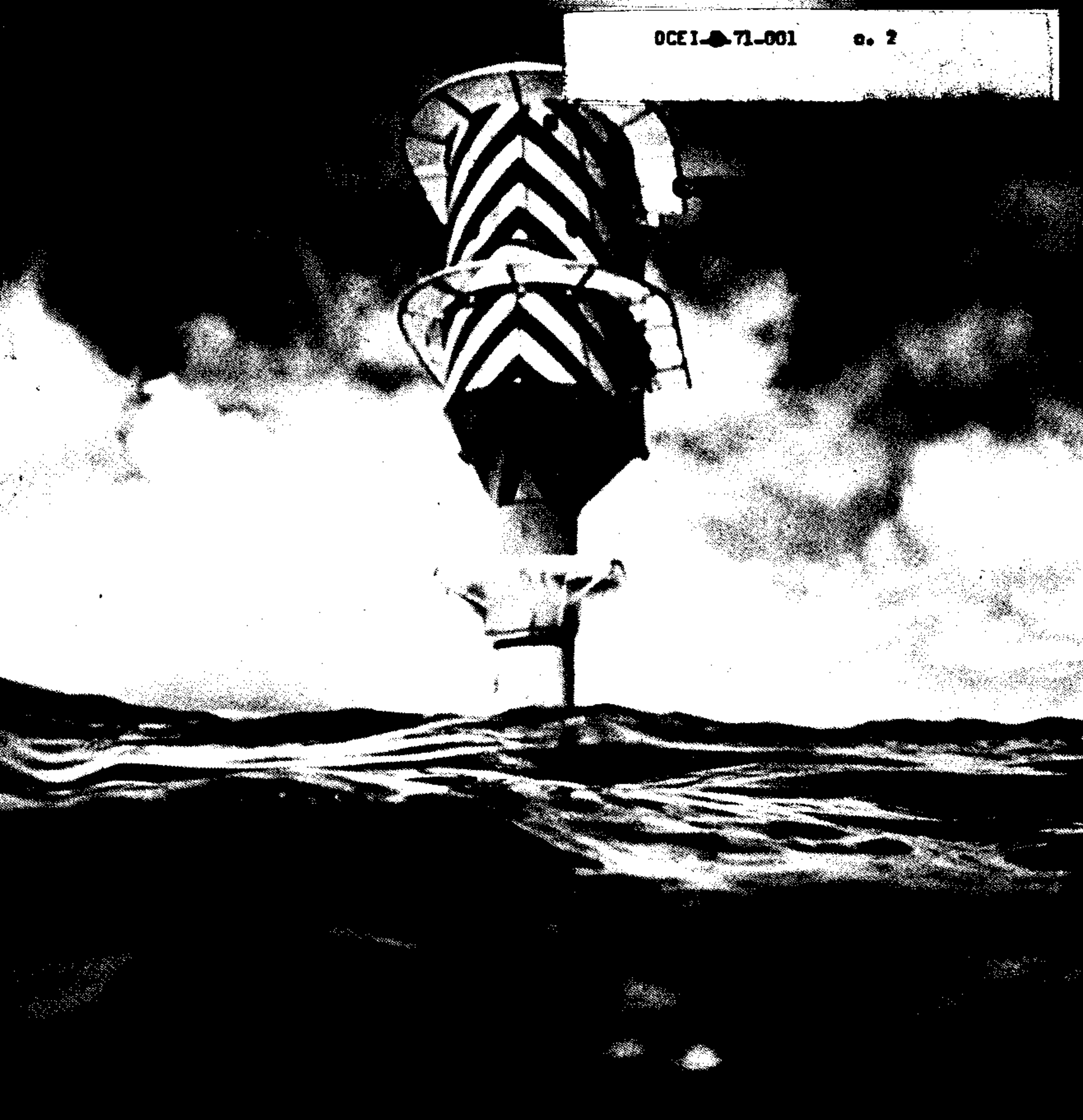

MOSES: A Feasibility Study

Oceanic Institute
Waimanalo, Hawaii

Report No. OI-70-28-1

MANNED OPEN SEA EXPERIMENTATION STATION (MOSES)
A Feasibility Study
Final Report on Phase I of a Coherent Area Program in Utilization of the Open Sea

by

OCEANIC INSTITUTE
the research division of
The Oceanic Foundation

Makapuu Oceanic Center
Waimanalo, Hawaii 96795

for

National Sea Grant Program
National Oceanic and Atmospheric Administration
U.S. Department of Commerce
Rockville, Maryland 20852

Principal Investigator - Kenneth S. Norris, Ph.D.
Director, Oceanic Institute

Project Manager - Joe A. Hanson, Chief Scientist
Systems Analysis Division

June 30, 1971

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Principal MOSES Phase I project staff members were:

Ernest R. Simmerer - Chief Engineer
Guy N. Rothwell - Project Engineer
Thomas C. Silkwood - Project Engineer
Harold Skowbo - Engineering Consultant
Michael Smookler - Quality Assurance Consultant
Dr. Ludwig Seidl - Mathematical Simulation
Capt. C. B. Momsen - Design Consultant
Dr. Frederick Speiss - Design Consultant
Dr. Steven Neshyba - Design Consultant
Donald A. Cole - Systems Engineering Consultant
Dr. Charles Bretschneider - Ocean Engineering Consultant
John Guswell - Scale Model Construction Supervisor
Dr. Walter Arnell - Photographic Recording
Charles Peterson - Photographic Recording
Diane Aller - Documentation
Carol Hanson - Project Secretary

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Front cover: 1:13 scale model undergoing ocean tests
Photo by Chuck Peterson, Makapuu Oceanic Center

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Dr. Richard Hallgren 1
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Rockville, Maryland 20852

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Rockville, Maryland 20852

Dr. Robert M. White 1
Administrator
National Oceanic & Atmospheric Administration
Rockville, Maryland 20852

Dr. Kilho Park, Head 1
Oceanography Section
Division of Environmental Sciences
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20550

Dr. Thomas Jones 1
Deputy Assistant Director
National and International Programs
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20550

Mr. David Wallace 1
Associate Administrator
National Oceanic & Atmospheric Administration
Rockville, Maryland 20852

David S. Johnson 1
Director, ESSA National Environmental Satellite Center
U.S. Department of Commerce
Washington, D.C. 20233

Dr. Stephen Neshyba 1
Oregon State University
Corvallis, Oregon 94331

Dr. Frederick Speiss 1
Scripps Institution of Oceanography
La Jolla, California 92037

Mr. C. B. Momsen 1
AC Electronics - Defense Research Lab
6767 Hollister Avenue
Goleta, California 93017

Mr. Donald Cole Informatics, Inc. 465 N. Kainalu Drive Kailua, Hawaii 96734	1
Dr. Charles Bretschneider Dept. of Ocean Engineering University of Hawaii Honolulu, Hawaii 96822	1
Dr. Ludwig Seidl Dept. of Oceanography University of Hawaii Honolulu, Hawaii 96822	1
Dr. John C. Craven Dean of Marine Affairs 255 Spalding Hall University of Hawaii Honolulu, Hawaii 96822	1
Dr. Morton Rosenberg Associate Dean of Research University of Hawaii Honolulu, Hawaii 96822	1
Dr. Sanford S. Atwood President, Emory University 1364 Clifton Rd., N.E. Atlanta, Georgia 30322	1
Dr. Joseph E. Henderson Applied Physics Lab U. of Washington 1013 N.E. 40th Seattle, Washington 98105	1
Dr. Gifford B. Pinchot John Hopkins University Baltimore, Maryland 21218	1
Dr. Edward F. Klima Director, National Marine Fisheries Service Pascagoula, Mississippi 39567	1
Mr. Taylor A. Pryor President, The Oceanic Foundation	1
Dr. Kenneth S. Norris Director, Oceanic Institute	1
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Dr. W. F. Hamner Department of Zoology University of California Davis, California 95616	1

Dr. R. D. Gerard 1
Lamont-Doherty Geological
Observatory
Columbia University
Palisades, New York 10964

Dr. Keith Chave 1
Chairman, Department of
Oceanography
University of Hawaii
Honolulu, Hawaii 96822

Mr. Arden L. Pratt 1
American Association of
Junior Colleges
One Dupont Circle
Washington, D.C. 20036

Dr. Willard J. Pierson, Jr. 1
Professor of Oceanography
School of Engineering & Science
New York University
University Heights
New York, New York 10453

Mr. Arthur Mathieson 1
Assistant Professor of
Botany
College of Agriculture
University of New Hampshire
Durham, New Hampshire 03824

Mr. J. E. Thomas 1
Director, Gulf Coast
Technical Institute
Mississippi State University
State College, Mississippi 39762

Dr. Tapan Banerjee 1
Southern Maine Vocational
Technical Institute
Fort Road
South Portland, Maine 04104

Mr. Gordon L. Chan 1
College of Marin
Kentfield, California 94904

Mr. S.T. Hsu 1
Professor of Mechanical
Engineering
College of Engineering
University of Maryland
College Park, Maryland 20742

Dr. Donald L. Woodrow 1
Department of Geology
Hobart & William Smith College
Geneva, New York 14456

Mr. Ted Boaz 1
Division of Technical &
Vocational Education
Del Mar College
Corpus Christi, Texas 78404

Dr. James M. Parks 1
Lehigh University
Bethlehem, Pennsylvania 18015

Dr. John Wood 1
Virginia Institute of
Marine Science
Gloucester Point, Virginia 23062

Dr. Harold J. Humm 1
Director, Marine Science
Institute
University of South Florida
Bay Campus
St. Petersburg, Florida 33701

Dr. John Noakes 1
Department of Geology
University of Georgia
Athens, Georgia 30601

Mr. James Andrews 1
Skidaway Institute of
Oceanography
55 West Bluff Road
Savannah, Georgia 31406

Mr. Paul Venno 1
Dept. of Sea & Shore Fisheries
State House
Augusta, Maine 04330

Dr. George Fulton 1
Department of Biology
Boston University
Boston, Massachusetts 02215

Dr. Alva Harris & Curt Rose 1
Dept. of Biological Sciences
Nicholls State College
Box 2021
Thibodaux, Louisiana 70301

Dr. Robert Corell 1
Chairman, Mechanical
Engineering Dept.
University of New Hampshire
Durham, New Hampshire 03824

Dr. Edward L. Beckman 1
University of Texas
School of Medicine
Galveston, Texas 77550

Dr. Warren R. Healey 1
Director, Marine Resource
Division
New England Council
Statler Office Building
Boston, Massachusetts 02116

Dr. Frank Mather, III 1
Woods Hole Oceanographic
Institution
Woods Hole, Massachusetts
02543

Dr. David Hickok 1
Director, Sea Grant Program
University of Alaska
108 East Third Avenue
Anchorage, Alaska 99501

Prof. Charles Stephan 1
Chairman, Department of
Ocean Engineering
Florida Atlantic University
Boca Raton, Florida 33432

Dr. Russell Riese 1
Chief, Coordinating Council for
Higher Education
1020 12th Street
Sacramento, California 95814

Dr. William Herrnkind 1
Project Director
Caribbean Institute
College of the Virgin Islands
St. Thomas, Virgin Islands 00801

Dr. Oswald Roels 1
Lamont-Doherty Geological
Observatory
Columbia University
Palisades, New York 10964

Dr. Alfred H. Keil 1
Head, Department of Naval
Architecture & Engineering
Massachusetts Institute of
Technology
Cambridge, Massachusetts 02139

Dr. Richard Tibby 1
Catalina Marine Science Center
University of Southern California
University Park
Los Angeles, California 90007

Dr. Rita Colwell 1
Department of Biology
Georgetown University
Washington, D. C. 20007

Dr. Wheeler North 1
California Institute of Technology
Pasadena, California 91109

Dr. Jack Davidson 1
Director, Sea Grant Program
University of Hawaii
2540 Maile Way
Honolulu, Hawaii 96822

Dr. John P. Harville 1
Director, Moss Landing
Marine Laboratory
Moss Landing, California 90350

Dr. Robert W. Holmes 1
Associate Professor of
Marine Biology
University of California
Santa Barbara, California 93106

Dr. Herbert Frolander 1
Director of Sea Grant Program
Oregon State University
Corvallis, Oregon 94331

Dr. Jack Armstrong 1
Sea Grant Director
University of Michigan
Ann Arbor, Michigan 48104

Dr. John Knauss 1
Graduate School of
Oceanography
University of Rhode Island
Kingston, Rhode Island 02881

Dr. Richard C. Bader 1
Associate Director, Institute
of Marine Science
University of Miami
Miami, Florida 33149

Dr. John C. Calhoun, Jr. 1
Director, Sea Grant Program
Texas A&M University
College Station, Texas 77843

Mr. Scott Daubin 1
Woods Hole Oceanographic
Institution
Woods Hole, Massachusetts 02543

Dr. Robert Ragotzkie 1
Coordinator, Sea Grant Program
University of Wisconsin
1225 West Dayton Street
Madison, Wisconsin 53706

Dr. John Lyman 1
Sea Grant Program Coordinator
University of North Carolina
Chapel Hill, NorthCarolina

Dr. Ramsey Parks 1
Santa Barbara City College
Cliff Drive and Leadbetter Drive
Santa Barbara, California 93105

Mr. William H. Diment 1
Dept. of Geological Science
University of Rochester
Rochester, New York 14627

Dr. John P. Breslin 1
Director, Davidson Laboratory
Stevens Institute of Technology
Castle Point Station
Hoboken, New Jersey 07030

Dr. Richard Ridenhour 1
Sea Grant Program Coordinator
Humboldt State College
Arcata, California 95521

Dr. William S. Gaither 1
Dean, College of Marine Studies
University of Delaware
Newark, Delaware 19711

Dr. Jack Van Lopik 1
Sea Grant Coordinator
Louisiana State University
Baton Rouge, Louisiana 70803

Dr. George Shor, Jr. 1
Associate Director, Scripps
Institution of Oceanography
La Jolla, California 92037

Captain Arthur Jordon 1
Sea Grant Coordinator
Cape Fear Technical Institute
Wilmington, North Carolina 28401

Dr. Donald F. Mulvilhill 1
Department of Marketing
Kent State University
Kent, Ohio 44240

Dr. Martin F. Stempien, Jr. 1
Osborn Laboratories of
Marine Science
New York Zoological Society
Seaside Park, Coney Island
Brooklyn, New York 11224

Mr. Nelson Marshall 1
Graduate School of Oceanography
University of Rhode Island
Kingston, Rhode Island 02881

Alfred J. Weinheimer 1
Professor of Chemistry
University of Oklahoma
660 Parrington Oval
Norman, Oklahoma 73069

Dr. Stanley Murphy 1
Director, Sea Grant Program
University of Washington
Seattle, Washington 98105

Mr. Glen Wade 1
Department of Electrical
Engineering
University of California
Santa Barbara, California 93106

Mr. John H. Lech 1
Department of Pharmacology
Medical College of Wisconsin
Milwaukee, Wisconsin 53233

Mr. Clarke Williams 1
Nassau-Suffolk Regional
Planning Board
Hauppauge, Long Island,
New York 11787

Mr. Robert W. Brody 1
College of the Virgin Islands
Caribbean Research Institute
St. Thomas, Virgin Islands 00801

Mr. James F. Wright 1
Executive Director
Delaware River Basin Commission
25 Scotch Road
Trenton, New Jersey 08628

Mr. Clinton Dawes 1
University of South Florida
Tampa, Florida 33620

Dr. Sidney Upham 1
Director, Universities
Marine Center
P.O. Drawer AG
Ocean Springs, Mississippi 39564

Mr. Ajay K. Bose 1
Department of Chemistry &
Engineering
Stevens Institute of Technology
Hoboken, New Jersey 07030

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ABSTRACT

This document contains a description of a manned stable ocean platform to support a program of research in utilization of the open sea. Operation and performance criteria for the platform are derived. A preliminary engineering design employing a single spar buoy approach is developed. The results of an original mathematical model of the buoy's dynamics are given. A scale model is built and tested in still water and at sea. The structure of a quality assurance program is developed. And an estimate of costs for final design, construction, quality control, and sea trials is presented. This work was performed by the Oceanic Institute, Waimanalo, Hawaii, under Sea Grant No. 1-35319, for the National Oceanographic and Atmospheric Administration, U.S. Department of Commerce, as Phase I of "A Coherent Area Program in Utilization of the Open Sea".

I. INTRODUCTION

A. The Problem

The world's resources for agricultural production are already reaching toward hard limits in terms of arable land, water for irrigation, mineral resources for production of fertilizer and economical energy availability. In addition, many of the world's current fisheries resources already show signs of over-exploitation, warning us that they will not sustain the enormous pressures our growing protein needs will impose on them.

Serious efforts have been made over the past half-century to culture edible marine forms as we do land forms. Now perhaps five to ten percent of the world tonnage of marine products are derived from such cultivation. Almost without exception, these cultivated crops have been raised in bays, estuaries, lakes or ponds, where drainage from the land enriches the waters with mineral and organic nutrients. While yields per acre are spectacular, showing great promise for marine agriculture (mariculture), the available acreage of this type is sharply limited. In addition, the wastes of expanding coastal populations are, at the moment at least, posing a serious threat to mariculture near areas of dense population. The problem to which we direct our attention in our Coherent Area Program, then, is that of determining means of utilizing the potentially vast protein resources of the open sea through advanced mariculture technology and improved pelagic organism attraction and capture techniques.

B. A New Potential Resource

If we examine the open oceans of the world, we find a quite astonishing picture. Most of the earth's oceanic surface is underlain by water depths greater than 1,000 meters. This deep, cold oceanic water fills ten times the entire volume of the continental land masses above sea level. The properties of this water should be examined carefully, because it may constitute the world's most abundant natural food resource.

From the viewpoint of mariculture, the surface waters of the tropical and temperate zone seas are relatively barren. However, directly below, in the colder layers shielded from sunlight, concentrations of nutrients are everywhere six to 200 times their surface values. Brought up into direct sunlight and warmed by solar radiation and surrounding waters, the nutrient-rich lower layers produce biological growing conditions similar to those found in estuarial water. Could this be done on a large enough scale, the potential approaches half the entire surface of the globe.

In all the history of agriculture, success was wrought through manipulating the crop, its environment or both. Certainly the same can be true in open-ocean mariculture. But a host of questions arise. First, can open-ocean mariculture of the type we envision be made to work? If so, what is the magnitude of the scale we may consider? What are the technological problems? What would be the effect of such a program on regional and global ecosystems? How would such an effort on a large scale fit into and modify international economics and politics? These questions and more are those to which we propose to attend in our Coherent Area Program in Utilization of the Open Sea. The design and fabrication of MOSES is the beginning.

C. The MOSES Program

The MOSES concept had its origin in a meeting at Makapuu in early 1970. In attendance were Taylor A. Pryor, Dr. Kenneth S. Norris, and Ernest R. Simmerer. At that meeting the concept of combining a large silo-type fish enclosure with a manned spar buoy that would be equipped with underwater observation stations and means for drawing up large quantities of nutrient-rich water was initiated. It was thought that, if such a system could be set adrift in the Pacific Equatorial current system for extended periods, it would allow observation and on-site analysis of the behavior of edible pelagic animals and provide an ideal platform for the conduct of open ocean mariculture research.

From that beginning a comprehensive program has developed, as outlined in the Oceanic Institute's proposal "A Coherent Area Program in Utilization of the Open Sea", submitted to the National Sea Grant Program of the U.S. Department of Commerce on September 22, 1970. This proposal, a subsequent Sea Grant Program site visit, and a later revised proposal resulted in Sea Grant No. 1-35319 to the Oceanic Institute for a feasibility study of the MOSES concept.

The work was completed in May 1971, and is designated as Phase I of our Coherent Area Program in Utilization of the Open Sea. Phase II, expected to begin in late 1971, will consist of final engineering design, construction, acceptance testing, and sea trials. This phase will occupy 18 months.

If the program proves viable, a series of moored and drifting expeditions in the Hawaiian area to perfect instruments, hardware and procedures will begin early in 1973. After this, the years 1974, 1975, and 1976 will see long-range drifting expeditions in the Pacific Equatorial current and perhaps other current systems. It is our intent that these expeditions will be supported from advanced bases on islands near the station's path.

Planned principal areas of investigation are:

1. The technology and logistics of open-ocean occupancy via a stable ocean platform

2. Utilization of the scattering layer

3. Open-sea mariculture technology

4. Attraction and capture techniques for pelagic organisms

5. The spread of pollutants in the open sea

6. Ocean current structures

7. Navigation and positioning techniques for a free-floating platform

Within the Coherent Area concept of the National Sea Grant Program, several cooperative programs are under development at the University of Hawaii. Some of these programs are in conjunction with the U.S. National Marine Fisheries Service, the B. P. Bishop Museum, and the ESSA Tsunami Group. As the MOSES program gains momentum, we feel no doubt that many other valuable open sea research programs will be attracted to this new capability.

II. RESULTS OF PHASE I: MOSES FEASIBILITY STUDY

In this section, the work performed under Phase I is summarized. Detailed documentary support for the summaries is contained in Appendixes A through F to this report. The major components of the work involved (1) the development of mission requirements and design criteria, (2) development of a preliminary engineering design, (3) testing of the preliminary design concepts through the application of computerized mathematical simulations, (4) testing of the completed preliminary design with a 1:13 working scale model of MOSES in real sea conditions, (5) development of the structure for a quality assurance and acceptance testing program to be employed in Phase II, and (6) the derivation of detailed Phase II cost estimates. The work began with the development of a tentative design approach even before formal application for a Sea Grant was made. The initial activity under the grant was a two day conference of MOSES project personnel and recognized authorities in wave dynamics, systems management and spar buoy design to examine the feasibility of the preliminary MOSES design approach. The above subjects are discussed in this section of the report.

A. Design Feasibility Conference

A two-day Design Feasibility conference was held early in the project. The purpose of this conference was to pool the knowledge and experience gained from previous large spar buoy projects with that of authorities in ocean wave theory and systems management, and to bring this experience to bear in a constructively critical atmosphere on the problems to be solved in the present case, as well as the design concepts held by MOSES project personnel. Attending the conference were:

Dr. Charles Bretschneider; Chairman, University of Hawaii Department of Ocean Engineering and Director of Look Laboratory of Ocean Engineering

Donald A. Cole; Manager, Informatics, Inc., Hawaii

Joe A. Hanson; Chief Scientist, Systems Analysis Division, Oceanic Institute and MOSES Project Manager

Capt. C. B. Momsen; Former Naval Project Director on the FLIP Spar Buoy project and Manager of the POP spar buoy program for AC Electronics Defense Research Laboratories

Dr. Stephen Neshyba; Director of the TOTEM project, Oregon State University

Dr. Kenneth S. Norris; Director, Oceanic Institute and Principal Investigator of the Institute's Coherent Area Program in Utilization of the Open Sea

Guy N. Rothwell; MOSES Project Engineer

Dr. Ludwig Seidl; Professor of Ocean Engineering, University of Hawaii

Thomas C. Silkwood; MOSES Project Engineer

Ernest R. Simmerer; Naval Architect and MOSES Chief Engineer

Harold Skowbo; Manager, Makai Range, Inc. and MOSES Project Engineer

Dr. Frederick Spiess; Scripps Institution of Oceanography, Director of the FLIP Program

The conference began with a presentation of the proposed Coherent Area program by Dr. Norris. The conferees explored the ramifications of the program in terms of required platform performance, and produced a draft statement of the main functional criteria the platform should be designed to meet. In this session the mariculture experimentation emerged as the prime factor in the MOSES design criteria.

The tentative MOSES single spar buoy with internal elevator design concept was then presented. Group critique then explored its suitability to the scientific program, structural adequacy, hydrodynamics, towing and translating, safety, ease of construction, operation, maintenance and cost. Several alternate design schemes were explored also. These included multi-legged platforms, a design similar to FLIP, and the use of an exterior submersible chamber for deep observation rather than the proposed internal elevator. The single spar buoy with internal elevator concept held valid throughout these explorations as the only one with a potential for meeting the mariculture requirements within reasonable monetary bounds. In detailed discussions, the conferees then examined the various systems MOSES would require--electrical, mechanical, and pneumatic--giving particular attention to safety and reliability.

On the last day of the conference, a revision of the original design concept was drafted and a fair consensus was achieved that, with appropriate modifications, it could work. Though, of course, no final conclusions were drawn, the MOSES concept gained greatly in clarity, breadth and confidence by this conference.

B. MOSES Operational Criteria

A working set of operational criteria has been derived, as a basic statement, which any platform design must meet in order to fulfill the requirements of the scientific program. This set of criteria stems from four sources:

- The scientific program itself,
- The use of Hawaii as home base, with other island ports in the Pacific as transient advanced bases,
- Operation of MOSES by Makai Range, Inc., and
- Safe, efficient operations within the ocean environment throughout the Pacific between latitudes 30 north and 30 south for extended periods without ship support.

Principal considerations are ability to handle safely all expected environmental conditions, under tow and in the vertical position; ease of operation, maintenance and at-sea resupply; crew comfort; and adaptability to a broad range of experiments.

A detailed discussion of these criteria is contained in Appendix A, Operational Criteria. They are intended to guide the MOSES final design, as they did the preliminary design. Appendix A should not require amendment except in response to substantial shifts in scientific mission requirements.

C. The MOSES Design Concept

There is nothing particularly novel about spar buoys. They are a proven means of attaining relative stability and of penetrating the upper regions of oceanic depths. Smaller, unmanned versions are in use as stable ocean instrumentation platforms and at least three large (200 ft +) manned--or mannable--versions (FLIP, SPAR, and POP) are in operation at present in the U.S. All the versions preceding MOSES, however, have been designed with floodable lower shaft sections, allowing the buoyancy of one end to be replaced with water to translate the buoy from the horizontal towing attitude to the vertical on-station attitude. MOSES, though, requiring one-atmosphere human occupancy inside its entire length, posed unique problems for its designers. To translate MOSES from the horizontal towing attitude to a stable vertical attitude, it is necessary to overcome the buoyancy of the air-filled shaft, since the shaft must necessarily remain unflooded. Moreover, since the lower shaft must resist external pressures of up to nine atmospheres (133 psi), it must be designed as a pressure vessel. In addition, the requirements for manned and unsupported operation for extended periods establishes requirements for fuel, fresh water, and waste containment as well as adequate human living and laboratory facilities.

The coupling of all these mission-based design requirements with economic considerations dictated the MOSES general design concept presented in Figure 1. The upper house provides living and working accommodations for a crew of eight as well as machinery and equipment space. The shaft is hollow and provided with elevator service and viewing stations along its entire length. Fixed lead ballast weights the lower end (bow in towing) to counteract the buoyancy of the lower shaft. A small laboratory is placed at the bottom of the shaft. Both the shaft and the bottom laboratory are maintained at one atmosphere pressure. The main ballast tank when emptied provides a means of overcoming the weight of the lead ballast to bring and hold MOSES in the horizontal position for towing. When flooded it allows MOSES to assume a stable vertical attitude. The variable ballast section allows control of overall buoyancy to adjust for variances in load as equipment and supply complements vary. The envelope which contains variable ballast also contains fuel, fresh water and sewage storage. The external elevator provides a mechanism facilitating at-sea service and supply and a means of transporting heavy items from the bottom of the upper house to the sea surface and down to forty feet below. The remainder of this subsection treats the design in somewhat more detail but still at a very general level. Appendix B contains an engineering description of the preliminary design. Figure 1 is a generalized sketch of MOSES in the vertical attitude showing its major features.

1. Main and Variable Ballast Tanks

Both the main ballast tank and variable ballast tank are designed to resist external as well as internal pressure. In both tanks flooding is accomplished by opening vent valves to the atmosphere and flood valves to the sea. Voiding is accomplished by introducing compressed air to force the contained water out through open flood valves. The main ballast section is divided into two parts capable of separate flooding and venting for purposes of assuring stability during translation. The displacement of the main ballast tank is 245 short tons and the weight of the variable ballast at load water line is 25 short tons. Construction material is 3/8" to 5/8" mild steel

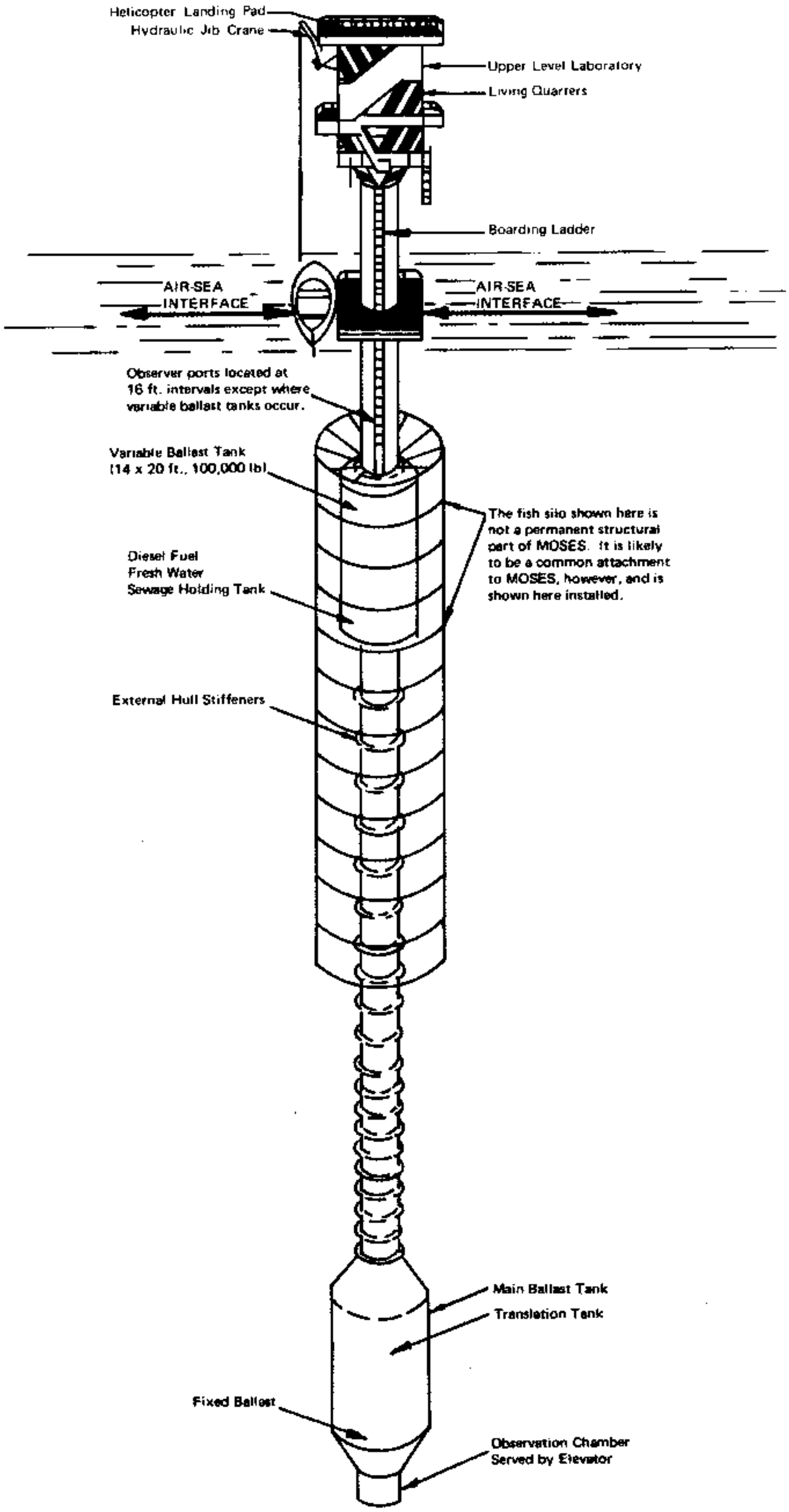

Fig. 1 Generalized sketch of MOSES in the vertical attitude showing its major features

2. Shaft

The 260 ft long main shaft is the buoy's primary structural element. It must resist substantial imposed loads. A shaft diameter of seven feet was selected as the minimum large enough to resist imposed loads and to contain the elevator shaftway plus observer stations and the necessary ducts, cables, tubes and conduits. Other conditions argue for the smallest possible diameter. These are: (1) minimum cross-section area at the water surface to minimize air-sea interface effects, and (2) minimum total buoyancy of the shaft in order to reduce the amount of fixed ballast needed.

While under tow in a seaway and during translation the major stresses are in bending. For example, one extreme bending condition, "sagging", occurs when the house and main ballast tank are buried in adjacent waves, leaving the middle portion of the buoy unsupported (Figure 2). The shaft is consequently made from a high-strength weldable Cor-Ten steel 1-1/2" thick. While vertical, the buoy's shaft must resist external hydrostatic pressure. So stiffening rings have been provided on the lower shaft to maintain elastic stability.

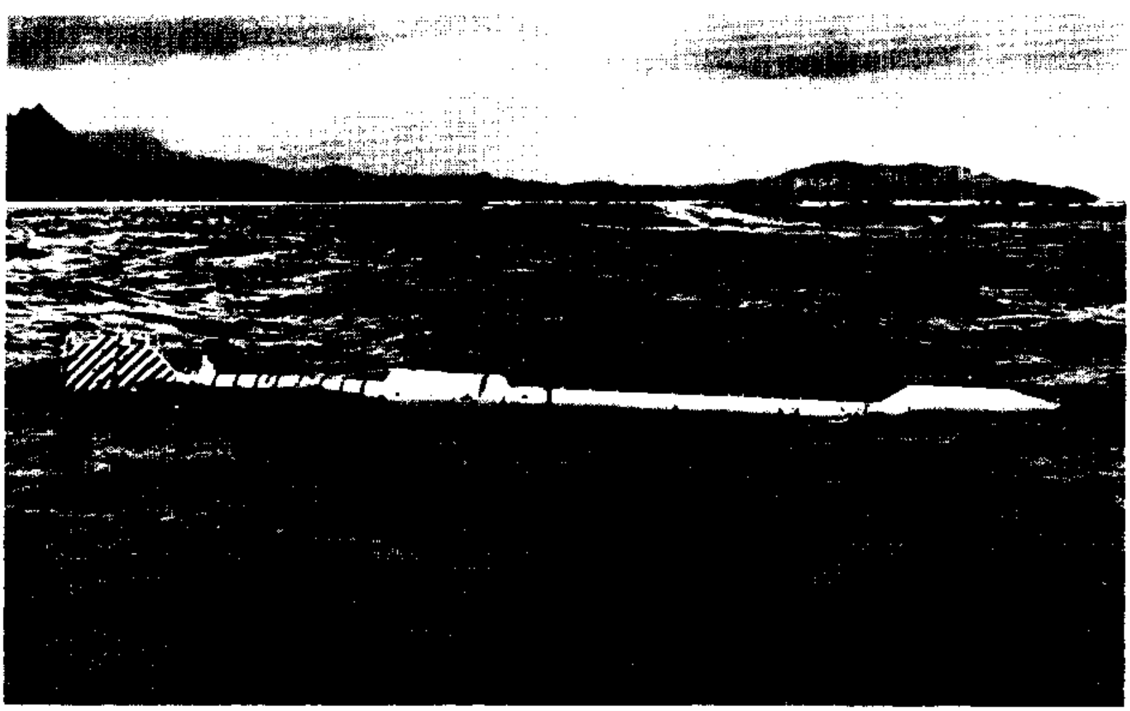

Fig. 2 Scale model of MOSES under tow, showing conditions which produce "sagging" stress.

3. Upper House

The upper house is a three story structure fabricated of corrosion-resistant aluminum. It is "D" shaped as viewed from above in order to stabilize the buoy's wind attitude in the vertical and provide roll resistance in the horizontal. Its lower portion constitutes a faired frustrum to the main shaft to reduce towing drag and to cushion the braking effect induced by the house's buoyancy in case of extreme heave motions. This lower frustrum portion is also the upper terminal of the elevator shaft. The first deck level contains machinery, equipment and storage space. The upper deck provides sleeping and sanitary accommodations for a crew of eight. The life support capacity of MOSES is a crew of four for thirty days of unsupported operation or a crew of eight for fifteen days. The middle deck level contains galley and laboratory facilities. The layout of this deck is purposely general in order that the widest possible variety of laboratory equipment may be accommodated on sequential missions.

The roof of the house is designed to be used as a helicopter landing pad as well as a base for meteorological observations. But it is so designed that additional enclosed laboratory space could be put there as well. External walkways are provided. Enclosed, watertight stairways connect all levels. All external hatches are watertight. The external elevator is reached via an outside ladder from the upper house; the internal elevator via an internal stairway. Heavy articles are handled by the jib crane located on the roof.

4. On-Board Systems

Most on-board systems can be used in both horizontal and vertical attitudes. But, because no one is expected to live aboard the buoy while it is horizontal, no provision was made for operating the plumbing system in the horizontal attitude. The buoy comprises fourteen major systems, including the hull structure, house structure, and miscellaneous finish items. Others are:

a. An external elevator, surrounding the main shaft, which can travel from from just below the house 60 feet downward to the upper ballast tank. With a 4000-lb live load capacity, it can be used to launch and retrieve small boats or a small submersible, to assist in resupply, and to support diving operations, sample recovery, handling of marine animals, and installation or dismantling of nets, cages, and other bulky experiments. It is operated by hydraulic power.

b. An internal elevator travels the entire length of the main shaft, from the lowest level of the house to the observation laboratory at 227 feet below sea level. Capacity is two men plus 600 pounds. It gives access to all parts of the main shaft, including all observer stations, storage lockers, air storage tanks, and all machinery located in the shaft. It is electrically powered.

c. The electrical system has for prime mover a pair of 37.5 KVA, diesel-driven alternators, with synchronizing and load-sensing gear, and transfer switching for connection to dockside power. Primary output power is 120/208 volt, 20 Kw battery charger. Output from the charger feeds a DC bus and floats the buoy's main battery, rated for 45 Kwh @ 120 volts. The DC bus powers the internal elevator, certain emergency pumps and lights, and a solid-state inverter which will deliver up to 10 Kw high-purity, 60-cycle, 120-volt AC power for instruments. The main battery is sized to allow up to eight hours silent ship* operation, with a nominal 16-hour recovery time.

Provision is made for demountable exterior lighting, both above and below water level. Underwater hull penetrations are provided at the bottom observation laboratory and at each observer station.

d. A 2200 psi hydraulic system is provided, to operate the external elevator and a jib crane, located on the upper deck of the house.

e. The pneumatic system supplies compressed air for blowing various tanks, including ballast tanks, sewage holding tank, and diesel and freshwater tanks, and operation of several remote valves. It also supplies medically filtered air for filling divers' SCUBA tanks. A total of 27,000 standard cubic feet of air is stored aboard, enough for two complete translation cycles. Recharge time, from an on-board compressor, is less than 24 hours.

f. Ventilating and air conditioning systems provide the machinery room and all spaces below the house with ventilation by forced-draft. Air quality monitoring equipment is provided in the bottom observation laboratory. Provision is made for installation of air-conditioning refrigeration and filtering.

g. A waste disposal system comprised of conventional marine plumbing and a 5,500 gallon sewage holding tank is provided to prevent contamination of nearby waters. The 5,500 gallon tank is considered to be nominally sufficient for 10 days. Its discharge point is located at the bottom of the variable ballast tank. Provision can be made for chlorinating sewage before discharge, but it is not considered necessary or desirable for discharge into the open ocean.

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* Operation with all major noise-producing machinery turned off; considered necessary for certain animal attraction experiments.

h. The water supply system furnishes pure fresh water for drinking and to domestic fixtures. A 3,500 gallon capacity is provided and it is refillable at sea. This system can include chlorination also. A similar system supplies salt water for the toilet, for washdown, and for laboratory wet tables. Except for exterior washdown, salt water discharges into the sewage holding tank.

i. Navigation and communication equipment includes a high-seas HV/VHF transmitter and receiver, UHF short-range transceiver, radar, loran, and a recording depth finder, as well as an internal intercommunication system and emergency sound-powered telephone.

j. Deck gear and ground tackle includes anchors, anchoring and mooring lines and deck hardware to permit mooring, anchoring and docking. Hardware for mooring in vertical attitude is not provided, as a mooring system has not yet been selected.

5. Details of the configuration of the interior spaces in the buoy are shown in Sheet 2 and Sheet 3 of the foldout drawings in Appendix B.

D. The Mathematical Simulation

Predicting the motions of a spar buoy (or any buoyant body) in a seaway is a rather complicated task for several reasons. First, real ocean waves occur in patterns so complex that the input forces they impose on a buoyant body cannot be satisfactorily dealt with by present techniques except through the use of the mathematics of probability. Thus use is made of a smoothed and normalized wave spectra in this type of simulation. For wave prediction, it is this somewhat simplified spectrum that must be related to wind velocity, fetch and duration, not individual wave histories over time.

Second, the buoy is perfectly free to respond to the waves that pass, and motions of one kind are often coupled to those of another kind. That is, heave is affected by pitch and vice versa. The degree of coupling is a property of the shape and mass distribution of the buoy itself. Because of coupling phenomena, the complete set of equations for the buoy's motions for any given wave spectrum must be solved simultaneously by means of a very large amount of computation.

The MOSES mathematical simulation consisted of a set of computer programs written by Dr. Ludwig Seidl of the University of Hawaii Department of Ocean Engineering. The input waves are represented by a modified Bretschneider spectrum. The buoy model accurately represented the shape and mass distributions described in Appendix B. Using these foundations, Dr. Seidl has modeled buoy response over a wide range of sea conditions in both the horizontal attitude to represent conditions at sea under tow, and in the vertical attitude. Vertical simulations were done on both a two-point, taut-wire moor and drifting. Response curves with their explanations are included in Appendix C, "Computer Simulation".

Even though details are given in Appendix C, Figure 3 illustrates the general form of the results, with representative sea states indicated. Sea state 7, for instance, is defined as a significant wave height of 30 feet, and a significant wave period of 13.6 seconds. The term "significant" refers to irregular waves wherein the average height of the highest 30 percent of the waves is 30 feet, and the average of the periods of these waves is 13.6 seconds. Thus some of the waves are higher than 30 feet, while most are smaller. The same definition of significance holds for the buoy's response in heave, shown in Figure 3 as $\pm$ 2.5 ft, or a double amplitude of 5 feet. What this curve says then, is that the average of the largest 30 percent of the buoy's heaving motions will be 5.0 feet in a state 7 sea; a small response indeed to a sea big enough to be rare in the tropical Pacific.

Three distinct conclusions have been derived from the mathematical simulation. These are:

1. Motions of the MOSES preliminary design are well within the response criteria dictated by mission requirements as set forth in Appendix A of this report.
2. The computer programs developed by Dr. Seidl are sufficiently general to allow simulation of a wide range of sea conditions and buoy configurations. This will be extremely helpful in Phase II in case changes in scientific mission requirements force changes in buoy size or configuration.
3. Where they can be compared, the program's results are in good agreement with the physical model results, as is shown in Appendix D, Model Tests.

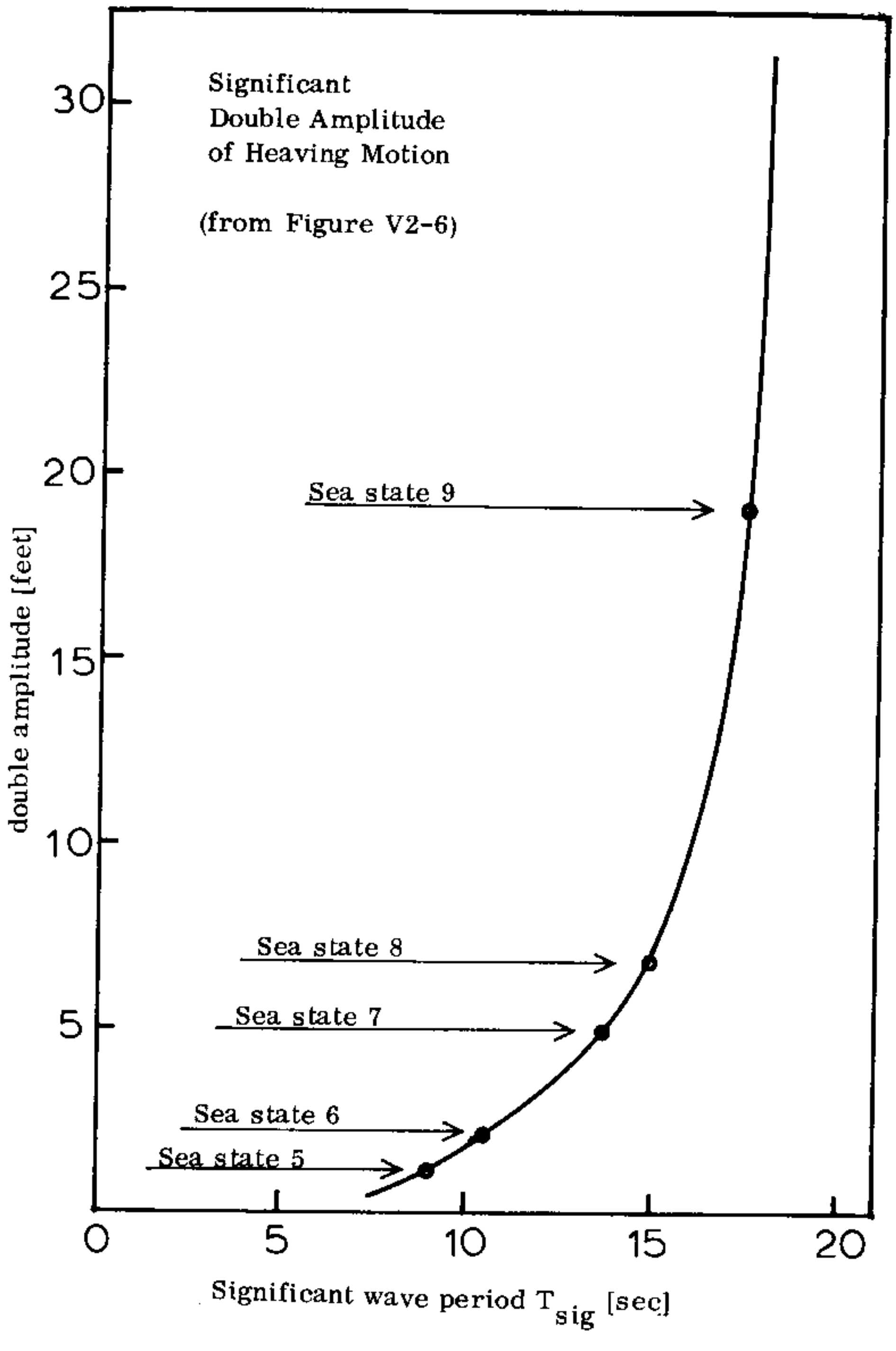


Fig. 3 General form of results of computer analysis

E. Physical Scale Model

A 1:13 working scale model of MOSES 22 feet in length was built to accomplish three things:

1. To investigate the buoy's behavior as a towed vessel on the surface. Of interest here are towing force, behavior in large waves, and ease of handling in close quarters. Test results indicate that MOSES can be handled by a moderate-sized towboat (1200 shaft hp) at up to 7 knots. The model was predictable and easy to handle while maneuvering, and showed no erratic tendencies while in rough water.

2. To investigate the buoy's behavior during translation between horizontal and vertical. The model's performance in this regard was significantly better than had been expected, and this was true in both smooth and rough water. Under all conditions it was unconditionally stable throughout translation, and repeatedly showed a fortunate tendency to come bow into the wind during initial flooding, remaining there until vertical, and then rotating to put the rounded portion of the house into the wind. On translation from vertical to horizontal, the exact reverse behavior was followed, regardless of sea conditions.

3. To verify the mathematical model. In those conditions where quantitative measures could be taken, agreement was excellent. Though rough-water tests within the scope of the Phase I effort did not yield measurements, the model's behavior as estimated by observation appeared to be well within the limits predicted, and no anomalies were observed. Figure 4 is a close-up photograph of the scale model's upper structure taken during the still-water tests.

Fig. 4 Upper structure of scale model shown during still water test

Overall, the model has performed very well in tests, and so has provided an increased level of confidence in the design. There are, however, two areas where further scale model testing is indicated by the Phase I results. First, in the still-water tests, the model shows much greater damping than predicted, more than seems explainable by scale effects alone. This should be investigated. Second, the rough-water tests should be repeated with sophisticated instruments. Properly done, tests of this type would yield both actual buoy motions and the spectrum of the sea that caused them. The model could then be simulated in the computer program to see if the program could predict the actual buoy motions from the actual sea spectrum. This would have the effects of (a) solidly verifying the computer program, (b) giving a very accurate understanding of the model's behavior, and (c) with both the model and program well understood, allow accurate simulation of silos, fish cages, and other bulky external experiments before taking the full-sized version to sea.

F. Quality Assurance and Acceptance Testing

Appendix E contains the structure of the quality assurance program which includes acceptance testing. This material is based on operational requirements presented in Appendix A, and on established Quality Assurance methods. It is intended to serve as one of the guides to preparation of construction specifications in the final design phase as well as to provide the basis for the final Quality Assurance Program.

The engineering and construction quality assurance (ECQA) program establishes a systematic basis for MOSES system, component and material specification accounting and an integrated record keeping capability. It also provides a methodology for minimizing duplicative inspections and tests and insuring its own error free conduct. The acceptance test structure is designed to be a safely progressive mechanism for proving MOSES at sea while providing operating crew training and finalizing MOSES documentation.

G. Costs

Table I contains a summary of estimated costs for MOSES final design, construction, ECQA and acceptance testing. This estimate covers the work required from the end of Phase I to the sea-ready MOSES. It is currently designated Phase II of our Coherent Area Program. It does not, however, include costs for planning or preparing any part of the scientific program.

TABLE I

Summary of Costs

I. MOSES Final Design, Program Management and Acceptance Testing		
	A. Final Engineering Design	$ 220,500
	B. Quality Assurance	76,750
	C. Acceptance Testing	69,360
	D. Program Administration	58,500
	Subtotal:	425,110
	E. Oceanic Institute overhead of 75% of allowable direct costs (allowable direct costs estimated at 80% of total direct costs)	255,066
	TOTAL:	$ 680,176
II. MOSES Construction		
	A-C. Hull Structure and House	$ 474,264
	D-N. All other buoy systems	402,930
	TOTAL:	$ 877,194
TOTAL DESIGN, PROGRAM MANAGEMENT, ACCEPTANCE TESTING, AND CONSTRUCTION		$ 1,557,370

For detailed costs, see Appendix F

III. CONCLUSIONS

This report is submitted as evidence of successful performance of Sea Grant No. 1-35319. In keeping with the intent and conditions of that grant, certain major conclusions are summarized here:

A. The feasibility of the MOSES design concept has been demonstrated.

B. A Preliminary Engineering Design has been prepared, which represents a feasible expression of that concept.

C. Verification has been provided in the form of preliminary design and design calculations, a mathematical simulation, simulation through a 1:13 working scale model, and a cost estimate.

D. Additional material has been provided in the form of operational criteria, preliminary design drawings and a basis for construction specifications, a quality assurance program, and an acceptance testing program, all for use as a guide in final design.

E. Additional work should be done in sophisticated model testing and in design of experimental apparatus, especially exterior fish silos, nets, and cages, before final design is frozen.

To date, biological field work to establish the volume, compartmentation, mesh sizes, water transport properties, tolerable water velocities and turbulence, etc. has not as yet progressed to the point where a fish silo configuration can be expressed in engineering terms. Hence this study has concentrated on the buoy itself. We expect, however, that to be effective the silo would have to be very large, impounding perhaps five to ten times the amount of water displaced by the buoy itself. Such a combination of buoy and silo present quite different problems in dynamics than those of the buoy alone. However, we believe that, with MOSES Phase I, we have achieved a good buoy design, the first step towards an overall solution.

We recommend as the next step, an investigation of the various ways the silo and buoy can be coupled together. This investigation should include alternate solutions--for instance, two or several silos located outboard of the buoy and elastically coupled to it. For each solution, some degree of modification of the buoy configuration may be expected.

APPENDIX A

OPERATIONAL CRITERIA

INTRODUCTION

This appendix is intended to provide a firm and detailed statement of the main operational criteria the MOSES system must meet. These operational criteria are derived from four sources:

MOSES was conceived in response to the demands of a series of planned scientific experiments to be conducted over a period of at least five years in the open ocean. These were described in "A Coherent Area Program for Utilization of the Open Sea: a Preliminary Proposal," submitted to NOAA by the Oceanic Institute on September 22, 1970. This proposal, with revisions, remains the source document for scientific mission requirements.

MOSES will be operated in the Pacific Ocean, with Hawaii as its home base. It is anticipated that for certain cruises, advanced bases will be set up at ports closer than Hawaii to the waters to be investigated.

MOSES will be operated and maintained by Makai Range, Inc. (MRI), a Makapuu Oceanic Center component organization, utilizing whenever possible MRI's present equipment, facilities and personnel.

MOSES must be stable, safe, and efficient within the ocean environment existing throughout the Pacific between latitudes 30 North and 30 South, with one stipulation, i.e., we do not plan deliberate exposure to western Pacific typhoons.

From these sources, so far as they are now known, MOSES has been characterized as a manned spar buoy, and its basic form, shape and size established. Further functional and material criteria are presented below. It is not anticipated that these criteria will substantially change in later phases of MOSES design, except in response to basic shifts in scientific mission.

MATERIAL AND FUNCTIONAL CRITERIA

I. Environment

Though prediction of actual conditions to be encountered in the Pacific over extended periods presents difficulties, a set of environmental parameters is here established for use in evaluating the performance of the buoy. These parameters are conservatively chosen, with the expectation that they will rarely if ever be exceeded in service. Sea State is here defined in terms of significant wave height and significant wave period, after a recently revised form of the Bretschneider spectrum.*

- Sea State 4. Buoy response very small. All servicing operations including resupply and exterior hull maintenance can be conducted without damage or danger.

- Sea State 6. All normal operations and experiments conducted without interruption.

- Sea State 8. The buoy and all experimental apparatus will survive without damage.

- Sea State 9. Buoy will survive without important damage or danger to human life.

- Both mathematical modeling and physical model testing shall be utilized to verify buoy dynamics, using recognized statistical models of fully developed sea states as inputs.

- Adequate structural capacity of the buoy hull, attachments and hardware shall be demonstrated for loads imposed by the above conditions.

II. Underwater Observation Positions

A. An observation laboratory shall be provided at the lowest possible point and at least 200 ft depth, furnishing a one-atmosphere environment and sufficient space, comfort, safety, and service by the buoy's systems for continuous occupancy by at least two persons, plus 25 cubic feet of apparatus. Visual access to the sea both horizontally and vertically downward shall be provided in this laboratory.

* Bretschneider, C.L. (1970). "Forecasting Relations for Wave Generation". Look Laboratory Magazine, Vol. 1, No. 3, July 1970.

B. There will be at least six additional observer stations at points between the observation laboratory and the design waterline. Each station shall provide space, comfort, safety, and service by the buoy's systems for continuous occupancy by one observer.

C. The observation laboratory, all observer stations, and all points within the main shaft of the buoy shall be accessible from an elevator equipped to carry 2 persons plus 600 pounds, and furnished with safety devices approved by the National Elevator code. The elevator shall have two operating modes:

1) automatic call system with top and bottom stations and at least five intermediate stations, plus indicators in cab, at top station, and at bottom station

2) manual control from within cab to allow positioning and locking of the cab at any point in the shaft. Normal cab speed will be 100 feet per minute.

III. Exterior Movable Platform

An exterior movable platform shall be provided, having at least 150 square feet of usable deck area, capable of supporting at least 5,000 pounds concentrated load, and manually controllable from two points, one on the platform and one on an exterior catwalk on the house structure. The two control points should be intervisible. The platform shall have locking devices to fix it to the main shaft at any position. Vertical travel shall be not less than 60 feet, extending from immediately below house structure to the top of the variable ballast tank. Normal travel speed shall be 20 feet per minute.

IV. Translation

A. The buoy shall be equipped and proportioned to allow safe translation from horizontal to vertical by admitting seawater ballast, and from vertical to horizontal by voiding ballast enclosures with compressed air.

B. Sufficient compressed air shall be stored aboard to perform two complete cycles of translation with 10 percent reserve.

C. Air system shall include a compressor with capacity to recharge the entire air storage bank in 24 hours or less. The storage bank shall be subdivided to preserve sufficient air for one translation cycle in case of failure causing air loss anywhere in the system.

D. Controls, regulators, valves, indicators, etc., shall be so arranged as to allow control of translation cycle by one person.

E. Provision shall be made for installation of radio remote control.

F. Emergency translation procedure in either direction shall take no more than fifteen minutes from commencement to overturn.

V. Variable Buoyancy

A. A variable buoyancy system shall be provided, adequate to adjust load waterline for changes in payload, assist in damage control, and raise and lower buoy in the water for servicing and maintenance.

B. Overall vertical range of adjustment of waterline shall be not less than 60 feet.

C. Ballast variation shall be accomplished by flooding/venting or voiding with compressed air.

D. Flood openings shall be provided with bi-directional pressure-tight, air-operated valves.

VI. Towing

A. Except while deployed at sea, the buoy will at all times be in horizontal mode. Close attention shall be paid to achieving acceptable towing characteristics, with the goal of towing speed 7 knots in sea state 6 with a towboat of not more than 1,200 shaft horsepower, and 5 knots in sea state 4 with a towboat of not more than 450 shaft horsepower.

B. The buoy shall be furnished with adequate deck hardware and ground tackle for mooring, anchoring and docking in the horizontal position.

C. Provision shall be allowed for bringing a tug alongside at variable ballast tank and at main ballast tank.

VII. Crew Support

The buoy is intended to remain at sea for periods as long as six months, continuously manned. Accordingly, strict attention must be paid to the safety, comfort and efficiency of its crew.

A. In operation and preventive maintenance, all controls and operating procedures shall be designed according to accepted principles of human engineering, to promote safety, efficiency, and avoidance of error.

B. All machinery and hardware shall be installed so as to allow access in both horizontal and vertical positions, for maintenance and repair.

C. Special attention shall be given to crew comfort in meal preparation, perishable food storage, sanitation, personal hygiene, privacy, restful sleep, and working conditions. Especially with regard to the observation laboratory and observer stations, care shall be exercised to promote psychologically comfortable surroundings.

D. Provision shall be made for safe transfer of personnel from the buoy to other craft, both under normal operating circumstances and in case of emergency such as injury.

E. Throughout the buoy, but especially for occupancy of the main shaft, provision shall be made for protection and safe evacuation in case of damage, flooding, or fire.

F. SCUBA diving operations will be conducted as part of the normal maintenance of the buoy and conduct of certain experiments. Proper provision shall be made for safe breathing air, diver communications, maintenance of diving gear, and emergency decompression.

G. All stairwells, ladders, catwalks, platforms, railings, gratings, etc., shall conform to the applicable provisions of the National Industrial Safety Code.

H. Personnel complement shall be 8 persons for 15 days or 4 persons for 30 days between resupply visits by attending vessels. It should be noted that for short periods (24 hours or less) as many as 15 persons may be aboard.

VIII. Special Experimental Support Requirements

A. Fish Silos

1. Cylindrical enclosures of netting and plastic over suitable frames will be rigged in the water adjacent to or concentric with the buoy.

Ideally these will be at least 30 feet in diameter and 70 to 100 feet deep, with internal subdivisions, and with their upper portions enclosed with plastic sheeting.

2. Since these silos will enclose rather large amounts of water, large inertial forces may be expected to develop in the members connecting them to the buoy.

3. At this writing, no designs have been fixed but it is possible to state that any such designs must be studied coupled together with the buoy as a single dynamic system, and adequate attachment on the buoy provided as required.

4. In all such designs careful attention should be paid to installation and removal, and jettisoning at sea in case of damage, heavy seas, or other emergency.

B. Provision shall be made for installation of deep water pumping gear, consisting of at least 1,500 feet of 6" diameter flexible hose, a reel or other means of storing and deploying the hose and pumps of 150-500 GPM capacity.

C. Special electronics gear which may be installed includes:

1. computers
2. satellite navigation equipment
3. satellite telemetry equipment
4. special sensors of various types
5. special communications equipment

Provision shall be made for space, environmental control, and high-purity AC power for these uses, not less than 10 Kw, continuous duty.

D. Storage space shall be provided for experimental materials, specimens, etc. Several hundred cubic feet of space are available in the main shaft between observer stations. Detailing and dress of pipes, conduits, cables and ducts shall take this requirement into account and allow for most efficient practicable use of this storage space. As a minimum, 500 cubic feet will be allotted to this use.

E. From time to time a pre-fabricated laboratory containing special equipment may be placed upon the top deck of the house. Alternatively, a helicopter may be operated from it. Provision shall therefore be made in the buoy design for a total deck load of 12,500 pounds, and adequate tie-down points, as well as outlets for fresh water, salt water, sewage, and electrical power. Gutters shall be provided around the margins of this deck with leaders connecting with the buoy sewage system.

F. Near each underwater observation position (7 total), and in at least five other locations, provision shall be made for installing electrical through-hull connections.

IX. Operation Support

A. Support at Sea

1. The buoy shall be capable of being towed long distances at sea unmanned. Provisions shall be made for:

   a. insuring watertight integrity of hull, including compartmentizations to prevent foundering through the loss of any one compartment
   b. navigation lights
   c. ventilation of interior spaces
   d. securing all on-board equipment, machinery, and stores
   e. disconnection and reconnection of towlines
   f. safe boarding and debarking at sea while the buoy is horizontal
   g. gangways, gratings and safety lines arranged to be useful in the horizontal mode.

2. Operation of small boats from the buoy will be routine. Provision for storing, maintaining, fueling, launching, and retrieving outboard powered rubber boats of a variety of sizes will be incorporated.

3. Operation of a small research submersible from the buoy is anticipated. The external movable platform shall be designed to accommodate the weight of a submersible of the NEKTON class (4,000 lbs. +), but no other special provision is required.

4. Mooring at sea in the vertical position is contemplated. Provision shall be made for putting the buoy in a two-point, taut-wire moor, with due consideration of the consequences of loss of buoyancy of mooring buoys.

5. The buoy will be resupplied at sea at frequent intervals. Due attention shall be given to the transfer of equipment, wet and dry expendables, and personnel. Some specific minimums are:

   a. Time to refuel: 1 hour
   b. Time to refill fresh water: 1 hour
   c. Jib crane on buoy: 1,500 lb. lift, 150 feet per minute

   In general, a normal reprovisioning and crew replacement should be accomplished in no more than four hours.

B. Support at Advance Base

Program planning calls for operation from advanced base for periods as long as a year, comprising two or more cruises with intervening repair, refit of experimental equipment, and hull maintenance. The supply vessel will operate from the forward base. Implications for buoy design are mainly that a drydock may not be available, that the buoy may have to operate under its own power while in port, and that some of the burden of carrying spares and maintenance equipment is shifted from the buoy to the supply vessel or ashore. On the other hand, maintenance of some equipment, especially electronic gear, may present serious problems. Some specific criteria derived from the above:

1. Ballast tanks shall be subdivided and piped to allow careening the buoy for bottom maintenance.

2. Wherever possible, electronic equipment shall be modular, to allow replacement of defective elements rather than on-board repair.

3. Wherever possible, machinery selected for the buoy shall be available off suppliers' shelves and so chosen that complete units, assembled and tested, are air transportable in standard air cargo containers.

4. Wherever the opportunity exists, units such as valves, regulators, circuit breakers, etc., of similar function or capacity shall be made identical, to simplify stocking of spares. This principle should extend to such items as portholes, ladder rungs, rail stanchions, bolts and rivets, paints and finishes, lubricants and preservatives.

5. In any case of machinery subject to repair or replacement between major home-port overhauls, care shall be exercised to avoid unnecessarily complex techniques for removal and replacement, e.g., inert-gas arc welding, precision machining, or the use of exotic materials.

6. In general, this section is meant to apply principally in the design of the buoy itself. Because of the cooperative, inter-institutional nature of planned experimental programs, much of the design of experimental apparatus will be accomplished beyond the scope of the designers and operators of the buoy. However, many opportunities will occur to influence the design of experimental apparatus toward the principles outlined above. This will be particularly true during final design, when detailed scientific requirements are better known, and in preparation of the owner's operation and maintenance manuals.

C. Support at Home Port

Home port will be Honolulu. Complete ship repair and maintenance facilities are available there as well as drydocks of sufficient size to accommodate MOSES. However, a few comments are in order, particularly as regards cost.

1. Being of shallow draft when horizontal, MOSES can be stored wet at mooring at much less cost than at dockside. Two areas close to Honolulu are Keehi Lagoon and Kaneohe Bay. Both afford protected water.

2. Because MOSES buoyancy distribution will require sufficient structural rigidity to permit support of the buoy's dry weight from the ends alone, it is quite feasible to lift her clear of the water with a pair of light-gage submersible pontoons at either end. Since Makai Range, Inc. who will operate MOSES, has already considerable experience with submersible pontoons, the cost-effectiveness of this approach to maintenance and storage should be investigated during final design.

APPENDIX B

PRELIMINARY ENGINEERING DESIGN

Introduction

The objective of the MOSES preliminary engineering effort was to carry design research to the point that a demonstrably feasible design concept was achieved. It was also necessary that the design be represented at a level of detail adequate to support preliminary cost estimates. The effort was, of course, guided by general consideration of the design's adequacy to meet the scientific mission requirements and safety concerns explicated in Appendix A as well as considerations of maintainability and cost.

This appendix presents first a summary of the MOSES design concept's evolution. This is followed by a description of the Phase I design concept.

I. MOSES Design Evolution Summary

The development of any new design is a highly iterative process of design formulation, analysis (or test), and reformulation. MOSES is no exception. The idea for employing a large spar buoy as a research station arose from mariculture research requirements for long term open ocean occupancy with stability and the ability to penetrate the upper, bio-productive, layers of the oceans with safety and comfort for extended periods.

Our initial analyses of the compatibility of the proposed research program and the spar buoy concept in early 1970 resulted in the conclusion that there were no overwhelming technical obstacles and in a preliminary concept for the buoy itself. In fairness, we must admit to our naivete at that time. During the ensuing months, however, we feel that we have not only demonstrated the validity of the original concepts, but also developed the designs of both the buoy and our scientific program to a point at which our contentions are indeed supportable while at the same time overcoming our original naivete in large measure.

By late summer of 1970 the MOSES design had evolved to that shown in Figure B-1. The buoy then was nearly 400' in length with a very thin shaft. Outrigger variable ballast tanks were employed to gain horizontal roll stability. The upper house was round and rather small and the machinery and equipment room was located below the surface in a compartment in juxtaposition with the variable ballast tanks. Figure B-1 is the design sketch provided in our proposal for "A Coherent Area Program in Utilization of the Open Sea", submitted to the Sea Grant Program Office in September 1970.

Before the Sea Grant site visit in October of 1970, continued analysis of factors relating to cost, buoy dynamics, and structural strength had evolved the MOSES design concept to that shown in Figure B-2. The buoy was shortened to 287 feet. The size of the upper house was increased. The outrigger-type variable ballast tanks were replaced by a single circular tank and off-set fixed ballast was used to achieve horizontal stability. This latter was done since subjective analysis and tests of a very small model indicated that, while

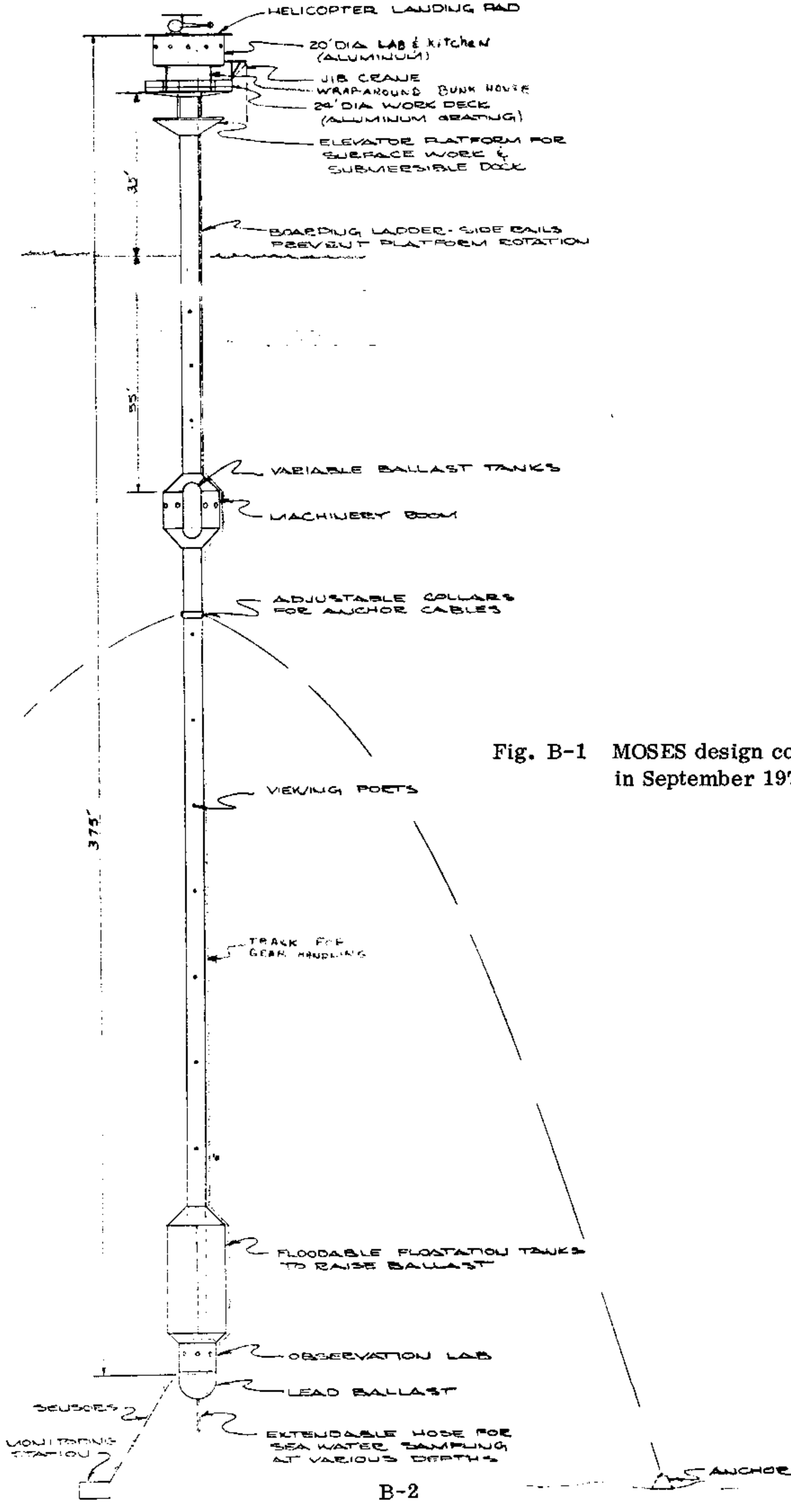


Fig. B-1 MOSES design concept in September 1970

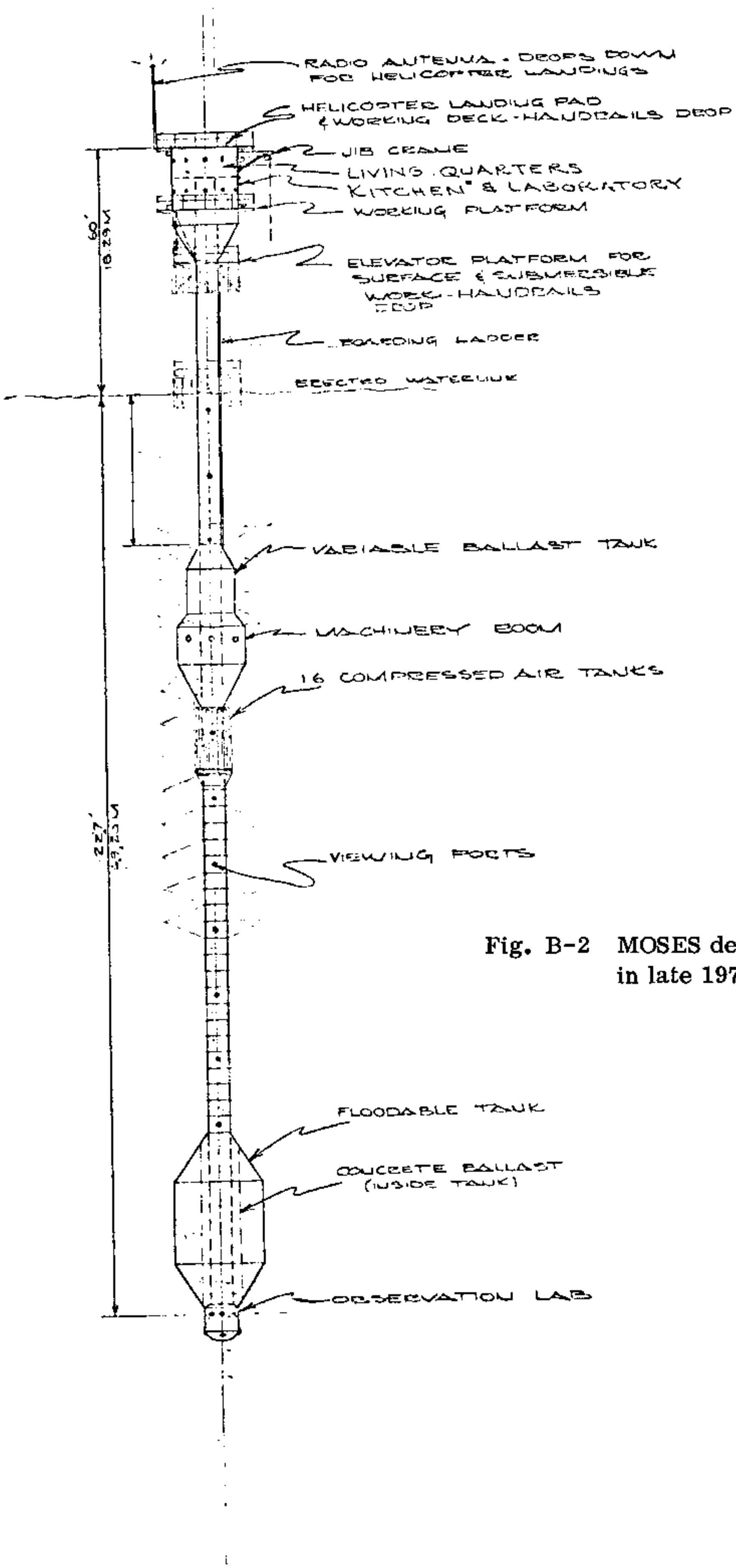


Fig. B-2 MOSES design concept in late 1970

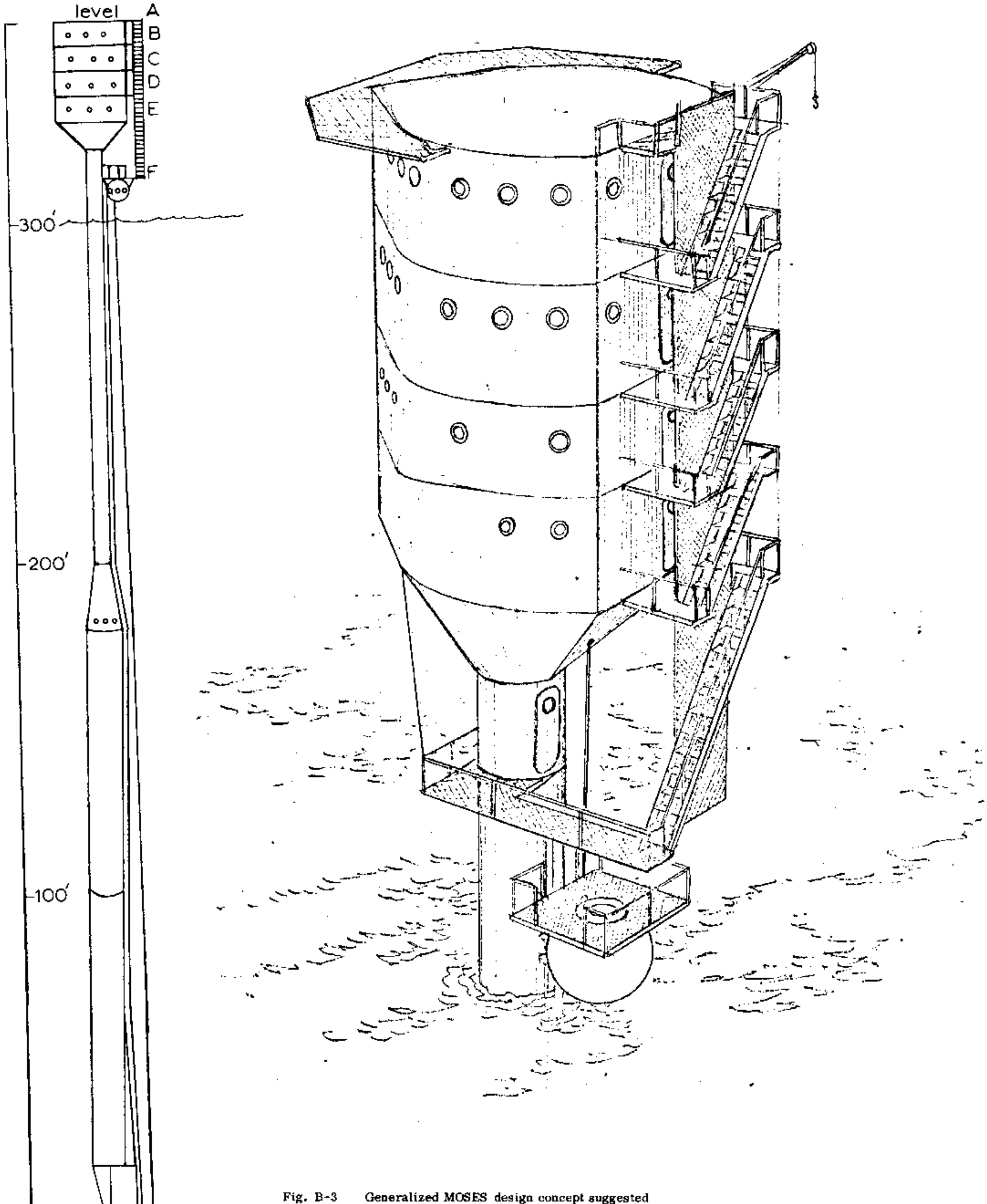


Fig. B-3 Generalized MOSES design concept suggested by C. B. Momsen the outrigger tanks provided adequate roll stability in calm and moderate seas, they would have a tendency to catch unequally in larger quartering seas and thus might roll the buoy 180°. The machinery and equipment room was still located in the variable ballast area and compressed air bottles for buoy translation and diver supply were located externally just below the variable ballast envelope.

Somewhat before and again during the design consultants' meeting, C.B. Momsen suggested design approaches following the lines of that shown in Figure B-3. The upper house was shaped to provide roll stability in the horizontal and wind stability in the vertical. The machinery and equipment room was located above the surface within the main house. The lower portions of the buoy were formed similar to a ship's bow and floodable. With floodable lower sections, it was necessary to abandon the internal elevator and replace it with an external submersible chamber.

Though the external submersible chamber was unacceptable for a combination of cost and functional factors and this obviated flooding the lower portions, this design alternative did produce a significant influence on the MOSES preliminary design.

The MOSES design concept that evolved from the Phase I effort is shown in Foldout Sheet 1. The tubular shaft configuration was retained because of its ease of construction, inherent strength and overall cost effectiveness. The shortened shaft was retained and increased in diameter as a result of detailed load computations. Roll stability in the horizontal attitude as well as wind stability in the vertical was increased by making the fixed lead ballast eccentric and changing the cross section of the upper house from its original circular shape to a modified "D" shape. Though the design team was aware that any tow with the length to beam ratio of MOSES in the horizontal would behave well, faired frustrums were retained on the main ballast tank and house to reduce required towing forces. The original B.G. was quite long, giving a degree of stiffness that was determined to be unnecessary. This was shortened as the preliminary design emerged. Internal subdivisions were simplified in the main ballast tank to save air in translation and to simplify piping and valving to reduce costs. The machinery and equipment room was moved from its underwater location in the variable ballast envelope to a location in an added third deck of the upper house. This was done to reduce costs and to reduce deleterious environmental effects under water.* Covers on underwater port lights were considered operationally undesirable. Thus, these ports are made of thick impact- and pressure-resistant lucite. Stiffening rings were added as an inexpensive means of adding shaft strength and providing attachments for the fish silo and other external equipment. However, the scale model tests indicate that their heave damping effect is extremely fortuitous. This is discussed in Appendix D.

* This was made possible by the reduction in B.G.

II. MOSES Preliminary Engineering Design

The primary purposes of the MOSES preliminary engineering effort centered about the structural design of the main hull and house components. It was this aspect of the effort, coupled with the mathematical simulation (where calculations of buoy dynamics were performed) and scale model program, that developed and proved the overall configuration of the buoy. Of significant but secondary importance were such systems as the internal elevator, electrical, hydraulic, pneumatic, ventilation, water supply, and waste disposal. It was necessary to design and size these in order to assure their compatibility with the structural design as well as to estimate their costs. Inclusion of such considerations as surface preparation and painting, navigation and communications, deck gear and ground tackle and miscellaneous finish work in the Phase I design investigation is primarily for purposes of cost estimation.

Throughout this document MOSES is presented as a set of integrated systems consisting of:

- Hull Structure
- House Structure
- External Elevator
- Internal Elevator
- Electrical
- Hydraulic
- Pneumatic
- Ventilation and Air Conditioning
- Waste Disposal
- Water Storage and Supply
- Surface Preparation and Painting
- Navigation and Communication
- Deck Gear and Ground Tackle
- Miscellaneous Finish Work

Each of these is discussed to a level of depth appropriate to its importance to the preliminary engineering objectives in the remaining pages of this appendix.

A. Hull Structure

The hull structure includes all structural materials, fabrication, shop finish, shell plating, framing, attachments and inserts such as porthole frames, hull penetrations, brackets and openings for mounting or installing the work of other systems, as well as all jigs, alignment and assembly fixtures and handling gear.

The critical element in the hull structure is the main shaft. Required to be small in diameter, it also receives, as the spine of the vessel, very large bending moments, especially in hog and sag in the horizontal attitude.

Generally design and detailing follow the ASME Code for unfired pressure vessels and all critical welds are to be radiologically inspected. In the design aspects shown in Foldout Sheets 3 and 5 and throughout the design process, attention was given to accessibility for inspection and maintenance. Hogging and sagging moments are given diagrammatically in Foldout Sheet 4.

Presented below are our calculations for:

- o Center of gravity and center of buoyancy
- o Heave period in vertical
- o Static list in vertical
- o List in 40 knot wind load
- o List in 60 knot wind load
- o Metacentric height in horizontal
- o Bending moments in hogging and sagging
- o Main shaft deflections in hogging and sagging
- o Maximum stress in critical sections of main shaft
- o Collapse pressure of variable ballast tank
- o Collapse pressure of deep observation laboratory

These calculations, the accompanying drawings, the tables of moments given in Tables B-I, B-II, and B-III , and the dynamic calculations given in Appendix C are presented as support for the MOSES preliminary design.

1. Calculation of Center of Gravity (CG), Center of Buoyancy (CB), and CG-CB Distance (BG) in the Vertical Attitude

Gravity and buoyancy moments were taken about the load water line (LWL) in the vertical attitude. In the vertical, gross weight of water in the main ballast tank and variable ballast tank are added to the weight of the dry vessel. Displacement is the total displacement of the vertical buoy at LWL.

a. Definitions

M_b = Moment of buoyancy in foot pounds (Table B-II)

M_w = Net moment in foot pounds

W = Gross weight in pounds (Table B-I)

Δ = Total displacement at LWL in pounds (Table B-II)

b. Calculation of M_w

(1) moments below LWL from Table B-I	=	193,765,634
(2) moments above LWL from Table B-I	=	2,816,842
M	=	190,948,792

TABLE B-I

Table of Moments (Weights)

Item	Description	Unit wt. (lbs)	Mom. Arm (ft)	Moments (ft-lbs)
MOMENTS BELOW WATERLINE				
1.	External ladder	1,100	4	4,400
2.	Platform #1	100	10.5	1,050
3.	Main Shaft	36,096	19	685,824
4.	Platform #2	100	24.5	2,450
5.	Platform #3	100	38.5	3,850
6.	Variable Ballast Tank	53,200	54.5	2,899,400
7.	Main shaft	152,432	92	14,023,744
8.	Winch & Platform	850	61.5	52,275
9.	Fresh water & diesel fuel	46,800	64.5	3,018,600
10.	Pumps & platform	600	69.5	41,700
11.	Platform #4	100	83	8,300
12.	Platform #5	100	99	9,900
13.	(8) Stiffening Rings	2,800	105	294,000
14.	Platform #6	100	115	11,500
15.	Storage platform	600	123	73,800
16.	Platform #7	100	131	13,100
17.	Platform #8	100	147	14,700
18.	Compressed air tanks (8)	5,500	148.5	816,750
19.	(11) Stiffening Rings	3,850	156	600,600
20.	Platform #9	100	163	16,300
21.	Main shaft	45,120	167.5	7,557,600
22.	Compressed air tanks (8)	5,500	172.5	948,750
23.	Platform #10	100	179	17,900
24.	Main ballast tank	52,000	198.5	10,322,000
25.	Main Shaft	15,960	199.5	3,184,020
26.	Ballast (lead)	198,520	216	42,880,320
27.	Observation Lab	23,000	220	5,060,000
28.	Main ballast	490,000	198.5	97,265,000
	Total	1,134,928		189,827,833

(TABLE B-I continued)

Item	Description	Unit wt. (lbs)	Mom. Arm. (ft)	Moments (ft-lbs)
MOMENTS ABOVE WATERLINE				
1.	Main Shaft	35,880	-16.5	592,020
2.	Movable Platform	4,000	-20.5	82,000
3.	Hydraulic Winches	1,000	-28	28,000
4.	Ia - Frustrum	10,500	-34	357,000
5.	Ib - first deck	12,940	-39.5	511,130
6.	Ic - second deck	3,365	-46.0	154,790
7.	House-structural	20,500	-47.5	973,750
8.	Id - third deck	1,895	-54.5	103,277
9.	Jib crane	250	-59.5	14,875
	Total	90,330		2,816,842

W below LWL (bal. fwd.)	=	1,134,928	M =	189,827,833
add W variable ballast	=	83,783	M =	3,937,801
W below LWL	=	1,218,711		
			Moment below LWL =	193,765,634
add W above LWL	=	90,330	- M =	- 2,816,842
Total W	=	1,309,041		
			Net Moment about LWL =	190,948,792

TABLE B-II

Table of Moments (Buoyancies)

Item	Description	Displacement (lb)	Mom. Arm. (ft)	Moments (ft-lbs)
MOMENTS BELOW WATERLINE				
1.	Main shaft	7,380	1.5	11,070
2.	Main shaft	79,680	19	1,513,920
3.	Variable Ballast tank	246,947	54.25	13,396,875
4.	Main Shaft	281,112	91	25,581,192
5.	(8) Stiffening Rings	576	105	60,480
6.	(11) Stiffening Rings	792	156.75	124,146
7.	Main Shaft	99,600	167.25	16,658,100
8.	Main Ballast Tank	5,900	198.5	1,171,150
9.	Main Shaft	32,160	199.5	6,415,920
10.	Ballast	17,894	217.5	3,891,945
11.	Observation Lab	47,000	220	10,340,000
12.	Main Ballast	490,000	198.5	97,265,000
	Total	1,309,041		176,429,798

TABLE B-III

Table of Moments (Weights)

Item	Description	Unit wt. (lb)	Mom. Arm. (ft)	Moments (ft-lbs)
MOMENTS TO VIEWING STATION SIDE				
1.	Pumps and Platform	600	2	1,200
2.	Diesel fuel & fresh water	46,800	0	
3.	Winch and platform	850	2	1,700
4.	Variable ballast tank	37,500	0	
5.	Platforms # 1-11	1,100	1.75	1,925
6.	External ladder	1,100	3.75	4,125
7.	External elevator platform	2,222.4	6	13,334.4
8.	Storage platform	300	1.75	525
9.	(12) Comp. air tanks	825	.75	618.75
10.	(4) Comp. air tanks	275	1.25	343.75
11.	Electrical Panel	350	5.5	1,925
12.	Work bench and tools	1,000	3.5	3,500
13.	Compressor	1,100	4.5	4,950
14.	Comp. Air Panel	300	9.5	2,850
15.	SCUBA gear	400	4.75	1,900
16.	Air tank	200	2.5	500
17.	Working Platform	2,795	9	25,155
18.	Work Bench & equip. drws	1,100	9	9,900
19.	Darkroom storage cntr.	200	3.5	700
20.	Darkroom sink	10	1	10
21.	Work bench & storage	1,100	2.5	2,750
22.	Bunks (4)	160	5.5	400
23.	W.C. w/water	150	3	450
24.	Desk	25	5.5	137.5
25.	Locker	50	8.75	437.5
26.	Stores under bunk	125	8.25	1,031.25
27.	Stores under bunk	125	2.5	312.5
28.	Jib Crane	250	10.5	2,625
29.	House (70% of structure)	14,350	5	71,750
30.	Safety ladder	1,000	1.75	1,750
31.	Comp. air piping	750	1.75	1,312.5
32.	Elec. conduits & wiring	4,500	2	9,000
33.	Piping (water, fuel)	1,000	1.5	1,500
34.	Hull Penetrations	250	3.5	875
35.	Towing eyes	100	1	100
36.	Shaft	3,731.45	.5	1,865.72
37.	Stairs - first deck	50	5.	250
38.	Stairs - first deck	50	5	125
39.	Ballast (lead)	89,300	5.5	491,150
	Total M, viewing station side			584,222

(TABLE B-III continued)

Item	Description	Unit wt. (lb)	Mom. Arm. (ft)	Moments (ft-lbs)
MOMENTS TO ELEVATOR CAR SIDE				
1.	Fresh air ducts	1,900	1	1,900
2.	Elevator car	500	1.5	750
3.	Elevator tracks	3,600	1	3,600
4.	Shaft	12,228.55	1.25	15,285.68
5.	Day Tank (diesel)	1,000	2	2,000
6.	Dry stores (frustrum)	500	1	500
7.	Gasoline	7,000	2	14,000
8.	Generators (vert)	4,200	0	
9.	Generators (horizont)	4,200	.5	2,100
10.	Batteries	3,000	4.75	14,250
11.	H.W. Heater	500	5.75	2,875
12.	A.C. Inverter (2)	500	3.5	1,750
13.	Blower	100	4	400
14.	Table & seats	100	2	200
15.	Counter	200	5	1,000
16.	Sink	10	5.75	57.5
17.	Storage	1,000	5.5	5,500
18.	Range	95	3	285
19.	Refrigerator	150	6.5	975
20.	Freezer	400	6	2,400
21.	Blower	100	7.75	775
22.	Desk	25	3	75
23.	Bunks (2)	80	5.5	440
24.	Drawers	50	5	250
25.	Storage	125	5.5	6,875
26.	Basin & cabinet	75	.5	37.5
27.	Working platform	1,505	4.25	6,396.25
28.	Ballast	121,000	6.5	786,500
29.	House (30% of structure)	6,150	3.4	20,910
30.	External elevator platform	1,777.6	5	8,888
	Total M, elevator car side			829,857

c. Calculation of CG

$$CG = M_w/W = \frac{190,948,792}{1,309,041} = 145.86 \text{ ft below LWL}$$

d. Calculation of CB

$$CB = M_b/\triangle = \frac{176,429,798}{1,309,041} = 134.80 \text{ ft below LWL}$$

e. Calculation of BG

$$BG = CG - CB = 145.86 - 134.80 = 11.06$$

f. Payload

Note:

It is generally valid to conclude that BG (coupled with practical space availability) constitutes the limiting factor in maximum payload determination as follows:

1) Given: For vertical pitch stability, BG must $\geqq$ 8 ft.

2) Given: For safety reasons, VBT must maintain a reserve buoyancy $\geqq$ 1/2 its total capacity of 83,783 lbs.

3) So propose worst case which is removal of 40,000 lbs of reserve buoyancy from the VBT and adding it to the centroid of upper house. This equates to a transfer of 40,000 lbs a distance of 100 ft, = 4,000,000 ft-lbs.

4) Then new $CG = \frac{190,948,792 - 4,000,000}{1,309,041} = 143.14$

5) New CB = 143.14 - 134.8 = 8.34

6) Conclusion: Maximum payload is sensitive to its own distribution, but may be assumed generally to be 40,000 lbs.

2. Calculation of Heave Period in Vertical Attitude

Heave period, as calculated here, ignores drag and induced mass, both of which tend to increase heave period. In Appendix C the above two effects are not ignored, yielding a longer heave period (26.7 sec).

a. Definitions

g = acceleration due to gravity
W = buoy gross weight in pounds ballasted to LWL
= 1,309,041 (Table B-II)
k = buoyant restoring force in lbs/ft = 2,460 (change in displacement per foot of immersion of buoy main shaft)

b. Calculation

$$\text{Still water period} = 2\pi\sqrt{\frac{W}{k\,g}} \doteq 2\pi\sqrt{\frac{1,309,041}{2460 \times 32.16}}$$

Heave period = 25.5 sec

3. Calculation of Static List in Vertical Mode

For purposes of roll stability in the horizontal attitude, it was necessary to locate the center of gravity of the buoy below the center line of the shaft. This results in a slight list when the buoy is in the vertical attitude which is calculated here. For this purpose it is first necessary to locate the amount of eccentricity.

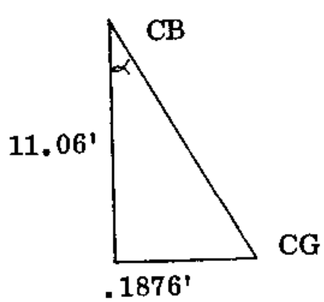
a. moments of eccentric weights (from Table B-III)

829,857 ft-lbs on elevator car side of buoy centerline
584,222 ft-lbs on viewing station side of buoy centerline
245,635 ft-lbs = net moment due to eccentricity

b. Eccentricity of CG in vertical attitude ballasted to load waterline

245,635/1,309,041 = .1876 ft = distance CG is removed from centerline of buoy in vertical mode

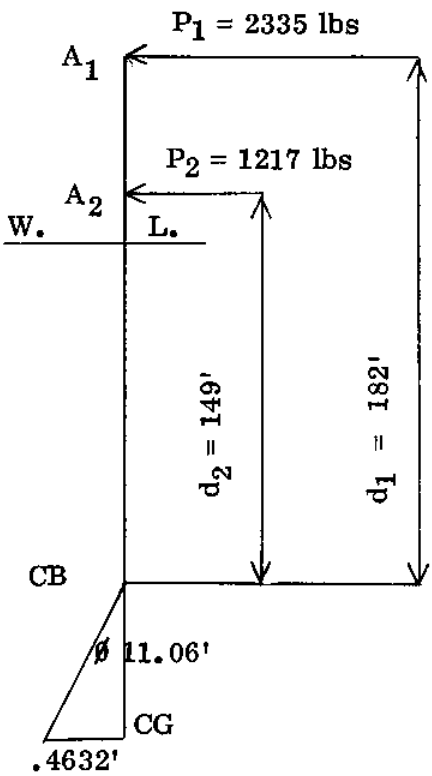
c. Vertical list = $\tan^{-1} \frac{.1876}{11.06} = 0^{\circ}\ 58'$ = static vertical list



4. Calculation of List in Vertical Mode due to Wind Load of 40 Knots

In this and the following calculation it should be noted that the "D" shape of the upper house causes it to "feather" with its rounded portion facing into even light winds. Because of the location of the CG eccentricity, the static list of the buoy (calculated above) causes the buoy's static list to be toward the prevailing wind. It thus tends to counteract wind-induced list and must be subtracted therefrom.

Assume: cylindrical shape factor of .6 = C_D
40 knot = 10.35 psf



16 x 23.5 = 376(.6) = 225.6 ft^2
7 x 28 = 196 (.6) = 117.6 ft^2

A_1 = 225.6 ft^2
A_2 = 117.6 ft^2

(225.6)(10.35) = 2335 lbs
(117.6)(10.35) = 1217 lbs

2335 (182) = 424,970
1217 (149) = 181,333
total M = 606,303

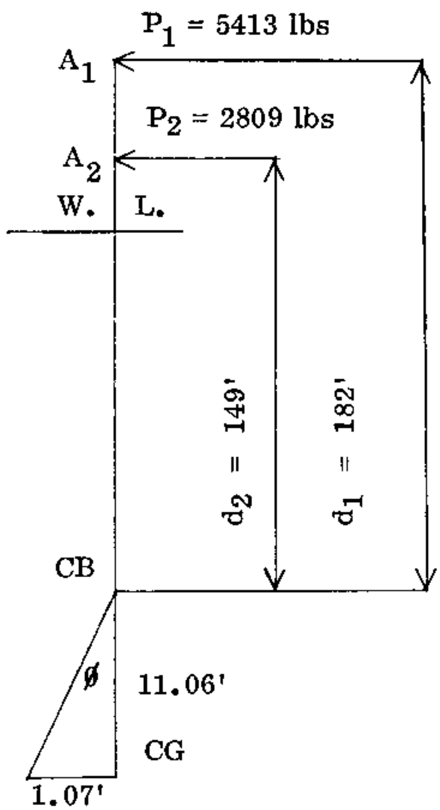
606,303/1,309,041 = .4632 ft

$$\phi = \tan^{-1} \frac{.4632}{11.06} = 2.4^\circ$$

- static list of 1.0° = 1.4° net

5. <u>Calculation of List in Vertical Attitude due to Wind Load of 60 Knots</u>

Assume: cylindrical shape factor of $.6 = C_D$
60 knot = 23.89 psf



16 x 23.5 = 376 (.6) = 225.6
7 x 28 = 196 (.6) = 117.6

(225.6) (23.89) = 5413.47 lbs
(117.6) (23.89) = 2809 lbs

5413.5 (182) = 985,257
2809 (149) = 418,541
1,403,798

$$\frac{1,403,798}{1,309,041} = 1.07$$

$$\phi = \tan^{-1} \frac{1.07}{11.06} = 5.5^{\circ}$$

- static list of $1.0^{\circ} = 4.5^{\circ}$ net

6. <u>Calculation of Metacentric Height in Horizontal Attitude</u>

For a variety of reasons a high degree of roll stiffness in the horizontal attitude was neither required nor desired. Therefore, a metacentric height (GM) of four inches was selected. The following calculations indicate how this value was achieved.

a. Definitions
   W = buoy weight in horizontal attitude
   M = net eccentric moment from Table B-III
b. Calculation
   GM = M/W = 245,635/735,258 = .334 ft = 4"

where

Dry weight	=	688,458
Wet stores	=	46,800
W	=	735,258

This value of GM was achieved by placing the CG of the fixed ballast sufficiently below the buoy centerline.

7. Calculation of Moment of Inertia and Section Modulus - Main Shaft

As stated elsewhere in this report, there are a variety of reasons for minimizing the diameter of the buoy's main shaft. The shaft diameter selected is as small as possible while providing adequate longitudinal strength and sufficient internal space to accommodate the elevator and necessary ducting. This is a shaft of internal diameter = 82 inches and thickness ranging through 1, 1-1/4 and 1-1/2 inches as bending moments dictated. Material employed is mild steel and Cor-Ten, a low alloy of medium strength with a minimum yield of 47,000 psi giving an estimated allowable fiber stress (3/4 of yield) of 35,000 psi. Because of the cyclical nature of shaft flexing, we have allowed a safety factor of 2.

In order to determine fiber stress, it was necessary to calculate the section modulus of the shaft for each wall thickness as well as the bending moments imposed by extreme sea conditions in the horizontal attitude. Compared to loads imposed in the horizontal, bending loads imposed under any conditions in the vertical and during translation are not of sufficient significance to influence the calculation. Cantilever loads that occur during translation are sometimes equal to but nowhere greater than those imposed under extreme hogging.

a. Definitions

D = 84" = OD, 1" wall	d = 82" = ID	R_1 = 42.25"
D_1 = 84.5" = OD, 1-1/4" wall	r = 41"	R_2 = 42.5"
D_2 = 85" = OD, 1-1/2" wall		

I = moment of inertia (7'-0" O.D.)
I_1 = moment of inertia (7'-1/2" O.D.)
I_2 = moment of inertia (7'-1" O.D.)

S = section modulus (7'-0" O.D.)
S_1 = section modulus (7'-1/2" O.D.)
S_2 = section modulus (7'-1" O.D.)

b. Calculations

$$I = \frac{(R^4 - r^4)}{4} = \frac{3.14\,(42^4 - 41^4)}{4} = 224{,}459 \text{ in}^4$$

$$S = \frac{224{,}459}{42} = 5344 \text{ in}^3$$

$$I_1 = \frac{(R_1{}^4 - r^4)}{4} = \frac{3.14\,(42.25^4 - 41^4)}{4} = \frac{3.14\,(3{,}186{,}448 - 2{,}825{,}761)}{4}$$

$$= 283{,}139 \text{ in}^4$$

$$S_1 = \frac{283{,}139}{42.25} = 6701.5 \text{ in}^3$$

$$I_2 = \frac{(R_2{}^4 - r^4)}{4} = \frac{3.14\,(42.5^4 - 41^4)}{4} = \frac{3.14\,(3{,}262{,}539 - 2{,}825{,}761)}{4}$$

$$= 342{,}871 \text{ in}^4$$

$$S_2 = \frac{342{,}871}{42.5} = 8067.5 \text{ in}^3$$

8. Calculation of Bending Moments - "Sagging"

Bending moments were derived using standard beam formulae. They were calculated for individual loadings (i.e. main shaft, external elevator, main ballast etc.). The individual moment diagrams are shown and graphically summed in Foldout Sheet 4 to give the total bending moment curves in both hog and sag.

$$M_1 = \text{shaft} = \frac{w\ell^2}{8} = \frac{1163.46\,(251)^2}{8} = \frac{1163.46\,(63{,}001)}{8}$$

$$= 9{,}162{,}373 \text{ ft lbs}$$

$$M_2 = \text{external elevator} = \frac{Pab}{\ell} = \frac{4000\,(26.25)\,(224.75)}{251}$$

$$= 94{,}018 \text{ ft lbs}$$

M_3 = variable ballast tank = $\frac{Pab}{\ell}$ = $\frac{37,500\ (101)\ (150)}{251}$

= 2,263,446 ft lbs

M_4 = diesel fuel and fresh water = $\frac{Pab}{\ell}$ = $\frac{46,800\ (110)\ (141)}{251}$

= 2,891,904 ft lbs

M_5 = stiffening rings = $\frac{Pab}{\ell}$ = $\frac{6650\ (177.5)\ (73.5)}{251}$

= 345,648 ft lbs.

M_6 = compressed air tanks (8) = $\frac{Pab}{\ell}$ = $\frac{5500\ (196)\ (55)}{251}$

= 236,215 ft lbs

M_7 = compressed air tanks (8) = $\frac{Pab}{\ell}$ = $\frac{5500\ (218.5)\ (32.5)}{251}$

= 155,605 ft lbs

M_8 = reverse moment in shaft = 210,300 (11.5) = 2,418,450 ft-lbs

$M_1 - M_8$ = 6,743,923 ft lbs

9. Calculation of Bending Moments - "Hogging"

m_1 = $P\ell$ = (83) (50,000) = 4,150,000 ft lbs

m_2 = $\frac{w\ell^2}{2}$ = $\frac{(1163)\ (73^2)}{2}$ = 3,098,813 ft lbs

M_1 = $m_1 + m_2$ = 7,598,813 ft lbs

$m_3 = P\ell = (10.5)\ (600{,}000) = 6{,}300{,}000$ ft lbs

$m_4 = P\ell = (5)\ (11{,}000) = 55{,}000$ ft lbs

$M_2 = m_3 + m_4 = 6{,}355{,}000$ ft lbs

$$M_3 = \frac{Pab}{\ell} = \frac{192{,}252\ (18)\ (76)}{94} = 2{,}797{,}880 \text{ ft lbs}$$

$$M_4 = \frac{w\ell^2}{8} = \frac{(1163)\ (94^2)}{8} = 1{,}284{,}533 \text{ ft lbs}$$

10. Calculation of Deflection in Main Shaft

Deflections were calculated on the bases of the moments and stiffnesses derived above using standard beam formulae.

a. "Sagging"

1) $\triangle$ at variable ballast tank $= \dfrac{P a^2 b^2}{3 E I \ell} = \dfrac{49{,}000 (1212^2)(1800^2)}{3(2.9 \times 10^7)(342{,}871)(3{,}012)}$

$$\triangle = 2.59 \text{ in.}$$

2) $\triangle$ at center $= \dfrac{5w\ell^4}{384\ E\ I} = \dfrac{(5)\ (96)\ (3012^4)}{384\ (2.9 \times 10^7)\ (300{,}000)}$
ave (I)

$$\triangle = 11.97 \text{ in.}$$

3) These are summed graphically on Foldout Sheet 4 to derive a total deflection of 14.7 inches over 287 feet which is well within acceptable limits.

b. "Hogging"

1) $\triangle_1 = \dfrac{Pa^2}{3EI}(\ell + a) = \dfrac{50{,}000\ (996^2)\ (3012)}{3(2.9 \times 10^7)(300{,}000)} = 5.724$ in.

2) $\triangle_1$ at center $= \dfrac{Pax}{6EI}(\ell^2 - x^2) = \dfrac{50{,}000\ (996)\ (1008)\ (2016^2 - 1008^2)}{6\ (2.9 \times 10^7)\ (342{,}871)\ (2016)}$

$$\triangle = 1.272 \text{ in.}$$

3) $\triangle_2 = \frac{w\ell^3 a}{24 EI} = \frac{(97)(2016^3)(996)}{24(2.9 \times 10^7)(300,000)} = 3.7912$ in.

4) $\triangle_2$ at center $= \frac{5 w \ell^4}{384 EI} = \frac{5(111.42)(2016^4)}{384(2.9 \times 10^7)(342,871)} = 2.4097$ in.

5) $\triangle_3 = \frac{w a^3}{24 EI}(4\ell + 3a) = \frac{(97)(876^3)[4(2136) + 3(876)]}{24(2.9 \times 10^7)(342,871)} = 3.4889$ in.

6) $\triangle_3$ at center $= \frac{w a^2 x}{12 EI}(\ell^2 - x^2) = \frac{(97)(876^2)(1008)[2016^2 - 876^2]}{12(2.9 \times 10^7)(342,871)(2016)}$

$\triangle = 1.0284$ in.

7) These, again, are summed graphically on Foldout Sheet 4 to derive a total of 15.0 inches, still within acceptable limits.

11. Calculation of Maximum Stress in Critical Sections of Main Shaft

Maximum fiber stress was computed by dividing the maximum moment by the section modulus of the shaft at that point. As the moments fell off, section moduli were reduced by reducing the wall thicknesses. Moments and section moduli are as shown in previous calculations.

a. Definitions

σ = maximum stress

M = bending moment, ft-lbs

S = section modulus

b. Calculations

M_1 = 9,200,000 ft-lbs = maximum sag moment for loading condition = 83,000 lbs variable ballast but no wet stores

M_2 = 10,400,000 ft-lbs = maximum hog moment for loading as for M_1 above

$M_3 = 11,850,000$ ft-lbs = maximum sag moment for loading as in M_1, but with 46,800 lbs wet stores added.

All these maximum moments occur at approximately the same section, just below the variable ballast tank (See Foldout Sheet 4).

$$I = 342,871 \text{ in}^4, \quad S = S_2 = 8067.5 \text{ in}^3$$

$$\sigma = M/S_2$$

$$\sigma_1 = \frac{9,200,000\ (12)}{8067.5} = 13,684 \text{ psi}$$

$$\sigma_2 = \frac{10,400,000\ (12)}{8067.5} = 15,479 \text{ psi}$$

$$\sigma_3 = \frac{11,850,000\ (12)}{8067.5} = 17,626 \text{ psi}$$

Based on allowable fiber stress of 35,000 psi, this gives an approximate safety factor of 2. This is considered adequate to accommodate dynamic loading factors. A similar safety factor was employed in determining the distributions of shaft wall thicknesses shown in Figure B-4.

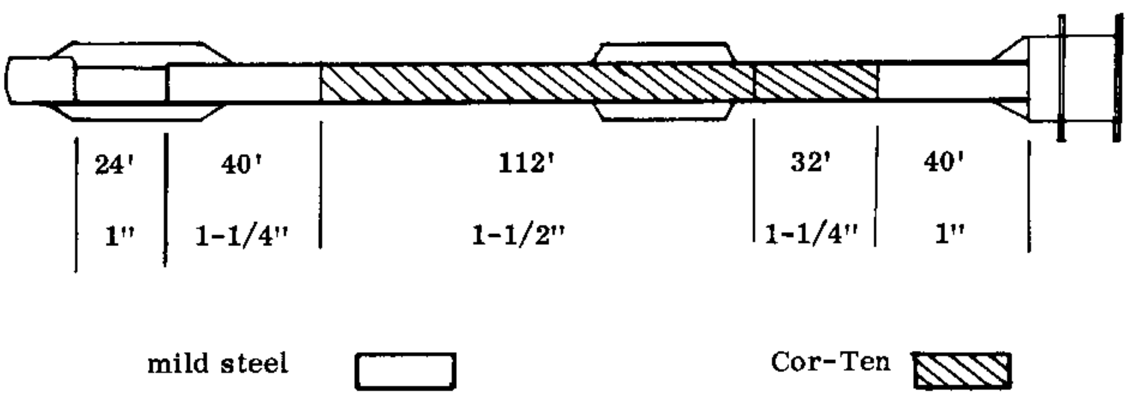


Fig. B-4 Distribution of shaft wall thicknesses and main shaft materials

12. Calculation of collapse pressure of variable ballast tank
(based on ASME Code VIII)

D_o = 168 in. L = 30 in. Temperature = under 300° F

t = 5/8 in. Design depth = 100' max

Design pressure = 44 psi = P (B) factor = $P(D_o/t)$

P_a = pressure allowable $D_o/t = 268.8$ $L/D_o = .2143$

$$P_a = \frac{B}{D_o/t} = \frac{15,000}{268.8} = 55.8 \text{ psi}$$

Stiffening Rings @ 30" C-C

$$I = \frac{bd^3}{12} = \frac{(.5)(9^3)}{12} = 30.4$$

L_s = 30 in. $A_s = 4.5 \text{ in}^2$

$$B = \frac{P(D_o)}{t + A_s/L_s} = \frac{44\,(168)}{.5 + 5/30} = \frac{7392}{.6666} = 11,372$$

(A) factor = .00015

$$I_s = \frac{D_o^2 L_s (t + A_s/L_s) A}{14} = \frac{(168)^2 (30) (.65) (.00015)}{14}$$

$= 29.48 \text{ in}^4$ = moment of inertia required

$I = 30.4 \text{ in}^4$ = moment of inertia of ring selected

Conclusion: 5/8" thick mild steel shell

1/2" plate x 9" deep stiffening rings (mild steel)
@ 36" centers

13. Calculation of collapse pressure of observation lab
(based on ASME Code VIII)

$D_o = 96$ in. $L = 36$ in. Temperature = under 300^o F

$t = 1$ in. Design depth = 250' max

Design pressure = P = 110 psi (B) factor = $P(D_o/t)$

P_a = pressure allowable $D_o/t = 96$ $L/D_o = .375$

$$P_a = \frac{B}{D_o/t} = \frac{17,000}{96} = 177 \text{ psi}$$

Stiffening Rings

$$I = \frac{bd^3}{12} = \frac{(1)(6^3)}{12} = 18 \text{ in}^4$$

$L_s = 36$ in. $A_s = 6$ in^2

$$B = \frac{P(D_o)}{t + A_s/L_s} = \frac{110\ (96)}{1 + 6/36} = \frac{10,560}{1.1666} = 9,051$$

(A) factor = .0006

$$I_s = \frac{D_o^2\ L_s\ (t + A_s/L_s)\ A}{14} = \frac{96^2\ (36)\ (1.1666)\ (.0006)}{14}$$

$= 16.59$ in^4 = moment of inertia required

$I = 18$ in^4 = moment of inertia of ring selected

Conclusion: 1" thick mild steel shell

1" plate x 6" deep stiffening rings (mild steel)
@ 36" centers

Porthole frames of flame-cut and machined Cor-Ten steel were selected. These will be welded in and faired to the hull. Acrylic portlights were chosen, 10" inner diameter by 14" outer diameter by 4" thick. These are very conservative, meeting N.C.E.L. recommendations for 5000 ft pressure depth. This extremely large safety factor, along with the ability of acrylic plastic to absorb impact energy removes the necessity for porthole covers.

B. House Structure

The house structure includes all structural materials, fabrication and shop finish, framing, shell plating, decks, catwalks, stairways, ladders, railing, closures for all openings, provision for mounting the work of other systems, together with all jigs, cradles, alignment and assembly fixtures, handling gear and means for making structural interconnection with the hull.

To minimize top weight, the house is of conventional welded aluminum construction, with scantlings based on an ocean-going vessel of 8 ft draft. Stresses used are for 7056, an alloy much used in aluminum open-water craft. The problem of electrolysis in the horizontal will be by no means negligible, and in detailing for final design, care must be taken to assure proper insulations in interconnecting house and hull. Use of a grounded electrical system may present problems.

Design line loads are 40 psf for interior decks, and 100 psf for catwalks and ladders. Top deck is designed for 100 psf or a 12,500 lb concentrated load. House details are shown in Foldout Sheet 2.

C. External Elevator

The external elevator system includes structural frame, decking, handrails, and all hardware mounted on the elevator, but does not include hydraulic controls, hoses, support cables or support machinery.

The external platform, shown in Foldout Sheet 3, is of mild steel welded construction. It is supported by lifting cables and large pre-loaded, rubber-tired rollers against the buoy main shaft. Simple manual means should be provided for locking the platform securely to the shaft for towing.

Lifting force is estimated at

$$F = (4000 + 5000)\ (1.10) = 10,000 \text{ lb}$$

for a live load of 5000 lb and a 10% allowance for friction. At 20 ft/min maximum speed, horsepower requirements are about

$$hp = \frac{10,000}{3 \times 550} \times \frac{1}{0.6} = 10$$

for an overall mechanical efficiency of 60 percent.

Gratings and railings should be designed to be removable for towing and special functions.

D. Internal Elevator

The internal elevator system includes the elevator car complete with controls, cables, rails, traction motor and motor controller, safety devices and indicators; but does not include supply wiring to motor controller or brackets to which rails are mounted.

No detailed elevator design has been completed. This is assumed to be supplied by a competent elevator contractor during Phase II. Design investigations did, however, proceed to the point that we could size the system for its impact on other systems and derive cost estimates as follows:

1. Determination of overall configuration to meet shaft space restrictions as shown in Foldout Sheet 3.
2. Determination of adequate space in the upper house frustrum to accommodate motor and winch.
3. Determination of a maximum speed of 100 fpm which indicates a minimum drive motor horsepower of 7.5.
4. Sizing of batteries to permit four elevator round-trips during silent ship operation while accommodating other critical power drains.
5. Provision of safety factors such as emergency locks, shock absorbers and top and bottom escape hatches.
6. A track configuration to permit operation in both horizontal and vertical attitude.

E. Electrical System

The electrical system includes engine generators and controls, fuel supply system, batteries, gimbal mounts, all switchgear and synchronizing equipment, together with all required indicators, panels, circuit breakers, motor starters, wiring and conduit, receptacles and fixtures including navigation lights and wiring-in of all motors on the buoy and installation of all built-in electrical appliances. Not included are any electrical hull penetrators or external underwater cabling, hardware of fixtures, but the installation of conduit and splice boxes for other wired systems is included.

Basic requirements of the electrical system are that it be:

(1) reliable,
(2) compatible with normally available shore power,
(3) able to supply high-quality power for instruments and electronics,
(4) able to supply essential loads during silent ship operation,
(5) operable in horizontal position,
(6) adequate in capacity, and
(7) safe against shock hazard and electrical fires.

Included below are a preliminary load analysis, one-line wiring diagram, list of major equipment items and hardware, and some additional details.

1. Load Schedule

a) D. C. Loads

	hp	KW	Duty cycle	KWH/hr (average)
Elevator	7.5	5.6	.07	.38
Blowers	2	1.5	1.0	1.5
House interior lights	-	0.5	.5	.25
Navigation lights	-	0.5	.5	.25
External lights	-	0.5	.5	.25
Underwater lights	-	4.0	.7	2.8
Shaft interior lights	-	1.0	1.0	1.0
Observation chamber lights	-	0.5	.5	.25
Fuel pump	1	0.8	.01	.008
High-quality AC	-	10	.5	5

Connected load	24.9	
Average battery drain		11.7
Allowance for recovery 50%		6.0
Capacity required for float charger		17.7
Charger supplied = 20 KW cont. duty 17.7		

For silent ship operation, battery drain will be 11,700/130 = 90 amp (average). With 400 A.H. battery furnished, silent ship operation of two 4-hour periods in 24 hours is permissible: 400/90 = 4.4 hr, with greater than 50% recovery provided.

b) A. C. Loads

	hp	KW	Duty cycle	KW (average)
Hydraulic supply	15	12.0	.05	.6
Air refrigeration	5	3.8	.50	1.9
Salt water pump	2	1.5	.25	.38
Fresh water pump	2	1.5	.05	.08
Sewage pump	2	1.5	.05	.08
Air compressor	5	4.0	.10	.4
Galley	-	5.0	.5	2.5
A. C. Lights	-	10.0	.4	4.0
D. C. Lights*	-	7.0	.7	4.9
Float charger	-	20	.7	14.0

Connected load	61.5	
Average power drain		28.84

* operate from either AC or DC bus.

2. <u>Power Generation and Distribution</u>

Select two 30 KW continuous duty engine generators, with load sensing and automatic start and synchronization. One generator carries average load, two carry total connected load. Two identical generators allow alternating the standby unit for equal wear.

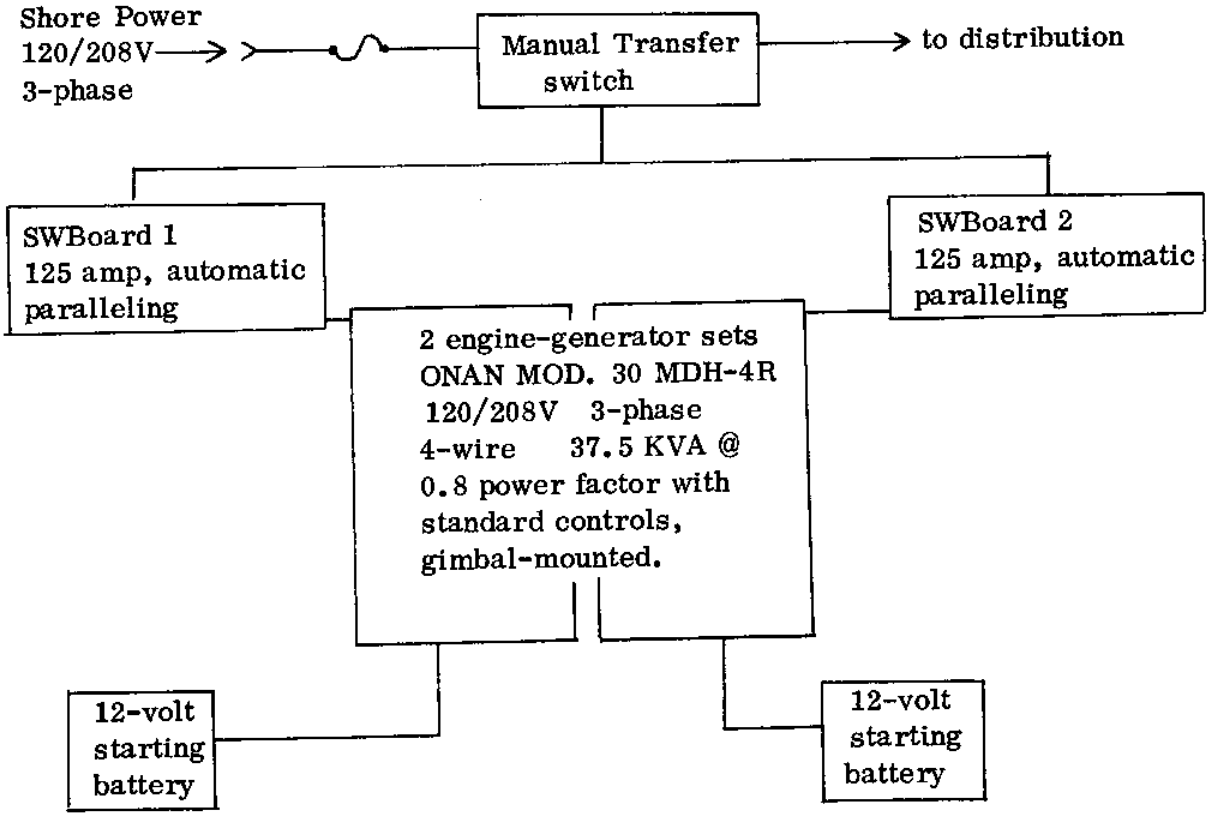
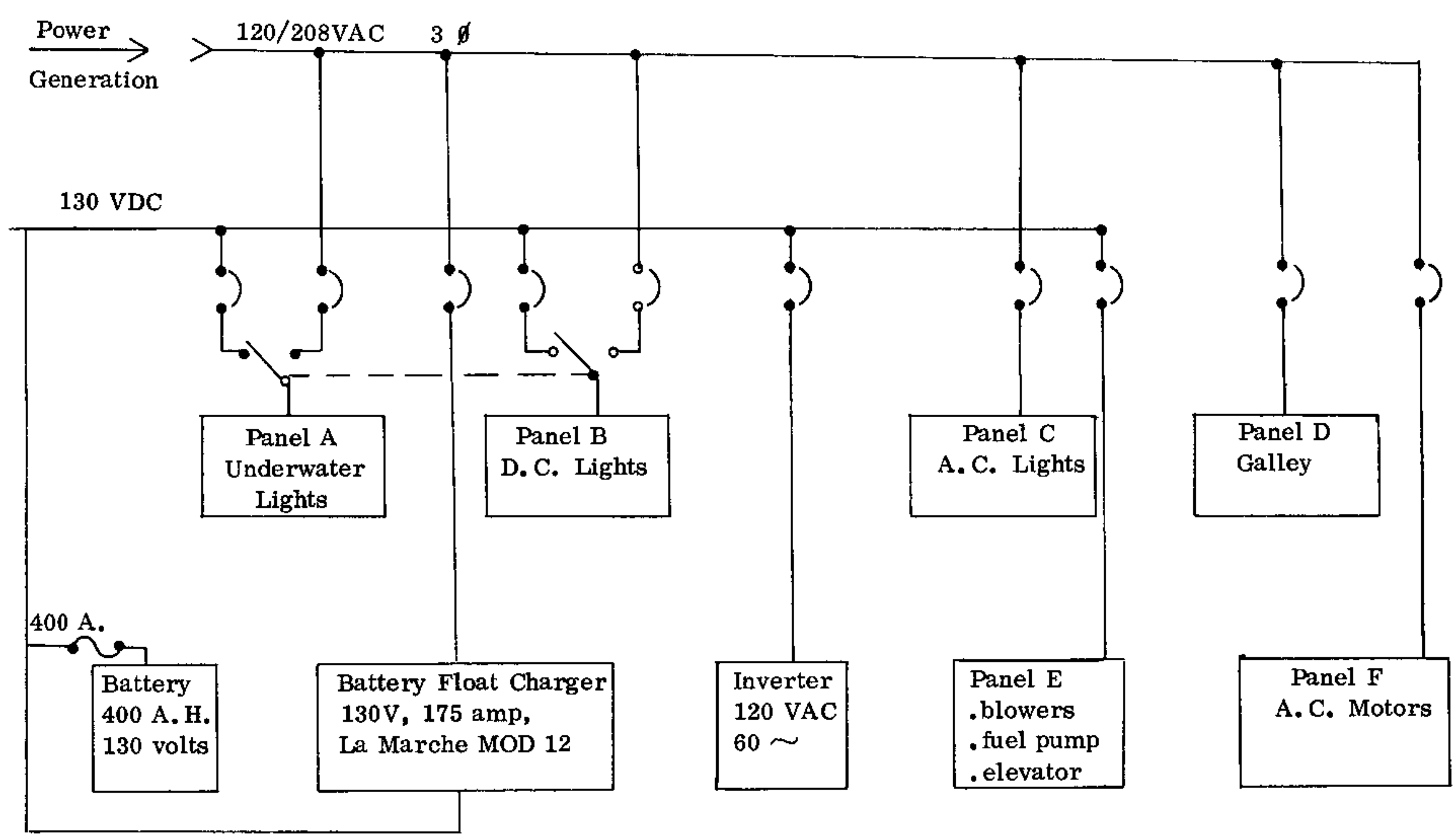


Fig. B-5 Schematic of MOSES electrical power generation subsystem

Fig. B-6 Schematic of MOSES electrical power distribution subsystem



F. Hydraulic System

The hydraulic system includes fluid supply pump, motor and controls, oil reservoir, all oil piping, valves, regulators, and associated hardware, as well as the complete jib crane and all machinery for the operation of the external elevator. The external elevator (see Foldout Sheet 3) is driven by a single positive displacement hydraulic motor through a gear reducer and auxiliary gearing to four individual wire drums contained within the frustrum of the upper house. See (C) above for horsepower requirements.

Foldout Sheet 6 includes a simplified diagram of the hydraulic system. The calculations below are pertinent to its sizing.

1. For external elevator

Calculate required pump, motor, and electric drive motor required for external elevator, at 20'/min with 10,000 lb lift force.

a. From C above, 10 hydraulic hp is required at elevator motor.
b. Select Webster HDP6260 hydraulic motor (12 gpm @ 1800 rpm). E_{vol} = 93%, 12 gpm/.93 = 12.96 gpm required.
c. Select Webster Pump C3PB, 13.6 gpm @ 1800 rpm max.
d. Select 15 hp electric drive motor, delivers 13.6 gpm @ 2200 psi max.

2. For jib crane

a. Winch motor for crane: 150 ft/minute max. lift speed desired
b. A capacity of 13.6 gpm @ 2200 psi available from 1.d above.
c. Assuming 50% overall efficiency

$$\text{lift capacity} = \frac{(13.6)\ (2200)\ (33{,}000)\ (.50)}{(1714)\ (150)}$$

$$= 1920 \text{ lb}, > 1500$$

3. Conclusion

The hydraulic supply derived in (1) above is adequate for either service singly, but not both at the same time.

G. Pneumatic System

The pneumatic system includes high-pressure air compressor and motor, air storage tanks, all piping, valves, regulators and associated hardware, including all pilot-operated valves in the buoy and all ballast blow and vent lines and fittings and air connections to other systems. A layout of the system is shown in Figure B-7. The following calculations are pertinent:

1. Air required for translation from vertical attitude:
   a. Moment to be removed is

      (1,309,041 lb) (11.06 ft) = 14,478,000 ft-lb

   b. By blowing 81,000 lb from upper portion of main ballast tank:

      buoy rises 81,000/2,490 = 32 ft.

   c. Therefore, 81,000 lb buoyancy is transferred from the CG of the lost buoyancy at the upper shaft to the CG of the gained buoyancy in the main ballast tank.

      M = (81,000) (199-16) = 14,823,000 ft-lb

   d. This is greater than the 14,478,000 required, so buoy will translate. When 81,000 lb of water have been displaced, buoy is 32' higher than LWL and air pressure in MBT is equal to

      sea pressure at flood valve = (.44)(215 - 32)/14.7 = 5.5 atm

      air required = (5.5) (81,000/64) = 6,960 SCF

2. When buoy is horizontal, flood valve is at 9 ft depth and air in MBT is at an elevated pressure of

   1 + 9/33 = 1.27 atm.

   a. Total quantity of air required to exhaust MBT is

      (7656) (1.27) = 9,723 SCF

   b. An additional (9723-6960) = 2763 SCF must be introduced into MBT after translation begins.

3. To blow VBT, 83,783 lb of water must be removed. Flood valve is at -8 ft in horizontal, therefore air in FBT must be brought to (1 + 8/33) = 1.24 atm.

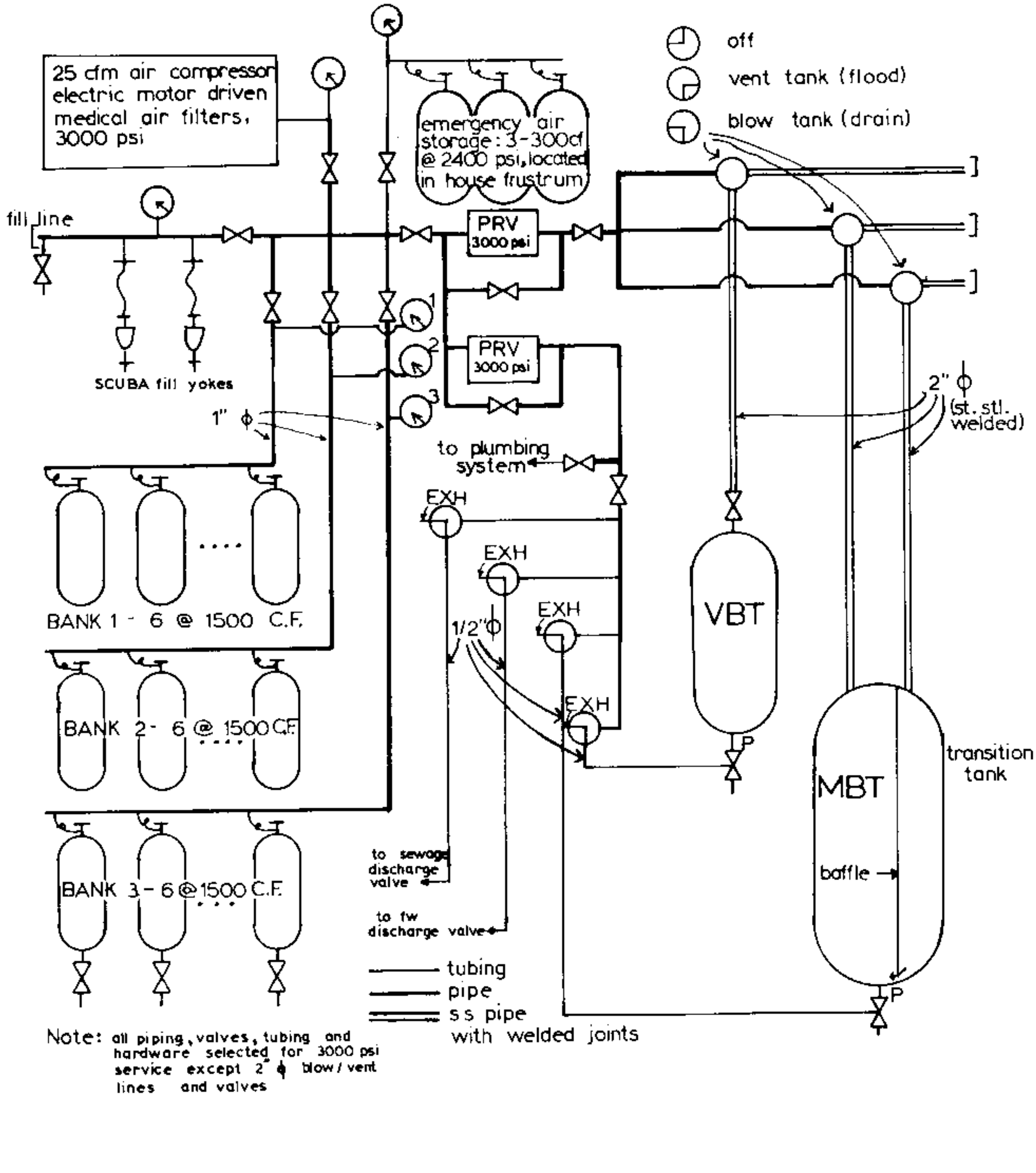
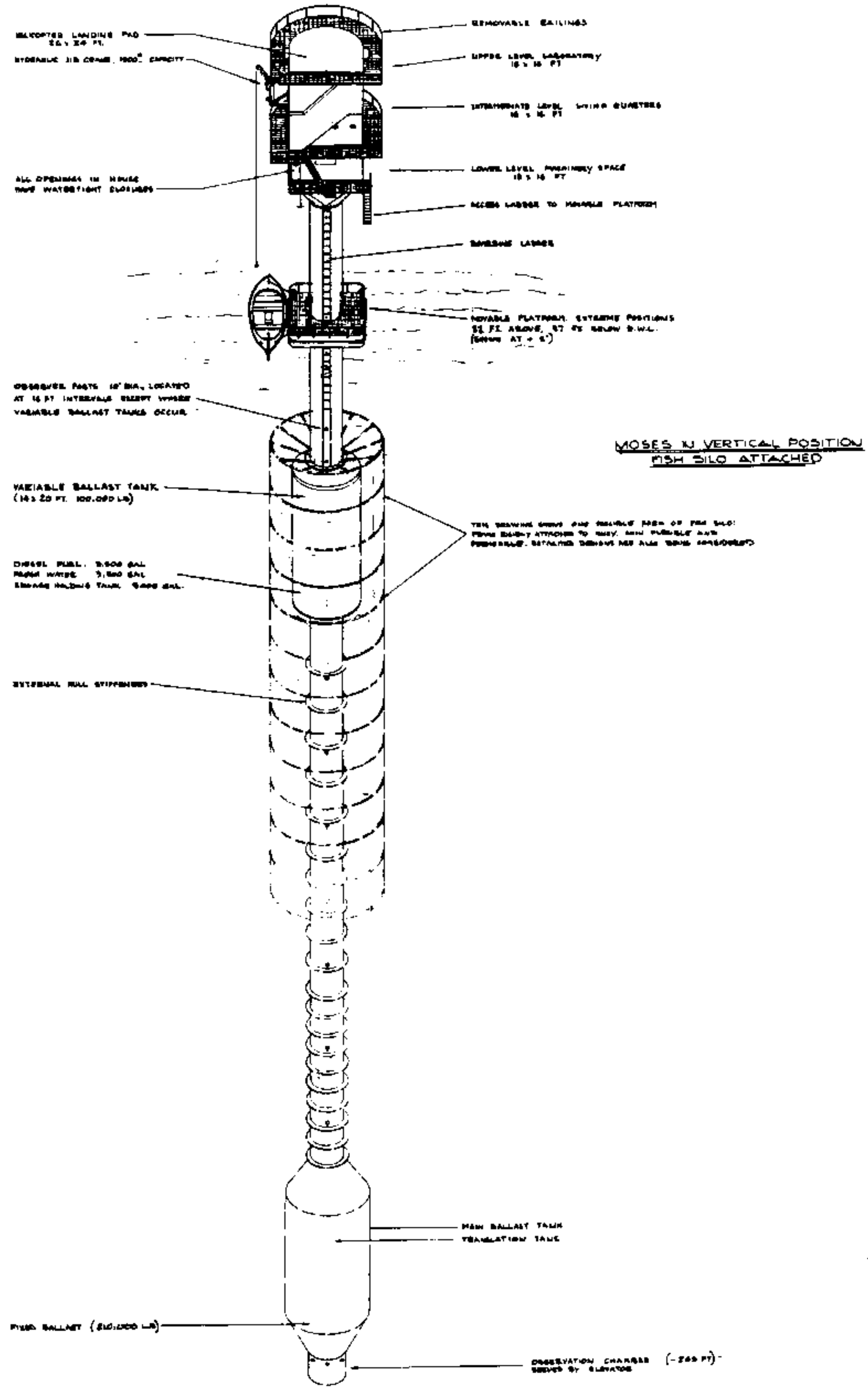


Fig. B-7 Layout of pneumatic system



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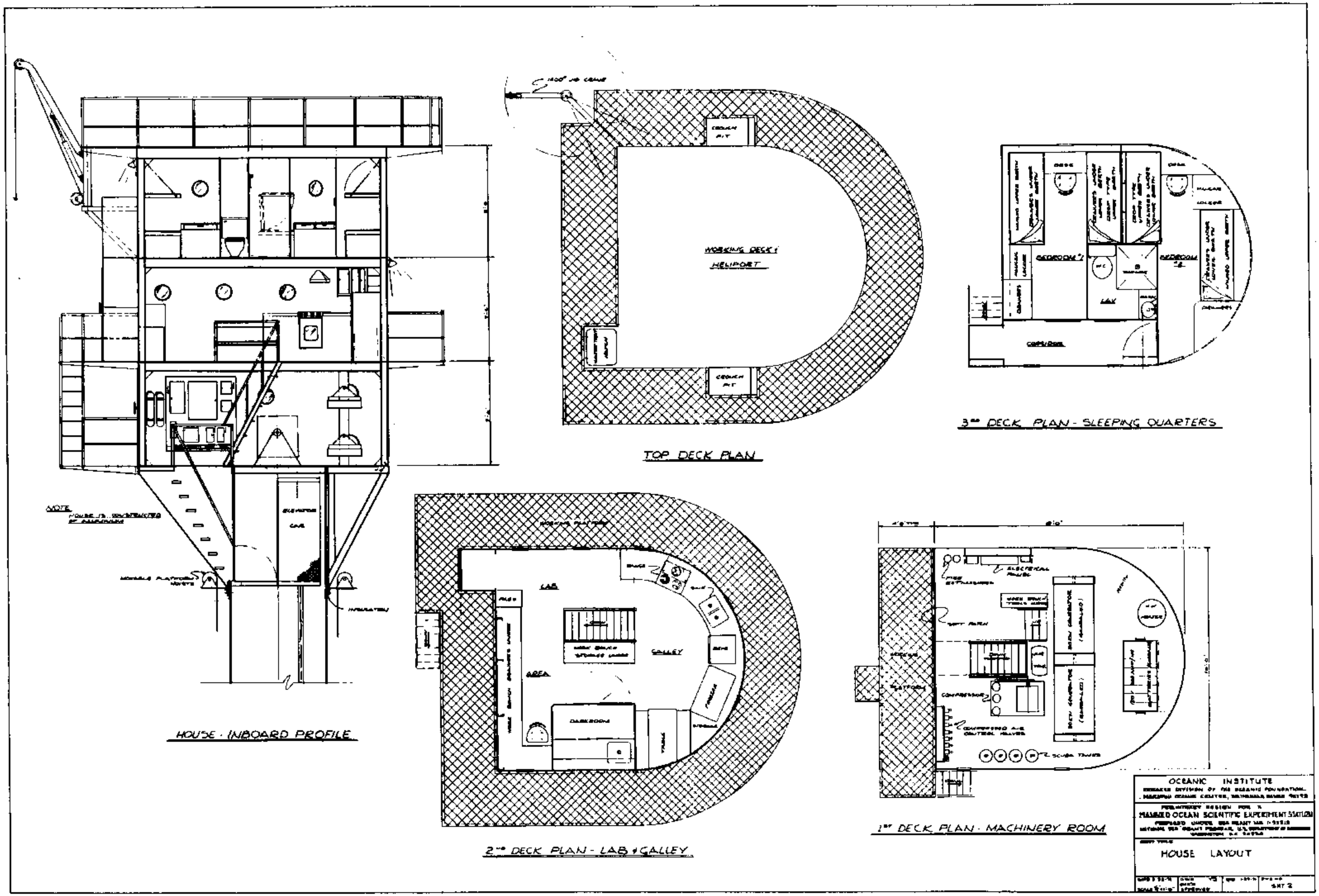
MOSES GENERAL LAYOUT

SHT - 1


HOUSE - INBOARD PROFILE
TOP DECK PLAN
WORKING DECK & HELIPORT
CROUCH PIT
1400# JIB CRANE
3RD DECK PLAN - SLEEPING QUARTERS
BEDROOM #1
BEDROOM #2
LAV
CORRIDOR
2ND DECK PLAN - LAB & GALLEY
LAB
AREA
GALLEY
DARKROOM
FREEZER
1ST DECK PLAN - MACHINERY ROOM
COMPRESSOR
SCUBA TANKS
ELEVATOR CAR
NOTE
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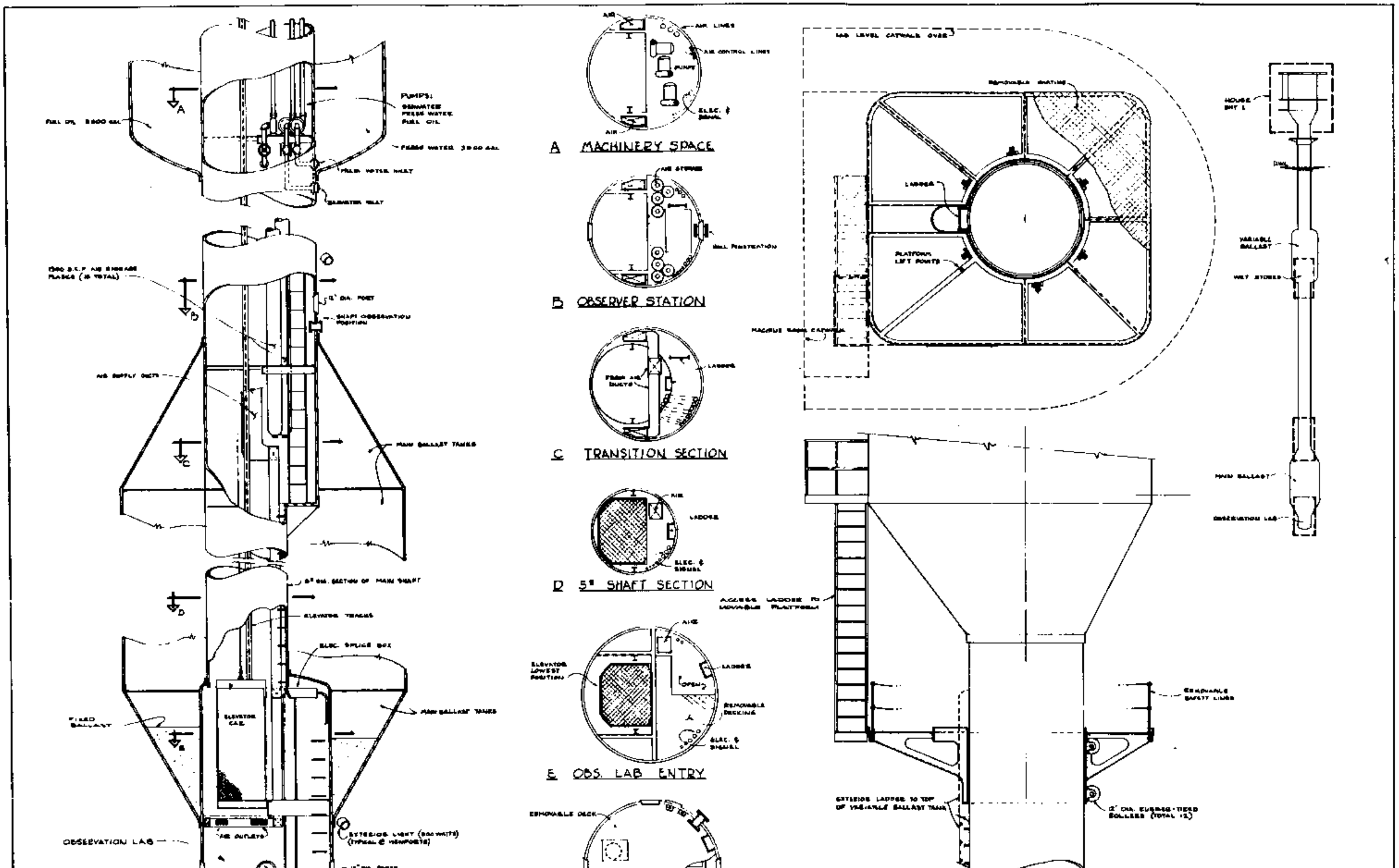
HOUSE LAYOUT
SHT 2



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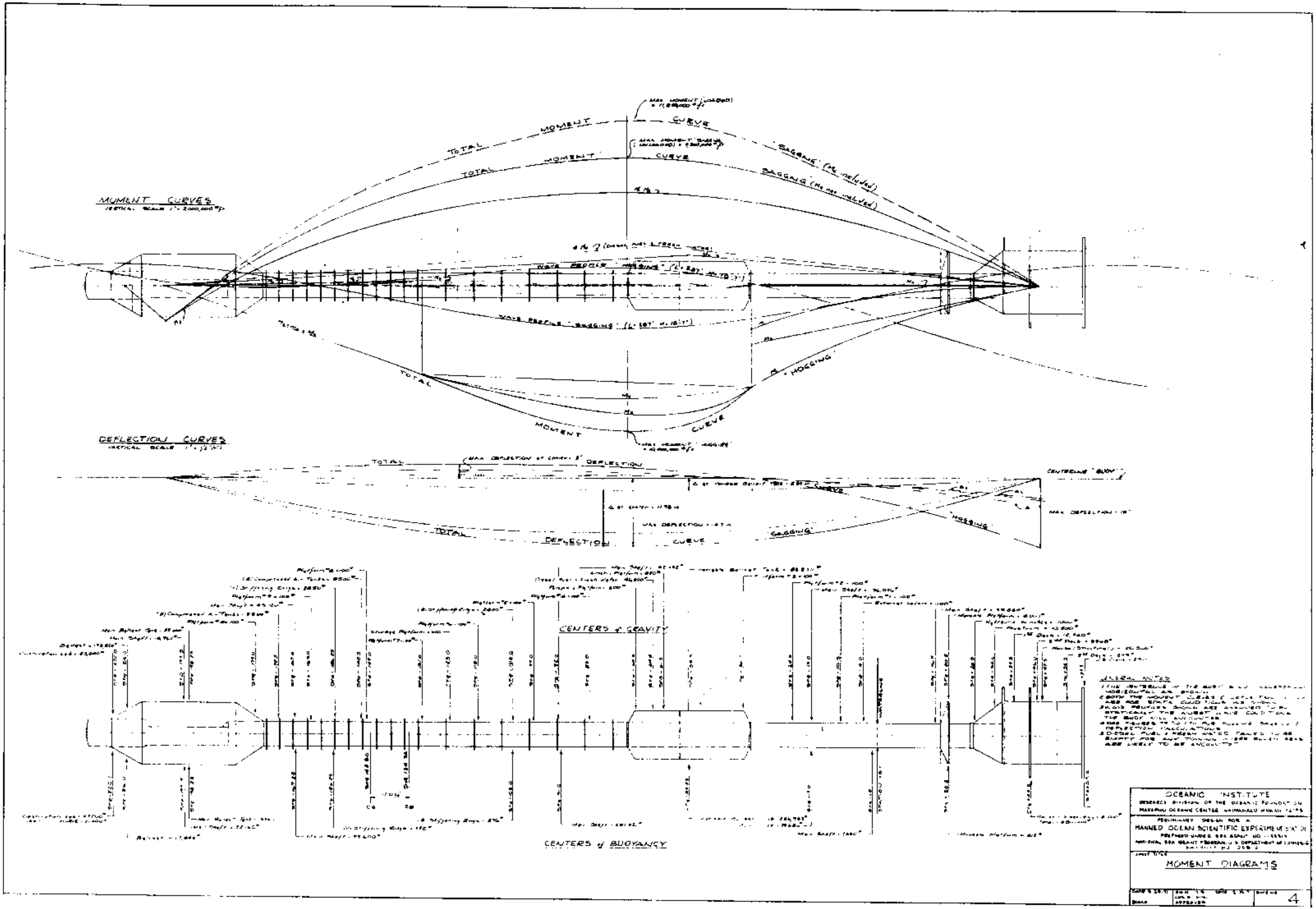
PRELIMINARY DESIGN FOR A
MANNED OCEAN SCIENTIFIC EXPERIMENT STATION

SHAFT & OBSERVATION-
LAB LAYOUT

SHT 3



MOMENT CURVES
TOTAL MOMENT CURVE
SAGGING
HOGGING
WAVE PROFILE
DEFLECTION CURVES
TOTAL DEFLECTION CURVE
CENTERS of GRAVITY
CENTERS of BUOYANCY
GENERAL NOTES
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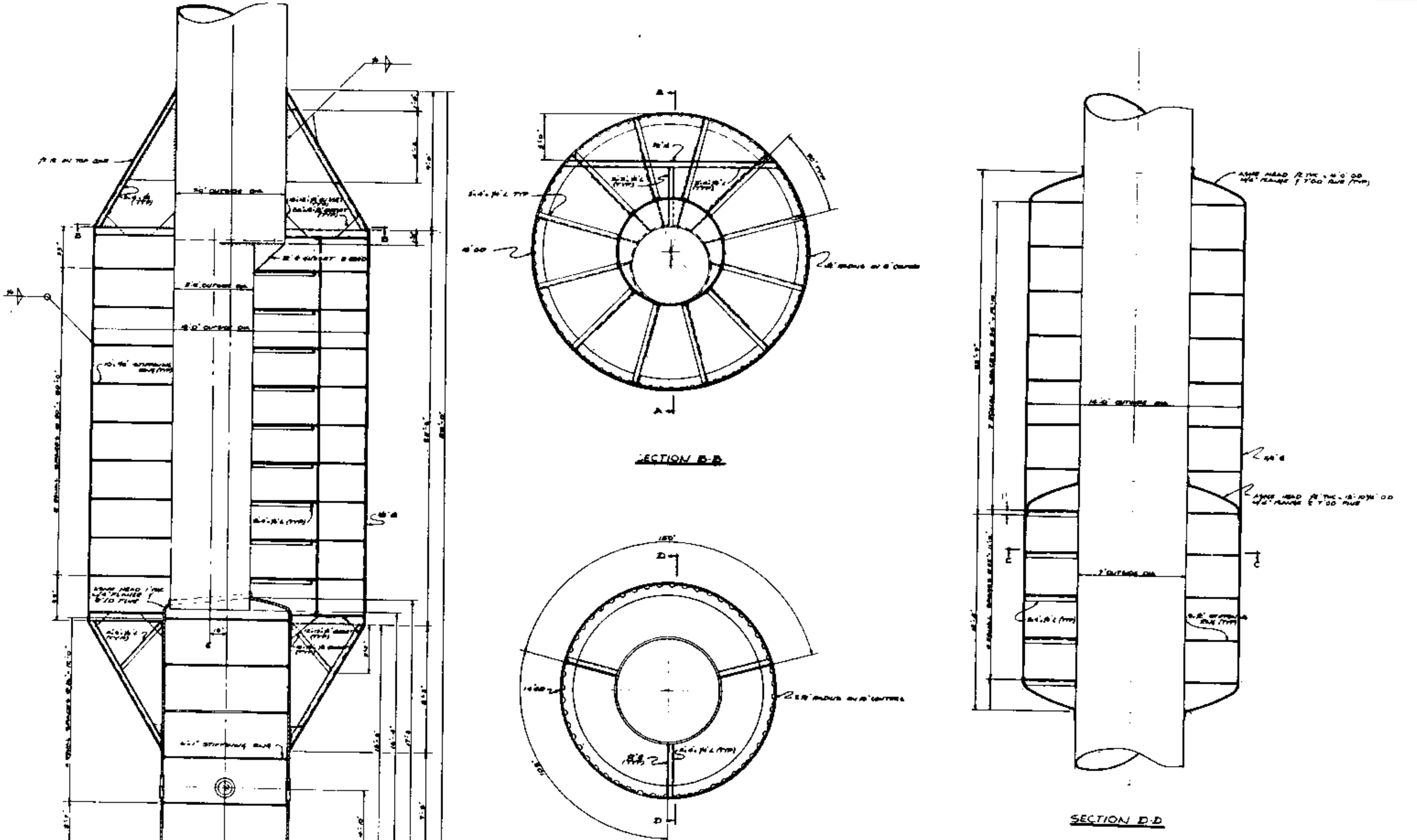
PRELIMINARY DESIGN FOR A
MANNED OCEAN SCIENTIFIC EXPERIMENT STATION
MOMENT DIAGRAMS
4



SECTION A-A

SECTION C-C

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PRELIMINARY DESIGN

MANNED OCEAN SCIENTIFIC EXPERIMENT STATION

STRUCTURAL DETAILS
BALLAST TANKS

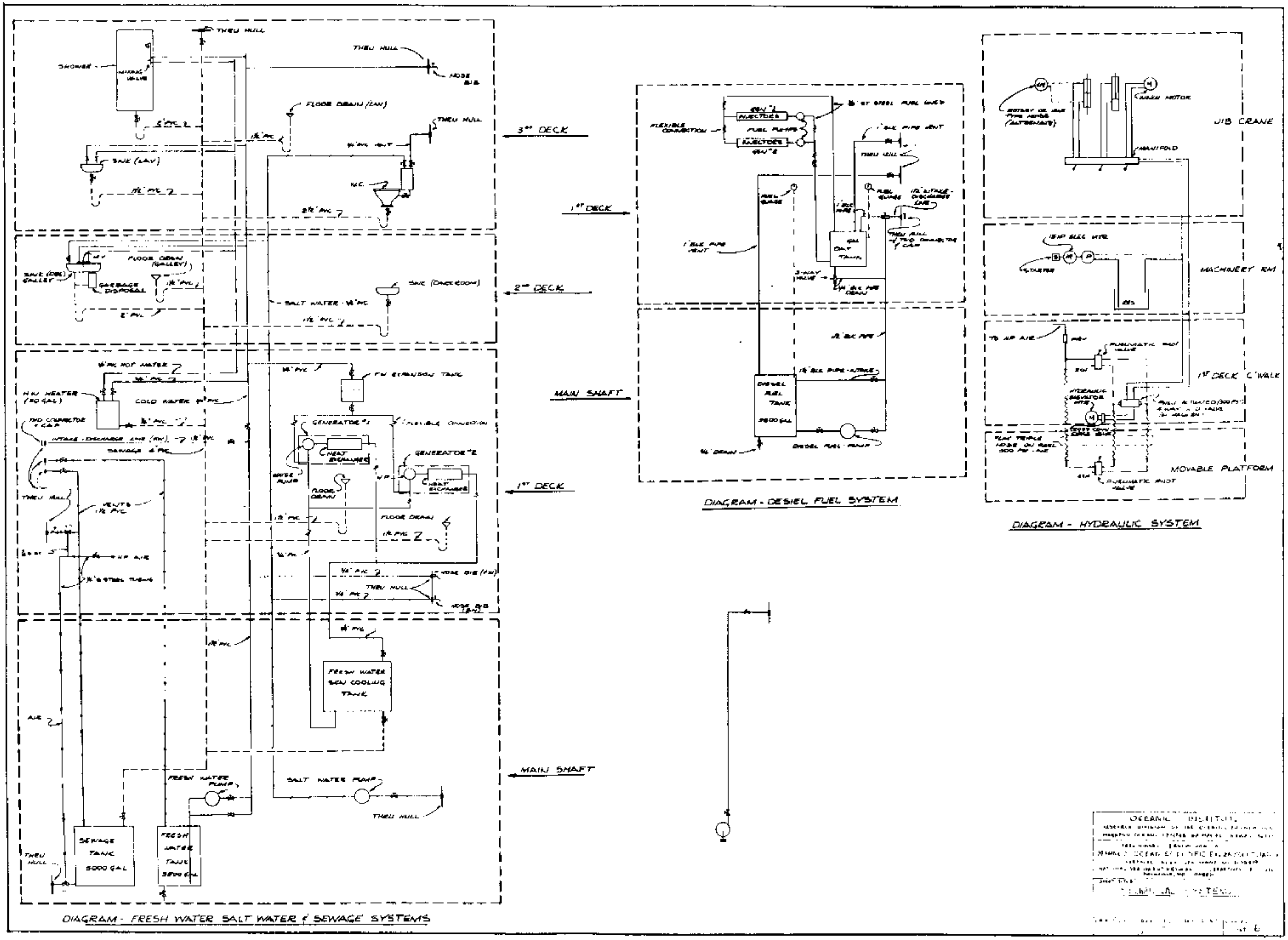
DIAGRAM - FRESH WATER SALT WATER & SEWAGE SYSTEMS
DIAGRAM - DESIEL FUEL SYSTEM
DIAGRAM - HYDRAULIC SYSTEM
3RD DECK
2ND DECK
1ST DECK
MAIN SHAFT
JIB CRANE
MACHINERY RM
1ST DECK C'WALK
MOVABLE PLATFORM
SHOWER
MIXING VALVE
THRU HULL
HOSE BIB
FLOOR DRAIN (LAV)
SINK (LAV)
W.C.
SINK (DBL) GALLEY
GARBAGE DISPOSAL
FLOOR DRAIN (GALLEY)
SINK (DARKROOM)
SALT WATER
H.W. HEATER (30 GAL)
COLD WATER
FW EXPANSION TANK
FLEXIBLE CONNECTION
GENERATOR #1
GENERATOR #2
HEAT EXCHANGER
FLOOR DRAIN
HP AIR
SEWAGE TANK 5000 GAL
FRESH WATER TANK
FRESH WATER PUMP
SALT WATER PUMP
FRESH WATER GEN COOLING TANK
FLEXIBLE CONNECTION
INJECTORS
FUEL PUMPS
DAY TANK
DIESEL FUEL TANK
DIESEL FUEL PUMP
MANIFOLD
STARTER
PNEUMATIC PILOT VALVE
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a. Air required is (140,000/64) (1.24) = 2712 SCF

b. Total air for one translation = 2712 + 9723 = 12,435 SCF

c. Two translations + 10% reserve were required:

Air storage = 2 (12,435) (1.10) = 27,357 SCF

4. Eighteen 1500 SCF flasks are provided = 27,000 SCF

5. Complete recharge in 24 hours or less requires

27,000/(24 x 60) = 18.75 SCFM

therefore, select 25 SCFM x 3000 psi compressor.

6. Note: The above computations assume that the VBT is blown dry on each translation from vertical to horizontal. In point of fact, the VBT will usually not be blown completely, but left partially full to provide proper trim. Therefore, air reserve capacity is very probably somewhat greater than indicated.

H. Ventilating and Air Conditioning System

This includes all blowers and motors, ducts, grills, registers and controls, as well as provision for the installation of filtering and refrigeration.

The only critical space for ventilation is the deep observation laboratory at the bottom of the main shaft. For four complete air changes per hour, a D.C.-operated blower is required which will supply 750 CFM at about 8 inches static pressure. The very deep and totally enclosed shaft presents considerable danger to occupants of the deep observation laboratory in case of blower failure or contamination of the air in the shaft by leakage of diesel exhaust gases, spillage of diesel fuel, or other toxic material. Therefore this system will include monitoring equipment and alarms for detection of the presence of CO, CO_2, and combustible hydrocarbons as well as loss of air flow in air supply ducts. Backup blowers will be provided.

In addition, the introduction of large amounts of warm and humid air into this water cooled compartment will cause significant condensation problems. Therefore, it will be necessary to dehumidify the input air before introduction. In the preliminary concept, this is done by a 5 hp refrigerator and warming with waste heat from the diesel engines. This, however, leaves the silent ship periods uncovered. Therefore, a D.C. warmer may be required.

I. Waste Disposal System

The waste disposal system includes all drain lines, floor drains and associated hardware, valves, traps and vents, and all plumbing fixtures connected thereto, as well as connections to sewage tank, level gages, and alarms. The sewage tank has a 10 day holding capacity (5500 gallons). Capabilities for preventing sludge formation and blowing the tank with compressed air are provided.

The piping and fixtures are conventional and are shown on Foldout Sheet 6.

J. Water Storage and Supply System

The water storage and supply system includes all piping, fittings, pressurizing units with motors and controls, all connected fixtures, tank gages and alarms, valves and indicators for fresh water storage and supply, and salt water supply. This system is shown on Foldout Sheet 6.

K. Surface Preparation and Painting

This covers all cleaning, sandblasting and painting of exterior and interior of the buoy structure, piping, conduits, ducts, partitions, machinery mounts, and where called for, installed machinery. Included is all color coding of painted surfaces for all systems. The hull is painted inside and outside with inorganic zinc silicate over bright sand-blasted metal, plus two coats of hard epoxy enamel. The interior finish coat will contain ground cork for insulation. No toxic anti-fouling paint is to be used. Although the house exterior could be otherwise left bright except for colored identification markings, it must be covered by an insulating paint to inhibit electrolytic reaction with the steel hull. House interior is epoxy enamel over zinc chromate primer.

L. Navigation and Communication

This includes basic electronics, comprising high-seas HF transmitter and receiver, UHF short-range transceiver, radar, loran, recording depth finder and public-address/intercom system. This suite of equipment is considered minimum and required for safety. Other communications or special-purpose electronics are outside the scope of the basic, sea-ready buoy.

M. Deck Gear and Ground Tackle (DGT)

This includes anchors, anchor and mooring lines, fenders, chocks, fairleads, bitts, winches and cleats to permit towing, docking and mooring while the buoy is in the horizontal mode, as well as fittings to allow attachment of a two-point moor while vertical.

N. Miscellaneous Finish Work

This work comprises all floor and wall coverings, cabinetwork, partitions, and miscellaneous items called for in interior fitting out. It will be subject to frequent change orders during construction and sea trial periods, and will be strongly influenced by mission requirements that are not yet known. Included are special storage requirements and provision for installation of special purpose equipment.

APPENDIX C

A COMPUTER ANALYSIS OF THE SEA KEEPING CHARACTERISTICS OF THE MANNED OPEN SEA EXPERIMENTATION STATION

by L. H. Seidl

NOTE:

The following statement of the problem and method of approach, equations of motion in abbreviated form, results, findings and conclusions are a simplified summary of Dr. Seidl's complete analysis. As such they comprise Part I of his report to the Oceanic Institute. Part I is reprinted in toto in the following appendix; Parts II and III will be included in the publication of the complete study at a later date. Part II details all the theoretical background and mathematical procedures. It includes three appendixes concerning: (a) the environmental parameters, wave theory and wave spectra, (b) the equations of motion, coefficients of these equations and forces as derived by a modified strip theory, and the solution of the equations of motion yielding the response of the buoy to regular waves, and (c) the application of correlation theory to the frequency response operators in order to obtain the average response of the buoy to an actual, irregular seaway. Part III contains listings of the various computer programs used and the lists of symbols for these programs. It also contains the data outputs of the programs corresponding to the diagrams included in the following statement of results.

ABSTRACT

Separate mathematical algorithms and computer programs have been developed for the prediction of the motion of the buoy in both the horizontal and vertical attitude. The motions of the buoy resulting from excitation due to both regular waves and actual sea conditions have been derived and presented in form of diagrams. The programs are general enough to readily allow incorporation of changes in the configuration of the buoy.

In the horizontal attitude the motion in heave and pitch are treated as coupled motions. In the vertical attitude the motion in surge and pitch are treated as coupled motions, while heaving motion in this attitude was considered uncoupled from surge and pitch. The method of calculation of the coefficients of motion is a modified strip theory.

The motion of the buoy in regular waves is derived for intermediate water depth and deep water, i.e. $d/\lambda > 1/10$. The buoy motion due to actual sea conditions is derived for all modes of motion discussed, assuming deep water, of $d/\lambda > 1/2$.

1. STATEMENT OF THE PROBLEM

A spar-type of buoy is to be towed in horizontal position at 5 to 7 knots to a given location. There the buoy has to be brought into vertical position by proper flooding of certain compartments. In the vertical position the buoy has to perform as a super stable platform. In this position the buoy can be either free floating or moored. To summarize, three phases of operation have to be considered:

1. towing phase (horizontal position, forward speed)
2. transition phase (from horizontal to vertical)
3. operational phase (vertical position, either moored or free drifting)

In phase one, no personnel will be aboard, and the motions of the buoy are only of importance with respect to the structural design of the buoy and to the towing characteristics, i.e. up to which sea state can the tow be undertaken.

The transitional phase is of short duration, but may be a hazardous one, if not clearly under control.

The operational phase is of greatest importance, since the actual mission of the project will be carried out in this phase. Therefore an exact prediction of the performance of the buoy in the vertical position is of great importance. A variety of sea conditions will be encountered during this phase. The question up to which sea state work on the buoy can properly be continued has to be answered. Of great importance, however, is the survival condition. During its life span, the buoy will have to be able to outrun the most severe sea condition. If the buoy is moored in coastal waters, the condition has to be established, up to which it can remain at the moor.

2. METHOD OF APPROACH

The dynamics of the buoy will be investigated separately for the horizontal and the vertical position of the buoy.

2.1 Horizontal position of the buoy (towing configuration)

In this position the buoy can be treated as a ship. In absence of a mooring it is deemed necessary only to calculate the heaving, pitching and rolling motion of the buoy. Of these, only the heaving and pitching motions have to be treated as coupled motions. These are so-called symmetric motions and it can be shown that rolling will not influence them. Therefore, the rolling motion can be considered separately. For the proposed towing speed of two to four knots, the forward speed can be neglected in the derivation of the coefficients of the equations of motion.

For a ship hull the equations of motion for heave and pitch can be established as a set of two simultaneous linear second order differential equations,

$$\sum_{j=1}^{2} a_{ij}\ddot{x}_j + b_{ij}\dot{x}_j + c_{ij}x_j = F_i(t) \qquad i = 1, 2$$

where

$a_{ij} \equiv$ inertial coefficients

$b_{ij} \equiv$ damping coefficients

$c_{ij} \equiv$ restoring coefficients

$F_i(t) \equiv$ wave excitation force

The coefficients in the above equations are derived by the so-called strip-theory. One assumption associated with the above set of equations is the so-called wall sidedness of the vessel, which means that the sides of the vessel are straight and vertical in the vicinity of the waterline. Due to this condition the equations obtained above are linear. In the case of our buoy this condition is satisfied only for very small waves and motions. For larger motions and waves the equations of motion of the buoy will come out to be non-linear. It will be necessary to linearize these equations, since at present no theory for non-linear stochastic processes is in existence. Since on the other hand regular waves are virtually non-existent in a storm driven sea, we have to take resort to a statistical description of a seaway rather than a deterministic one. This is done by describing a sea condition in terms of its energy spectrum.

Solution of the above equations of motion yields the complex frequency operators $H_i(j\sigma)$ for each mode of motion. The amount of this quantity gives then the response (i.e. the amplitude of motion) of the buoy to regular waves. The spectral density of motion in an irregular seaway is then given by

$$S_i(\sigma) = S_\eta(\sigma) \left| H_i(j\sigma) \right|^2$$

where

$S_\eta \equiv$ energy spectral density of the sea state

and from this the statistical quantity of the significant motion can be obtained as

$$(\bar{X}_i)_{sign} = \sqrt{\int_{\sigma min}^{\sigma max} S_i(\sigma)\, d\sigma}$$

$(\bar{X}_i)_{sign}$ = significant double amplitude of motion in mode i

and

i = 1 denotes heave
i = 2 denotes pitch

(the term 'significant' means the average of the highest one third values)

Analogously one proceeds for the calculation of roll. Much of the above is standard naval architectural procedure in elaborate analytical investigations. Good agreement with measured prototype data has been shown.

The main limiting factor in the present investigation lies in the necessity to linearize the equations of motion. However, the author considers that this procedure is warranted and sufficient for the scope of the present study.

2.2 Vertical position of the buoy

2.2.1 Moored

The buoy is assumed to be held on position by a mooring system. The mooring exerts thereby a restoring force at a given point on the buoy. This will be the only influence of the mooring system on the motion of the buoy. The equations of motion can be written, in principal, as for the horizontal buoy, however, we now have three degrees of freedom (surge, heave, pitch). Hence the equations are

$$\sum_{j=1}^{3} a_{ij}\ddot{x}_j + b_{ij}\dot{x}_j + c_{ij}x_j = F_i(t) \qquad i = 1, 2, 3$$

In this case, the equations are already linear, so that the linearizing process mentioned in the previous paragraph is not necessary. When establishing the wave excitation forces the change of the water particle motions with water depth will, of course, be taken into account. It is noted, that in this attitude only the surge and pitch motions have to be treated as coupled motions, while heave can be considered separately.

The solution of the above system of differential equations yields again the response operators, which will be used for the spectral analysis as discussed in the previous paragraph.

2.2.2 Free-floating (unrestrained)

The solution for this case proceeds as in the previous one, however with only two degrees of freedom (heave, pitch), since there is no surging oscillation possible without a mooring system. Roll and pitch are identical.

3. RESULTS

3.1 Horizontal Attitude (all figures denoted by H)

3.1.1 Heave and Pitch in Regular Waves

Figure H1-1 depicts the responses in the modes heave and pitch. Very useful for comparing the results with other ships is the pitching response ratio normalized by the wave slope. Both heave and pitch responses show no particularly unusual behavior.

Figure H1-2 shows the amplitude of the relative displacement between the top of the deckhouse (at centerline) and the sea surface in regular waves.

Figures H1-3 and H1-4 give again the unit amplitude responses in heave and pitch for head seas, but in addition the responses for oblique wave headings are presented.

Figure H1-5 gives the relative displacement between the top of the deckhouse and the sea surface for oblique wave headings.

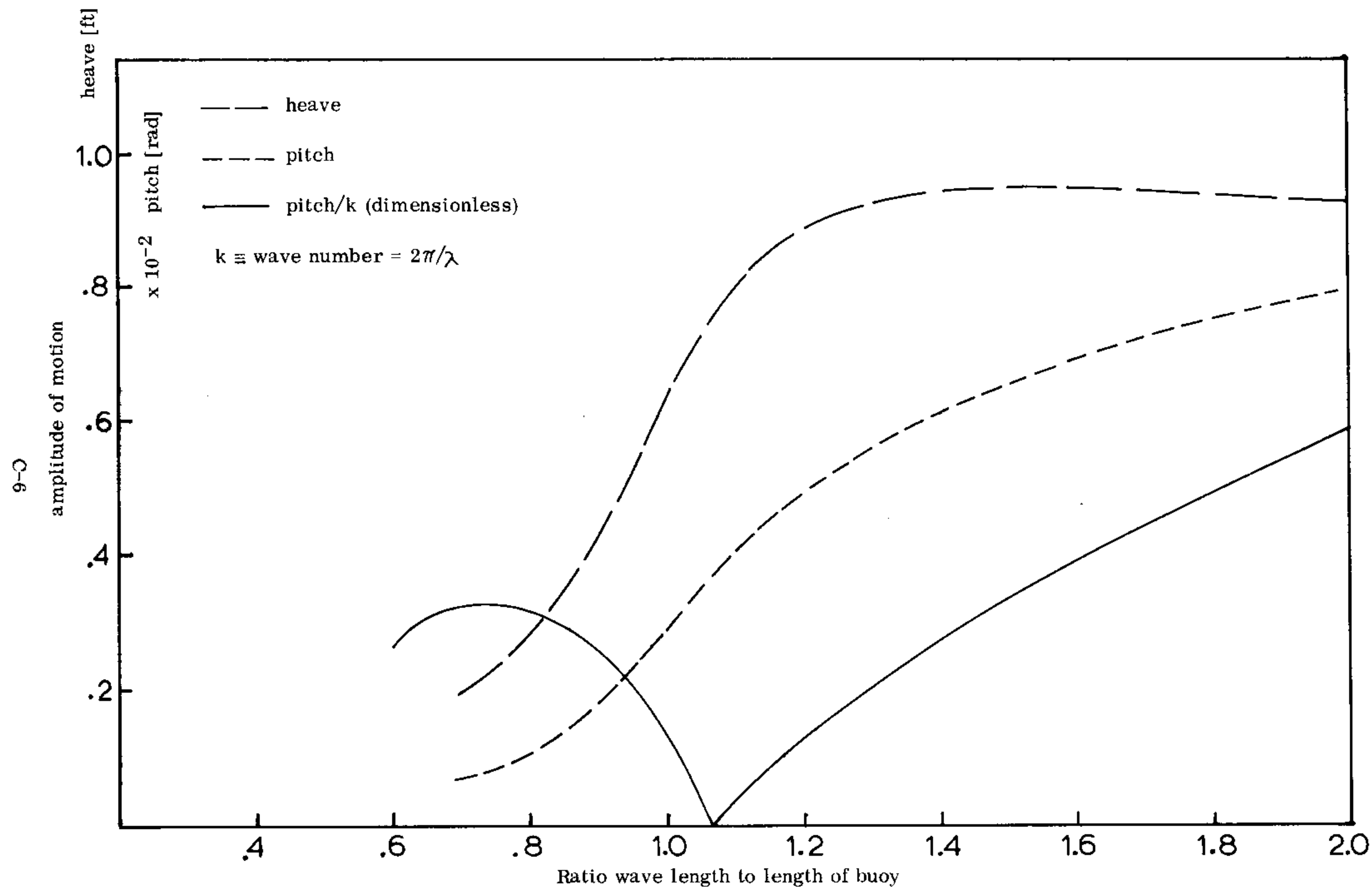

Fig. H1-1 Horizontal Attitude of Buoy - Heaving and pitching motions of the buoy in regular waves of unit amplitude

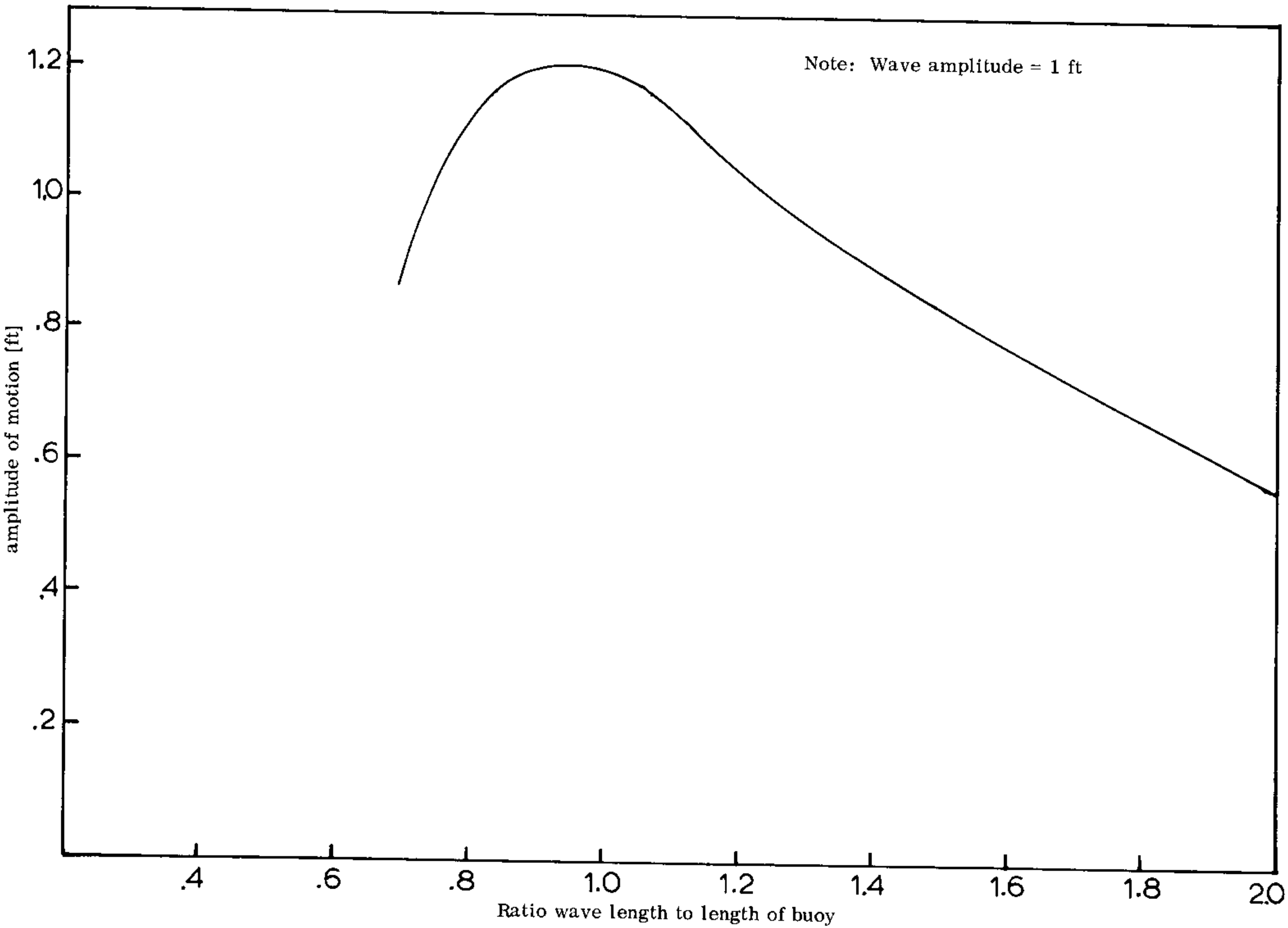

Fig. H1-2 Horizontal Attitude of Buoy - Amplitude of Relative Vertical Motion of Deckhouse with respect to water surface

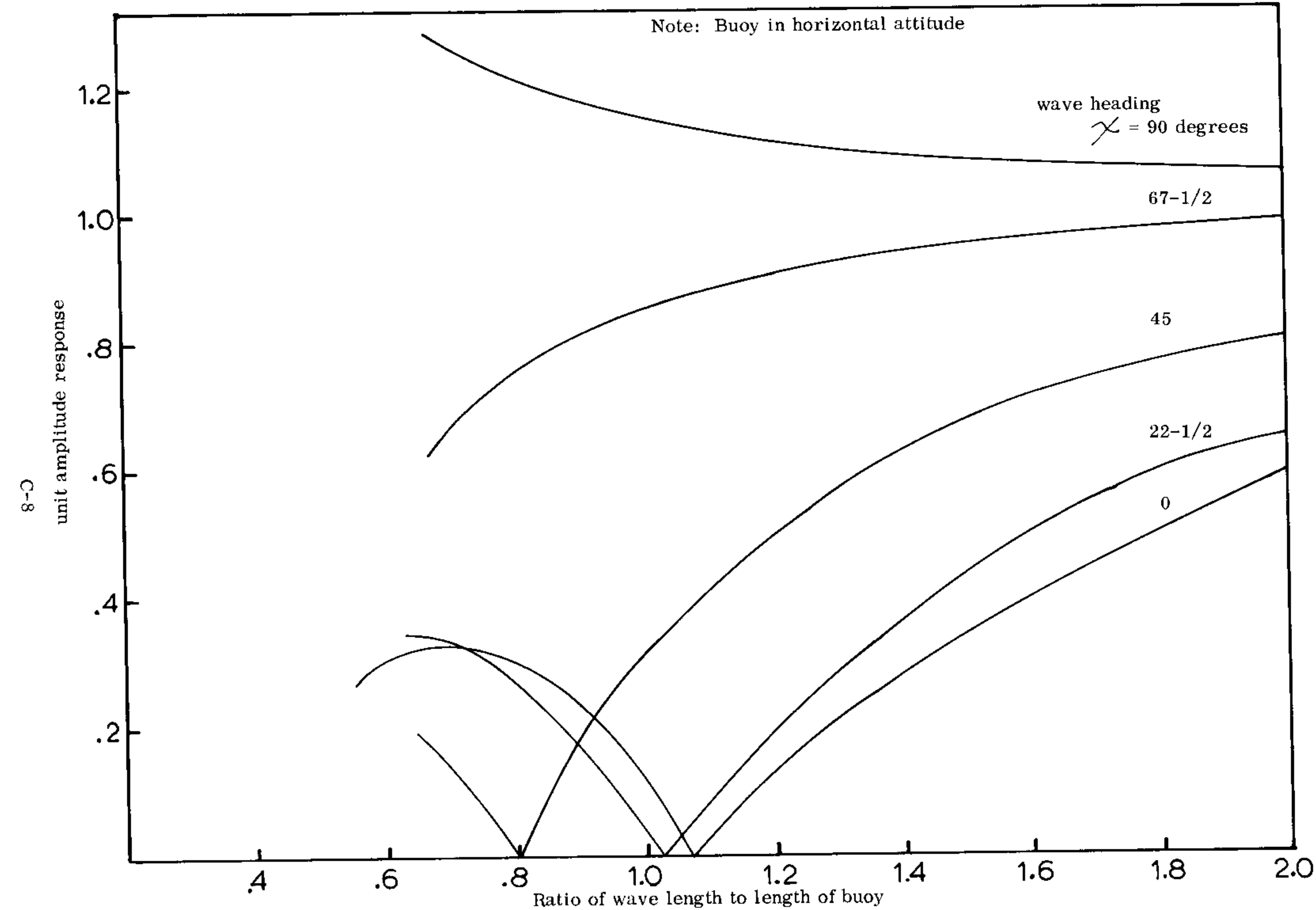

Fig. H1-3 Heaving Response of Buoy in Regular Waves for Various Wave Headings

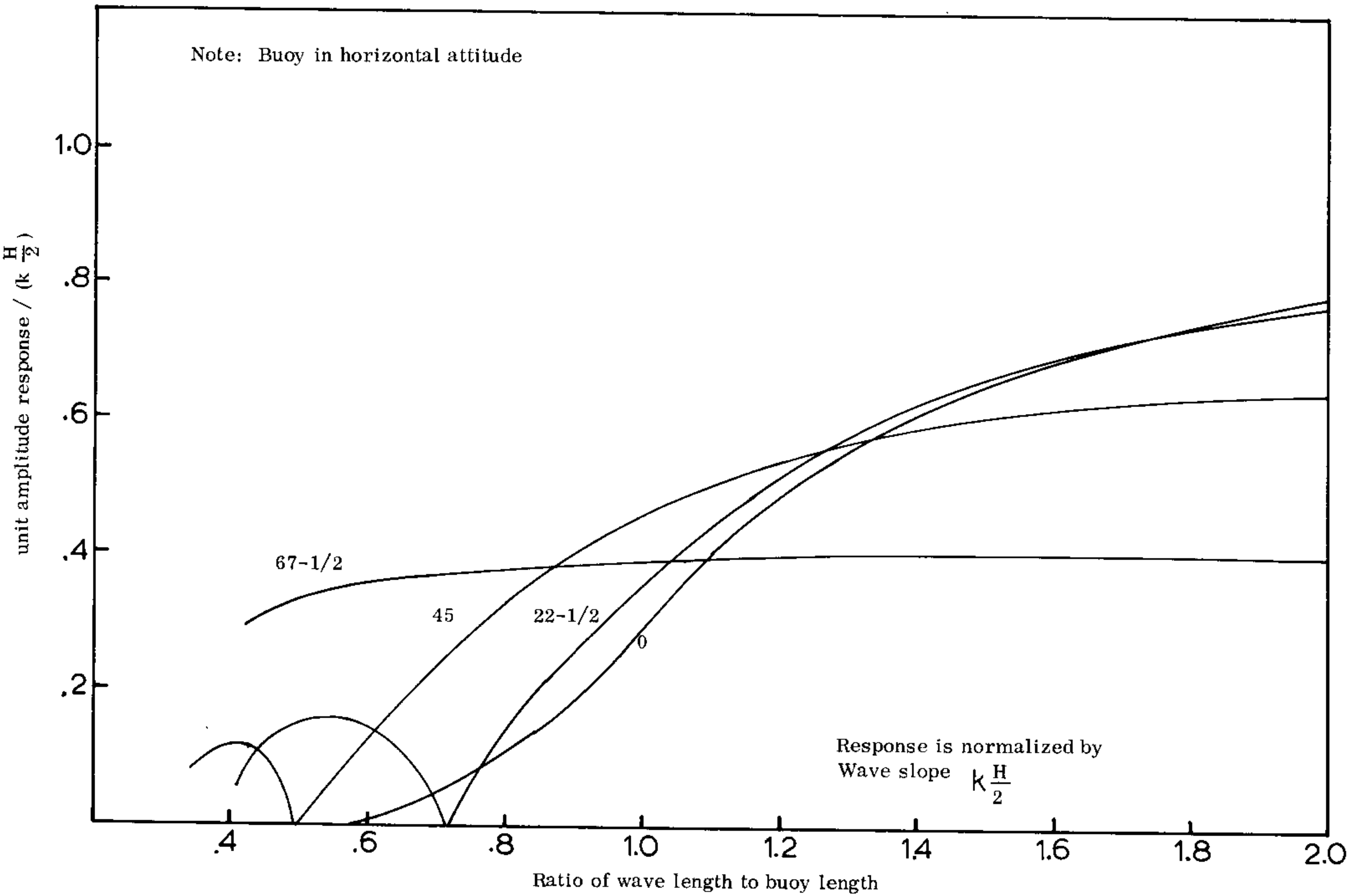

Fig. H1-4 Pitching Response of Buoy in Regular Waves for Various Wave Headings

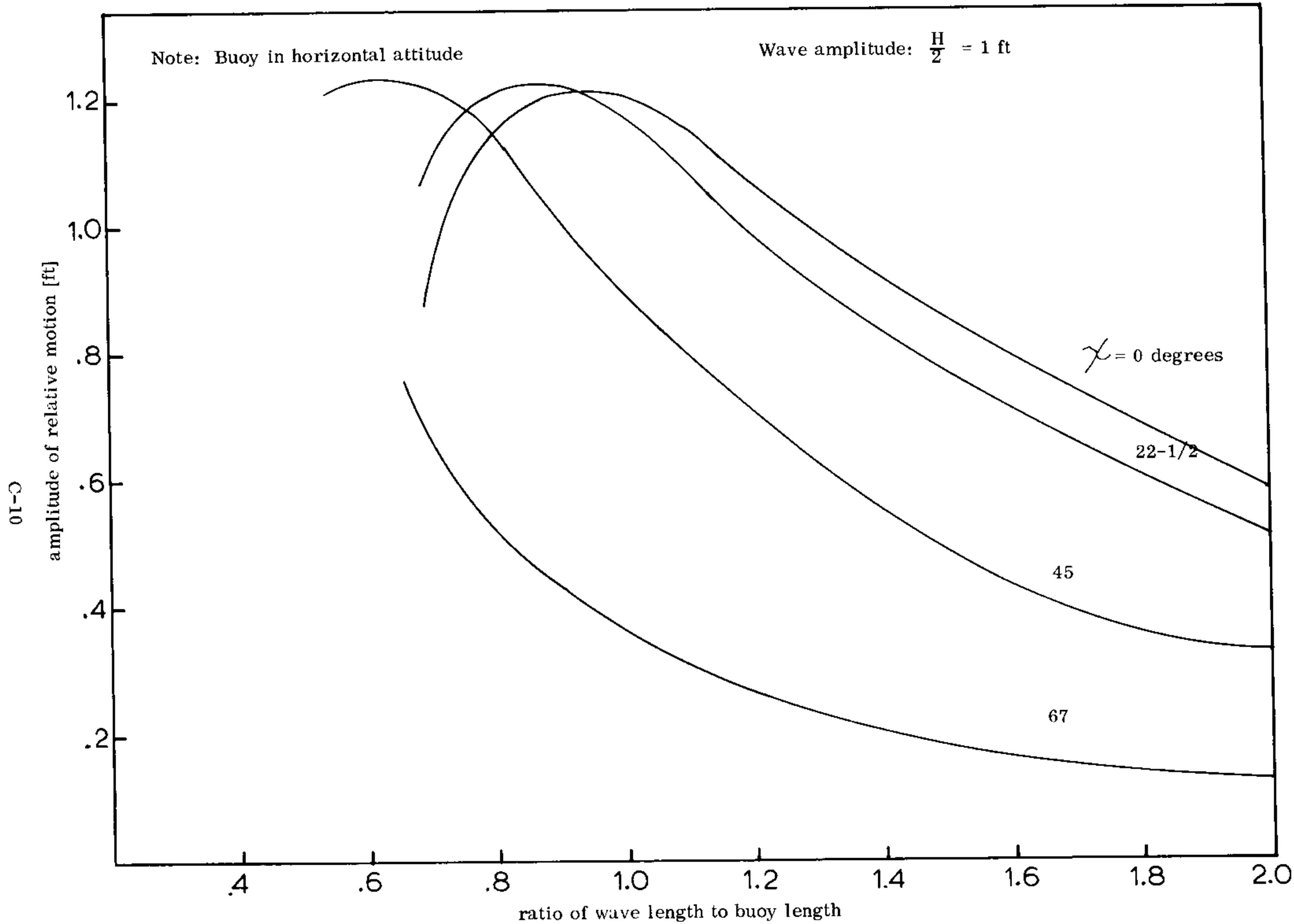

Fig. H1-5 Relative Vertical Motion between Deck House and Water Surface for Various Wave Headings (regular waves)

3.1.2 Heave and Pitch in Irregular Seas

A summary of the significant heaving and pitching double amplitudes is presented in Figure H-6. The term 'significant' pertains to the average of the 30 percent of highest values.

Figures H-7 and H-8 depict the energy spectral densities of the heaving and pitching motion in sea states 3, 4, and 5, which are of particular interest for the towing of the buoy. The dashed lines depict the results of calculations assuming a uni-directional, but otherwise irregular sea state, while the solid lines correspond to a two-dimensional sea state with waves of varying directions as given by an assumed spreading function. The energy spectral densities in heave are mostly greater in the two-dimensional case, which is explained by the fact that the buoy generally responds more in heave to oblique waves than to head on waves (see Figure H1-3). In pitch the opposite would be expected, but only to a much lesser degree, as is shown in Figure H-8. In both cases, heave and pitch, the two-dimensional sea spectrum does not give zero motion at certain frequencies, for which theoretically the wave forces would cancel each other out at some wave headings. The double amplitudes given in Figure H-6 correspond to the two-dimensional sea spectra.

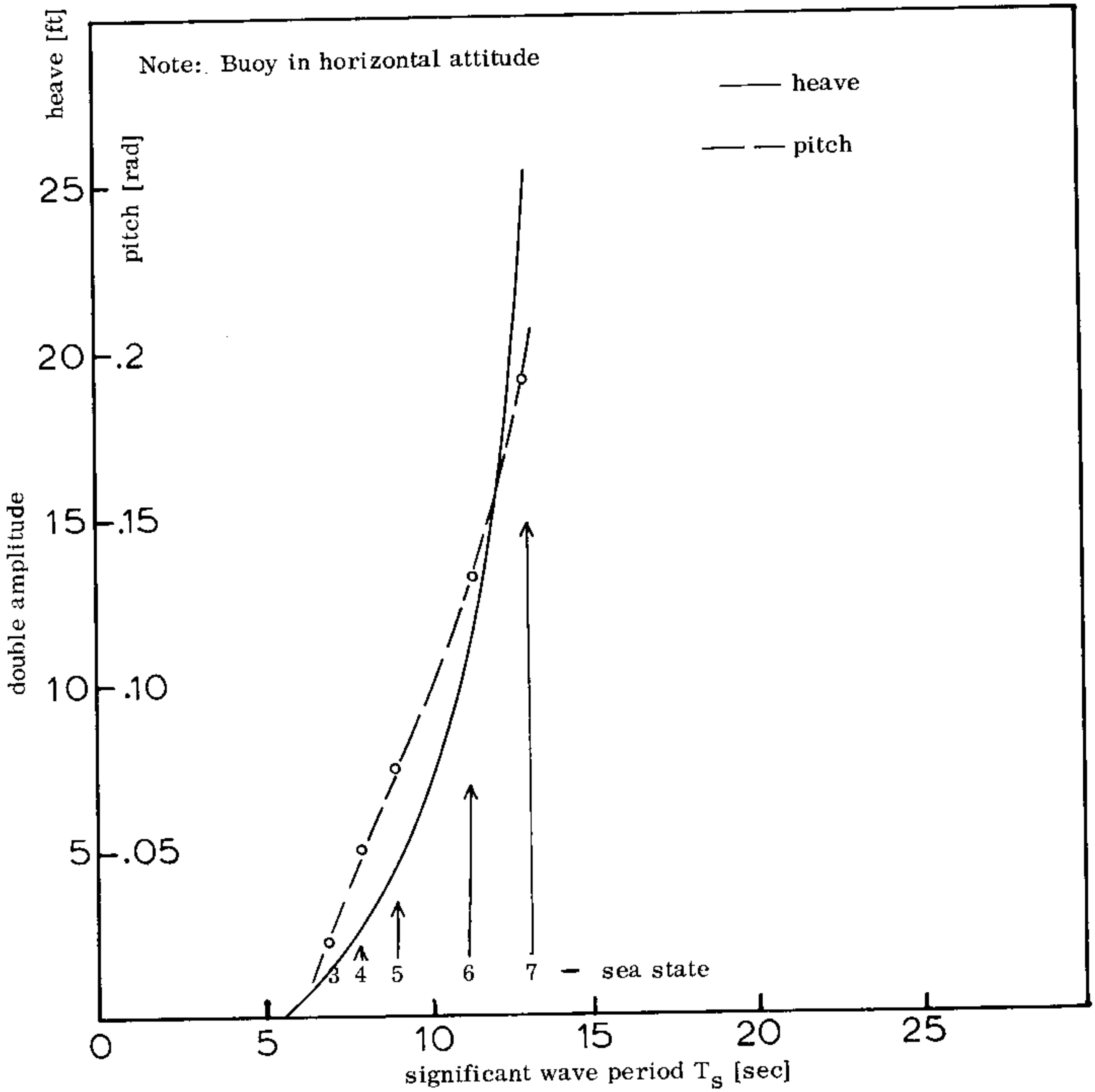

Fig. H-6 Significant Double Amplitudes of Heaving and Pitching Motions in Actual Seas

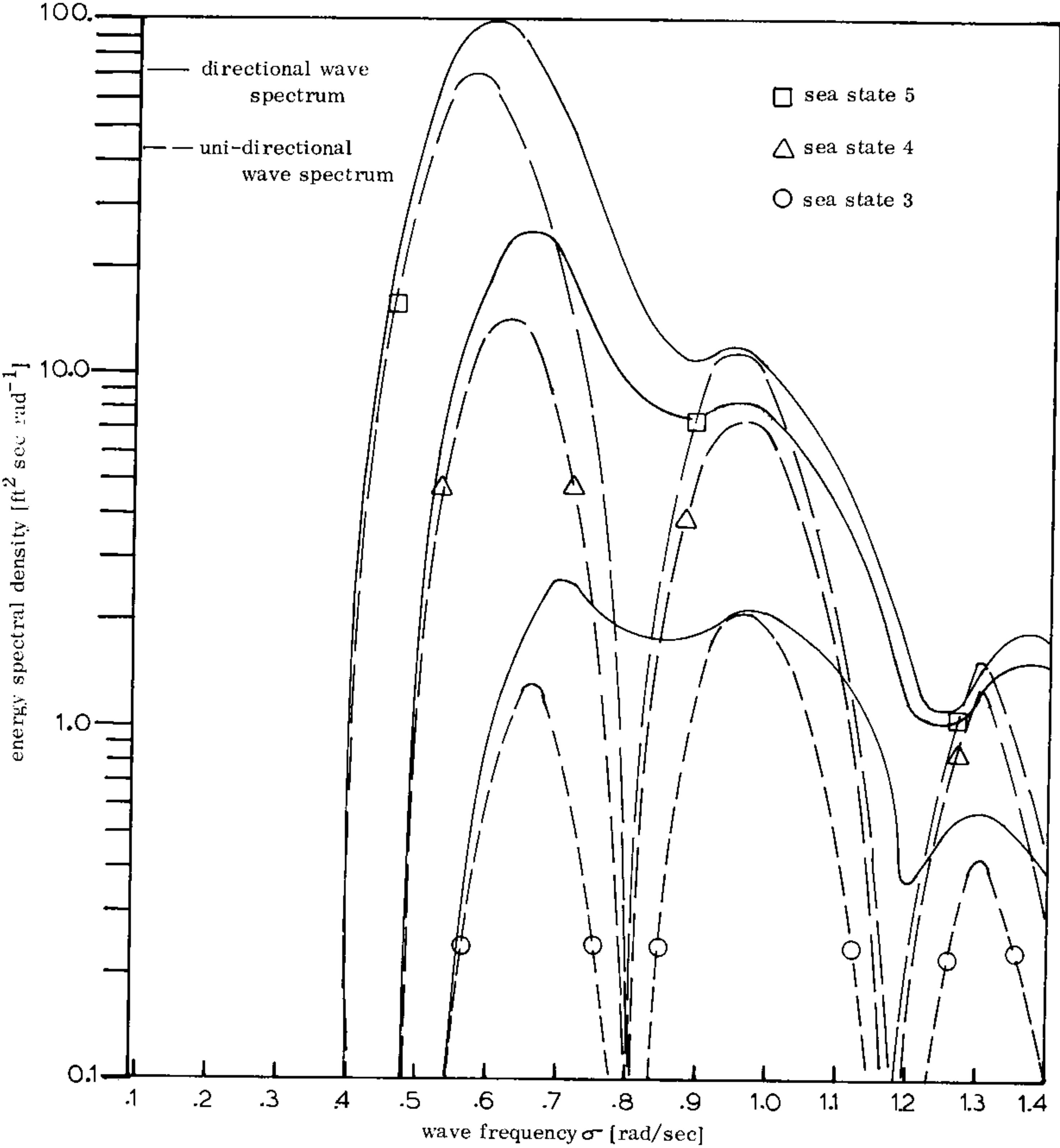

Fig. H-7 Energy Spectral Density Distribution of Heaving Motion

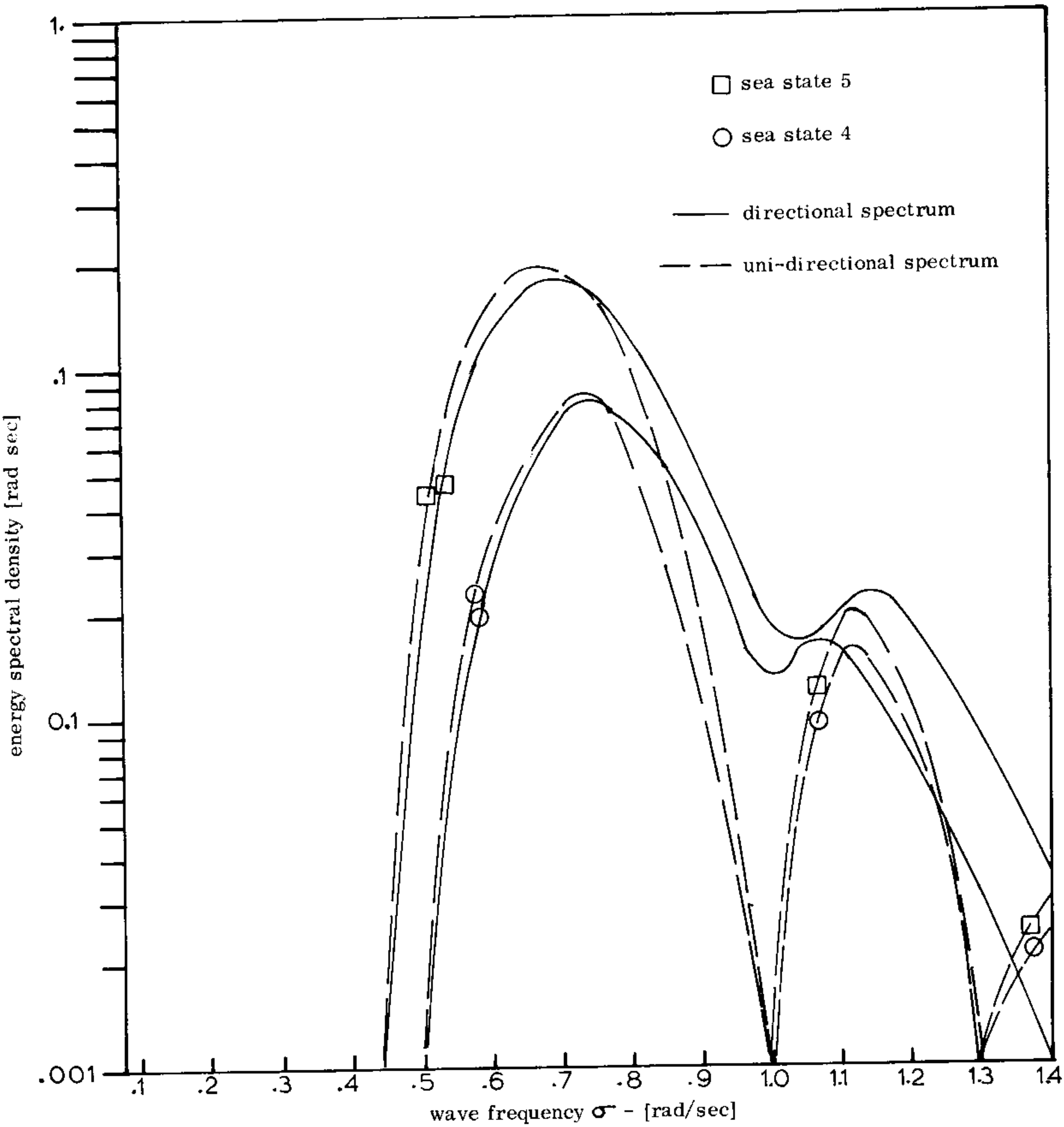

Fig. H-8 Energy Spectral Density Distribution of Pitching Motion

3.2 Vertical Attitude (all figures denoted by V)

3.2.1 Surge and Pitch in Regular Waves

Surge

The unit amplitude response in surge is plotted in Figure V1-1 as a function of wave frequency. For calculating the surge response a hypothetical two point moor was assumed, the mooring lines of which would be attached at the center of gravity of the buoy in vertical attitude. The "spring constant" of this moor was assumed such as to yield a natural period of surging oscillation of 50 seconds. As Figure V1-1 depicts, the surging motions are quite small for most wave frequencies, however, waves of frequency $\sigma = 0.2$ or period T = 30.5 seconds will give double amplitudes of motion equal to the wave height. Even this case is not dangerous as waves of this period are usually not very high.

Pitch

The unit amplitude response in pitch is plotted in Figure V1-1 and is to be read off on the right hand ordinate, which is marked in degrees for convenience. A useful quantity for assessing the pitching motion is the ratio pitching amplitude to wave slope - $\psi_o/k\,H/2$. This quantity is also plotted in Figure V1-1. It shows also that the pitching response of this buoy is very small for all wave frequencies. For convenience, the normalized pitch response - $\psi_o/(k\,H/2)$ is plotted in Figure V1-2 as a function of wave period. The dip in the curve of the latter figure near 30 second waves is explained by the small value of the pitching response at $\sigma = 0.2$ in Figure V1-1. It is caused by the geometry of the buoy, due to which the pitching moment (moment of wave forces about the center of gravity) is almost cancelled out for very long waves. This fact is illustrated by Figure V1-3. The overturning moment due to wave forces increases for higher frequencies, because for such waves the particle motion decays rapidly with depth, so that an unbalanced "top heavy" wave force acts on the buoy.

3.2.2 Surge and Pitch in Irregular Sea

The spectral energy density distributions for surging and pitching motions of the buoy for fully developed wind driven seas given by various sea states are depicted in Figures V1-4 and V1-5, respectively. The significance of these diagrams is to show from which ranges of frequencies the motion spectral energy is derived. In particular, note that all surging energy is virtually nil for wave frequencies higher than 0.75, while at these frequencies still some energy in the pitching spectrum is left. The diagrams have to be interpreted keeping in mind that the ordinates are given in logarithmic scales. The diagrams show that most energies for both motions lie in the range of long waves. The smallest sea state shown in the graphs is sea state 6, the motions in lighter sea states being not important.

A summary of the significant double amplitudes of surging and pitching motions in irregular seas is presented in Figure V1-6. The abscissa of this diagram is the significant wave period which characterizes a particular sea state.

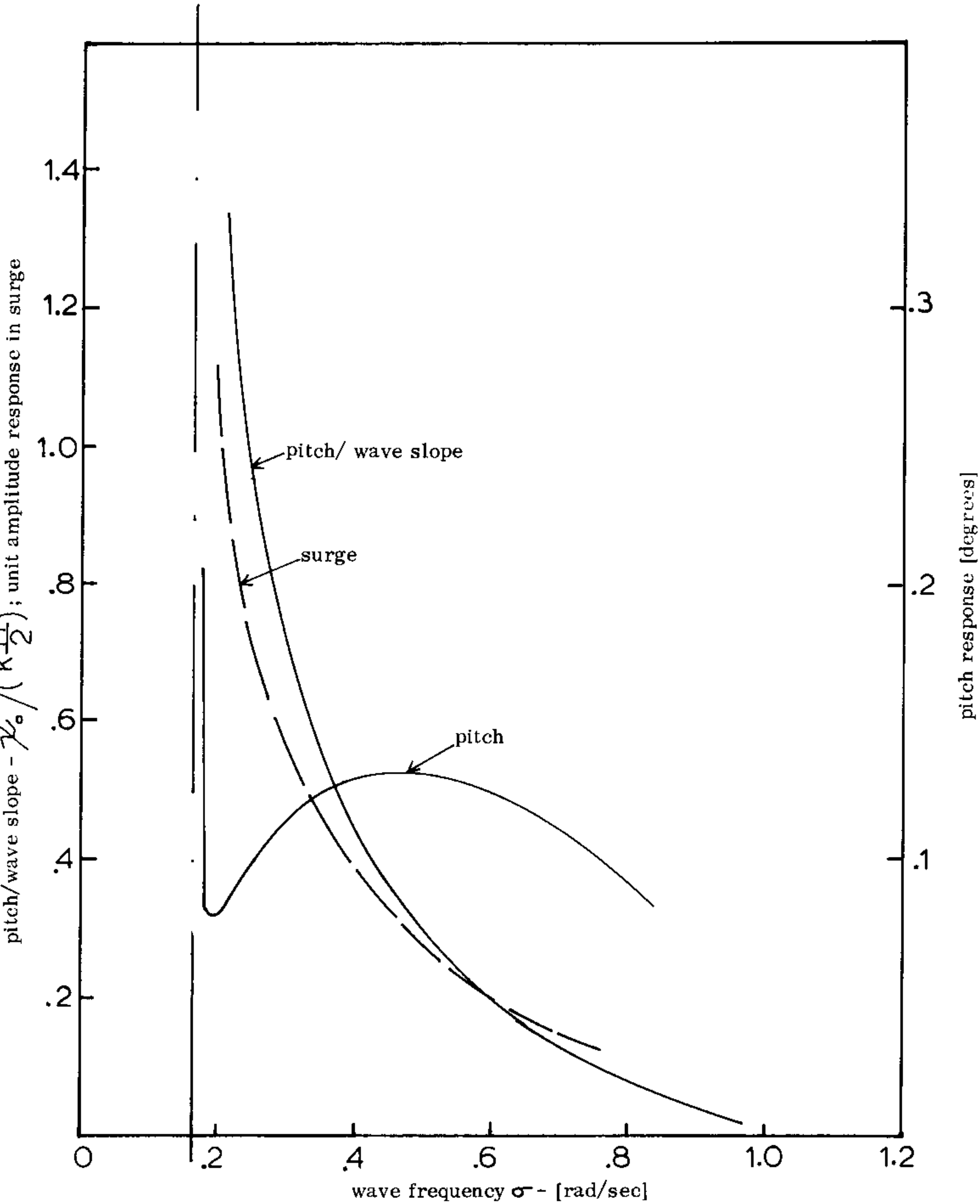

Fig. V1-1 Response Ratios in Surge and Pitch

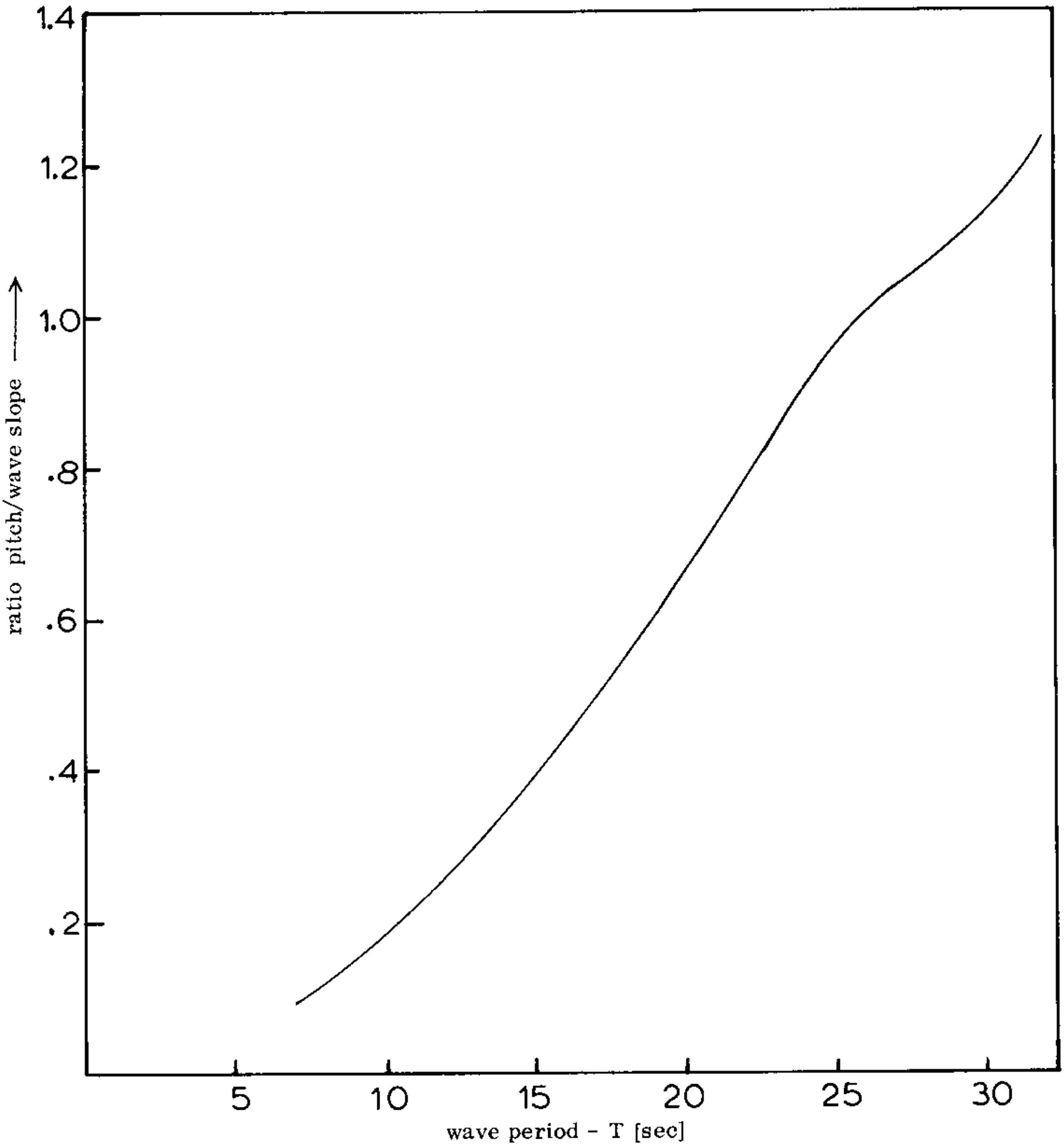

Fig. V1-2 Response Ratio in Pitch (normalized by wave slope)

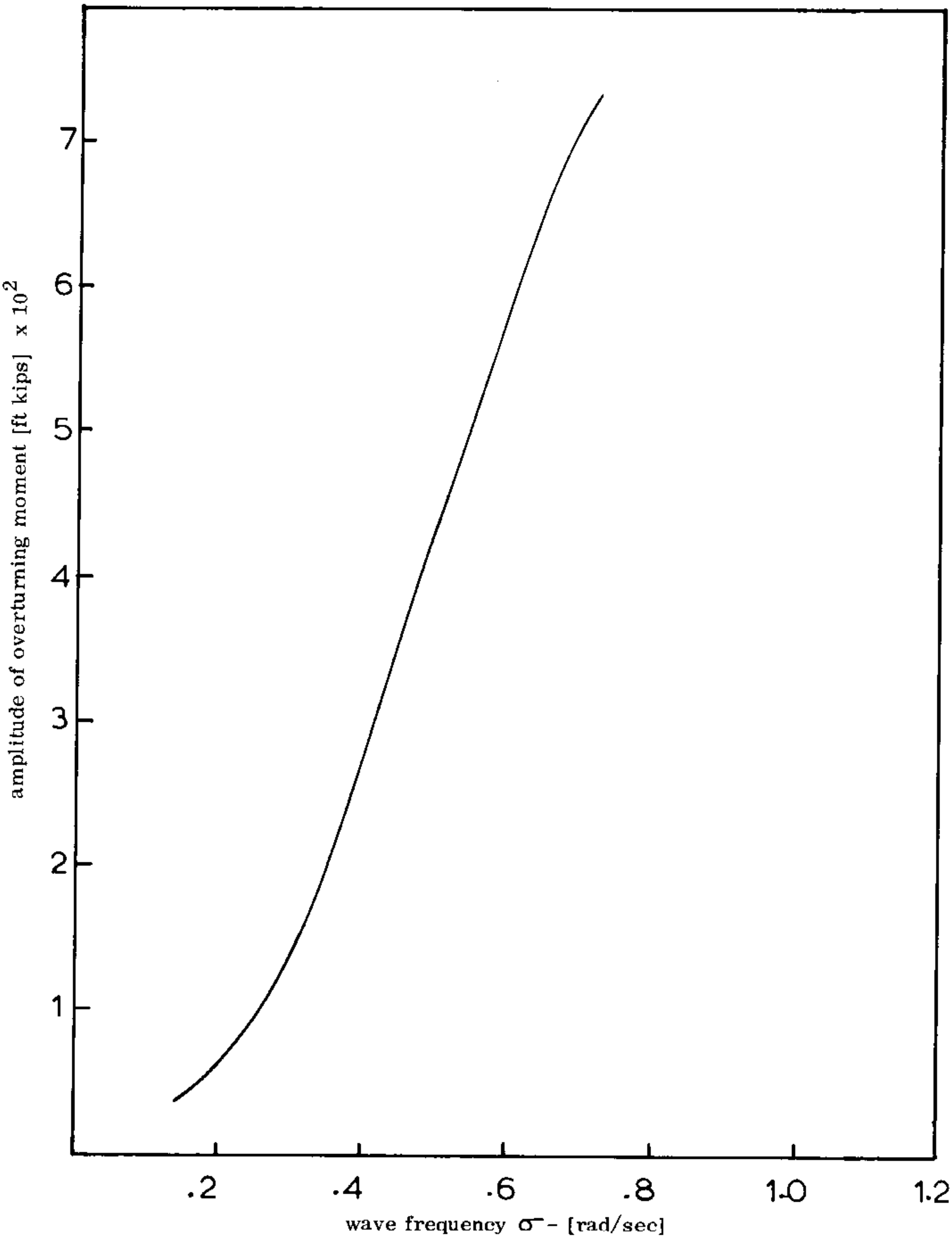

Fig. V1-3 Moment of Wave Forces about Center of Gravity

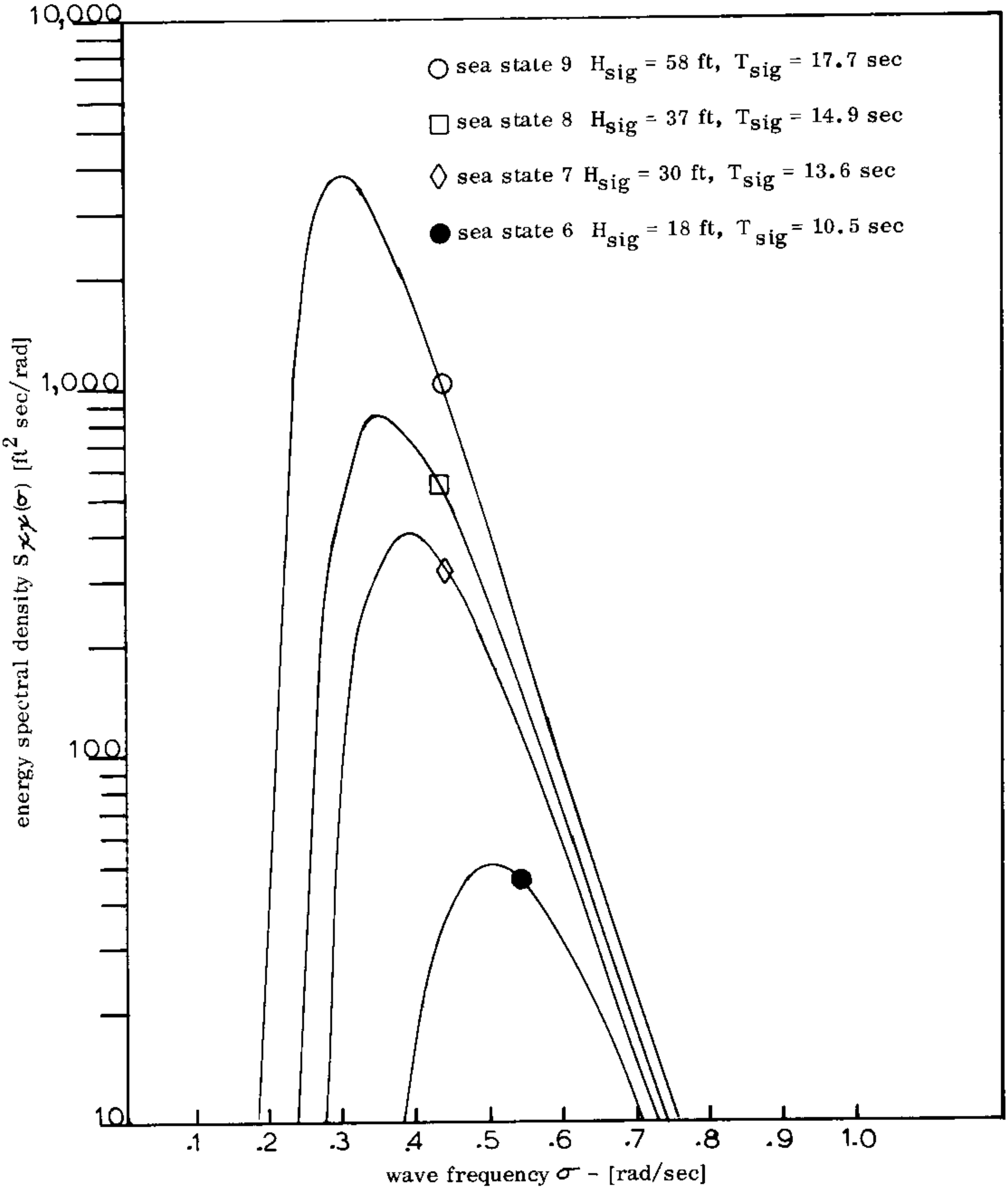

Fig. V1-4 Energy Spectral Density Distribution of Surging Motion of Buoy

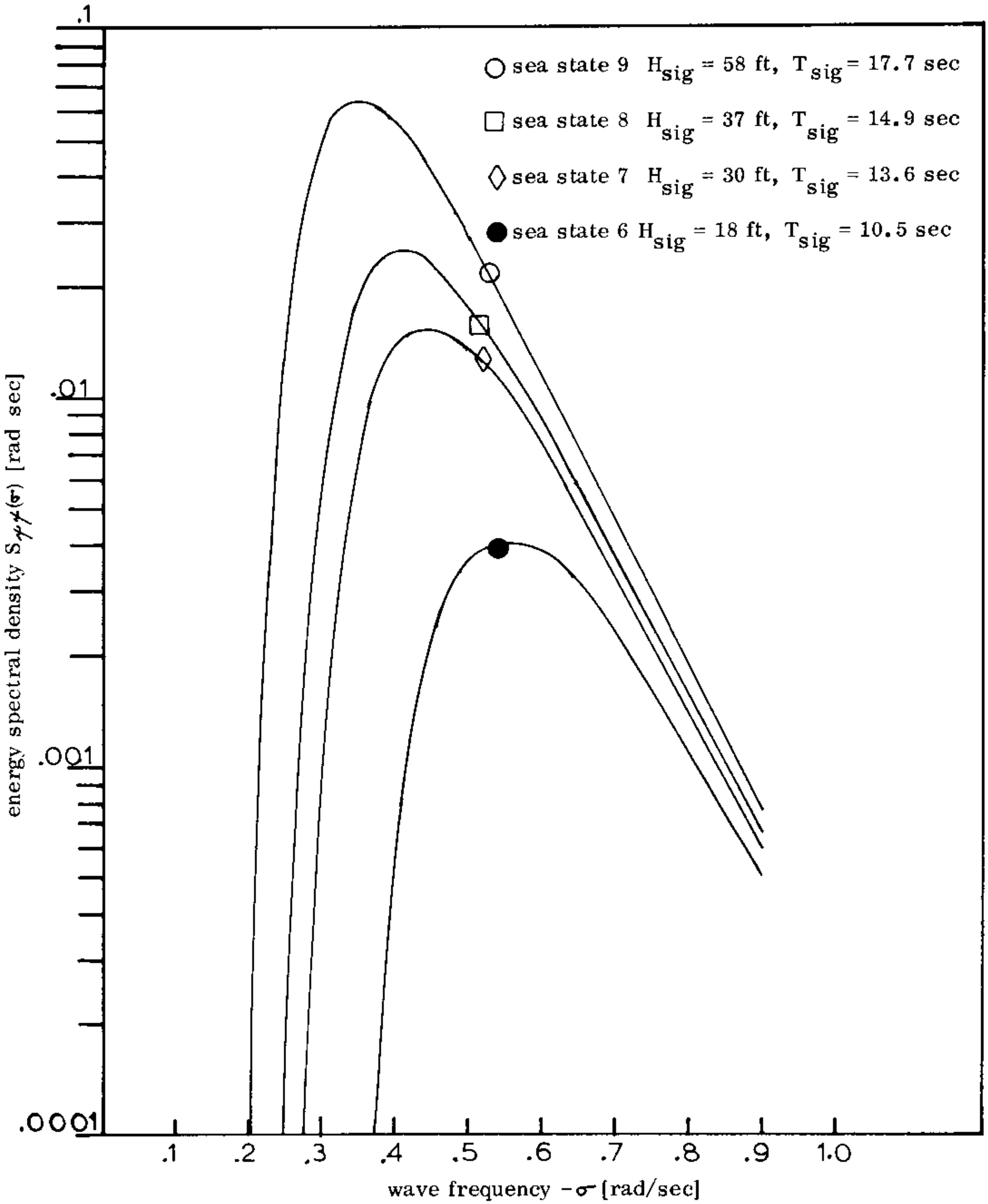

Fig. V1-5 Energy Spectral Density Distribution of Pitching Motion of Buoy

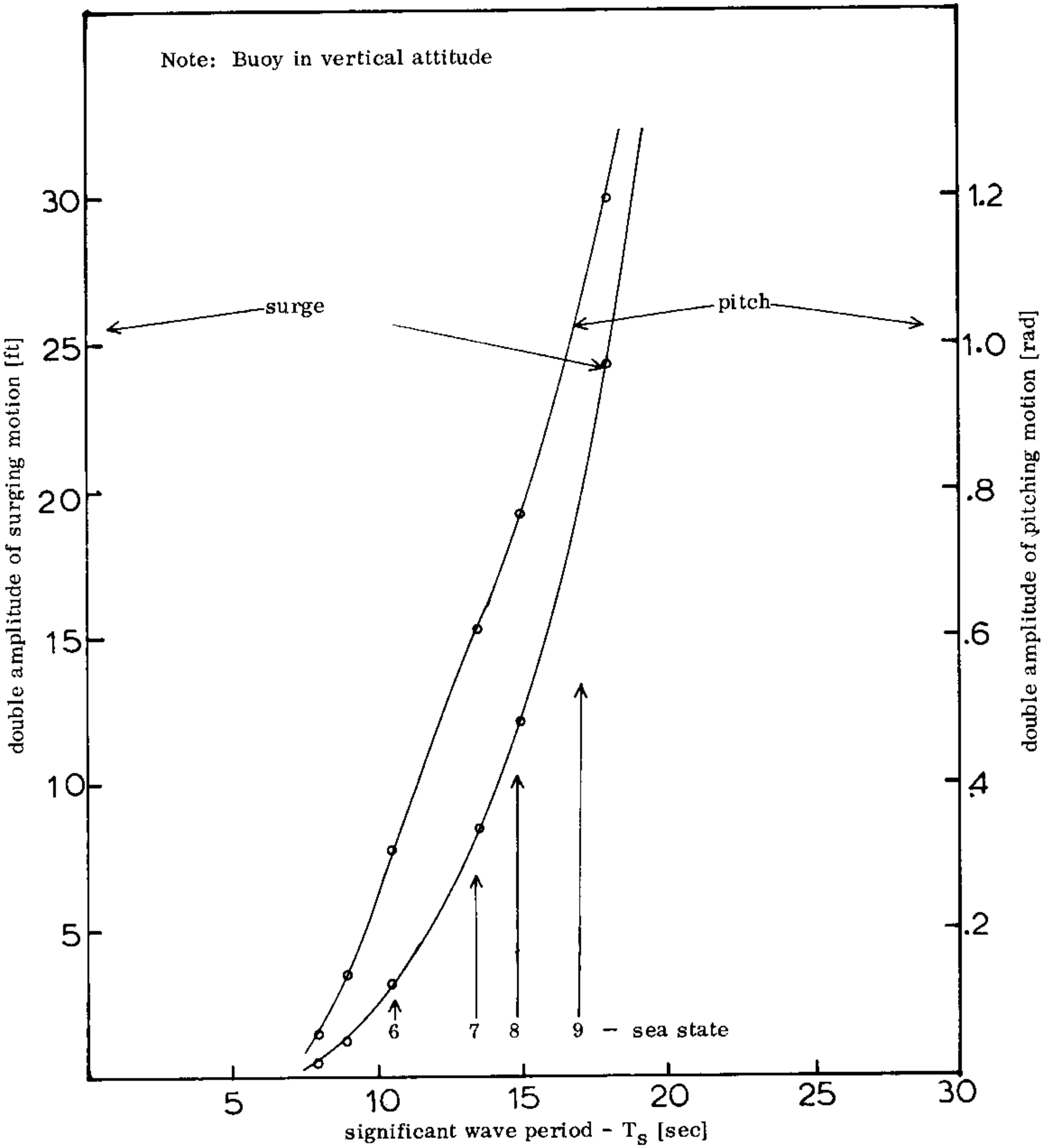

Fig. V1-6 Significant Double Amplitudes of Surging and Pitching Motions in Irregular Seas

3.2.3 Heave in Regular Waves

The unit amplitude response in heave is plotted in Figure V2-1 as a function of wave frequency and for convenience in Figure V2-2 as a function of wave period. Also the phase lag between wave crest and heaving motion of the buoy is plotted on this graph. As the tuning factor for virtually all waves that will be encountered is greater than unity, the motion of the buoy will always be 180 degrees out of phase with the exciting wave force. The wave force on a wall-sided floating body, on the other hand, is always in phase with the wave, i.e., the wave force is a maximum and directed upward as the wave crest passes amidships. For our particular buoy this holds only for long waves. For shorter waves ($T < 19$ sec) the wave force is negative as the wave crest passes by, or 180 degrees out of phase with the wave. This explains the distribution of the phase lag as shown in Figure V2-2.

Figure V2-3 shows pressure and inertia forces (due to water particle acceleration) acting on the buoy. It is seen that the pressure force changes sign at about $T = 19.7$ seconds. The negative sign means that the pressure force tends to push the buoy down at the time when the wave crest is over the buoy, rather than providing an upward (buoyant) force as in the regions of periods $T > 19.7$ seconds.

Figure V2-4 gives detailed results for the components of the pressure force.

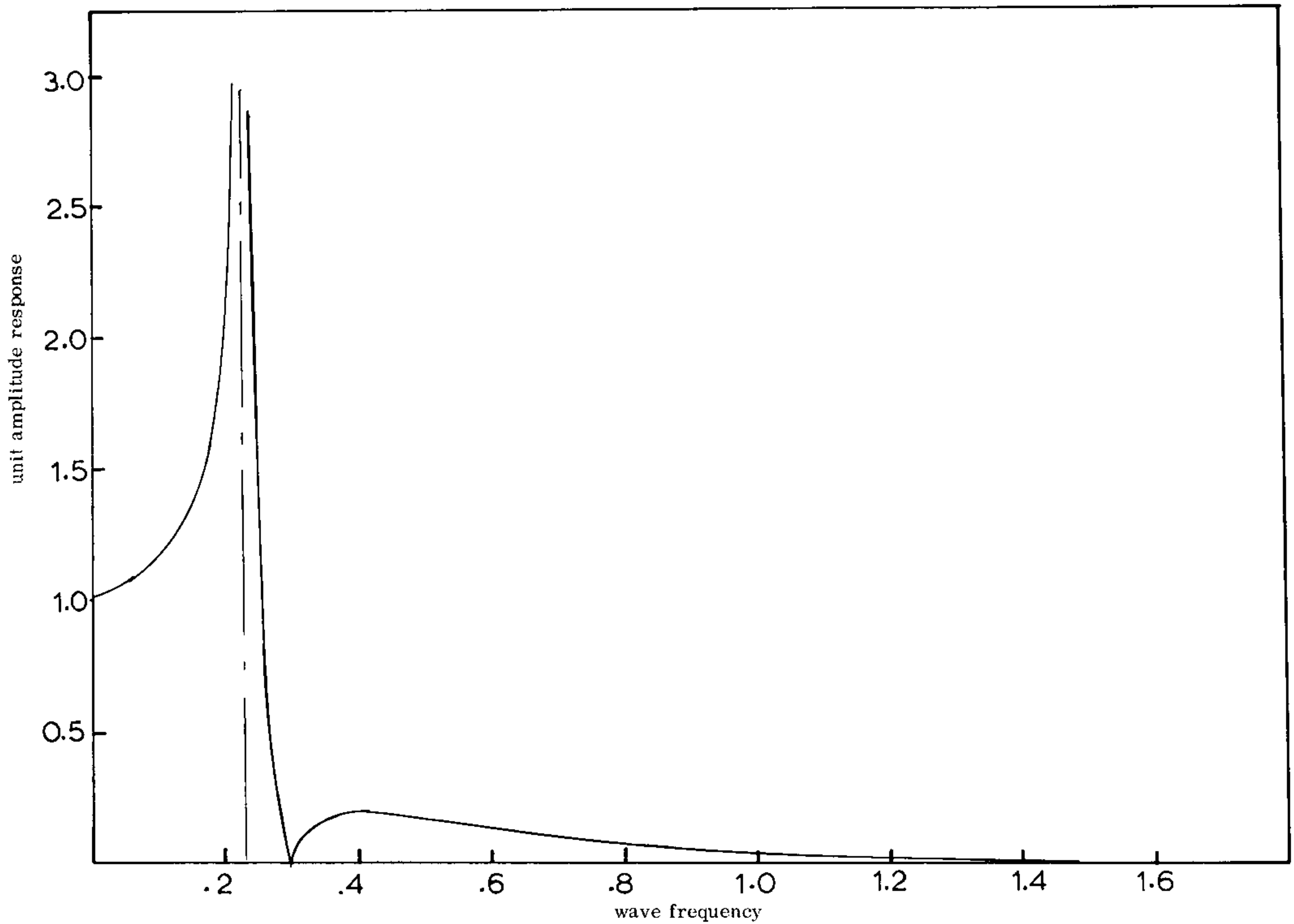

Fig. V2-1 Unit Amplitude Response in Heave

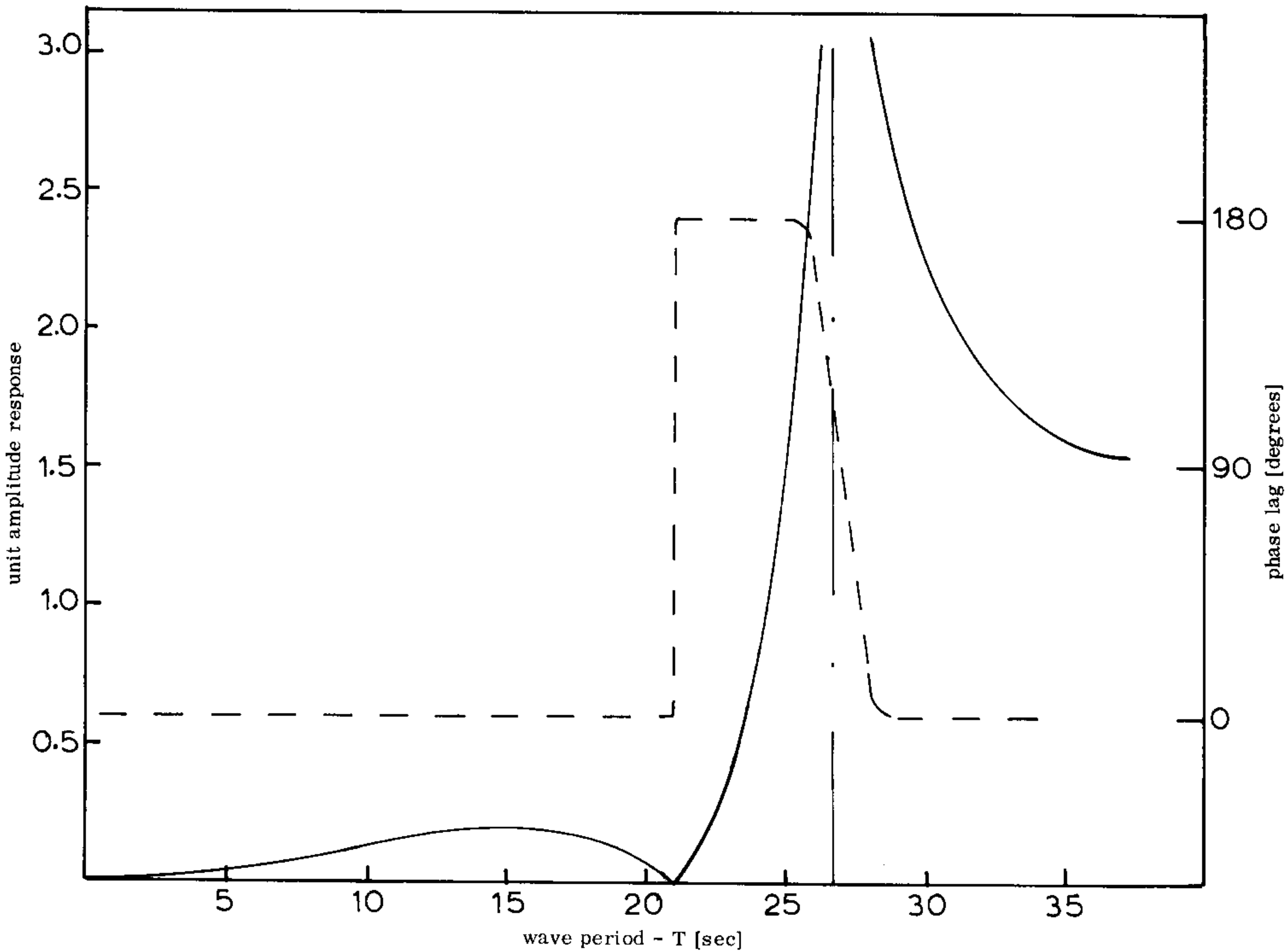

Fig. V2-2 Unit Amplitude Response in Heave

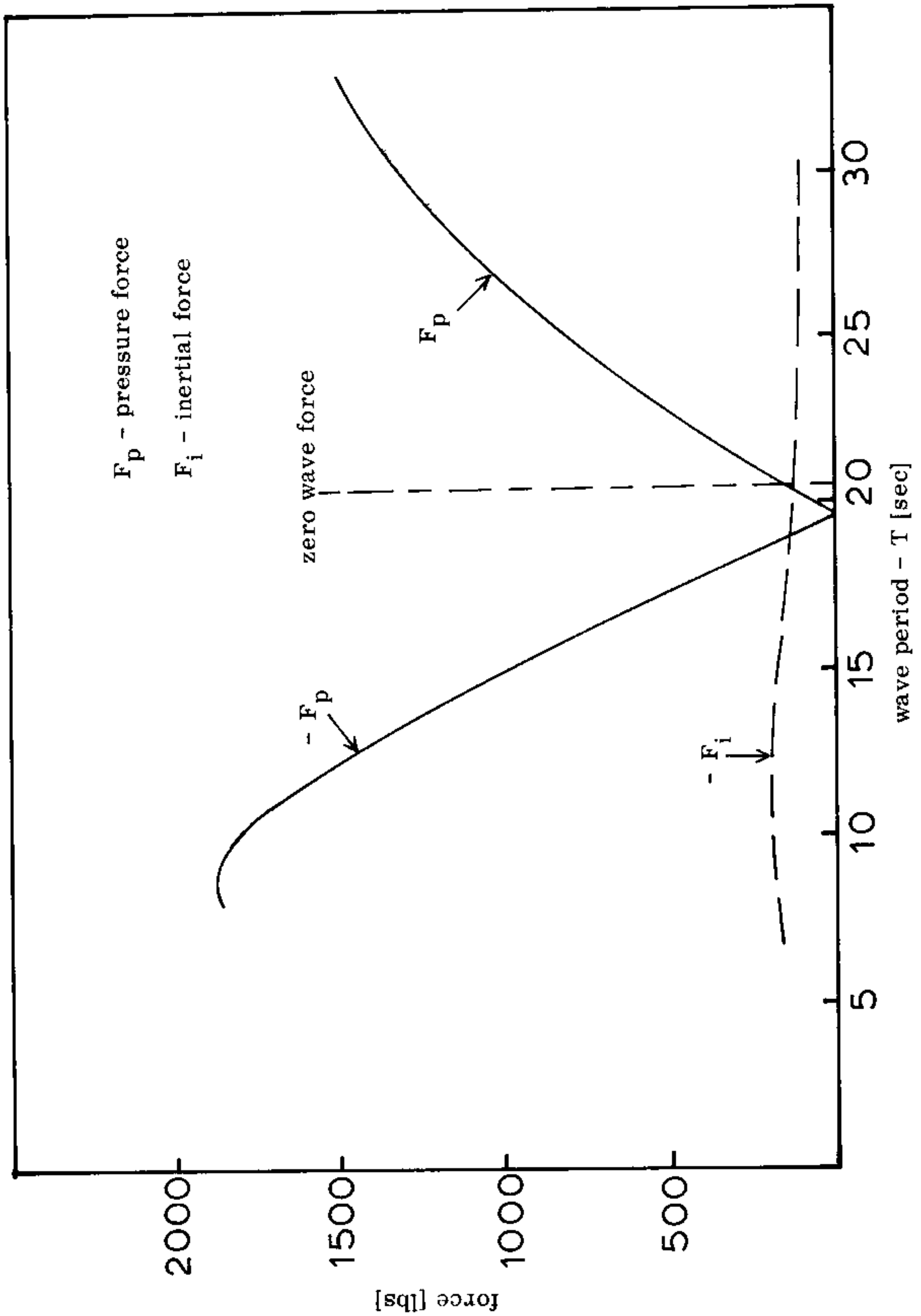

Fig. V2-3 Wave Force

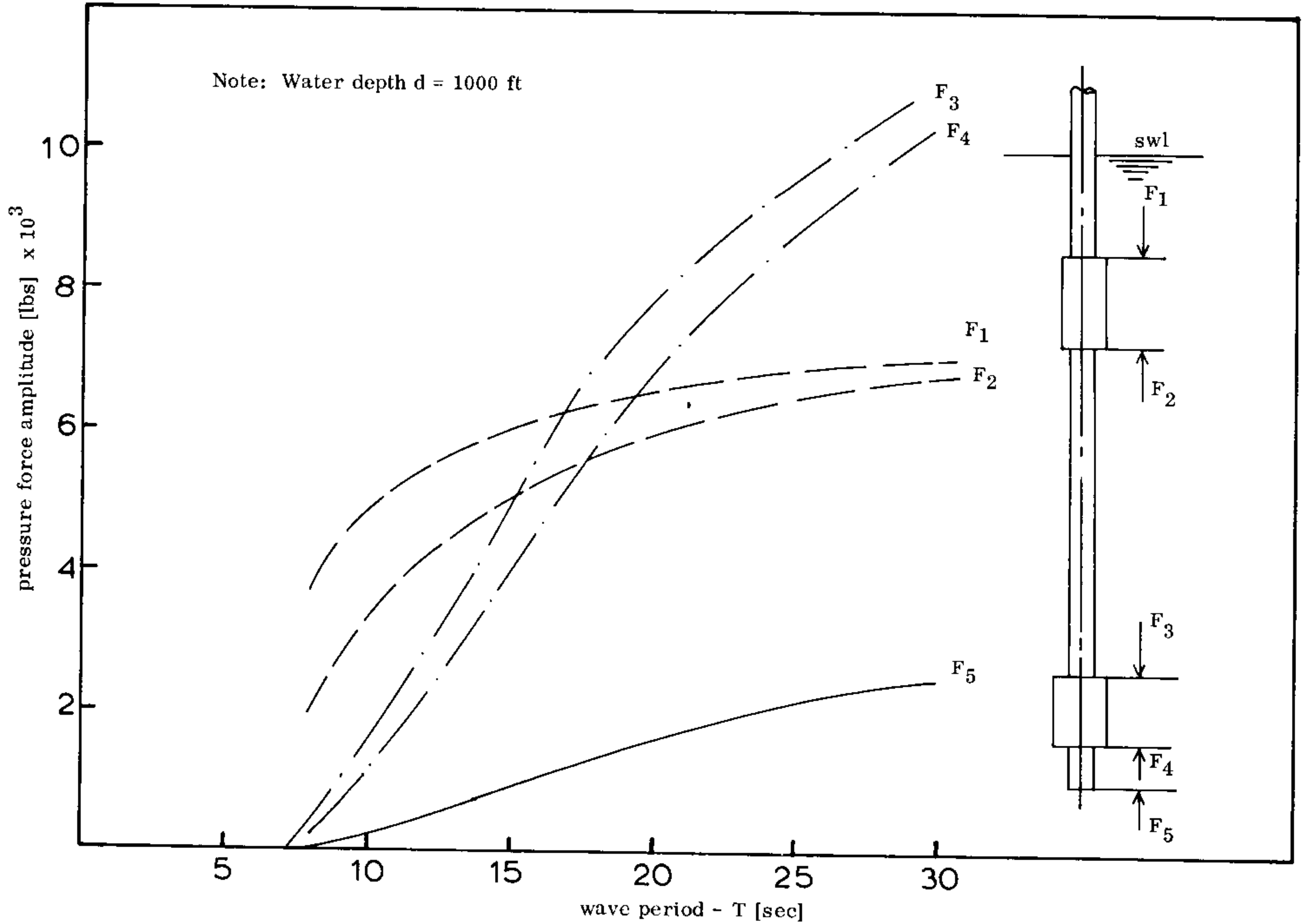

Fig. V2-4 Wave Pressure Forces Acting on the Buoy

3.2.4 Heave in Irregular Waves

The significance of Figure V2-5 is that it shows the frequency ranges from which the motion spectral energy is derived. The area under the motion energy spectrum corresponds to the energy of motion. Taking, e.g. the spectra corresponding to sea states 8 and 9, we see essentially two major areas, say one for frequencies between 0.2 and 0.3, and another for frequencies greater than 0.3. The former corresponds to the product of relatively little energy in the wave spectrum and the high near resonant response of the buoy. The second area (frequencies greater than 0.3) is dominated by large energy content in the wave spectrum and a relatively small response of the buoy to waves of that frequency. It is noted, however, that the area under the spectrum in this frequency range is a considerable segment of the total area.

Figure V2-5 depicts some energy spectral density distributions of the heaving motions of the buoy corresponding to some assumed sea state, i.e., significant wave heights and periods. The significant heaving motions corresponding to these sea states are given in Figure V2-6.

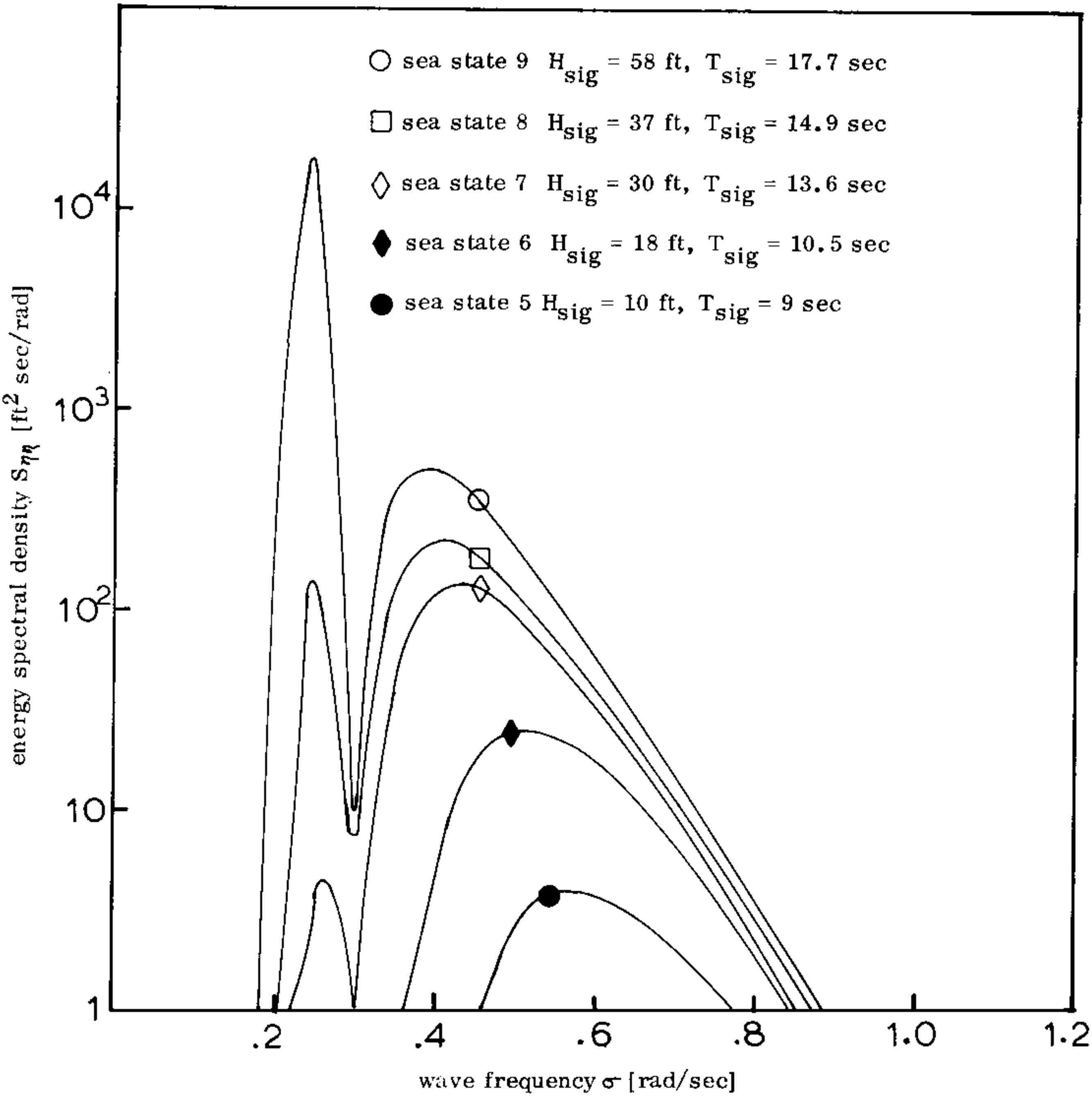

Fig. V2-5 Energy Spectral Density Distribution of Heaving Motion of Buoy

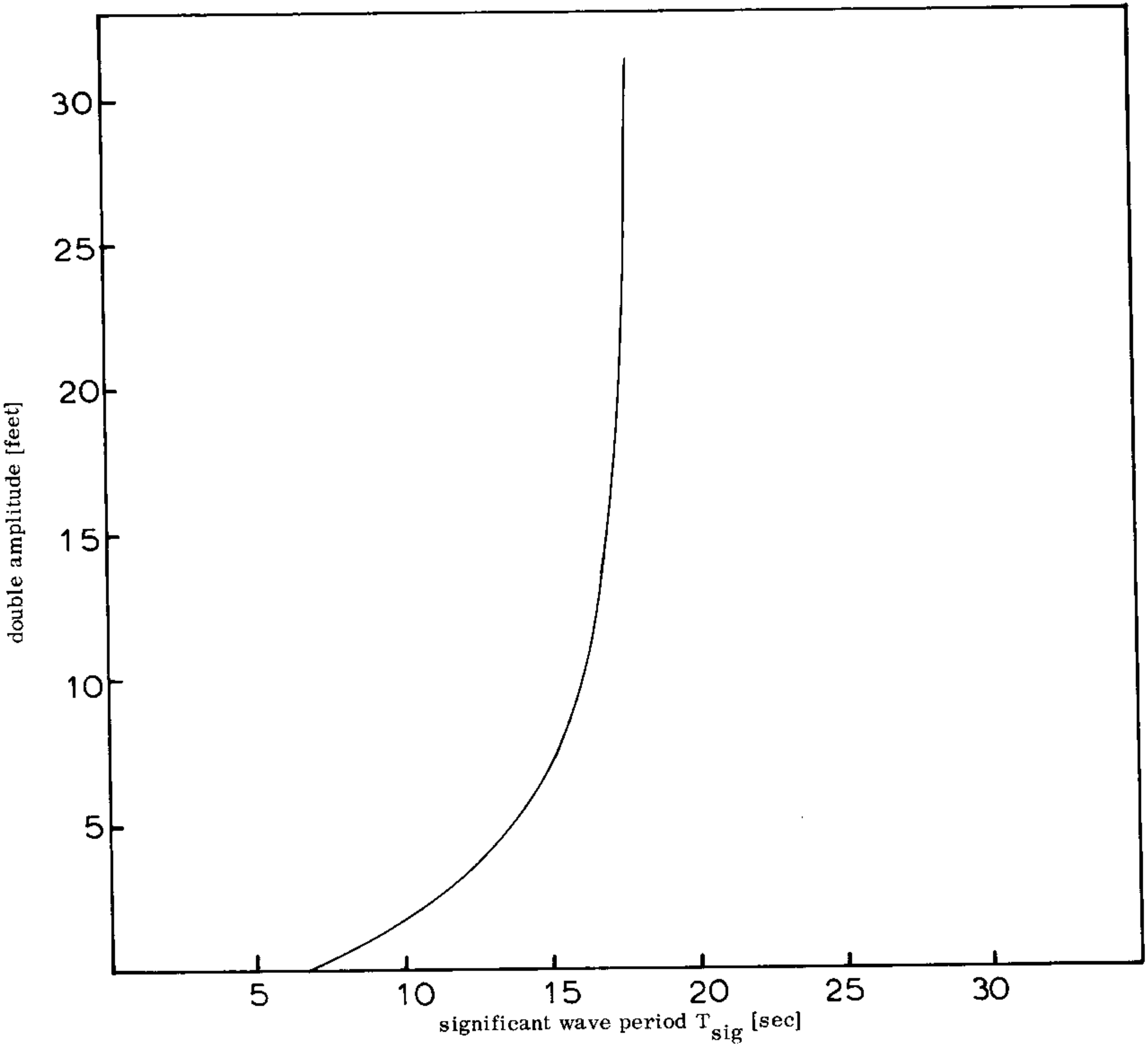

Fig. V2-6 Significant Double Amplitude of Heaving Motion

APPENDIX D

MOSES PHASE I SCALE MODEL PROGRAM

Introduction

A share of the Phase I effort was devoted to the construction and testing of a 1:13 working scale model of MOSES. The purpose of these tests was to verify the MOSES design with a physical model. A modeling scale of 1:13 was selected as a good compromise between the loss of fidelity as the prototype model scale ratio increases and, on the other hand, the prohibitive costs and handling problems encountered as the ratio approaches unity.

The validity of our results rests on three experimental assumptions:

- o The model faithfully represents the prototype
- o Froudes scaling laws apply
- o Sea conditions presented to the model are representative of those MOSES will encounter in service.

The first assumption was verified by measurement and computation. The second is supported by many years of experimental work throughout the world, on many types of hydrodynamic models. The third assumption is not so secure, because, due to time and financial constraints, we must be satisfied by the natural wave trains that were available locally during the ocean testing period.

The model was designed by the project engineering team as an adjunct to the preliminary engineering effort. Mr. John Guswell was in charge of construction and the major metal fabrication was done by Aloha Welding Co. of Honolulu, Hawaii.

Dry land measurements and tests were conducted in the facilities of the Naval Undersea Center's Hawaii installation. We are deeply indebted to them for their courtesy and assistance. Still water tests were conducted in Sea Life Park's Whaler's Cove which provided a near ideal, deep, calm, protected and accessible body of water--available nowhere else in the State.

Two sets of rough water tests were conducted, one representing moderate conditions, in Kaneohe Bay, and the other at sea off Makapuu representing very large waves.

During tests in Kaneohe Bay, conditions remained fairly constant with wind velocity 10-12 knots, accompanied by an irregular wind sea of significant height about one foot and wave periods one to three seconds. This corresponds roughly to prototype H_{sig} = 13 ft, T_{sig} = 10 seconds. Water depth was 30 feet.

During tests at sea off Makapuu, wind and sea conditions varied, and the wave pattern was more complicated. A local wind sea was present of H_{sig} about 1.5 feet, wind varying from five knots to fifteen knots in gusts. In addition, wave trains were present that had been refracted around Manana Island, a small volcanic cone lying 3/4 mile to windward of the test site.

This mixture produced a confused and very short-crested sea with H_{sig} varying during the day from 3.5 to 4 feet, and T_{sig} in the neighborhood of seven seconds. Translated into terms of the prototype, these conditions are fairly rigorous, featuring large amounts of wave energy near heave resonance, and maximum wave heights of about 60 feet.

In this appendix we first describe the model itself. This is followed by a description of the four components of the model test program: dry land, still water, moderate ocean conditions, and rough ocean conditions. The test program description is followed by a summary of the test results and a statement of conclusions and recommendations.

I. The 1:13 MOSES Scale Model

The model was designed to an exact 1:13 scale with respect to external dimensions, weights, buoyancies, tank capacities, and weight and buoyancy distributions. The shaft and ballast tanks were rolled and formed from Cor-Ten and mild steel sheet respectively. The house structure itself was made of molded plywood and fiberglas with external walkways and ladders of hand formed aluminum. The external elevator platform was also fabricated of aluminum. It was made to be manually movable and located with set screws. The scaled lead ballast is attached to a threaded shaft which is located in the center of a removable plug at the bottom end of the shaft. This arrangement allows movement of the lead ballast for fine balancing of the model. Since the model was required to withstand transportation and repeated handling ashore, unnecessary fragile details such as the jib crane and hand and guard rails were omitted. The red and white finish is in accordance with suggestions provided by the U.S. Coast Guard, though that agency informed us it has no restrictive painting regulations pertaining to "special" buoys.

The internal configuration of the main and variable ballast tanks replicates that of the full scale MOSES; the main ballast being divided into two compartments capable of separate flooding and blowing, and the variable ballast envelope being divided into the variable ballast tank itself and liquid storage (to represent fuel, fresh water and sewage loads). Internal tubing connects the ballast tanks with air and vent connections located just below the upper house. Flood valves are represented by holes in the tank stopped by rubber plugs.

The model control system consisted of a SCUBA tank for high pressure air, a pressure reduction valve, a bank of three-way valves for ballast blowing and flooding, and three flexible, lightweight vinyl hoses fifty feet in length which connect each valve with its ballast connection on board the model MOSES. This configuration was as originally designed and it worked perfectly throughout the test series. No modifications were required. It should be mentioned that the vinyl hoses were taped to the model at the design water line and ran up to their on-board connectors from there. This was done to preclude contamination of buoy motions by hose weights and forces. During all wet tests care was taken to assure that the hoses were floating free and therefore imposing minimum forces on the model. Figure D-1 is a photograph of the model in still water with control hoses attached.

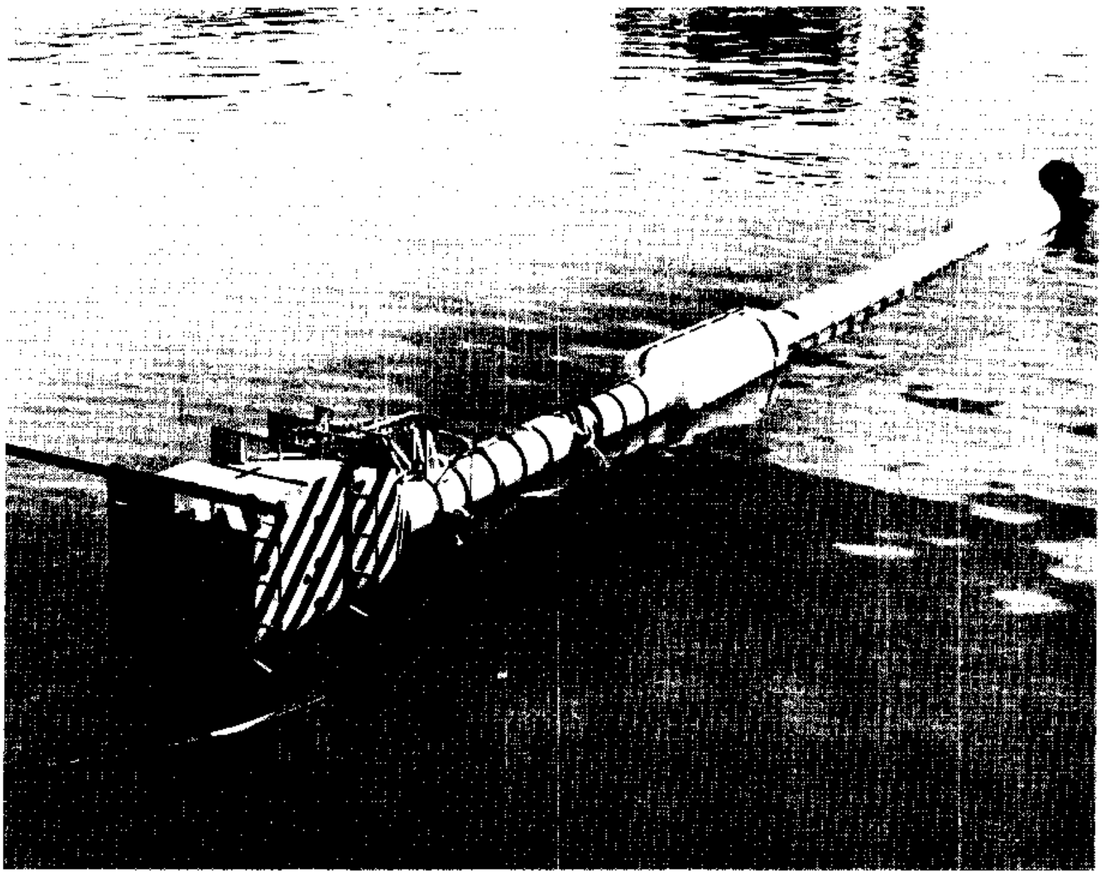

Fig. D-1 The MOSES 1:13 scale model during its first still water test with translation control hoses attached.

Since the actual construction of the model differed significantly from that of the full scale version, the model being not only stronger but qualitatively different, it would not be possible to derive a linear stress coefficient suitable to the accurate prediction of full scale bending stresses from model bending stresses. Therefore, strain gage measurements were not employed. An unbonded strain gage accelerometer with $\pm$ 5 g range driving an FM encoder was located in the upper house. The accelerometer sensed translation and towing accelerations which were transmitted to a tape recorder via the encoder and a cable to the towboat. Other documentation of model behavior during tests was accomplished with 16 mm moving pictures.

II. Phase I Model Testing Program

The Phase I model testing program consisted of dry land tests and measurements, still water tests, and two simulated open ocean tests. These are described below.

A. Dry Land Measurements and Tests

The model was first weighed and measured carefully. This process began with verification that all external dimensions were accurately reproduced to scale. This was followed by verification of ballast tank capacities which was done by successively filling the tanks with water and weighing the model. Next, measurements of weights and weight distribution was made with ballast tanks both full and empty.

The model's center of gravity was determined with ballast tanks full and empty by simple sequential single point suspension tests. Following this, moments of inertia with ballast tanks empty and full were determined with swing tests. In the swing tests, the model was suspended at its center of gravity, free to rotate through a measured arc. Torque was applied by a small weight connected to the model with a light line run through a simple pulley system, the weight being allowed to fall a measured distance to initiate the rotation. A movie camera was set up to record the time the weight reached the end of its downward travel, and the time it took the buoy to rotate through a measured angle at constant velocity. Measurements were made with main ballast tank full and empty. Figure D-2 is a photo of the overall setup. Figure D-3 shows the marked area just passing the end of its arc with weight and clock in position.

B. Still Water Tests

The goals of the still water tests were to make observations and recordings and to derive accurate measurements of the buoy's characteristics in the calmest conditions possible. Included were: (1) fore and aft trim in the horizontal attitude, (2) roll period and stability in the horizontal, (3) roll stability during translation, (4) heave period and heave damping coefficient in the vertical attitude, (5) pitch period in the vertical, (6) general behavior in horizontal and vertical attitudes and during translation in both directions, and (7) adequate performance of the model's translation control system.

1. Fore and aft trim was recorded by waterline measurement and film recording.

2. Roll period was determined by timing a number of roll cycles.

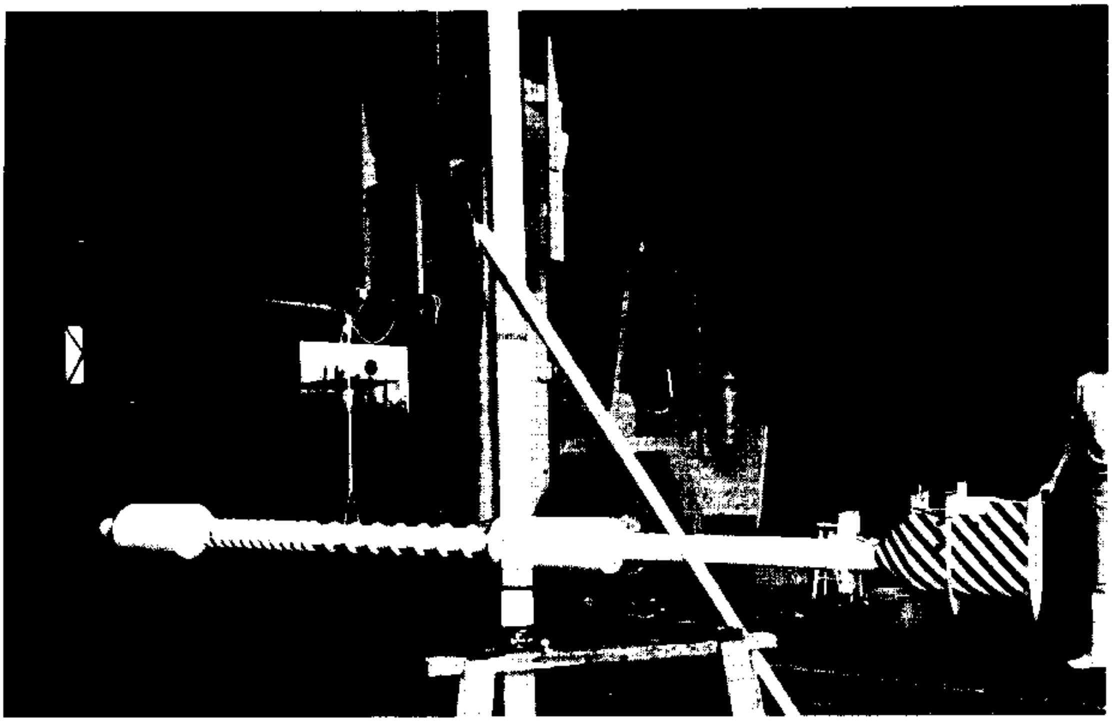

Fig. D-2 Test setup for determining radius of gyration.

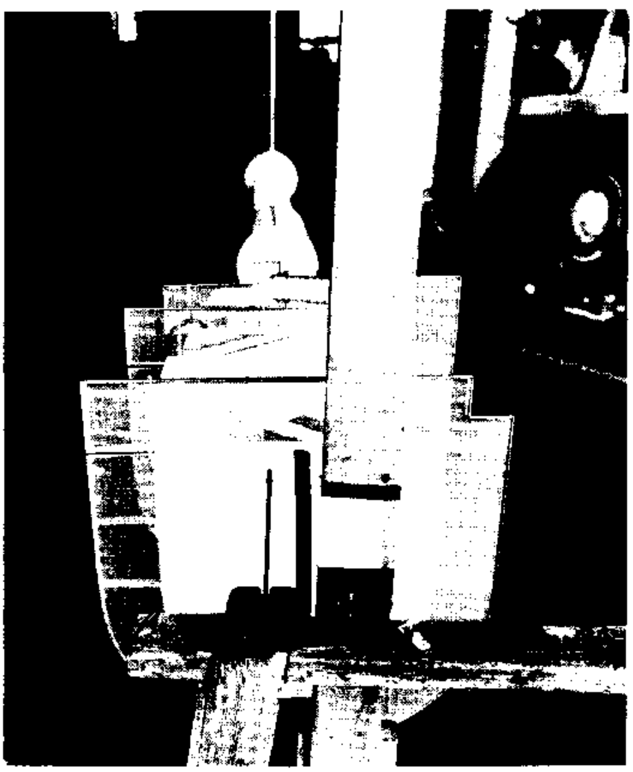

Fig. D-3 Close-up of model swing tests showing mark on model just passing reference marker.

3. Translational roll stability was obtained by measuring changes in roll period while flooding down the main ballast tank in increments to the point of translation.

4. Heave period and heave damping were determined in a manner similar to that employed for determining roll period and stability. However, in this case, a swimmer weighted the buoy downward a predetermined increment. When the weight was released, the buoy's heave amplitudes, complete oscillation times and number of observable oscillations were recorded. The bare model exhibited unexpectedly large heave damping. We hypothesized that the stiffening rings might be responsible. Consequently heave damping was re-tested with stiff acetate shrouds covering the stiffening rings and the results compared.

5. Pitch period was measured with a procedure similar to the above two.

6. The model's overall behavior was recorded by still and movie cameras during all experiments.

7. The translation control system was exercized fully as a natural consequence of these tests.

C. Moderate Open Sea Simulation Tests in Kaneohe Bay

The objectives of the Kaneohe Bay tests were to: (1) determine towing forces required through a realistic range of towing speeds in calm water, (2) observe and record towing behavior in moderate seas, (3) observe and record translational behavior in moderate seas, and (4) observe and record vertical behavior under moderate sea and wind conditions.

The towing force tests were conducted in the calm waters of the Kaneohe Yacht Club's harbor where fixed reference points were available. The test procedure consisted of towing the buoy on a 50-foot line with a small boat at gradually increasing speeds across a line of sight while simultaneously measuring and recording tow-line stress with a horizontal spring scale. A test crew on shore established the line of sight and timed the traverse periods to derive actual speeds. Though the prevailing wind was light, multiple tows both up and down wind were made at each speed and averages derived.

Towing behavior tests were conducted in the bay using a larger tow boat while the smaller boat dropped markers, timed the marker traverse period to record actual speeds and recorded the buoy's behavior with a 16 mm movie camera. Still photographs were taken simultaneously from the towboat.

Winds during the test were fairly steady at 10-14 mph producing deep water waves 10-12 inches in height with a three-second period. The buoy was towed several miles and subjected to multiple translations and free drifts in the vertical attitude. During translations and vertical drifts, its behavior was observed by the test crew and recorded by still and movie cameras.

D. Rough Water Tests off Makapuu

An area in the lee of Manana Island, offering semi-exposed conditions and a depth of 36 feet was marked with an anchored reference buoy before the tests began. The MOSES model was launched at the Makai Range pier and towed to this site where multiple translations were made. The conditions prevailing here are described in the introduction to this appendix.

These tests were subjective in that it was not possible to measure wave parameters or buoy motions accurately. The test objective was simply to observe and record the model's behavior under rough water conditions and verify that its behavior under these conditions was within tolerable limits. Towing behavior in large head-on, quartering and following seas was observed and recorded as was translational behavior and vertical drifting behavior.

Figure D-4 shows the model in the vertical attitude, and Figure D-5 shows the model being towed in rough water conditions.

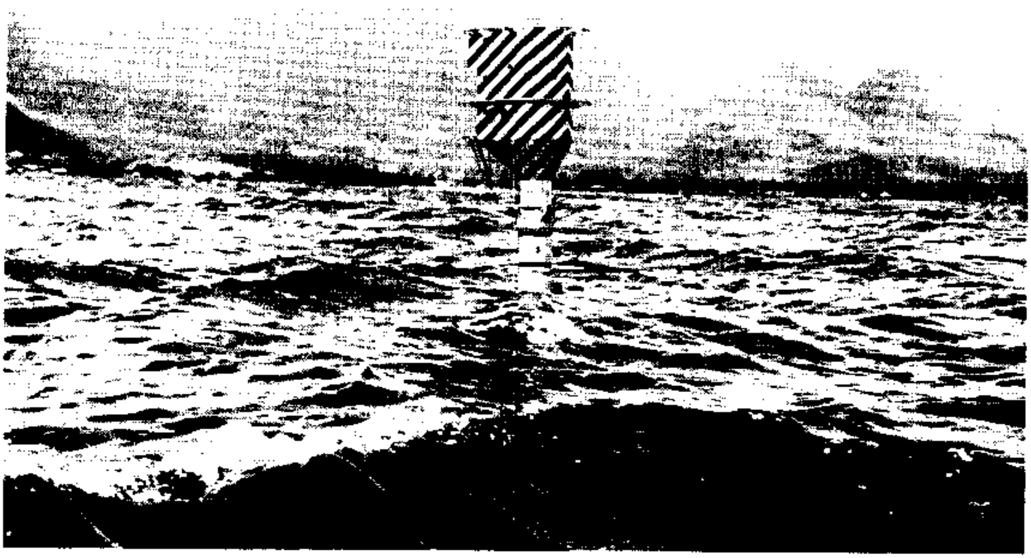

Fig. D-4 MOSES 1:13 scale model in the vertical attitude during rough water tests off Makapuu, Hawaii.

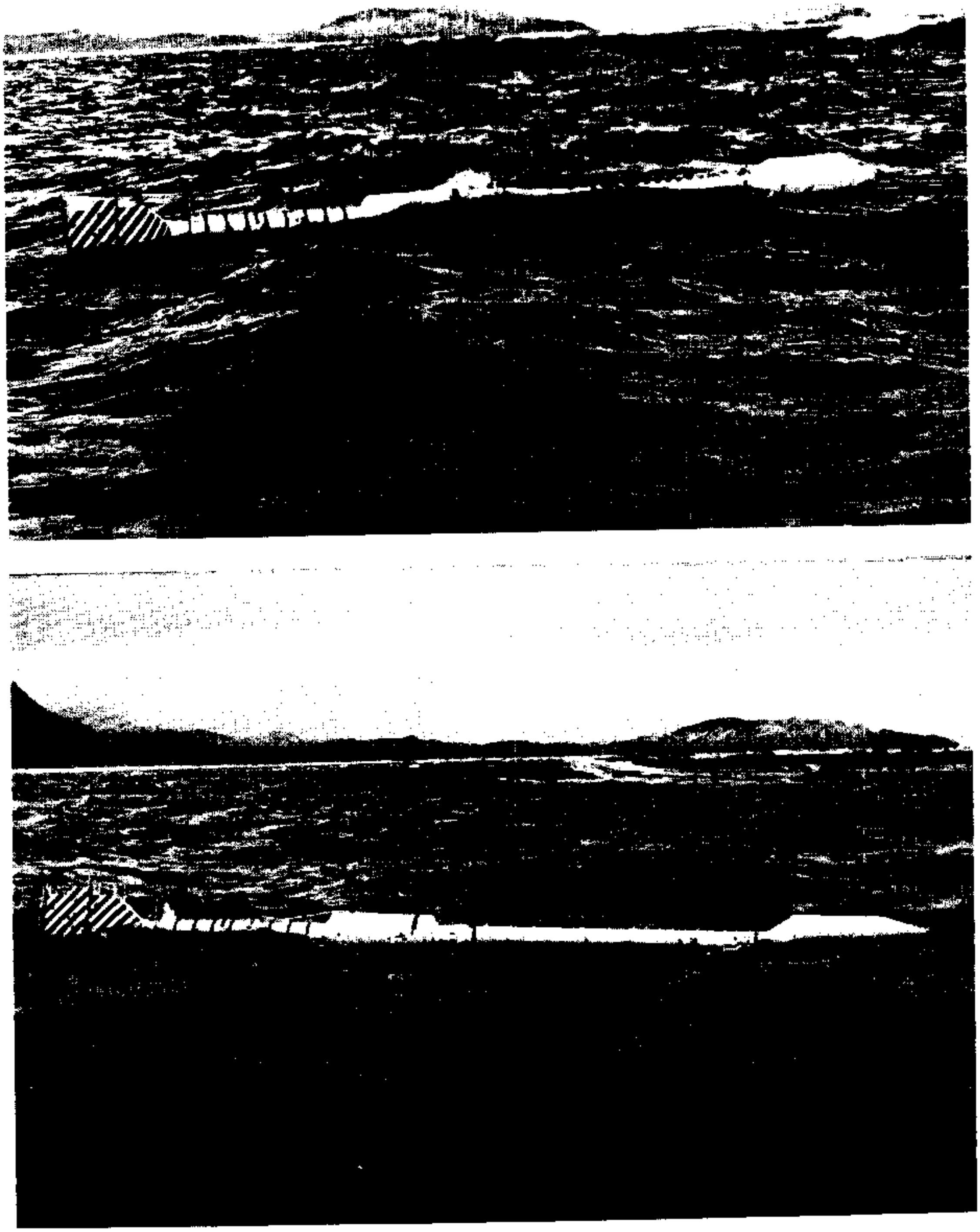

Fig. D-5 MOSES 1:13 scale model under tow during rough water tests off Makapuu, Hawaii, showing extreme "hogging" and "sagging" conditions.

III. Summary of Test Results

This section summarizes the significant results obtained from the tests. First the important measurement comparisons are tabulated and analyzed. Then the results of our experiments with heave, radius of gyration, pitch, surge, roll, towing, and translation are presented.

A. Measurement Comparison

	Prototype	Scaled from Prototype	Model
Dry Weight	688,458 lb	313.5 lb	321.5 lb
Wet stores	46,800	21.3	12.0[1]
Main ballast	490,000	223.0	224.0
Variable ballast	83,783	38.1	38.4
LWL Displacement	1,309,041 lb	595.9 lb	595.9 lb
L.O.A	287.33 ft	22.10 ft	22.06 ft
Shaft diameter	7' 1"	6.539 in	6.545 in
VBT diameter	14.00 ft	1.077 ft	1.08 ft
Max. variable ballast	140,000 lb	63.7 lb	64 lb
MBT diameter	18.00 ft	16.615 in	16.495 in
MBT volume	7,656 cf	3.484 cf	3.496 cf
Fixed ballast	198,520 lb	90.35 lb	90.0 lb
Stiffening ring width	9.0 in	.692 in	1.0 in
Heave period (vertical)	26.7 sec	7.417 sec	7.5 sec
Pitch period (vertical)	--[2]	--[2]	10.5 sec
Radius of gyration	88.12 ft	6.78 ft	7.01 ft
BG	11.06 ft	0.85 ft	0.85 ft
Transverse GM (horizontal)	4.0 in	5/16 in	5/16 in

In most ways the model is strikingly similar to the prototype design. Important departures are: (1) the dry model is 8 pounds heavy; (2) the model's radius of gyration is significantly larger; and (3) the model's stiffening rings are larger than scale. In all other ways the model appears to truly represent the design. The differences noted above are not considered great enough to distort the behavior of the model seriously;[3] so no corrections have been made as yet.

---

[1] Model dry weight was 8 lbs larger than scale; load in wet stores compartment reduced to compensate.

[2] MOSES natural pitch period was not calculated. Pitch response to both regular and irregular seas is analyzed in Appendix C, part 3.2.

[3] The heave damping effect of the oversize stiffening rings is discussed in B below.

B. Heave

Measurements were made in still water with the buoy ballasted to its load waterline. The buoy was held at about six inches below load water line and released. Beginning at the top of the first rise, four or six complete cycles were timed by stopwatch on each of five trials, and results averaged. Amplitude at beginning and end of the timed period was estimated by observing marks taped on the buoy shaft at the waterline.

Measured period was 7.5 seconds. This is in excellent agreement with calculated period for the prototype of 26.7 seconds:

$$(7.5)(\sqrt{13}) = 27 \text{ seconds.}$$

However, heaving motion showed strong damping, approaching 10% of critical. As this did not agree with the damping coefficients chosen for the mathematical model ($\zeta < 1\%$), a second heave measurement was made to determine the importance of the oversized stiffening rings on the lower shaft. Two sets of trials were performed. In the first, the buoy was not modified but extra care was taken to estimate amplitude of motion at the beginning and end of the timing period. In the second set of trials, acetate sheet was wrapped tightly around the rings and taped on to present a smooth, unbroken surface from the top of the main ballast envelope to the bottom of the variable ballast envelope (Fig. D-6). Thus shrouded, the rings could have no effect on the buoy's damping characteristics.

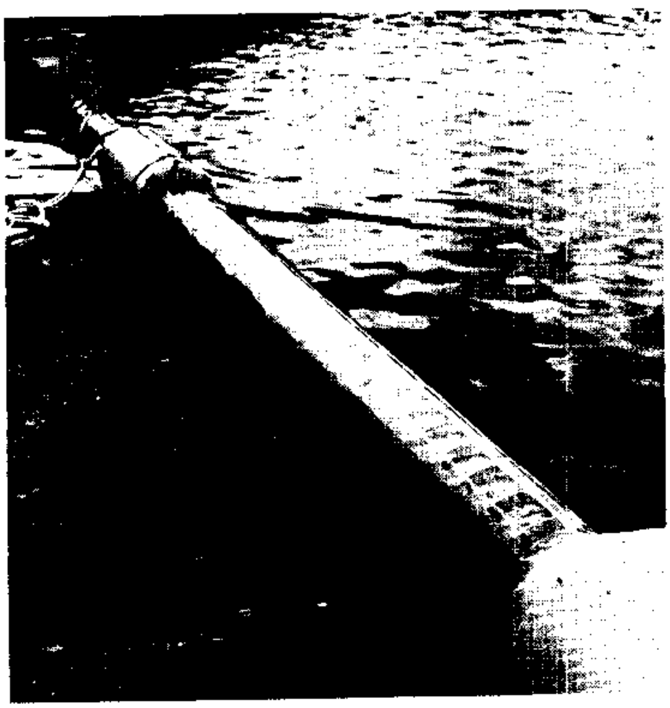

Fig. D-6 MOSES model with acetate shroud over stiffening rings prior to heave tests.

In the first, or unmodified trials, heave period was again 7.5 seconds, while in the second, shrouded trials, heave period increased to 8 seconds.

In the following, viscous damping ζ is assumed, and can be characterized by the expression

$$\frac{\chi_n}{\chi_o} = e^{-\Delta} = e^{-2\pi n \zeta/(1-\zeta^2)^{1/2}}$$

$$\Delta = \log \frac{\chi_o}{\chi_n} = \frac{2\pi n \zeta}{(1-\zeta^2)^{1/2}}$$

where ζ = fraction of critical damping

Δ = logarithmic decrement

n = number of cycles

What was measured is χ_o/χ_n, the ratio of initial peak heave amplitude to the peak amplitude at the end of a timed period of several cycles. For small ζ, ($\zeta < 0.2$) the expression above for Δ is approximately

$$\Delta \cong 2\pi n \zeta \text{, and}$$

$$\zeta \cong \Delta / 2\pi n.$$

For the first trial, with rings exposed, n = 4 cycles, and

$$\frac{\chi_o}{\chi_n} = \frac{9}{1.35} = 6.7, \ \log 6.7 = 1.9$$

$$\zeta \cong \frac{1.9}{(6.28)(4)} = .075 = 7.5\% \text{ of critical}$$

For the second trial, with shroud in place, n = 6 cycles, and

$$\frac{\chi_o}{\chi_n} = \frac{9}{6} = 1.5, \ \log 1.5 = 0.4004$$

$$\zeta = \frac{0.4004}{(6.28)(6)} = 0.01 = 1\% \text{ of critical}$$

The assumption of viscous drag is a simplification, total drag being a combination of skin friction, eddy making, and frontal pressure effects. However, the dramatic decrease in total drag achieved by shrouding the rings suggests that the rings do play a significant role in heave damping and are very possibly vortex generators.

The strong damping contributed by the rings was impressive to watch in the model. In the unshrouded case it was difficult to follow the heaving motion beyond 4 cycles because by that time the amplitude was so small (typically $< 1''$) that timing by stop watch became uncertain. In the shrouded case, observers had the impression that motion might continue for several minutes if not stopped.

Again, in rough-water tests the unshrouded buoy was never observed to exhibit persistent oscillations in heave, but appeared to follow the variations in wave height fairly closely. The shrouded buoy was not tested at sea. Figure D-7 shows near-maximum heave response in rough water. Oscillations did not persist following such a response.

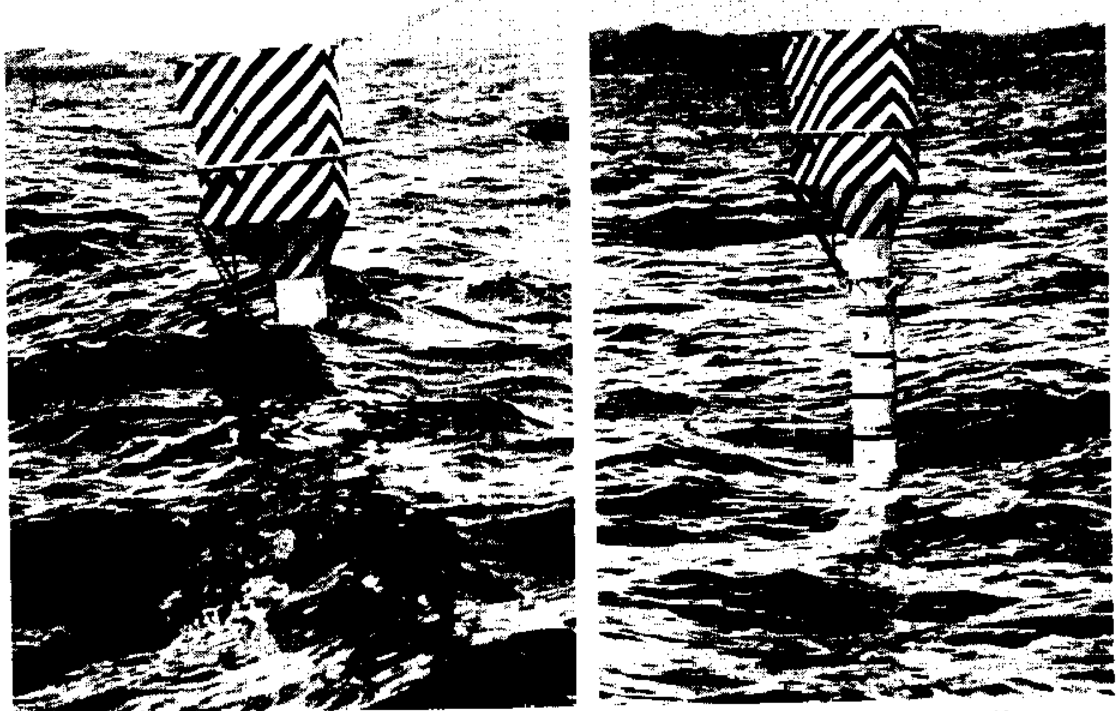

Fig. D-7 Near-maximum heave in large, very long period waves off Makapuu.

Calculated displacement to Load Water Line is 590.5 lbs, without the shroud, which adds another 110 lbs.

On mass considerations alone, the buoy's heave period should be

$$t = 2\pi\sqrt{W/kg}$$

W = buoy weight, including on-board wet ballast

$$= 2\pi\sqrt{590.5/(14.73 \times 32.16)}$$

k = buoyant restoring force of 14.73 lb/ft

$$= 7.04 \text{ seconds}$$

Yet the measured period is 7.5 seconds. While viscous damping tends to lengthen the resonant period, the effect is very small at $\zeta < 10\%$. Therefore most of the discrepancy must be due to induced hydrodynamic mass. If a mass coefficient of one is assumed, the magnitude of induced mass will be about

$$m_h = 595.9 \ [(7.50/7.04)^2 - 1] = 80 \text{ lb.}$$

In the shrouded case, the buoy's heave period should be

$$t = 2\pi\sqrt{705.9/(14.73 \times 32.16)} = 7.66 \text{ seconds}$$

whereas measured t = 8 seconds.

The contribution of hydrodynamic mass would then be

$$m_h = 705.9 \ [(8/7.66)^2 - 1] = 64 \text{ lb.}$$

This leaves about 16 pounds attributable to the rings, which indicates that whereas they appear to be efficient energy dissipators, they have little effect on period. In fact, it may be useful during the final design to look into the notion of optimizing the rings for damping, especially in view of the buoy's tendency to respond out of phase at wavelengths approaching resonance (see Appendix C).

C. Radius of Gyration

Measurement was made by allowing a weight to fall three feet, this weight being connected by a monofilament nylon line over two pulleys to the top of the house end of the buoy model, which was freely suspended in a horizontal attitude at its center of gravity. The resulting angular velocity was measured, and from this and the geometry of the setup, the angular acceleration of the buoy was calculated. As the weight used was small (2.5 lbs), friction in the pulleys was not negligible, and was estimated at 5% for each pulley.

Case I: buoy suspended with 20 lbs water in wet stores compartment, all ballast tanks dry.

R = distance of C.G. below top of house = 13.895'

F = effective accelerating force = 2.005 lbs

α = angular acceleration = 0.053 rad/sec^2

$$I = gFR/\alpha \quad \sqrt{\frac{(32.16)(2.005)(13.895)}{(.053)}} = 16,905 \text{ lb-ft}^2$$

$$\text{radius of gyration } k = \sqrt{\frac{I}{W}} = \sqrt{\frac{16,905}{344}} = 7.01'$$

This agrees well with calculated k for the prototype of 88.12' (7.01 x 13 = 91.13')

Case II: buoy suspended with 20 lbs water in wet stores compartment, main ballast tanks full.

R = 16.23'

F = 2.07 lbs

α = 0.049 rad/sec^2

$$I = \sqrt{\frac{(32.16)(2.07)(16.23)}{0.049}} = 22,060.5 \text{ lb-ft}^2$$

$$k = \sqrt{\frac{22,060}{559.5}} = 6.28' \qquad (6.28 \times 13 = 81.6')$$

calculated k for prototype is 77.24'

D. Pitch

In still water tests pitching was excited by a swimmer giving the buoy a shove at about the waterline. It proved impossible to produce pitching motion without accompanying heave. The pitching motion was heavily damped. Only two full cycles could be reliably timed. This heavy damping probably stems from the fact that the buoy's center of gravity and center of lateral resistance are located far apart, forcing the buoy to move in surge as well as pitch. In any case, the measured period was 10.5 seconds, corresponding to a pitch period in the prototype of almost 38 seconds.

Both at Kaneohe Bay and at Makapuu, the buoy was observed to pitch very little, perhaps a degree or two in the intermediate conditions at Kaneohe Bay, and at most 5 degrees under the worst conditions at Makapuu. Predicted pitch response is also small, making for good agreement between the mathematical model and the physical model.

E. Surge

On the other hand, accelerations in surge are likely to be fairly high. The mathematical simulation predicts surge amplitudes of the same order as the exciting wave amplitudes for waves of longer periods. This was borne out by the observations at Makapuu, where no discernable wake occurred as the larger waves went by. The absence of a wake suggests that the buoy was following the horizontal component of the wave's orbital motions.

F. Roll (Horizontal)

The preliminary engineering design for the buoy includes a transverse G.M. of four inches for the horizontal condition. This small value was chosen because it was felt that an easy rolling motion would be beneficial to equipment and supplies stored aboard during long tows, and because the hull, being a figure of revolution, would not give rise to large rolling forces. However, this meant an actual G.M. in the model of 5/16 inch, a dimension difficult to achieve. It appears that the model, in fact, has a negative G.M. when on an even keel without some load of ballast in the variable ballast tank. In this condition it will take a list of about 13 degrees. The model is completely stable against capsizing, but just doesn't want to stand upright. With 30 lbs of water in the variable ballast tank, approximately correct for floating at L.W.L. in the vertical, the model shows no list, however.

The very small G. M. led us to wonder whether the buoy would become unstable at some point during translation. Accordingly, the roll period was taken at several intervals during flooding of the main ballast tank. Roll period was measured first with the tank dry. At intervals of approximately 20% of ballast required for overturn, flooding was halted and roll period taken. The curve of Fig. D-8 shows roll period rapidly increasing until the main ballast tank is about 40% full, then abruptly decreasing, so that the vessel is stiffer in roll just before overturn than when it is horizontal. The last point on the curve represents a condition where the house is entirely clear of the water, the main ballast tank is entirely submerged, and the buoy has a bow-down angle of about 15 degrees. This behavior has not been thoroughly analyzed. But it seems reasonable that roll stiffness decreases as the house is lifted out of the water, but that the fixed ballast in the bow exerts more righting force as it sinks deeper into the water. This behavior may be very sensitive to placement of the C. G. of the fixed ballast, and to free-surface effects in the large ballast tanks, and should be carefully studied in final design.

In all towing tests, in calm water and rough, the buoy showed no tendency to roll heavily, and never showed instability. This helps us believe that our choice of a small G. M. was correct.

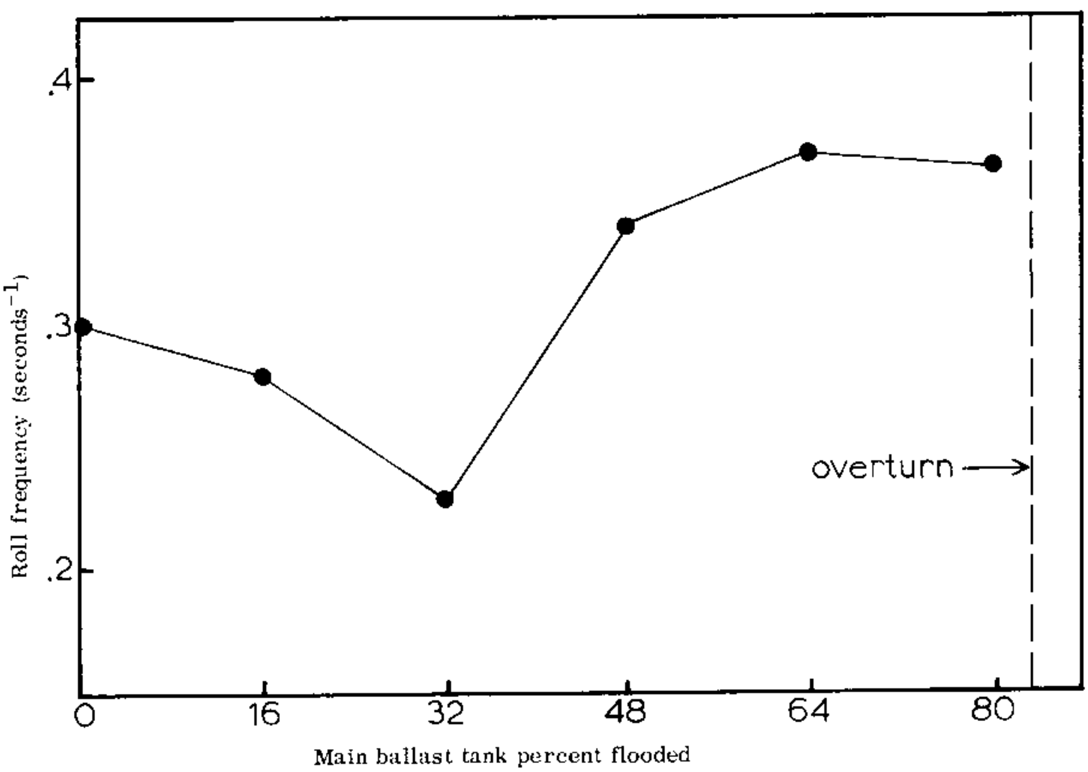

Fig. D-8 Roll frequency as a function of main ballast flooding.

G. Towing

Towing behavior was generally satisfactory. The model's roll characteristics are described above. Before the model was towed, much was made of its peculiar shape, the sharp discontinuities at the ends of the three large volumes (the house and the two ballast envelopes), the wide stiffening rings, the catwalks and gratings extending out and down into the water from the house, and the slight bow-down trim. However, in practice the model turned out to be easy to tow, showing none of the feared tendencies to plunge, yaw, broach, roll, or skid. Figure D-9 shows drawbar forces over model and prototype speed. The characteristic knee occurs between five and seven knots, leading to the conclusion that

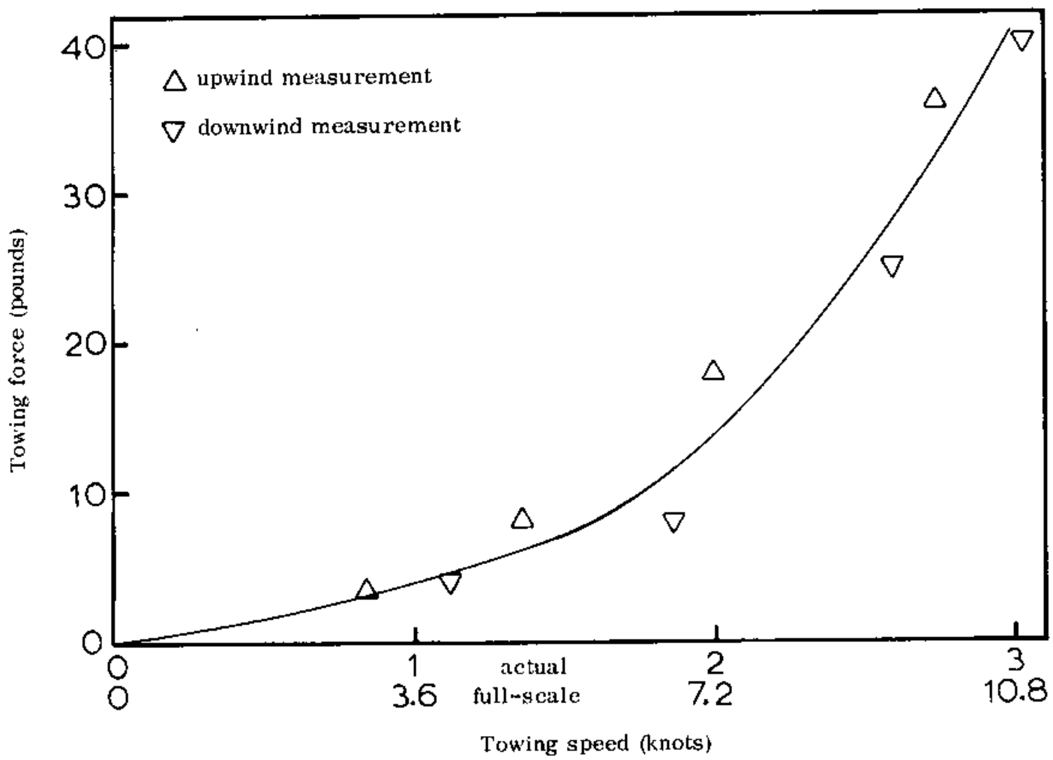

Fig. D-9 Towing force as a function of towing speed.

the prototype can be towed by a very moderate towboat at over 5 knots. The knee appears to be related to the "hull speed" of the large volumes of the hull, all about 35 feet long. When towed at prototype speeds over 12 knots the bow tends to dive (Fig. D-10) and each major discontinuity in the hull generates its own heavy wake.

One towing characteristic merits special mention, namely the model's very great lateral stability. It doesn't want to turn. At sea this is all to the good, but the buoy will require careful handling in close quarters.

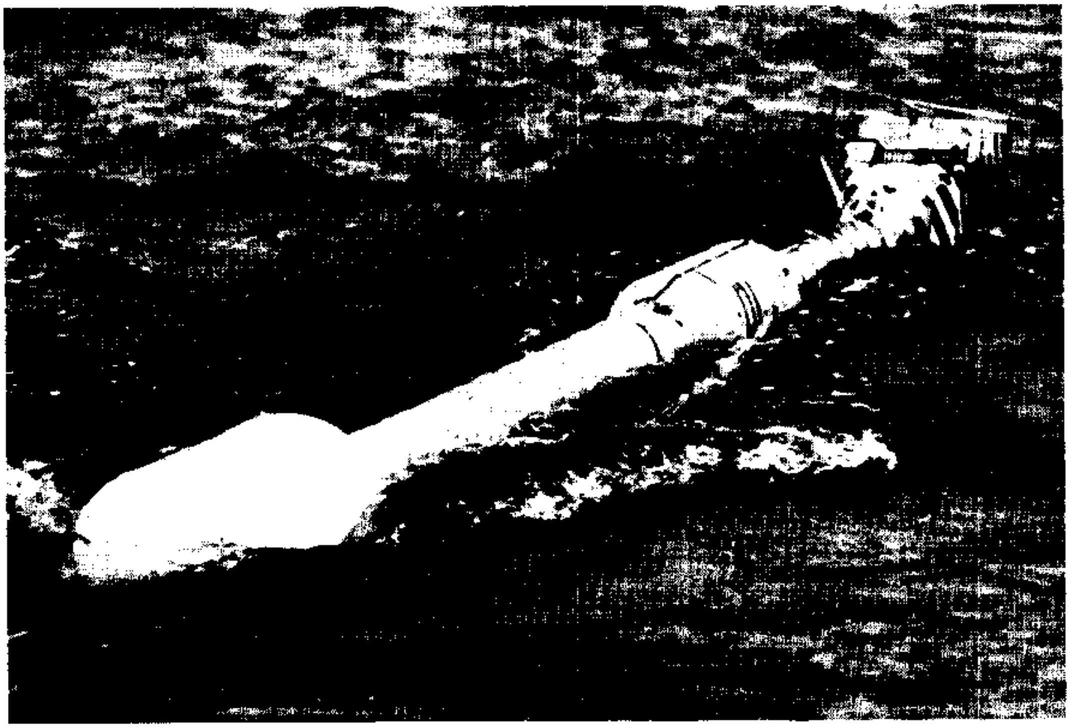

Fig. D-10 MOSES model under high speed tow in Kaneohe Bay.

H. Translation

One of the main purposes in building the model was to investigate the dynamics of translation. We know of no analytical method that would substitute.

The main ballast tank is subdivided by a baffle, primarily to aid in translating from vertical to horizontal. It was felt that the initial increment of buoyancy--enough to produce overturn--should be as eccentric as possible to insure that the buoy would translate right-side up. The two parts of the main ballast tank are interconnected at the bottom of this baffle, so that the air already in the upper tank can expand and drain the remainder of the ballast as the tank rises toward the surface.

On the first translation test, from horizontal to vertical, the variable ballast tank was empty. The model developed a heavy port list as the bow settled, with only the upper portion of the main tank being vented. Apparently a large amount of water got above the baffle before overturn, because after the model began to swing toward vertical, it made a rapid full revolution around its long axis, and plunged rather deep, coming to rest at a water line about six inches above the top of the variable ballast tank.

In subsequent translations, the variable ballast tank was vented and allowed to flood about half full before overturn, and only the lower section of the main ballast tank was vented. This proved to be the cure, and all subsequent erections were handled the same way. On de-erecting, the upper portion only of the main ballast tank was blown, and the variable ballast tank was not blown until the buoy was horizontal, if at all. No trouble or instability was encountered on any later translation, even in very rough water. Figure D-11 shows a rough water translation sequence.

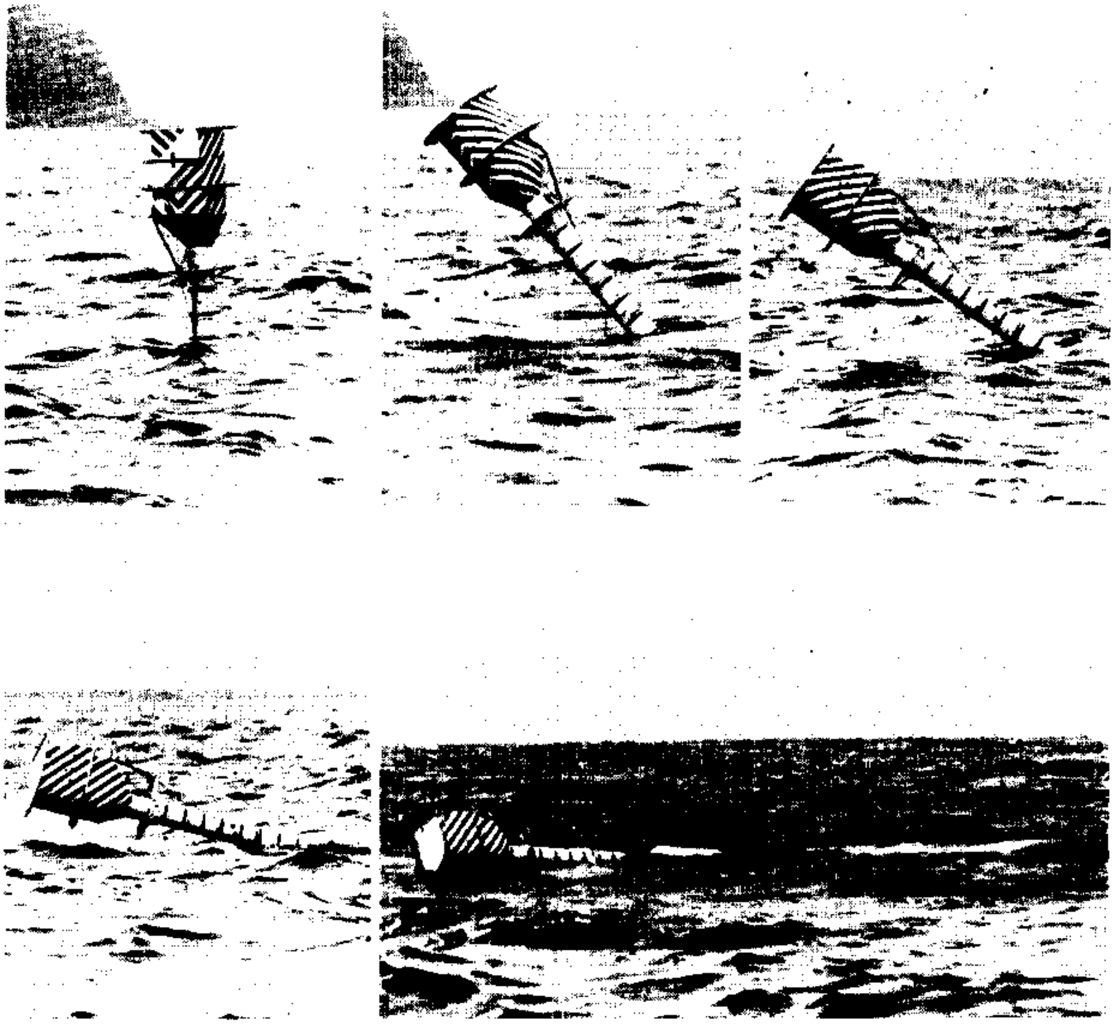

Fig. D-11 Translation in rough water off Makapuu. In the vertical position the rounded portion of the house is facing into the wind. As translation begins, the model rotates 180° to both align itself with the wind and place the rounded portion of the house down.

We had felt concern about wave-slap during periods when the house was nearly or just clear of the water surface, believing that at these times the house might take a severe pounding. Based on our observations, the problem does not appear serious; on erection, the house sticks to the water all the way to overturn, hesitates for two or three seconds, then leaves with deliberate speed. On de-erection, the main buoyancy tank evidently has acquired considerable excess buoyancy by the time the house reaches the water, for it deliberately enters the water and stays there. On one occasion at Kaneohe Bay the house took two slaps as it left the water, registering on the accelerometer in the house at about 1/4 gravity, rather lower than expected. At no time did the house receive a severe blow.

On reaching vertical, the model has a tendency to plunge. This was measured in still water and found to be, from deepest immersion to peak of rebound, 20 inches. This seems mild, representing a double amplitude of about 22 feet on the prototype. In the model, the main ballast tank continues to vent air for several seconds after reaching vertical. Further, the increase in air pressure due to depth is just over half an atmosphere. In the prototype, the compression ratio will be about six, and the ballast tank will therefore lose buoyancy rather more rapidly as it descends than does the model. Hence we should be prepared for a tendency to greater angular velocity and deeper plunging in the prototype.

IV. Conclusions and Recommendations

A. Conclusions:

1. Assumptions

The three experimental assumptions advanced at the beginning of this Appendix are generally supportable with minor qualifications.

The first, that the model represents the prototype, is supported by reference to paragraph III-A, Measurement Comparison, on page D-9.

The second assumption, that Froude's scaling laws apply, is sustained except with reference to heave damping, which probably does not closely represent prototype performance, due to differences between Froude scaling and Reynolds scaling.

The waves presented to the model represented prototype conditions reasonably well, being short-crested wind seas with significant dimensions close to the model scale ratio.

2. Model Performance

In general, the model performed very well. To the extent measurements could be obtained, the mathematical model was confirmed by still water measurements, while informed observers of the rough-water tests concluded that the model's behavior was essentially as predicted.

B. Recommendations:

1. Some further combined scale model and mathematical simulation work would be highly desirable. First, the effects of the model's stiffening rings, and the relation of these effects to the prototype should be further investigated. Second, roll characteristics in the horizontal mode should be studied more fully. Finally, additional tests should be conducted with better instruments to quantify the model's rough-water performance, especially with a view to verification of the mathematical model. See Attachment D-1 for a more detailed discussion.

Attachment 1 to Appendix D

Note:

This attachment is a memorandum written toward the conclusion of the scale model test series. It has been slightly abridged. The memorandum contains the essence of our present concepts for more extensive testing of the 1:13 scale model and concurrent further development of the mathematical simulation.

MEMORANDUM
April 29, 1971

To: Joe A. Hanson, MOSES Project Director
From: G. Rothwell, Ludwig Seidl

Subject: <u>Model Testing</u>

1. Except for two stillwater measurements, which we would like to re-run, we have now finished preliminary tests on the 1:13 model and have made a comparison of these results with the output from Dr. Seidl's dynamics program. We find that the two models (math and physical) are generally in excellent agreement for both horizontal and vertical modes. Both models are showing us that we have a successful and fully feasible design.

2. The physical model which contains a working ballast system has given us good insight into the nature of the translation process and has strongly confirmed our predictions of smooth and unconditionally stable translation performance.

The rough water tests being conducted at sea, we have no opportunity to take actual time histories of the water surface nor could we measure the true buoy motions. Thus, while by observation we feel there is good agreement between the physical and math models, this is only an estimate.

3. The math model is very complete and flexible providing us the ability to modify the shape, size, loading condition and several other important parameters of the buoy as well as the wave input. As a consequence of this and the fact that we have apparently already produced a buoy design fairly close to the hydrodynamic optimum, we feel further model testing will be extremely useful to explore and verify certain aspects of its behavior. We would recommend the following further steps.

a) Using our present program, model the 1:13 physical model in the computer so as to explore and verify its large damping characteristics; i.e., determine what part of this effect stems from scale effects and what part from the buoy's shape.

b) When this has been done, test a small (1:50) model in regular waves. This model will be constructed so as to allow easy alteration of its shape. A suitable wave tank is available at the Look Lab of the University of Hawaii. These tests will have two benefits: (1) determination of the values of the sensitive parameters for "fine tuning" the buoy's behavior and (2) verifying the calculated coefficients in the math model's transfer functions (that part of the program which solves the input sea condition for resulting buoy motion).

c) When the steps (a) and (b) are completed, the 1:13 model will be properly instrumented to measure its actual motion in a seaway as well as the actual wave input. Thus, in a variety of actual sea states obtainable in bays and at sea hereabouts, we will get measurements of real waves and the response of a real buoy.

d) It will then be possible to enter the real wave data obtained in (c) into the computer model as described in (a) above. This model should then predict the actual response to the physical model obtained in (c), and it can be validated against the actual wave histories and model responses we recorded in (c).

4. The benefits gained from all this will be two:

a) We will have a fully accredited computer program that we can use with confidence for confirming the MOSES final design and adjusting that design to produce the responses that best fit the buoy's experimental program. (In no case except the trivial one of dead calm will the buoy's motion be zero.) As experimental design proceeds, requirements for tolerable buoy motion will become more evident. An example: for a 6-month cruise in the equatorial current, how large can a fish silo be and still have a 95% chance of surviving the weather to be encountered throughout the cruise? This is a hard question to answer. At the present stage of our knowledge we have to say we don't know. However, the testing program outlined above will give us much of the data we need.

b) We will understand the 1:13 model well enough to allow its use later on in the testing of various designs for fish cages and other external attachments.

cc: MOSES Men

APPENDIX E

MOSES QUALITY ASSURANCE PROGRAM

Introduction

The appendix is composed of two major sections. The first is concerned with the preliminary design of a program to assure that MOSES components, materials and fabrication methods meet applicable quality standards and performance criteria. The second is concerned with the design of an acceptance testing program to assure that MOSES performs as expected under operational conditions and that owner acceptance is appropriate.

I. THE ENGINEERING AND CONSTRUCTION QUALITY ASSURANCE PROGRAM (ECQA)

A. Development of Standards and Criteria

MOSES as a whole may be viewed as consisting of a variety of systems each of which, in turn, is made up of components which, in turn, are made of specified materials. It is our thesis that a thorough quality assurance program must be founded on a recognition of this hierarchial structure and upon an understanding of the complex interdependencies that will exist between many elements of MOSES. The Engineering and Construction Quality Assurance (ECQA) then will begin with materials and components and follow fabrication and assembly through to the completion of each major system. Acceptance testing of the total MOSES platform will then establish the quality of MOSES as a whole under operational conditions.

It is convenient at this point to define the various systems involved. The classification below follows closely both functional boundaries and the natural divisions of work that will occur in construction. In general, it is intended that the functions grouped under each system (or section) will provide the basis for a separate subcontract.

1. MOSES System Definitions:

a. Hull Structure (HST). This comprises all structural materials, fabrication of the hull, provision for in-progress testing, and shop finish. It includes shell plating, framing, attachments and inserts such as porthole frames, hull penetrations, brackets and openings for mounting or installing the work of other systems, as well as all jigs, alignment and assembly fixtures and handling gear.

b. House Structure (HOS). Includes all structural materials, fabrication and shop finish, framing, shell plating, decks, catwalks, stairways, ladders, railings, closures for all openings, provision for mounting the work of other systems, together with all jigs, cradles, alignment and assembly fixtures, handling gear and means for making structural interconnection with the hull.

c. External Elevator (EEL). Includes structural frame, decking, handrails, and all hardware mounted on the elevator, but does not include hydraulic controls, hoses, support cables or support machinery.

d. Internal Elevator (IEL). Includes elevator car complete, with controls, cables, rails, traction motor and motor controller, safety devices and indicators, but does not include supply wiring to motor controller or brackets to which rails are mounted.

e. Electrical System (EES). Includes engine generators and controls, fuel supply system, batteries, gimbal mounts, all switchgear and synchronizing equipment, together with all required indicators, panels, circuit breakers, motor starters, wiring and conduit, receptacles and fixtures including navigation lights and wiring-in of all motors on the buoy and installation of all built-in electrical appliances. Does not include any electrical hull penetrators or external underwater cabling, hardware or fixtures, but does include installation of conduit and splice boxes for other wired systems.

f. Hydraulic System (HYS). Includes fluid supply pump, motor and controls, oil reservoir, all oil piping, valves, regulators, and associated hardware, jib crane complete, and all machinery for the operation of the external elevator.

g. Pneumatic System (PNE). Includes high-pressure air compressor and motor, air storage tanks, all piping, valves, regulators and associated hardware, including all pilot-operated valves in the buoy and all ballast blow and vent lines and fittings and air connections to other systems.

h. Ventilating and Air Condition System (VAC). Includes all blowers and motors, ducts, grills, registers and controls, as well as provision for the installation of filtering and refrigeration. Includes monitoring equipment and alarms for detection of the presence of CO, CO_2, and combustible hydrocarbons, and associated wiring.

i. Waste Disposal System (WDS). Includes all drain lines, floor drains and associated hardware, valves, traps and vents, and all plumbing fixtures connected thereto, as well as connections to sewage tank, level gages, and alarms.

j. Water Storage and Supply System (WSS). Includes all piping, fittings, pressurizing units with motors and controls, all connected fixtures, tank gages and alarms, valves and indicators for fresh water storage and supply and salt water supply.

k. Surface Preparation and Painting (SUR). This section covers all cleaning, sandblasting and painting of exterior and interior of the buoy structure, piping, conduits, ducts, partitions, machinery mounts, and where called for installed machinery. Included is all color coding of painted surfaces for all systems.

l. Navigation and Communication (NAC). Includes basic electronics, comprising high-seas HF transmitter and receiver, UHF short-range transceiver, radar, loran, recording depth finder and public-address/intercom system. This suite of equipment is considered minimum and required for safety. Other communications or special-purpose electronics are outside the scope of the basic, sea-ready buoy.

m. Deck Gear and Ground Tackle (DGT). Includes anchors, anchor and mooring lines, fenders, chocks, fairleads, bitts, winches and cleats to permit towing, docking and mooring while the buoy is in the horizontal mode, as well as fittings to allow attachment of a two-point moor while vertical.

n. Miscellaneous Finish Work (MSC). This work comprises all floor and wall coverings, cabinetwork, partitions, and miscellaneous items called for in interior fitting out. This section will be subject to frequent change orders during construction and sea trial periods, and will be strongly influenced by mission requirements that are not yet known. Included are special storage requirements and provision for installation of special purpose equipment.

During the MOSES final design, these systems, their boundary limits and interfaces with other systems will be defined in detail.

2. Systems Quality Standards and Performance Criteria

System quality standards and performance criteria derive from three major sources: (1) MOSES operational and scientific requirements, (2) applicable Federal regulations, notably U.S. Coast Guard and the American Bureau of Shipping, and (3) industry standards.

3. Standards for Components

Typically, each system is made up of a variety of components. In some cases, USCG and ABS standards will apply directly to these items. In most cases, however, component standards will be those which, in composite, are required by the design characteristics of the system of which they are elements. In all cases, both sources will be employed to develop specific and detailed statements of structural standards and performance criteria.

4. Material Standards

Wherever possible, recognized industry standards shall be used in the selection, purchasing, testing, fabricating and installing of materials. Notable here are the applicable standards of: the (1) American Society for Testing Materials, (2) American Society of Mechanical Engineers Code for unfired pressure vessels, (3) Federal Specifications for paints and finishes, (4) National Electrical Code, and those provisions of (5) Interstate Commerce Commission Regulations covering the design, installation and operation of high pressure gas systems, (6) for breathing air, U.S. Navy standards for medical air, etc. In cases where commonly used standards are not available or do not insure sufficient quality or performance, special sections will be written to provide in detail for the required quality level.

5. Critical and Non-Critical System Elements

Critical elements are systems and components in which failure or operation beyond specified limits would endanger human life or the safety of the platform itself, or, at best would result in termination of an operation. Non-critical elements are those in which failure or operation beyond specified limits would not result directly in any of the above conditions. Typically, quality standards for critical elements will be set higher and with higher safety factors than will those for non-critical elements. During the design of the quality assurance program, all system elements will be classified as critical or non-critical, and this classification will affect the value of the standards set for them.

6. Complex and Non-Complex System Elements

An element may be either complex or non-complex in terms of its structure and functions. Standards for non-complex elements are typically themselves non-complex and phrased in terms of straight-forward measurement of physical or chemical properties. Quality standards for complex elements, on the other hand, must typically be phrased in terms of performance standards within a rather broad range of possible operational circumstances. Therefore, quality assurance for complex elements will consist of establishing performance tests that the element must pass successfully to achieve acceptance.

7. Special versus Common (Off-the-Shelf) Elements

MOSES and all of its systems will be "special", i.e., one-of-a-kind. However, in the interests of cost/effectiveness, the MOSES design will employ common components and materials to the greatest extent consistent with system and subsystem performance requirements and quality standards. Where common elements are employed, the manufacturer's specifications or MILSPEC's will form the basis of such employment. In these cases, the quality assurance program will be required to verify only that the component as delivered complies with the specifications. In all cases this verification will be accomplished prior to the incorporation of that component into its system. Common components employed in our deep diving mobile habitat "AEGIR" will very likely be appropriate for MOSES. Where such applicability exists, we intend to employ these proven components.

8. Cost/Effectiveness

To the MOSES quality assurance program, cost effectiveness will mean a variety of things. As mentioned above, it will mean that off-the-shelf system elements will be used insofar as practical. It will mean further that designs will be balanced in such a way that use of off-the-shelf components can be maximized to attain necessary quality standards at minimum cost. It means that thorough planning and systematic design of the quality assurance program will be employed to minimize duplicative quality assurance testing and inspection and to employ only that testing and inspection necessary to demonstrate adequately the quality and performance characteristics of all system elements. Finally, it means that standards will not be set any higher than is warranted by the criticality of each system element.

Cost effectiveness, however, does not cease to be a consideration upon completion of construction. The concept extends into operation and maintenance during the entire life of MOSES. So cost effectiveness also means that the MOSES quality assurance program must attend to durability and maintainability when setting standards for MOSES system elements.

B. Structure of Quality Assurance Standards and Recordation of Inspection and Testing Results

The general structure appropriate to the MOSES quality assurance program may be accurately represented as a matrix such as that shown in Figure E-1.

Matrixes of this type for each subsystem will provide summary information as well as indexing to detailed documentation as follows:

1. Component Coding

   a. Each of the MOSES systems will be identified by a unique three-character alphabetical code that is indicative of its name as shown in the listing of MOSES systems in (A) above.

   b. Each component will be identified by three alphabetical characters indicating its type (VTV = Vent Valve; HPV = High Pressure Valve, EMT = Electric Motor, etc.) followed by three decimal digits which uniquely identify it within its component type.

   c. Each type of material employed in the construction of MOSES components will be identified (when such identification is necessary) by a unique three-character alphabetic symbol. So a given component code will be prefixed by the three-character designator of the system to which it belongs and may be suffixed by one or more codes designating the materials employed in its construction, to form the code AAA-AAANNN-AAA-------AA. For example, a vent valve-type three in the pneumatic system which is made of core 10 steel would carry the code PNE-VTV003-CORE10.

   d. Where a given, common component occurs in more than one system, it will retain its unique four-alpha, three-decimal and its material codes throughout. The system code, though, will reflect the system of which it is a part.

This type of coding will allow not only unique identification of MOSES components, but also quick and easy association of all components with their systems, and easy recognition of all components contained

	Standards, Criteria, Inspection and Testing				Other Considerations			
	Structural Standards (Coded)	Performance Criteria (Coded)	Inspection Code & Date Performed	Testing Code & Date Performed	Criticality	Complex or non-Complex	Special or Common	Direct Interface
System AAA								
Component ID Codes								

Material ID Codes								

Components ID Codes								

Materials ID Codes								

Fig. E-1 Sample System ECQA Summary Matrix in any given system. A significant additional benefit will accrue also. This is that it will be rather simple to discern all the systems in which any common component or material is employed and so to aggregate quality requirements and subsequently derive simplified quality standards for that common component or material.

2. Coding for Standards, Criteria, Inspection and Testing

The MOSES quality assurance program will attempt to minimize the variety of special inspection and testing procedures required. As a consequence, it may be expected that there will be significantly fewer sets of inspection and testing procedures than there are system elements. Thus, for each element listed in the basic matrix, it will be sufficient only to identify by a simple code the inspection and testing procedures to be employed and to set down the structural standards and performance criteria that apply to that element for that procedure. This will be done in the first four parts of the matrix shown in Figure E-1. The details of inspection and testing procedures will be contained in a separate file indexed by their code numbers.

3. Dating

The matrix will contain the dates on which each required type of inspection and testing was completed successfully on each component. These dates will be included in the intersection boxes that contain the inspection and testing codes themselves.

4. Other Considerations

Other information that will be made available at a glance in the matrix will include each element's criticality level, whether it is special or common, and what other elements interface with it directly. This information will be provided in the set of columns shown in the right-most part of the matrix.

5. Back-up Files

The matrix does not, of course, contain all the information necessary. Rather, it is a means of structuring, of providing basic information at a glance and an index to more detailed files. There will be two of the latter. The first, already mentioned, is the file of inspection and testing procedures. This will include detailed instructions for inspection and testing as well as materials and equipment required. The second is a complete file on all system components including their specifications, documentation, and inspection and testing history. It will be indexed by the system component code described previously.

6. Tagging and Stamping

Each system component will be identified by its code in all engineering drawings in which it occurs. When the element is completed or received from its supplier, it will be stamped or permanently tagged with its code. The date on which the element successfully completed all QA tests will be included in the stamp or tag following completion of the tests. No MOSES component will be incorporated into its system until this date has been added to its code. All stamping and tagging will be done on the main part of the element in such a position that it will be easily readable after assembly into its system.

C. Engineering and Construction Quality Assurance (ECQA) Procedures

This program will begin early in the final engineering phase and continue through the construction phase up to the point that MOSES is turned over for acceptance testing. Should significant deficiencies become apparent during acceptance testing, ECQA procedures will be re-initiated to cover whatever modifications may be required. The general flow of ECQA procedures is shown in Figure E-2.

1. During Engineering

ECQA procedures will be established and initiated during the early stages of final engineering. These procedures will be designed to assure that the systematic identification procedures described earlier in this section of the appendix are employed correctly and thoroughly in all final engineering work.

2. During Procurement

Materials and components will be selected from manufacturers' catalogs when their stated specifications are found to meet requirements. However, catalogs are general and requirements specific. Frequently, therefore, some communication with one or more manufacturers will occur prior to final selection of materials and other off-the-shelf elements. It will be a responsibility of the MOSES ECQA group to assure that correspondence with manufacturers leaves no questions concerning the performance and quality standards that must be met. Beyond this, the ECQA group will assure that the manufacturer agrees legally to supply an element meeting necessary standards prior to the issuance of a purchase order. MILSPEC components will be employed wherever appropriate.

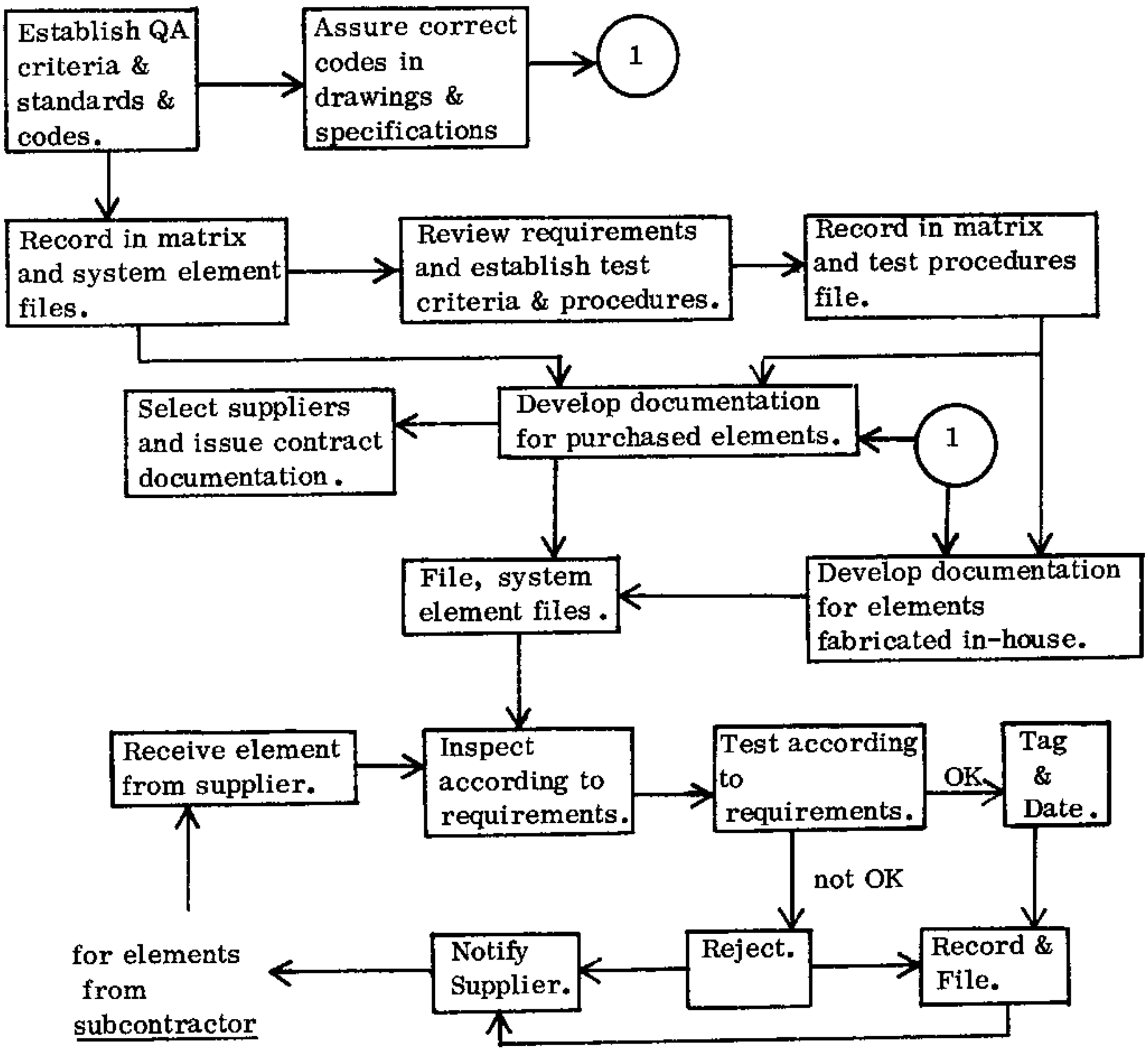

Fig. E-2 General Flow of ECQA Procedures
(page 1 of 2 pages)

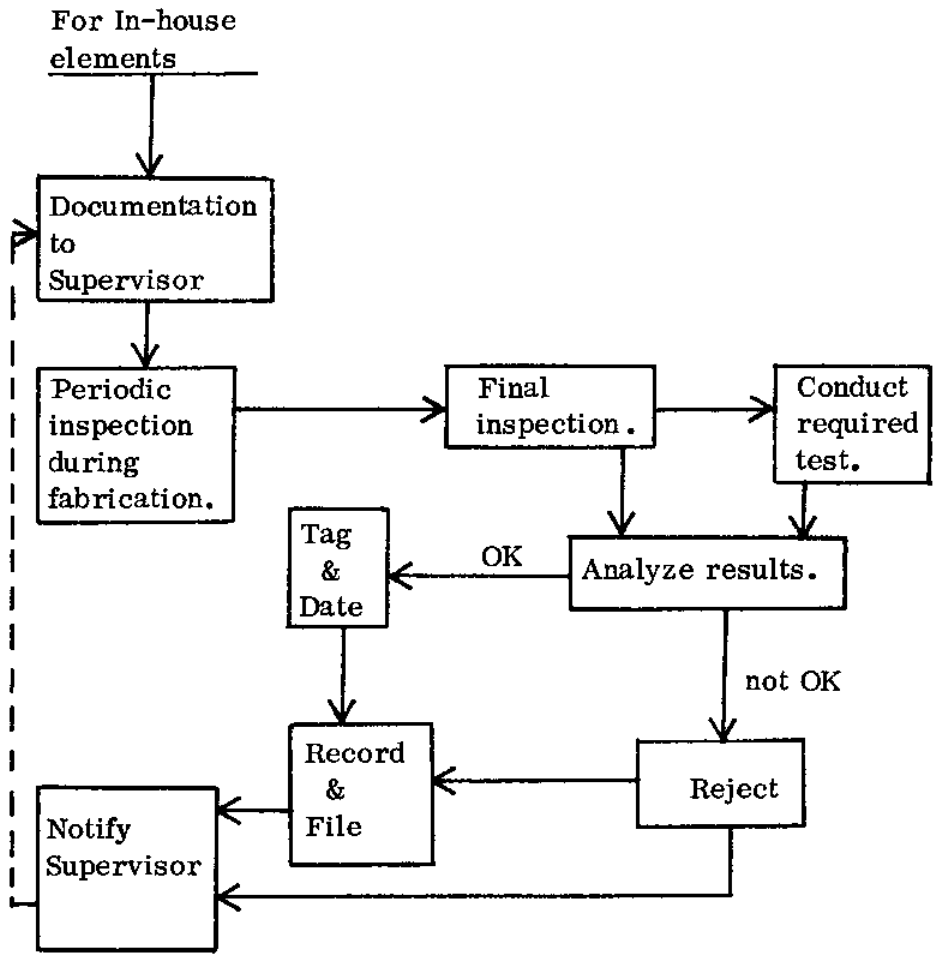

Fig. E-2 (page 2 of 2 pages)

The purchase order or contract will state explicitly and in detail the quality standards and performance criteria that each item must meet. Manufacturers will be expected to verify attainment of standards and criteria prior to shipping of a system element. Nevertheless, all non-MILSPEC components supplied by subcontractors will be re-examined and re-tested by the MOSES ECQA group prior to their acceptacne and inclusion in their system. Generally, MILSPEC components will be tested only if shipping damage is indicated. Where a large number of identical items is involved, random sampling will be employed.

3. During Fabrication

For the most part, components will be supplied either as off-the-shelf or special order items by subcontractors. But some components may be assembled by the prime contractor. ECQA during procurement of off-the-shelf items was discussed above. ECQA during fabrication of special components and all systems will proceed as follows:

a. The ECQA group will assure that each subcontractor and its own personnel as well are completely aware of all quality standards and performance criteria that must be met by any element for which they are responsible. Generally, engineering drawings, material specifications and descriptions of required ranges of performance plus any special characteristics will be supplied.

b. The ECQA group will assure that each element has been accepted prior to its incorporation into a component or system.

c. Generally, fabrication techniques will be specified in the engineering data. The ECQA group will routinely inspect subcontractors and its own fabrication facilities to assure that these techniques are employed as specified. Spot inspections for non-apparent joints and fits will be employed utilizing appropriate techniques and measurements.

d. Once a component is completed, it will be subjected to appropriate inspections and tests. Only when all such have been completed satisfactorily will it be accepted for inclusion in a system, stamped with the acceptance date and recorded as accepted.

e. Where a large number of identical elements are involved, random sampling will be employed.

4. Acceptance and Non-Acceptance

When an element is found acceptable, it will be so tagged and recorded. Its supplier will be notified and remuneration procedures initiated.

When an element is found to be unacceptable, its supplier will be so notified immediately. The notification will be accompanied by the detailed reason for non-acceptability and actions to alleviate the deficiencies initiated. Where samples are taken at random from a large group of identical components show unacceptability rates in excess of 2 percent, the entire batch of elements will be judged defective. The batch will subsequently be treated as a single, non-acceptable component.

II. ACCEPTANCE TESTING

This section contains a general specification for acceptance testing and crew training procedures for use by the owner (Makai Range, Inc.) in accepting MOSES from the builder.

A. Objectives

The procedures outlined herein have four objectives:

1. To establish that the builder has successfully and completely discharged his obligations to the MOSES fabrication contract.

2. To determine the material, functional, and dynamic properties of the completed MOSES platform.

3. To determine that MOSES systems and MOSES as a whole perform in accord with design criteria and mission requirements.

4. To assure that the owner's assigned crew is fully competent to operate and maintain the platform.

B. Applicable Documents

1. Furnished by the Builder

a. Construction contract documents, including plans, specifications, approved changed orders and substitutions, and copies of all formal contracts, including subcontracts.

b. Complete as-built drawings and specifications.

c. Complete vendor specification sheets, catalogs, identification data and manuals for all materials and hardware items.

d. Draft operations and maintenance manuals.

2. Furnished by QA Program

All documentation developed within the QA program.

C. Inspections and Tests

Inspections and tests include thorough structural inspections and static and dynamic tests as described below. All inspections and tests shall be performed by a team which includes representatives of the designer, the owner, the owner's QA program, the builder, and the crew training program. Where applicable, a technical representative of the vendor of the element under test shall also be present. In general, the builder shall have charge of and responsibility for inspections and tests, and owner's personnel will act in a technical support and training capacity.

1. Inspections

A thorough inspection of the entire platform shall be documented, verifying that every element called for in the contract documents is

(a) physically present, (b) of the type called for, (c) correctly installed and connected, and (d) has been passed by the ECQA program. Any discrepancy shall be corrected by the builder before the system of which it is a part is tested.

2. System Tests

For each individual MOSES system (see I.A.1 above) a test procedure designed to prove the system's function shall be performed. Within each test procedure, the system under test shall be exercised in all reasonable operational modes and stressed to the maximum level expected in service, plus an appropriate margin.* Any discrepancy shall be corrected by the builder, after which the system shall be re-tested. During each test, strict attention shall be paid to elements exhibiting marginal functioning, (e.g., excessive deflection of structure or supports, excessive voltage drops, motors and mechanical drives laboring under load, etc.) as signifying doubtful reliability.

3. Dockside Trials

When all individual systems have been proved functional insofar as possible before sea trials, dockside trials may begin. Dockside trials shall consist of two parts: operational simulation and hydrodynamic tests.

a. Operational Simulation

Integrated test procedures will be designed to simulate actual operating conditions of the entire platform insofar as is possible at dockside. These will be designed as initial tests of interaction among the various systems (e.g., cycling the battery while under realistic loads, including periods of peak loading of the engine generators). Any discrepancies noted under these test conditions shall be corrected by the builder, and appropriate re-tests conducted.

b. Hydrodynamic Tests

These tests will include inclining and trim measurements, measurements of rates of flooding and venting of ballast compartments, and such other tests and measurements as the designer shall deem necessary to verify the hydrodynamic properties of the platform.

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* Since operation in the vertical position and during translation will constitute a critical variable for some systems, system testing will extend into sea trial phases.

4. Towing and Handling Tests

With previous tests completed successfully, sea trials will commence with in-harbor handling, followed by open sea towing and handling.

a. In-Harbor Tests

In-harbor berthing and handling exercises shall be performed to establish proper placement of fenders, bitts, cleats, chocks, etc., and to verify that the vessel can be berthed and unberthed by a single towboat, as well as to refine techniques for performing the process.

b. Towing and Handling at Sea

The MOSES shall be towed at sea for a total of not less than 100 miles by a towboat competent to achieve at least seven knots towing speed, with a recording dynamometer in the towline. If possible, a portion of this test shall be conducted in sea conditions above state 5. Behavior of the tow in roll, yaw, broaching, surfing, and surge will be recorded and analyzed. In case of damage to any attached structures, such as catwalks, ladders, the movable platform, etc., the cause shall be ascertained and corrective action taken, e.g. reinforcement or re-design. Any failure internally, of supports, brackets or restraining gear shall be corrected in the same manner. All closures and the interior of the hull generally shall be inspected for stress and failure.

5. Translation and Vertical Performance

Once handling and towing characteristics and structural integrity are verified, tests of translation and vertical performance may begin. At least three translation tests shall be conducted, all in the drifting mode. These may be done concurrently with tow tests, providing at-sea inspections reveal no failures of the type described in (4) above.

The first translation test shall be performed in moderate or light sea conditions, and shall consist of translation to vertical, adjustment of variable ballast over its entire range, operation of all systems, and re-translation to horizontal. These tests shall be conducted by the builder's personnel.

The second translation test shall be performed in moderate to light sea conditions, and shall consist of the items listed above, but the buoy shall remain in the vertical for not less than 12 hours, during which period routine operating procedures shall be performed, all on-board electronics shall be operated, and the exterior platform shall be load-tested. These tests shall be conducted by the owner's assigned crew, under the supervision of the builder's representative. During all or part of the vertical period, the buoy may be tethered to the accompanying vessel if this proves desirable.

The third translation test shall be similar to the second, except that it may omit the platform load test. It shall extend over a period not less than 24 hours, including two translation cycles and a silent-ship period of not less than 4 hours. At least one exercise shall be conducted by divers, who shall ride the movable platform through its full range of movement. Tests shall be conducted by the owner's crew, in the presence of the builder's representative.

Measurements of the buoy's motion shall be made as required by the designer. These shall consist of not less than four 15-minute recordings of the buoy's accelerations in heave and pitch, plus simultaneous water surface recordings from an appropriate wave gage.

D. Analysis and Documentation

After all the above tests have been performed successfully, the owner and builder will jointly compile all test results and all documentation from whatever sources into a permanent file for the use of the owner.

At this point a thorough analysis of test results and performance criteria will be performed to determine finally that the completed MOSES meets its operational specifications. Any significant variance from specifications will be explicated and individually accepted by the owner with reasons for variance, and acceptance in spite of variance, described completely. These documented analyses and results will become a part of the owner's documentation.

E. Crew Training and Owner's Manual Revision

Crew training shall be conducted by the builder during and after the tests, until by mutual agreement all crew members understand the buoy and its systems and performance sufficiently to allow competent operation and maintenance by the owner's crew. At this point the operation and maintenance manuals will be revised for final compilation.

APPENDIX F

MOSES SEA-READY COST ESTIMATE

Introduction

This appendix contains a summary of the costs the MOSES Phase I staff estimates will be required to bring MOSES from the design stage reached in Phase I to a completed and sea-ready state. These costs specifically exclude any and all instrumentation and extra equipment design required by scientific experiments. That is, they are the costs to bring the MOSES buoy alone to a sea-worthy state.

With respect to cost estimating, there are two rather important questions that have not yet been settled. These are: (1) where will MOSES be built? and (2) how will the design and construction organization be structured? If MOSES is built on the mainland, it will have to be towed to Hawaii at considerable cost. If it is fabricated in Hawaii, Hawaii's higher labor and material costs will increase the price. For purposes of this estimate, we have therefore chosen to assume the total costs to be equal in both cases and used Hawaii fabrication costs as the basis for our estimates.

With respect to the structure of the design and construction organizations, we have assumed the following:

- o The Oceanic Institute will have responsibility for final design and contract documentation, quality assurance and overall program management.

- o A prime construction contractor will be selected from among several qualified shipyards which will bid on the basis of complete contract documentation (final engineering specifications, QA requirements, fabrication schedules, etc.) provided by the Oceanic Institute.

Therefore, present Oceanic Institute overhead rates are employed where indicated. Prime fabrication contractor and subcontractor overhead and profit are included in the prices themselves.

We have, by necessity, taken three routes to cost estimates given in this appendix. Where practical, we have obtained actual quotes from certain prospective contractors. Where quotes were not practical, we have either obtained estimates from contractors or made them ourselves after catalog review and communications with prospective contractors. The method used for each estimate is noted in the following tabulations.

As a final note to this introduction, we wish to point out that these quotes and estimates are made on the basis of material and labor prices prevailing at the date of this report. They contain no contingency factors whatever and are, of course, sensitive to any changes that might occur in regional and national economics.

Cost tabulations are presented in two parts. Part I covers design, development, quality assurance and acceptance testing; Oceanic Institute functions. Part II covers fabrication costs.

I. MOSES Final Design, Program Management and Acceptance Testing

A. Final Engineering Design (our estimates)		
1. All engineering calculations including structural dynamics analysis	$ 55,000	
2. Systems integration	11,000	
3. Production of all working drawings and specifications	89,000	
4. Contract documentation	11,000	
5. Materials and supplies, reproduction, clerical, administrative and other support costs	54,500	
Subtotal:		$ 220,500
B. Quality Assurance (our estimate -see Attachment F-9)		$ 76,750
C. Acceptance Testing (our estimates)		
1. Launching charges	$ 18,000	
2. Acceptance Testing Program (see attachment F-8)	51,360	
Subtotal:		$ 69,360
D. Program Administration (our estimates)		
1. Program Manager	$ 27,000	
2. Principal Investigator (2 man-months)	5,000	
3. Chief Scientist, Systems Analysis Division (6 man-months)	11,000	
4. Clerical support (18 man-months)	10,500	
5. Equipment and supplies	5,000	
Subtotal:		$ 58,500
TOTAL		$ 425,110
E. Oceanic Institute overhead at 75% of allowable direct costs (allowable direct costs estimated at 80% of total direct costs: .80 x 425,110 = 340,088)		255,066
GRAND TOTAL		$ 680,176

II. MOSES Construction

A, B, and C. Hull Structure and House		
1. Shaft sections fabricated and shipped to Hawaii by Kaiser Steel (letter quote)	$ 65,764	
a. Transshipment from dock to shop (our estimate)	1,500	
2. Additional structural fabrication and assembly- includes entire assembly of all hull components and fabrication, hauling to launching site, all leads in place with welds as required. Does not include shaft (from mainland), paint, portholes, although does include installation of portholes (quote from Mutual Welding)	386,500	
3. Portholes assembly, complete, fabrication only (pressure portholes and house portholes our estimate)	10,500	
4. Brackets for other systems, misc. hull penetrations, and miscellaneous work (our estimate)	10,000	
Subtotal:		$ 474,264
D. Internal Elevator Complete (our estimate)		50,000
E. Electrical System Complete (as per our detailed estimate in Attachment F-1)		97,770
F. Hydraulic System Complete (our estimate as per Attachment F-2)		20,700
G. Pneumatic System (our estimate as per Attachment F-3)		65,160
H. Ventilating and Air Conditioning System (our estimate as per Attachment F-4)		6,960
I. and J. Plumbing and Waste Disposal (estimate of K. Miura modified by us, see Attachment F-5)		15,840
K. Painting and finishing (contractor estimate)		65,000
L. Navigation and communication complete (our estimate as shown in Attachment F-6)		38,100
M. Deck Gear and Ground Tackle (our estimate, see Attachment F-7)		8,400
N. Miscellaneous Finish Work (our rough estimate since design was not included in Phase I)		35,000
TOTAL:		$ 877,194

ATTACHMENT F-1

Electrical equipment list

Engine Generators & Switch gear	$ 25,000	
Installation (Gimbals, Brackets, etc.)	5,000	
Fuel System (Day Tank, Pump, Controls)	1,500	
Splice Cams & Conduit to Panels	1,000	
Power Generators		$ 32,500
Panels A, B, C, D @ $400 each	1,600	
Battery, including Gimbals	6,000	
Motor Starters - 6 @ $375	2,250	
60-cycle inverter, 10 KW, regulated	6,750	
Labor	8,000	
Power Distribution		$ 24,600
Conduit and wire 3,500 lbs. @ $1.75/lb	6,125	
Receptacles, splice boxes - 100 @ $15	1,500	
Labor	5,000	
		$ 12,625
Navigation and exterior lights -10 @ $150	1,500	
House lighting, 25 fixtures @ $50	1,250	
Shaft & Observation Lab, 25 fixtures @ $40	4,000	
Labor	5,000	
		$ 11,750
Subtotal:		81,475
Overhead & Profit @ 20 percent		16,295
TOTAL Electrical System		$ 97,770

ATTACHMENT F-2

Hydraulic System

Hydraulic Supply including: 15 hp electric motor, 136 pm pump, 5 gallon reserve, strains, relief valves, gages		$ 3,500
Movable Platform:		
Motor	375	
Gear reducer & angle boxes	550	
Drums & Wire - 4 @ 350 each	1,500	
Misc. valves	175	
Air hose and reel	400	
Air operated valves - 2 @ $175	350	
Hydraulic piping - 300 lbs @ $2.50/lb	750	
Jib Crane, complete	7,250	$ 11,350
Installation & Labor		2,400
Subtotal:		17,250
20 percent overhead		3,450
TOTAL Hydraulic System		$ 20,700

ATTACHMENT F-3

Pneumatic System Equipment List and Labor Estimate

Air compressor, 25 cpm, complete with 5 hp electric motor, filters and controls	$ 3,750	
Air flasks, 1500 cf, 18 @ $350	6,300	
Air flasks, 300 cf , 3 @ $150	450	
Valves, pigtails and manifolds for above	1,800	
2" vent/blowlines 700' @ $10/ft	7,000	
1/2" tubing, 1000' @ $3/ft	3,000	
1" pipe, 800' @ $7/ft	5,600	
Valves, 40 @ $30	1,200	
Pressure reducing valves, hi-volume	2,750	
Pressure Reducing Valve, lo-volume	450	
Flood valves, 16" air operated, 3 @ $1,250	3,750	
2" vent/blow valves, 3 @ $200	600	
Pressure gages, 5 @ $30	150	
Remote operated valves, 4 @ $125	500	
Misc. hardware and fittings	5,000	
Labor	12,000	
Subtotal:		$ 54,300
Overhead @ 20 percent		10,860
TOTAL Air System		$ 65,160

ATTACHMENT F-4

Ventilating System

four 1/2-hp blower units @ $175	$ 700	
Ducts 400 LF @ $1.50	600	
Watertight closers, 8 @ $150	1,200	
Dampers, grills and registers	300	
		$ 2,800
Air monitoring set	2,750	
Remote alarm	250	
		3,000
Subtotal:		5,800
20 percent overhead		1,160
TOTAL Ventilating System		$ 6,960

ATTACHMENT F-5

Plumbing System

Complete piping system for MOSES includes: Fresh water system, salt water system, cooling piping for generator heat exchanger, plumbing waste piping, hot water piping, supply 1-W.C. with S.S. tank - estimated, K. Miura	$ 10,700
Pumps	1,000
Sinks	1,000
Sewage Agitator	500
Subtotal:	13,200
20 percent overhead	2,640
TOTAL Plumbing System	$ 15,840

ATTACHMENT F-6

Navigation and Communication System

Radar, 25 mile range, Decca	$ 18,750	
HF transmitter-receiver	3,000	
UHF Short-range receiver	1,800	
Loran C	1,850	
Depth-finder	2,750	
P.A. System	1,000	
Sound-power phones, 4 @ $275	1,100	
		$ 30,250
Wiring, brackets, antenna installation, etc.		1,500
Subtotal:		31,750
20 percent overhead		6,350
TOTAL Navigation and Communication System		$ 38,100

ATTACHMENT F-7

Deck Gear and Ground Tackle

Anchor	$ 500
Lines and chains	1,000
Chocks, bitts, fairleads and cleats	2,500
Two-point moor fittings	500
Finders and camels	2,500
Subtotal:	7,000
20 percent overhead	1,400
TOTAL Deck Gear and Ground Tackle	$ 8,400

ATTACHMENT F-8

Acceptance Testing Costs

MRI People and Equipment

168 man-days @ $120/day	$ 20,160	
HOLOKAI, 10 days @ $1000/day	10,000	
OG Tug for H.S. Towing - 1 day	2,000	
Dockage, etc.	3,000	
Documentation Production	4,000	
		$ 39,160
Construction Contractor Surcharge, 18 man-weeks @ $400/man-week		7,200
Light provisions and supplies		5,000
TOTAL		$ 51,360

ATTACHMENT F-9

Quality Assurance Program Costs

Salaries	
Professional QA engineer (18 months)	$ 27,000
Senior clerical assistant (18 months)	12,750
Travel for QA engineer	7,000
Materials and equipment for QA testing and costs of testing by outside laboratories	30,000
TOTAL	$ 76,750