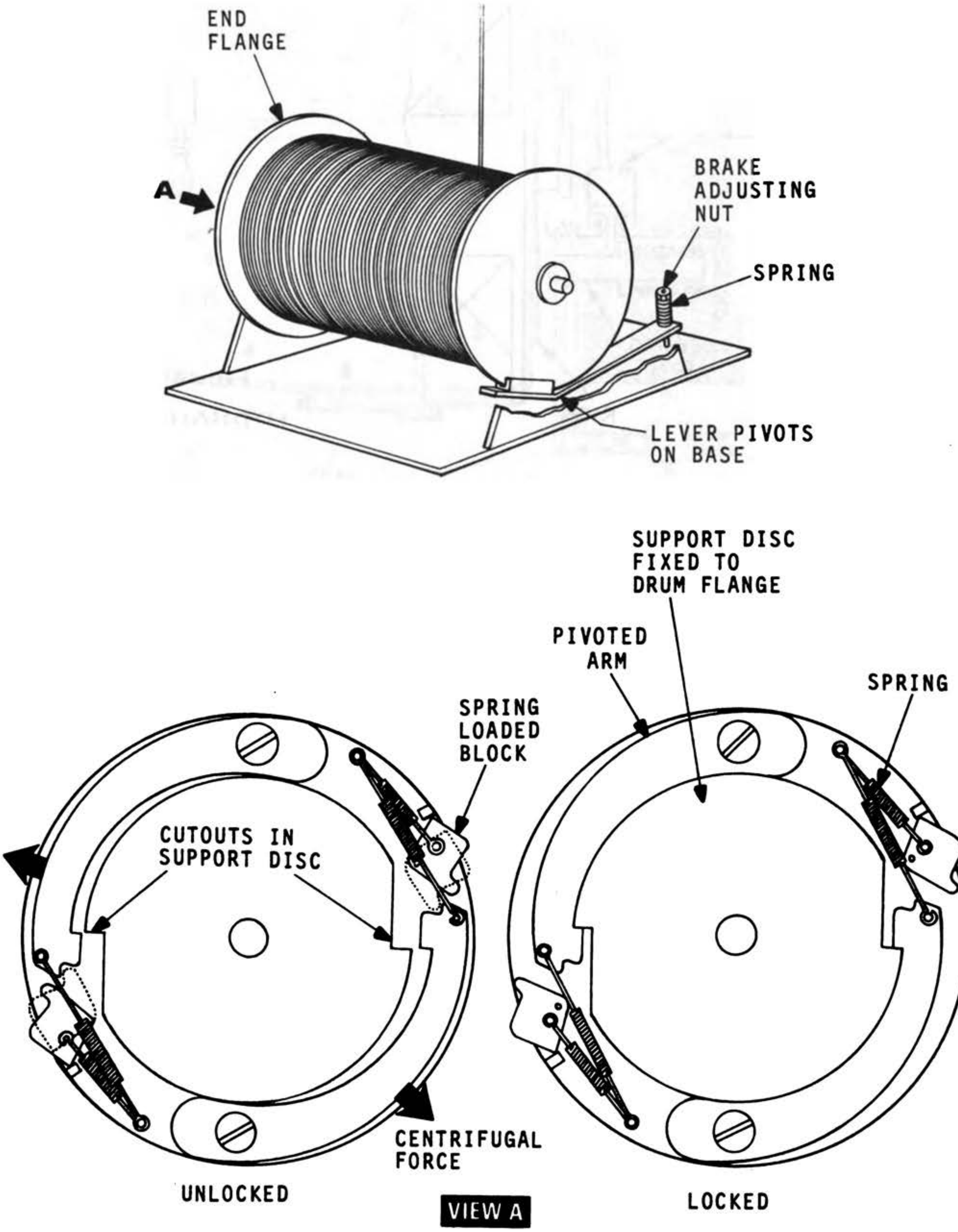
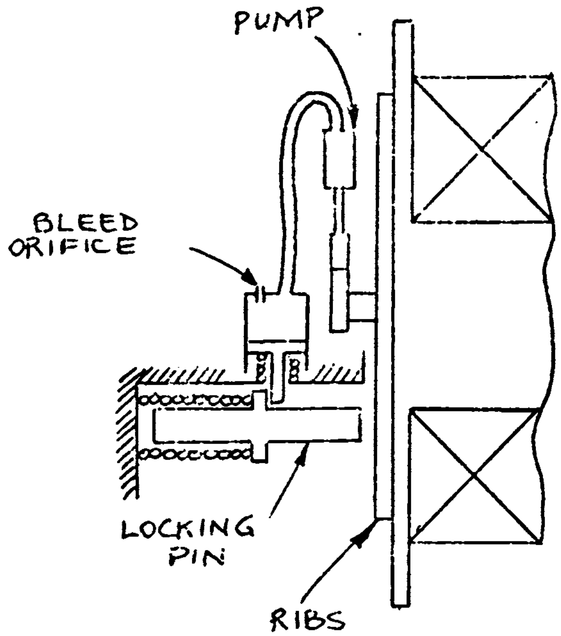


FIGURE 6 HERMES ELECTRONICS
SELF-LOCKING ANCHOR DRUM



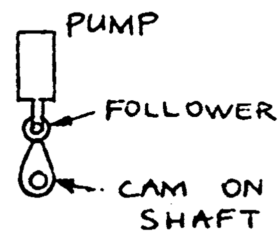
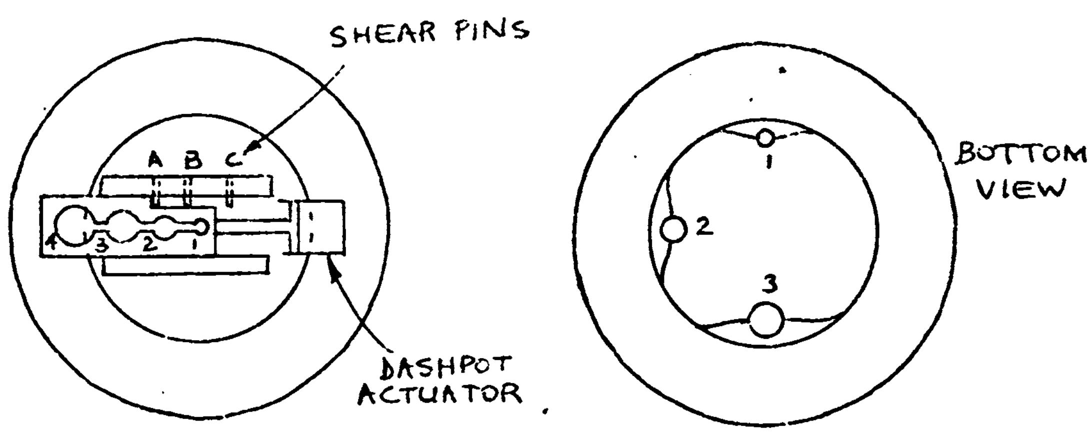
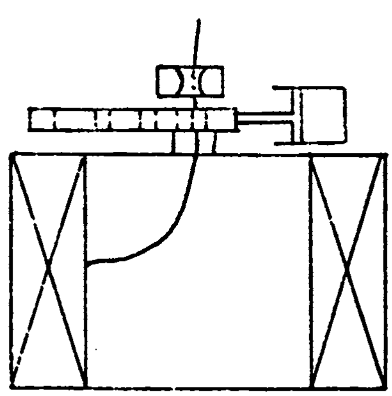


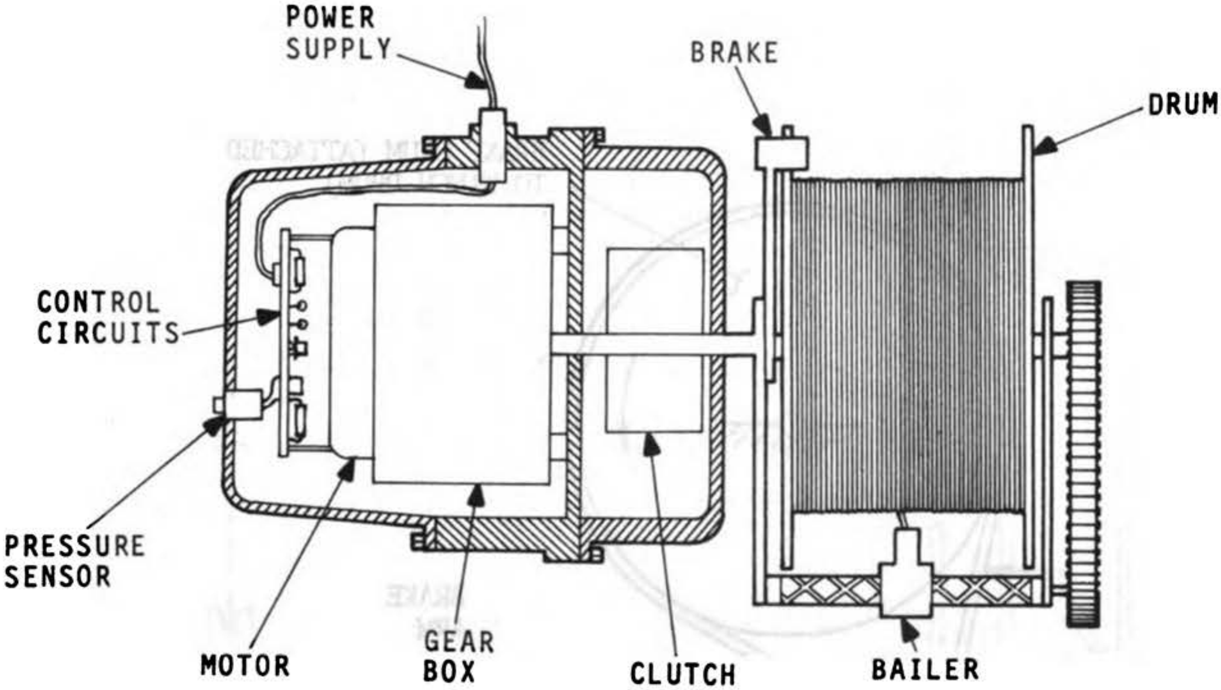
FIGURE 7
HYDRAULIC LOCK



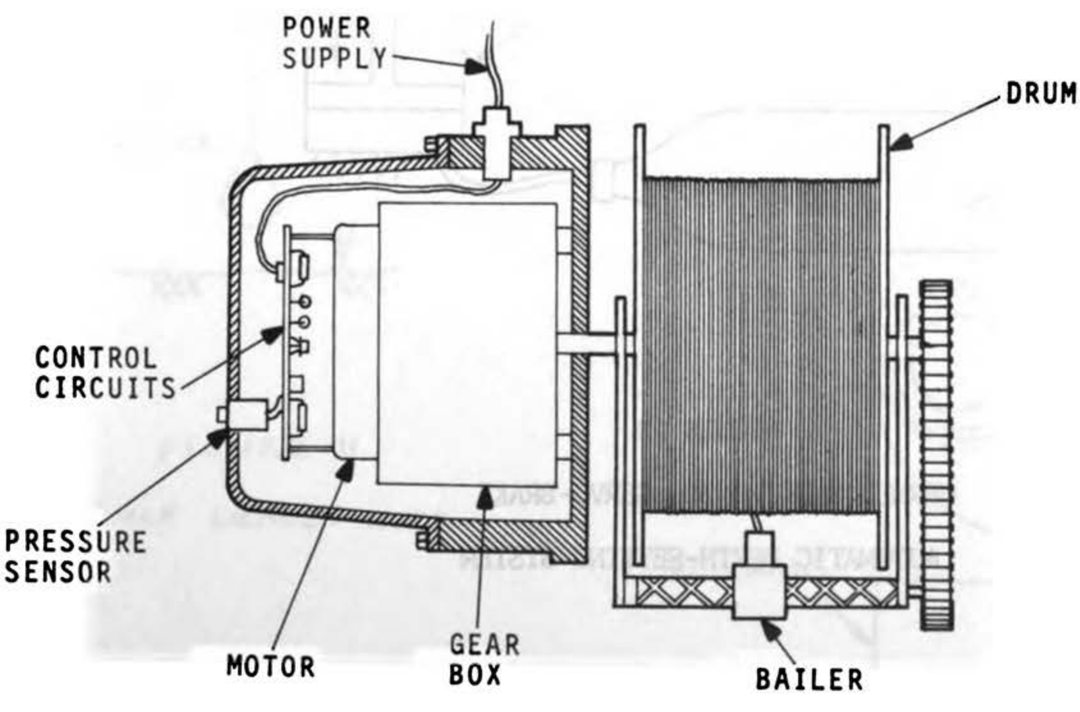


- SWAGED BALL 1 CATCHES IN GATE 1, ETC.
- LOCATING SHEAR PINS ARE SUCCESSIVELY SHEARED BY SEA PRESSURE

FIGURE 8
SWAGED BALL /GATE PAYOUT CONTROL



(a) WINCH UP



(b) WINCH DOWN

FIGURE 9 HERMES ELECTRONICS DEPTH-SETTING PRESSURE-SENSITIVE WINCHES

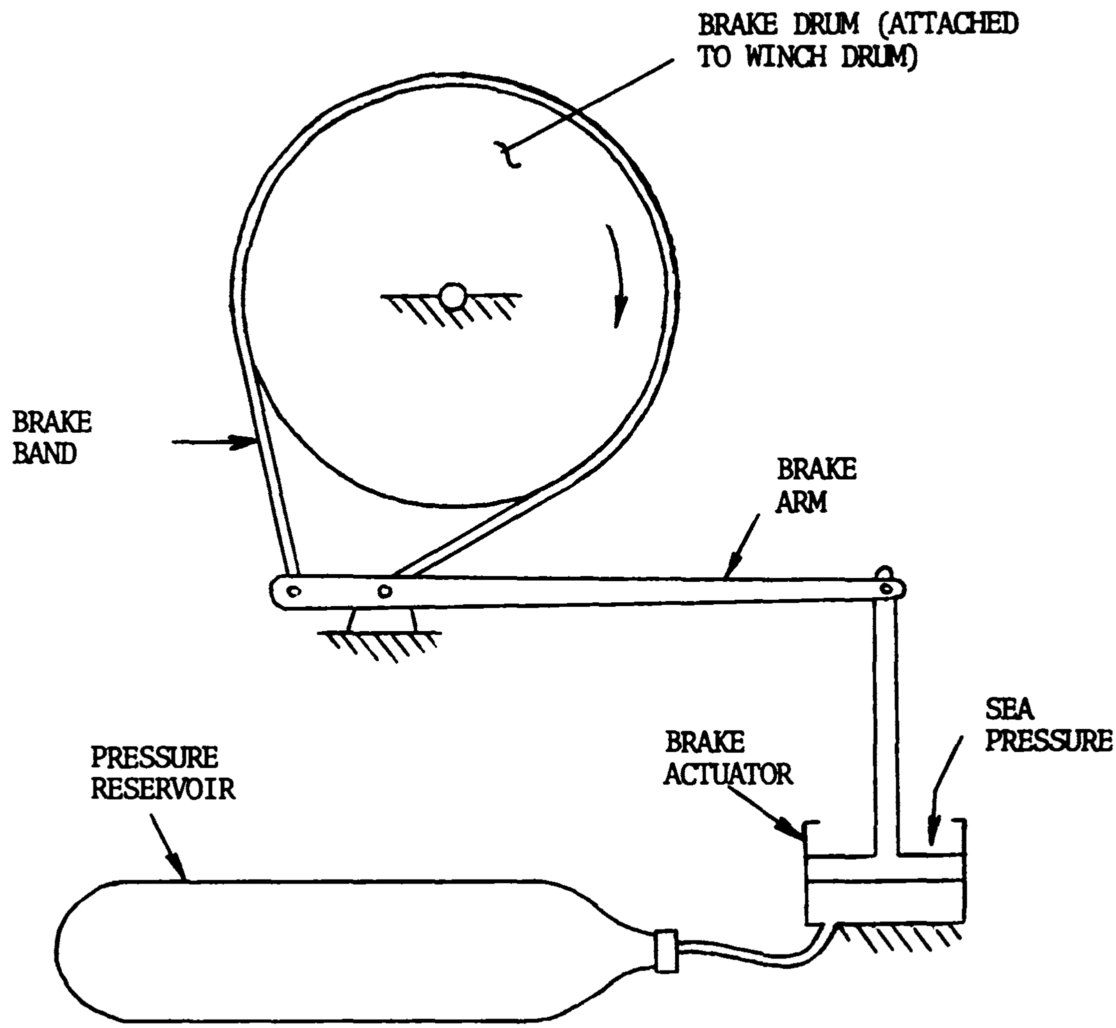


FIGURE 10

HERMES ELECTRONICS SERVO-BRAKE

AUTOMATIC DEPTH-SETTING SYSTEM

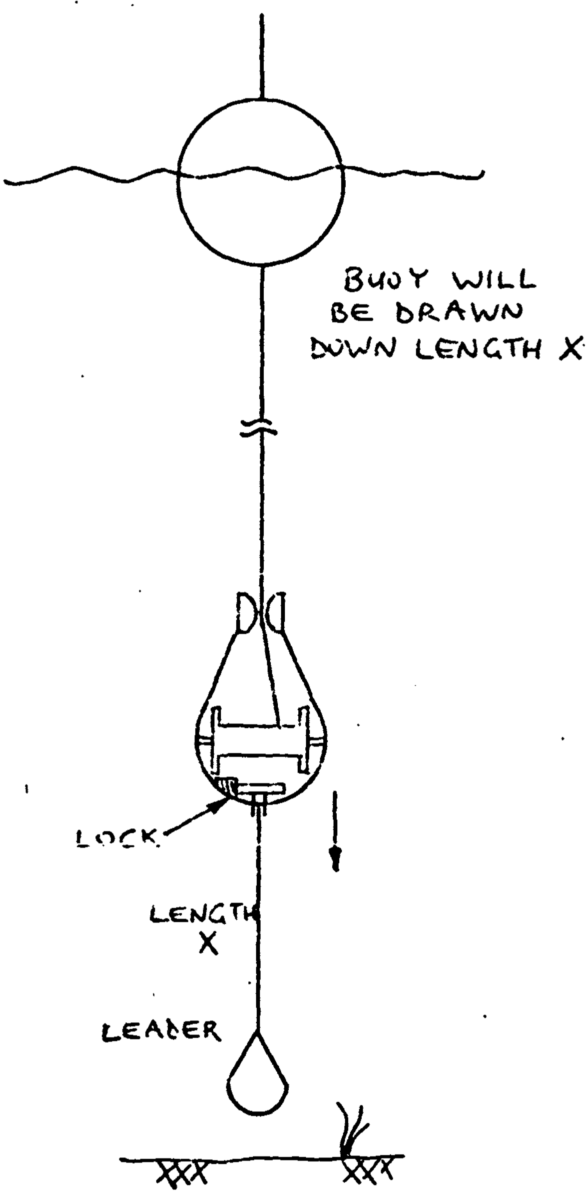


FIGURE 11

ANCHOR LEADER LOCK

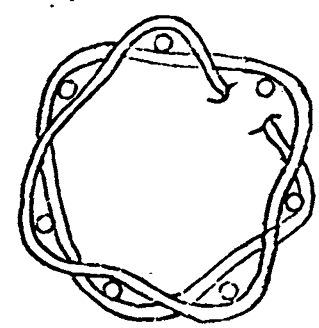


FIGURE 12
BASKET CABLE
WINDING

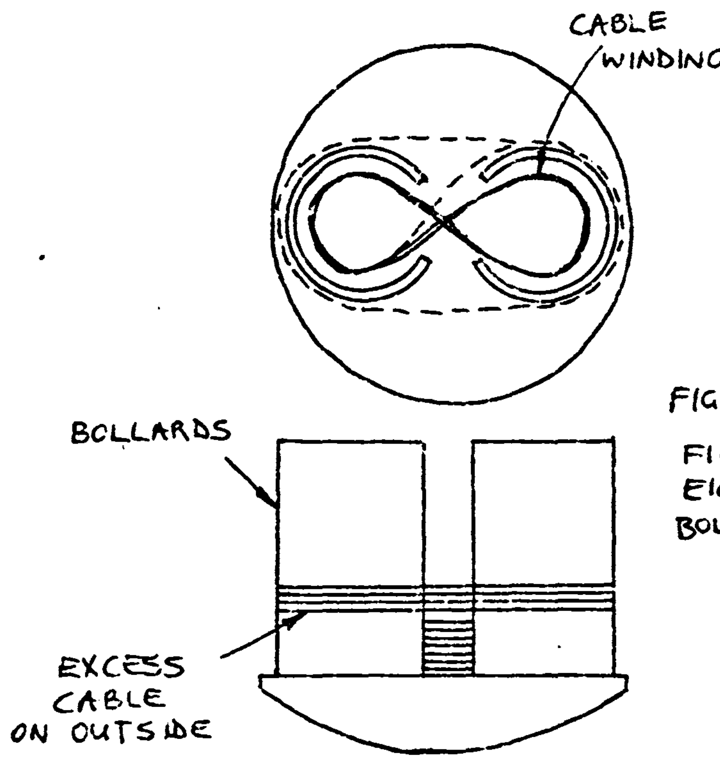


FIGURE 13

FIGURE
EIGHT &
BOLLARDS

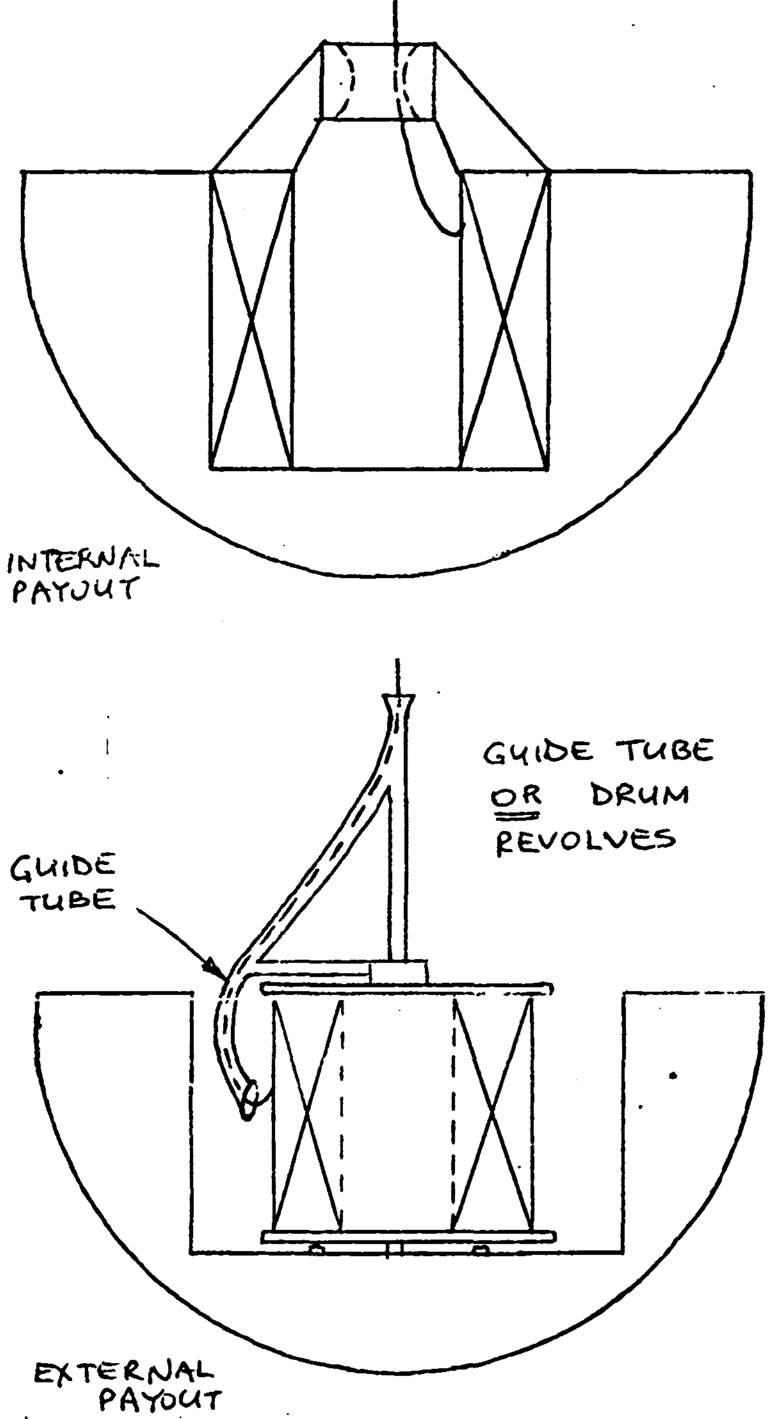


FIGURE 14
PAYOUT
SPOOLS
(VERTICAL
AXIS)

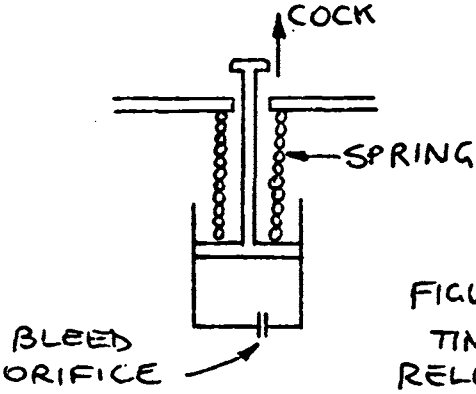


FIGURE 15
TIMED
RELEASE

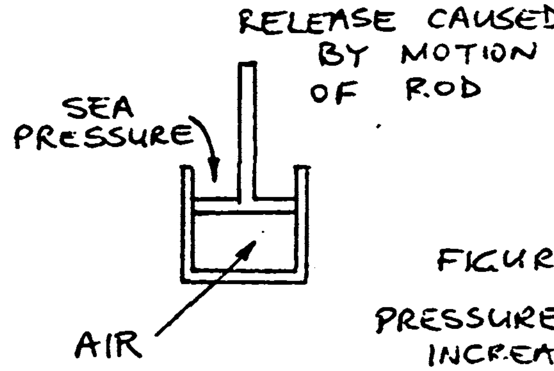


FIGURE 16
PRESSURE-
INCREASE
RELEASE

BASIC PROBLEMS IN MATHEMATICAL ANALYSES OF MOORING CABLE HYDRODYNAMICS AND STRUCTURAL DYNAMICS

by

J. H. Nath

School of Oceanography
Oregon State University
Corvallis, Oregon 97331

BASIC PROBLEMS IN MATHEMATICAL ANALYSES OF MOORING CABLE HYDRODYNAMICS AND STRUCTURAL DYNAMICS

by

John H. Nath

The basic problem is that we cannot describe mathematically, and with confidence, the response of tethered systems to the loads from hydrodynamics, gravity and structure-fluid interaction. Nevertheless, designers must try to predict, with safety and economy, the loads within tethered systems so that the line size and type can be specified.

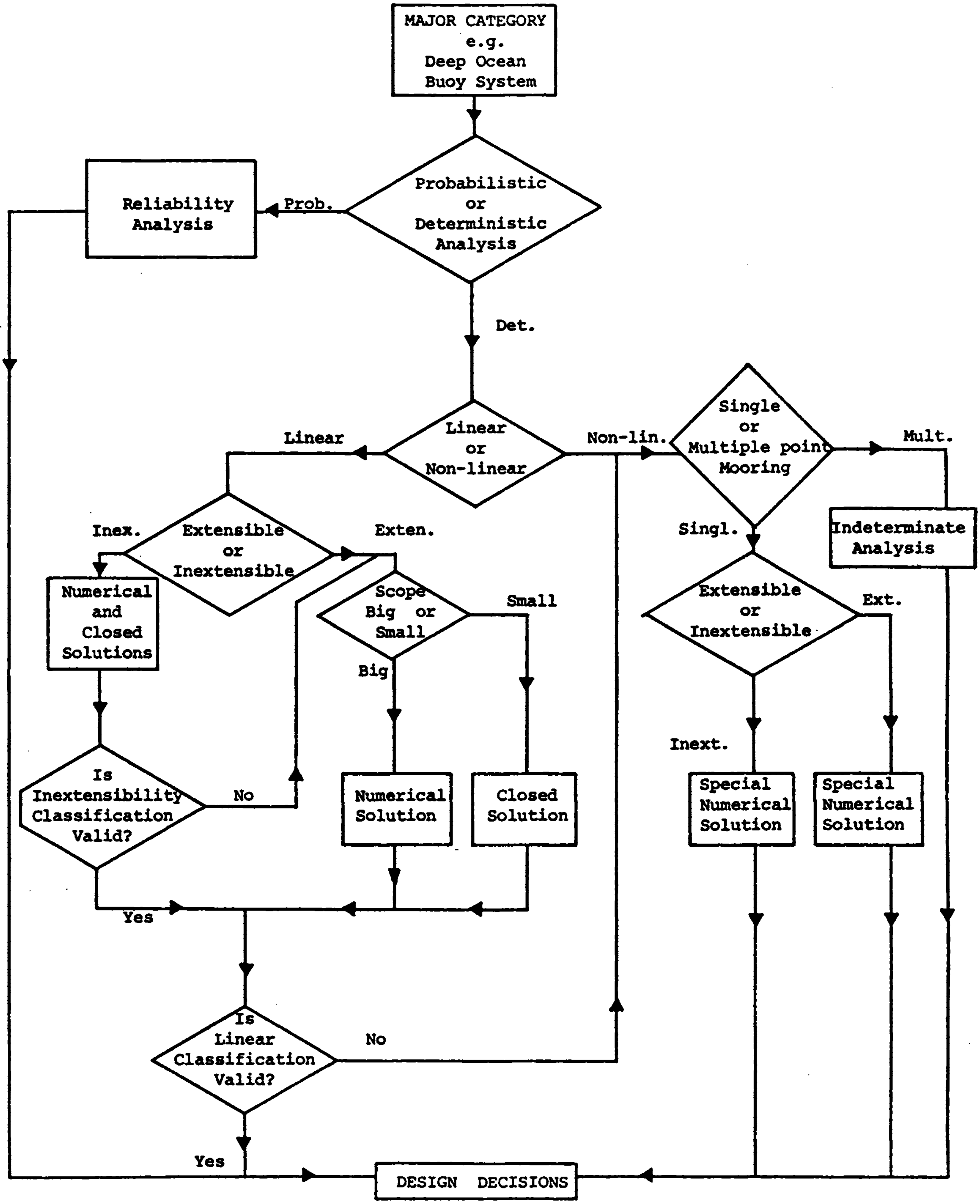
The basic problem can, of course, be divided into subsidiary problems, a major one of which is the lack of fundamental information. Examples of the kinds of information needed are the dynamic load-elongation characteristics, in air and in water, of various ropes; the details of vortex shedding and the resulting reaction and interaction of tethers; the hydrodynamic drag characteristics, both perpendicular and tangential to the line, of all the more important ropes; the hydrodynamic characteristics of the various surface and sub-surface float forms, including ships; and the best and most economical method for obtaining the forces within a tether.

The last problem given above is one which has been considered seriously by the author. This problem, stated differently, is that a designer may need aid in determining which mathematical method to use when designing the tethers of a certain system. He may err, for example, by trying to use a very expensive numerical approach for a system configuration which should be analyzed with a simple, inexpensive, closed solution, or by some other technique. A case in point, for example, is the mistake of using the method of characteristics solution for steel wire rope -- a procedure that requires excessive computer time and considerable cost. The designer could similarly err by insisting on using linearization techniques based on small motions, in order to get low-cost solutions in a frequency domain, when perhaps he should concentrate on large non-linear motions, using solutions in the time domain in order to obtain desired accuracy, for particular cases.

This paper should be considered as a first attempt to organize the general topic of the analysis of tethered systems into areas for consideration by the designer. The objective is to try to categorize the various systems in such a way that the designer can be directed to the most efficient method of analysis for his particular problem. Much of the category breakdown depends upon the characteristics of the dynamics of the system. Admittedly, part of the organization is arbitrary and is subject to change and reorganization as future facts become known and replace intuition.

It is felt that the entire subject of the design of tethered systems can be treated in the manner that will be presented; however, complete details are given for only the subsets of problems dealing with oceanographic marine moorings. Again, it should be emphasized that this is a first attempt at such an organization and it may be that certain important aspects have been overlooked, or that certain items have been placed in the wrong category, or that some methods of analyses have been unintentionally omitted. More time and effort is needed to develop a complete and useful chart or system of presentation for the designer.

CATEGORIES OF ANALYSES FOR THE LINES OF TETHERED SYSTEMS



MAJOR CATEGORIES OF TETHERED SYSTEMS

Bottom Mounted Guyed Tower

Ship Berthing

Deep Ocean Semi-submersible or Ship Mooring

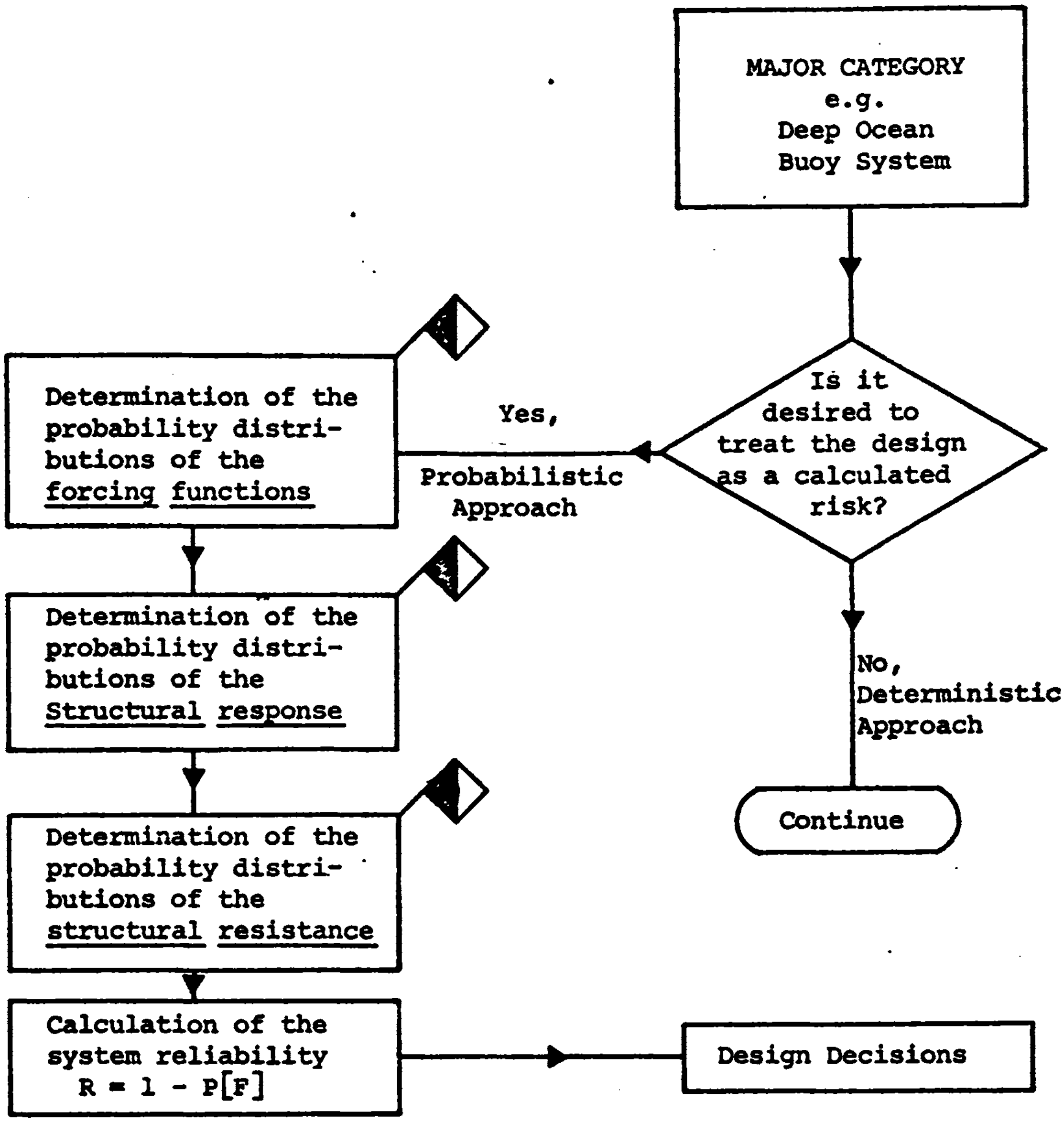
Deep Ocean Operational Buoy System

Anchor Last Mooring Procedure

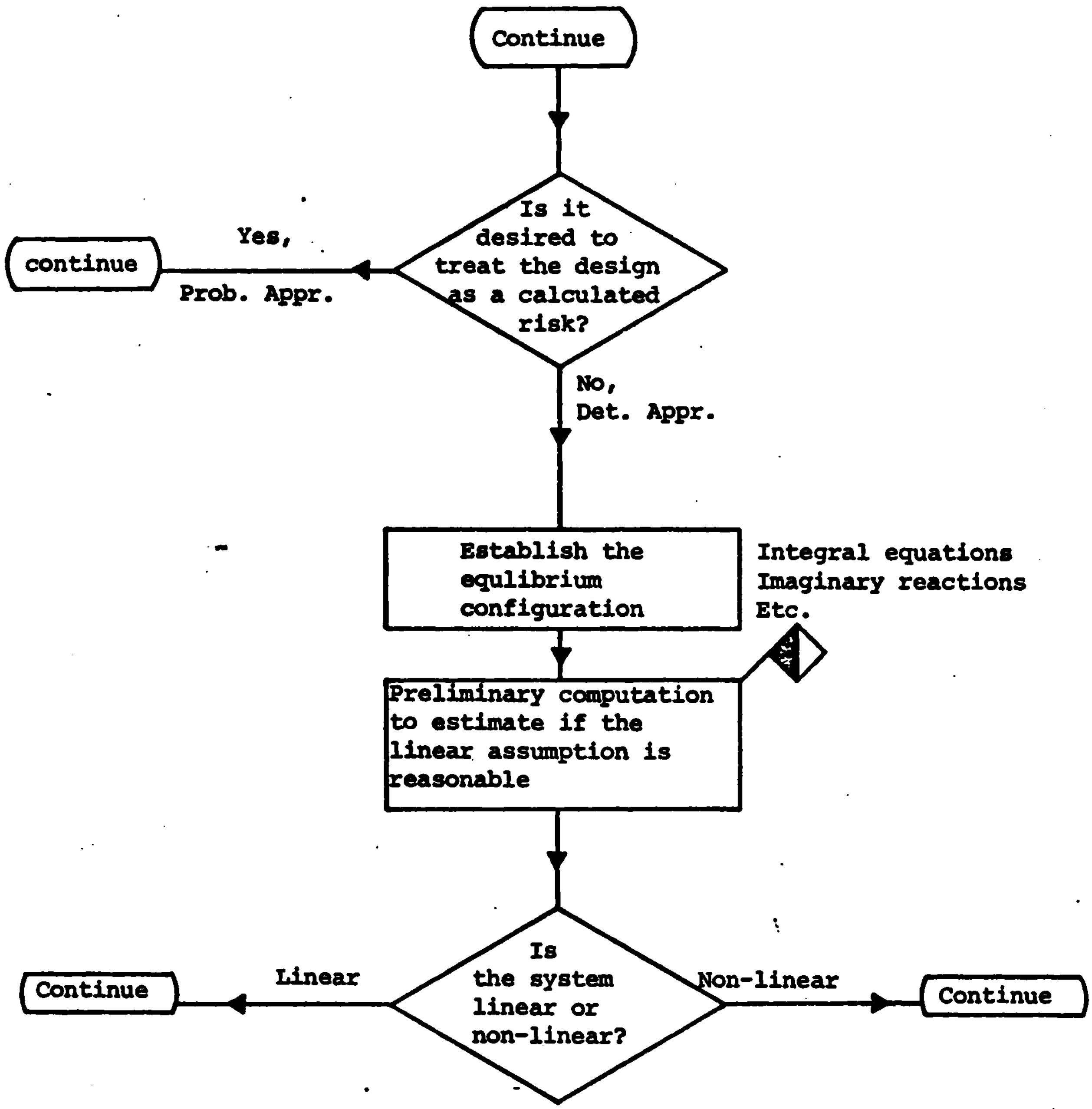
Cable Laying Operations

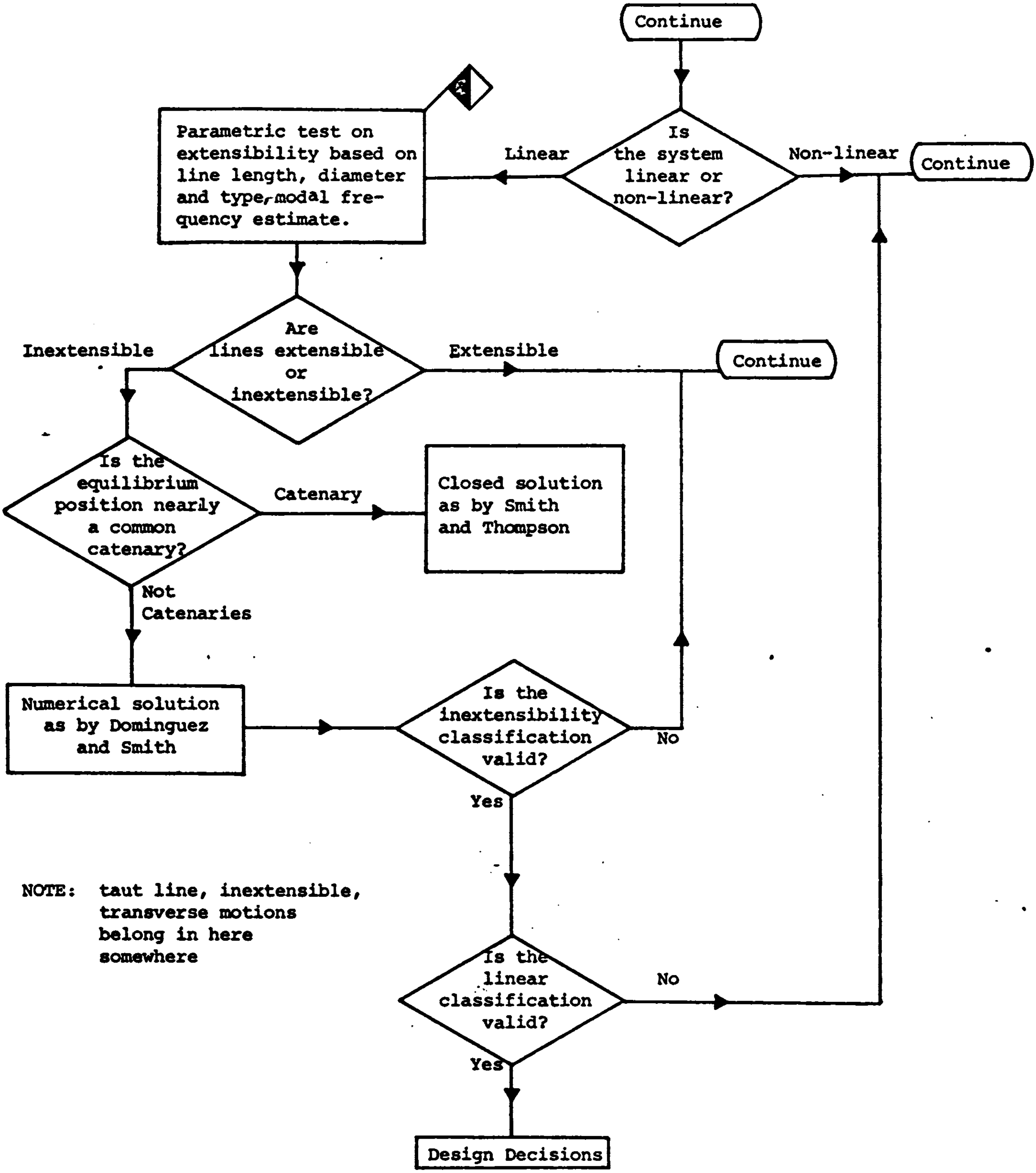
Tethered Balloons

Tethered Space Walker



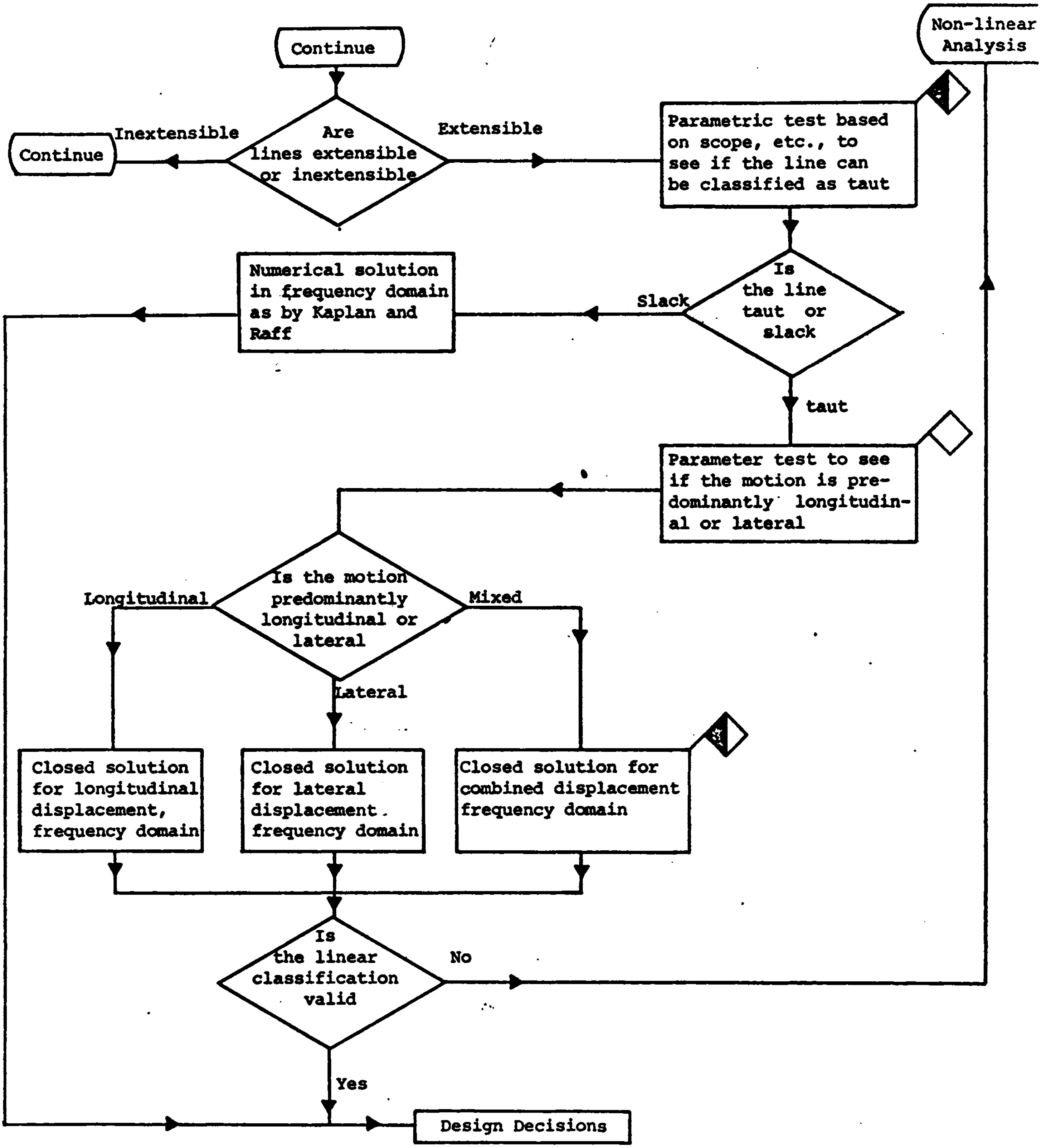
Note: Flags indicate problem areas that require additional work, with the darker the flag, the greater the problem.

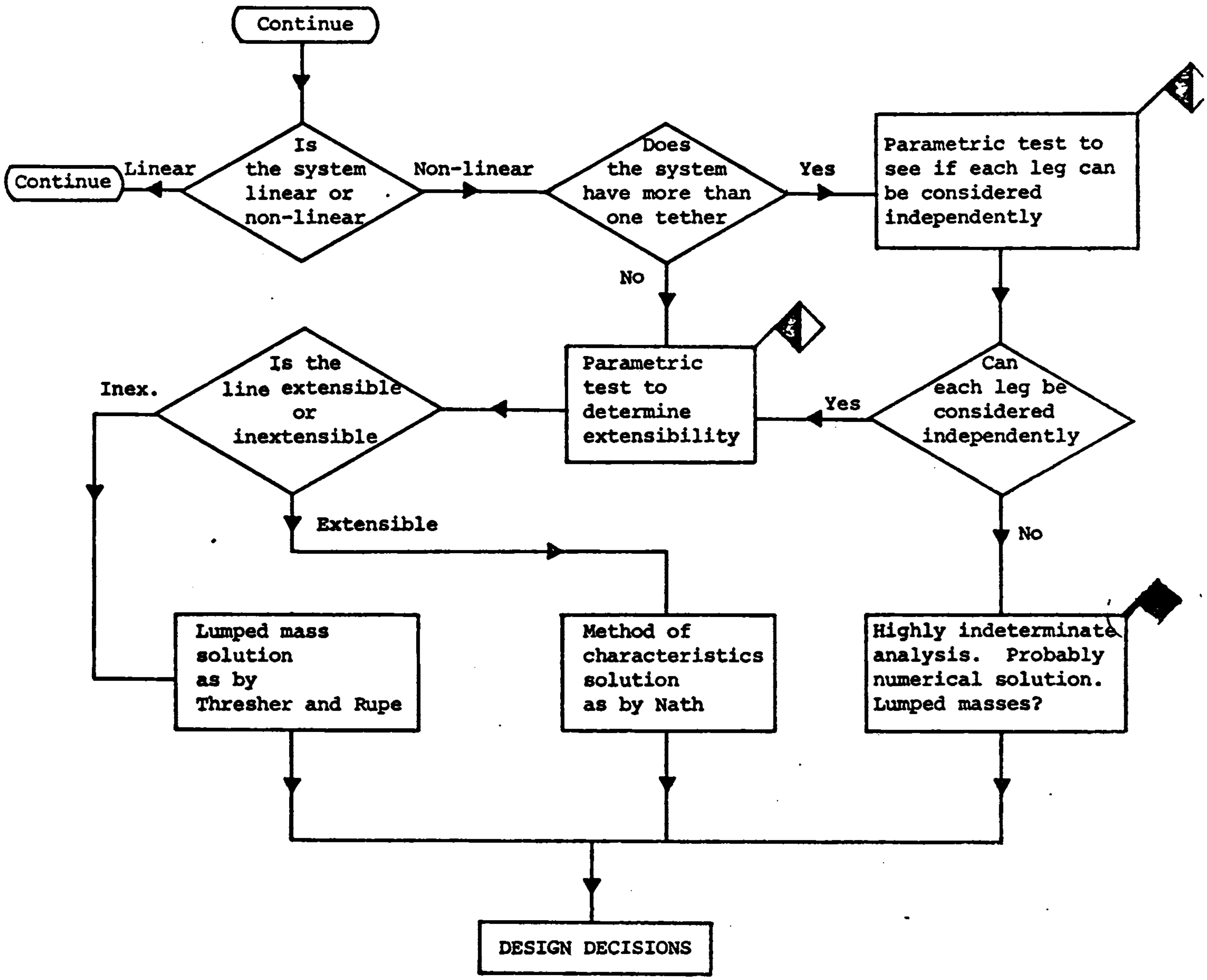

Continue
Is it desired to treat the design as a calculated risk?
Yes, Prob. Appr.
continue
No, Det. Appr.
Establish the equlibrium configuration
Integral equations
Imaginary reactions
Etc.
Preliminary computation to estimate if the linear assumption is reasonable
Is the system linear or non-linear?
Linear
Continue
Non-linear
Continue



NOTE: taut line, inextensible, transverse motions belong in here somewhere

Linear Analysis




Continue
Is the system linear or non-linear
Linear
Continue
Non-linear
Does the system have more than one tether
Yes
Parametric test to see if each leg can be considered independently
No
Parametric test to determine extensibility
Can each leg be considered independently
Yes
Is the line extensible or inextensible
Inex.
Extensible
No
Lumped mass solution as by Thresher and Rupe
Method of characteristics solution as by Nath
Highly indeterminate analysis. Probably numerical solution. Lumped masses?
DESIGN DECISIONS

FREE-FALL ANCHORING SYSTEMS

by

R. M. Snyder

Ocean Science and Engineering, Inc.
Riviera Beach, Florida 33458

Reprinted from: MARINE SCIENCES INSTRUMENTATION, Vol. 4
(Plenum Press, 1968)

FREE-FALL ANCHORING SYSTEMS

Robert M. Snyder
Ocean Science and Engineering, Inc.
Riviera Beach, Fla.

SNYDER OCEANOGRAPHY SERVICES
169 BEACON LANE
JUPITER FL 33458

ABSTRACT

The determination of performance parameters for free-fall systems is not always a straightforward matter. The theoretical approach to hydrodynamic drag and stability is imperfect and complex and must be performed by an expert. The empirical approach has generally proved more rewarding but many shapes used by the ocean engineer are not covered in the literature. This paper covers by example one approach which may be used effectively when time and budget restrictions prohibit model or full scale test programs.

INTRODUCTION

In the development of free-fall systems the engineer must interface his payload with a physical design which is capable of the desired performance. He is not always able to use the most desirable shape due to space and weight restrictions. As with most engineering problems his design is the result of compromise and design flexibility is often at a minimum. Once a shape is determined the engineer must search the literature to determine the drag coefficient and the static and dynamic stability characteristics of his device. Since cost is nearly always a consideration in oceanographic instrumentation, and since performance, statistically at least, is a direct function of simplicity of design, the odds of finding directly applicable data are not favorable.

A proper understanding of the principles of drag and stability combined with a "feeling" acquired by experience can lead to reasonable estimates of these parameters without recourse to theoretical studies or experimentation. In the following example the results obtained from field-trials verified the applicability of this approach.

THE PROBLEM

The problem may be briefly stated as follows: Provide a system to automatically anchor a buoy in the shortest possible time in any water depth between 500 and 18,000 feet.

DESIGN CONSTRAINTS

Package size must be limited to 21.5 inches in diameter and 28 inches in length. Package weight, including payload, cannot exceed 900 pounds but should be kept as lightweight as possible.

PERFORMANCE PARAMETERS

The mooring wire must have a minimum breaking strength of 1300 pounds and must last a minimum of 90 days with no more than 10% degradation of strength. The anchor must fall stably with no measurable deviation from the vertical in still water and no excess wire should be payed out. The mooring wire must be automatically the instant the anchor impacts with the bottom.

PRELIMINARY DESIGN

Since a high descent rate was of prime importance and automatic lock-up upon bottom impact was required, the servo type payout mechanisms were ruled out. Previous experience supported the feasibility of a completly free wire payout package. Also, because it was not considered desirable to rely on the mooring wire as a signal conductor, the aotomatic lock-up mechanism should be located at the anchor. This, in turn, meant that the wire must be payed out from the anchor. A second major advantage accrues if the wire is placed in the anchor; the excess wire weight is added to the anchor weight rather than detracting from the surface buoyancy when the mooring is made at the shallower depths.

On the other hand, to provide for mooring in 18,000 feet of wire a total length of 20,000 feet of wire was specified. This wire had to be placed in the 21 inch diameter by 28 inch long cylinder along with appropriate mechanisms for providing full strength, automatic lockup. To provide the 1300 pound breaking strength in this space required the use of high-tensile rocket wire. High-tensile rocket wire is high in carbon and therefore susceptible to rapid corrosion in sea-water. An impervious, thin, tough, pin-hole-free covering had to be extruded over the wire. The automatic lock-up had to be designed so as not to damage the coating. This and the production of 20,000 foot, fully protected unbroken lengths of wire presented some interesting engineering and quality control problems which were eventually overcome.

Having assumed that these problems could be solved the next step in the design was to determine the best shape within the constraints of the payload and allowable package size.

HYDRODYNAMIC STABILITY

A literature search turned up one unclassified[1] and one classified report on the stability of blunt bodies. The unclassified report covered bodies with length to diameter, L/D, ratios greater than 1.5:1. These devices also used flared tail sections (figure 1) which were not possible to use in our case due to the payload requirements and the limited package diameter. The other report covered L/D ratios less than 1.5:1 but was limited to parabolic shapes. The maximum allowable L/D ratio in our case was 28 inches over 21.5 inches = 1.3. Tests showed that the parabolic shapes with sharp trailing edge showed good dynamic stability. Useing a parabolic shape, however, would severely increase the cost of our anchor package, not only in the manufacture of the shape itself, but because the wire package would have to be tailored to this shape. From a mechanical design standpoint a shaped nose terminating in a cylindrical section was preferable.

The basic principles of stability were reviewed to determine the factors that contribute to instability. An excellent presentation of these principles is given in reference 2. According to the authors, a body is considered to be stable in any particular state of rest or motion if it ultimately returns to the same initial state after perturbation by an external force or moment.

The authors deal with the several cases of stability associated with submarines. Static stability is not hydrodynamic in origin but must be included when considering dynamic stability because a static righting moment will itself become a perturbing force after an external force disturbs the initial equilibrium.

Motional stability is hydrodynamic in origin and is of different kinds. In the first case of motional stability the body assumes a new straight line of motion after a disturbance. Case I is called straight-line stability. In Case II the body resumes straight-line motion in the same direction. Case III is the same as Case II but with critical damping. Cases II and III are termed directional stability which is obviously what is required of our anchor. Case III is preferable because any oscillation will tend to decrease the speed of descent and cause excess wire payout.

Associated with each kind of stability is a numerical index which by its sign designates whether the body is stable or unstable.

Reference numbers are keyed to the bibliography

Since we are dealing with a body which is symetrical about the axis of motion we need not differentiate between pitch and roll. The index of static stability, then, is the derivative of the upsetting moment with respect to the angle of heel. A negative index (moments in opposition to angles) indicates stability.

The indices associated with directional stability are more complex and are seperated into four categories.

1) Angle of attack measured between the velocity vector and the intended axis of motion.
2) Angular position of the intended axis of motion and the gravity vector.
3) Angular velocities of the body.
4) Angular accelerations.

The indices for directional stability involve some combination of the force and moment derivatives with respect to the above orientation and motion categories. These are called stability derivatives. The relationship between the stability derivatives and the stability indices are obtained from the equations of motion involving the forces and moments on the body.

Combining the force and moment equations yields a third order differential equation which can be solved in terms of the two angles noted above. The indices are found by substitution and solution of a cubic equation. All three values must be real and negative for critically damped directional stability to obtain.

This is all very interesting and informative and the equations are straightforward to use but the forces and moments are unknown for our shape. As with most other hydrodynamic parameters they must be determined empirically. A further aspect of interest results from pursuing the theoretical approach to stability, however, even though we cannot calculate the desired performance characteristics. All of the hydrodynamic stability derivatives are essentially constant with speed for a free fall anchor. The static stability index (gravity couple), on the other hand, is strongly dependent on speed of fall. At low speeds the stability is governed by the gravity couple. As speed increases the motion stability becomes more and more dependent upon the hydrodynamic derivatives, and at very high speeds the static stability index has essentially no effect on the stability of descent. For our anchor then, the gravity couple will have effect only during the first few fractions of a second after the anchor is released. This means that the stabilizing moments will have to derive from hydrodynamic phenomena.

Still, without testing and without being able to calculate the stability indices we we still may be able to draw some conclusions which will be helpful in finalizing our design.

Figure 1 shows the two blunt shapes of known static and dynamic stability. Figure 2 indicates the maximum space available for our anchor shape. In figure 3 are essentially all the of the reasonable shapes available for the anchor design. Since we are also trying to achieve a low drag coefficient the nose of the anchor must be faired. In fact, drag and stability are inter-related to some degree if only because they are both hydrodynamic in origin.

In figures 1,2 and 3 the intended direction of flow is upwards. In order to try to determine if the alternate shapes will be dynamically stable we must consider angles of attack up to about 45^o from the intended axis of flow. All shapes are assumed to be ballasted with lead at the bottom to provide high static stability.

The shape shown in figure 3a can reasonably be assumed to be stable even though it has a somewhat greater L/D ratio than those tested by NASA (figure 1b). This shape would, however, complicate the manufacture of both the anchor shell and the wire package. From a cost standpoint it is preferable to use one of the other shapes. Figure 3b shows a shape which may be dynamically stable but, since static stability will have no effect at high speeds, it appeared to this observer at least, that the shape would tend to oscillate causing excess wire payout and higher effective drag coefficient.

Even so this shape would have the lowest drag coefficient of any of those shown because, at the Reynolds numbers involved, the seperation point would move aft. The ring shown in the sketch would be made to subtend a solid angle of about 50^o or slightly less than the ultimate flow seperation point in supercritical flow. The sphere does present interesting possibilities but, because of the above uncertainties and the reduction in the available volume for the wire, the sphere was ruled out for this particular anchor application.

The shape in figure 3c is basically the same as that shown in figure 1a but without the tail skirt. The tail skirt (reference 1) was found necessary for dynamic stability at supersonic speeds. Referring to figure 3c it can be seen that flow at moderate angles of attack could be accompanied by flow seperation at the line where the parabolic nose joins the cylindrical shell. Figure 4 is a sketch of the possible flow pattern. This flow pattern would obviously produce two couples; one tending to decrease the angle of attack (trailing edge burble) and the tending to increase the angle of attack (nose-body interface burble).

It is not possible to be definative about the magnitude of the forces involved in these couples although one would expect the righting moment to be stronger than the upsetting moment. Again, it must be remembered that, at high speeds, the gravity couple will have little effect.

Even if this shape possessed straight-line stability without the tail skirt it is doubtful that it would be critically damped once disturbed.

Figure 4d shows a hemi-sphere joined at the equator to a circular cylinder. The chance of flow seperation at the hemi-sphere cylinder juncture is much less than with shape 4c. This shape is also eaiser to fabricate and imposes minimum constraints on the packaging of the wire. This shape was chosen for the anchor. This shape could have been chosen strictly from a standpoint of mechanical engineering with the same end result. Even though no calculations were made and no directly applicable data were found, however, the above exercise increased the engineer's confidence to the point where active control surfaces were considered unnecessary. Field trials indicated that the confidence was justified.

HYDRODYNAMIC DRAG

The overall system that the anchor was designed to moor included an automatic winch which would be activated after the anchor impacted with the sea-floor. For simplicity a timing device was chosen to activate the winch. It therefore became important to be able to accurately estimate the terminal speed of the anchor.

Again, a literature search failed to turn up any applicable data. A double interpolation found in the published literature under supplimentary notes[3] coupled with data from reference 4 produced suprisingly accurate results.

Figure 5 shows data from tests of a two dimensional shape with three different L/D ratios. The first is a 2-dimensional version of the hemisphere. The L/D ratio of our anchor is 1.3:1 and lies between shapes 5a and 5b. Figure 6 is a plot of the drag coefficients, C_D, of these 2-dimensional bodies. Also indicated is the C_D for an L/D ratio of 1.3:1. We can assume then that if our body were 2-dimensional its drag coefficient would be 0.75.

In Volume II of Saunders (ref. 4), under appendage resistence, we find the drag coefficient of a hemisphere with convex side toward the stream to be 0.34 for supercritical flow. This is the three-dimensional equivalent of the 2-dimensional shape shown in fig. 5a. If we ratio these drag coefficients we can calculate the C_D for a three dimensional body with an L/D of 1.3:1.

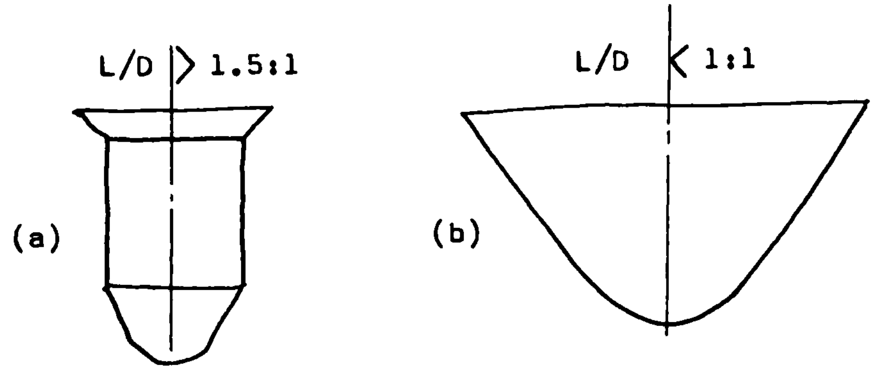


Fig. 1. Bodies of known Dynamic Stability.

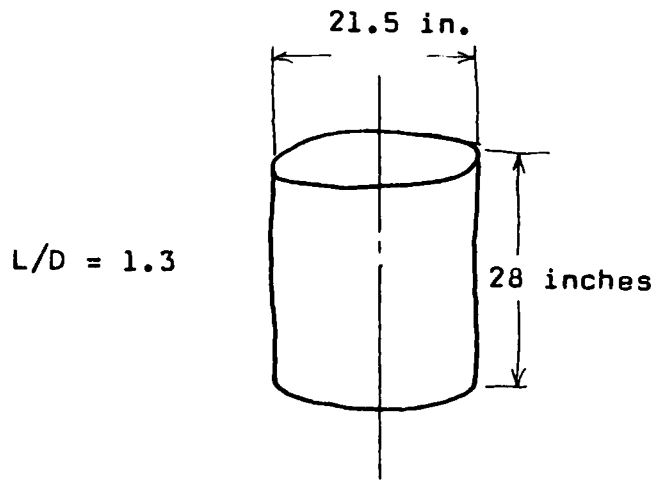


Fig. 2. Maximum space available for anchor shape

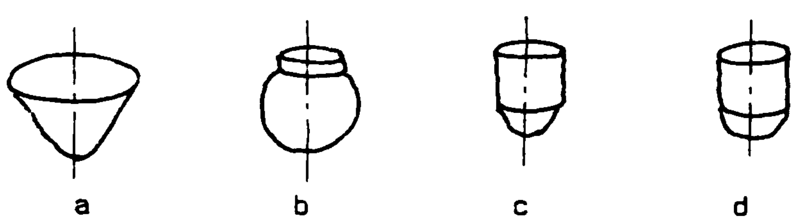


Fig. 3. Alternatives available for anchor shape

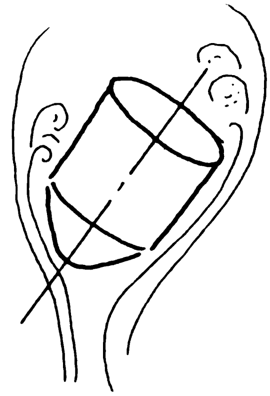


Fig. 4. Possible flow seperation around shape of fig.3c.

L/D = 0.5   1.5   2.5

C_D = 1.16   0.70   0.58

Fig. 5. Known drag of 2-dimensional shapes.

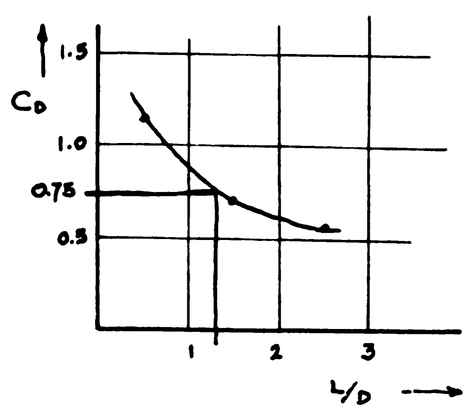


Fig. 6. Plot cf data in fig. 5.

let x equal C_D for the 3-dimensional shape of interest.

then $x/0.75 = 0.34/1.16$

or $x = 0.22 = C_D$

The drag force on the anchor is:

$$F = C_D\ A\ v^2\ \rho/2$$

where A = cros-sectional area
v = speed
= mass density of sea water

The gravitational force is the weight of the anchor which was 725 pounds for the device tested.

therefore;

$$725\ \text{lbs} = C_D\ A\ v^2\ \rho/2$$

Solving for terminal speed v, yields 38 feet per second.

RESULTS

Figure 7 is a photograph of the anchor with the winch section attached. Figure 8 is a reproduction of an echo sounding record of a test drop where the anchor can be seen on each successive three second sweep. The anchor travels between 72 fathoms and 167 fathoms in five three second intervals. This yields a terminal speed of 570ft/15sec. The measured terminal speed is 38 feet per second.

A series of drops in shallow water indicated that the anchor indeed possessed critically damped straight line stability. Further tests in deep water indicated that no excess wire was payed out.

CONCLUSIONS

An appreciation of the basic physical principles involved in hydrodynamic stability and drag are helpful in interpreting and interpolating existing data where specifically appropriate data are not available.

The case related above shows essentially perfect agreement between the results of the data interpolation and the field trials.

The engineer cannot expect to be this fortunate in all cases and the author hopes that more experimental work will be conductedspecifically for the problems unique to ocean engineering. On the other hand, the necessary work still to be conducted can possibly be reduced if the above techniques are kept in mind when planning experiemntal programs.

REFERENCES

(1) Dubose, H.C., "Static and Dynamic Stability of Blunt Bodies", Advisory Group for Aeronautical Reserrch and Development, NATO Report 347, April 1961.

(2) Arentzen, Capt. E.S., and Philip Mandel, "Naval Architectural Aspects of Submarine Design", The Society of Naval Architects and Marine Engineers, Reprints of Annual Meeting, November, 1960.

(3) Hoerner, S.F., "Fluid Dynamic Drag", Published by the author, New Jersey, 1951.

(4) Saunders, Capt. H.E., "Hydrodynamics in Ship Design", SNAME, New York, 1957.

Fig. 7. Automatic anchor with winch section attached.

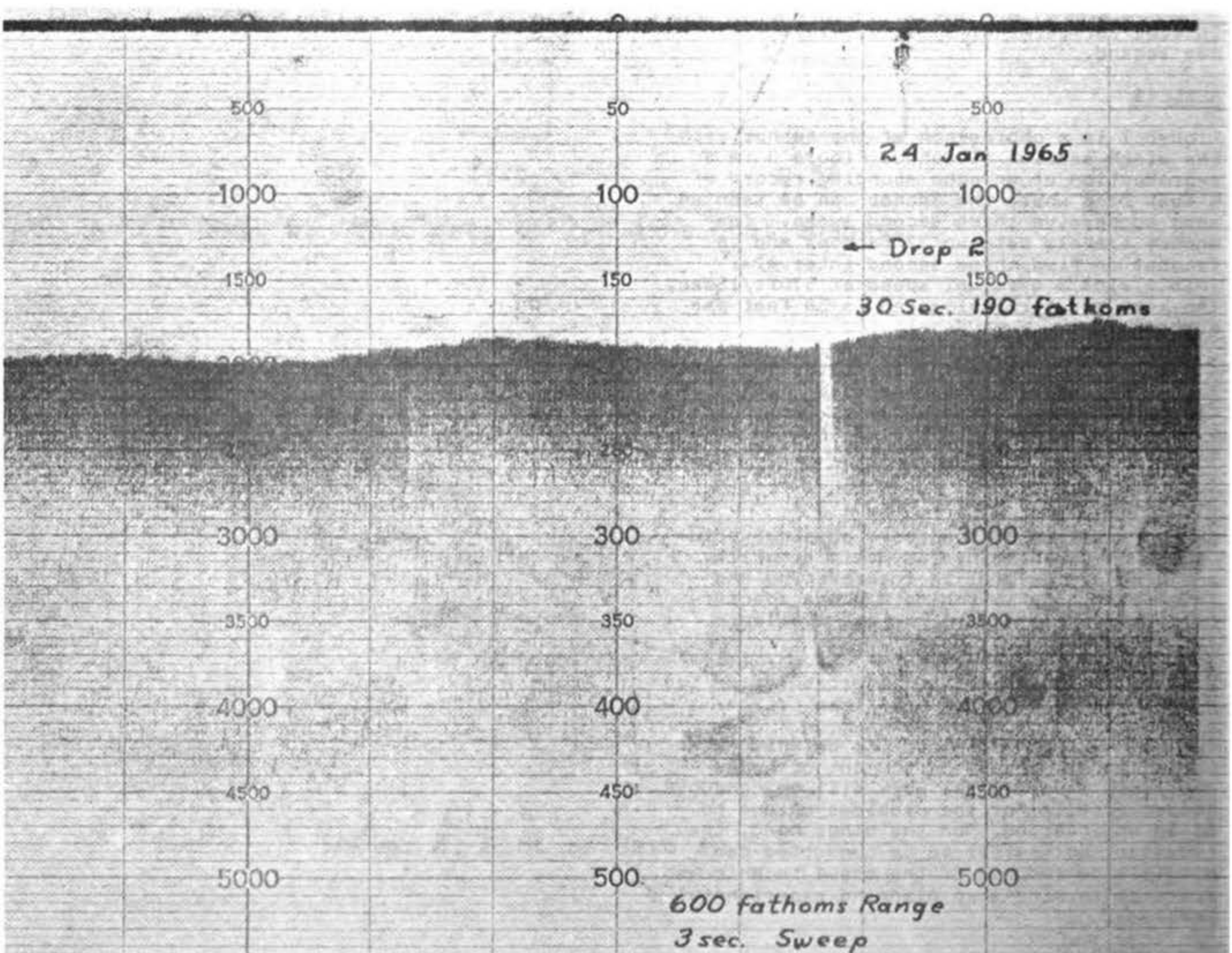


Fig. 8. Echo sounding record showing anchor descending.

Part IV. ELECTRONICS/SENSORS

Cassis, R. H. State of the Art of Data Buoy Sensor System Technology.

Folkert, M. B., and R. V. Woodle. Status of Environmental Sensing Systems for Unattended Ocean Buoys.

Livingston, T. L., and P. L. Grose. State of the Art in Data Handling, Communications and Processing for Environmental Data Buoys.

Siegelin, D. W. Present Capabilities to Determine Deployment Position, Operational Position, and Reference Direction for Buoy Systems.

Van Leer, J. Buoy Deployed Profilers.

Prepared for:

National Academy of Engineering
Marine Board
Buoy Technology Workshop
26-29 June 1973

This paper has been prepared as a summary statement of the general limitations of sensing of the environment from data buoys with respect to reliability, stability and accuracy of measurement, reduced cost, reduction of self-noise and simplicity of operation. The information has been derived during more than three years of intimate involvement in the contractual development of advanced state-of-the-art meteorological, oceanographic and water quality sensing systems, as well as some transducer development. The development referred to is being carried out at the NOAA Data Buoy Office.

My assessment of the current state of the art tends to include more of the systems aspects than strictly those of the transducers. Of greatest importance to the successful deployment of data buoys is the reliability of the hardware. We have deployed and kept buoys moored in most areas of the oceans; we have demonstrated the ability to achieve successful communications with the buoys; but we have not provided buoy instrumentation payloads with sufficient reliability. Clearly, the impact of the environment upon the exposed transducer is causing degradation of data and in some cases, ultimate catastrophic failure. The Westinghouse-designed meteorological sensors have experienced about 65 failures which have been analyzed. Of these, 27 resulted in component replacement. One was an outright random failure, and several had the same cause; for example, a faulty lot of aspirator fans. We have just begun to deploy significant numbers of ocean sensors, but have had one on EB-03 for nine months with no failures. As we acquire operating time, we are finding new problems, such as connector failures. Detailed lists of failures are reviewed to see if there are underlying common causes. Where noted, these deficiencies are being corrected.

I believe that the limitations imposed by the state of the art fall in five general categories. First is the limited knowledge possessed by instrument manufacturers, or the large spectrum of knowledge required to design a reliable instrument system. Few companies possess the necessary expertise, and fewer still can effectively apply it. Data buoy instrumentation systems still include designs which are poor because the manufacturer failed to apply existing technology. The inability to perform an unattended stable double integration of acceleration for wave data is a good example.

The second limitation is closely related: we still don't know enough about environmental impact on the instrumentation. There is unique knowledge associated with materials in the ocean which still must be developed. For example, the most effective anti-foulants we could find were used in EEP, but a recently recovered ocean sensor shows fouling. Westinghouse used LEXAM in its hardware, but the performance is based on theory and must be proved in the field.

A third significant reliability factor is the degree of quality control imposed by the manufacturer. Many of our failures which have been avoidable include such causes as bent connector pins, faulty solder joints, and improperly fitted O-rings, in spite of the fact that this was a high-reliability program. Reliability is classically dependent upon parts population. Environmental instrumentation is complex and the number of components results in inherently low system reliability. Although high mean times between failures are often quoted, the statistical basis is so limited that a very low confidence level must be placed on these estimates.

A final serious limitation on the reliability, which is not a current state-of-the-art technical factor, but is indeed a state-of-the-art business factor, is the severe cost constraints imposed on manufacturers. The market is not big or rich enough to allow a high-reliability approach. Low cost and high reliability are not necessarily found in the same instrument and may be mutually exclusive.

Stability and accuracy of measurement are limited predominately by transducer technology. Unfortunately, the instrument designers must detect, and record with high resolution, a very small range signal. The problem is greatly compounded by instruments which depend upon changes in geometry to function, such as barometers, some current transducers, potentiometer readouts, and water pressure transducers. Many transducers use a principal which provides an inherently small signal-to-noise ratio. Others provide a signal of a complex waveform which, when coupled with the desire to have simple data processors, is difficult to handle. The global radiation (infra-red) is an excellent example of the former, and the Doppler current meter of the latter. Another factor which affects the stability of the measurement is the unknown or unconsidered environmental impact on the transducer previously mentioned. The uncertainty introduced by poor standards, and poorly defined and performed calibrations, also contributes to the problem.

Reduction of self-noise is limited by transducer technology, sampling techniques and disturbance of the ambient by the presence of the sensor. The NDBO has recognized the need for, and applied information theory to, environmental sensing system designs in the areas of matching time constants, sampling ratios and durations and data processing techniques to the environmental measurand's known characteristics. However, with commercially available sensing systems, there are still too many instances where the manufacturer has failed to comply with well proven sampling theory. In some cases, not enough is known about the characteristics of the environment being sampled to adequately specify the sampling techniques. Transducers, thermal coefficients, spurious signals, hysteresis, and multi-parameter response also complicate the problem. Although it is conceded that the physical hardware disturbs the ambient conditions, not enough is known or applied to eliminating this noise, either by systems design, instrument design, or pre-and post-sampling data processing.

The limitation imposed on simplicity of operation is hard to assess. Complexity often reflects the complexity of the desired parameter. A good example is salinity which is a multi-parameter measurand. Complexity is also increased when the requirements of the ultimate data customer include averaging, extreme accuracy, or real-time data transmission. A strong case can be made for an argument that the current state-of-the-art instruments are already relatively simple devices in view of the requirements they are expected to satisfy.

The problem of limitations imposed by the current state of the art on system cost is addressed last. Unfortunately, cost is too often defined as the procurement cost of a buoy, with little or no consideration given to life cycle costs. Notwithstanding this short-sighted view, it is an economic fact of life that procurement costs must be "reasonable." Unfortunately, the solutions to the limitations problems imposed by increased reliability, more representative data, and reduction of self-noise all tend to increase the cost. One area which caused higher costs in both the Westinghouse and EG&G sensor designs was the rather severe power limitations imposed by the system. The need for low power consumptions caused the latest technology to be applied, and it is always expensive to push the state of the art. System complexity and uneconomical designs greatly increase the cost. For example, connectors, which incidentally are also a reliability problem, are expensive, as are unnecessarily elaborate housings or over-specified tolerances on manufactured pieces. Many publications discuss the fact that it is extremely difficult to contractually implement a low-cost design. Contributing to the cost problem are limited competition, small production quantities, and lack of committed follow-on work. Finally, overstatement of the real requirements by the user results in striving to constantly exceed the state of the art. More realistic performance specifications should allow improvements in reliability and other system features.

In summary, the NDBO believes the ability to measure the most important meteorological parameters (temperature, pressure, wind speed and direction, dew point) reliably, economically and accurately has been demonstrated. The ability to measure the oceanographic parameters of temperature, pressure and conductivity will be demonstrated within 12 months. Current and wave will probably be measurable in an acceptable fashion within the next 18 months. Water quality instrumentation exists, but requires substantial development to meet the long-term stability and reliability requirements.

SENSING OF ENVIRONMENTAL SENSING SYSTEMS FOR UNATTENDED OCEAN BUOYS

by

M. V. Folkert and R. V. Woodle

Electronics Division
General Dynamics
San Diego, California 92138

STATUS OF ENVIRONMENTAL SENSING SYSTEMS FOR UNATTENDED OCEAN BUOYS

by

M. B. Folkert and R. V. Woodle,
Electronics Division of General Dynamics

INTRODUCTION

This review of the status of sensing systems for unattended ocean buoys is based on the comprehensive experience acquired at General Dynamics during the development, deployment, and operation of ocean data stations in support of Office of Naval Research and National Science Foundation programs, and on company-funded sensor development activities over the past 13 years. Development was initiated in 1960; the first station was deployed in 1964. Since that time there have been numerous long-term deployments of ONR and NSF ocean buoys, the latest being a 40-foot discus buoy moored approximately 17 miles off San Diego in April 1973 as a platform for the qualification of recently developed sensing systems. This deployment incorporates an ocean-bottom seismometer system developed cooperatively with the University of Hawaii's Institute of Geophysics. The seismometer sensor is located approximately one mile from the buoy's mooring anchor and is hardwired through the mooring line to the surface, from which point the data is telemetered to shore. As in this instance, in most cases the technology is here to do a quality job of environmental sensing.

Realization of the quality latent in available technology, however, requires consideration of the total system and careful attention to detail in the light of design limitations, applications, and operational experience. Often seemingly minor items can have major effects on system performance.

This review first addresses several significant topics regarding the status of environmental sensing systems: accuracies attainable, error sources, sensing system calibration, natural variability and buoy motion considerations, reliability, stability, and sensing system costs. It then proceeds to describe some desirable new sensor developments.

STATE-OF-THE-ART SENSING SYSTEM ACCURACIES AND ERROR SOURCES

For most environmental parameters of interest sensors are available which, with proper modifications to adapt them to the buoy mission, can be configured to produce measurements of sufficient accuracy for operational and scientific use. The attainment of acceptable accuracy requires, in addition, careful attention to calibration, signal conditioning design, and installation.

The results of a recent sensing system error analysis for some of the major parameters are summarized in Table 1. The performance estimates given are those associated with a wave-following discus buoy having its meteorological suite located at the standard 10-meter level above the surface. The range of each meteorological and oceanographic parameter considered is that which would be encountered in ice-free oceans. Gains in performance can be realized if consideration is given to specific deployment regions. The error source which is the principal or most significant contributor to each performance estimate is denoted in the table with an asterisk. For the twelve parameters considered, the principal error source in five of the cases is the transducer itself. In three cases it is the signal conditioning or self-heating. Calibration is one of the principal sources only in the case of the wave height measurement.

Environmental effects are a significant error source in only four of the measurements. Solar heating affects the daytime temperature measurements; platform motion affects wind direction and the precipitation measurement; heading error is a significant contributor to surface current direction errors.

The fact that each performance estimate contains a principal error source does not mean that the estimate is unacceptable. It does suggest, however, that the required accuracy, based on the requirement to which the data from the measurements will be applied and the natural variability to be expected, must be examined. For instance, the air pressure performance estimate (0.81 millibars) is adequate for most meteorological monitoring in the northern latitudes where pressure varies over a wide range. On the other hand, for scientific studies in the tropics where air pressure is usually very stable, system performance on the order of 0.02 millibars may be desired. Transducers for this degree of accuracy are available — at a sixfold increase in cost — with a combined transducer, signal conditioning, and A/D conversion error contribution of 0.015 millibars. More elaborate calibration procedures can also be used to reduce the total error contribution to 0.05. Wind effects on pressure measurements in this region are also significantly less. The result is a performance estimate using selected sensing equipment very close to that desired for tropical monitoring. However, although this technology for the very accurate measurement is available, it can hardly be justified in the air pressure sensing system unless it is really required, because of cost.

The air temperature measurement also deserves special comment. As shown in the table, the daytime accuracy estimate is 0.64°C; the corresponding nighttime value is 0.39°C. If greater accuracy is required for a particular mission, the technology is available to provide it with an attendant increase in cost. First of all, solar heating can be made arbitrarily small by employing a more efficient radiation shelter. The transducer itself is very good. Methods for implementing very stable signal conditioning for digitized outputs while producing a negligible amount of self-heating in the

Table 1. Representative Error Contributions for Meteorological and Oceanographic Sensors

MEASUREMENT PARAMETER	UNITS	ERROR CONTRIBUTION									
		TRANSDUCER	SIGNAL CONDITIONING	SELF HEATING	CALIBRATION	WIND EFFECTS	A/D CONVERSION	SOLAR HEATING	PLATFORM MOTION	HEADING	PERFORMANCE ESTIMATE
Air Pressure	mb	*0.78	0.15		0.10	0.1	0.09				0.81
*Air Temperature	°C	0.03	0.28	0.27	0.02		0.024	*0.50			0.64
Wind Speed	m/sec	*2.4	2% of value		0.8		0.048		5% of value		2.5 ± 5.3% of value
Wind Direction	Degrees	1.0	1.0		0.1		2.9		*5	2.3	5.5
Dew Point	°C	*0.49	0.03		0.2		0.024				0.53
Global Radiation	Ly/min	*0.054	0.014		0.02		0.0012		0.015		0.06
Precipitation	mm	0.95	0.09		0.01		0.05		*1.3		1.63
Surface Current											
Speed	Cm/sec	3.0	*5.1		1.5		0.18		4.5		7.6
Direction	Degrees	2.0								*2.3	3.0
Water Pressure	Kg/cm^2	*0.04	0.02		0.002		0.012				0.047
Water Temp	°C	0.02	*0.066	*0.066	0.03		0.02				0.1
Wave Height	Meters	0.2	*0.22 (1% FS)		*0.22 (1% FS)				0.13		0.39

transducer have been developed. The result is an equipment-related error of 0.034°C which, when combined with the calibration error, yields a performance estimate of 0.047°C.

The accuracies cited for the remaining measurements in the table could be similarly improved if necessary but appear adequate for both scientific and operational uses at all latitudes, despite the natural variability and environmental differences indigenous to the various latitudes.

A few remarks concerning the surface current measurement are in order. The measurement is customarily made with the transducer mounted less than one meter below the discus buoy hull. The flat plate of the bottom prevents significant flow relative to the current meter axis normal to the buoy bottom. As a result, the effects which have been observed when meters are axially "pumped" by mooring line motion are greatly reduced. Because the flow below the buoy is altered somewhat by the presence of the hull, the exact location of the meter must be carefully selected to minimize the effect on the reading.

The fact that the discus buoy is a surface follower causes it to behave much as a water particle when subjected to wave action; this has been verified through correlation studies of pitch and longitudinal acceleration, and of roll and lateral acceleration. Thus the apparent current variation relative to the meter due to wave action is very small and non-linearities in the measuring system do not seriously affect the accuracy of the current measurement. This is in sharp contrast to results obtained when current meters are attached to mooring lines some distance below the buoy, such that mooring line motion induced by the surface conditions can cause large oscillatory motions both vertically and laterally relative to the water mass whose transport is to be measured.

The mounting locations of all sensors must be selected with extreme care to prevent inaccuracies from being introduced. Some sensors are attitude sensitive. Others, such as those for global radiation and precipitation, require an unobstructed installation. Wind sensors must be located so that the flow field is not significantly disturbed by adjacent structural members or the presence of other sensors. Barometric measurements are sensitive to the porting, or venting to atmosphere, employed. If not properly executed, mounting can introduce large errors in the output of an otherwise high-quality measurement system.

CALIBRATION

The accuracy of the measurement can be no better than the calibration accuracy. Calibration establishes the residual error related to sensor random errors, non-linearities, the cross-coupling effects of naturally occurring ranges and combinations of environmental parameters, and the effects of sensor orientation. The methods employed can themselves introduce residual uncertainties due to the inaccuracies of the measurement standards employed, the basic calibration techniques, and the disturbing influences of the calibration apparatus on the sensor environment. Adequate standards and laboratory techniques are available for the meteorological transducers, but very careful supervision of the procedure is required to produce a quality calibration. The human factor can have a very strong influence on the validity of the results. Moreover, the calibration must be carried through the entire range of the parameter to be measured, must include a sufficient number of points to ensure the detection of significant non-linearities, and must be repeated at selected points in the range to produce an assessment of the scatter which may be introduced by the procedure or by the random errors in the transducer.

The calibration of the signal conditioning, including the A/D conversion, is as important as the calibration of the transducer. When the sensor has a digital output or the signal conditioning equipment is co-located with the transducer, both transducer and signal conditioning can be calibrated as a unit. But for applications where the signal conditioning equipment is some distance from the transducers, as when transducers at different locations share conversion equipment, the signal conditioning and A/D conversion equipment must be installed on the buoy in the configuration in which they are to be operated before their calibration is accomplished to avoid inaccuracies in the digitized data because of the effects of cable runs, stray currents, etc. The transducer output is then simulated by substitution methods. For example, a platinum wire resistance element for sensing air temperature can be simulated by a standard resistance decade box stepped over the resistance range of the transducer to establish the relationship between input resistance and digital output. The transducer data and signal conditioning data are combined by curve fitting programs to produce an overall calibration relating the parameter to be measured to the digital output.

The calibration of oceanographic transducers requires a combination of laboratory, field, and simulated field techniques. For water temperature and pressure sensors, conventional laboratory techniques are available. Laboratory methods for calibrating inductive conductivity sensors, however, are to some degree suspect when salinity calculated from CTD measurements is compared with in situ field Nansen bottle casts. This may be due, in part, to the fact that calibration tanks usually enclose a limited volume of water and do not represent the volume of ocean water included in the CTD measurement. A second possibility may be that the equations relating C, T, and D to salinity are based on data which include spurious effects.

A procedure has been developed which appears to circumvent these effects and yields a quality salinity calibration; it employs a combination of laboratory and in situ methods. The procedure first involves laboratory calibrations for temperature and pressure (depth), and a calibration of the conductivity channel digital output as a function of standard resistance (conductance) values coupled through the conductivity head. Then, since conductivity and conductance in the ocean are related through a head constant, this relationship can be established by in situ field measurements of salinity and the calculation of conductivity from the in situ sensor readings of temperature and depth. Applying the head constant to the laboratory resistance calibration provides the calibration relationship for the conductivity sensor. This procedure of course requires ship time — which is very expensive. Consequently, the development of a capability for complete high quality calibration of conductivity sensors in the laboratory would be very desirable.

The calibration of wave-height sensing systems is difficult. Since the measurement of wave height involves the double integration of low frequencies, the calibration of the accelerometer transducer must be very precise. Laboratory techniques with the required accuracy are available but must be carefully applied. Substitution methods, for example, may suffer degradation by the small-amplitude subharmonics produced by standard signal generators normally found in laboratories. An alternate method not requiring substitution techniques would be desirable.

Also in a special category is the calibration of current meters. Calibration of these meters under steady flow conditions in tanks or flumes may have a very poor correspondence to performance under actual operating conditions. The actual performance, depending on the type of meter, can be affected by oscillatory components of current flow, vertical "pumping," and current shear. The state-of-art yields calibrations with errors of 50 to 100% for mooring line applications. Even for applications where the environment is under better control, current meter calibration leaves much to be desired.

NATURAL VARIABILITY AND BUOY MOTION CONSIDERATIONS

When a parameter measurement is to be sampled periodically, either for storage or transmission to shore, the effects of the natural variability of the parameter or, in some instances, the apparent variability introduced by buoy motion, can cause energy associated with frequencies near or above the sampling rate to appear in the sampled information as low-frequency artifacts. To insure accurate unaliased measurements variability spectra, transducer signal filtering and sampling requirements demand careful consideration.

For instance, to prevent aliasing when the sensors are interrogated hourly, the measurement should have little energy at frequencies above one-half cycle/hour. For some parameters such as air pressure, air temperature, and water temperature, the natural variability contains little energy above this frequency. Parameters such as wind speed and direction, current speed and direction, and global radiation, however, have considerable energy at the higher frequencies. The transducers for these parameters should therefore be equipped with filters with corner frequencies of one-half cycle per hour or less to ensure that serious aliasing does not occur.

Measurement filtering prior to sampling must also consider buoy motion. For those sensors with linear or near-linear response to buoy motion, the effect of the motion on the measurement may be reduced to insignificance by filtering to prevent aliasing of the measurement. Two types of motion are possible: the first is induced by wave action giving rise primarily to roll, pitch, and heave; the second is induced by wind and current which cause the buoy to translate within its watch circle. Translational frequencies tend to be below one-half cycle/hour and consequently do not alias the sampled data. They may, however, be present as an artifact in the hourly sampled data but can be removed later by long time-period averages, if desired, for large-scale air/sea interaction studies. For operational uses, the presence of such artifacts is insignificant.

Wave-induced frequencies usually have a period of 25 seconds or less. They should therefore be removed prior to the hourly sampling to prevent aliasing. A filter with a corner frequency of 1/25 cycle per second (180 cycles per hour) is adequate to eliminate artifacts in the sampled data due to wave-induced motion.

Vector quantities such as wind and current should be resolved into an earth-oriented axis system before long time-constant filtering is applied since moored buoy induced velocities must average to zero in this reference system. Additionally, average transport is usually the parameter of primary interest. The buoy itself acts as a low-pass filter with a cutoff frequency on the order of 1 cycle per second. Natural variability in this frequency regime is also small. Consequently, low-pass filtering below 1 Hertz prior to the nonlinear coordinate transformation can be used to suppress system noise and reduce the bandwidth of the transformation without affecting data quality. Platform heading data must be introduced to perform the transformation to earth-oriented coordinates. Discus buoy headings change very slowly in contrast to those for nonsymmetrical buoy shapes. As a result, the heading filter requirements are not critical. However, extreme care must be exercised in selecting the compass mounting position to preclude a serious nonlinear response due to local distortion of the earth's magnetic field. Although compensation or computational linearization of the measurement is possible, proper placement of the compass to avoid this difficulty is the better solution.

The above filtering techniques can be used to good advantage to preserve and enhance the quality of the data. They, of course, do not decrease the effects of nonlinearities in the transducer or the effects of mounting structures or other sensors on the parameters being measured.

RELIABILITY

When properly engineered, sensing systems on buoys are quite reliable. The money and effort spent to achieve high reliability sensing systems produce a significant payoff when the costs of servicing less reliable sensors on a buoy at sea are considered. Particular emphasis must be given to proper mountings, ruggedness of bearings in rotating parts, mounting locations, and environmental protection, as well as to electronic and transducer performance reliability. Table 2 summarizes our MTBF experience with meteorological sensors when proper care is taken.

Table 2. Typical Meteorological Sensor Mean Time Between Failures

SENSOR	MTBF (HOURS)
Air Temperature	88,700
Wind Speed and Direction	30,100
Barometric Pressure	47,400
Rainfall	28,000
Global Radiation	35,000
Dew Point	9,900

If a buoy is equipped with two sensors of each type operating in parallel, the computed mean time before both fail is 50 percent greater than the MTBF of a single sensor — provided the sensors exhibit the same failure rate and failures are not due to wear-out. Although redundancy of this type can be advantageous, the benefit cannot be realized unless the sensors are adequately designed to preclude serious wear or aging during the time period of the deployment; redundancy in itself is no substitute for adequately configured and engineered equipment. Of the sensors listed in Table 2, the dew point sensor is the only one in the wear-out category. Our experience with this sensor suggests that the way to take advantage of redundance is to maintain one sensor in a deactivated state until the first has failed. Usually, however, dew point is not one of the high priority measurements and the additional complexity of such an arrangement may not be warranted. More reliable dew point sensors would obviously be very desirable.

Table 3 is typical of our experience with underwater sensors.

Table 3. Typical Underwater Sensor Mean Time Between Failures

SENSOR	MTBF (HOURS)
Water Surface Temperature	100,000
100-Meter Thermistor String	
Temperature	31,300
Pressure	11,200
Mooring Line CTDs	
Conductivity	26,300
Temperature	26,300
Pressure	23,200
Hull-Mounted Current Meters	5,200

Failures in subsurface sensors can be particularly troublesome because servicing, i.e., retrieval of the sensors from the mooring line or sensor string, is more complex and sometimes difficult without unmooring the buoy. Even with a significant state-of-the-art advancement for mooring line CTDs or in-the-mooring-line current meters, it is hard to envision — assuming the application of redundancy which is very expensive for these types of sensors — that reliabilities appropriate for several-year deployments will be achievable. A better approach might be the use of profiling sensors which are returned to the buoy each time data is taken. This approach makes them accessible for servicing and allows them to be stored in a controllable environment between data acquisition times, thus prolonging their life and reducing exposure to fouling.

STABILITY

In general, the stability of meteorological transducers is excellent if they are properly mounted at a sufficient height above the sea surface. Under these conditions the aging effects are moderate and similar to that observed in a seaside environment. With proper sealing and purging, the signal conditioning aging is similarly minimal. The sensor most affected by the environment is that for global radiation. Salt spray produces an encrustation which affects the transmission through the quartz dome. Tests and field experience indicate that the effect on the readings is less than five percent. In areas with frequent rain showers, the effect is negligible since the encrustation is washed away by the rain.

The stability of underwater sensors can be seriously affected by corrosion and fouling unless special precautions are taken during sensing system design and fabrication. The detailed procedures for the application of anti-foulants can be particularly importan exposure to the atmosphere for extended periods renders some of them ineffective. Careful selection of materials and designing for exposure to seawater can eliminate the effects of corrosion on the stability measurements.

The stability attainable with underwater sensors is demonstrated by the array of CTD sensors installed on Buoy ALPHA during its deployment from September 1969 to July 1970. Eight sensors were deployed on the buoy mooring line. During the deployment an oceanographic ship made several independent lowerings of an STD or Nansen bottles in the immediate buoy area for comparison with data from the sensor array. Data from these ship samplings were differenced with the salinity values computed from the telemetered buoy data taken within 45 minutes of the ship sampling.

For the sensors above the 200 meter level, the natural variability of salinity in space and time prevented an assessment of the salinity determination capability through comparison of buoy and ship data. Although there are probably some variability effects in the comparisons of data for sensors below this depth, the comparisons tend to be illustrative of the stability attainable from CTD sensors. A summary is shown in Figure 1. The points on the plot represent the mean of the differences for data taken within a 24-hour period at various times during the deployment. The bias between the CTD data and reference sources does not vary significantly with time, indicating a high degree of long-term sensor calibration stability.

The root mean squared error between the individual differences and the mean of the differences is shown in Figure 2. While several factors influence this uncertainty — such as proximity of comparison, time separation, and sensing error — if sensing error is assumed to be the dominant term, then the cumulative sensor error is less than 0.04 percent. The error is probably considerably less than this.

The conclusion is that the error due to long-term drift and aging is less than the sensor measurement error.

COSTS

The cost of a sensor data channel, including transducers modified and ruggedized for use in the buoy environment, the signal conditioning and filtering electronics, and installation aboard the buoy to interface with the data acquisition system, is moderate with respect to total system cost.

Typical costs for the meteorological suite and subsurface temperature measurements are less than $1,500 per channel. An exception is the dew point measurement which, due to the higher cost of the transducer, is on the order of $3,500 per channel.

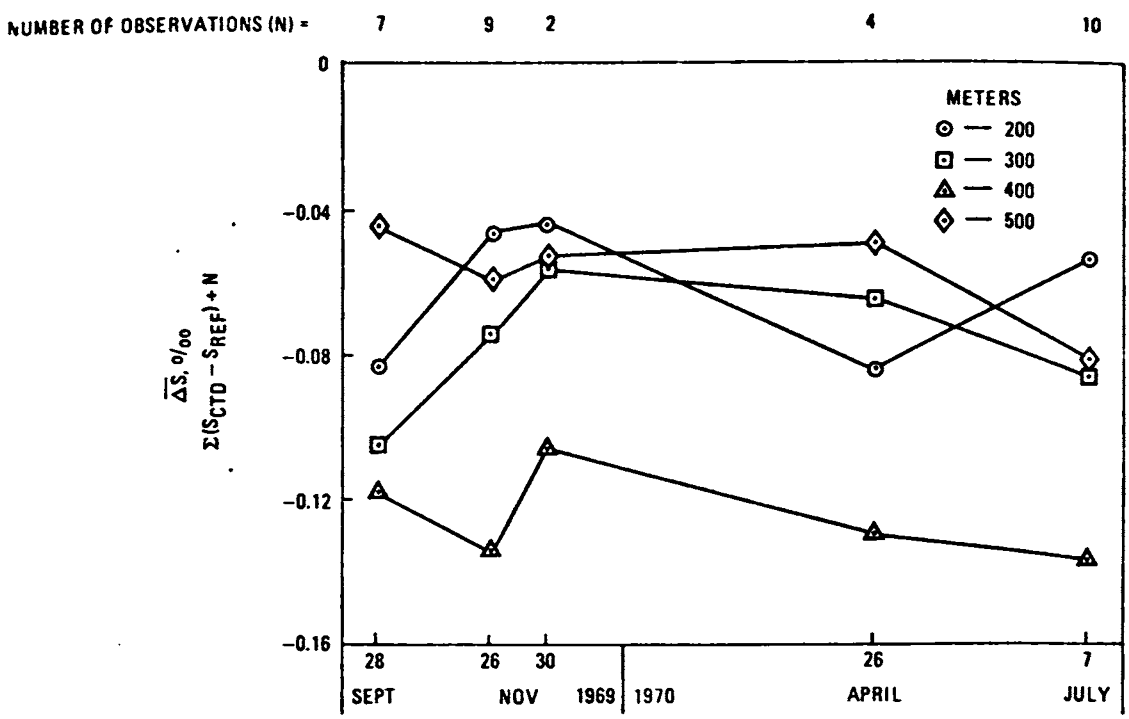


Figure 1. Mean of Differences Between CTD and Reference Casts Taken Over 24-Hour Period

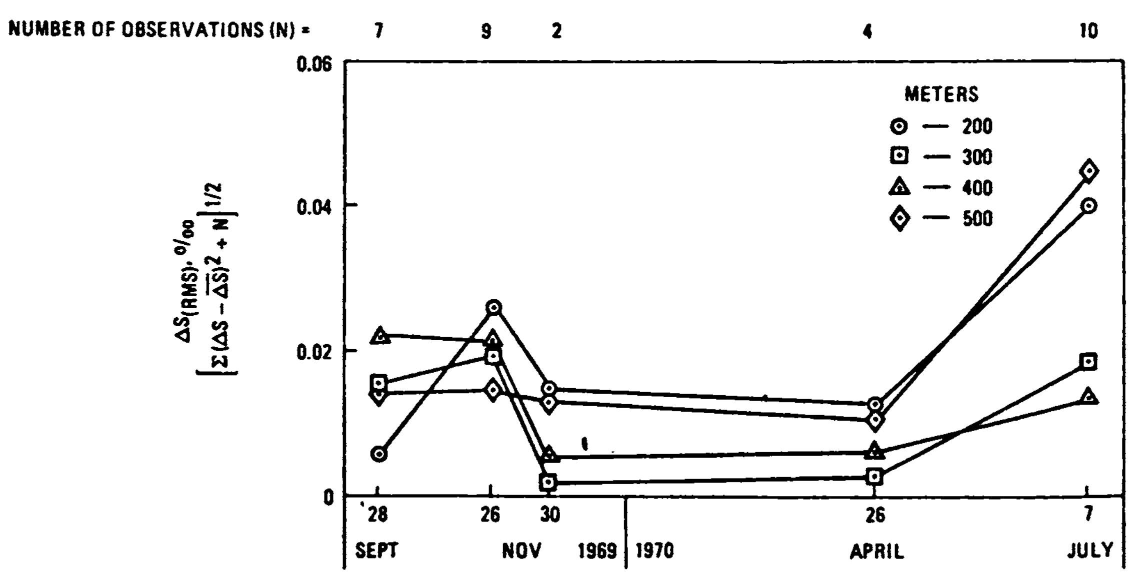


Figure 2. Root Mean Squared Error Between Individual Differences and the Mean of the Difference Between CTD and Reference Casts Taken Over 24-Hour Period

Subsurface sensing systems such as current meters and mooring line CTDs can have a more significant effect on total system cost. Current meter channel costs can range from $4,000 to $8,000 depending on the type of current meter and signal conditioning used. The three-channel cost associated with a single CTD sensor package is on the order of $29,000. For applications where subsurface profiles are required, the number of channels desired for even a coarse profile causes sensor system costs to be a major fraction of buoy system costs. Consequently, emphasis should be placed on reducing sensing system costs or using alternative, less expensive, approaches for obtaining profile data. The result could be a very significant improvement in the cost-benefit for buoy oceanographic measurements.

NEW SENSOR DEVELOPMENT

Buoy sensing systems have a good capability for monitoring the environmental parameters at the buoy near the air-sea interface. New sensor developments which would extend the capability to allow monitoring conditions remote from the buoy platform should be emphasized. Sensors for monitoring the spatial averages of parameters, as well as sensors for providing parameters profiles, would significantly enhance the future usefulness of buoy monitoring stations.

As part of the continuing sensor development program at General Dynamics, two sensor systems in particular, both well along in their development cycle, offer a potential for significantly increasing the capability and usefulness of buoy platforms for environmental data acquisition. The first is an oceanographic sensor with the capability for producing a detailed depth profile of the water column. The second is a vertical atmospheric temperature sensor with the capability for producing a profile of temperature for the lower 20,000 feet of the atmosphere. They are briefly described in the following paragraphs.

The profiling oceanographic sensor uses a specially designed hydrodynamic transducer housing which contains a platinum-wire thermometer, a strain gage type pressure transducer, and associated signal processing components. During free-fall to its limiting depth, the sensor drops at approximately 2.5 meters per second. Temperature and pressure data are sampled and digitized within the sensor at the rate of one data sample for each 4 centimeters of depth. Temperature data accuracy over the range of 0 to 30°C is ±0.034°C. Pressure data accuracy over the range from 0 to 33 bars is ±0.04 bars. Both temperature and pressure data are communicated to the surface through a signal cable that also serves as the means for returning the sensor to the winch mechanism within the buoy hull.

The winch consists of an articulated spool with its axis vertical during sensor deployment to permit the cable to freely spool as the sensor falls. This configuration effectively decouples the falling sensor from any surface motions at the winch support. For the retrieve cycle, the winch spool is rotated until its axis is horizontal, after which the sensor cable is wound onto the spool by a motor drive. A complete drop-and-retrieve cycle requires approximately 5 minutes. Examples of some recent profile data are shown in Figure 3. The drops shown were taken at intervals of approximately 15 minutes.

The vertical atmospheric temperature profiler uses a specially designed infrared grating spectrometer to acquire atmospheric radiance measurements. The environmental housing provides accessibility to the atmosphere through a shutter that is open only during the atmospheric data acquisition period. Protection of the optics is provided by a slight overpressure with gaseous nitrogen. A detector mounted on the exterior of the spectrometer enclosure prevents the shutter from opening during heavy rain.

The time interval between profiles is preset — typically to hourly intervals. Automatic initiation of the operating cycle starts spectrometer atmospheric radiance data acquisition in eight narrow spectral regions in the 15μ band of carbon dioxide. These data are augmented by a single measurement in the 11μ atmospheric window and three measurements in the 18μ water vapor band. Total acquisition time is approximately 4.5 minutes. Following the acquisition of atmospheric data, a black body is driven into the instrument's field of view and the data-taking sequence is repeated to provide a calibration for data processing. The radiance measurements and the calibration are used to calculate the vertical temperature profile. The computer software mathematical inversion program produces 7 temperature estimates along the profile from the ground to the 500 mb level (approximately 20,000 ft).

A comparison of 21 profiles taken by both balloon radiosonde and the vertical atmospheric temperature profiler show an overall root-mean-square difference between the two methods of 1.58°C, which is of the same order of accuracy as the balloon measurements. Figure 4 shows a typical profile. A feature of interest is the ability to detect the temperature inversion.

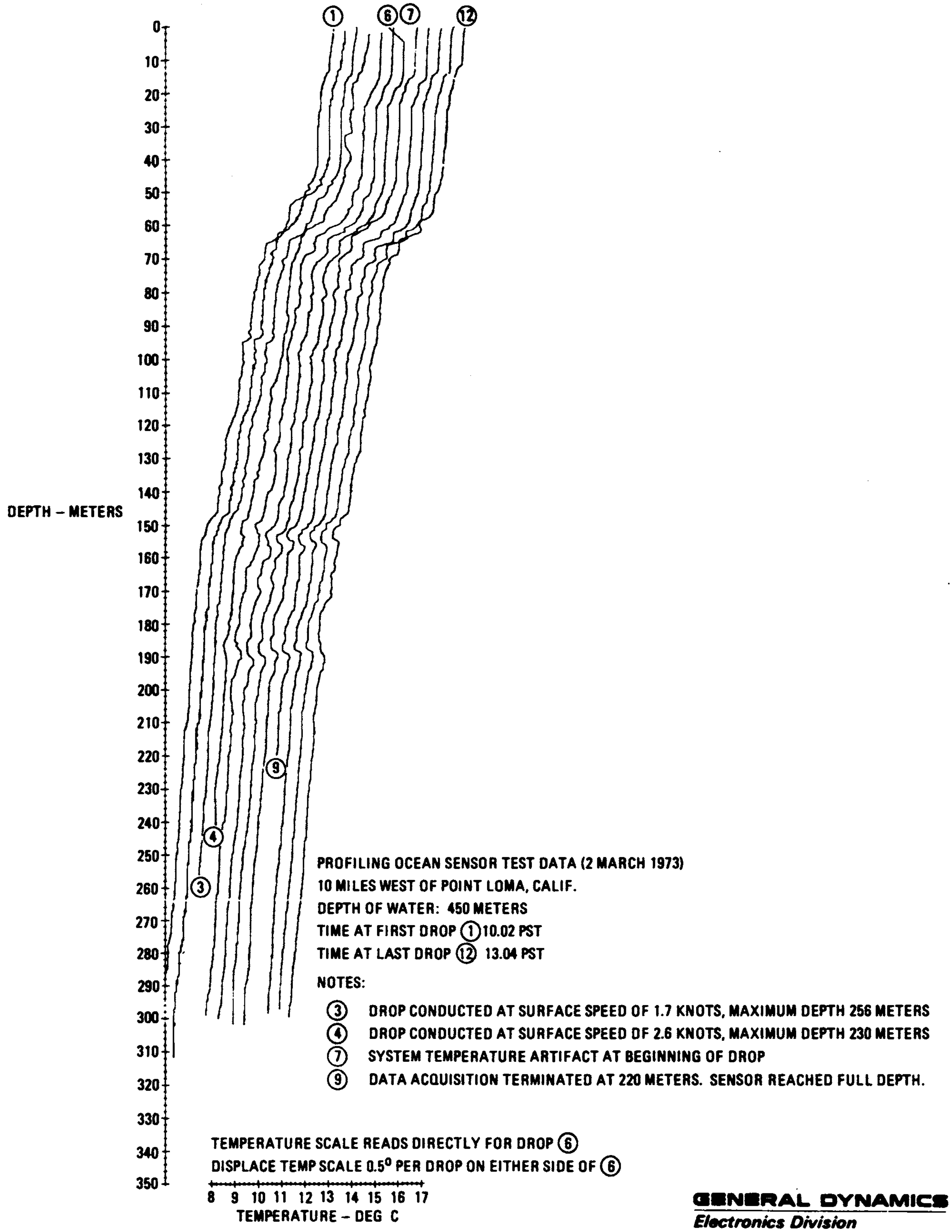


Figure 3. Profiling Ocean Sensor Test Data

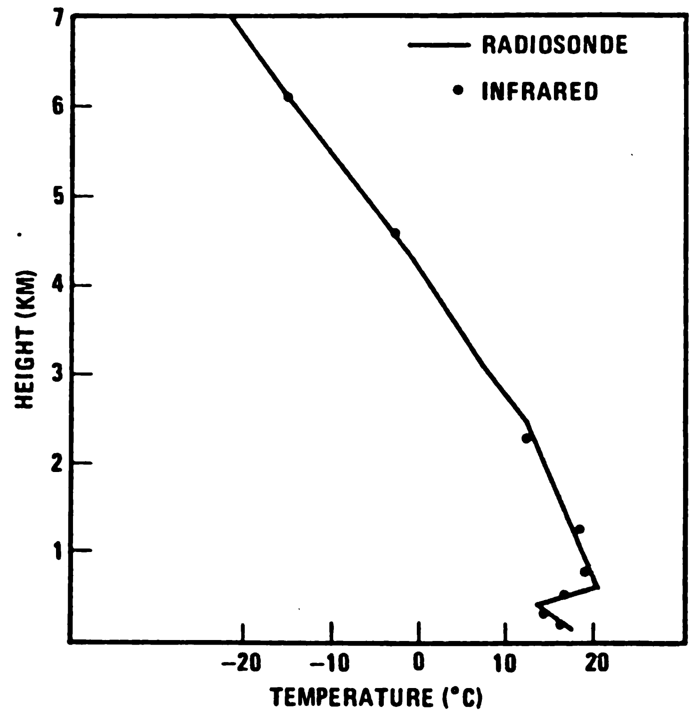


Figure 4. Typical Comparison of Infrared and Radiosonde Temperature Profiles

STATE OF THE ART IN DATA HANDLING, COMMUNICATIONS AND PROCESSING FOR ENVIRONMENTAL DATA BUOYS

by

T. L. Livingston and P. L. Grose

NOAA Data Buoy Office
Mississippi Test Facility
Bay St. Louis, Mississippi 39520

Space Support Division
Sperry Rand Corporation
Mississippi Test Facility
Bay St. Louis, Mississippi 39520

STATE OF THE ART IN DATA HANDLING, COMMUNICATIONS, AND PROCESSING FOR ENVIRONMENTAL DATA BUOYS

Prepared for: Buoy Technology Assessment Workshop

26-29 June 1973, Kingston R.I.

T. Layne Livingston
NOAA Data Buoy Office
Bay Saint, Louis, Mississippi 39520

Dr. Peter L. Grose
Space Support Division
Sperry Rand Corporation

INTRODUCTION

This paper presents the authors' views on the present state of the art in the handling, communications and processing of data from Environmental Data Buoys. It begins with a review of the basic problems in handling and processing buoy-collected data, continues with the alternatives available and the tradeoffs associated with them, and then concludes with recommendations for future direction.

REVIEW AND STATEMENT OF PROBLEM

The role of data handling and processing in the context of Environmental Data buoys is "to make information acquired by a sensor available to a User in a meaningful manner". "A meaningful manner" is solely dependent upon the requirements of each User. Delivery of "meaningful data" can range from something as simple as providing to the User a copy of an on-board recorded tape containing analog frequencies, to something as sophisticated as dissemination of ten minute averages in engineering units within one hour of acquisition from a buoy network to an International User. Clearly the User requirements dictate what is involved in data processing and handling. For each individual case, the User requirements will control the level of sophistication and complexity required to make the data available to him. The funding available to accomplish the task will dictate the mechanism of implementation and its associated risk and reliability.

In general, implementation of data handling and processing is composed of four interrelated parts as shown in Figure 1.

- On-board data processing
- Communication of data to shore
- Shore processing
- Dissemination to users

Identical end results can be accomplished using many different schemes, each tailored to optimize one or more parts of the flow at the expense of complicating the others. For any single User's requirements there probably is one optimum scheme in terms of cost, reliability, maintainability and risk. However, there is no optimum system which satisfies all Users' requirements.

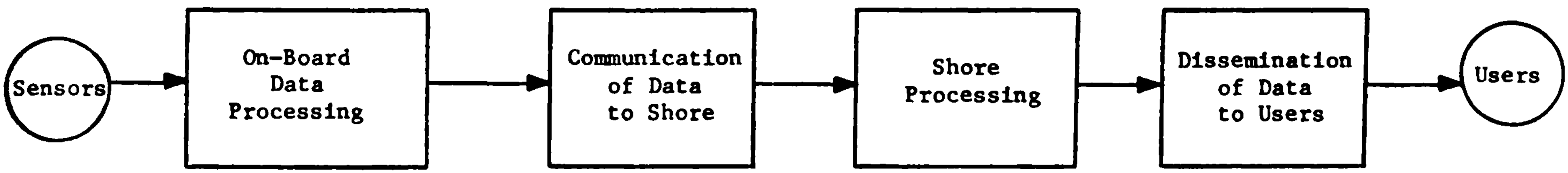


Figure 1. System Components of Data Handling and Processing for Environmental Data Buoys

The problem areas and design considerations in the data handling and processing portion of a buoy system are summarized in Figure 2. As discussed in the next section many of these problem areas have fairly well known solutions and defined trade-off criteria. However, others do not and a prime example is the proper mix of hardware optimization and software optimization, which, in general, has yet to be adequately evaluated. Typically the final design goes to extremes one way or the other and ends up causing low system reliability and high risk.

PROBLEM AREA	DESIGN CONSIDERATIONS
Flexibility	Control - Duplex Communication Hardwire vs. Programmable
Power	Duty Cycle Data Rates
Communication	Bandwidth - Frequency - Rate
Complexity	Ashore - On-Board
Costs	Hardware - Software
Reliability	Redundancy
Quality Assurance	Hardware - Software
Modifications	Hardware vs. Software
Maintenance	Expendable vs. Refurbishable
Software	Machine Language vs. High Level Coding

Figure 2. Problem Areas and considerations for Design of Data Handling and Processing Systems for Environmental Buoys

STATE OF THE ART IN DATA HANDLING, COMMUNICATIONS AND PROCESSING

The present state of the art for handling and processing of data from Environmental Buoys covers the full spectrum from logging data on magnetic tape for subsequent delivery to a User, to delivering synoptic weather data to NWS within one hour of acquisition. The alternatives presently available are shown in Figure 3. Each alternative has its advantages and disadvantages as well as proper and improper implementation. In the following paragraphs a short discussion will be presented of each, high-lighting some of their advantages and implementations. Following these discussions an attempt will be made to integrate them into viable systems to meet selected User requirements.

ON-BOARD DATA PROCESSING

Five alternatives exist with their respective advantages and implications:

- No on-board processing
- A/D conversions only
- Transfer to a format for communication
- Simple non-programmable special purpose computers
- Complex programmable general purpose computers

No Processing

The alternative of no processing (analog recording only) has the advantage of the simplest on-board system into which can be incorporated high reliability and lowest cost. Its disadvantages are that the status of the system cannot be determined remotely and periodic visits to the buoy must be made to retrieve the data. A direct implication of this approach is that all data processing will be done ashore requiring most likely A/D conversions, error detection and

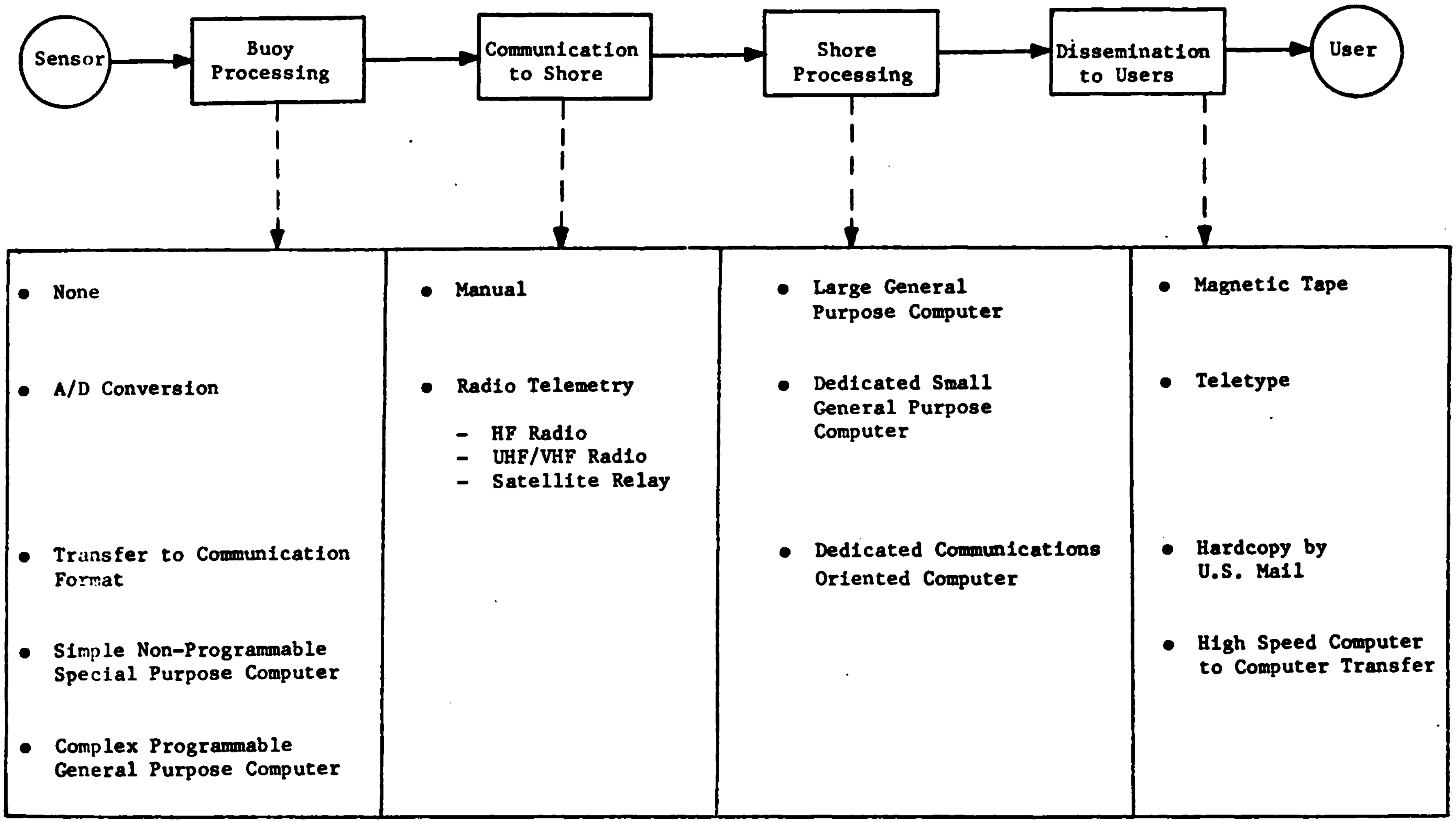


Figure 3. Data Handling and Processing Alternatives

scaling. A direct outcome of this form of implementation is that usually most of the data either goes unprocessed, or is processed so long after its acquisition that its purpose is lost, and in hindsight, probably should not have been acquired. With the exception of highly specialized short term operations this approach is not viable in practice.

Analog to Digital Conversion and Recording only

The alternative of analog to digital (A/D) conversion followed by logging on magnetic tape has all the disadvantages of no processing except that system noise can be greatly reduced and outputs from the buoy can be made directly into a computer ashore for reduction and further processing. Again, as with the alternative of no processing, this implementation is only viable under specialized circumstances.

Transfer to a Communications Format

The alternative of transferring data into a communication format implies a communication system for actual data transfer. Complexity is increased as well as costs; however, the User is now capable of getting data remotely. This has two distinct advantages: first the data can be used while it is fresh and current, and second, verification that the system is operating can be made in real or near real time. A sometimes hidden disadvantage of this form of implementation is that data arrives ashore independently of activities there. Data can easily be lost because of failure of non-buoy, system components such as receiver stations and communication links which may not be under User or Implementer control. Again as with previously described alternatives, this form of implementation is usually viable only under specialized conditions and short term operations, as little or no flexibility is available.

Simple Non-Programmable Special Purpose Computer

Inclusion of a special purpose non-programmable computer on-board the buoy begins to open a Pandora's Box with some major advantages and disadvantages. In terms of advantages it allows data condensation and limited processing which increases data reliability, quality, and utility while at the same time decreases the demands on the communications link and processing ashore thus preventing bottlenecks at these points in the chain of handling. The system also begins to be capable of some degree of flexibility and alternative modes of operation. However, for the advantages gained by adding this small black box the penalty of increased complexity must be paid. This penalty arises in increased power requirements - which generally can be offset by use of Complementary Metal Oxide Substrate (Cosmos) logic, - and increased costs as the specialized computer must be designed and built separately for each application and set of requirements. In spite of these penalties this form of implementation does maintain some degree of simplicity, and high reliability can be fairly easily achieved. For operational buoy networks this alternative appears to be the most viable.

Complex Programmable General Purpose Computers

Inclusion of a programmable general purpose computer on-board a buoy nears the ultimate in flexibility and complexity in on-board data processing. Virtually any form of processing can be accomplished as well as alterations of the processing scheme without reconfiguration of hardware. Also, because general purpose computers are not tailor-made for each application, their costs are reasonable and they are available in proven forms as contrasted to special purpose hardwired computers. However a penalty is paid in both power consumption and reliability. In addition to the above pros and cons a new problem arises in implementing the software. To date, most systems implemented have been done so in machine language code. While this method does optimize computer memory allocation and throughput, it negates all other advantages. Although the hardware cost of additional core memory is relatively small ($.60 per word), program implementation is an order of magnitude more complex and software maintenance is virtually impossible.

COMMUNICATION OF DATA TO SHORE

The alternatives for communication of data to shore can be grouped into two categories:

Manual Communication

Manual communication consists of periodically going out to the buoy and retrieving data tapes or film containing the data acquired by a buoy. Clearly this implementation suffers from the disadvantages of logistic operations involving ships and is usually extremely expensive.

Radio Frequency Data Link

The alternatives applicable to the choice of data link are shown in Figure 4. Additional alternatives are listed in Figure 5. A more detailed examination of the various alternatives and applications for buoy communications is presented as follows:

- Very Low Frequency (VLF) - VLF propagation is generally identified as "ultra reliable". This is brought about by the predictable VLF propagation which directs along the surface of the earth and is constrained similar to signals in a waveguide. The major limitations associated with VLF propagation are the requirements for long antennas

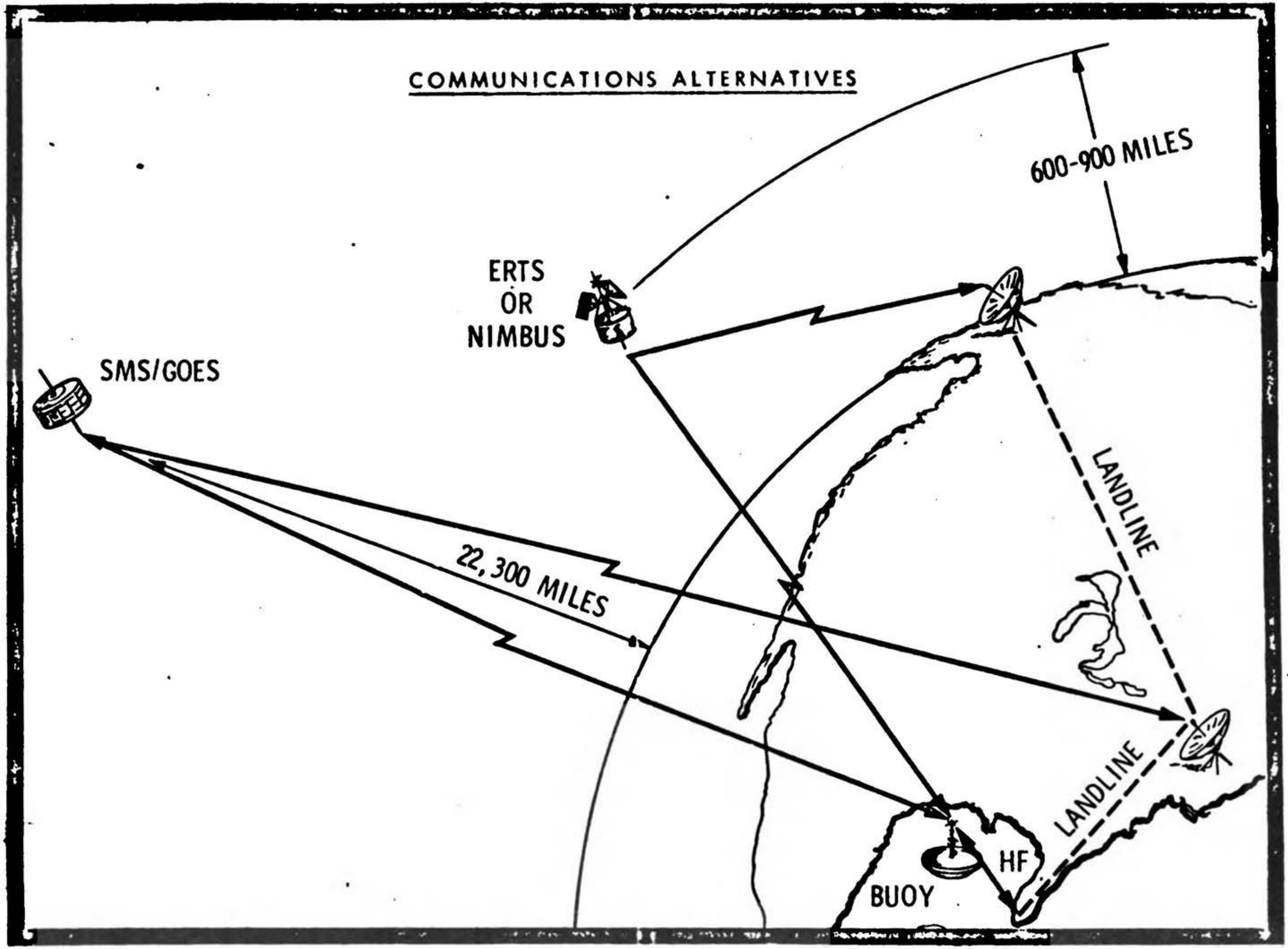

COMMUNICATIONS ALTERNATIVES
600-900 MILES
ERTS
OR
NIMBUS
SMS/GOES
22,300 MILES
LANDLINE
LANDLINE
HF
BUOY

FIG. 4

FIGURE 5 COMMUNICATION APPROACHES FOR BUOY TO SHORE COMMUNICATIONS

COMMUNICATION APPROACH		APPLICABLE TO BUOYS
VLF	Requires Massive Antenna Arrangement	No
VHF-UHF Conventional	Limited to Line of Sight Ranges	Yes
HF	Subject to Ionospheric Vagaries - Reliability Limited to approximately 90 Percent	Yes
Satellite(Synchronous)	Frequency Operation Below 500 MHz. Must Rely Upon Availability of Satellites	Yes
Satellite(Polar Orbit)	Not Compatible with Synoptic Reporting and Data Dissemination	Yes
Scatter	Requires High Power and Large Antenna Aperture	No

to efficiently propagate the VLF signals and the attendant low data rates brought about by inherently low bandwidths. Because of these limitations, VLF is generally not applicable to buoy communications.

- High Frequency (HF) - HF communications has matured to the point where reliable predictions and hardware afford good long range communication characteristics, albeit at modest data rates of approximately 75 bits per second. Communication reliability is limited by ionospheric vagaries to an upper value of 90%. There are periods of low communication reliabilities, but by proper selection of frequency of operation and adhering to predictions published by the Department of Commerce, periods of poor HF performance can be kept to a reasonable minimum.

- Very High Frequency/Ultra High Frequency (VHF/UHF) - Generally reliable communications, high data rates, mature technology and short antennas are associated with this mode of operation. The major limitation associated with VHF/UHF operation is that of range between transmitter and receiver which is limited to "line-of-sight". This range limitation generally makes VHF/UHF application on data buoys unfeasible.

- Satellite - Satellite communications, with both synchronous and orbiting spacecraft, show the greatest promise for providing high reliable link and equipment performance. Satellite technology is here and cooperative buoy satellite systems have been positively identified. 1974 will witness the launch of the Synchronous Meteorological Satellite (SMS) and NIMBUS-F to provide buoy satellite communications with geostationary and orbiting spacecraft respectively.

FIGURE 6

COMPARISON OF APPLICABLE BUOY COMMUNICATION APPROACHES

FEATURE	HIGH FREQUENCY	SMS/GOES STATIONARY SATELLITE	NIMBUS F (RAMS) ORBITING SATELLITE
Interrogation	Yes	Yes	No
Synoptic Data Transmission	Yes	Yes	No
Data Volume	High	High	Limited
Data Rate	75 bps	100 bps	100 bps
Coverage	2-3 K miles	Satellites Area of View	Worldwide
Equipment Reliability	Good	Poor (5300 hrs MTBF Predicted)	Potentially High
Long-term Availability	Good	Good (over 5 yrs.)	Poor (2-3 yrs.)
System Status	Proven	Unproven	Unproven
Link Availability	On Demand	On Demand	When satellite orbit is in view

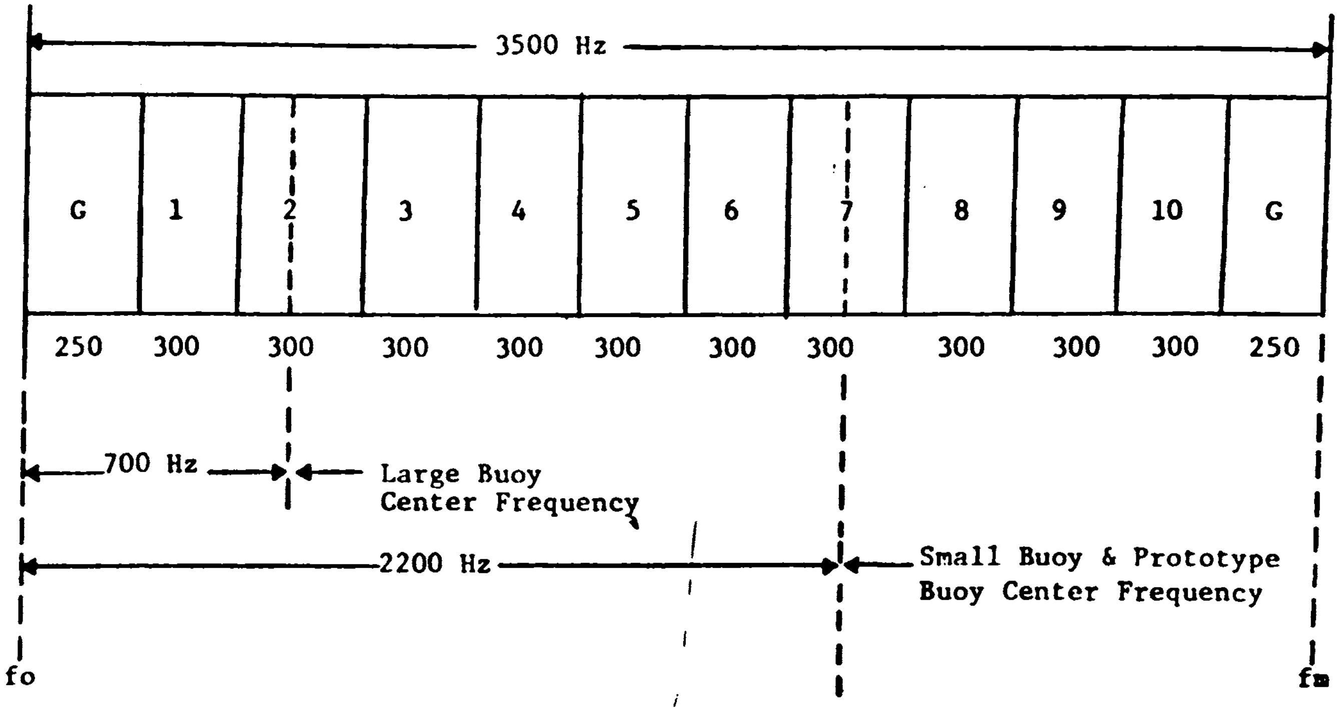
FIGURE 7

HF COMMUNICATIONS ON NDBO BUOYS *

BUOY TYPE	FREQ. SELECT.	OUTPUT POWER	POWER CONSUMPTION STDBY	POWER CONSUMPTION XMT	SIZE	WEIGHT	ANTENNA
Large Buoys	3	100 W	28 W	310 W	62" x 27" x 32" (31 ft^3)	350 #	Disc-sleeve
Small Buoys	2 or 3	100 W	Less than 1 W	280 W	Approx. 5" x 14" x 15" (.7 ft^3)	16 - 35 #	Vertical Whip 20'

* . 75 bps data rate

. 170H3 FSK



fo =	4.16250 MHz	fm =	4.16600 MHz
	6.24450 MHz		6.24800 MHz
	8.32800 MHz		8.33150 MHz
	12.47950 MHz		12.48300 MHz
	16.63650 MHz		16.64000 MHz
	22.16050 MHz		22.16400 MHz

G = Guard Channel

fo = Lowest frequency in assigned HF band

fm = Upper frequency in assigned HF band

Figure 8 WARC Channeling Scheme Applied to NDBO Operations

A table of recommended engineering characteristics is presented below indicating the adopted NDBO parameters and the International Telecommunications recommendations (ITEL):

PARAMETERS	ITEL	NDBO
Modulation	FSK	FSK
Deviation	± 42.5 Hz	± 85 Hz
Channel Utilization	170 Hz	300 Hz
Modulation Rate	Less than 100 baud	75 baud
Frequency Stability	Less than 2.5 Hz	Less than 5 Hz

The frequency deviation and channel utilization by NDBO, for all buoys, are ± 85 Hz and 300 Hz rather than the ± 42.5 Hz and 170 Hz proposed by ITEL. The wider shift equipment is more resistant to noise and fading, which are the most significant contributors to error rate in HF data communication systems. The wide shift demodulators at the SCS use separate mark and space filters and variable threshold detectors to overcome the effects of selective fading of the mark and space tones.

<u>Large Buoy Technology</u>

A block diagram of an NDBO large buoy HF Communication (HFC) system is shown in Figure 9. This equipment is functionally able to receive and demodulate simultaneously on three separate HF bands and modulate and transmit on any one of the same three RF bands. The specific operating bands will be selected from those allocated by WARC based on ionospheric predictions for reliable communications between the deployed buoys and the Shore Communication Station. All channel assignments for the large buoys are on the 700 Hz channels.

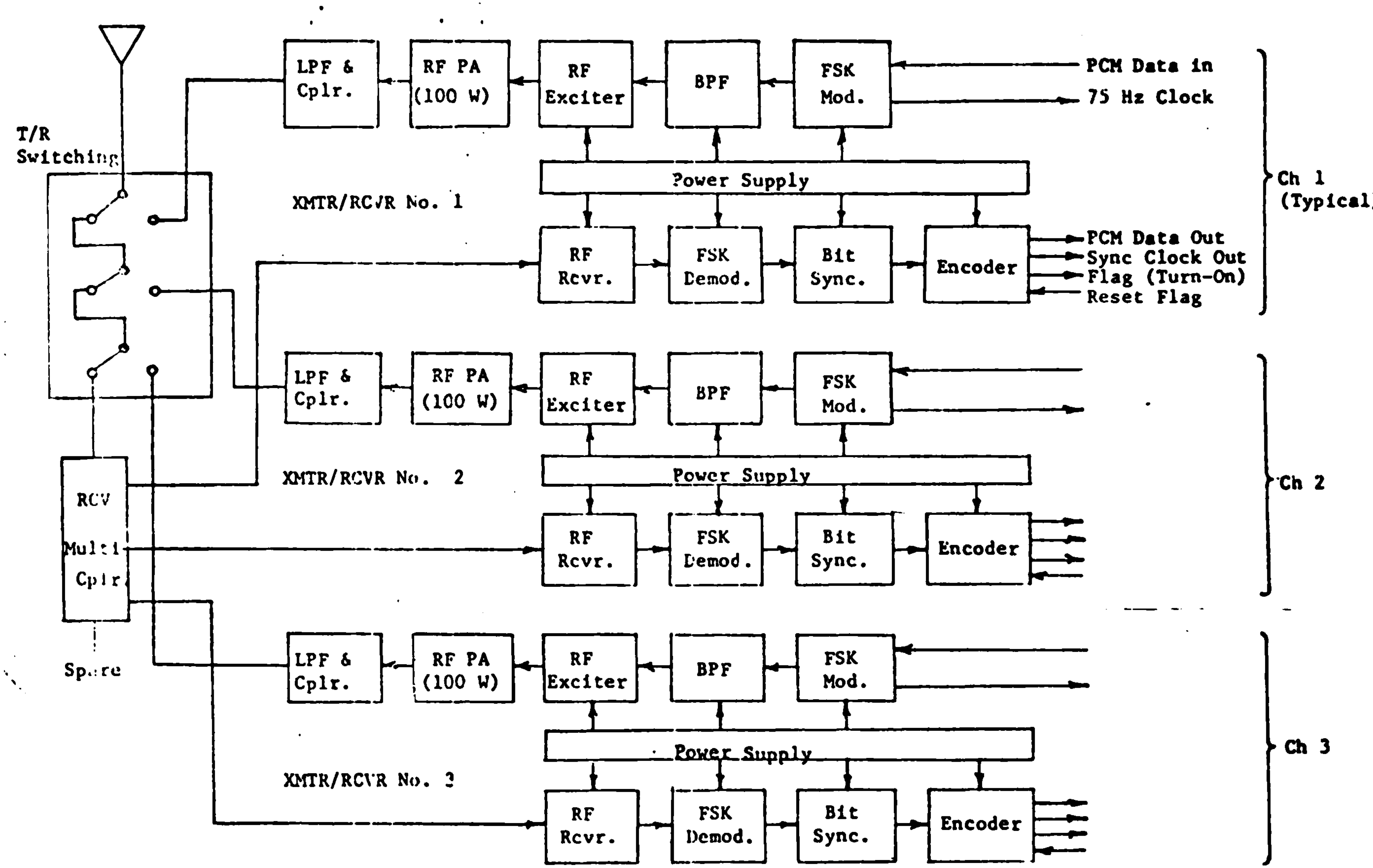


Figure 9 HFC Block Diagram

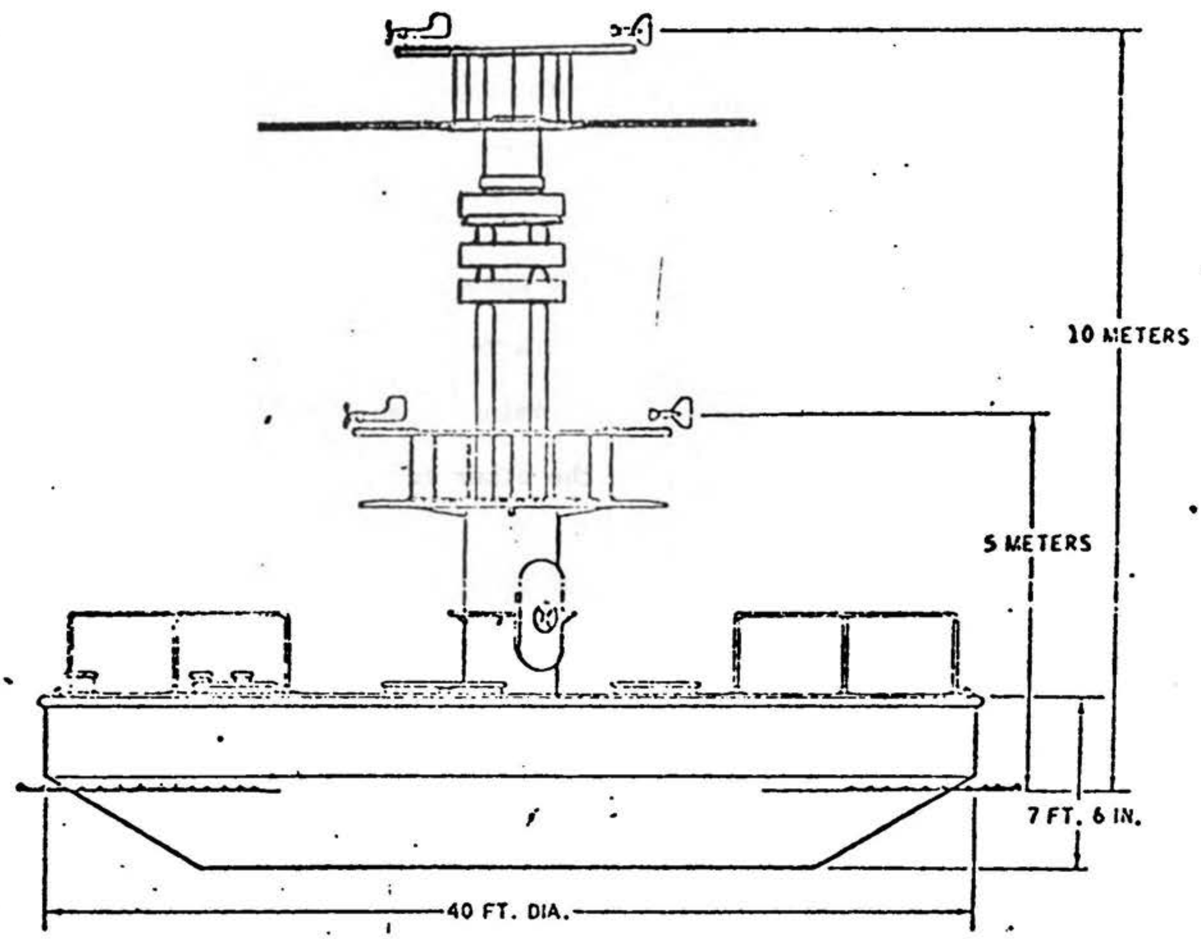


Figure 10 Large Buoy Disc-Sleeve Antenna

Representative of buoy technology, in addition to the large buoy, NDBO has deployed three classes of smaller buoys. These buoys are the GE moored and drifting configurations, the Lockheed Missile and Space Division (LMSC) moored configuration and the Magnavox drifting configuration. The antennas for all small buoys are whips with associated tuning units.

LMSC:

A block diagram of the LMSC communication system is shown in Figure 11. The LMSC interrogation approach is based upon a simultaneous receive capability on three separate channels on a 24 hour a day basis. When the bit sync is recognized on one of the incoming three channels, the on-board processor is activated and locks out the other two channels.

Normal synoptic transmission is accomplished by repetition of the message on each of the three HF bands. This transmission is self-initiated and requires no interrogation command from the shore station. Transmissions in response to commands are performed on either all three frequencies or only the one frequency commanded, depending upon the interrogation command.

Magnavox:

A block diagram of the Magnavox communication system is shown in Figure 12. The Magnavox approach for the reception of interrogation commands is based upon a frequency hopping scheme. The rate of frequency hopping is such that the dwell for each frequency is on the order of a few hundred milliseconds. This rate is sufficiently high to enable two complete frequency scans on each frequency band for every bit synchronization interval. For transmission a command frequency is employed for interrogated transmissions and a programmed frequency is employed for self-initiated transmissions.

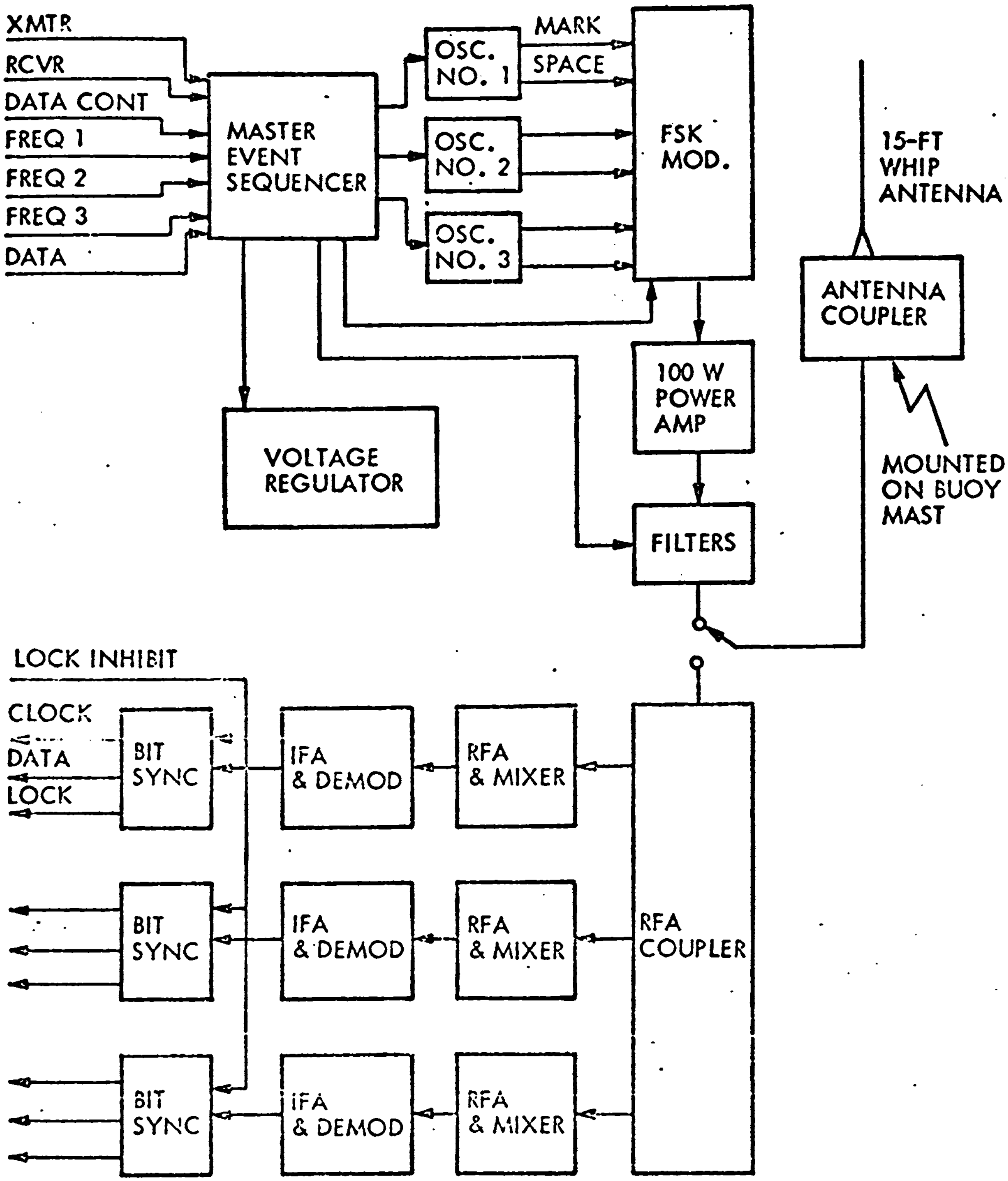


Figure 11. LMSC HF Communications System - Block Schematic .

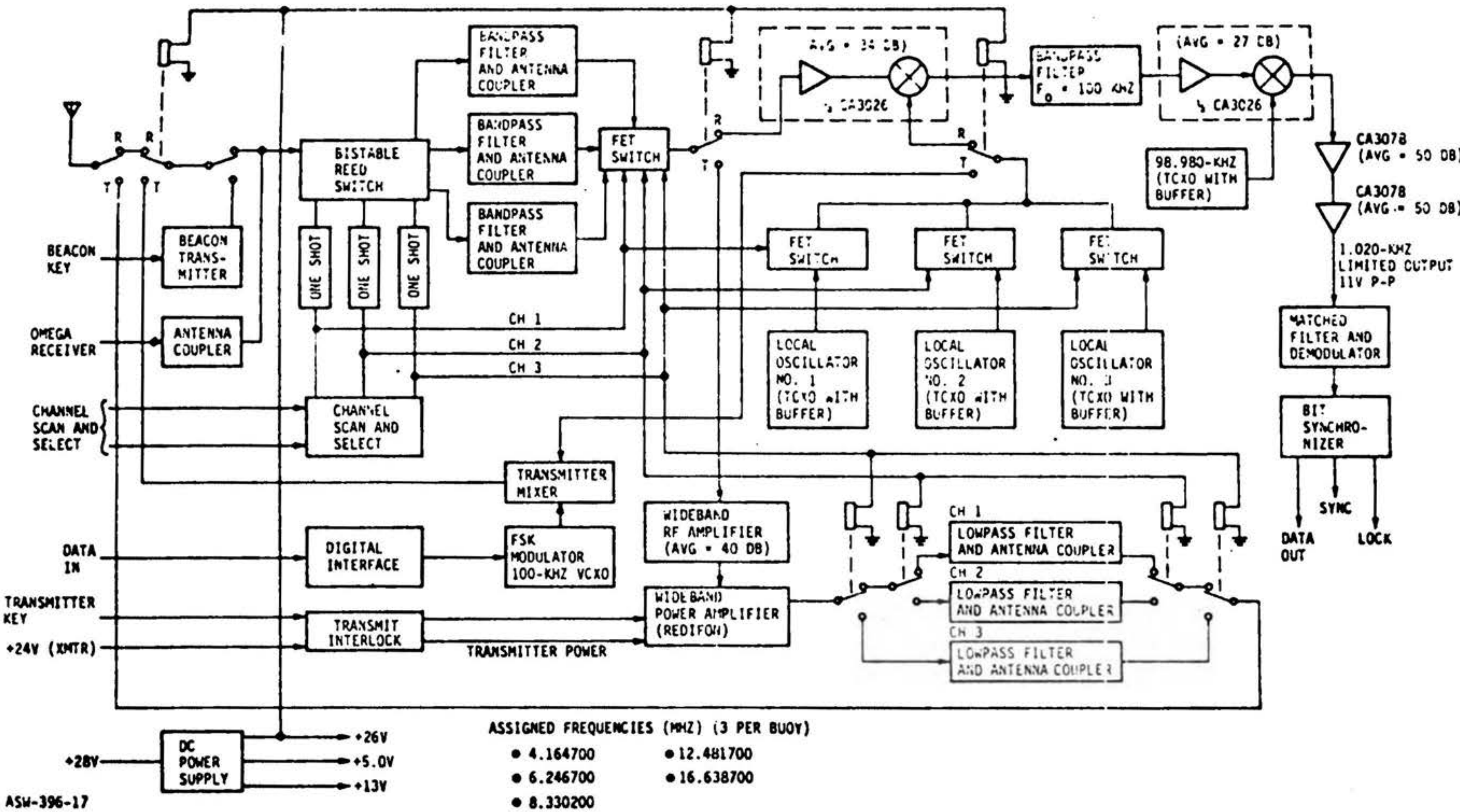


Figure 12. Magnavox HF Communication System, Block Diagram

GE:

The General Electric approach for reception and transmission of synoptic data is essentially a "static" one. In the interrogation mode, one of two frequencies are open for monitoring the shore station transmissions on a continuous basis. The command from the shore station includes a frequency select capability for interrogated transmissions. In the synoptic, self-initiated mode, one frequency is pre-designated as a function of the time of day.

State of the Art (Satellite)

The realization that virtual 100% communication could be attainable by use of a buoy-to-satellite communications mode prompted the NDBO quest for satellite and associated satellite element resources.

Since the late 1960's, maritime satellite communications test, indicated that communications between a ship (ocean platform) at sea and a shore station employing a VHG satellite was readily achievable. Among the results derived from these tests were the noted variations in received signal levels during any one test period.

Experimental satellite communication activities were conducted in late 1969. The purpose of these experiments was to evaluate long-range communication between large, moored, unmanned ocean platforms and a shore station via satellite. Overall, these experiments demonstrated the feasibility of two-way satellite relay communications from and to an unattended ocean platform. However, reliability performance in terms of the successful number of interrogations responded to, was a shade above 50%. It was reasoned that the major cause for the number of unsuccessful communication attempts, as well as many of the bit errors, was frequent deep fading. The emphasis then is to include some additional margin to counteract the effects of fades noted on both the maritime and buoy satellite tests. A list of experiments applicable to buoy communications is shown in Figure 13.

SATELLITE EXPERIMENTS APPLICABLE TO BUOY COMMUNICATIONS

SATELLITE	REMOTE STATION	REMARKS AND CONCLUSIONS	
ATS-I	Data Buoy Alpha	• 38° elevation angle • 75 Hz data rate • BER of 10^{-2} to 10^{-3}	• RFI difficulties • 1970 - 70.6% successful interrogations • Fade variations to 7 dB
ATS-III	SCOMB-1 Norwegian buoy	• 9° buoy/satellite angle • 7° ground station/satellite angle	• Successful "buoy transmissions" • Unreliable interrogations
ATS-I	CGC STATEN ISLAND	• Demonstrated communication out to 3° elevation angle	
ATS-III	CGC GLACIER	• Good communication at 3° elevation angle	
ATS-I and III	SS SANTA LUCIA	• Link sensitive to antenna gain and direction • Fade depths of 12 dB on 12 of 52 tests lasting 5-20 sec	• 200W and 400W transmissions • BER of 10^{-3} to 10^{-4} at 600 beeps per second
ATS-III	Sea Robin Buoy	• 68% responses detected • 10^{-4} to 10^{-8} BER for 305 beeps per second	• BER 3.3 x 10^{-2} at 2441.4 beeps per second for "Best Quality" data
NIMBUS III & IV	Arctic Data Buoys	• 65% successful interrogations • 21 interrogations scheduled daily • Position accuracy ca. 1 n. mile	• 96% data received was meaningful • 49 bits per interrogation
ERTS	USGS DCP	• Avg 17 transmissions per platform per day • Better than 10^{-6} BER	

Developed by T. L. Livingston and P. L. Grose

SATELLITES APPLICABLE TO BUOY COMMUNICATIONS

SATELLITE	AGENCY	LAUNCH	ORBIT	FREQUENCY	EIRP	APPLICATION TO BUOYS
ATS - 1	NASA	7 Dec. 1966	22,300 Miles (149°W) Stationary	149.22 MHz Up 135.6 MHz Dn	48 dbm	Limited - No information storage. Buoys must be close to earth Station - ATS is tired & unreliable
ATS - 3	NASA	5 Nov. 1967	22,300 Miles (70°W) Stationary	149.22 MHz Up 135.6 MHz Dn	48 dbm	Limited - No information storage ATS is old - erratic
LES - 6	USAF	Sept. 1968	22,300 Mi. Stationary	303.4 MHz Up 254.1 MHz Dn.	29 dbw	Subject to allocation which may be difficult. Otherwise could be applicable
TACSATCOM	DOD	Feb. 1969	22,300 Mi. Stationary	303.4 MHz Up 249.6 MHz Dn.	41 dbw	Limited - No information storage. Satellite is tired & unreliable.
EOLE (IAS-A)	Centre Nat'l d'Etudes Spatiales	16 Aug. 1971	560 Mi. Alt. Circular - Inclin. 50°	400 MHz Up 464 MHz Dn.	6 dbw	Feasible for DLCB's - Inherent Design for drifting balloons - Has Range/Rate PFS
ERTS - A	NASA	23 Jul. 1972	920 Km Alt. 99° Inclin. Sun Synchronous	401.55 MHz Up	-	Feasible - No PFS-No interrogation No storage capability
SMS/GOES	NASA	Early 1974	22,300 Mi (100°W) Stationary	401.9 MHz Up 468.825 MHz Dn	16 dbw	Designated for NDBO operation - Communication mode only, No PFS capability (Must use on board PFS)
NIMBUS F	NASA	June 1974	1100 Km 100° Inclin. Period = 108 Min	401.2 MHz Up		Very good application Doppler PFS Limited quantity of data
QUICKSAT	U.S. NAVY	Fall 1974	Stationary	UHF Up Dn.		Limited to buoys in common view with ground station - no interrogation No storage capability - No PFS
TRACKING DATA RELAY SATELLITE	NASA	Fall 1976	Stationary	136-144 MHz 148-149.9 MHz		May be feasible for buoys Range and Range Rate PFS
NIMBUS G	NASA	1978-9	Orbiting			May be feasible No data collection planned
TIROS N & NOAA SATELLITES	NASA	1977-78-79-80	900 nmi Orbiting	Approx. 401 MHz		Feasible for buoys. Parameters similar to NIMBUS F

FIG. 14

SATELLITE DATA COLLECTION PLATFORM PARAMETERS

SATELLITE	MODULATION	MODULATION RATE (bps)	CHANNEL BW (Hz)	XMTD DATA/ XMSN	SIZE	RADIATED POWER (W)	POWER CONSUMPTION STDBY	POWER CONSUMPTION XMT	DUTY CYCLE	WEIGHT	COST
GOES (DCPRS)	± 70° PSK	100	1.5K 3.0K	Amt. desired	6x9x20 .64 ft^3	40	.5W	266W	Variable	30#	$3-5K
NIMBUS F (RAMS)	±60° PSK	100	30KHz	4-8 bit words	4" diam 22" long	.6 1.2 2.4	.15W	8W	1 sec / 60 sec	5#	$1K
ERTS	±5 KHz FSK	2.5K	100K	8-8 bit words	6"x10"x 8.5"	5-20	30MW	(Ave) 75W	38 Msec / 180 sec	15#	$2.2K
EOLE	Analog FM	15-20 KHz 48(interr)	-	4-Channels	8"x19"x 20" 3" diam x 75" length	3	.4MW	15.6W	-	55# 2.2#	$15K
TIROS N	PSK	400	24K	4-8 bit words	-	3	-	-	400 M sec / 60 sec	-	

Figure 15

SATELLITE ANTENNA PROCUREMENT ACTIVITY

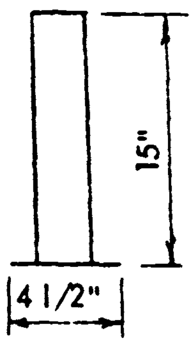
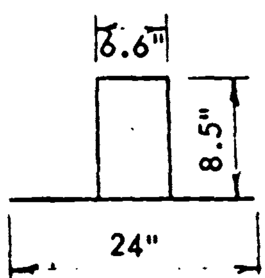
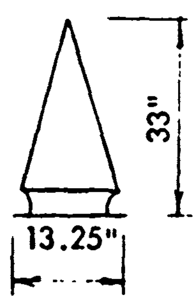
MANUFACTURER	CONFIGURATION	USE	PRODUCTION COST (PER UNIT) (Approx.)	MAX. GAIN
Chu MOD CA-3140		ORBITING	$250	3 db
ECI MOD 681	 20 LBS	ORBITING/ STATIONARY	$500	6.8 db
GEOTRONICS		STATIONARY	$500	6.8 db

Figure 16

Operational Environmental Satellite (GOES) System. The DCPRS was initially designed to provide the communication interface between remote land based platforms and the GOES spacecraft. The initial design was based upon pre-design studies, undertaken by Magnavox, to determine the impact on the selection of modulations schemes and this impact on the design of the DCPRS for operating either @ S-Band or @ UHF on the platform to spacecraft link. The results of these studies indicated that the most cost effective operation would be at UHF and that a differential PSK provides a moderate detection advantage over other schemes possessing similar cost and complexity of techniques.

NDBO is currently under contract, via the procurement facilities of NESS, for modified DCPRS units for NDBO use. The modified DCPRS is capable of operating in both a self-timed and interrogated mode. To facilitate timing and make judicious use of the spacecraft highly stable Cesium frequency standard, the DCPRS has been designed to continuously receive GOES signals to obtain a precise 100 Hz clock reference and recognize the presence of a primary or secondary command address when sent. Message replies are manchester coded, serial digital data at a 100 bit per second rate on one of two frequencies. One frequency will be used for self-initiated reports and the second interrogated reports.

An additional modification will be incorporated into the DCPRS to provide a System Test Capability (STC). The STC will enable validation of the predicted reliability of the buoy - GOES data link on an empirical basis. In addition, the STC will enable on-board equipment/system design changes to enhance DCPRS performance and equipment reliability.

Buoy Transmit Terminal - Drifting buoys, which will comprise several classes of buoys within the general buoy community, will require both a position fixing and a data transmission capability. The marriage of these two functions into one piece of hardware and integrally systematized into an operational system have brought about the design and procurement of the BTT.

The Random Access Measurement System (RAMS) equipment operating on board the orbiting satellite, NIMBUS F, affords the cooperative spacecraft for the BTT.

SHORE PROCESSING

Requirements for shore processing of data depend heavily on what the User wants in terms of data delivered to him and the amount of data processing conducted on-board the buoys. In general this can range from none to a complete analysis. Ignoring the trivial case of no processing, the minimum requirement requires message switching to allow transfer of radio communicated data from buoys to be sent to the proper User. From this minimum to the complete analysis case three alternatives exist:

- Dedicated small general purpose computer
- Dedicated communication oriented computer
- Large shared general purpose computer

Dedicated Small General Purpose Computer

Small general purpose computers have been utilized quite extensively up to the present and they are quite satisfactory for such processing as scaling and error detection. Their major limitation or disadvantage appears to be in their ability to be adequately interfaced into communications equipment for both input and output. Most existing systems continue to rely heavily on human operators to accomplish these required tasks, which clearly decreases their effectiveness.

Communications Oriented Computer

The next step up from the small general purpose computer is the use of a dedicated communication oriented computer. Since it is designed to interface with communication oriented input/output it can more than adequately handle the throughput of any conceived buoy system because it does not require interfacing through an operator. It also can generally handle the error detection and scaling required before dissemination to Users. Clearly this type of hardware for shore processing is the most viable for any net of buoys.

Large Shared General Purpose Computer

Large shared general purpose computer systems are generally only required for the most complex data processing and are not useful without some special form of interface for data input. When utilized as a part of a buoy system they generally are used with a small dedicated computer serving as a data input handler to buffer the data from the communications system. The exception to this would be processing of digital magnetic tape retrieved from buoys.

For all of the above alternatives careful consideration must be made to the level of coding used in their programming as was the case for on-board computer programming. The trap of using machine language code must be carefully evaluated on a basis of downstream change and maintenance as well as initial implementation.

DISSEMINATION TO USERS

Almost every conceivable method of data dissemination to Users has been employed in buoy systems. Among the most common are: delivery of a magnetic tape copy of the data, teletype, hardcopy delivered by U.S. mail, and high speed computer to computer transfer. The optimum method depends solely on the requirements levied by the User. Usually several of these methods are combined.

Magnetic Tape

Dissemination by magnetic tape copy can be a convenient method where the User intends to perform further processing and does not require immediate receipt of the data. Problems arise using this method generally because of lack of agreement or understanding between the tape producer and the User on the format and contents of the tape.

Teletype

Dissemination via teletype is an inexpensive method which can be successfully used if data volumes are low and the User either requires only hardcopy or, has the facility to input data coming over the telephone line into a computer or generate an automatic data processing compatible copy of the data.

Hardcopy by U.S. Mail

Where only hardcopy is required, delivery of U.S. mail can be viable implementation. The only problem with this technique is the unreliability and uncertainty in time of delivery which the User must be willing to accept.

High Speed Computer to Computer Transfer

For large data volumes where timeliness is a factor, the implementation of computer to computer transfer is the only viable technique. This form of implementation has the distinct problem of being expensive to coordinate and implement.

VIABLE STATE OF THE ART SYSTEMS

An attempt will be made here to combine the previously discussed data handling and processing alternatives into viable systems. The systems will be constructed all based on a network of buoys. They will include a short term system for engineering data, an operational synoptic weather network, and a scientific network.

Engineering Data Network

This network configuration is based on a requirement to get limited high data volume over short time periods, similar to hull motion dynamics on test hulls. A state of the art system would consist of a digital data logger with on/off control via a one way VHF communication link. Recorded data would be retrieved at hull retrieval time and all subsequent processing would be conducted on a large general purpose shared computer.

Operational Synoptic Network

This network configuration is based on a requirement to deliver to a User within one hour of data acquistion, averages of measured parameters every three hours, 7 days a week, similar to the Weather Service requirement. A state of the art data handling system would consist of a specialized hardwired computer on-board each buoy which would acquire and average the required data items at the required acquisition times. Two way communications controlled by a dedicated communications oriented computer would retrieve their data, perform simple error detection and quality assurance (bounds and limits), format the data, and relay it to the User. This particular configuration has to be highly automated to achieve reliability.

Scientific Network

This scientific network is based on requirements for data items over a large geographic area incorporating expendable drifting buoys for minimum hardware cost, similar to the Antarctic Current Experiment (ACE). This data handling system will consist of an on-board processor which performs analog to frequency conversion and averages frequencies by counting over preset time intervals. Data communications would be one-way every minute through a satellite Relay to a dedicated communication oriented computer which outputs to a large general purpose shared computer for detailed processing. The buoy equipment is purposely made simple for this system to keep cost down. Moreover hardware reliabilities are made compatible with their limited life and expendability.

RECOMMENDATIONS FOR FUTURE DIRECTION

Unlike many other areas of buoy technology, the present state of the art of data handling and processing for Environmental Data Buoys is quite adequate for the next five years. Existing components will suffice as building blocks for future system. Naturally, component reliabilities could be improved especially in the area of on-board general purpose computers. However, because of its low purchase volume of these computers, the buoy community will have little impact on bringing this about.

The prime concern for future direction lies in prudent design and use of the existing technology. Far too often, buoy system requirements are implemented with data handling and processing as an apparent afterthought. As a result, data is either delivered to the User in a awkward manner or more likely the User does not get all the data he desires, because of bottlenecks in the data handling system. Typically, system implementations end up relying heavily on manual handling and control of data processing because of funding limitations. The net result is a backlog of data which occasionally gets bypassed because of lack of time. It cannot be stressed too heavily, that without proper considerations and implementation of the data handling, communication and processing portion of a buoy system, the Data User will not receive his required data in a "meaningful manner". Thus the prime recommendation for future direction must be a proper emphasis in both design and funding allocation for the data handling portion of a buoy system.

Reliable data links from the buoys to shore and the command links from shore to buoys are a critical part of experimental and operational buoy systems. Several alternative approaches have been identified and the basic choice has been narrowed to HF ionospheric propagation and UHF relay via synchronous or orbiting satellites. Theoretical predictions and occasional experimental results have indicated that HF ionospheric communication path reliabilities on the order of 90 percent can be achieved. On the other hand, higher data rates and reliabilities approaching 100 percent may be possible using satellite relay. Buoy operations with both GOES and NIMBUS F are expected to significantly enhance the overall buoy data link. Extensive operation with both SMS/GOES and NIMBUS F will clearly indicate the extent satellites will supplement or replace HF communications.

An additional concern lies in the proper balance between optimized software implementation and downstream software change and maintenance. It is recommended that the use of machine language coding in any portion of the data handling and processing portion of a buoy system be restricted to only those functions which cannot be accomplished in higher level languages such as FORTRAN.

PRESENT CAPABILITIES TO DETERMINE DEPLOYMENT POSITION, OPERATIONAL POSITION AND REFERENCE DIRECTION FOR BUOY SYSTEMS

by

D. W. Siegelin

Sensor Engineering
The Magnavox Company
Fort Wayne, Indiana 46804

PRESENT CAPABILITIES TO DETERMINE DEPLOYMENT POSITION, OPERATIONAL POSITION AND REFERENCE DIRECTION FOR BUOY SYSTEMS

by

Dale W. Siegelin
Program Manager
The Magnavox Company

ABSTRACT

In the operation of most oceanographic buoy systems, the determination of position location and buoy reference direction are essential to operational success of the system. This paper represents the currently available performance in three specific areas:

(1) Deployment Position
(2) Operational Position (Post-Deployment)
(3) Buoy Reference Direction

The first is presumably of greater interest for moored buoys while the second is of interest to free floating, or drifting, buoys. The third is of interest on any buoy where one of the measurands is described by direction (e.g. wind direction, current direction, acoustic noise, etc.).

The performance descriptions provided are limited to those systems which have been successfully reduced to practice unless specifically noted otherwise.

DEPLOYMENT POSITION

In most operational situations the deployment position of a moored buoy is used for two reasons:

(1) It identifies the geographic position of the data that is collected and reported by the buoy.
(2) It is required for retrieval or servicing visits to the buoy by the support ship.

\

A number of factors relate to the buoy position at the time of its deployment. Generally, the desired deployment location has been selected well in advance of the actual deployment. In practice, the design of the mooring system, including its sensitivity to depth variations, and the deployment technique used can influence the final deployment location. Furthermore, the buoy mooring system usually permits the hull to move in a watch circle whose dimension is of the same order or greater than the position determination accuracy of the deploying vessel.

Consider now the various factors which influence the overall emplacement error.

Ships Position

A number of navigation systems are commonly used on vessels used for buoy deployments. These systems include NNSS (Navy Navigation Satellite System), Loran, and Omega. The principles of operation of these systems are well known with each having its respective advantages and disadvantages.

The NNSS is worldwide but provides fixes intermittently (dependent on latitude but typically every two hours). It must depend on some other input to compute position between fixes. Normally ships speed and heading are provided to the shipboard satellite navigation equipment yielding a continuous readout resulting from the actual satellite fix and the integrated ship's data. The accuracy of a single fix can be on the order of one hundred feet with the inter-fix accuracy largely dependent on the accuracy of the ship's input data.

The Loran and Omega systems share the common disadvantage that currently neither provide worldwide coverage. Omega is presently planned to be operational on a worldwide basis in the mid 1970's. Figure 1 shows the planned locations of the Omega stations and their present status. Table 1 summarizes the currently anticipated completion dates for the stations. Accuracies of the Omega system are in the 1-2 nm range (1.8 - 3.6 km).

Loran A is still widely used and does provide coverage in most geographic areas which are of interest for buoy deployments. Present oceanic coverage by Loran A is shown in Figure 2. The system yields typical accuracies of one to five nm depending on the ship's position relative to the transmitting stations. These receivers are presently available on most ships which would be used for buoy deployments, and specifically are available on USCG Buoy Tenders.

Loran C provides better accuracies than Loran A but is much more limited in its geographic availability (see Figure 3). Accuracies on the order of hundreds of yards can be achieved, again dependent on location within the hyperbolic grid. Loran C coverage is currently available off the Atlantic coast, in the Gulf of Mexico, and in the Gulf of Alaska. Coverage is not provided in the Pacific off the west coast of CONUS.

The USCG Cutter Acushnet has employed a combination of NNSS and Loran C which reportedly affords continuous accuracies of hundreds of feet in the Gulf of Mexico.

Position Uncertainty in Deployment

The position of the deployment is usually best described by the position of the anchor on the ocean bottom since buoy position is uncertain due to the watch circle permitted by the mooring system. It is therefore desirable to position the anchor immediately beneath the selected position (on the surface). While this appears simple, significant errors can result depending on the anchor system and the mooring deployment technique utilized. Using the "float first, anchor last technique", a horizontal error as great as 30% of the mooring depth can be realized. The Sea Lanes[2] report estimates a horizontal movement of the sinker of about 750 to 1,050 feet in deployment depths of about 3,600 feet. With repeated experience on the same buoy this error should reduce to the order of 10% of the mooring depth.

Buoy Watch Circle Uncertainty

As previously mentioned, the buoy watch circle also represents an error or uncertainty in the buoy position. For most taut moorings, the watch circle can typically have a radius of up to 40% of the mooring depths, depending on surface and subsurface current conditions. The Sea Lanes[1] report identified radii ranging from 380 feet to 2,260 feet for various buoys moored in approximately 3,600 feet of water.

Summary of Emplacement Uncertainty

Currently implemented systems readily provide ship positioning accuracies equivalent to or better than that desired for most buoy work. The Loran A system affords good coverage up to 500 nmi from most coastal areas and receivers are currently available on many ships. For more precision, the NNSS and Loran C systems are available. NNSS offers worldwide coverage while Loran C is limited and currently does not provide coverage in the Pacific off CONUS. In the next few years, when Omega achieves complete operational status, it will also provide worldwide coverage with accuracies similar to those of Loran A. Table 2 summarizes the respective merits of these systems.

In certain scientific experiments and other applications (where, for example, the buoy might function as an element of a precision navigation system) it may be important that the position be established with a maximum uncertainty on the order of hundreds of yards. In these cases, position fixing systems with the desired accuracies have been developed; however, their availability is generally limited.

OPERATIONAL POSITION

The reasons previously stated for requiring the deployment position of the buoy are also applicable to the on-going position location of a (presumably drifting) buoy. Additionally, in certain scientific experiments, the geographic position is the parameter of primary importance.

There are several systems or techniques which have been postulated and/or demonstrated as applicable to position fixing on a remote platform. Overall system considerations suggest that the package on the platform (or buoy) be simple, low power, reliable, and inexpensive. These desired attributes, when evaluated with the other performance considerations of accuracy, coverage, and fix frequency reduce the number of potential systems to be considered from several down to two or three which warrant serious evaluation.

Although numerous evaluations of position location techniques applicable to buoys have been made, Beery[2] provides a good summary of the selection process. The following systems are considered:

(1) Decca
(2) Interrogation, recording and location systems (IRLS)
(3) HF direction finding
(4) Consol/Consolan
(5) Omega
  (a) Omega Position Location Equipment (OPLE)
  (b) Digital Omega Receiver (DOR)
(6) Loran A
(7) Loran C
(8) Navy Navigation Satellite System (NNSS)
(9) Random Access Measurement System (RAMS)
(10) Tone-Code Ranging and Data Acquisition System (TCRDAS)

From the above list, two systems were selected and have been developed and deployed on Data Buoy systems. These are the Omega (an adaptation of the DOR) and the NNSS. A third system, RAMS, is being built for evaluation and operation in 1974. It is these three systems which will be considered in the following discussion.

Omega

The overall system advantages and disadvantages of Omega for buoy position fixing are essentially the same as described for the ship problem.

A total of five engineering models have been fabricated for use by the Data Buoy Program. The associated software programs for the shore based processing have also been developed. The buoy units receive the Omega signals for six minutes each hour. Each set of fix data can include up to four LOP's (from four station pairs). The units determine the (sub-cycle) phase difference in centicycles for each of the selected station pairs. Lane count (integral cycles) is not computed in the buoy unit but is established in the shore based processing (assuming the data points are frequent enough).

The limited test data available to date indicate that, when working properly, the Omega PFS units can provide fixes with RMS accuracies in the 2 to 3 nm range[3]. Frequently, these units have not been able to acquire fix data; this has apparently been caused by a combination of factors including: (1) intermittent Omega transmitting station operation, (2) weak signal levels from the Norway and Hawaii stations, and (3) design or reliability problems in the PFS units.

Physically the unit is compatible with most buoy designs. It measures 5 x 10 x 18.25 inches and weighs approximately 20 pounds. During the six minute ON time each hour it draws approximately 7 Watts.

In summary, the widespread usage of Omega for buoy position fixing appears to be limited until the post-1975 time frame. This is primarily dependent on the operational availability of the Omega stations. There is no reason to doubt that such a system could be produced which would provide accuracies in the 2 nm range with acceptable reliability and power levels.

NNSS

As with Omega, the advantages and disadvantages of a buoy based NNSS system are similar to those for the ship. Typically, the buoy system is significantly simplified from the ship unit and is expected to produce accuracies more in the range of 0.5 to 2.0 nm compared to much better accuracies achieved with shipboard systems. These units also require software processing on shore to calculate actual position. The buoy unit receives, processes, and stores "doppler count" data received during a single satellite pass. Satellite ephemerous data, which is provided as modulation on the satellite signal is not decoded by the present system. It must therefore be acquired from some external source for input to the software solution.

A total of four engineering models of the NNSS PFS have been procured by the Data Buoy project. The associated software has also been provided. Several tests have been conducted and much of the data is still in the process of evaluation. After screening for obviously invalid data and undesirable passes (elevation angles less than 15^{o} or greater than 45^{o}) an RMS accuracy of better than 2.5 nm has been achieved[3]. Modifications and improvements to both the hardware and software are being made with the expectation of improving the system performance and accuracy.

This unit is physically the same size as the Omega PFS and weighs approximately 20 pounds. It draws .34 Watts in the standby mode and approximately 2.6 Watts during the search, acquisition, and track modes. Statistically, the PFS would be in the search, acquisition, and track modes approximately 45 to 70 minutes per fix. (This is dependent on latitude.)

It has been suggested[4] that the complexity (and hence cost) of the NNSS PFS unit could be reduced considerably if the receiver control and processing function could be performed in an external microprocessor. The benefits are further enhanced if the microprocessor can accommodate most of the buoy's data processing functions.

The operation of the NNSS PFS at high latitudes warrants some additional discussion. At these latitudes, the polar satellites are more frequently in view of the receivers. This reduces the "wait time" for a fix but also increases the probability of two satellites being in view simultaneously and thereby the possibility of mutual interference. If this situation is intolerable or undesirable, two alternatives are available.

The first is to increase the sophistication of the receiver control (processing) circuitry to prevent the receiver from switching from one satellite to another. The second technique is to command the buoy to commence a position fixing sequence at a time when only one satellite will be in view. This process can also allow the selection of only those passes whose elevation angles are desirable. It does, obviously, require that the buoy contain a receiver and also that the shore station be capable of predicting future satellite passes at the buoy location. This technique does significantly reduce the required battery energy per pass by powering-up the (NNSS) receiver only as the satellite rises.

The NNSS PFS has demonstrated its performance ability (at least to the 2 nm range) and it does offer worldwide coverage. Its size, weight, and power are compatible with most buoy systems. It is reasonable to expect that performance (accuracy) can be increased with improvements in both hardware and software. The intermittency in fixes might present a problem for certain applications but should be acceptable for most buoy work.

RAMS

The RAMS (Random Access Measurement System) has not demonstrated its operational capability; however, it warrants consideration because, if successful, it could offer the PFS capability for buoys at a significantly lower cost per buoy unit. It is currently in the development stage for TWERLE (Tropical Wind, Energy Conversion and Reference Level Experiment) and is expected to be in operation in mid 1974. The RAMS package will be deployed on the NIMBUS-F satellite.

The principle of operation of RAMS is similar to that of NNSS except the position of transmission and reception are reversed. Each platform transmits for one second out of a minute with each transmission containing a preamble, bit sync, word sync, platform ID, and 32 bits of sensor data. The satellite receives these transmissions, achieves sync, decodes the ID and sensor data, and measures the received carrier frequency. The decoded data and the carrier frequency are combined with an accurate time tag and stored in the NIMBUS-F memory for subsequent dump to the Fairbank's ground station.

The satellite package is designed to handle up to eight transmissions simultaneously (assuming each is received at a different frequency). The concept depends upon varying doppler shifts and statistical variations in the oscillators in the platforms to achieve the spread in the received frequencies at the satellite. It is expected that the platform oscillators will experience long term drift, however, in the short term (10-15 minutes) of a pass the oscillator must exhibit very good stability.

In order to determine a fix (and velocity for the TWERLE balloon test), the satellite must receive several one-second transmissions from a platform on each of at least two of three successive satellite passes. The satellite read-out, after receipt at Fairbanks, is transferred to Goddard where it is supplied as input to the software program for position computation. As a design goal, the platform position is to be computed with an accuracy of ±2.7 nm (±5 km).

As with the other systems, there are disadvantages of the RAMS application to ocean buoy systems. Some of these are:

(1) At best only two fixes are provided each day.
(2) The system places rather stringent demands on the buoy antenna system in order to maintain the signal received at the satellite within an acceptable 10 dB window.
(3) The RAMS package is currently planned for the NIMBUS-F and its future beyond that is not known.
(4) The performance goals advertised for the system may not be initially achieved and the system may require iterations (as was true with the NNSS).

Summary of Buoy Position Fixing Systems

Table 3 presents a summary of the merits of the position fixing systems considered. The NNSS system is the only one which currently could provide broad geographic operational. The RAMS is to be demonstrated in 1974 and, if successful, could provide the PFS function at lower (per buoy) cost than the other systems considered. Omega PFS operation has been demonstrated and further utilization awaits the completion of the transmitting station network.

BUOY REFERENCE DIRECTION

After searching for various alternates, it is possible to conclude that, today, the use of the earth's magnetic field is the only practical means of determining reference direction on most buoys. Considerable data has been collected on the earth's field in terms of its intensity, declination, dip or inclination, and various rates of change. It is therefore theoretically possible to accurately determine reference direction given adequate instrumentation to measure the desired magnetic components.

There are two general problems which limit the accuracy of establishing the buoy reference direction for surface ocean measurements. These are:

(1) the effects of ferro-magnetic material used in the construction of the buoy platform and
(2) the inability to keep the sensing element in the horizontal plane.

For subsurface, oceanographic measurements, these items usually do not present a problem. In these cases, the system accuracy is mainly determined by the inherent performance of the compass sensor.

The problem of magnetic material in the hull is preferably avoided in the system engineering and early design stages by the selection of non-magnetic materials in areas near the magnetic sensing element (or compass). Realizing that ferro-magnetic materials are often present, it is frequently possible, by using standard techniques, to compensate for minor variations caused by these materials. In certain cases, however, it has not been possible to achieve compensation and the compass must be physically and electronically remoted from its associated meteorological sensor. Usually in these cases, the compass is located near the top of the buoy, close to the center vertical axis of the buoy. The wind direction (or other directional measurand) is referenced to a buoy heading and then translated to magnetic North using the buoy heading data derived from the compass. This does, however, introduce another potential error source.

Secondly, it is important to maintain the magnetic sensing element in a horizontal plane in order to avoid tilt induced errors. These errors result because the compass is sensitive to the vector component of the earth's magnetic field projected into its reference plane. If the compass is tilted, the vertical component now causes an error because a component of it is projected into the plane of the compass. The amount of error is related to the dip angle of the earth's magnetic field and also to the angle between magnetic North and the axis of buoy rotation, or tilt.

Some degree of static tilt compensation is usually provided in the available compasses. This is accomplished by simple gimballing or through the use of a floating element. These techniques afford good compensation for static tilt angles up to the 15° to 30° range. As buoy dynamics are introduced, however, the compass element tends to align itself in a plane normal to its apparent gravity vector. This vector is the resultant of true gravity and the buoys acceleration forces, both translational and rotational. In order to minimize the effect of rotational accelerations, it is desirable to locate the compass near the buoy's center of rotational motion. This requirement is, unfortunately, counter to the previous discussion which suggested that the compass be located near the top of the buoy mast to avoid local body effects caused by structural, ferro-magnetic materials.

Compass sensors are available which provide 1° RMS accuracies in the static mode, although accuracies of 2-5° are more common. An RMS accuracy of 0.33° is claimed for the compass used in the Measurement Comparison System[5]. Compensation for the effects of ferro-magnetic materials is possible. In one case, the compass associated with the wind sensor at the 10 meter level of the 40 foot EEP buoy has been reportedly compensated to within 1° RMS in the static situation.

The instantaneous, motion induced error, however, is typically larger than the compensated error for any location where there is a significant vertical component to the earth's magnetic field. Respectable accuracies may be gained through the use of averaging techniques if the tilt or motion induced error is reasonably small.

The magnitude of the tilt induced error is obviously greater at higher geomagnetic latitudes. The inclination, or dip, angles for selected interest areas are as follows:

Area	Magnetic Dip Angle Range(°)
US East Coast	60 - 75
Gulf of Mexico	55 - 62
US West Coast	60 - 70
Gulf of Alaska	65 - 74

In the Southern Gulf of Mexico, the horizontal intensity is 0.28* and the vertical intensity is 0.40 (as given by the Smithsonian Physical Tables[6]). For the Northeastern coast of CONUS or the Northeastern edge of the Gulf of Alaska, the horizontal intensity is approximately 0.15 and the vertical intensity is about 0.54. Over this range, the ratio of vertical intensity to horizontal intensity (tangent of dip angle) varies from 1.4 to 3.6 or by a factor of 2.5. Other things being equal, then, the tilt-induced error at the least desirable location could be a factor of 2.5 times worse than the corresponding error at most desirable locations.

There is very little, if any, empirical data which describes the compass error on a deployed buoy. The best estimate is probably derived from the summation of static error (which can be measured) and the dynamically induced tilt error. This latter error can be treated analytically. Considering the effects of averaging the output over a long period (many cycles of buoy motion), this error should reduce to the 1-15° range, depending on buoy geometry, angle to the axis of rotation (pitch), and the magnetic dip angle.

In summary, the accuracy of establishing a reference direction on a buoy is not significantly limited by the inherent performance of the magnetic sensor. It is rather a function of the magnetic properties of the hull, the location of the sensor on the hull, and the dynamic

---

* In cgs units.

motions of the hull. It is sometimes possible to compensate for some of the errors caused by the ferro-magnetic hull structures if the compass is located in a desirable position. In certain cases (e.g., the 5-meter level of the 40 foot EEP hull) compensation has not been possible. The motion induced errors are minimized if the compass is located near the center of angular buoy motion and, in general, tend to average out over symmetrical motions. Motion induced errors also increase with the dip angle of the earth's magnetic field.

Tilt compensated (in the static condition) compasses are available which can provide accuracies of 1° RMS, however, most buoy systems deployed to date which employ averaging probably yield actual accuracies more in the range of 5° - 20° due to the factors described above.

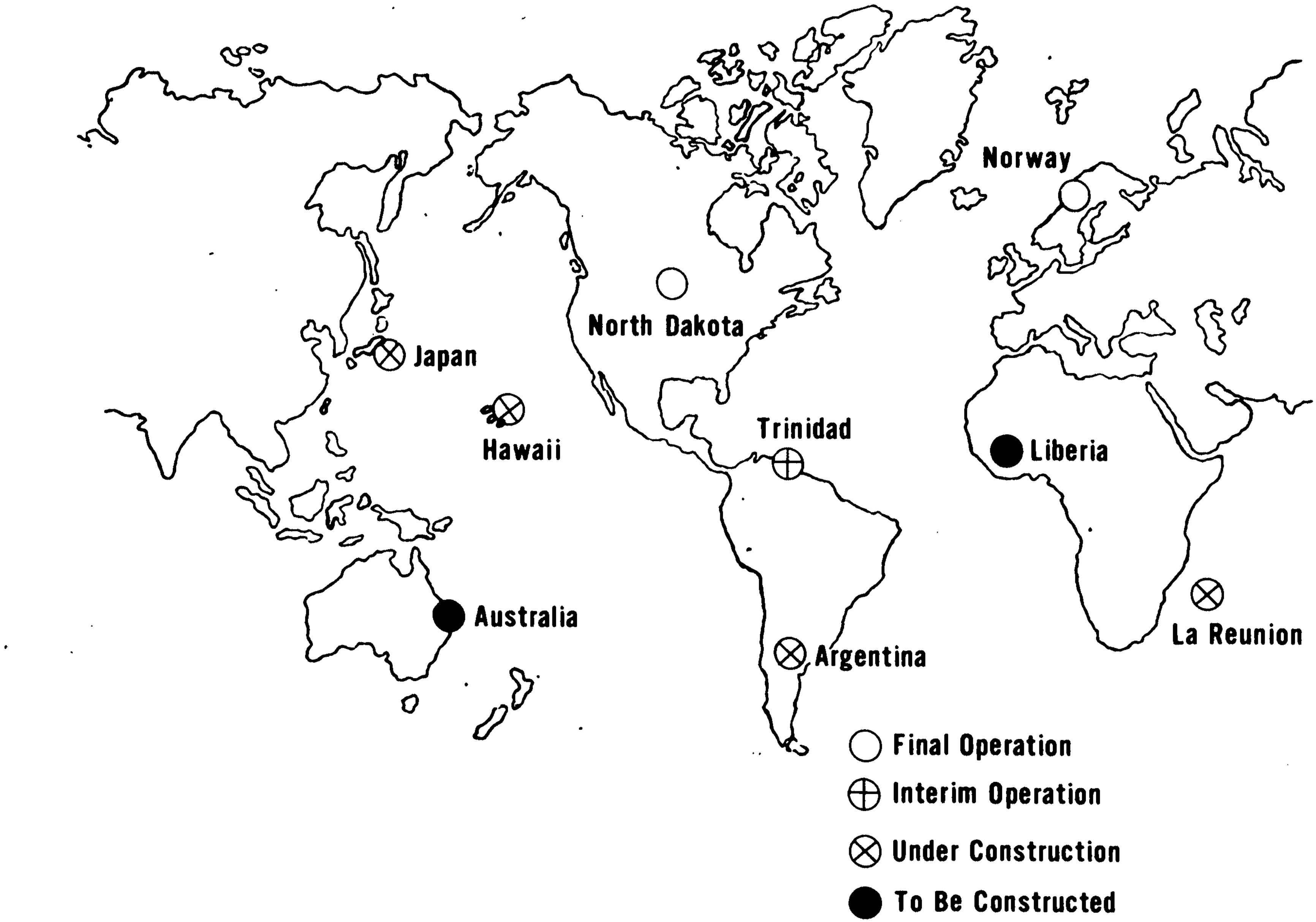


Figure 1. Planned Locations of OMEGA Stations

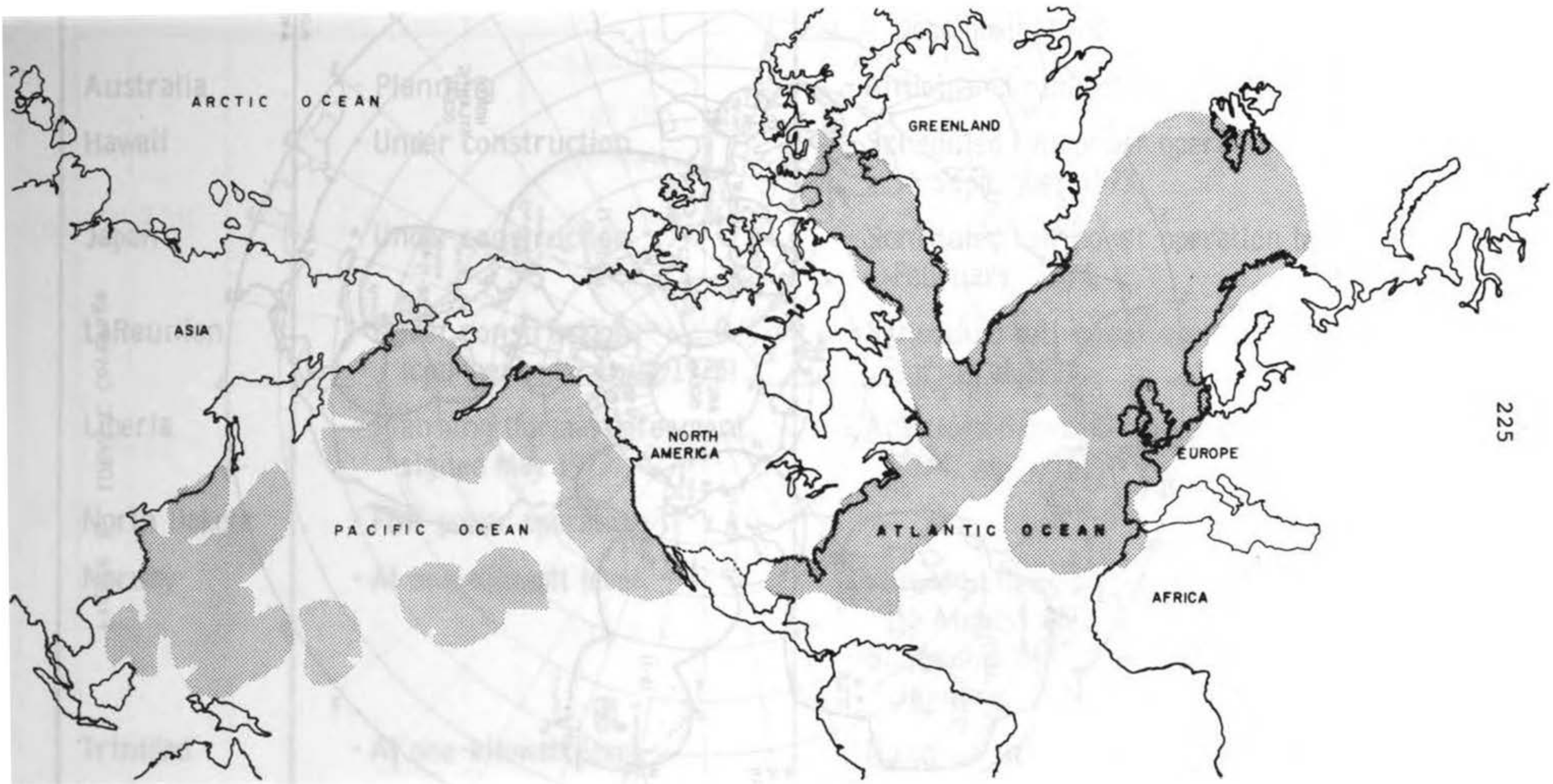


Figure 2. Ocean Coverage by LORAN-A

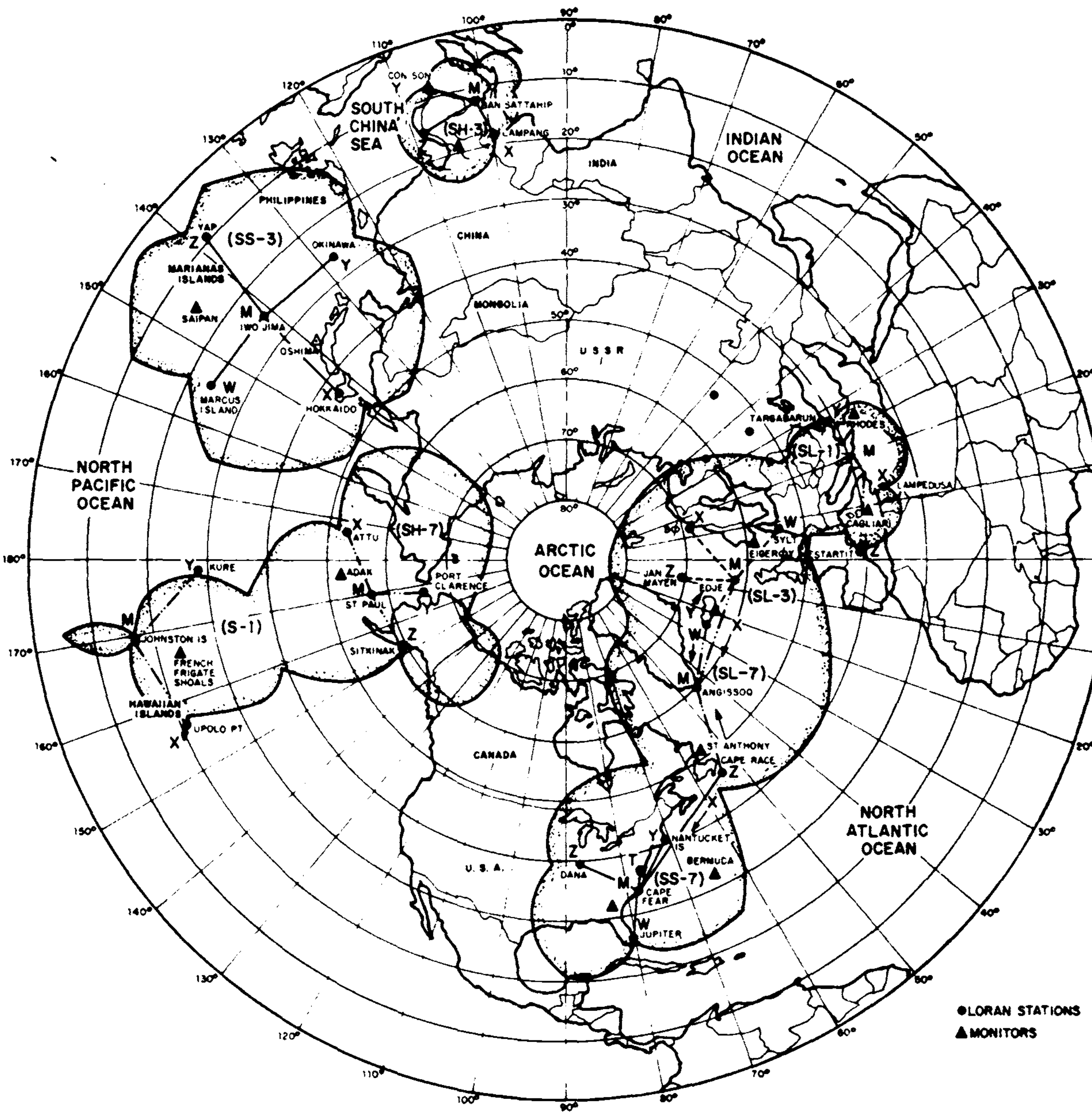


Figure 3. LORAN-C Coverage

STATION	PRESENT STATUS (JUNE 1973)	REMARKS
Argentina	- Under construction	- Scheduled full-power operation by December, 1974
Australia	- Planning	- Anticipated completion by 1975.
Hawaii	- Under construction	- Scheduled full-power operation by 15 September 1973.
Japan	- Under construction	- Scheduled full-power operation by February, 1974.
LaReunion	- Under construction (commenced 7 June 1973)	- Scheduled full-power operation by spring of 1975.
Liberia	- Planning (formal agreement signed May 1973)	- Anticipated completion by late 1974, early 1975.
North Dakota	- Full-power operation	
Norway	- At one-kilowatt level	- Will shut down for construction 15 August 1973. - Scheduled full-power operation by January, 1974.
Trinidad	- At one-kilowatt level	- No construction planned. Will be utilized as back-up station.

Table 1. OMEGA Navigation Station Status

SYSTEM	FIX ACCURACY (NMI)	COMMENTS
Loran A	1 to 5	- Coverage in most ocean areas of interest.
		- Nominal range for coastal areas of 500 nmi.
		- Continuous fixing possible.
Loran C	0.05	- No Pacific coverage.
		- Coverage limited to northern hemisphere.
		- Continuous fixing possible.
NNSS	0.02	- Worldwide coverage
		- Nominal time between fixes, 120 minutes.
		- At high latitudes (> 70^{o}), possibility of mutual interference between two satellites.
OMEGA	1 to 2	- Presently not in full operation.
		- Scheduled full northern hemisphere coverage by spring of 1974.
		- Planned worldwide coverage by end of 1975.

Table 2. Summary of Considered Ship Navigation Systems

SYSTEM	FIX ACCURACY (NMI)		COMMENTS
	DEMONSTRATED	EXPECTED	
NNSS	2 to 3	0.5 to 1	- Worldwide coverage.
			- Nominal time between fixes, 120 minutes.
			- At high latitudes (> 70^{0}), possibility of mutual interference between two satellites.
OMEGA	2 to 3	1 to 2	- Presently not in full operation.
			- Scheduled full northern hemisphere coverage by spring of 1974.
			- Planned worldwide coverage by end of 1975.
			- Continuous fixing possible.
RAMS	N/A	2.7	- Has not been operationally tested.
			- At most, two fixes per day.
			- Requires a buoy antenna that provides a signal at the satellite which remains within a 10 dB window.
			- Currently planned only for the Nimbus-F satellite to be launched in 1974.

Table 3. Summary of Considered Buoy Position Fixing Systems

REFERENCES

1. Hartmen, P. J., Sea Lanes Test-Operations Report, National Data Buoy Systems, NDBCM W6222-1, 1971

2. Beery, Wesley M., Position Location Techniques for the National Data Buoy Systems, Institute for Telecommunications Sciences.

3. Gilbert, M. E., Livingston, L., Haas, G., The Development and Test of Position Fixing Systems for Drifting Buoys.

4. Final Report, A Study of the Feasibility of Combining the Requirements for a GOES Communication System and a Position Determinations System Into One Piece of Hardware, The Magnavox Company, Contract NAS8-29475, 1973

5. A Discussion of the Measurement Comparison System, NOAA Data Buoy Office, April 1973

6. Smithsonian Physical Tables, Ninth Revised Edition, 1964

BUOY DEPLOYED PROFILERS

by

J. Van Leer

Rosenstiel School of Marine and Atmospheric Sciences
University of Miami
Miami, Florida 33149

Introduction

Meteorologists for years have made profiles of the lower atmosphere with radiosondes and rawinsondes. With these synoptically distributed profile measurements, plus surface pressures, they have developed an understanding of the large-scale physics of the atmosphere which allows them to predict future states of the atmosphere during the next few days. A synoptic grid of stations for making profile measurements in physical oceanography has, until recently, implied the use of a dedicated ship for each desired grid point. Such an approach is at least an order of magnitude more expensive than a grid of radiosonde stations. This in part accounts for the late emergence of synoptic oceanography.

In the sections that follow, the advantages of buoy-deployed profiling systems will be discussed. The major reason for using profiling systems is to reduce spatial sampling errors, so sampling will be covered first in the greatest detail. Then the order of topics will be: present technology, cost, accuracy, self-noise, and operational simplicity.

Spatial Sampling Errors

In the design of ocean sensors and their associated data buoy systems, the expected oceanic variability must be included as an element of a complete system. This is typically done at present by selecting the proper full scales of sensors and their frequency of sampling in time. However, the spatial variability of the ocean is usually not included explicitly in ocean sensor and data buoy design. While it is recognized widely among oceanographers that no significant coherence exists between current meters vertically spaced 100 meters or more apart in inertial and internal tidal frequency bands, major field experiments are mounted using 100, 200, and 500 meter instrument spacing. Since inertial and internal tidal motion often contain a major portion of the horizontal kinetic energy, it is poor engineering to spatially alias these signals into the lower-frequency part of the spatial spectrum. Similar remarks can be made about estimating the heat content of surface layers of ocean with fixed temperature sensors. For example, the depth of the base of the surface mixed layer is usually crudely bracketed within a 20 to 50 meter region. The exact position of this interface can make a difference in the heat content estimate of the surface mixed layer exceeding the total solar input over weeks or months. This makes near-surface heat budgets estimated from a small number of fixed sensors practically worthless. Because very little energy is contained in the temporal frequency band above 8 to 12 cycles per day, one can use a vertically moving sensor package to resolve the high spatial frequencies without becoming seriously aliased in time.

Present State of Profiling Technology

Several vertical profiling techniques are presently available using a manned platform. The most widely used is the STD/CTD system. The vertical microstructure probe of Cox has had the highest resolution. Velocity profilers such as those of Sanford, Düing,and Rossby are also available for ship-attended operations. All of the above profiling techniques have shown temperature, salinity, or current structure rich in high spatial frequencies. The high cost of ship time will make the use of unattended profiling techniques attractive.

Two unattended profiler techniques are presently designed and built. The General Dynamics profiling oceanographic sensor measures temperature and depth to 300 meters. It employs a falling body similar to an XBT and an articulated winch. This system has been ship-deployed successfully and will be tried on a buoy this summer. Due to its large power requirements, it will be useful only on very large data buoys. The Cyclesonde developed at the University of Miami measures temperature and current speed and direction as a function of depth and time to 200 meters. It rises and falls on a taut wire mooring due to changes in its displacement above and below its neutrally buoyant displacement at preset pressures. During the first year of operation (FY 1973) over 4,000 profiles were made by Cyclesonde in field experiments. Data durations to 5.5 days have been achieved with the initial (MK-1) Cyclesonde making arrays of a dozen or more instruments practically maintainable by a single ship.

Cost

The major cost advantage of buoy-deployed profilers is that one sensor package does the job of many. Above this direct saving is sensor costs; one also saves expensive intercalibration costs. If the cost per mooring can be substantially reduced, the number of moorings can be increased to truly resolve synoptic horizontal scales. Although substantial development costs may be required to extend record lengths beyond a month, the cost benefits will be great in many scientific experiments.

Stability and Accuracy

A profiler can be expected to give a more accurate spatial representation of the vertical structure of the environment than an economically reasonable number of fixed sensors. For example, how many sensors would be required to accurately resolve the spatial structure of the temperature and current structure shown in Figure 1? It may be argued that even a less accurate profiling sensor (± 10 or 20% for example) would provide a more representative measurement than half a dozen ideal error-free sensors at fixed depths.

Derivative quantities such as shear, density gradient or Richardson Number can be computed with greater accuracy because the differences will no longer depend on the long-term stability of a large number of sensors. A profiling instrument can also be self-calibrating in some cases. An oxygen sensor which periodically enters an oxygen-saturated surface mixed layer or an anaerobic near-bottom region will be self-calibrating. If one used a profiler which went deep enough to find a region with stable temperature-salinity structure, these sensors could be self-calibrated. Near-surface measurements can be made while limiting sensors exposure to Euphotic zone fouling.

Self-Noise

Profiles can be easily decoupled from the motion of a surface buoy. This decoupling makes them a relatively noise-free platform for sensor operation. Motion-related problems such as rotor pump-up and salinity spiking can be reduced or eliminated by the profilers' slow, monotonic rising or sinking motion relative to the water. Sensors can be easily "biased" away from low-speed threshold problems like self-heating, rotor stall or oxygen depletion in the boundary layer near an oxygen sensor.

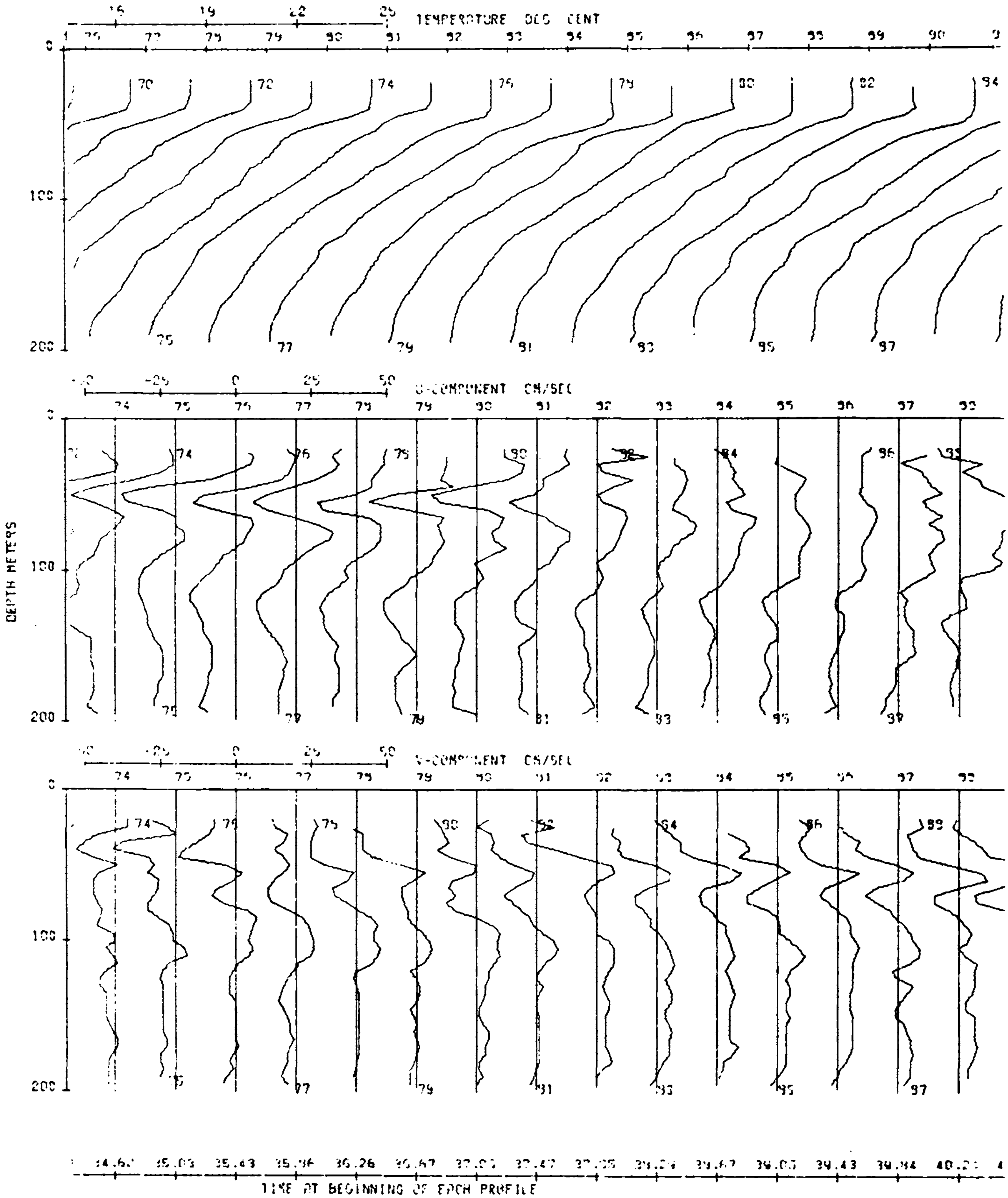
Simplicity of Operation

Several aspects of buoy-deployed profilers simplify mooring operations. Since profilers are not built into the mooring wire, they can be removed for service without removing the entire mooring. In some cases, even the surface buoy may be left in the water. The mooring cable can be made in one or two pieces requiring the minimum number of failure-prone terminations, shackles, and fittings. This permits an entire mooring to be spooled on a hydro or trawl winch for easy, precise, and anchor-first deployment using standard blocks and hardware. The profiler mooring has one light-weight, easily detached sensor package which can easily be handled with a small boat. Cyclesonde moorings have been deployed and serviced from 47 and 59 foot research vessels in shallow water less than or equal to 200 meters.

Conclusions

The development of synoptic physical oceanography will progress as cost-effective profiler technology becomes available. Some promising first steps have been made in reducing the cost and improving the representativeness of ocean data through the development of buoy-deployed profilers. If such profilers can be connected to ship or shore by a reliable radio telemetry link, only those instruments requiring service need be disturbed. If the bandwidth of telemetry systems can be increased to about 10,000 bits per hour, real-time forecasting of future states of the ocean will be possible.

CYCLESONDE PROFILES JANUARY 1973



NOAA DATA BUOY OPERATIONS SUPPORT

(2 Parts)

by

W. M. Flanders

NOAA Data Buoy Office
Mississippi Test Facility
Bay St. Louis, Mississippi 39520

Part I. The Essentials of Support: One Year's Operations on Three Coasts

Approximately one year has run its course since the NOAA Data Buoy Program began extensive deployment and support of buoy hardware in the ocean environment. Forty-foot discus buoys were set as follows: EB-10 in the Gulf of Mexico, EB-01 in the Atlantic, and EB-03 in the Gulf of Alaska. A mix of 10 small moored and drifting buoys was deployed in the Gulf of Mexico for periods of three to four months. Another large buoy, EB-02, with boat-shaped hull and deep stabilizing keel, was recently deployed in the Gulf of Mexico. With these deployments, the Data Buoy Office undertook the operational maintenance and support of buoys off all three continental coasts.

This geographic dispersion forced NDBO to utilize support and data handling concepts as though operating CONUS-wide buoy systems (although at the pilot level). Furthermore, frequent failures of this initial equipment required a servicing rate which might be expected from a greater number of buoys in each area. Thus, our support experience has been quite realistic and emphasizes the need for proper Integrated Logistic Support Planning in development of equipment where, for example, the act of implantation is but a small facet of the overall logistic and maintenance support system that must be established for operations.

Key points of this planning effort are to assert and maintain control over life cycle cost, in which support and maintenance are a major factor, and to assure performance in not only reliability but availability, in which support and maintenance are also a major factor. One of the key NDBO program areas of emphasis in the development of new equipment and the modification of existing equipment is the reduction of buoy support costs.

The support system to date may be described as a four-level system: (1) at sea, (2) at the advance staging base, (3) at the NDBO repair depot, and (4) vendor plant repair. The first and second support levels were accomplished primarily via reliance on the already established USCG system of bases, depots, communications facilities, ships, and aircraft. Table 1 indicates the extent of vessel services utilized to deploy, retrieve, and/or support on-scene repairs of data buoys. The USCG facilities at Seattle and

Kodiak provided the essential second-level resources for receiving equipment and supporting the fitting out of buoy and support vessels for EB-03 in the Alaskan Gulf. The USCG base and supply depot at Portsmouth, Virginia provided similar services for EB-01 and, as well, provided industrial support for refurbishment and redeployment of this buoy last summer after nearly two years on station.

Operations in the Gulf of Mexico at both levels two and three were supported primarily by the buoy repair facility established at MTF. Here the NASA building for staging and storage of the Apollo second stage is found constructed as though the support of ocean environmental buoy systems were foremost in the architect's mind. Industrial floor area provides for the accumulation of equipment and contractor integration, testing and delivery of the large and small buoys within the building (see picture). Electronic spaces have been furnished for repair and testing of buoy instrumentation and electronic units utilizing buoy-unique bench systems and with data handling equipment similar to that at the buoy telemetry station in Miami. Other NASA general-purpose facilities round out the support picture, including machine shop, laboratories for analysis and calibration, warehousing, materials procurement, handling and transport, graphics/technical documentation, and, most important, computer processing of the already extensive environmental and engineering data received from the buoys.

The nature of buoy operations is similar to that of any other system consisting of a multiple number of remote, unmanned, automated pieces of equipment, dispersed over a wide geographic area; by analogy, our satellite systems and the Coast Guard navigation networks are similar. Operations and maintenance control are closely tied, if not identical, functions, and begin with the daily monitoring and analysis of ADP-manipulated, telemetry data from the buoys.

Valid output to users is controlled by our remote fault detection capability and our remote remedies for out-of-tolerance situations via selection of redundant equipment, remote switchover capability, and remotely programmable software. If these fail, repair strategies are formulated and repair equipment and maintenance crews are prepared for at-sea operations. These range from a quick aircraft inspection or search (if adrift and lost) to actual slugging with the elements at the scene of the recalcitrant buoy equipment. At-sea repairs are accomplished by two methods: board via small boat, or hoist and repair on deck, depending on the size of the buoy. Fortunately buoy sizes presently in inventory are either large enough or small enough to utilize existing ship support. Repairs on any intermediate size would be impossible without special handling systems being developed concurrently with the buoys.

At-sea maintenance operations may be further categorized into (1) routine scheduled changeout or extensive maintenance by vessels with on-scene capability and equipment to carry out the operations and (2) contingency correction of buoy operation through a visit by a technician with limited repair equipment. In our experience, many different "contingency" vessels have been utilized to enable our technicians to visit by small boat or rubber raft; the high-speed visit and turnaround by the hydrofoil vessel TUCUMCARI was one impressive example.

Recognizing these differences in maintenance requirements, it may be well to provide for different types of support vessels. The conflicting requirements for range, stability, payload, and low-speed power versus high-speed and number of vessels needed appear nearly irreconcilable. It may be well to emphasize tender design capabilities for all-weather operations on scene at the expense of other factors and to rely on the existing multi-mission fleet or some other specific type for contingency support.

TABLE 1

NDBO AT-SEA OPERATIONS

BUOY	ACTIVITY	SUPPORT SHIP	TRIP DATES (INC.)	REMARKS
EB-10	Deploy	ACUSHNET	June 14 - 17, 1972	
EB-10	Repair	ACUSHNET	June 22 - 26, 1972	DPS Failure
EB-10	Data Quality	ACUSHNET	July 9 - 12, 1972	Sensor System
EB-03	Deploy	YOCONA	September 4 - 15, 1972	Mooring Failure
EB-10	Repair	ACUSHNET	August 29 - Sept 1, 1972	DPS Failure
EB-10	Repair	ACUSHNET	September 18 - 22, 1972	DPS Failure
EB-03	Redeploy	CITRUS	October 3 - 8, 1972	
EB-01	Deploy	CHEROKEE	October 4 - 8, 1972	
EB-01	Ocean Data	TUCUMCARI	October 16, 1972	Abort - WX
EB-01	Ocean Data	MADRONA	October 21 - 23, 1972	
EB-10	Repair (Quarterly Inspection)	DEPENDABLE	October 24 - 30, 1972	DPS Failure
EB-01	Repair	CHEROKEE	October 30 - Nov 1, 1972	Power System
EB-32	MLDL Test	ACUSHNET	December 8 - 9, 1972	
EB-10	Inspection	ACUSHNET	January 9, 1973	Flooding Alarm
EB-10	Quarterly Inspection	ACUSHNET	January 22 - 28, 1973	
EB-32	Deploy	SALVIA	January 22 - 28, 1973	Combined Operations
EB-51	Drift Test	SALVIA/ACUSHNET	January 22 - 28, 1973	
EB-62	Drift Test	SALVIA/ACUSHNET	January 22 - 28, 1973	
EB-03	Repair	CITRUS	January 29 - Feb 4, 1973	DPS Failure Sensor System
EB-01	Repair	CHEROKEE	February 12 -17, 1973	Sensor System DPS Failure - Abort WX
EB-01	Repair	CONIFER	February 22 - 26, 1973	DPS - Sensor System
EB-36	Deploy	SALVIA	February 21 - 24, 1973	Abort
EB-52	Deploy	SALVIA	February 21 - 24, 1973	Combined Operations
EB-61	Deploy	SALVIA	February 21 - 24, 1973	
EB-01	Repair	CHILULA	March 12 - 17, 1973	Power System
EB-31	Deploy	SALVIA	March 7 - 11, 1973	
EB-36	Deploy	SALVIA	March 7 - 11, 1973	Combined Operations
EB-53	Deploy	SALVIA	March 7 - 11, 1973	
EB-02	Deploy	ACUSHNET	March 20 - 24, 1973	
EB-02	Repair	ACUSHNET	April 1 - 10, 1973	Power System (Unsuccessful)
EB-10	Repair	ACUSHNET	April 1 - 10, 1973	DPS
EB-36	Repair	ACUSHNET	April 1 - 10, 1973	Antenna Combined Operations
EB-01	Repair	MADRONA CONIFER	April 12 - 14, 1973 April 15 - 18, 1973	DPS; Abort - WX
EB-37	Deploy	SALVIA	April 23 - 25, 1973	Combined Operations
EB-32	Replace	SALVIA	April 23 - 25, 1973	
EB-02	Repair	SALVIA	April 23 - 25, 1973	
EB-03	Repair	CONFIDENCE	April 25 - 27, 1973	
EB-10	Repair	ACUSHNET	May 8 - 12, 1973	
EB-02	Repair	ACUSHNET	May 8 - 12, 1973	Combined Operations
EB-32	Repair	ACUSHNET	May 8 - 12, 1973	

Part II. The Essentials of Support From the Integrated Logistic Support Point of View

NDBO ILS planning based on experience to date is summarized by the following excerpt from a paper prepared by NDBO for possible use in a Federal Plan for Environmental Data Buoys earlier this year.

Integrated Logistic Support

Integrated logistic support (ILS) is directly involved in all phases of development from concept formulation through operational deployment of hardware. Support costs are a major consideration, and the proper balance between performance and life cycle cost can only be achieved by addressing logistic support as an integral part of data buoy systems. Recognizing the inseparability of hardware and logistic support of hardware, the Federal policy should be to integrate the design, development, acquisition, and implementation of logistic support with the design, development, acquisition, and operation of data buoy systems. Integrated logistic support includes the following eight items.

Maintenance: With the exception of overhauls, most scheduled and unscheduled buoy maintenance will be accomplished on site by the directing agency. On-site maintenance will be limited to servicing and preventive maintenance and the replacement of failed assemblies or line replaceable units (LRU's) which may vary from small plug-in modules and engine injectors to complete electronics drawers and major items of equipment such as engine generators, tape recorders and sensors. Major maintenance such as LRU/module repair will be performed at a centralized facility or at manufacturers' plants. Buoy hull and mooring maintenance may be performed at the centralized maintenance facility or at staging bases. The number of maintenance echelons needed for the support of data buoy systems could vary. The following four echelons are normally established.

- Field repair -- on buoys, aboard service ships and at shore communication stations

- Staging base repair -- at strategically located support bases which will be established near deployed data buoys and supported by the centralized depot repair facility

- Depot repair -- at centralized module repair facilities

- Factory/vendor repair -- at manufacturers' plants. Maintenance beyond the capability of the depot repair facility or maintenance which can be performed more expeditiously or economically by the contractor

Support and Test Equipment (S&TE): The maintenance concept dictates the acquisition and distribution of S&TE. Maximum use should be made of government standard test equipment. Data buoy system design will be influenced by efforts to standardize and minimize test equipment requirements. Support ships will be provided with common S&TE devices of the go/no-go type required for field maintenance. The centralized depot maintenance facility will be equipped with repair and calibration equipment. Special handling devices, tools and fixtures will be available aboard service ships, at staging bases, and at the depot facility.

Supply Support: The supply center will be located at the Central Support Facility (CSF), and minimum supply operations will be conducted in staging bases. A standard provisioning formula will be established and used for initial and follow-on provisioning. The formula will consider densities, locations, meantime between failures, maintenance concepts, float items, item redundancies, etc. Supplies to support at-sea servicing visits will be assembled at the CSF and forwarded to staging bases for timely transfer to support ships. Inventory management will be controlled at the CSF. Property accountability procedures will be followed at all echelons.

Transportation and Handling: Transportation and handling includes:

- Devices to support, move, launch, service, and recover complete data buoys

- Preservation, packing, working, shipping, and handling of supplies, components, S&TE, sensors, explosive devices and special handling devices

- Transportation of personnel

Maximum government-owned and contracted air, sea, and land transportation will be used for shipment of supplies and personnel. Special devices for handling buoys and buoy components on shore and at sea will be prescribed in hardware design specifications. Buoys normally will be deployed and retrieved by dedicated support ships. Transportation of all items will be directed and scheduled by the central support facility. Special packaging and handling criteria will be included in design specifications to allow standardized, cost-effective processing and efficiency throughout.

Technical Data: Operations and maintenance manuals for buoys, buoy components, and related dedicated equipment will be prepared and published in a standardized format which permits Federal cataloging and provisioning. All specifications, designs, modifications, maintenance supply operations, and other pertinent activities will be controlled by the cognizant agencies' configuration management plan. Training literature will be contracted and produced in-house as the need dictates. Plans for all Integrated Logistics Support (ILS) activities will be prepared and published for each buoy program in consonance with prescribed government procedures, concepts, and test methodologies.

Facilities: Facilities will be established and maintained to provide the following:

- Depot repair of data buoy subsystems and modules
- Overhaul and refurbishment of ocean platforms
- Laboratory services
- Calibration services
- Shipping and receiving
- Installation and checkout of data buoy components and subsystems
- Depot-type storage (including bonded storage space)
- Dockside predeployment test

- Document storage
- Office space
- Data processing center
- Supply operations

Personnel and Training: A long-term goal for Federal data buoy programs is to deploy equipment that can be operated and maintained by government personnel. Contractor personnel will be used during early stages of data buoy development and will develop personnel selection criteria, training facilities, and training programs necessary to provide skilled government personnel to assume a progressively more responsible role.

Maintenance at the platform level and at shore communications facilities will initially be performed by contractors. At six-month intervals during the initial phase, maintenance actions will be analyzed to define maintenance time and personnel requirements. An objective of design and maintenance analysis is the attainment of equipment, to be maintained by personnel with moderate levels of skill with a minimum of support equipment, that is relatively free from human-induced error.

Generally, government personnel will continue to manage Federal data buoy activities, and to fill key billets including those for repair technicians of all echelons. Use of hardware contractors will be minimized. Plans will include training programs, demonstrations, on-the-job training, formal classroom instruction, contract training and refresher training on an as-required basis. Training devices will be included in hardware contracts as required.

Integrated Logistic Support: Specific requirements within the framework of the eight logistic support elements discussed must be considered for the implementation and operation of a logistic support program. These requirements are relevant to any data buoy program and concern the support of hardware during and subsequent to deployment. The requirements may be satisfied through contractor support, interagency support agreements, direct acquisition, or in-house support capability. The requirements include:

- Ships and trained crews for deploying, servicing, and retrieving the buoys
- A central system support station for repairing and refurbishing faulty equipment, storing spare parts, calibrating sensors and test equipment, and testing and integrating buoy systems
- Field staging bases where buoy systems can be received from the central system support station or directly from the vendors for final assembly, transfer to deployment vessels, and Hull/Mooring System maintenance
- Supply support operations to provide spares, repair parts, consumables, and total inventory management
- Administrative facilities and procedures
- Personnel and training programs necessary for effective and safe operations and maintenance

During the initial phases of development, data buoy support is generally obtained through contractors, interagency support agreements, direct acquisition and in-house capability.

ON THE PROBLEM OF IMPLANTING COMPLEX SYSTEMS AT SEA

by

R. M. Snyder

Davidson Laboratory
Stevens Institute of Technology
Castle Point, Hoboken, New Jersey 07030

FINAL REPORT SIT-DL-71-1577

ON THE PROBLEM OF IMPLANTING COMPLEX SYSTEMS AT SEA

Robert M. Snyder, P.E.

Technical Report 101-C-010.1

Prepared for:

Stevens Institute of Technology
DAVIDSON LABORATORY
Castle Point
Hoboken NJ 07030

22 DEC 71

CONTENTS

		page
	SUMMARY	1
1	STATEMENT OF THE PROBLEM	3
2	METHOD OF APPROACH	4
3	THE TWO-SHIP PROBLEM	6
	Figure 1	8
4	PROGRAM INPUTS	9
	4.1 FIXED INPUTS	9
	4.1.1 Ships (A) & (B)	10
	4.1.2 Lowering Cable, Instrument Cable, Tether Cable	10
	4.1.3 Lowering Wincy, Instrument Cable, Tether Cable	10
	4.1.4 Weight and Instruments and Appurtenances	10
	4.2 VARIABLE INPUTS	11
	4.3 PROGRAM RESULTS	12
	4.3.1 Design Calculations	12
	4.3.2 Implantment Monitoring	13
	4.3.3 Implantment Control	14
	4.3.4 Logistics	12
5	OPERATIONAL ANALYSIS	15
	5.1 TYPICAL SYSTEMS	17
	Figure 2	18
	Figure 3	20
	Figure 4	22
	Figure 5	23
	5.2 SUBSYSTEM DESCRIPTION	24
	Figure 6 & 7	25 & 28
	5.2.1 Winds	26
	5.2.2 Seas	26
	5.2.3 Ocean Currents	29
	5.2.4 Bottom Conditions	29
	5.2.5 Ship Motions	29
	5.2.6 Ship Propulsion	30
	5.2.7 Other Vessels	30
	5.2.8 Cable Segments	31
	5.3 DEVELOPING THE ANALOG	31
	Figure 8	33
	5.4 TYPICAL INPUT FUNCTIONS	35
6	PROGRAM DEVELOPMENT	35
	6.1 PHASE I - Subsystem Modeling	36
	6.2 PHASE II - System Integration	36
	6.3 PHASE III - System Conversion	36
	6.4 PHASE IV - At-Sea Demonstration	37
	REFERENCES	R-1

ON THE PROBLEM OF IMPLANTING COMPLEX SYSTEMS AT SEA

SUMMARY

In open-ocean multiple ship implantments of special complex systems, it is seldom possible, because of insufficient time and funding, to manufacture large scale models or prototypes and to conduct at-sea tests of the implantment procedure. Also because of scheduling problems and the lack of sufficient funds, it is often not possible to employ specialized ships and equipment to implant the system. Because of this, the systems are frequently damaged or lost during installation.

It would be very valuable to the government and to industry to be able to improve the reliability of complex at-sea implantments without going to the great expense of 100% testing of components, subsystems and launch procedures.

This report describes a methodology which can be developed - primarily from existing information and hardware - that would greatly enhance our confidence in mounting implantment expeditions.

The method employs electro-mechanical analogs of the system to be implanted. The analogs can be used to develop final

designs and launch procedures, to monitor the at-sea operations and to actually control critical aspects of the implantment procedure.

I. STATEMENT OF THE PROBLEM

A great deal has been learned about the ocean in the last two decades. Our knowledge has advanced from cursory, explorational bits of information to well documented and cataloged graphs, tables, formulas and mathematical models of practically all aspects of ocean science. Possibly the most difficult field to comprehend to a fine degree of predictability is underwater acoustics. This field is extremely important in furthering our capability in the field of pro - and anti-submarine warfare. Our theoretical and empirical knowledge has advanced to the point that, in order for us to make any real strides forward in either operational systems or research programs, we must be able to implant large complex systems in great depths of water and in some cases far from land.

To date, the approach has been to define the problems scientifically, design and plan an electro-mechanical system to do the job and then, using whatever was available in ships and equipment, to attempt to implant the system on a tight schedule and tight budget without the previous opportunity to practice any appreciable part of the operation. The success with these implantments has been understandably limited. Rather than pursue the expensive and time consuming statistical approach to success, as we did in the early days of rocketry, it is perhaps worthwhile to analyze the problem in detail in hopes of finding a degree of order which will allow us to develop methods to accurately evaluate the chances of success of any particular system and then to improve those chances by a judicious application of the methodology developed. The remainder of this report is devoted to outlining, in some detail, one approach to developing the necessary methodology.

2. METHOD OF APPROACH

Because the installation of these complex systems is not a routine affair, the operations are often interrupted by difficulties encountered when previously untried components, schemes, etc., do not behave as anticipated or when unforseen circumstances prevent the operation from proceeding as planned. It is therefore necessary to immediately know the consequences of such delays in terms of ship drift, line tension build-up and other parameters which will affect the implantment. Even if the operation goes essentially as planned, it is well to have a complete, accurate and up-to-the-minute accounting of all aspects of the operation so that the proper maneuvering orders can be issued and command decisions can be made at the appropriate times.

To accomplish this, we have to understand the mechanics and hydrodynamics involved in every detail of the operation so that we may predict the forces and movements that will occur under any given set of circumstances.

Once this is accomplished, then the preliminary launch operation can be planned and an electro-mechanical analog can be assembled first to predict, next to train launch personnel and later to monitor and control the forces and movements involved in each phase of the operation whether proceeding as planned or interrupted for modifications or repairs.

In the prediction phase of the program, various values can be assigned to both the design and environmental parameters and the launch sequence can be controlled by external means such as a potentiometer in the analog which controls the lowering speed of an anchor or other device. Line tension, ship positions, etc., can be plotted as outputs. This should prove to be an extremely useful research tool as well as a valuable design tool to obtain optimum component's specifications for complex systems. Potentially hazardous or destructive conditions can be analyzed and the effects of work stoppages can be determined by fixing certain values in the analog system and allowing others to seek equilibrium.

Once the final system design is arrived at and the launching sequences are detailed, then the analog can be set up to receive the fixed inputs extant at the time and place of the launching and the inputs for the variable parameters can be fed from line-counters, tensionmeters, navigational systems, etc. Analog outputs could include deviations from predicted values and the nature and extent of corrective actions.

This latter output can be used to control or direct the control of winches and propulsion devices.

In the light of past experiences with large complex system installation and in light of the high cost of ship time, the development of a methodology to de-bug system designs, to analyse launching procedures and to actually monitor and control the at-sea operations could easily prove cost-effective even for one operation. If the methodology is carefully developed so as to be applicable in the general case, the project could significantly reduce the costs of not only RDT and E programs but Navy Operations as well.

In the following section, a typical two-ship implantment operation is analyzed as a specific example of the type of methodology outlined above.

3. THE TWO-SHIP PROBLEM

Consider the problem of two ships working in consort to

(Fig. 1) lower a large weight to the ocean floor in 18,000 feet of water. As indicated in figure 1, ship Ⓐ is supporting the weight while lowering it from a winch containing a heavy lowering cable. Ship Ⓑ is paying out an instrument cable to which may be attached transducers. This cable also may be made neutrally buoyant by the addition of floats.

Referring to figure 1, the task for the initial phase of the operation may be described as follows:
Weight ③ must be lowered to point 0,0,0 on cable ② from ship Ⓐ while instrument cable ⑤ is payed out from ship Ⓑ. This must obviously be accomplished without unduly straining the lowering cable ②, the instrument cable ⑤ or any of the fittings or lowering devices. Also, care must be taken to assure that the instrument cable ⑤ is not fouled with the weight ③ or the lowering cable ②.

The bitter end of the instrument cable ⑤ must end up in a specific geographical position x_4, y_4, z_s. Two different methods may be used to accomplish this latter task: in the first case, the assist vessel Ⓑ may be tethered to the command ship Ⓐ by tether cable ⑦ around winch ⑥. In this case, the assist vessel will assume a position determined by wind acting on itself and currents acting on the instrument cable ⑤. The assist vessel Ⓑ may put on turns to

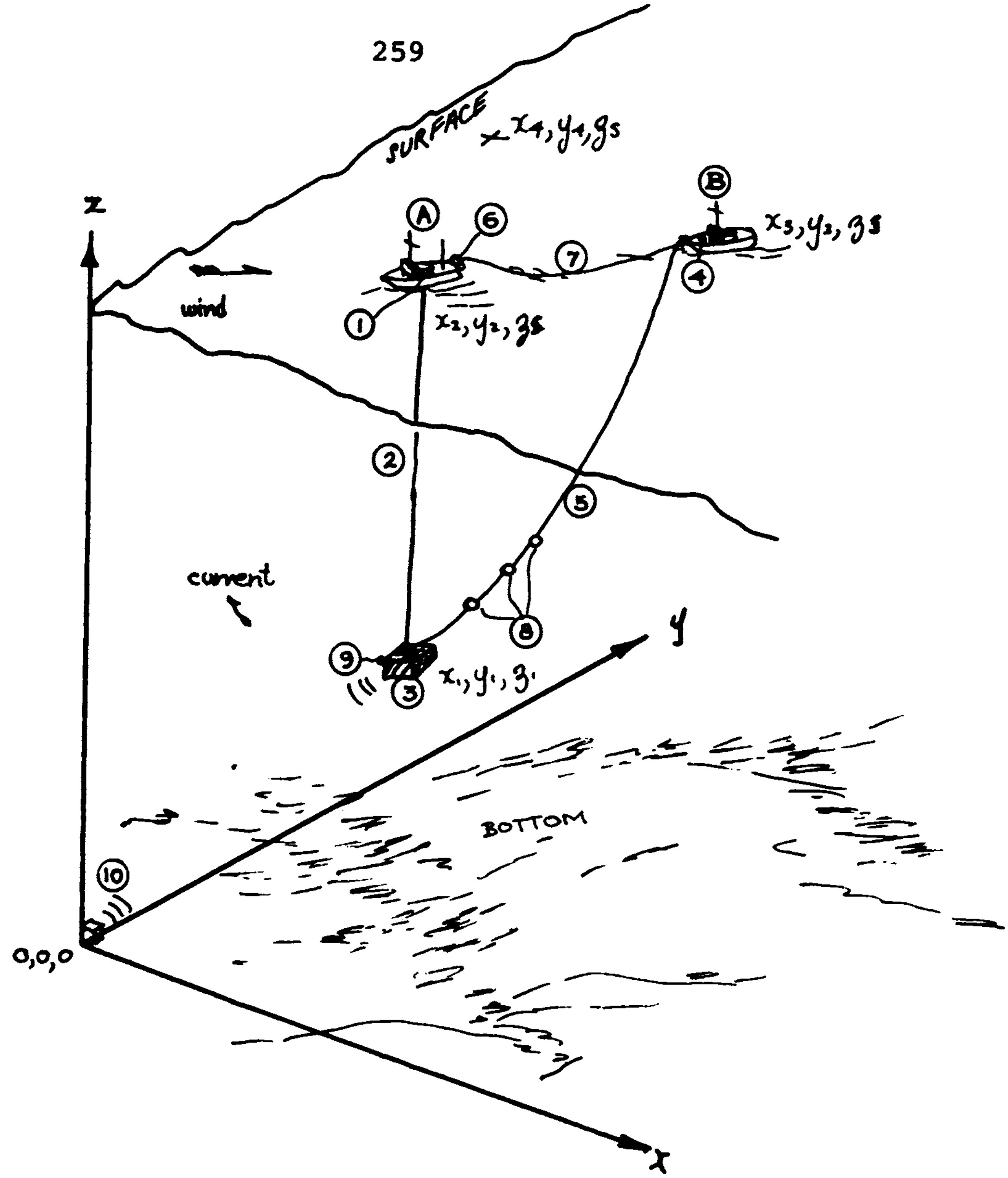


FIGURE 1 - NOMENCLATURE

A	LAUNCH/COMMAND SHIP	5	DATA CABLE WITH TRANSDUCERS
B	ELECTRONICS/ASSIST VESSEL	6	TETHER CABLE WINCH
1	LOWERING WINCH	7	TETHER CABLE
2	LOWERING CABLE	8	TRANSDUCERS
3	WEIGHT	9	ACOUSTIC TRANSMITTER
4	DATA CABLE WINCH	10	TRANSPONDER

relieve any high strain on the tether cable ⑦ but her object is to reduce stresses in the instrument cable. After the weight ③ has reached bottom, then the assist vessel Ⓑ may cast off from the command ship Ⓐ and proceed to the designated geographic point x_4, y_4, z_s. It will probably be necessary to provide a towing span or warp to the instrument cable to bring the tow point forward of the rudder post. In the second case, both the command ship Ⓐ and the assist vessel Ⓑ will maintain position independently so that when the weight ③ reaches bottom the bitter end of the instrument cable is on-station. This puts an entirely different set of strains on the system components and launch equipment.

Either or both of these cases can be programmed and studied during the design phase of the project. The first case will be utilized to develop a definition of the methodology.

4 PROGRAM INPUTS

The inputs required for the program are of two types:

- Parameters fixed by System design
- Environmental and operational variables

4.1 FIXED INPUTS - The fixed inputs include all of the physical, mechanical and hydrodynamic values of the designed system. These, of course, may change during the design phase if the program shows that the design is marginal. The following list indicates typical fixed inputs. It should be noted that some of these inputs are functions the value of which depends upon environmental factors such as winds and currents or physical factors such as orientation, length or load. These factors are followed in the listing by (f).

4.1.1 Ships Ⓐ & Ⓑ -

- response operators vs. sea state and heading for roll, pitch, heave, yaw, surge and sway. (f)
- drag coefficients vs. orientation for winds and currents. (f)
- power and maneuvering characteristics. (f)
- peculiar capabilities.

4.1.2 Lowering Cable ②, Instrument Cable ⑤ and Tether Cable ⑦ -

- weight per unit length
- diameter
- drag coefficient (f)
- added mass (f)
- elasticity
- Strouhel number (f)
- yield strength
- breaking strength
- torque characteristics
- natural frequency of torsional oscillation (f)
- natural frequency of lateral vibration (f)
- natural frequency of longitudinal vibration (f)
- spring constant

4.1.3 Lowering Winch ①, Instrument Cable Winch ④ and Tether Cable Winch ⑥

- stowage capacity vs. line size
- hauling speed vs. load
- maximum load capability
- acceleration characteristics
- braking and hold capabilities

4.1.4 Weight ③ and Instruments and Appurtenances ⑧ and ⑨

- weight (mass)
- dimensions (areas and volume)
- drag coefficients for each of six linear directions (f) plus six rotational directions (f)
- added mass for each of six linear directions (f) plus six rotational directions (f)

The above lists, which are not exhaustive, do, nevertheless, indicate the scope of the program. All of the inputs followed by (f) are functions involving outside influences and these can be entered with function generators. Many of these functions are non-linear and others are not well known or are poorly understood. This will also be true of certain of the variable inputs, particularly the environmental factors. It is important to realize that, regardless of the precision of the calculations, there are wide limits of error in some of the variables and functional inputs, and precision analyzes should be made to determine the overall limits of error in the output functions. One should be wary of the temptation to use digital computations to improve the precision of the results since the accuracy inherent in the program may not justify it. What we are trying to do is not to calculate the results of an experiment but to construct an actual analog of our system during implantment so that we can determine:

- if it is feasible
- if it is optimally designed
- what the lowest capability vessels are that can be used with still a resonable safety margin
- where the inherent problems are, and finally
- how the actual launch is proceeding.

The variable functions are dealt with below.

4.2 VARIABLE INPUTS - The variable inputs are of two kinds. The first kind involves the environmental factors. Some of these will require monitoring at the scene.

The environmental inputs include:

- water depth
- bottom topography and composition
- sound velocity profile
- current velocity profile
- wind speed and direction
- sea state.

Variables to be monitored are:

- tension at the lowering winch ①, instrument cable winch ④ and tetering winch ⑥.
- line speed and direction at ①, ④ & ⑥
- line payed out at ①, ④, & ⑥
- accelerations at ①, ④, & ⑥
- wire angles at ①, ④, & ⑥
- ship's position relative to the bottom
- ship's position relative to each other.

4.3 PROGRAM RESULTS - As noted earlier, the program results are used in three separate ways:

- for design calculations
- for monitoring the operations
- for actual implantment control.

4.3.1 Design Calculations - Once the basic design is arrived at, certain subsystems can be programmed to determine if the components are properly chosen and properly sized for the loads expected. Factors to be looked at include:

- lateral vibrations and the attendant increase in hydrodynamic drag for cable ② & ⑤.
- longitudinal vibrations in ② & ⑤ under various loads. NOTE!! THE RESONANT LENGTHS of these cables must be determined for all conditions that can possibly occur during launch operations. Then the resonant length must be passed through quickly and damping should be provided.
- optimum ship's position vs. depth of weight ③
- optimum lowering speed for ③
- maximum stresses on cables and winches
- pendulum movements of weight ③
- horsepower and maneuvering requirements of ships
- accuracy requirements of navigation systems.

After the final overall design is reached, the analog system can be set up to conduct a simulated implantment. Certain criteria can be used as program inputs to determine the preferred values of other parameters. For example, we can use the following criteria for launch inputs:

- set lowering speed of cable ②
- constant angle of instrument cable ⑤ with vertical at connection point to weight ③
- fixed current profile
- fixed winds
- fixed water depth
- fixed sea state.

In this case the outputs would be:

- position of both ships vs. time
- cable tension at any point vs. time
- cable and weight accelerations vs. time

In addition to the above, the program can be stopped at any time to determine the effects of implantment interruptions. Numerous variations can be made in the program until the best launching methodology is arrived at.

4.3.2 Implantment Monitoring - When the system is ready to go to sea, the appropriate portions of the analog system can be placed aboard the command ship and connected to the various devices which measure the implantment forces, motions, and positions. Since the optimum launch methodology has been determined in the laboratory, we know what our ship positions, tensions, etc., should be vs. time or vs. depth of the weight ③. We can compare the actual case with the optimum design case and record deviations at the control station on the command ship.

Analog simulation also easily lends itself to differentiation and integration of signals so that velocities and accelerations can also be recorded to indicate trends before they are otherwise noticeable.

This methodology provides a great deal of knowledge of and control over, an implantment situation. The program outputs, in some cases, can be used directly to control launch equipment during the operation.

4.3.3 Implantment Control - In very critical operations where close coordination is required between a number of simultaneous operations it may be appropriate to control the operations automatically from the output signals generated by the analog.

Ships have been dynamically positioned in this fashion and it is conceivable that the entire operation could be set up with a single central control console with automatic control. Obviously, manual over-rides would have to be provided but even then the analog could monitor itself and signal danger or actually effect shutdown.

4.3.4 Logistics - Such a program as outlined above could also help to:

- determine the degree of criticality of all the implantment parameters
- point out manpower requirements

- generate new product specifications
- determine necessary ship and equipment modifications
- determine environmental limits for implantment
- determine allowable errors in implantment procedures.

5. OPERATIONS ANALYSIS

When considering the requirements of systems for research or for ASW purposes, it is not enough to investigate just the stresses and strains on the system in-situ - the entire operation from drawing board to eventual retrieval or serviceing or repair must be analyzed. Such tasks as manufacture, delivery to dockside, staging and loading aboard ship can present serious problems in the overall operation and, if not handled correctly, can cause damage to system components which could result in failure during implantment.

Once the implanting expedition has left the dock, the problem becomes one of subsystem identification and description. We tend to think of the system and subsystems as they are supposed to appear after implantment. They often never reach this point, however, because of the fact that we often fail to consider the behavior of the system components when undergoing implantment, a time at which they form systems and subsystems of a completely different description than those envisaged by the engineer or scientist during system conception.

After a thorough operationsanalysis is made of a particular system in all aspects of staging, implantment, operation, modification, repair and retrieval, a series of diagrams should be developed which depict the operation in each phase in which the components, including ships and equipment, comprise a distinct system not mutable to another such system.

Each of these "transient systems" must be analysed on its own to determine the scope and seriousness of any operational problems that may arise during the period of its existance. Each transient system can be broken down into a number of sub-systems which fit our generalized subsystem description (Fig. 6).

(Fig. 6)
See p..25

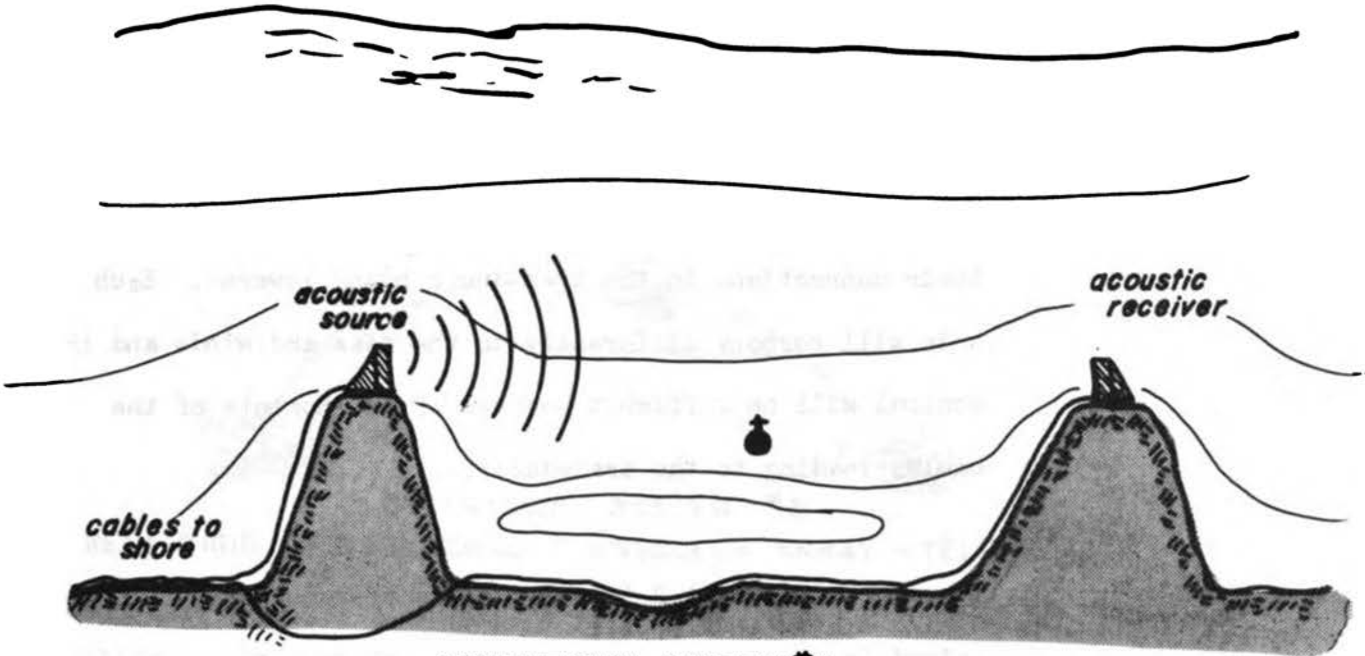
Each subsystem must then be described in terms of environmental inputs, operational parameters, transfer functions and equations of motion so that the appropriate analog can be assembled. A series of de-bugging runs would then be made for all subsystems and all transient systems until the components are compatable from one transient system to another and finally to the operational subsystem. At this point the design details can be engineered while the analysis group begins to generate implantment booklets and appropriate training and monitoring analogs.

Obviously the more this methodology is used, the more valuable and less costly and time consuming it will become since inputs, transfer functions and subsystem operators will tend to become standardized, more simplified and more reliable as experience is gained, both with the analog and with the at-sea operations.

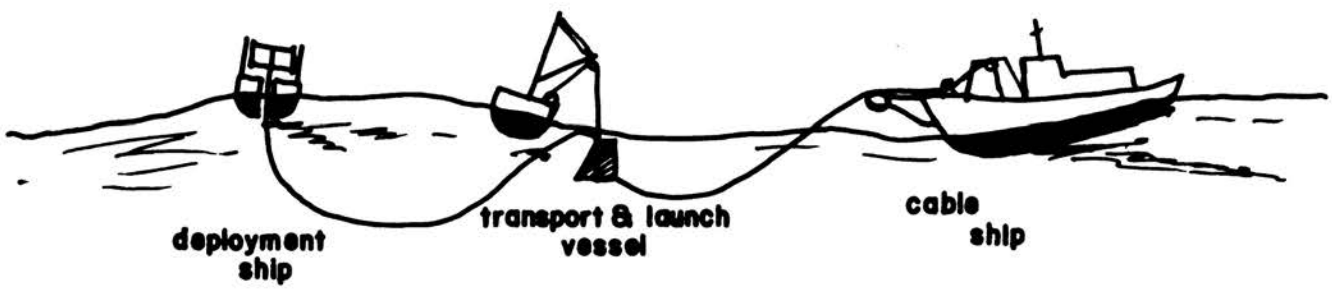
5.1 TYPICAL SYSTEMS - As noted above, the systems to be considered must include not only the sucessfully implanted operational system but also all of the transient systems which evolve during the transport and implantment procedure. Figures 2 thru 5 show a number of operational system concepts and a few transient systems associated with each.

(Figs. 2 - 5)

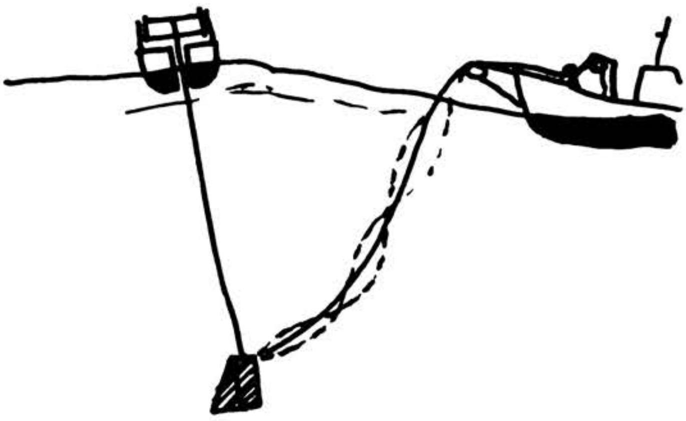
Operational system #1 is a large, active acoustic range installed below diver depth with cables run ashore. The dynamics of the system is nil once installed and operating. Implanting it, however, is a very different matter. When the tranducer is first placed over the side, it must be attached to three separate vessels necessitated by the fact that no one or even two vessels possessed the capability for 1) lifting the massive transducers over the side, 2) accurately lowering the transducers to a final spot on a sea mount, and 3) laying a heavy power/communication cable from the transducers to shore. This need for three ships leads to Transient System #1-A.



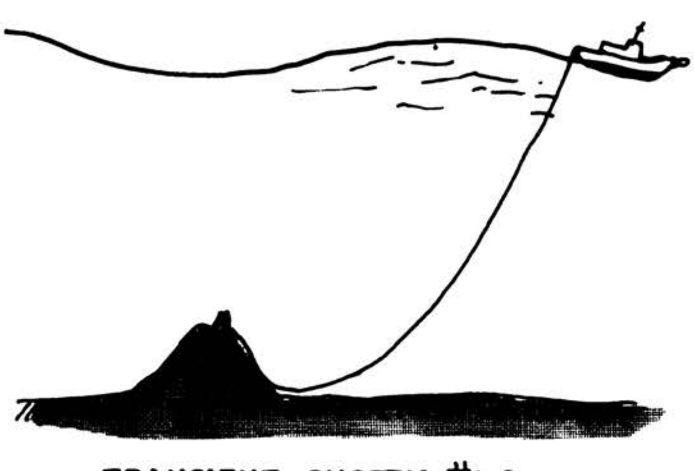
OPERATIONAL SYSTEM #1
ACTIVE ACOUSTIC RANGE BELOW DIVER DEPTH WITH
CABLES ASHORE - TRANSDUCERS MASSIVE, CABLES LARGE



TRANSIENT SYSTEM #1·A



TRANSIENT SYSTEM #1·B



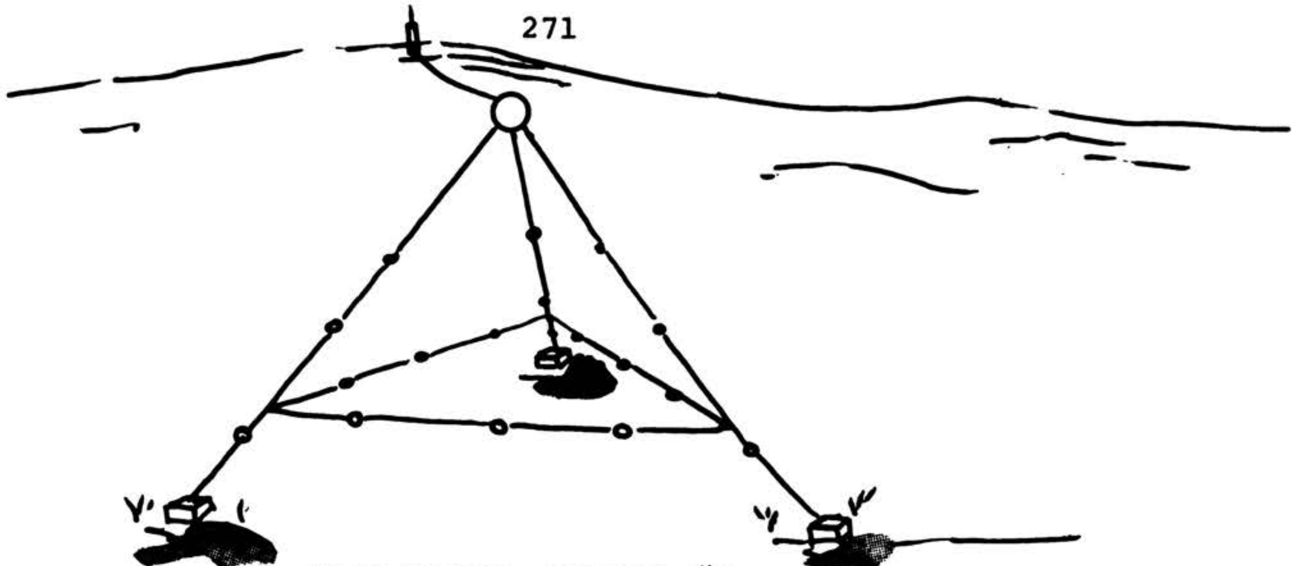
TRANSIENT SYSTEM #1·C

FIGURE 2

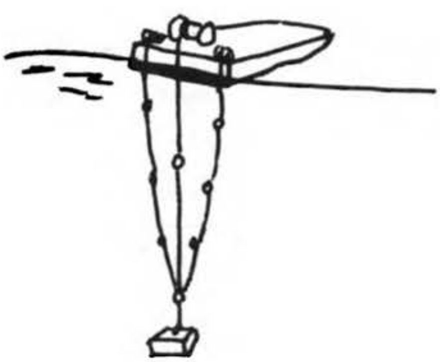
In this case, there are three subsystems interacting through their connections to the transducer being lowered. Each ship will respond differently to the seas and winds and their control will be difficult because of the moments of the cables leading to the transducer.

Transient System #1-B is somewhat simpler but must be sustained for a longer period of time with precision position control. Transient system #1-C can be considered a standard system as it is typical of open ocean cable laying operations. It would be doubly valuable to study this system on the analog.

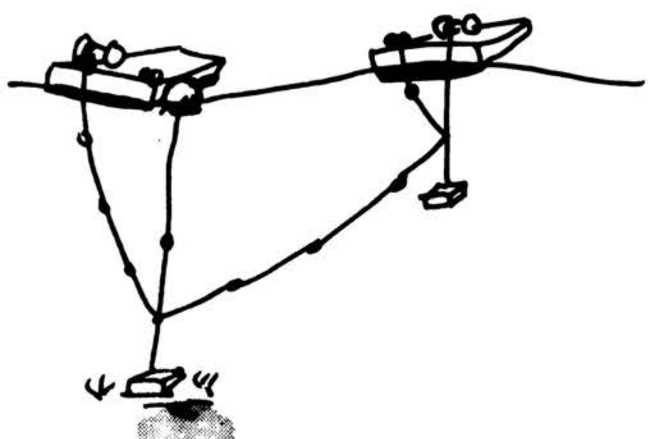
Operational system #2 is a semi-rigid, 3-dimensional tranducer array. The in-situ dynamics of this system are quite complex and very critical to the successful operation of the system. These dynamics have been studied extensively with the aid of digital computers and the existing programming and mathematics should prove useful. The system implantment brings about a number of very complex transient systems. In Transient System #2A, the stretch and torque characteristics of all three cables are very important as the cables are very susceptible to alternating tension induced twisting. Also important are the resonant length of the main lowering cable and the station keeping ability of the launch craft. If this



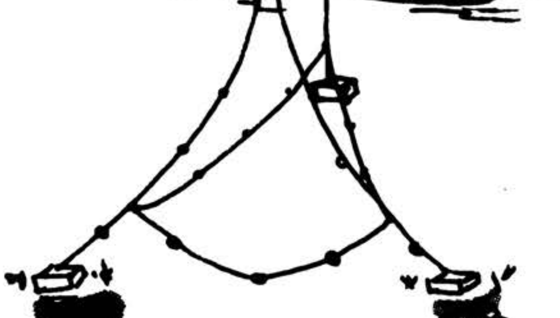
OPERATIONAL SYSTEM #2
SEMI-RIGID 3-DIMENSIONAL TRANSDUCER ARRAY - TELEMETERING



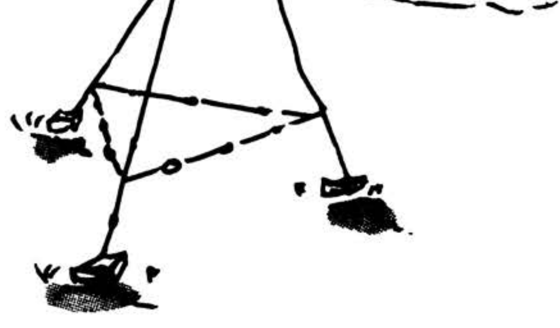
TRANSIENT SYSTEM #2A



TRANSIENT SYSTEM #2B



TRANSIENT SYSTEM #2C



TRANSIENT SYSTEM #2D

FIGURE 3

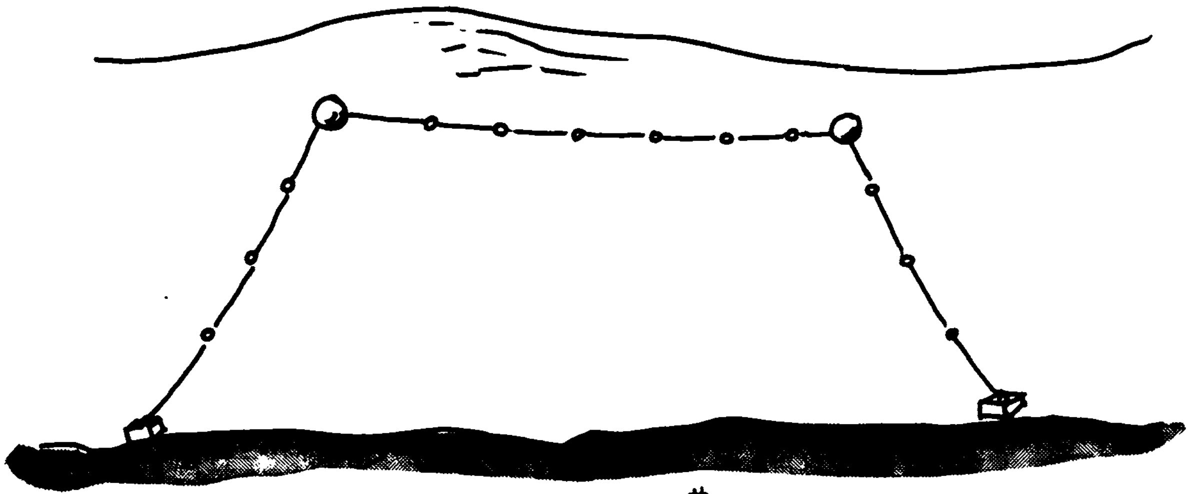
system drifts very far off station during this stage, it will be very difficult to bring back.

In Transient System #2B, the station keeping ability of the first vessel must be very good or the first subsystem must be able to act as a mooring for the first launch vessel. Also, the 2nd launch vessel must either have good maneuverability or it will be essentially moored to the first anchor by a horizontal hydrophone string. Again, torque and stretch characteristics of the cables are important.

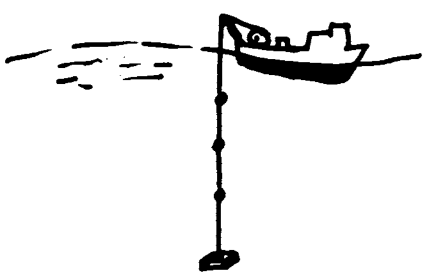
Transient System #2C is analytically very complex and position keeping ability here is extremely critical. The final transient system (#2D) is complex in that the subsurface buoy must be hauled beneath the surface to its design depth.

No doubt other methods of implantment could be devised. A real value of the proposed analog would be to evaluate alternate schemes to determine the problems and vessel requirements of each.

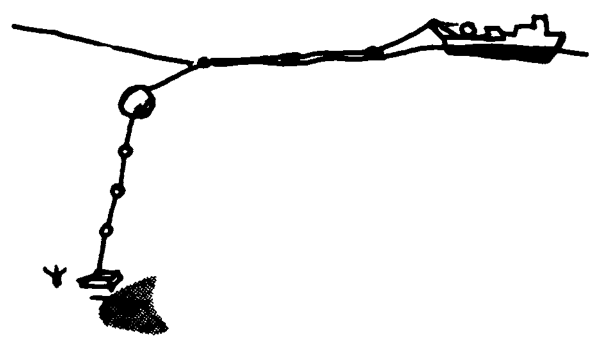
Operational System #3 is a semi-rigid 2-dimensional transducer array - much simpler than Operational System #2 but still susceptible to the same problems during implantment.



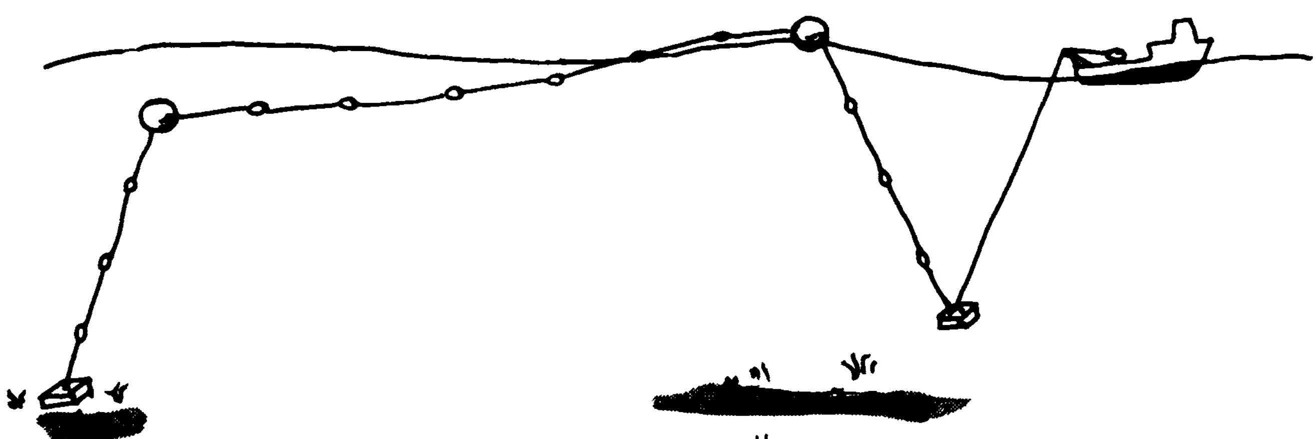
OPERATIONAL SYSTEM #3
SEMI-RIGID 2-DIMENSIONAL TRANSDUCER ARRAY



TRANSIENT SYSTEM #3A

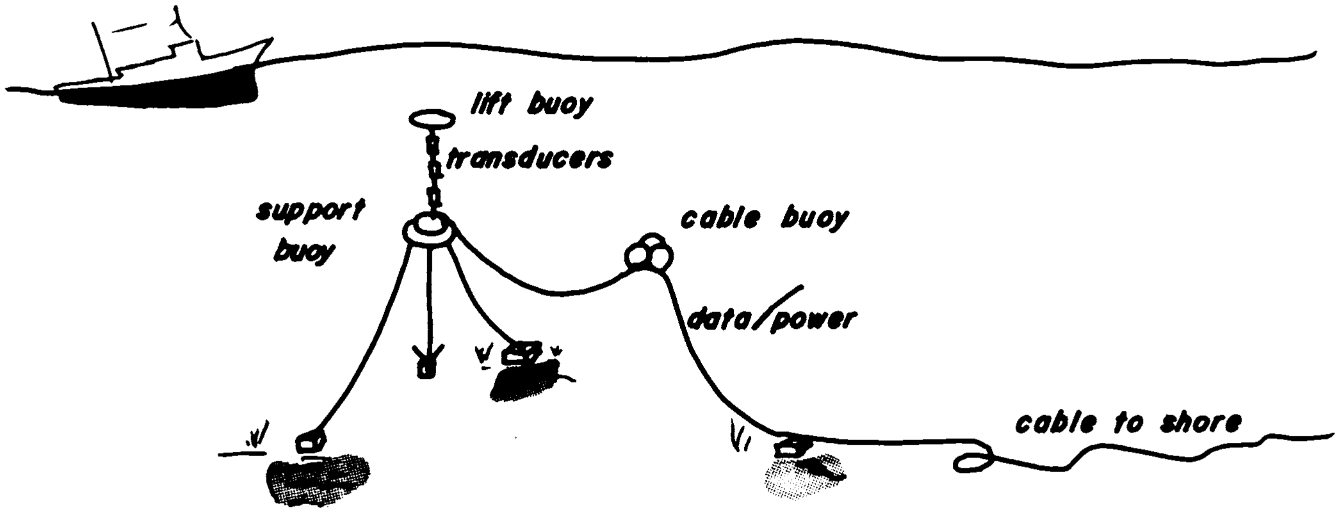


TRANSIENT SYSTEM #3B



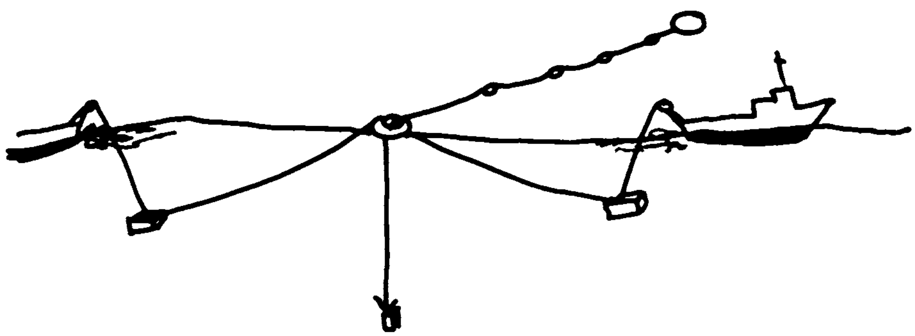
TRANSIENT SYSTEM #3C

FIGURE 4

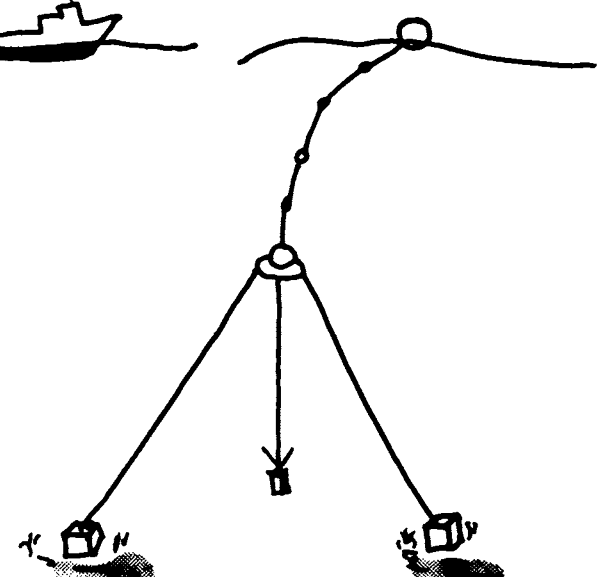


OPERATIONAL SYSTEM #4

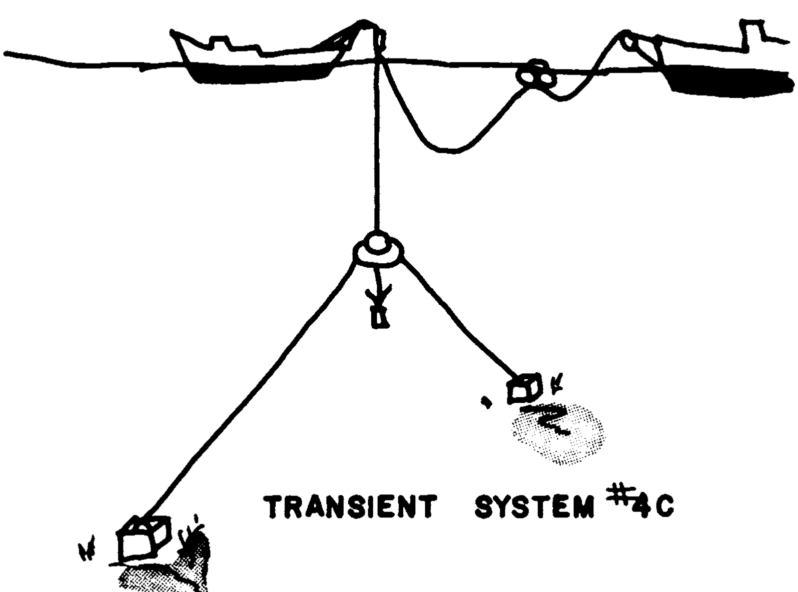
ACOUSTIC CALIBRATION SYSTEM



TRANSIENT SYSTEM #4A



TRANSIENT SYSTEM #4B



TRANSIENT SYSTEM #4C

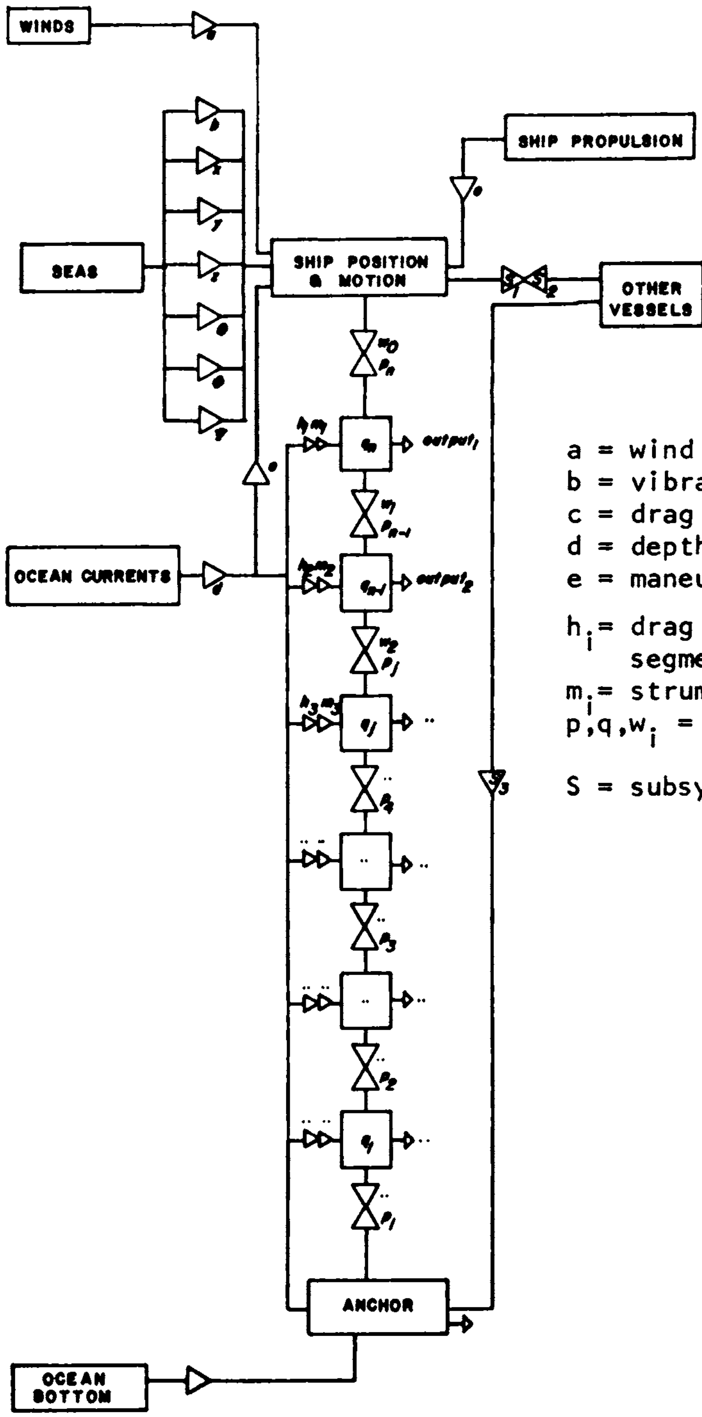
FIGURE 5

Operational system #4 is unique in that the vertical transducer string must be retrievable for maintenance and repairs without disturbing the main support system. These systems are very massive and positioning is critical. It can be seen from these four examples that, while there is a great diversity in the appearance of the Operational Systems, the transient systems fall into a limited number of different configurations. This is even more true of the subsystems that appear during launch operations.

5.2 SUBSYSTEM DESCRIPTION - If the analog, or for that matter any computer program, is to be valuable as a basic design, planning and training tool, then it should be made up of somewhat standard basic building blocks so that the experience gained in designing and analysing one system will be at least partially applicable to future problems. In this way, the more the system is used, the more valuable and more efficacious it will become.

A subsystem may be defined as a group of elements tied together by cables having unlimited environmental inputs but only discreet point-applied inputs from other subsystems.

(Fig. 6) Figure 6 is a block diagram of the generalized subsystem. The cable system is represented by the elements q_j . . .



a = wind drag characteristic
b = vibrations
c = drag characteristics - ship
d = depth profile currents
e = maneuvering characteristics

h_i = drag characteristic - cable segment i
m_i = strumming characteristic do
p,q,w_i = cable subsystem characteristics
S = subsystem operator

GENERALIZED SUBSYSTEM

Figure 6

It is operated on by the ship (or buoy) at the surface and by the anchor at the bottom. Other "point" inputs may exist at the surface, at the bottom or at any points in-between. The individual inputs are described below.

5.2.1 Winds - Wind forces on ships and surface buoys can be calculated in each instance according to well established relationships between wind force and ship profiles. The application of an average steady force is probably realistic because of the momentum of the ship and because operations would not normally be planned for severe conditions. One of the real advantages of this analog approach, however, is that the engineer(s) can experiment very easily to see just what the effects of gustiness are on ship motions and decide whether or not to include it after seeing the results.

5.2.2 Seas - During the initial phases of a study of implantment systems, the effects of ocean waves on the ships, cables and various other subsystem components involved can be simulated by means of techniques described in pertinent literature. The complexities required for simulating short-crested seas although most realistic are considered too great compared with the benefits at this time. Consequently, the suggested wave field generator yields a simulated long-crested or uni-directional sea composed of either a fully developed irregular sea with a Pierson-Moskowitz spectrum or a regular swell or both.

(Fig. 7) The required components for simulating a uni-directional irregular sea are shown in the block diagram in Figure 7, and the physical outputs are illustrated in the sketch. Following the methods derived by Dalzell (1971), the wave height $\eta(x_1,t)$ at a suitably chosen reference point can be generated. Then using the transfer functions derived by Henry (1969), the various required wave field characteristics can be simulated with proper consideration of the actual correlation between various characteristics. The various components can be developed for either digital or analog simulation.

5.2.3 Ocean Currents - Ocean current forces on ships, like wind forces, are fairly well understood and may be calculated "on-line" and fed to the analog. The vertical variation of steady state currents (including tidal currents for our purpose) is negligible as far as ship hull drafts are concerned so that the current force variations will depend only upon ship orientation.

Current forces on the mooring cables are much more complex but sufficient work is described in the literature to generate meaningful force distributions over suspended cables.

WAVE FIELD GENERATOR

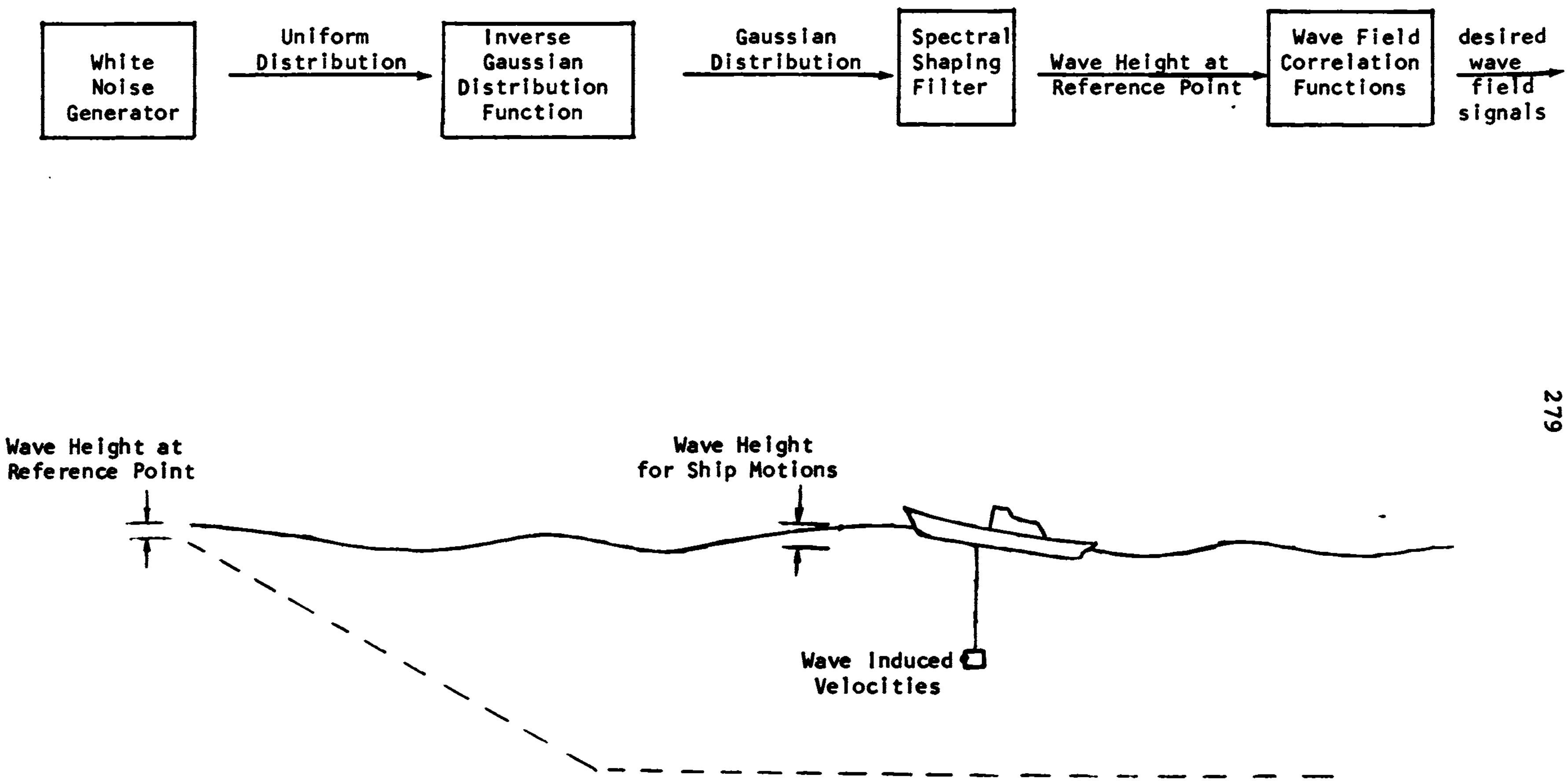


FIGURE 7

5.2.4 Bottom conditions - When any system of major proportions is to be designed for a particular area of the world ocean then, where not already available, samplings should be taken of bottom sediments to determine their engineering properties. Also the bathymetry is important in that rough areas or chasms could cause discontinuities in system behavior. On the analog these discontinuities can be simulated by throwing a switch to determine what the influences are.

5.2.5 Ship otions - Once all the above environmental parameter descriptions have been developed, their outputs can be applied to develop the ship position and motion input to the top of the cable.

Ship motions in irregular or regular waves can be simulated by utilizing the impulse response operator technique as illustrated by Breslin, Savitsky, and Tsakonas (1964). The required response operators can be calculated by means of available computer programs which have been derived and illustrated by Kim (1970, 1971A, 1971B, 1971C). These computed motions have shown good agreement with model test results for conventional ship-type hulls as well as for barges, in six degrees of freedom. All motions can be represented adequately by linear equations except for roll motions of conventional displacement ships. In this case, a non-linear element can be included easily.

Other factors affecting ship motions are 1) reactions from the cable/anchor system as further influenced by bottom contact of the anchor, 2) the reactions to other ships which may be directly tethered to the ship in question or may be reacting through connection to the cable or anchor, and 3) the ships propulsion system. The latter factor is the only one under the direct control of the subsystem commander.

5.2.6 Ship Propulsion - This is an input which can and should remain under the control of the analog operator(s). It will have limits imposed by the ship's specifications. Its affects will either be seen to be adequate or not in preventing over stressing or catastrophic failure of the subsystem under question.

5.2.7 Other Vessels - Other vessels may act directly or through other complex subsystems. Their inputs can be modified by their subsystem commander within prescribed limits. Each subsystem will have an output to a central control station so that the subsystem operations can be coordinated. Breakdowns can be simulated by switching off the propulsion input to any particular subsystem.

The possibilities for experimenting to learn the affects of any parameter become apparent when one considers the fact that each input can either be manually controlled or its limits can be manually changed. It is also significant that non-linearities can be exactly included in the analog simulation.

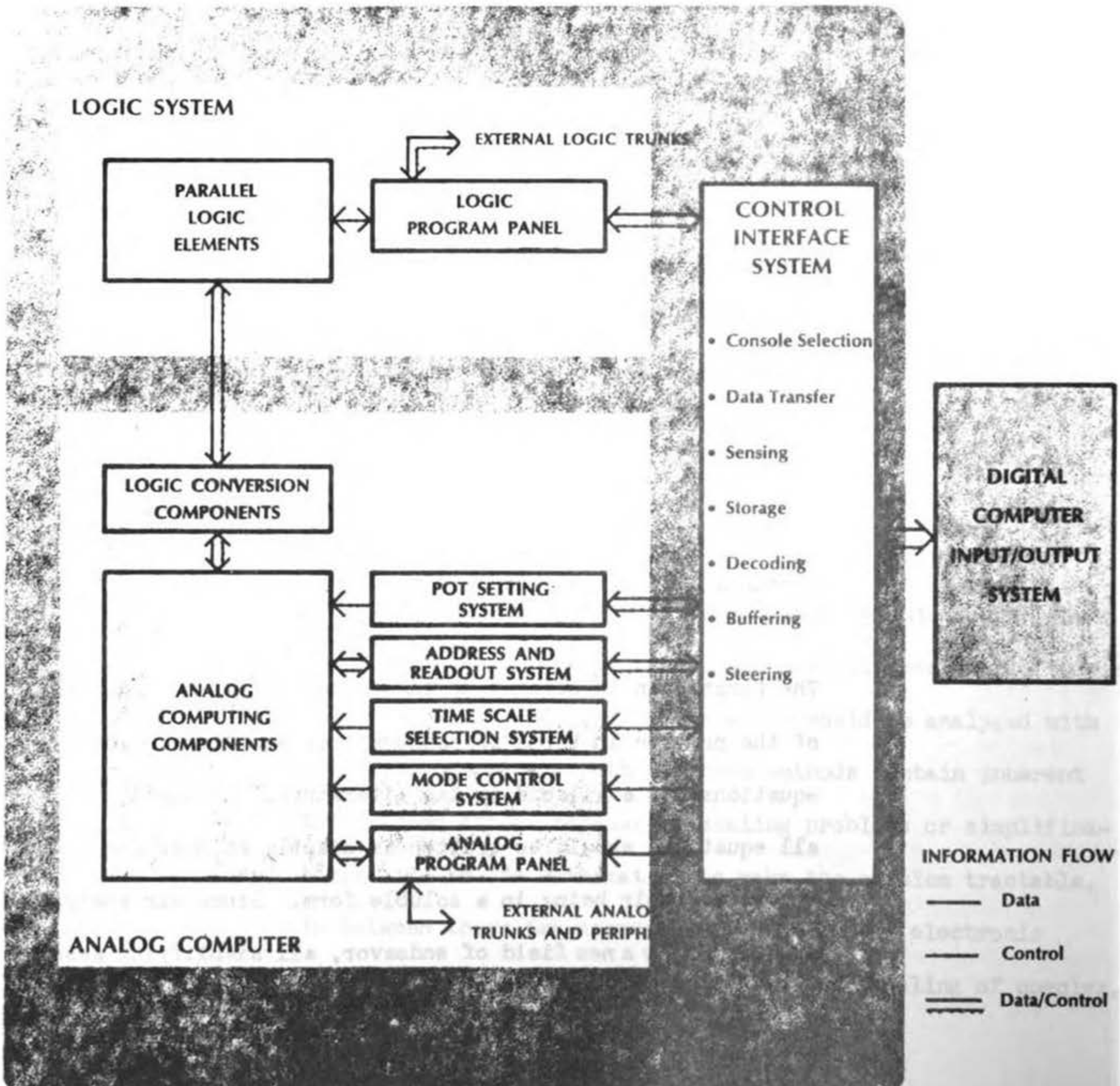
5.2.8 Cable Segments - The cable, as a whole, is operated on by external and internal forces. The external forces are ship motion, anchor motion and currents. Internal forces are internal friction, stretch, torsion, harmonic oscillation (lateral, longitudinal and torsional), mass etc. Since the cable or its connections are usually the weakpoints in the system, it is the element to be most intensely studied. All other parameters can be varied either to see what developments will break the cable or what can be done to prevent its being over stressed. The principal program output will be cable tension along with ship, anchor and cable segment position, velocity and acceleration.

5.3 DEVELOPING THE ANALOG - There are different ways in which our systems can be simulated. These range from strictly mechanical models to strictly mathematical models which could be analyzed with a digital computer. Both of these methods contain inherent distortions either because of scaling problems or simplifications made in the mathematics to make the problem tractable. In between these two approaches is the modern electronic analog. It is particularly suited to the modeling of complex, non-linear systems with complex feedback networks. It also allows the operator to observe operations as they take place and to insert upsetting inputs at will, eg. a cable can be broken, a winch can be made to break down or slip, a ship can be made to loose propulsion, an anchor can be dropped, etc., all by the flip of a switch. These capabilities have to be programmed for, of course, but the options are great.

There are certain functions in our overall program which are more efficiently done by a digital computer and programs are already available. There are other functions, such as the independent variation of forces from outside sources such as other subsystems or direct outputs from models in wave tanks, that might be better handled by manual or mechanical input.

(Fig. 8) Figure 8 is a block diagram of a modern Hybrid computer which combines all of these capabilities into one desk-top machine.

The first step in setting up the analog is to state all aspects of the problem in terms of mathematical equations. The equations are available in the literature. To begin with all equations should be written as exactly as possible without regard to their being in a soluble form. Since our analysis is essentially a new field of endeavor, all simplifying assumptions must be thoroughly reviewed in light of their possible



EAI 580 ANALOG/HYBRID COMPUTING SYSTEM

affect on the operation of the analog. The first objective is to be able to test implantment schemes to determine whether or not the system can be implanted with certain vessels under certain environmental conditions. In our analog we must be able to change our system parameters, the environmental inputs and the ship's capabilities to fulfill our second objective which is to see if the proposed conceptual system could be implanted at all and still be realistic. Ultimately it would be valuable to be able to optimise a system design in terms of cost/performance/delivery tradeoffs.

These objectives must be explicitly stated in terms of the computer functions to be performed. A complete block diagram showing exactly what operations must be performed in what order must be produced very early in the program. Along with this the appropriate boundary values, initial conditions, orders of accuracy required, desired readout arrangements, etc., will be listed.

It is imperative (since once the program has progressed to the operating stage the mathematics will be "locked in") that all assumptions, simplifications, linearizations, etc., be noted, analysed and cataloged so that reviews can be made when new systems are to be analyzed to determine whether or not a re-evaluation of the mathematics is in order.

A meaningful method of evaluation will be noting the location or occurances where limits are exceeded. The limits placed on the system will be component location, velocity and acceleration; line tensions and vibrations; and relative component positions.

All the above preparation will be necessary in order to assure that the computer program development is efficient and that the programs themselves will have maximum utility and flexibility. The actual programming will be conducted by standard methods.

5.4 TYPICAL INPUT FUNCTIONS - Input functions to the analog will be in the form of mathematical formulas, response curves, model movement and manual manipulations. Many of these functions are well known and can be found in the literature. Others can be developed from available reports. There are none that, at this writing, are beyond the state-of-the-art. Use of the analog, however, will undoubtedly point up areas where original research would be cost effective.

6. PROGRAM DEVELOPMENT

A program of this nature, while it does not involve original research in the basic sciences does, however, involve sufficiently complex maniuplations as to have the explorative nature of a research program. It is therefore unrealistic to attempt to define the entire scope and costs in detail at the outset. The program is therefore divided into four phases, each dealing with a specific set of related tasks which depend, for final definition, upon successful completion of the preceding phase. The four phases are:

PhaseI - Subsystem modeling
PhaseII - System integration
PhaseIII - System conversion (laboratory to shipboard)
PhaseIV - At-sea demonstations

6.1 PHASE I - SUBSYSTEM MODELING - This first phase of the program will concentrate on developing the Generalized Subsystem of figure 6. This will include collecting all the mathematics and programming both the digital and analog portions of the computer. Certain particular known subsystems will be analyzed in this phase to determine what problems will be encountered in integrating subsystems in Phase II.

(Fig. 6)

6.2 PHASE II - SYSTEM INTEGRATION - During this phase the Generalized Subsystem programs will be applied to all the transient systems and these will be integrated to determine where further simplifications can be made to keep the overall program tractable while still retaining the flexibility inherent in analog systems.

6.3 PHASE III - SYSTEM CONVERSION - This phase will deal with converting the laboratory computer system to one that can be used aboard ship. It will include specifying what equipment will be used to monitor tensions, line payout, etc., to feed back to the on board control program.

6.4 PHASE IV - AT-SEA DEMONSTRATION - Once Phase III is complete, a hardware system will be put together to demonstrate the usefulness of the system in a simplified implantment program. Results of Phase IV will be recorded to provide feedback to improve the basic computer programming.

REPORT
REFERENCES

Breslin, J., Savitsky, D. and Tsakonas, S., [1964] "Deterministic Evaluation of Motions of Marine Craft in Irregular Seas," Fifth Symposium on Naval Hudrodynamics, Bergen, Norway.

Dalzell, J., [1971] "A Study of the Distribution of Maxima of Non-Linear Ship Rolling in a Seaway", Davidson Laboratory Report SIT-DL-71-1562.

Henry, C., [1069] "Deterministic Response to Free Surface Waves," Journal of Hydronautics, " Vol. 3, No. 2.

Kim, C. and Chou, F., [1970] "Prediction of Drifting Force and Moment on an Ocean Platform Floating in Oblique Waves," Stevens Institute of Technology, Report SIT-OE-70-2.

Kim, C. and Chou, F., [1971A] "Motions of Jackup Drill Rigs in Head Seas," Stevens Institute of Technology, Report SIT-OE-71-3.

Kim, C. and Chou, F., [1971B] "Wave-Exciting Forces and Moments on an Ocean Platform," Stevens Institute of Technology, Report SIT-OE-71-6.

Kim, C., Henry, C. and Chou, F., [1971C] "Hydrodynamic Characteristics of Prismatic Barges," Stevens Institute of Technology Report SIT-OE-71-7.

GENERAL REFERENCES

1. Abkowitz, Martin A., THE MOTION OF A BODY IN A FLUID IN THE RANGE OF NON-LINEAR FORCES, PhD Thesis, Harvard University, June 1953.

2. Barakat, Richard, A SUMMARY OF THE THEORETICAL ANALYSIS OF A VERTICAL CYLINDER IN A REGULAR AND AN IRREGULAR SEAWAY, WHOI, Ref. No.57-41, July 1957.

3. Barr, Roderick A., MOTIONS OF TILT FLOAT VEHICLES IN WAVES, Hydronautics, Inc. Technical report 237-1, October 1963.

4. Beebe, K. E., MOORING CABLE FORCES CAUSED BY WAVE ACTION ON FLOATING STRUCTURES, Wave Research Lab., IER, University of California, Series 3, issue 366, June 1954.

5. Bert, Charles W., Stein, Robert A., STRESS ANALYSIS OF WIRE ROPE IN TENSION AND TORSION, Battelle Memorial Institute, reprinted by WIRE AND WIRE PRODUCTS, May and June 1962 issues.

6. Cuthill, Elizabeth H., FORTRAN PROGRAM FOR THE CALCULATION OF THE QUILIBRIUM CONFIGURATION OF A FLEXIBLE CABLE IN A UNIFORM STREAM, David Taylor Model Basin Report 1806, AD 438 421, March 1964.

7. Dale, J. R., WATER DRAG EFFECTS OF FLOW INDUCED CABLE VIBRATIONS, Report Nom NADC-AE-6731, Aero-Electronic Technology Department, Department of the Navy, September 1967.

8. Dennis, S.C.R., Shimshoni, M., THE STEADY FLOW OF A VISCOUS FLUID PAST A CIRCULAR CYLINDER, ARC 26 104, DDC, AD 450 760, August 1964.

9. Devereux, R., et. al., DEVELOPMENT OF AN OCEAN DATA STATION TELEMETERING BUOY, General Dynamics, GD/C-65-018, 1965.

10. Dominguez, Richard F., Nath, John H., Neshyba, Steve, Young, David A., ANALYSIS OF A TWO-POINT MOORING FOR A SPAR, Reference 69-34, Data Report 38, Oregon State University, Department of Oceanography, December 1969.

11. Drucker, D. C., Tachau, H., A NEW DESIGN CRITERION FOR WIRE ROPE, from Journal of Applied Mechanics, March 1945.

12. Fofonoff, N. P., Garrett, John, MOORING MOTION, Reference No. 68-31, WHOI, May 1968.

13. Fofonoff, N. P., DYNAMICS OF A SIMPLE SPAR, personal communication for Robert M. Snyder, January 1967.

14. Gary, Shelton M., Jr., NEW ENGINEERING TECHNIQUES FOR APPLICATION TO DEEP-WATER MOORING, Hydrospace Research Corporation, 66-PET-31, July 1966.

15. Gerrard, J. H., THE CALCULATION OF FLUCTUATING LIFT ON A CIRCULAR CYLINDER AND ITS APPLICATION TO THE DETERMINATION OF AEOLIAN TONE INTENSITY, Report 463, Advisory Group for Aeronautical Research and Development NATO, April, 1963.

16. Harleman, R. F., Shapiro, William C., THE DYNAMICS OF A SUBMERGED MOORED SPHERE IN OSCILLATORY WAVES, Hydrodynamics Laboratory, MIT, Staff publication, S-60.

17. Iversen, H. W., Balent, R, A CORRELATING MODULUS FOR FLUID RESISTANCE IN ACCELERATED MOTION, Journal of Applied Physics, VOL 22, Number 3, March 1951.

18. Keim, S. Russell, FLUID RESISTANCE TO CYLINDERS IN ACCELERATED MOTION, Journal of Hydraulics Division Proceedings of the American Society of Civil Engineers, paper 1113.

19. Kim, W. D., ON THE HARMONIC OSCILLATIONS OF A RIGID BODY ON A FREE SURFACE, May 1964, revised July 1964.

20. Kobus, Helmut E., EXPERIMENTAL STUDY OF METHODS OF DETERMINING WAVEMAKING RESISTANCE BY MEANS OF SURFACE-PROFILE MEASUREMENTS, Institute of Hydraulic Research, University of Iowa, AD 621 740, March 1965.

21. Laura, P. A., DYNAMICS OF CABLE SYSTEMS, Themis Program 893, Catholic University of America, May 1969.

22. Lacy, R., PITCH AND HEAVE RESPONSE IN WAVES OF A SPAR-SHAPED HYDROPHONE PLATFORM (VERTICAL ATTITUDE), LSCC/0000911, July 1961.

23. Leendertse, J. J., WAVE-INDUCED MOTIONS OF A ROCKET VEHICLE DRIFTING IN A VERTICAL ATTITUDE, U. S. Naval Civil Engineering Laboratory, Technical Note N-402, AD 252 880, January 1961.

24. Le Mehaute, Bernard, THEORY, EXPERIMENTS, A PHILOSOPHY OF HYDRAULICS, Journal of Hydraulics Division, Proceedings of the American Society of Civil Engineers, January 1962.

25. Martin, M., EQUATION OF MOTION FOR A FLOAT SUPPORTED CRAFT IN A SEAWAY, Hydronautics, Inc., AD 639 205 May 1966.

26. Mercier, John A., A METHOD FOR COMPUTING FLOAT PLATFORM MOTIONS IN WAVES, Davidson Laboratory, Report 1322, October 1968.

27. Millard, Robert C., Jr., OBSERVATIONS OF STATIC AND DYNAMIC TENSION VARIATIONS FROM SURFACE MOORING, WHOI, Reference No. 69-29, May 1969.

28. Nath, John H., DYNAMICS OF SINGLE POINT OCEAN MOORINGS OF A BUOY--A NUMBERICAL MODEL FOR SOLUTION BY COMPUTER, Oregon State University, Department of Oceanography, Reference 69-10, July 1969.

29. Newman, J. N., THE MOTIONS OF A SPAR BUOY IN REGULAR WAVES, Hydromechanics Laboratory, Report 1499, AD 406 333, May 1963.

30. Newsham, Arthur D., A PRELIMINARY STURY OF THE EFFECT OF THE FREE SURFACE ON THE DRAG OF A TRUNCATED 2:1 ELLIPSOID, Institute of Hydraulic Research, University of Iowa, AD 605 582.

31. O'Brion, W. Terence, Francis, Arthur J., CABLE MOVEMENTS UNDER TWO DIMENSIONAL LOADS, Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, June 1964.

32. Pao, Hsien-Ping, DYNAMICAL STABILITY OF TOWED THIN FLEXIBLE CYLINDER, Themis Program No. 893, Department of Space Science and Applied Physics, Catholic University of America, December 1969.

33. Paquette, Robert G., Henderson, Bion E., THE DYNAMICS OF SIMPLE DEEP-SEA BUOY MOORINGS, GM Defense Research Laboratory, Sea Operation Department, TR 65-79.

34. Pochapsky, T. E., THE FORCED MOTION OF A NEUTRALLY BUOYANT FLOAT, Hudson Laboratories, Technical report No. 99, AD 299 986, October 1962.

35. Poffenberger, J. C., Capadona, E. A., Siter, R. B., DYNAMIC TESTING OF CABLES, Research & Engineering Department, Preformed Line Products Company, reprinted from Exploiting the Ocean, June 27-29, 1966.

36. Redd, Bass, Olsen, Dennis M., Barton, Richard L., RELATIONSHIP BETWEEN THE AERODYNAMIC DAMPING DERIVATIVES MEASURED AS A FUNCTION OF INSTANTANEOUS ANGULAR DISPLACEMENT AND THE AERODYNAMIC DAMPING DERIVATIVE MEASURED AS A FUNCTION OF OSCILLATION AMPLITUDE, NASA TN D-2855.

37. Rudnick, Philip, THE MOTION OF A SPAR BUOY IN SWELL, PART I, University of California, AD 615 882, June 1960.

38. Rudnick, Philip, THE MOTION OF A SPAR BUOY IN SWELL, PART II, University of California, AD 615 886, July 1960.

39. Sanders Associates, LOLITA REPORT, 1964.

40. Savitsky, Daniel, ANALYSIS OF SELF-INDUCED VIBRATION AND HYDRODYNAMIC DRAG OF MOORING CABLE, Davidson Laboratory OL 9-7700, November 1960.

41. Seidl, Ludwig H., ON THE DYNAMICS OF MOORED VESSELS IN IRREGULAR SEAS, University of Hawaii, October 1968.

42. Skop, Richard A., O'Hara, George J., THE STATIC EQUILIBRIUM CONFIGURATION OF CABLE ARRAYS BY USE OF THE METHOD OF IMAGINARY REACTIONS, Naval Research Laboratory, NRL Report 6819, February 1969.

43. Skop, Richard A., ON THE SHAPE OF A CABLE TOWED IN A CIRCULAR PATH, Naval Research Laboratory, NRL Report 7048, April 1970.

44. SNAME, PITCH, HEAVE AND SURGE, Section 2, Principles of Naval Architecture.

45. SNAME, THEORY OF THE HEAVING MOTION.

46. Snyder, Robert M., LONG PERIOD WAVE GAUGE DEVELOPMENT - PHASE I, FEASIBILITY STUDY, USAEC Contract AT(26-1) - 280, January 1967.

47. Snyder, Robert M., RECOMMENDATIONS FOR AN INTEGRATED BUOY-SYSTEM ENGINEERING RDT&E PROGRAM, presented at workshop on Problem Areas in Buoy Design, USNRL, Washington DC, 13-13, November 1969.

48. Snyder, Robert M., BUOYS AND BUOY SYSTEMS, Section 9-4, Handbook On Ocean and Underwater Engineering, Myers, Holms, McAllister, eds, McGraw-Hill, 1969.

49. Snyder, Robert M., NON-LINEAR RESPONSE OF BUOY SHAPES, Transaction of the 2nd International Buoy Symposium, MTS,

50. St. Denis, Manley; Pierson, Willard J. Jr., ON THE MOTIONS OF SHIPS IN CONFUSED SEAS, Transactions Society, N.A.M.E. VOL 61, 1953.

51. Starkey, W. L., Cress, H. A., AN ANALYSIS OF CRITICAL STRESSES AND MODE OF FAILURE OF A WIRE ROPE, Journal of Engineering for Industry, November 1959.

52. Vytlacil, N., PITCH AND HEAVE RESPONSE IN WAVES OF A MANNED, FREE-FLOATING OCEANOGRAPHIC STATION, LSCC/C000911, February 1961.

53. Walton, Thomas S., Polachek, Harry, CALCULATION OF TRANSIENT MOTION OF SUBMERGED CABLES, Reprinted from Mathematical Tables and Other Aids to Compution, DTMB 158 X 537, January 1960.

54. Walton, Thomas S., Polachek, Harry, CALCULATION OF NON-LINEAR TRANSIENT MOTION OF CABLES, R & D report David Taylor Model Basin, Report 1279.

55. Weinblum, George: Brooks. Samuel; Golovato, Paul, David W. Taylor Model Basin; OSCILLATIONS OF A SPHEROID AND SURFACE SHIP IN FREE HEAVE, DTMB/C579 AD 471 308, November 1955.

56. Weinblum, George; St. Denis, Manley; ON THE MOTIONS OF SHIPS AT SEA.

57. Young, David A., Neshyba, Steve, ENGINEERING DESIGN AND USAGE OF THE TOTEM BUOY, Technical report 187, reference 70-19, Department of Oceanography, Oregon State University, June 1870.

58. Zajac, E. E., DYNAMICS AND KINEMATICS OF THE LAYING AND RECOVERY OF SUBMARINE CABLE, reprinted from Bell System Technical Journal, September 1957.

59. AN ASPECT OF OBSERVATIONAL DATA ACQUISITION IN OCEANOGRAPHY AND METEOROLOGY BUOY TECHOLOGY, MTS supplement.

60. BUOY TECHNOLOGY, AN ASPECT OF OBSERVATIONAL DATA ACQUISTION IN OCEANOGRAPHY ABD METEOROLOGY, MTS, MARCH 24, 25, 1964, Washington.

61. CIVIL ENGINEERING IN THE OCEAN, ASCE Conference, San Francisco CA September 6-8, 1967.

62. CIVIL ENGINEERING IN THE OCEAN, II, ASCE Conference, Miami Beach FL., December 10-12, 1969.

A GRAPHIC INVENTORY OF EXISTING ENVIRONMENTAL DATA BUOYS

Compiled by Clifford Petersen; based on information received by the Panel on Buoy Technology Assessment, from the Office of Naval Research and the NOAA Data Buoy Office

University of Rhode Island
Kingston, Rhode Island 02881

CONTENTS*

Linear Sketches

NDBO Severe Environment Buoy (I)
NDBO Severe Environment Buoy (II)
NDBO Severe Environment Buoy (Deep Keel Hull)
NDBO Moderate Environment Buoy (I)
NDBO Moderate Environment Buoy (II)
NDBO Moderate Environment Buoy (III)
NDBO Mild Environment Buoy
NDBO Drifting Research Buoy
NDBO Marker Buoy
NDBO Polar Ice Buoy
WHOI Surface Mooring
FLIP
TOTEM
SODS
Mollo-Christenson SPAR
MONSTER
ERTS & RAMS Track Buoy
WHOI Subsurface Buoy
WHOI Bottom Mooring Buoy
Typical Taut-Wire Current Meter Array
Current Profiler -- Diving
Current Profiling Array (NISKIN)
Tide Data Buoy
Data Buoy Layout

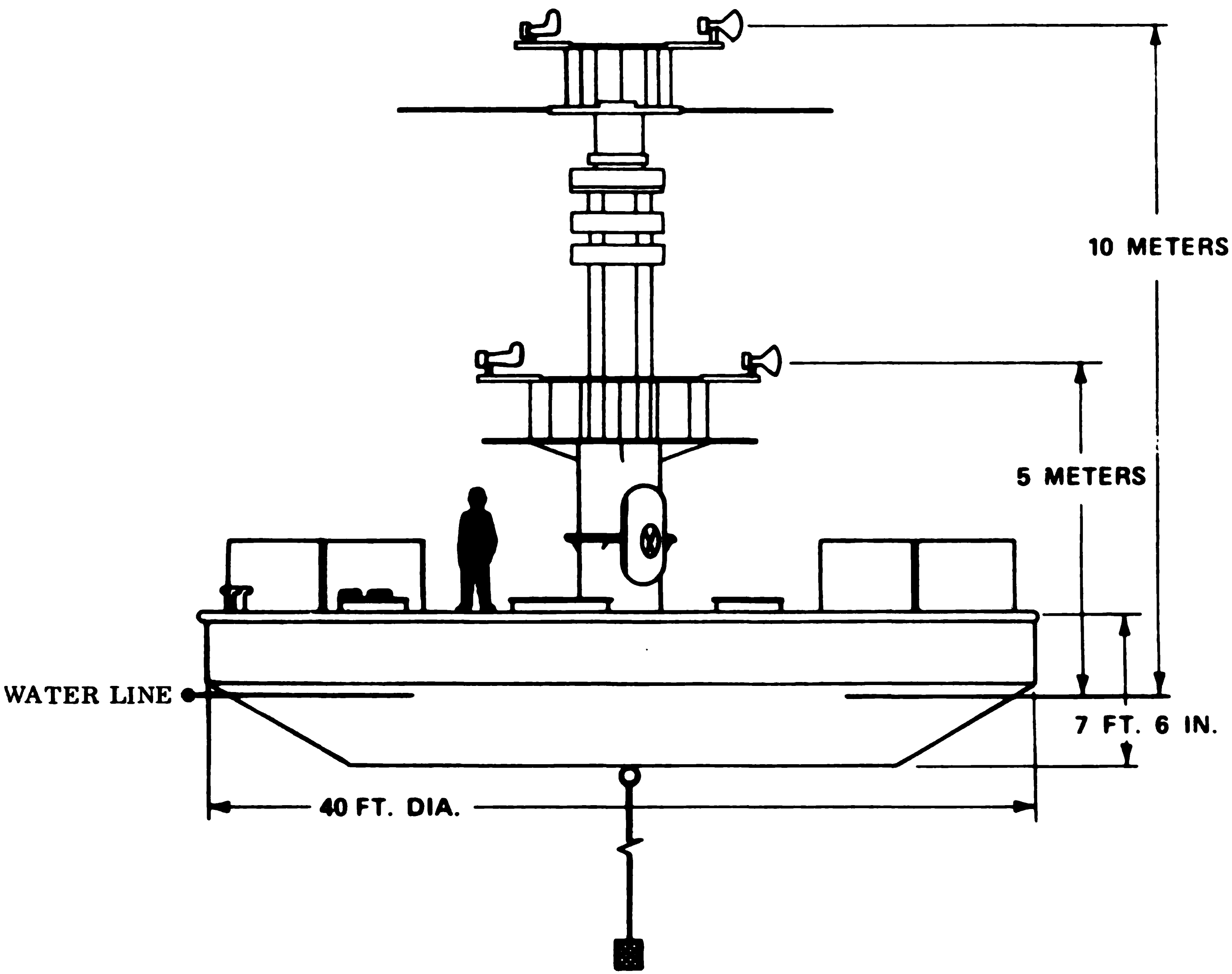
Tables

Environmental Data Buoys
NOAA Environmental Data Buoys

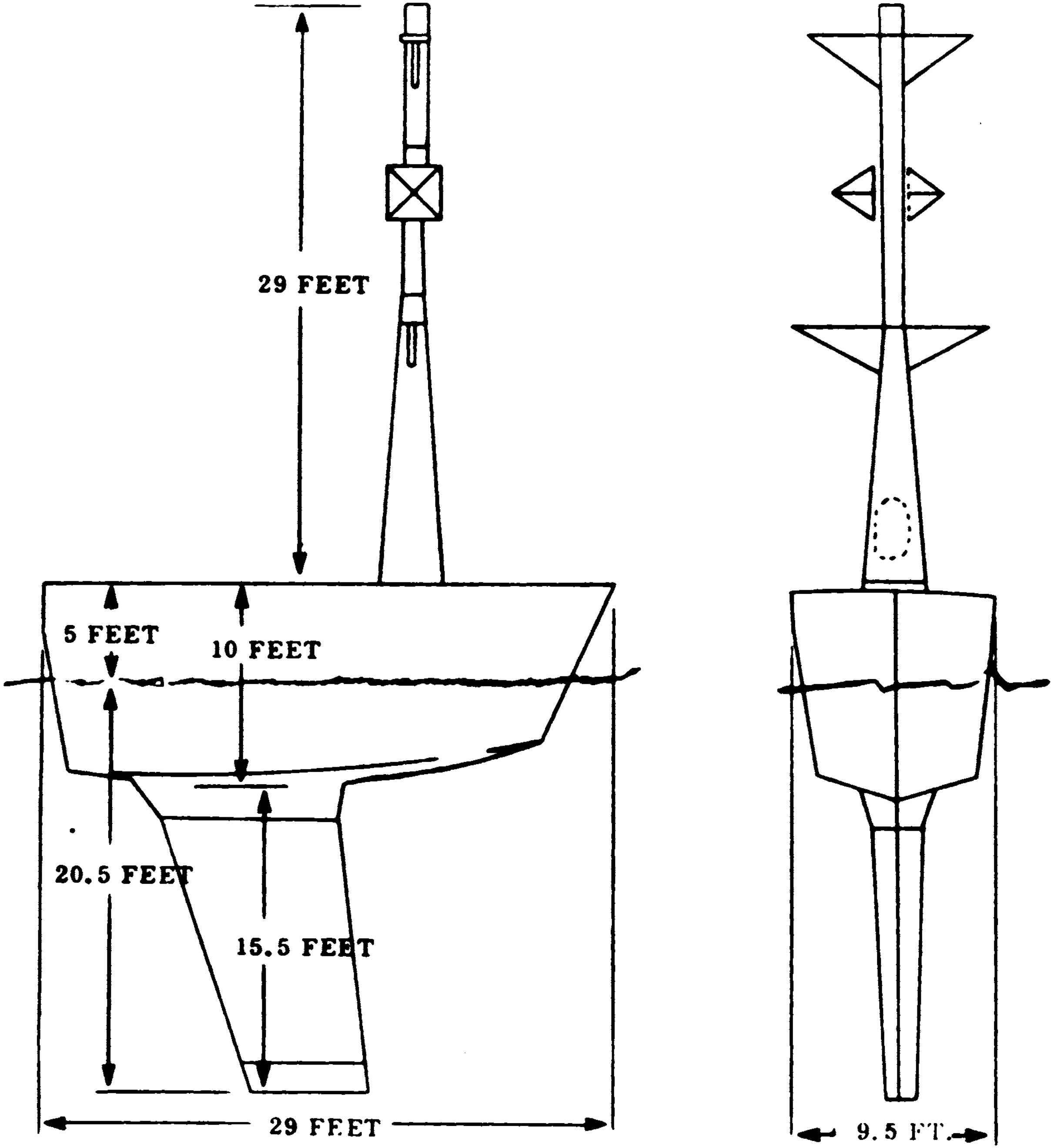
---

* In order of arrangement in the following pages.

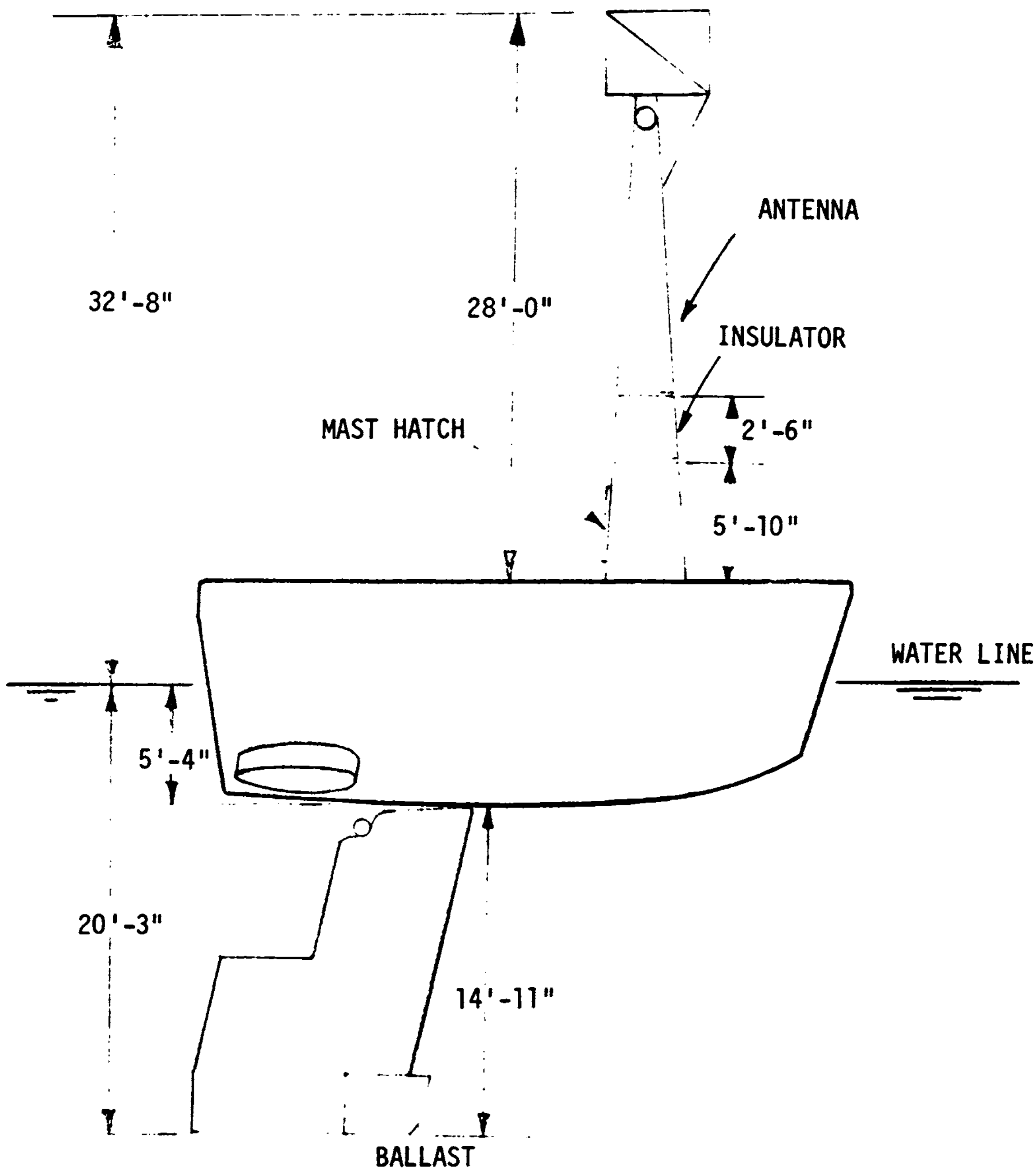
LINEAR SKETCHES



NDBO SEVERE ENVIRONMENT BUOY (I)

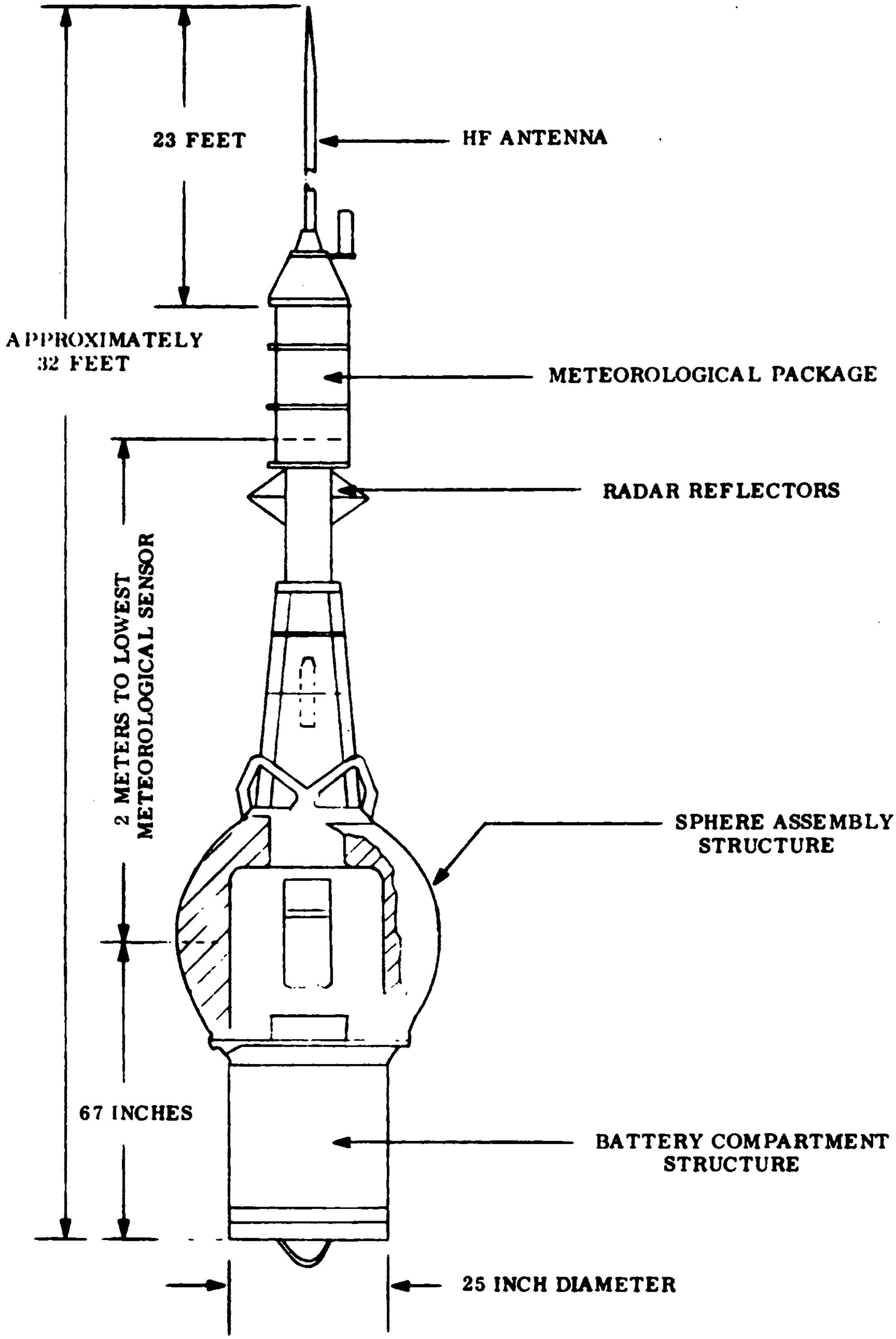


NDBO SEVERE ENVIRONMENT BUOY (II)

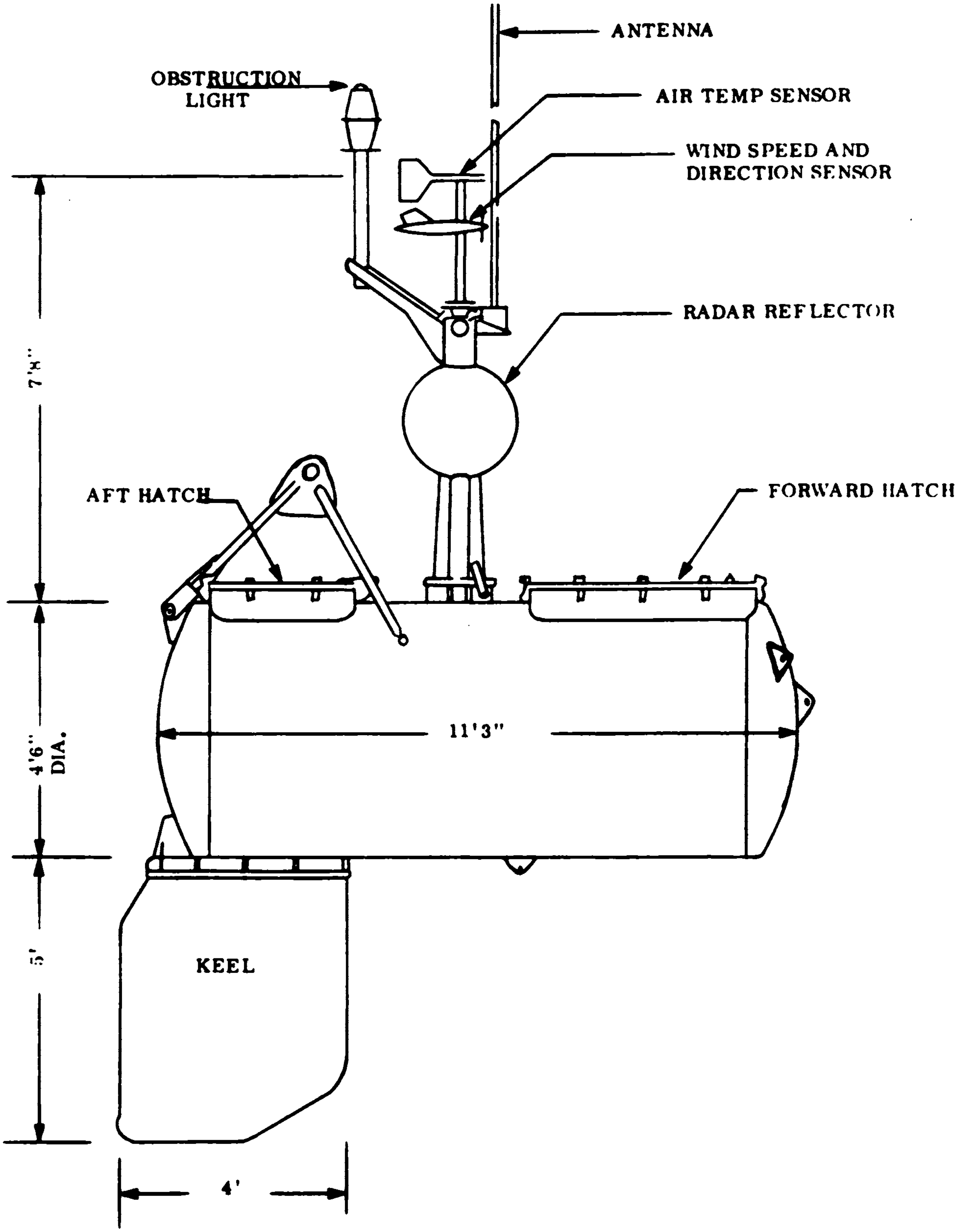


NDBO SEVERE ENVIRONMENT BUOY

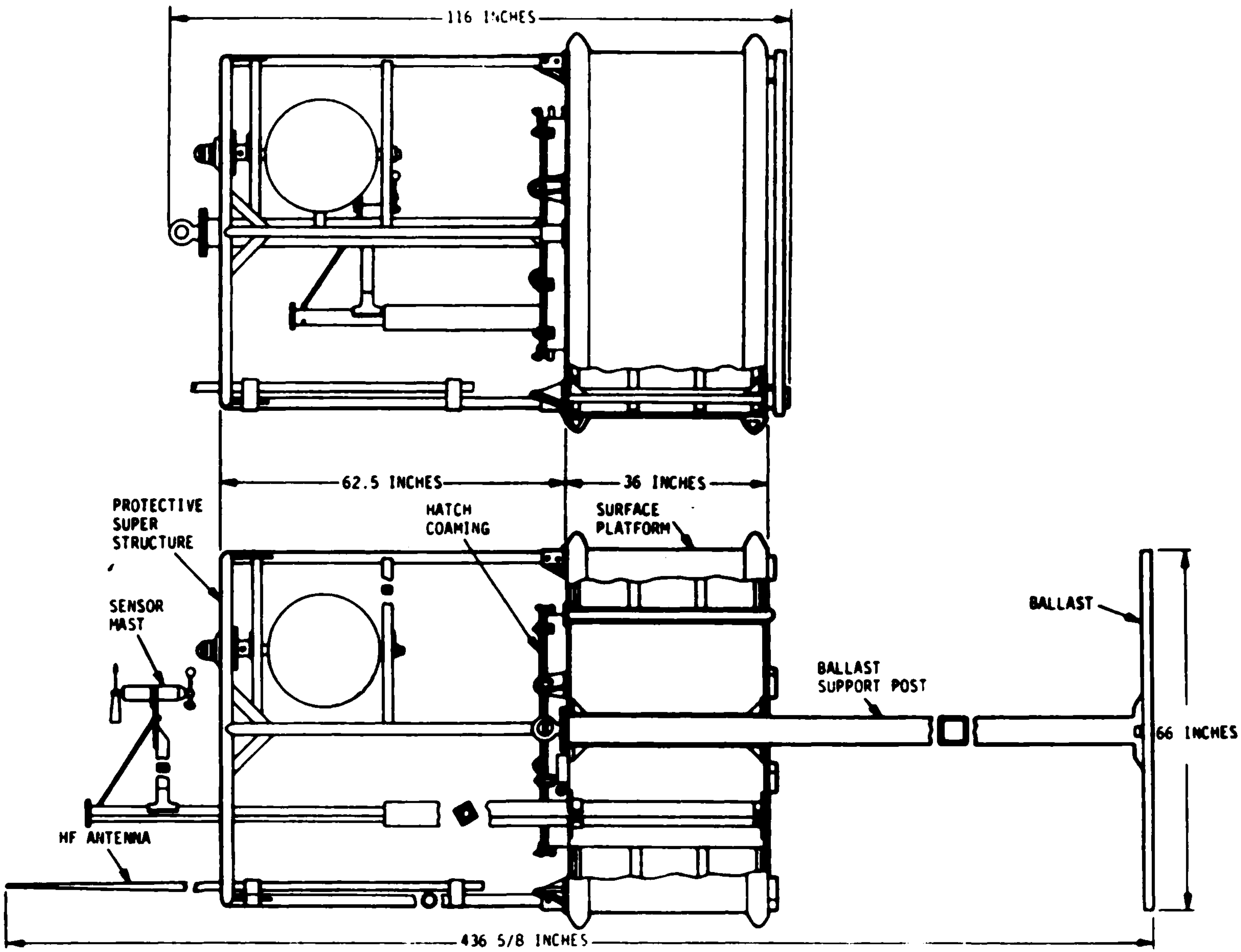
(DEEP KEEL HULL)



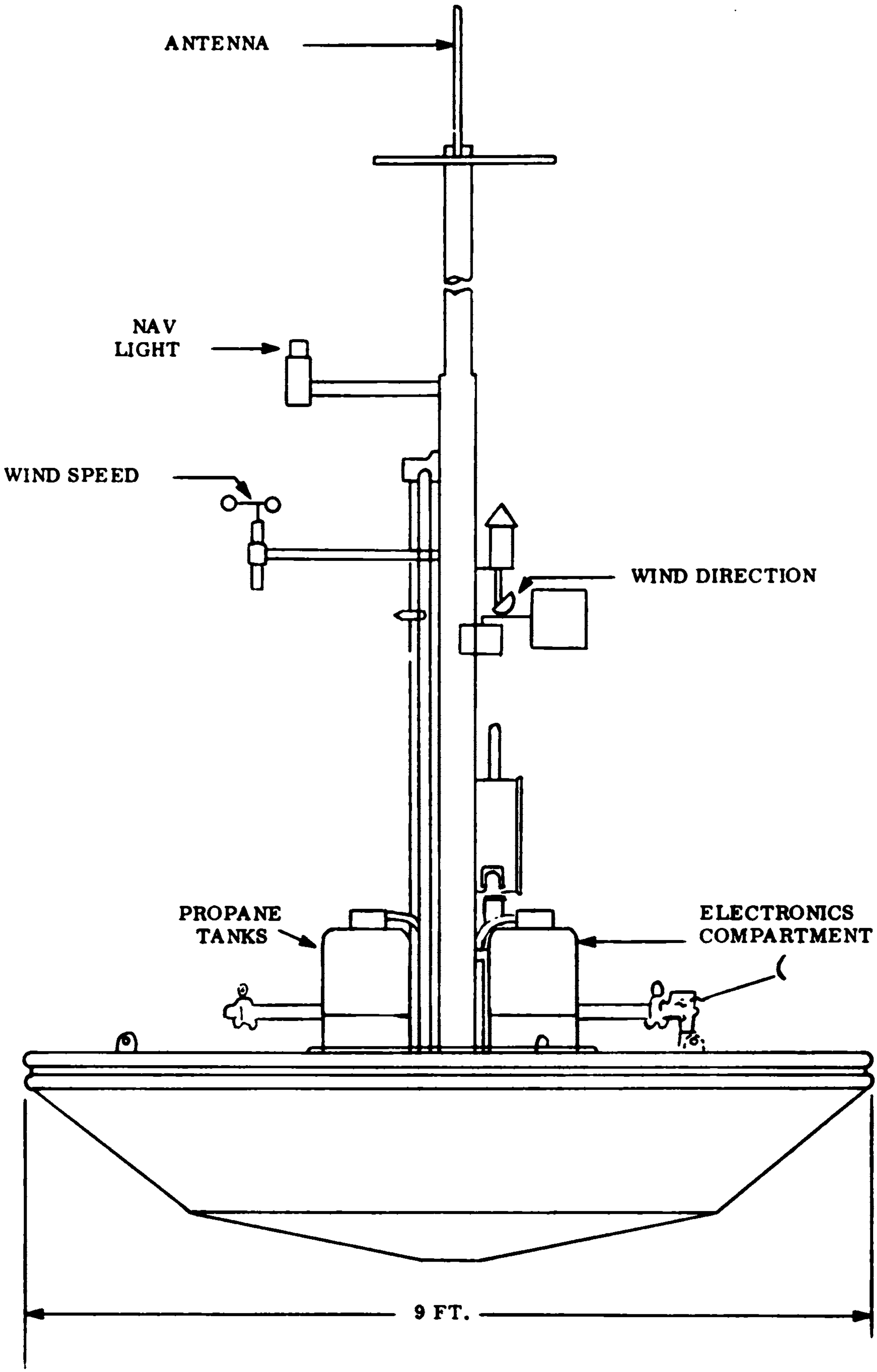
NDBO MODERATE ENVIRONMENT BUOY (I)



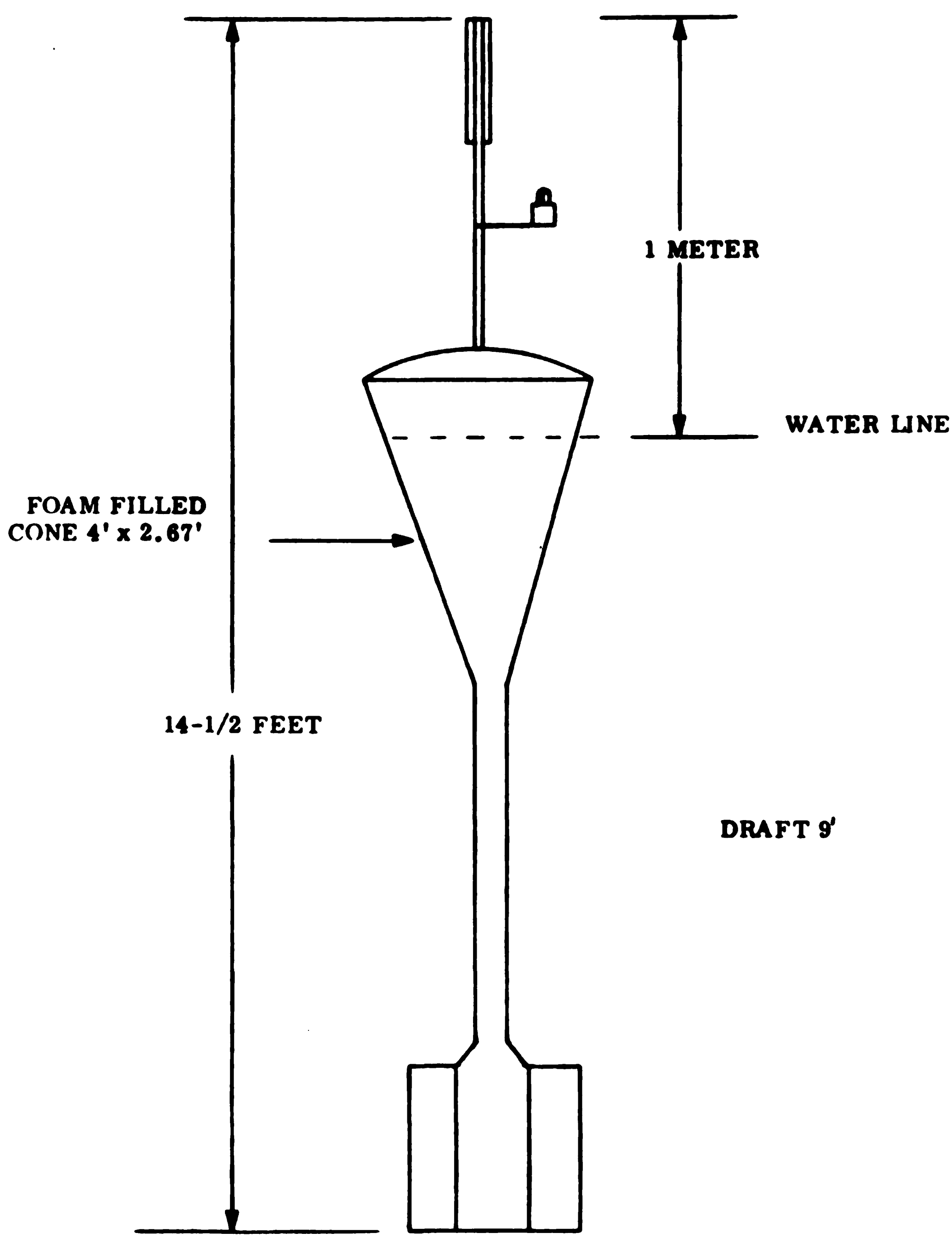
NDBO MODERATE ENVIRONMENT BUOY (II)



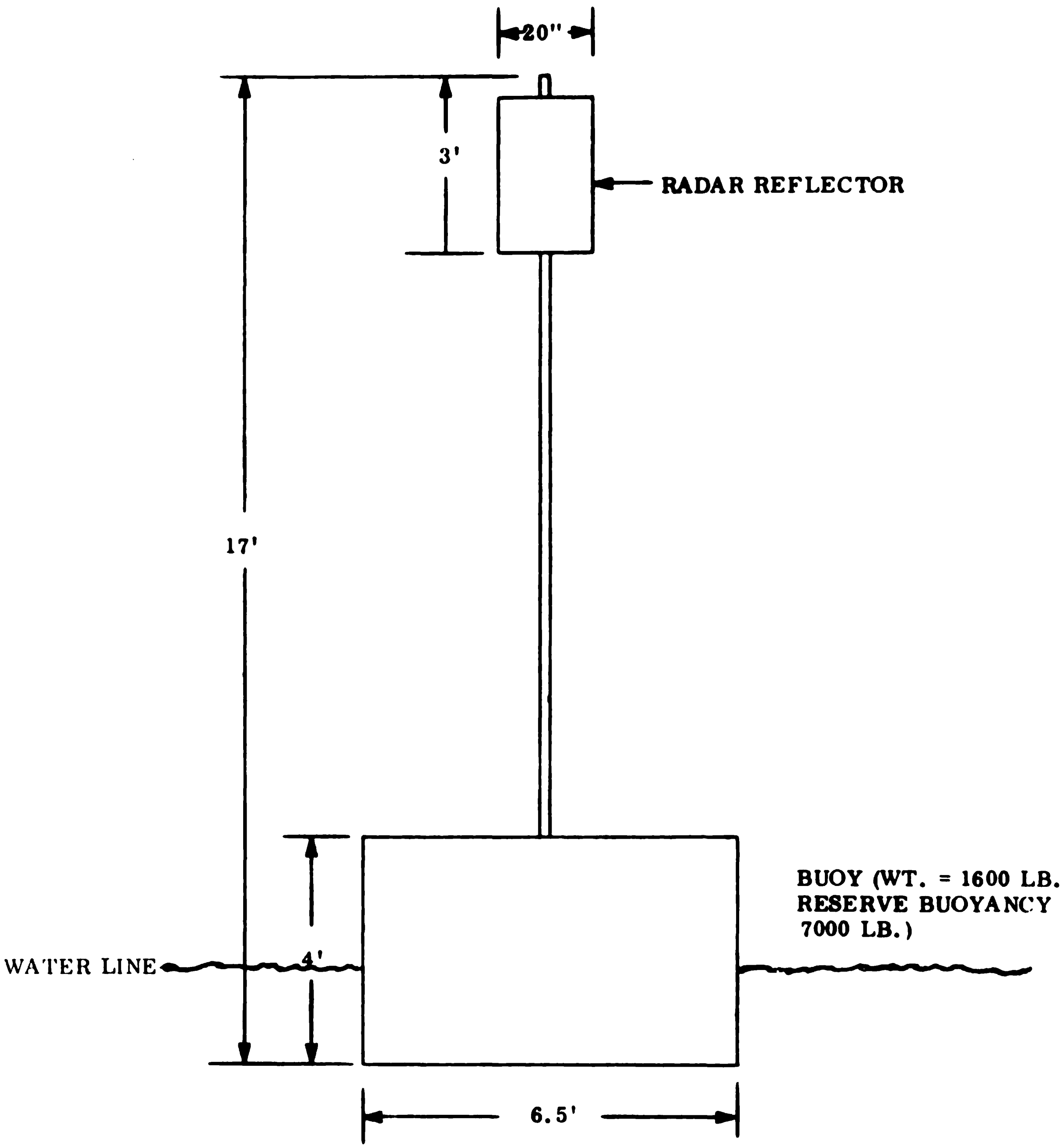
NDBO MODERATE ENVIRONMENT BUOY (III)



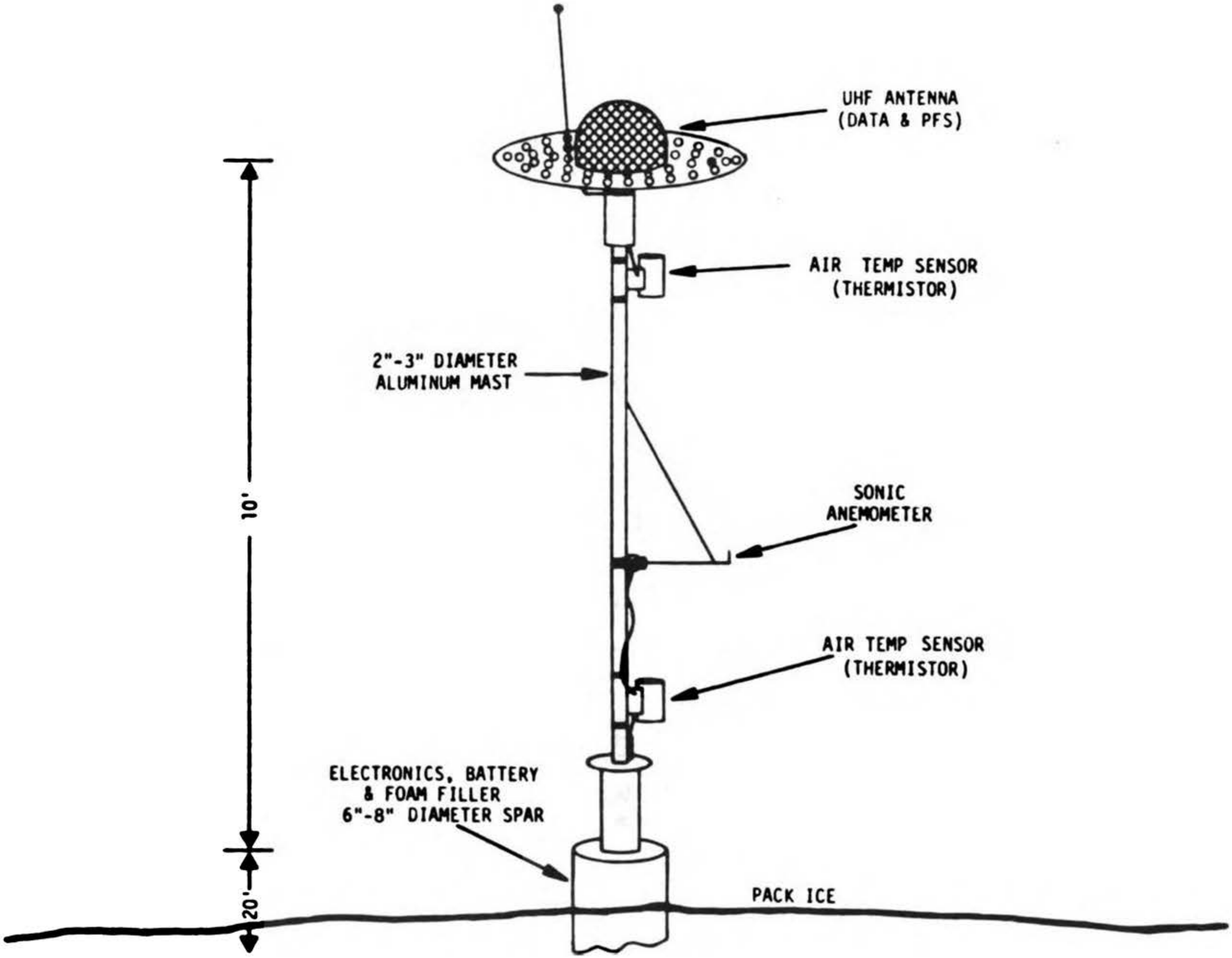
NDBO MILD ENVIRONMENT BUOY



NDBO DRIFTING RESEARCH BUOY

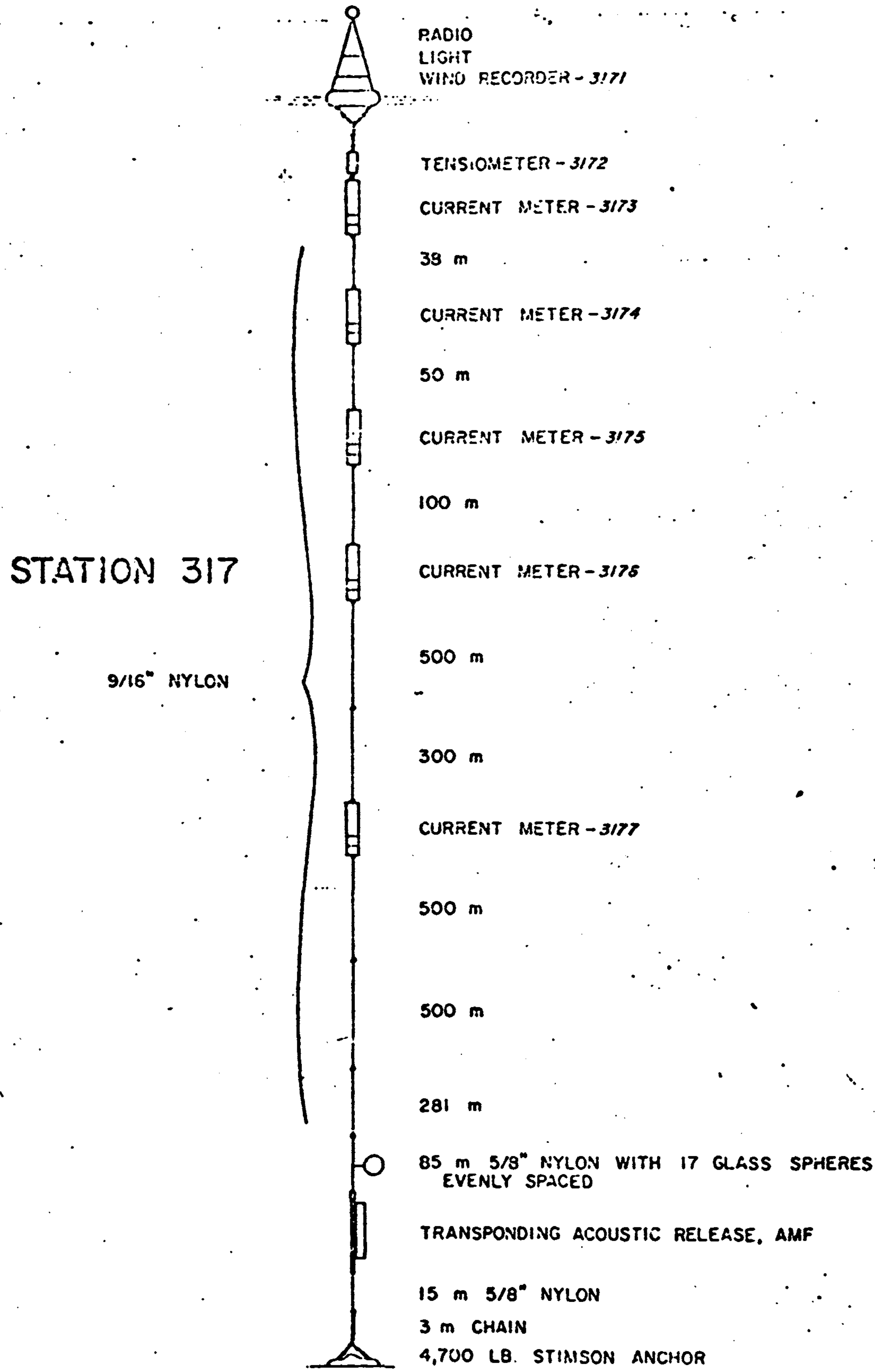


NDBO MARKER BUOY



NDBO POLAR ICE BUOY

WHOI SURFACE MOORING



FLIP

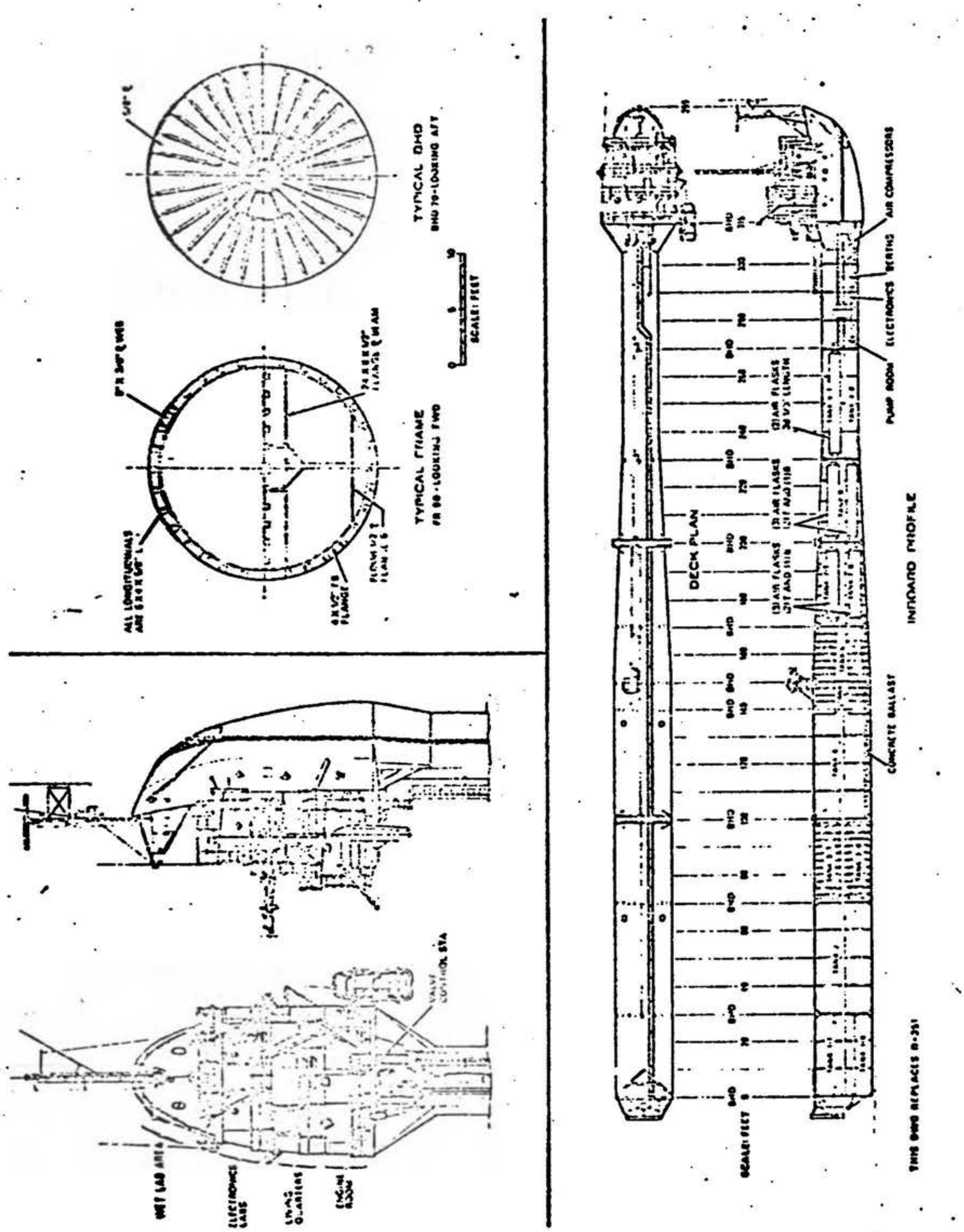
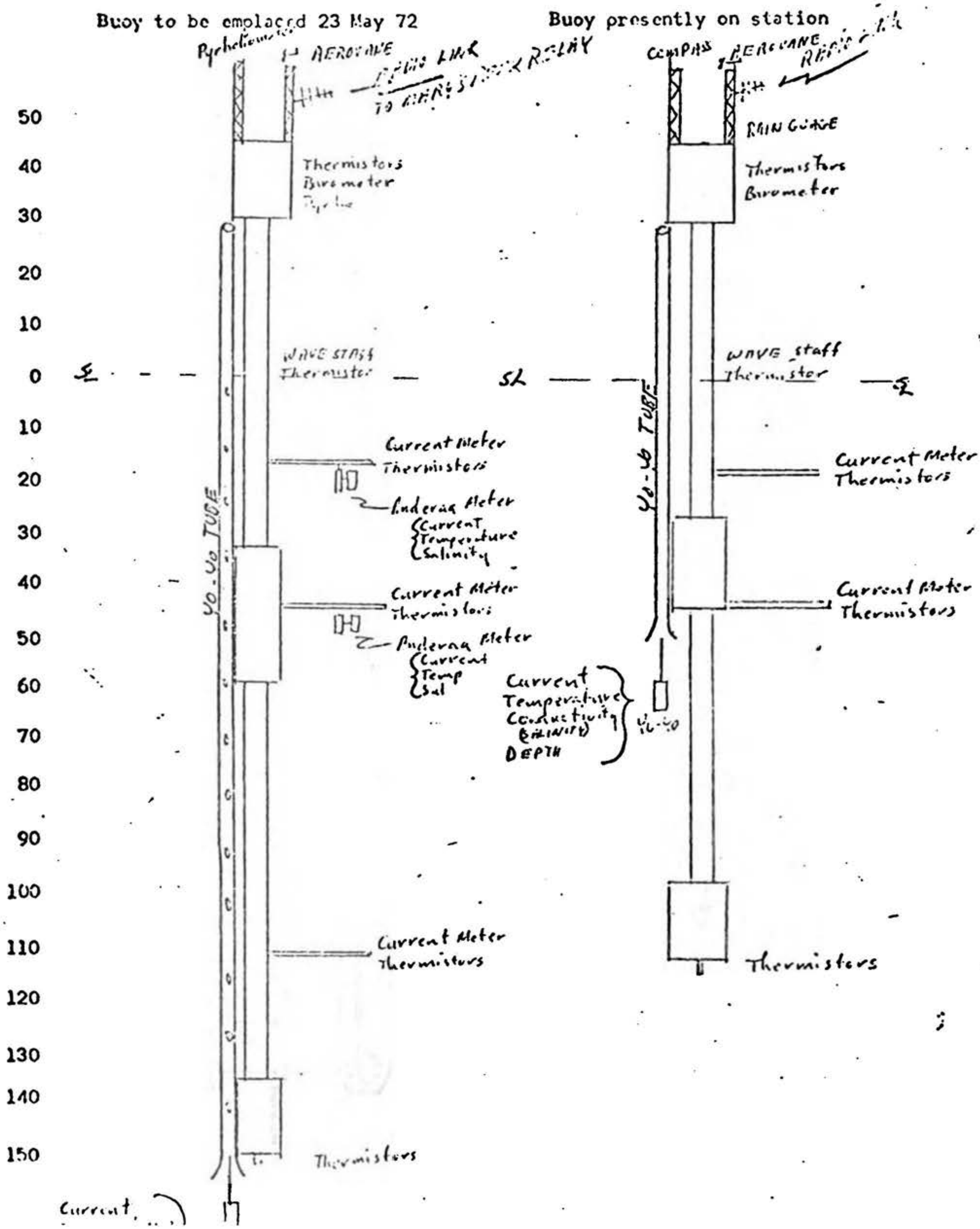


FIGURE 1

TOTEM

COMPARISON OF BUOY STRUCTURE AND INSTRUMENTATION



SODS

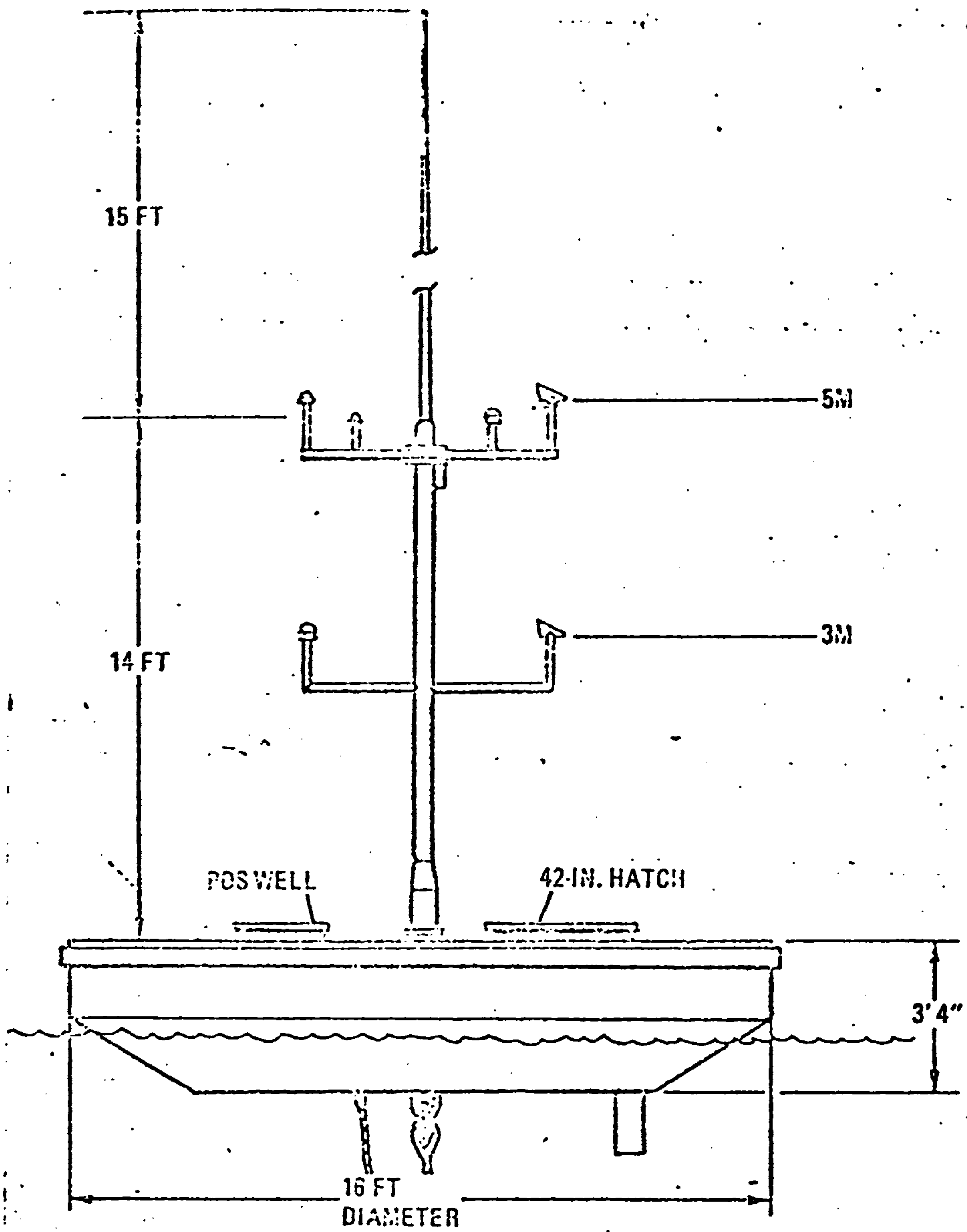


Figure 3.3.2.1-2. ODS Overall View

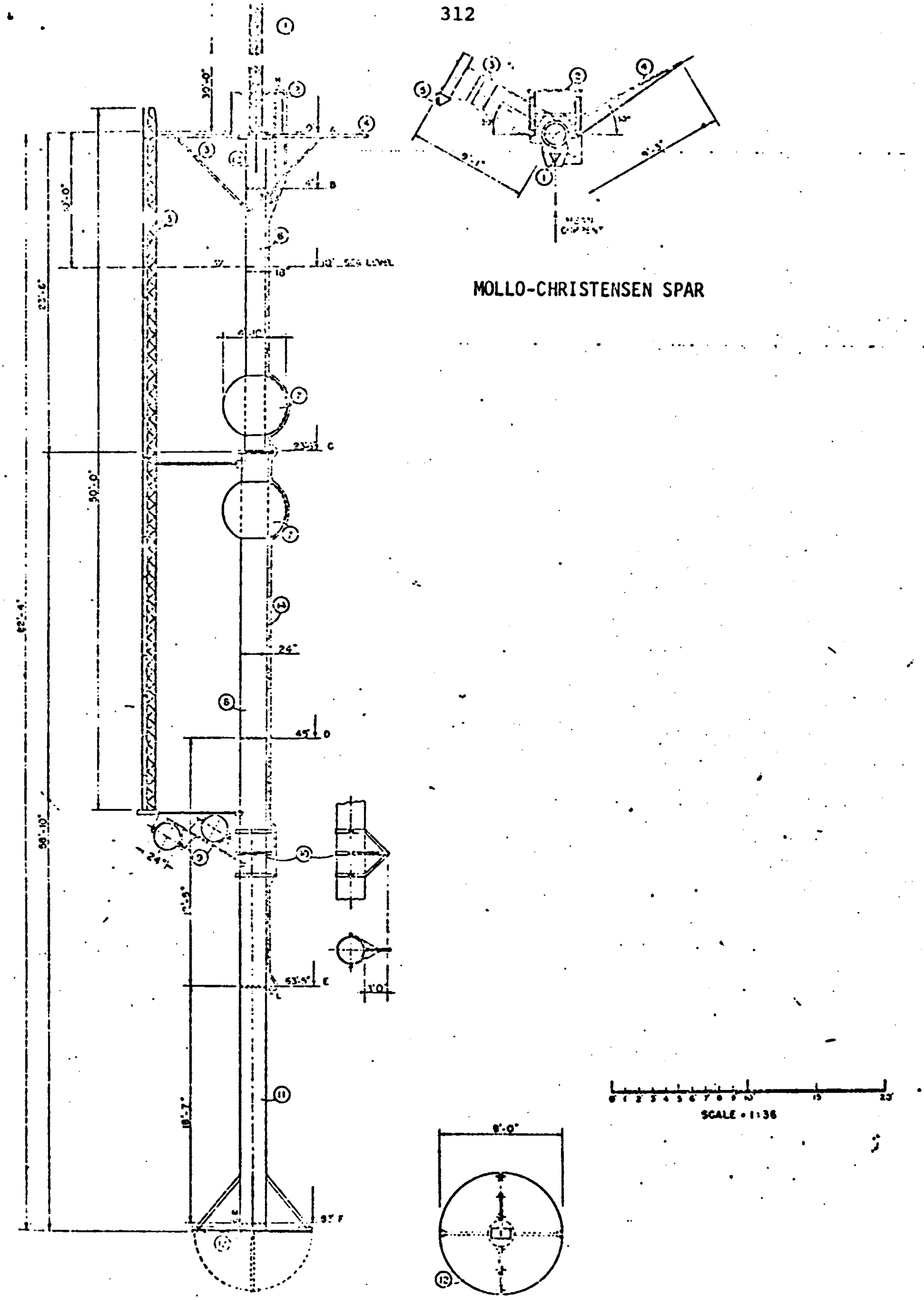


FIG. 1: Spar Buoy

MONSTER

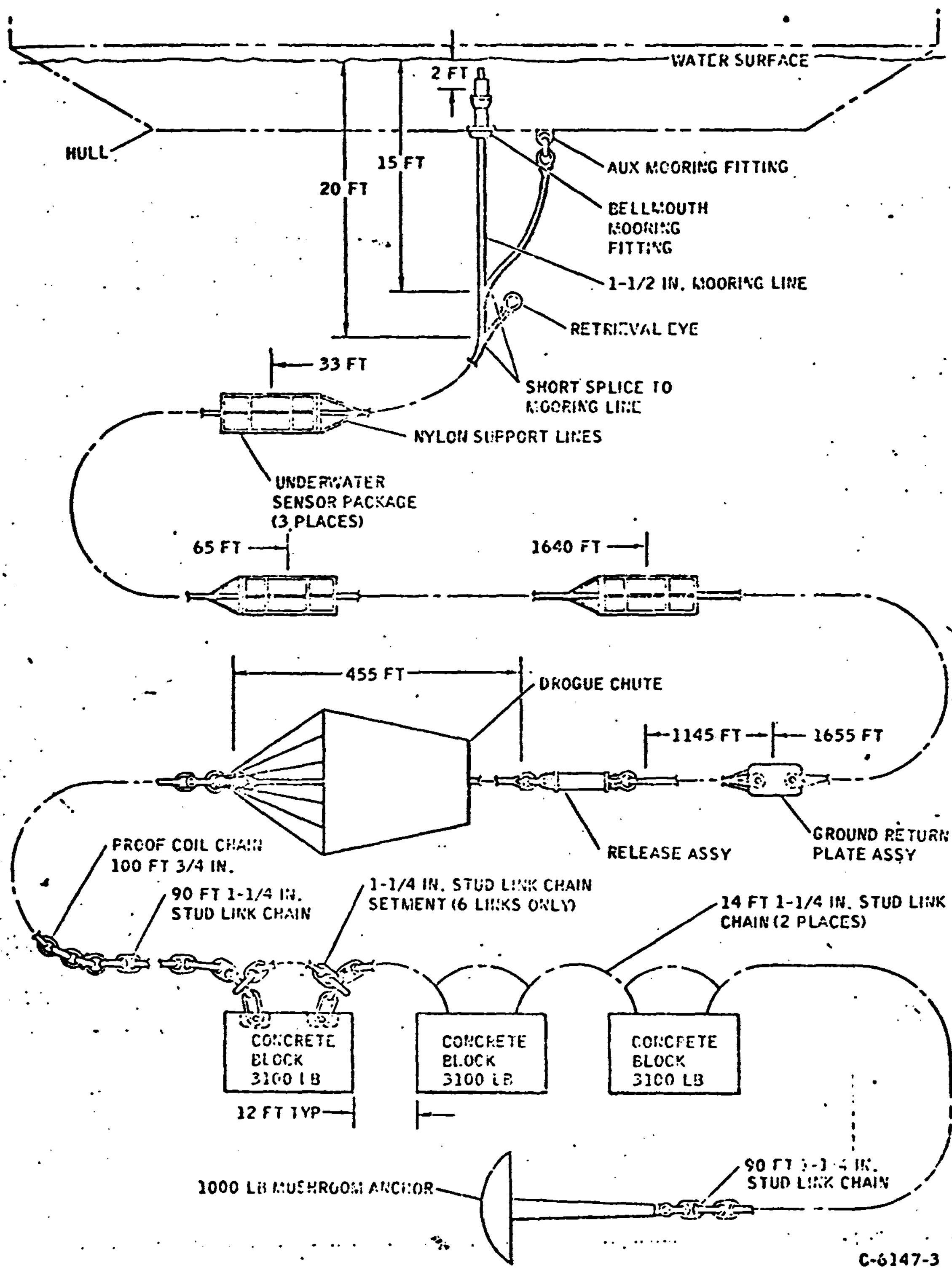


Figure 2-17. Long Range Telemetry Test Mooring Configuration

ERTS & RAMS TRACK BUOY

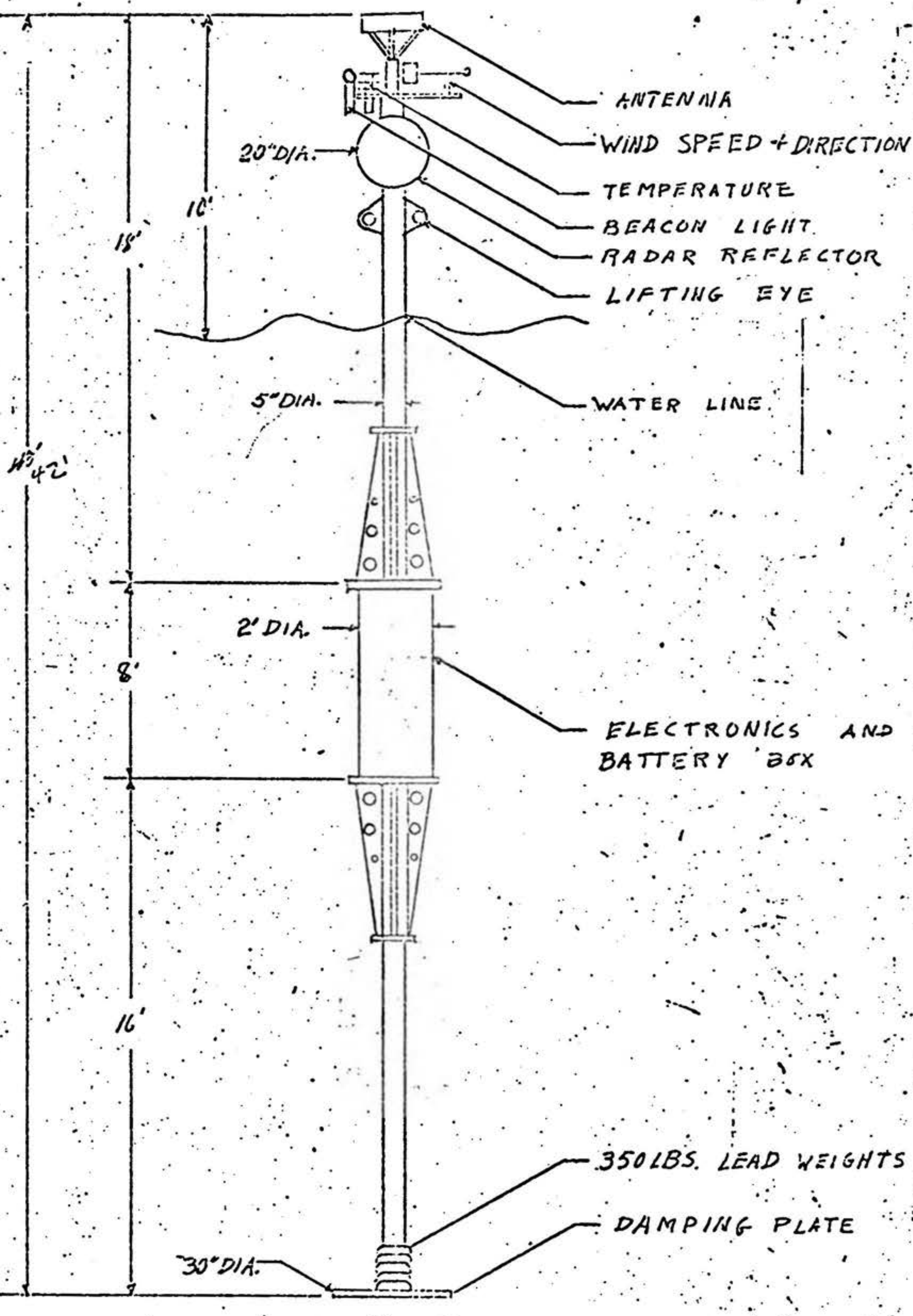


Figure 1

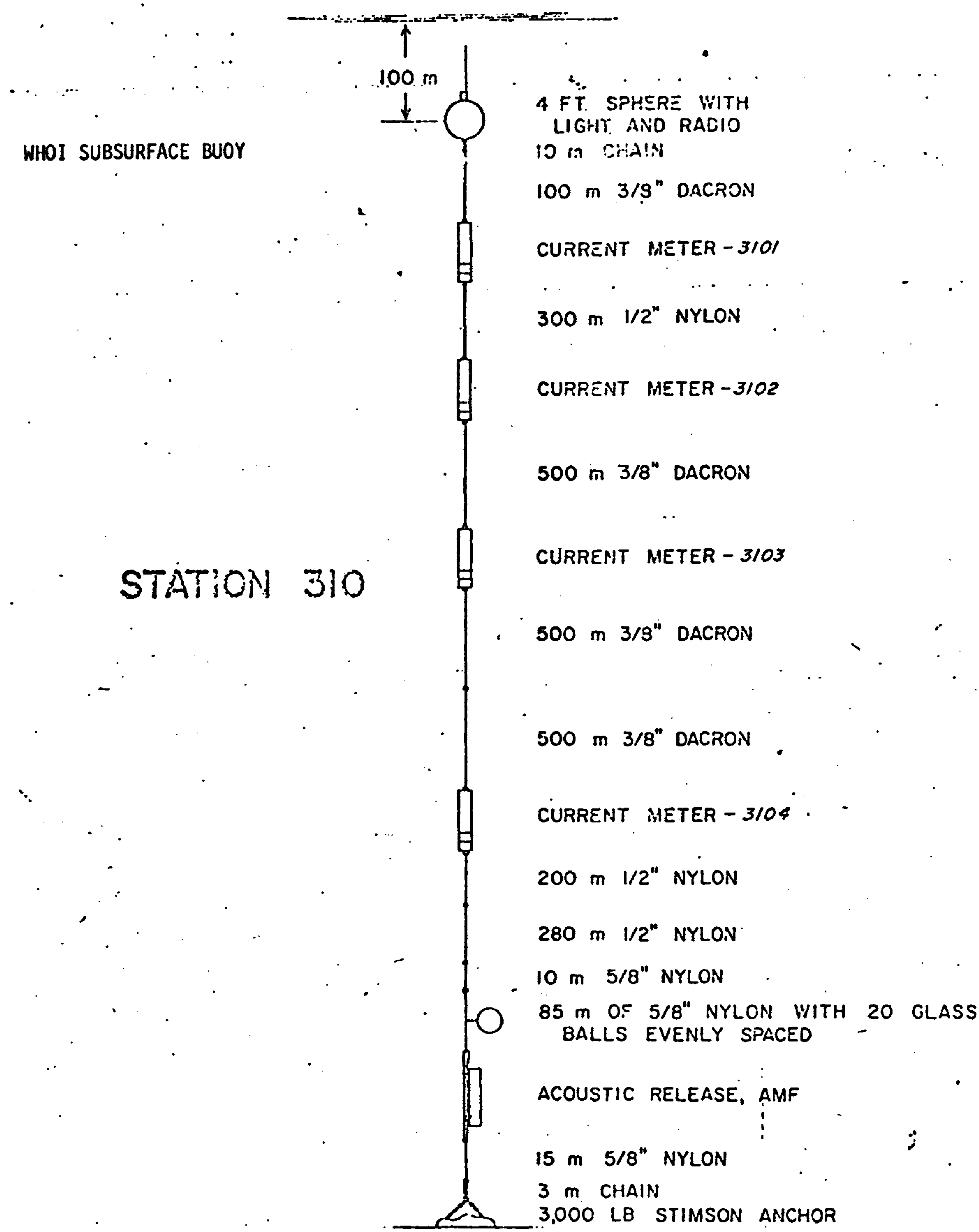
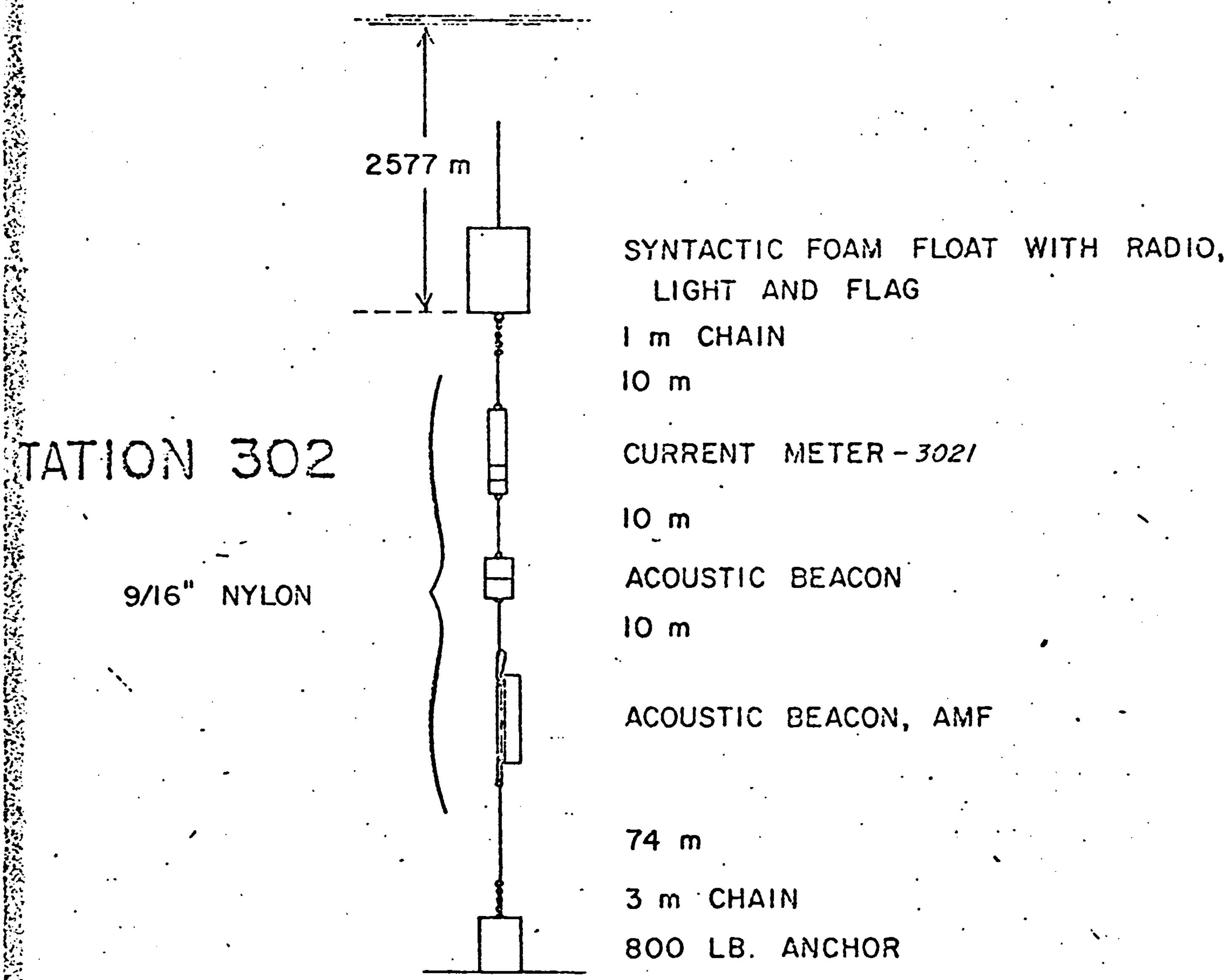
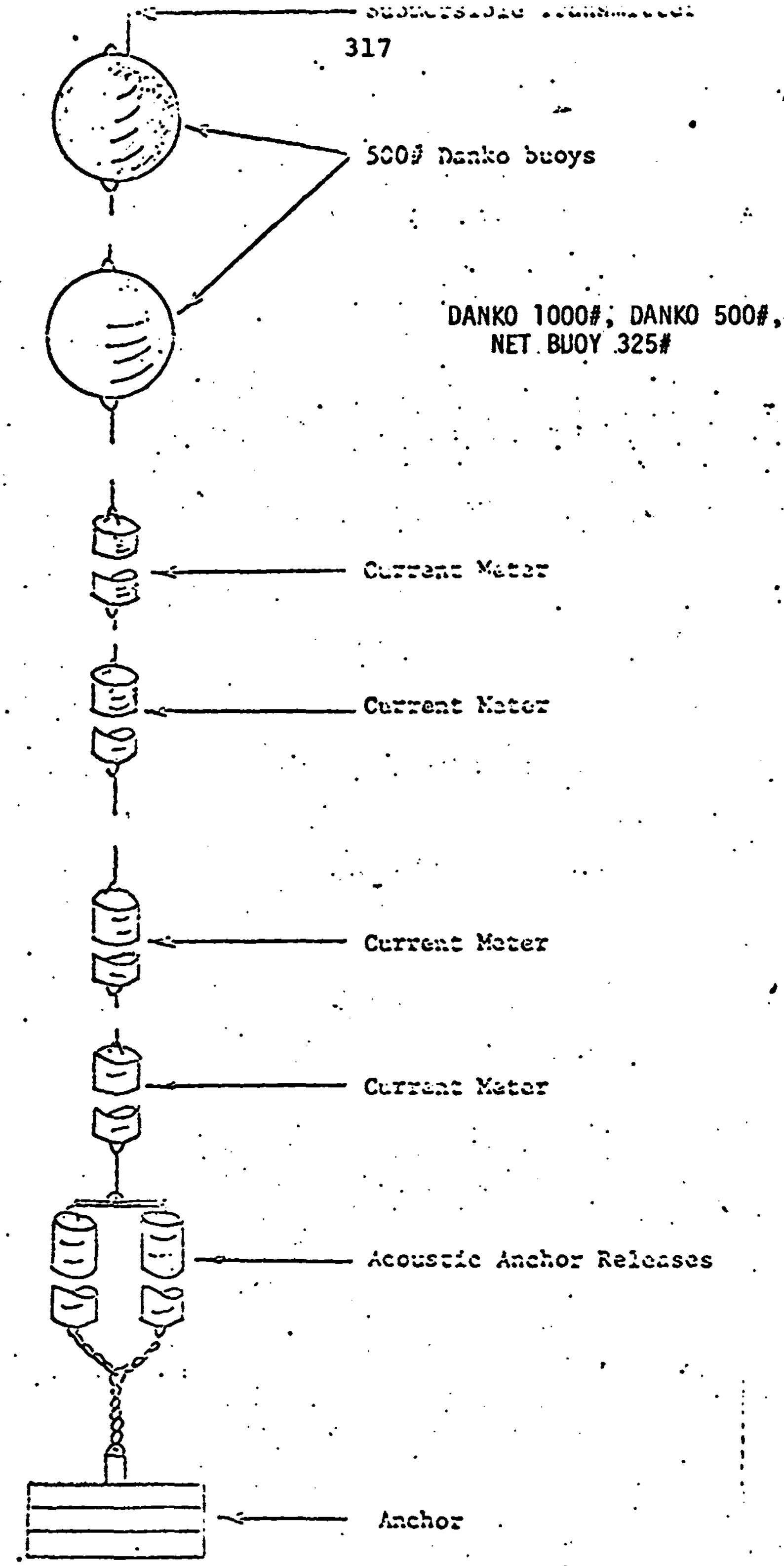

100 m
WHOI SUBSURFACE BUOY
4 FT. SPHERE WITH
LIGHT AND RADIO
10 m CHAIN
100 m 3/8" DACRON
CURRENT METER - 3101
300 m 1/2" NYLON
CURRENT METER - 3102
500 m 3/8" DACRON
STATION 310
CURRENT METER - 3103
500 m 3/8" DACRON
500 m 3/8" DACRON
CURRENT METER - 3104
200 m 1/2" NYLON
280 m 1/2" NYLON
10 m 5/8" NYLON
85 m OF 5/8" NYLON WITH 20 GLASS
BALLS EVENLY SPACED
ACOUSTIC RELEASE, AMF
15 m 5/8" NYLON
3 m CHAIN
3,000 LB STIMSON ANCHOR

Figure 22

WHOI BOTTOM MOORING BUOY





TYPICAL TAUT-WIRE CURRENT METER ARRAY

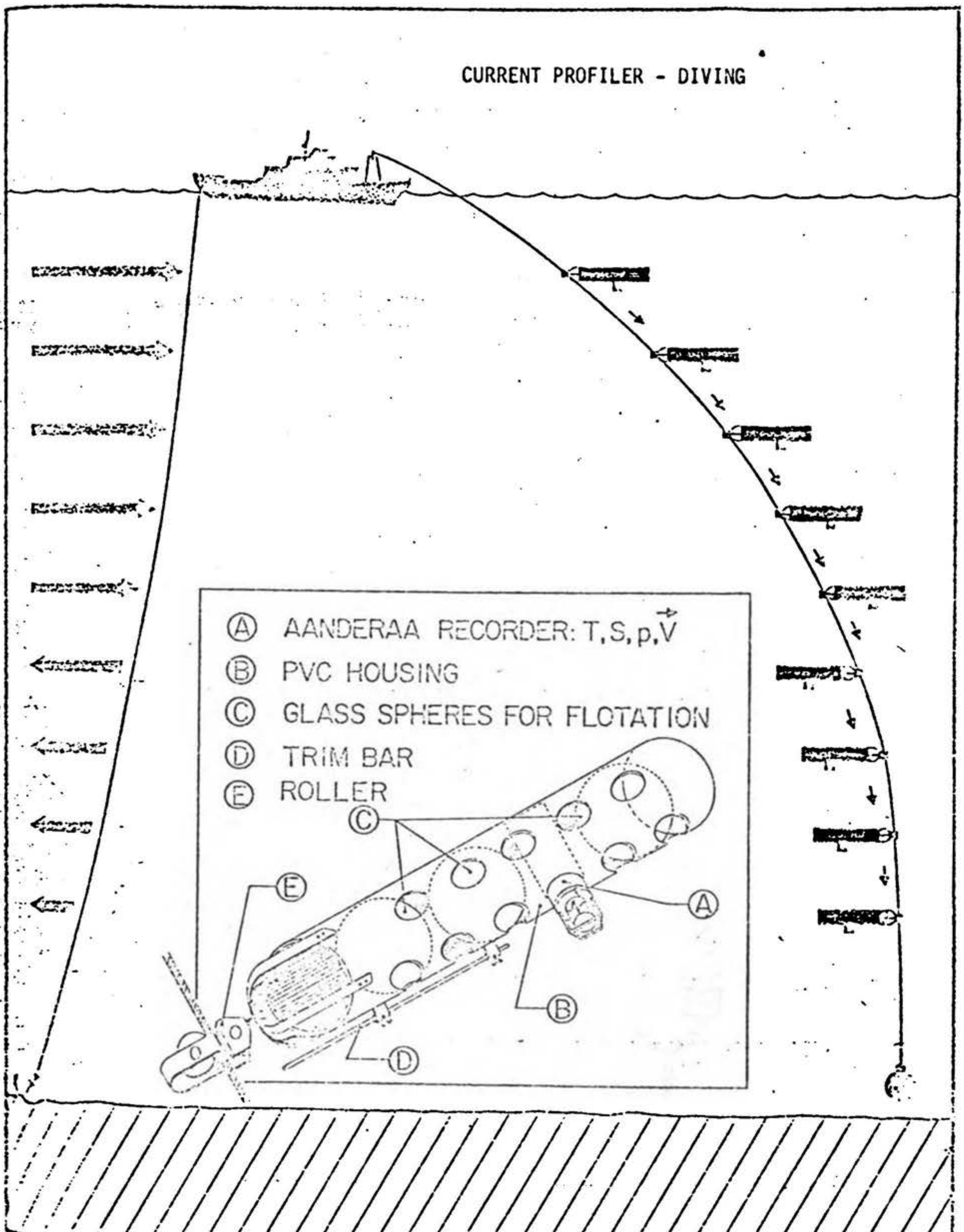
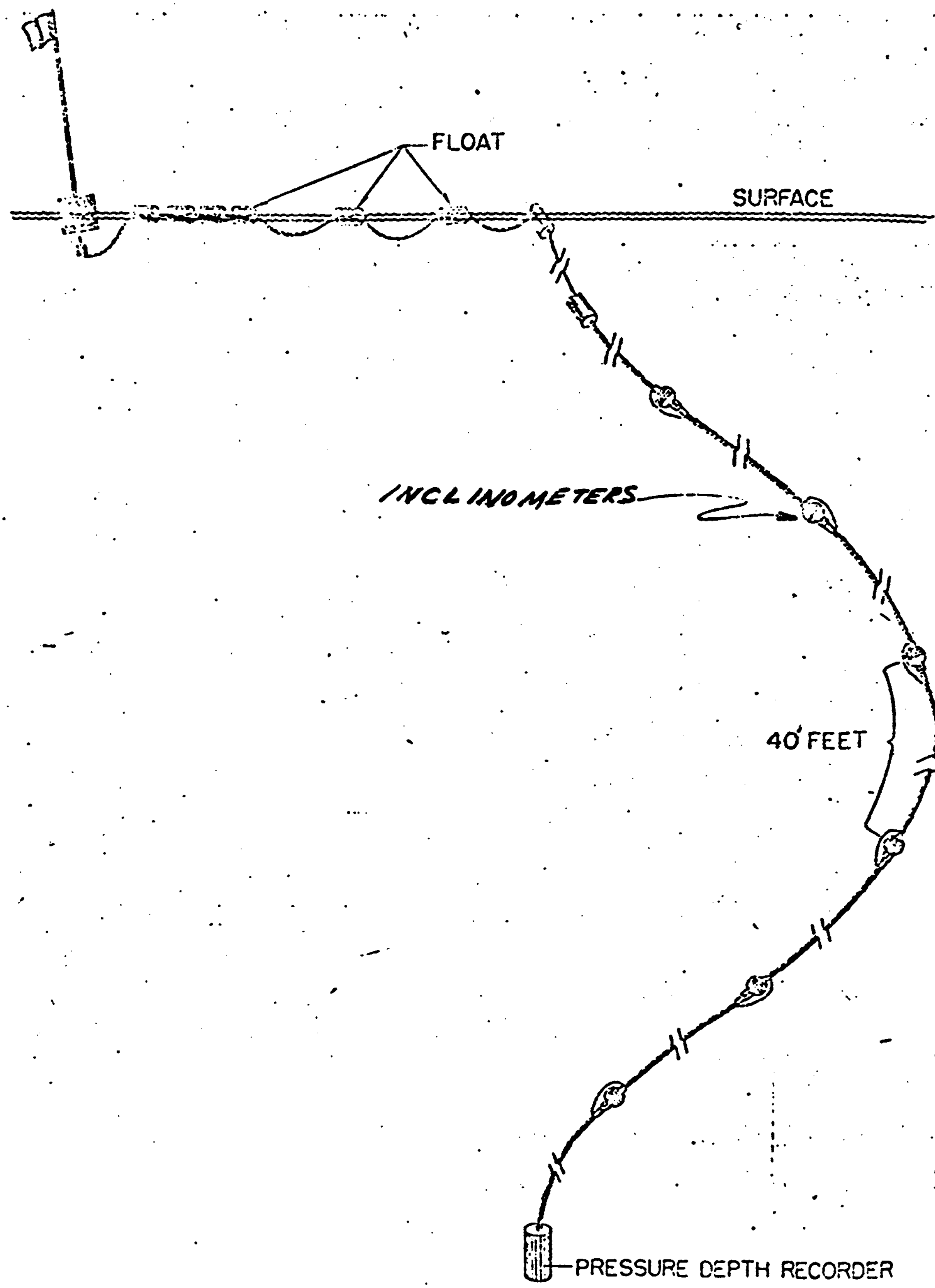
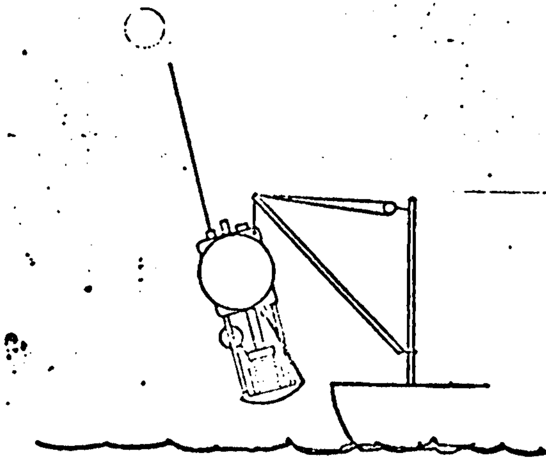


Fig. 1: Principle of current profiling method used in the Florida Current.

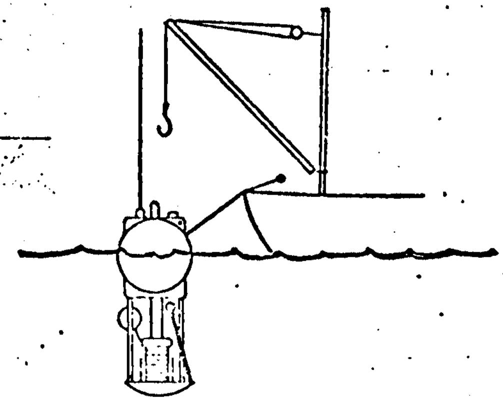
CURRENT PROFILING ARRAY (NISKIN)



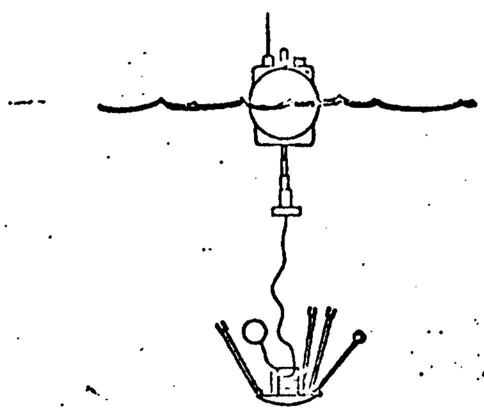
DATA BUOY LAUNCHING SEQUENCE



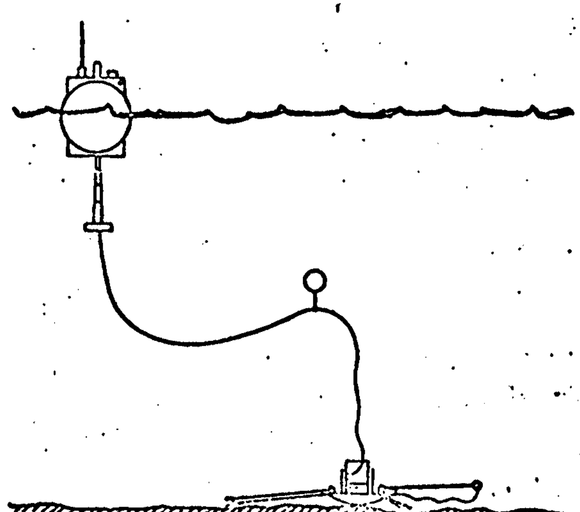
1. BUOY SUSPENDED ON DERRICK. ANTENNA ALREADY MOUNTED.



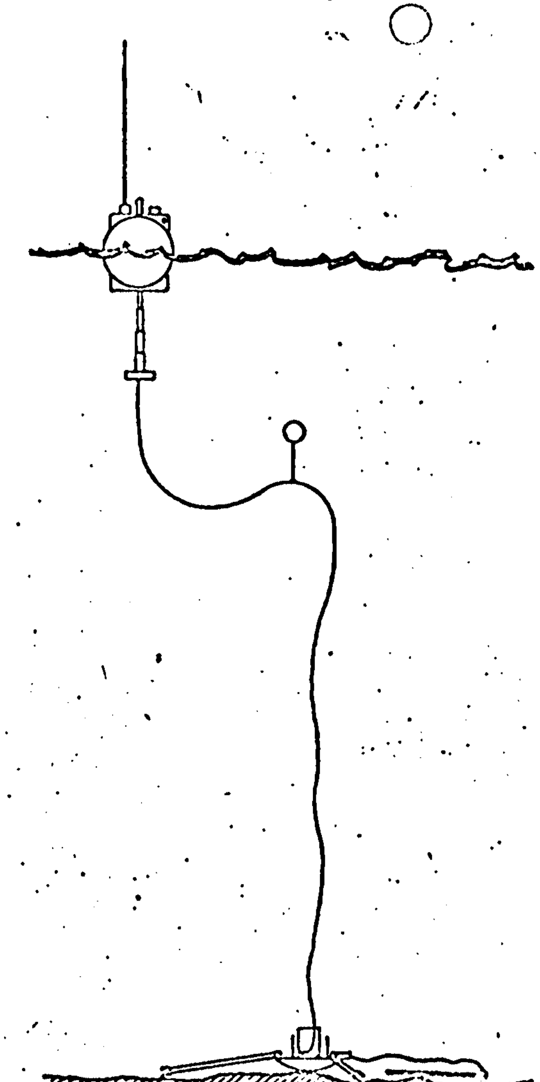
2. BUOY IN WATER FREE OF DERRICK. READY TO BE RELEASED BY RIP CORD.



3. RIP CORD RELEASE OPERATED AND ANCHOR RELEASED. COUNTER-WEIGHT FULLY EXTENDED.

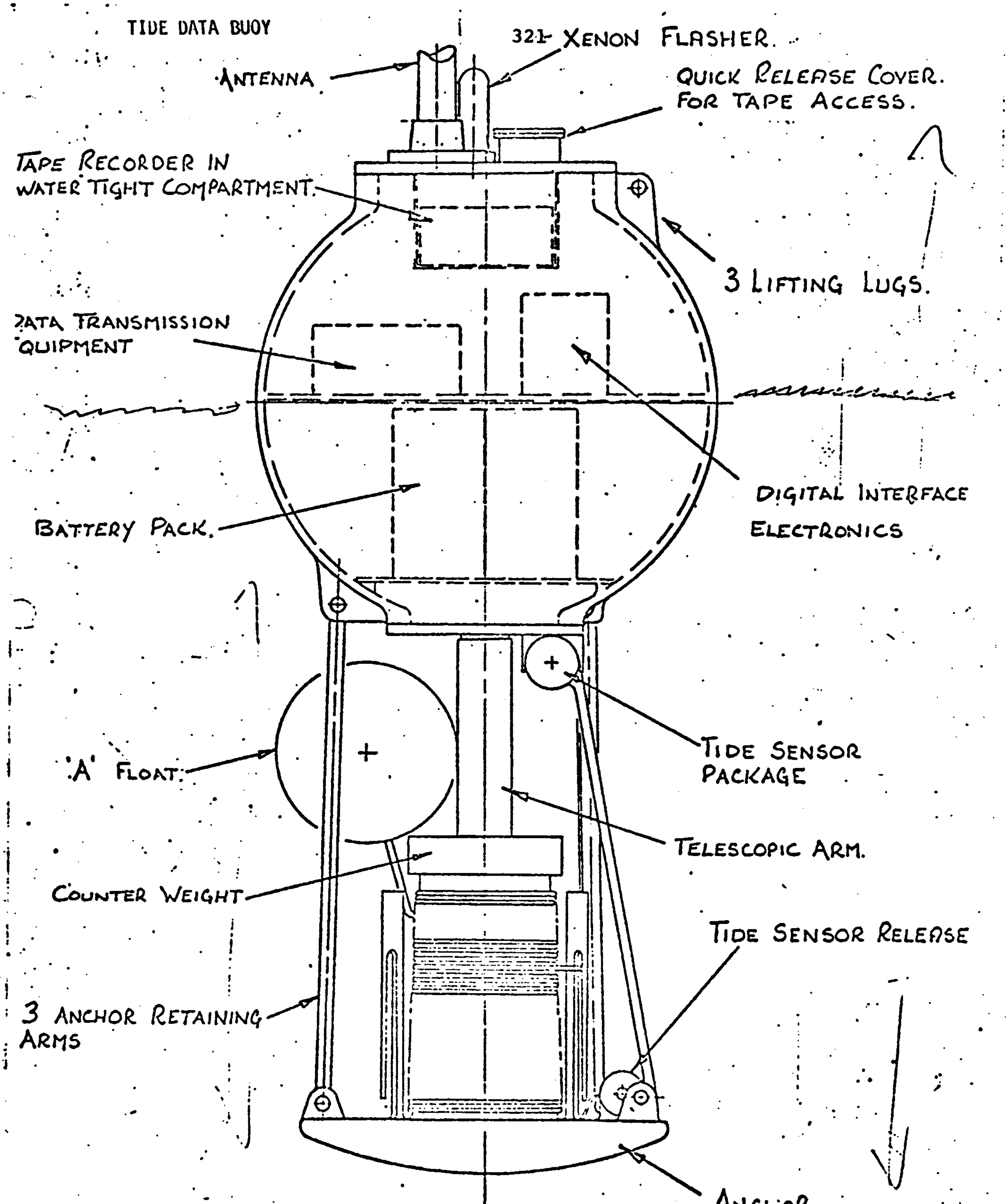


4. ANCHOR RESTING ON SEA BED WITH CABLE DEPLOYED AND RETAINING ARMS LOCKED DOWN. SENSOR STILL ATTACHED.



5. SENSOR DEPLOYED AWAY FROM ANCHOR BY TIMING DEVICE AND SYSTEM FULLY OPERABLE.

TIDE DATA BUOY



DATA BUOY LAYOUT

TABLES

ENVIRONMENTAL DATA BUOYS

	BUOY TITLE	PURPOSE AND USE	NUMBER OWNED	SIZE AND SHAPE	INITIAL PURCHASE PRICE
SURFACE BUOYS					
1.	WHOI SURFACE MOORING	Measure current profiles	several	8 ft diam Toroid	$22.000 + 7/600/m
2.	NOMAD BUOY (AN/SNT-1)	Environmental data collection and transmission	2	Boat - length 20' beam 10' height 9	$80,000
3.	NAFI (AN/SNQ-4)	Automatic meteorological station for shallow water	3	8 ft diam Toroid	$58,000
4.	BUMBLE BEE	Monitor weather and sea temperatures for long periods	4	Spotted cylinder 12' long 8' diam	$27,200
5.	FLIP	Research (oceanographic and acoustic)	1	Cylindrical spar 355' long 20' diam	$650,000
6.	TOTEM	Offshore sensing of atmospheric and ocean conditions, real-time telemetry to shore based computer	2	Spar 184' x 40"	$60,000
7.	SODS	Oceanographic research	2	16 ft diam Discus	$450,000
8.	MOLLO-CHRISTENSEN SPAR	Air-sea interaction studies	2	Cylindrical spar 72'4" x 18"	$100,000
9.	MONSTER	Oceanographic research	2	40 ft diam Discus	$450,000
10.	ERTS & RAMS TRACK BUOY	Satellite telemetering of oceanographic data and satellite tracking of ocean currents	3	42' long 2' max diam	$13,000
SUBSURFACE BUOYS					
1.	WHOI SUBSURFACE operating depth 100 m	Measure current profile	3	4" diam sphere	$58,000
2.	WHOI BOTTOM MOORING operates 100 m off bottom	Measure bottom currents	1	short cylinder	$10,000 + 7,600/m
3.	DANKO 1000#, DANKO 500#, NET BUOY 325# operating depth (1-2) 2000' (3) 300'	Measure subsurface current	13 18 108	(1) 1000# buoyancy sphere (2) 500# sphere (3) 325# sphere	$35,000
COMBINATION BUOYS					
1.	CURRENT PROFILER-DIVING	Ocean current profiling	1	Bottle slides from ship, up and down a taut line	$25Ç000
2.	CURRENT PROFILING ARRAY (NISKIN)	Current profiles	1	Surface-floating instrument line Subsurface spheres	$20,000 - 50,000
3.	TIDE DATA BUOY	Monitor shallow-water bottom temperatures and pressures	1	Surface-30" sphere Subsurface-18" sphere	$50,000

Developed by Clifford Petersen

NOAA ENVIRONMENTAL DATA BUOYS

SURFACE BUOYS

	BUOY TITLE	PURPOSE AND USE	SIZE AND SHAPE	COST*
1.	NDBO Severe Environment Buoy (5)**	Environmental data collection and transmission	40' diam discus	$450K
2.	NDBO Severe Environment Buoy (Prototype)	Environmental data collection and transmission	29' long deep keel buoy	$450K
3.	NDBO Moderate Environment Buoy (4)**	Environmental data collection and transmission. Drifting or moored	46" diam sphere	$100K
4.	NDBO Moderate Environment Buoy (3)**	Environmental data collection and transmission	Horizontal cylinder 11 1/4 long by 4 1/2 diam	$100K
5.	NDBO Moderate Environment Buoy (3)**	Environmental data collection and transmission Drifting	Vertical cylinder, 10' high by 5 1/2 diam	$100K
6.	NDBO Drifting Research Buoy	Research Drifting meteorological	12' long modified spar	$ 5K
7.	NDBO Marker Buoy (3)**	Radar Reflector Buoy	Vertical cylinder 4' high by 6.5' diam	$1.5K
8.	Mild Environment Buoy (10)**	Environmental data collection and transmission (sheltered areas)	9' diam conical/ discus	$ 15K
9.	NDBO Polar Ice Buoy	Environmental data collection and transmission	30' spar implanted in pack ice	$7.5K

* Reproducible cost -- total cost would depend on mooring.
** Number of buoys available