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SEAFLOOR CONSTRUCTION EXPERIMENT, SEACON I

AN INTEGRATED EVALUATION OF SEAFLOOR CONSTRUCTION EQUIPMENT AND TECHNIQUES

CIVIL ENGINEERING LABORATORY (NAVY)

FEBRUARY 1975

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A series of interrelated seafloor engineering experiments was conducted in 600 feet of water on the seafloor 7 miles south of Santa Barbara, California, between July 1969 and August 1972. The experiments involved the evaluation of equipment and techniques by the Civil Engineering Laboratory (CEL) at Port Hueneme, California. The Navy Seafloor Construction Experiment (SEACON) demonstrated a capability to construct operating facilities at the bottom of the ocean and pointed up deficient areas in the state of the art.

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equipment, foundations (structures), acrylic resins, hulls (marine), vehicles, windows, hulls (structures), anchors (structural), embedding, concrete structures, concrete, controlled atmospheres, undersea habitat atmospheres, penetration, corrosion, seawater corrosion, fouling, antifouling coatings, electric power, underwater, electric batteries, electric cables, mechanical cables, cables, electric connectors, underwater lights, underwater equipment.

Block 20. Continued

The focal point of the SEACON I experiments was the construction and evaluation of an unmanned, one-atmosphere concrete structure placed at the 600-foot site. Experimental evaluations of hardware and techniques for site selection and investigation, seafloor construction, and structural and electrical elements were coordinated with the year-long seafloor testing of the concrete structure. The construction site was investigated using tools operated from towed vehicles and manned submersibles as well as surface vessels. In-situ tests to determine short- and long-term settlement behavior of model footings were performed. These data were used along with laboratory test data and theoretical considerations to design the SEACON I structure foundation. The foundation performed approximately as predicted. A seafloor transponder navigation system was installed to accurately position the foundation. A wire guideline system was used to mate the structure with the foundation. NEMO, an acrylic-hulled manned submersible, dove to the SEACON I structure to evaluate NEMO's construction inspection capabilities. Structural elements evaluated included a 42-inch-diameter acrylic window, window cleaning hardware, waterproof paint systems, and experimental utility penetrators. Wet and dry high-power electrical connectors were successfully used to periodically power the structure for nearly one year; the wet connector was successfully mated underwater by divers. After 314 days on the seafloor the SEACON I structure was successfully refloated and towed back to Port Hueneme where analysis of its performance was made.

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SEAFLOOR CONSTRUCTION EXPERIMENT, SEACON I

AN INTEGRATED EVALUATION OF SEAFLOOR CONSTRUCTION EQUIPMENT AND TECHNIQUES

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CONTENTS

CHAPTER 1

INTRODUCTION

by T. R. Kretschmer

SUMMARY

The Navy Seafloor Construction Experiment (SEACON I) was conducted by CEL as part of the Deep Ocean Technology (DOT) Project, under the sponsorship of the Navy Facilities Engineering Command. SEACON I consisted of a group of interrelated seafloor engineering experiments which involved sea tests and evaluation of both equipment and techniques. The experiment culminated in the construction and evaluation of an unmanned concrete structure (Figure 1.1.1) on the seafloor beginning in August 1971. The experiments were performed in the Santa Barbara Channel, about 8 miles south of Santa Barbara, California, in 600 feet of water. After 314 days on the seafloor the SEACON I structure was successfully refloated and towed back to Port Hueneme where analysis of its performance was made.

OBJECTIVE

The purpose of SEACON I was to provide a visible demonstration of the capabilities for constructing a complex seafloor installation at a depth of 600 feet and to identify deficiencies in present seafloor construction technology. The ultimate goal of the SEACON series of experiments is to achieve a demonstrated capability for the construction of military seafloor installations such as described in the Deep Ocean Technology (DOT) Project Technical Development Plan (TDP) [1.1.1].*

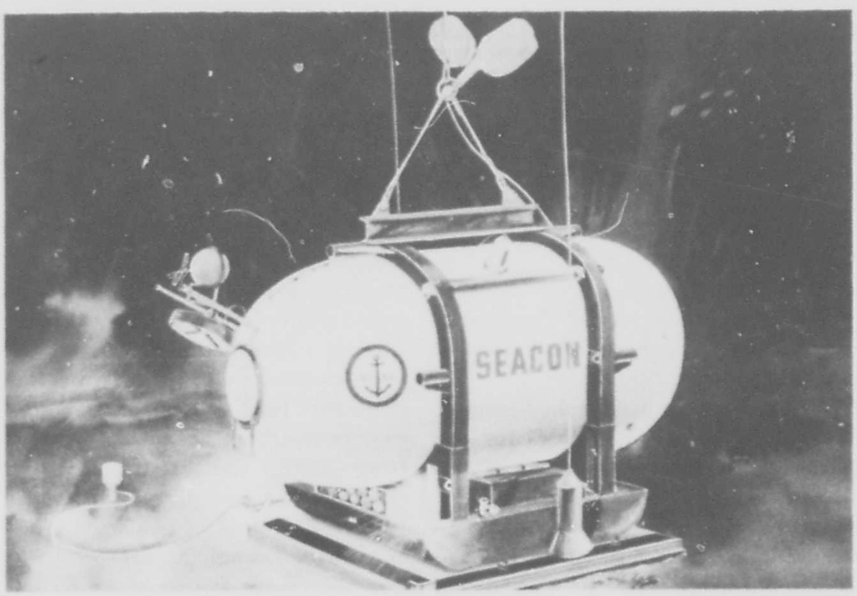

Figure 1.1.1. SEACON installation.

* Numbers in brackets refer to References listed in back of Report.

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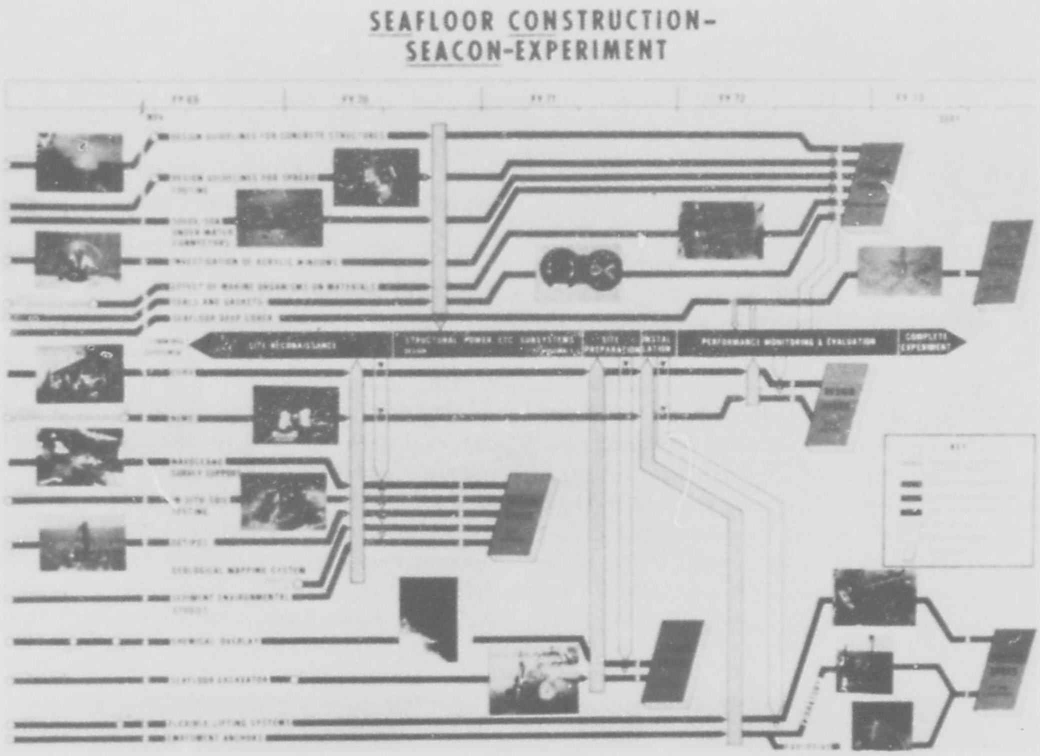

Figure 1.1.2. Relationship of ocean engineering work units to SEACON experiment.

BACKGROUND AND HISTORY

A series of seafloor construction experiments is required to periodically evaluate recent technological developments in seafloor construction and to determine critical deficiencies.

The SEACON task was outlined in the Technical Development Plan for DOT and provided for the development and demonstration of many of the technologies required for implementation of the Navy's plans as expressed in the Plan for Definition of NAVFAC/NCF Role in Ocean Engineering [1.1.2], the Navy Deep Submergence/Ocean Engineering Program (Proposed) 1970-1980 [1.1.3], and the Navy's role in the Exploitation of the Ocean (Project BLUE WATER) [1.1.4].

The SEACON task was established in October 1968 in response to a request from NAVFAC [1.1.5] to develop plans for a Seafloor Construction Experiment. A description of the SEACON project, along with preliminary plans and a cost estimate, was completed in January 1969 [1.1.6]. Criteria for selecting a construction site were established, and the Site Selection phase of the project was begun in December 1968. Experimental plans and funding requirements were submitted by project engineers in June 1969. Initially, the construction of the experimental installation was scheduled for April 1970. A deferment of funding in FY-70 delayed the construction until August 1971. The SEACON structure operated successfully on the seafloor for nearly 11 months and was recovered in June 1972.

APPROACH

Initial plans for the SEACON I experiment were formulated by reviewing all on-going work units in CEL's ocean engineering department to assess each one's stage of development and how it might contribute to constructing an installation in the seafloor. Plans for experiments were then solicited from work unit engineers; these plans were integrated into a system designed to evaluate the total process of constructing an installation on the seafloor using the latest developments in seafloor construction technology (Figure 1.1.2). Where possible, the individual experiments were designed so that if an experiment failed or was delayed it would not jeopardize the overall construction experiment.

Since the DOT project is primarily directed toward developing seafloor construction technology at depths greater than diver capability, the main emphasis in SEACON I was on developing and evaluating techniques which were not dependent upon divers except for near-surface functions, such as connecting and disconnecting handling lines.

ACKNOWLEDGMENTS

The authors wish to acknowledge the key role played by the CEL trades division personnel in the successful fabrication, seafloor construction, and recovery of the SEACON I installation.

SECTION 1

EVALUATION OF SITE INVESTIGATION TECHNIQUES FOR SEAFLOOR CONSTRUCTION

by M. C. Hironaka and J. R. Padilla

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OBJECTIVE

The objective of this phase of SEACON I was to evaluate surface-deployed site investigation techniques and then to conduct detailed surveys of the selected site.

INTRODUCTION

This section documents the site investigation aspects of SEACON I [2.1.1] performed off the coast of Southern California by CEL. The site survey was performed to collect data for designing the structure and for supporting other experiments, while simultaneously evaluating site survey techniques and equipment. The parameters investigated included meteorology, sea surface conditions, physical oceanographic, biological oceanographic, and geologic characteristics. This section includes all site surveying techniques used except those utilizing *DEEP QUEST*, *CURV*, and *TELEPROBE*; techniques utilizing these vehicles are discussed in Chapter 2, Section 3.

SITE CONSTRAINTS

The primary site criteria were:

1. Be within 40 miles of Port Hueneme
2. Have a minimum water depth of 600 feet
3. Seafloor be of cohesive sediments
4. Seafloor slope be less than 5%

The 40-mile criterion was established for logistic reasons. The minimum 600-foot water depth was selected in order to extend the state of the art in seafloor construction technology. Cohesive sediments were set as a criterion to provide a challenge for foundation studies.

PRELIMINARY SITE SURVEY

With existing bathymetric maps, nine potential areas located on relatively level ocean floors were identified; these areas are shown in Figure 2.1.1. Area 9 (San Clemente Island) did not meet all of the primary site constraints, but it was included as a potential area because of its proximity to logistic support from Navy-operated facilities on the island.

Areas 6, 7, and 9 were eliminated without collecting new data. The remaining six areas were subjected to reconnaissance surveys. The first reconnaissance survey, covering Areas 1, 3, 4, and 5, was conducted from the *USNS DAVIS* (AGOR-5) in

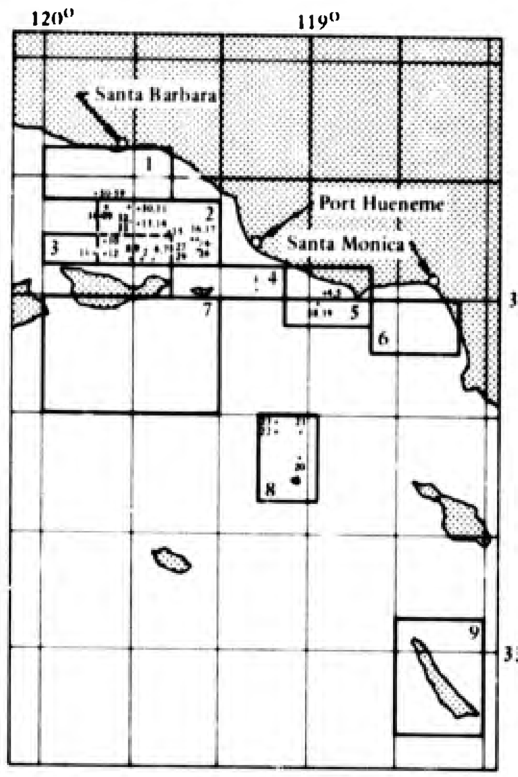

Figure 2.1.1. Locations from which each core sample listed in Table 2.1.3 was taken.

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Table 2.1.1. Tasks Scheduled for Cruise Aboard *USNS DAVIS* (AGOR-5) in December 1968

Area	Core Samples Obtained	Grab Samples Obtained	Underwater Photography	Standard and Velocimeter Probes	Satellite Navigation Use
Santa Barbara (1)	1	–	none taken because camera inoperative	none taken because of lack of time	system was inoperative
North Santa Cruz (3)	1	–			
Port Hueneme (4)	unsuccessful	1			
Point Dume (5)	2	–			

Table 2.1.2. Tasks Scheduled for Cruise Aboard *USS MUNSEE* (ATF-107) in May 1969

Area	Core Samples Obtained	BT Casts	Current Meter Measurements	Transmissometer Readings	Water Casts	Standard Casts	Topographic Survey
Santa Barbara Channel (2)	15	5	4	unsuccessful	1	5	no
North Santa Cruz (3)	7	5	4	unsuccessful (3 trials)	1	3	no
Point Dume (5)	2	1	1	unsuccessful	0	1	yes
Santa Barbara Island (8)	4	3	1	none tried	0	2	no

December 1968. A summary of the tasks scheduled to be performed on the cruise and the degree of success in completing each task are shown in Table 2.1.1. Although all the tasks scheduled were not completed, enough information was obtained for selecting a site. The LORAC B radio-navigation system stations were not transmitting during much of the time when the sediment samples were being taken; the positions of these samples were determined by radar.

The second reconnaissance survey was conducted from the *USS MUNSEE* (ATF-107) in May 1969. The objective of the cruise was to collect information on topography, sediment properties, current intensity, and water characteristics. Table 2.1.2 is a summary of the tests performed on this cruise. Problems were encountered with the LORAC B system on this cruise.

Table 2.1.3 is a summary of all the core samples taken in the above cruises and subsequent cruises as part of the survey for SEACON I. It can be seen that the only two sites possessing the required clayey sediments were the Santa Barbara Area (1) and the Santa Barbara Channel Area (2). These locations are plotted in Figure 2.1.1. Based on the analysis of the information collected on the cruises and the

Table 2.1.3. Summary of Core Samples Taken for SEACON Site Survey

Core No.	Latitude (N)	Longitude (W)	Water Depth (fm)	Core Length (in.)	Sediment Type	Potential Site
1	34°17.40'	119°43.50'	93	36	clayey silt	Santa Barbara (1)
2	34°06.00'	119°39.10'	96	21	sand	North Santa Cruz (3)
3	34°03.50'	119°13.80'	141	–	silty sand	Port Hueneme (4)
4	34°00.00'	118°56.80'	98	5	silty sand	Point Dume (5)
5	34°00.00'	118°56.35'	96	26	silty sand	Point Dume (5)
6	34°06.15'	119°37.3'	109	10	silty sand	North Santa Cruz (3)
7	34°05.85'	119°37.175'	100	18	silty sand	North Santa Cruz (3)
8	34°06.46'	119°42.38'	99	29	sand-silt-clay	North Santa Cruz (3)
9	34°06.42'	119°41.96'	98	15	silty sand	North Santa Cruz (3)
10	34°07.96'	119°47.60'	105	1.5	silty clay	North Santa Cruz (3)
11	34°07.18'	119°47.46'	106	2	silty sand	North Santa Cruz (3)
12	34°07.24'	119°46.98'	109	1	silty sand	North Santa Cruz (3)
13	34°12.50'	119°39.7'	83	none	–	Santa Barbara Channel (2)
14	34°12.3'	119°39.6'	100	3	silty sand	Santa Barbara Channel (2)
15	34°11.4'	119°35.4'	90	15.5	clayey silt	Santa Barbara Channel (2)
16	34°09.4'	119°28.4'	103	8	sand	Santa Barbara Channel (2)
17	34°09.25'	119°28.3'	113	6	sand	Santa Barbara Channel (2)
18	33°59.44'	118°58.975'	98	none	–	Point Dume (5)
19	33°59.78'	118°58.55'	90	16	silty sand	Point Dume (5)
20	33°33.5'	119°01.5'	90	none	–	Santa Barbara Island (8)
21	33°37.2'	119°02.1'	100	7	sand	Santa Barbara Island (8)
22	33°35.8'	119°05.8'	104	none	–	Santa Barbara Island (8)
23	33°39.5'	119°05.4'	91	2	sand	Santa Barbara Island (8)
24	34°08.5'	119°25.1'	104	none	–	Santa Barbara Channel (2)
25	34°08.35'	119°24.7'	102	none	–	Santa Barbara Channel (2)
26	34°08.45'	119°24.45'	100	none	–	Santa Barbara Channel (2)
27	34°09.4'	119°27.7'	100	8	sand	Santa Barbara Channel (2)
28	34°09.45'	119°27.4'	100	none	–	Santa Barbara Channel (2)
29	34°09.55'	119°27.3'	91	6	silty sand	Santa Barbara Channel (2)
30	34°14.03'	119°39.28'	98	21	sandy silt	Santa Barbara Channel (2)
31	34°14.12'	119°39.01'	97	30	silty sand	Santa Barbara Channel (2)
32	34°14.85'	119°40.78'	102	37	sand-silt-clay	Santa Barbara Channel (2)
33	34°14.93'	119°40.575'	101	38	sand-silt-clay	Santa Barbara Channel (2)
34	34°14.81'	119°44.26'	100	3	silty sand	Santa Barbara Channel (2)
35	34°14.80'	119°44.85'	100	3	silty sand	Santa Barbara Channel (2)
36	34°14.61'	119°44.32'	100	3	silty sand	Santa Barbara Channel (2)
37	34°14.67'	119°44.52'	100	39	sand-silt-clay	Santa Barbara Channel (2)
38	34°14.61'	119°44.42'	100	none	–	Santa Barbara Channel (2)
39	34°14.64'	119°44.38'	100	39	clayey silt	Santa Barbara Channel (2)
40	34°14.68'	119°44.43'	100	39	clayey silt	Santa Barbara Channel (2)
41	34°14.54'	119°44.62'	100	27	clayey silt	Santa Barbara Channel (2)
42	34°14.56'	119°44.48'	100	27	clayey silt	Santa Barbara Channel (2)

continued

Table 2.1.3. Continued

Core No.	Latitude (N)	Longitude (W)	Water Depth (fm)	Core Length (in.)	Sediment Type	Potential Site
43	34°14.57'	119°44.44'	100	none	–	Santa Barbara Channel (2)
44	34°14.44'	119°44.39'	100	none	–	Santa Barbara Channel (2)
45	34°14.74'	119°44.41'	100	none	–	Santa Barbara Channel (2)
46	34°14.59'	119°44.50'	100	27	clayey silt	Santa Barbara Channel (2)
47	34°14.67'	119°44.52'	100	none	–	Santa Barbara Channel (2)
48	34°14.68'	119°44.48'	100	15	silty sand	Santa Barbara Channel (2)
49	34°14.64'	119°44.37'	100	36	clayey silt	Santa Barbara Channel (2)
50	34°16.55'	119°43.07'	100	not recorded	not analyzed	Santa Barbara (1)
51	34°16.82'	119°43.10'	100	not recorded	not analyzed	Santa Barbara (1)
52	34°16.63'	119°43.18'	100	not recorded	not analyzed	Santa Barbara (1)
53	34°16.75'	119°43.20'	100	not recorded	not analyzed	Santa Barbara (1)
54	34°17.33'	119°42.85'	100	none	–	Santa Barbara (1)
55	34°17.15'	119°42.70'	100	none	–	Santa Barbara (1)
56	34°17.38'	119°42.98'	100	none	–	Santa Barbara (1)
57	34°17.23'	119°42.93'	100	not recorded	not analyzed	Santa Barbara (1)
58	34°17.05'	119°42.83'	100	not recorded	not analyzed	Santa Barbara (1)
59	34°17.18'	119°42.73'	100	not recorded	not analyzed	Santa Barbara (1)

information that was available in the literature, eight of the nine areas were eliminated for the following reasons:

Operational restrictions – Areas 1, 4, 6, and 7

Topography (>5 percent slope) – Areas 5, 7, and 9

Sediment type – Areas 3, 4, 5, and 8

Area 2 (the Santa Barbara Channel) was the final selection; Figure 2.1.2 shows its location. The sediments at the 100-fathom contour south of the knoll were found to be sandy, and the slopes were steeper than 5%. The remaining western portion of the area was inspected with *CURV II*, an unmanned, tethered submersible vehicle, in June 1969. This area offered good visibility and a practically featureless area of cohesive sediment. Therefore, the western portion of Area 2 was selected to be the site for SEACON I.

DETAILED SURVEY

Initial Site

The following tasks were performed in the detailed survey of the selected area:

1. Topographic survey with LORAC and fathometer aboard ship

2. Subbottom profiling with the shipboard sparker system

3. Magnetic intensity profiling with the shipboard magnetometer

4. Underwater photography

5. Core sampling:

   Ewing corer, six samples

   Hydroplastic corer, seven samples

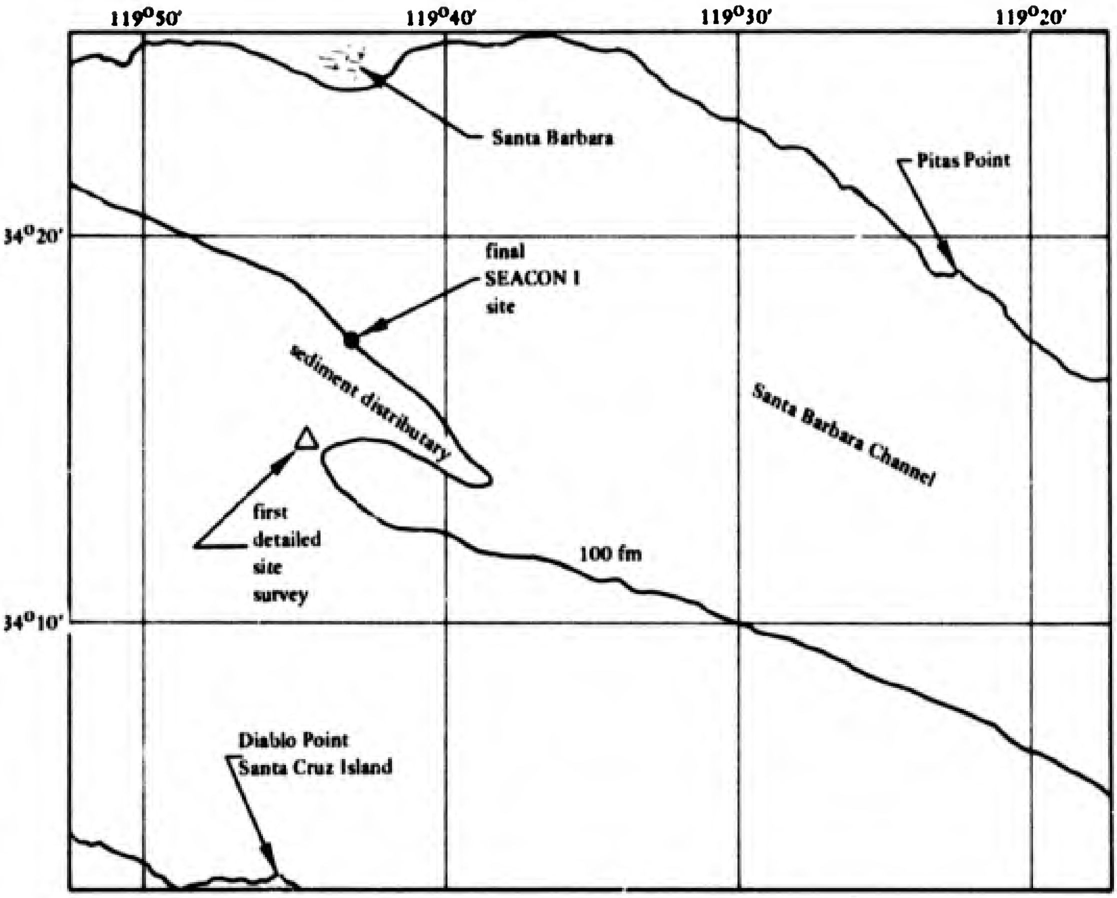

Figure 2.1.2. Location of SEACON I construction site.

6. Casts for water samples, two casts

7. Temperature measurements:

   Expendable BT, eight casts

   Mechanical BT, three casts

8. Current measurements, five deployments

9. Movie of surface survey operations

10. In-situ vane shear and cone penetrometer tests with the DOTIPOS

11. NAVOCEANO TELEPROBE checkout

Items 1 through 9 were conducted using the *USNS BARTLETT* (T-AGOR-13). Items 10 and 11 were performed from the *USS SUMNER COUNTY* (LST) and *USNS DE STEIGER* (T-AGOR-12), respectively. Problems with the LORAC positioning system were also encountered on the cruise with the *USNS BARTLETT*; it was necessary to return several times to Port Hueneme to recalibrate the system.

Revised Site

It was later learned that the site surveyed in the vicinity of 34°14'53"N by 119°44'25"W was approximately 1/2 mile inside of an existing oil lease. Permission was subsequently obtained to conduct SEACON I in the surveyed area, but it was decided it would be prudent if the experiments were conducted outside of the oil lease.

Therefore, the site was moved about 3 miles to the north, just inside of the south boundary of Area 1 (Figure 2.1.1). This final site (Figure 2.1.2) is 7-1/2 miles southwest (193°T) of Stern's Wharf, Santa Barbara, and is approximately 26 miles from Port

Hueneme. The geographical center of the 1,500-foot-square site is 34°17'12"N by 119°42'47"W. The site is plotted on the 100-fathom contour found on Coast and Geodetic Survey Charts 5120 and 5202; the LORAC coordinates for the center of the site are 89.1 Red, 757.56 Green; and it is within Block 50N, 67W of the U.S. Department of Interior, Bureau of Land Management Map No. 6B, "Outer Continental Shelf Leasing Map-Channel Island Area." The block was not under lease to any oil company.

The following surface ship survey operations were performed in the newly selected site.

1. Subbottom profiling – with NAVOCEANO 18,000-joule arcer and 3.5 kHz profiler

2. Topographic survey – with NAVOCEANO fathometer

3. Nansen water cast, two casts

4. Core sampling:

   Hydroplastic corer, three trials (core barrels split; no core recovered)

   Ewing corer, seven samples (2- to 3-foot cores)

5. Installation of current meter array

These operations were performed with the *USNS BARTLETT* on two cruises. On the first cruise, subbottom and seafloor topographic data were collected. It was estimated upon return to the LORAC calibration point at Port Hueneme Harbor that the survey work had been performed 2 miles from the location of the intended area; these first two operations were later repeated at the SEACON I site. Positioning was not a problem on the second cruise.

Information collected from the initial phase of the detailed survey showed that the site being investigated would be satisfactory for SEACON I. Survey operations were continued for the assessment of other parameters (Table 2.1.4).

Atmospheric Conditions

Wind data for the 1/2-degree quandrangle containing the SEACON I site are presented in Figure 2.1.3. The wind blows predominantly from the southwest in Santa Barbara. Between the construction site and Santa Barbara, the wind direction normally differs slightly, being more westerly at the site. Complete reversals in the wind direction are not totally unexpected during the early morning hours (from midnight to 0600); the winds are generally offshore rather than onshore during these hours.

The winds at the SEACON I site represent the strong constant winds west of Point Conception. These winds are diminished by the Santa Inez mountains. The winds from the west are generally stronger than those from the north and northwest and produce worse sea conditions because of the relatively unrestricted fetch.

Air-Sea Interface

Sea and swell information is presented in Figures 2.1.4 and 2.1.5 as a monthly average. Experience has indicated quite a latitude within any given month.

The sea and swell approach the site predominantly from the west and northwest directions. Seas from the southwest are experienced a small percentage of the time during the winter months. Maximum swell reaches 18 to 19 feet, but most of the time it is less than 5 feet. Seas can build to 20 feet in the Channel during storms, but these are infrequent enough to be of little concern.

Water Column

The water column information was obtained from instrumented arrays placed at the site by CEL in January 1970. This type of information was collected until the SEACON I structure was removed from the ocean floor. Oceanographic data taken from adjacent areas were obtained from the literature and from oceanographic cruises performed by NCEL during the site selection stages of the SEACON I experiment. Station data for the SEACON I site are discussed in Chapter 2, Section 2.

Frequent and unpredictable days of near zero visibility (<3 feet) on the seafloor construction site hampered inspection and working dives of manned and unmanned submersibles. The proximity of a trough, labeled Sediment Distributary on Figure 2.1.2, to the site may have been to blame. Drake et al. [2.1.4] demonstrated that much of the

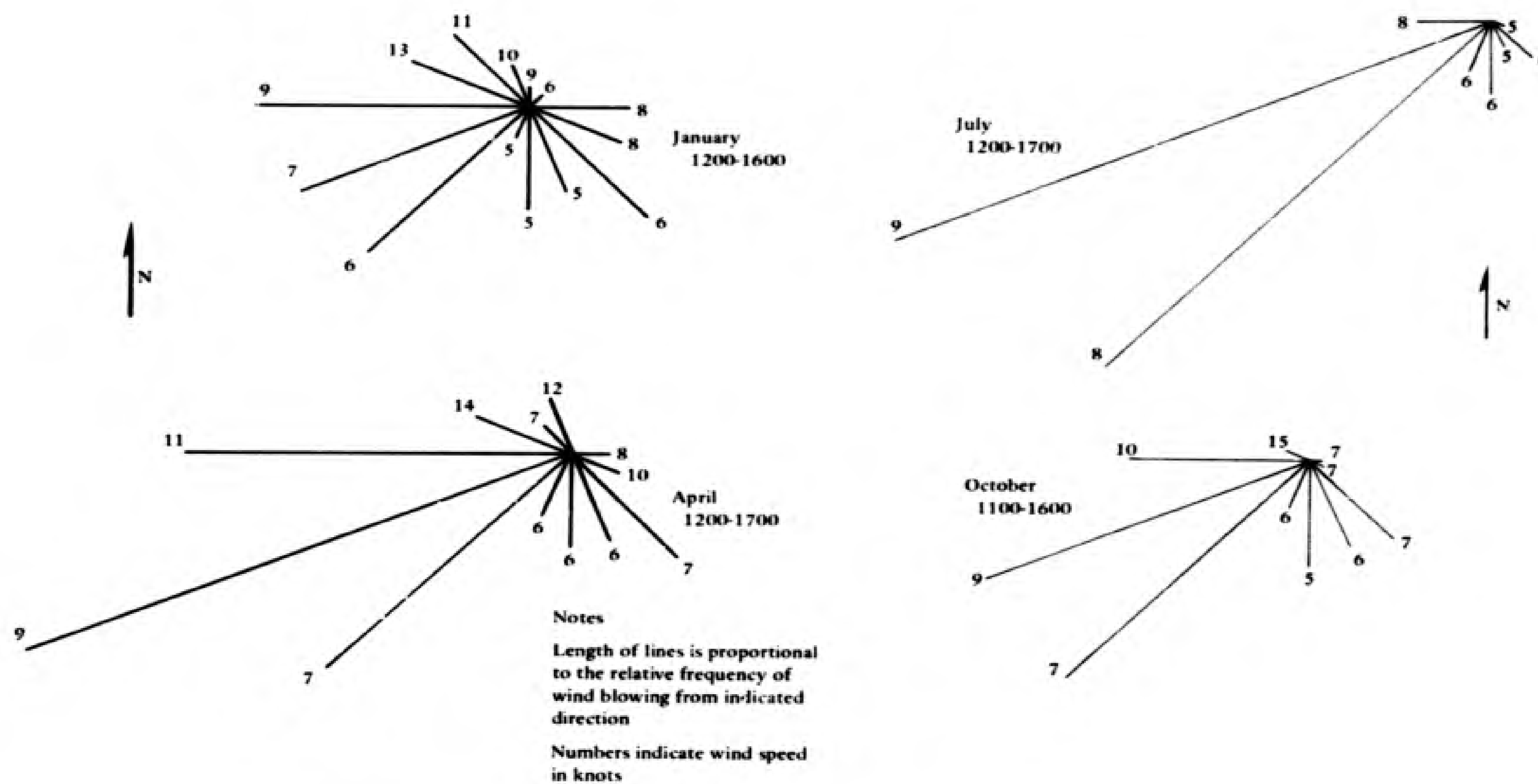

Figure 2.1.3. Wind rose for Santa Barbara [2.1.2]: (a) January and April. (b) July and October.

Table 2.1.4. Oceanographic Data Collected by CEL in 1968-69
for the SEACON Site

Depth		Temperature (^{o}C)	Salinity ($^{o}/oo$)	σ_t	Velocity (m/sec)	0_2 (ml/l)
Meters	Feet					
0	0	15.00	33.500	24.84	1505.5	6.5
15	49.20	13.11	33.396	25.15	1498.4	4.38
30	98.4	11.77	33.470	25.47	1495.3	3.99
45	147.6	11.21	33.546	25.63	1493.6	3.75
60	196.8	10.42	33.580	25.88	1491.05	3.43
75	246.0	10.37	33.746	25.93	1490.35	3.11
90	295.2	10.13	33.833	26.05	1490.95	3.12
105	344.4	9.69	33.887	26.15	1489.55	3.11
116	380.5	9.55	33.919	26.20	1489.20	2.75
132	432.9	9.39	33.975	26.28	1489.1	2.60
146	478.9	9.27	34.091	26.39	1488.8	2.37
152	498.5	9.20	34.112	26.41	1488.45	2.33
173	567.4	8.65	34.112	26.50	1489.95	2.14
189	619.9	8.43	34.113	26.54	1486.36	1.87

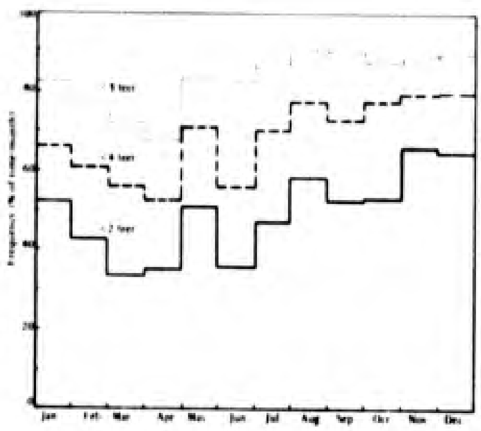

Figure 2.1.4. Sea states at SEACON I construction site [2.1.3].

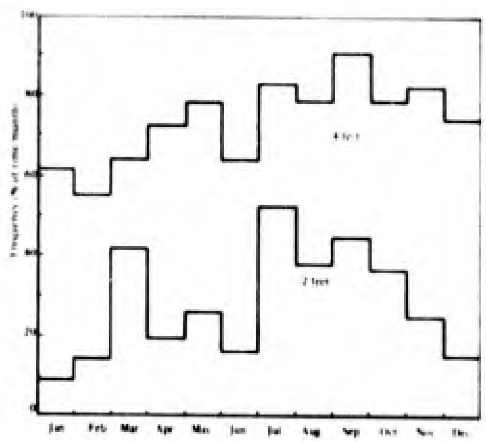

Figure 2.1.5. Sea state at SEACON I construction site [2.1.3]: percent of time per month swells are lower than 2 or 4 feet.

sedimentary fill of the Santa Barbara Basin by the Ventura and Santa Clara Rivers passes through this trough. The extent and duration of poor visibility caused by these aperiodic sediment flows cannot be forecast even though sediment conduits can be recognized topographically. By instrumenting the seafloor near well-defined sediment paths, it is possible that long-term transmissivity monitoring could divulge patterns that would correlate rainfall and sea state with sediment dynamics to permit the forecasting of visibility conditions on adjacent seafloors.

Current measurements made from three current meters placed at the construction site for 5-month periods are discussed in Chapter 2, Section 2.

Seafloor Topography

The bathymetry of the SEACON I site was determined by a conventional depth sounding survey. Approximately 15 nautical miles of tracklines (Figure 2.1.6) were run by the *USNS BARTLETT* (AGOR-13) during 27-28 January 1970. A standard Navy AN/UQN 60-degree beam, 12-kHz transducer was triggered at 1-second intervals, and the echo events were recorded on a Precision Graphic Recorder (PGR) operating at a sweep rate of 18 ips. Corrections were negligible for sound velocity, and no slope corrections were applied. Navigational control was provided by LORAC B.

Fathograms of the SEACON I area depicted a featureless surface sloping a gentle 2.0% (90 feet in 4,500 feet); a zone of slight flattening extended northwest to southeast across the site proper between the 99- and 100-fathom isobaths. This zone averaged 1.2% slope (6 feet in 500 feet) in the northwest corner to 1.5% (6 feet in 400 feet) in the southeast corner of the 1,500-foot-square site. Figure 2.1.7 shows a portion of the fathogram recorded along the trackline indicated in Figure 2.1.6.

Sediment Properties and Seafloor Structure

An olive-gray clayey silt was found at the SEACON I site. Data from the laboratory analysis of core no. 600-C-1 are presented in Chapter 2, Section 4.

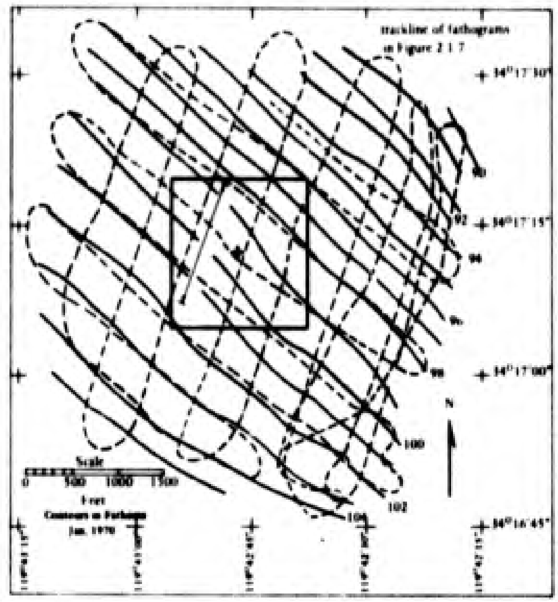

Figure 2.1.6. SEACON I site bathymetric map and depth sounding tracklines.

The subbottom structure at the site, shown in Figure 2.1.8, is composed of unconsolidated sediment to a depth of approximately 50 feet underlain by bedrock.

DISCUSSION

The use of the LORAC B positioning system in the site surveys created the most trouble. Problems were encountered with the system on five out of six of the cruises involved in site surveying. These problems originated from such sources as breakdown in the receiving units, changes in calibration, power failure aboard the survey ship, breakdown of the transmitting station, shutdown of the network by the operating organization, and procedural errors. Positioning is critical in site surveying, and these problems became serious ones in spite of the fact that the eventual site was only 8 miles from shore.

The equipment used to measure the various site parameters was adequate for the requirements of SEACON I with the possible exception of the coring capability. The Ewing and Hydroplastic corers were only able to obtain a maximum sample length of approximately 3-1/2 feet. This sample length was not

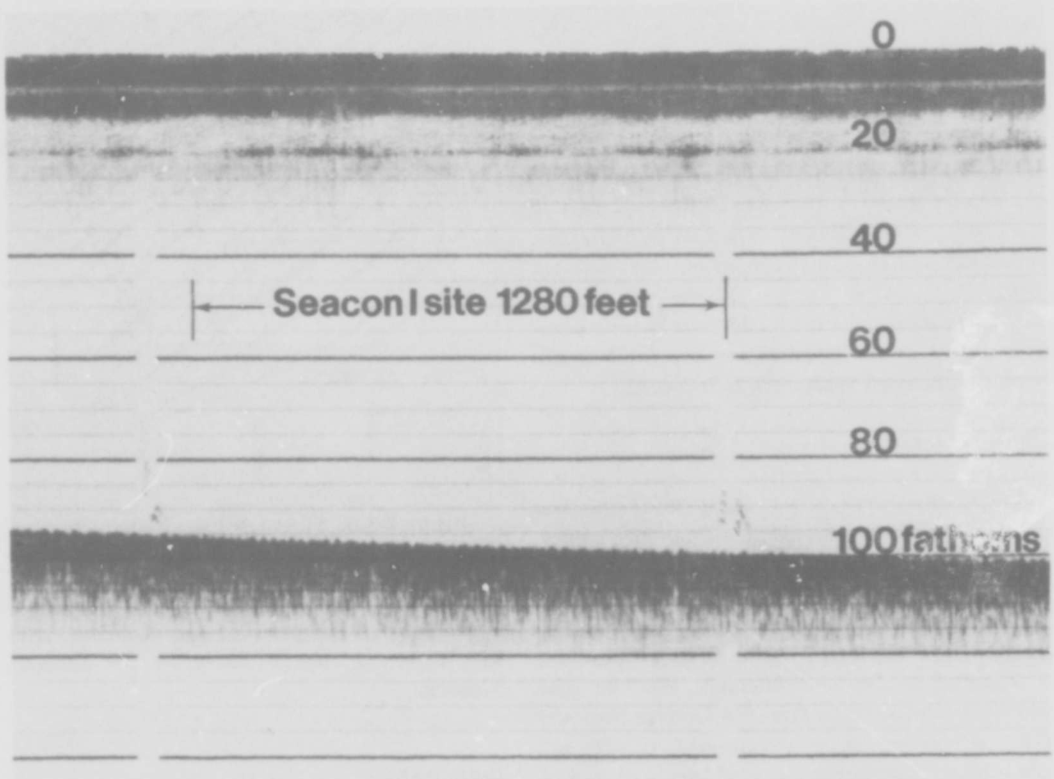

Figure 2.1.7. Fathogram recorded along trackline indicated in Figure 2.1.6.

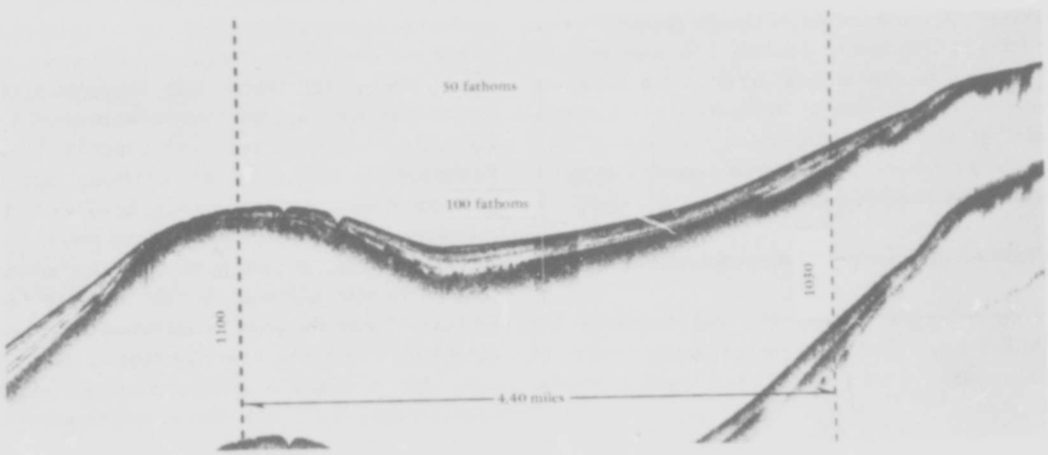

Figure 2.1.8. Record of subbottom structure at SEACON I site obtained with a 3.5 kHz profiler (ship course 220 degrees, sweep rate 1/2 second, *USNS BARTLETT*, 6 May 1971).

adequate for the design of the foundation on which the SEACON I structure was to be placed. It was desirable to obtain a 20-foot undisturbed sediment sample, but there is no equipment which can consistently do this. The DOTIPOS coring device obtained a sample about 7-1/2 feet long; this is an improvement over the gravity corer, but still is less than desirable. A corer designed to take 50-foot undisturbed cores has recently been developed and is scheduled to be tested at sea in October of 1974.

Long-range weather forecasting from the Pacific Missile Range was used extensively. Among the environmental parameters having a major effect on the program, the greatest deficiency was in the prediction of wind and sea state conditions at the site. This is understandable, since weather data are not regularly collected west of the construction site, and the weather approaches from the west.

CONCLUSIONS

1. The site survey was adequate for SEACON I in spite of frequent equipment failures.

2. Problems were encountered with the LORAC B system (receiver or transmitter) on the majority of the site survey cruises. Such problems negated the value of some of the data collected on those particular cruises.

3. Site survey equipment was available to measure the parameters required for the SEACON I experiments, but its reliability generally needs improvement. However, there was no corer available which could recover a 20-foot undisturbed core from the SEACON I site.

4. Better ways are needed to predict visibility in the ocean.

RECOMMENDATIONS

Although sediment distributaries can be identified bathymetrically, the frequency and volume of sediment transport are difficult to predict even when core data are available. The SEACON I experiment suggested that the sediment clouds, which frequently caused poor visibility, had a causal relationship with river-deposited sediments, storm waves, and the proximity of a sediment distributary (in this case a well-defined trough). Additional research, such as instrumenting the seafloor with transmissometers, may provide the means for predicting poor visibility on the seafloor using readily available weather and sea and swell parameters.

SECTION 2

OCEANOGRAPHIC ARRAYS FOR MEASURING CONSTRUCTION SITE ENVIRONMENTAL PARAMETERS

by J. R. Padilla

OBJECTIVE

The objective of this project was to evaluate equipment and procedures for obtaining oceanographic parameters at potential construction sites. In addition, it was to provide the other SEACON experiments with data on important oceanographic parameters at the construction site.

INTRODUCTION

Most site selection surveys are performed in two phases: preliminary and detailed [2.2.1]. Generally, a preliminary survey is performed to obtain data on several candidate sites. With most ocean construction sites, available data from the literature are insufficient to solve engineering design problems. Therefore, specific environmental data for the chosen site are collected in the second phase of the survey. For the SEACON site [2.2.2], very few recorded data existed on the environmental parameters that affect the design and the performance of the installation. This section deals with the equipment and procedures used to obtain environmental data at the SEACON site.

The speed and direction of the surface water current at the construction site were desired to predict when and how surface operations would be performed. Long-term data had to be collected to determine the optimum time of year to perform critical surface operations and to know what to expect at any time throughout the year that the experiment was in progress.

Currents also had to be known at the seafloor to determine the foundation and structural designs. Scour calculations rely on current speed data, and current velocities are needed to determine the optimum orientation of the structure on the bottom. The current pattern throughout the water column, or current profile, affects the lowering operations and the positioning tolerances required during construction.

Current meter arrays were designed with three current meters suspended in the water column to record current speed and direction over an extended time. An array was to be deployed for a 6-month period, then retrieved and refurbished. The data from it would be reduced and analyzed. The entire array would then be re-emplaced for another 6-month period. It was planned to collect data for at least 1 year prior to the SEACON structure's deployment in 1971 and throughout the year the structure was to be on the bottom.

The series of arrays was to collect as much oceanographic data as possible, with each array providing current speed and direction at a minimum of three depths. A meter that collects temperature, conductivity, and pressure data as well as current speed and direction was incorporated in one of the later arrays of the series. These data were collected at the seafloor only. The collecting of information concerning the biological activity at the site was provided by the arrays, as well as a means of obtaining materials performance data pertinent to the SEACON project.

ARRAY DESCRIPTION

Array Number One

The first array, deployed on 28 January 1970, consisted of three Richardson current meters programmed to record current speed and direction on film and on magnetic tape at 30-minute intervals for a 6-month period. The meters were placed at the bottom (182 meters), mid-depth (90 meters), and near the top of the array (15.5 meters below the surface). The array with the meters was suspended with an aluminum subsurface buoy and was held in place by a concrete anchor block as shown in Figure 2.2.1. Three-eights-inch wire rope was used between the meter mounting brackets. A 38-inch-diameter 6061-T6 aluminum buoy was sandblasted and painted

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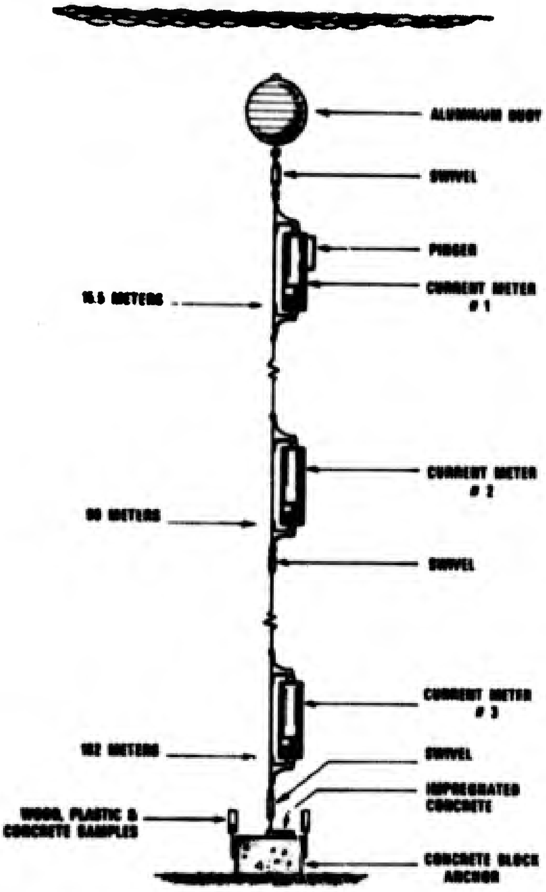


Figure 2.2.1. Schematic of oceanographic array no. 1 deployed at the SEACON I site from 28 January to 23 July 1970.

orange. The steel meter mounting brackets were sandblasted and painted with zinc powder paint. The concrete anchor block was used also to support test samples for biodeterioration and fouling studies. On this first array only one slab of creosote-impregnated concrete was tied to the lifting eye of the concrete anchor block.

Subsurface Buoy. Past experiences at CEL have shown that the lifetime of surface markers of any type is short, unless they are of such a size that premature removal from the site would be difficult. Surface buoys have been carried away in storms, been stolen, or damaged by vandals. In addition, surface effects on the buoy could seriously affect the validity of the current data. Because of these factors, a buoy was installed 46 feet (14 meters) below the surface to suspend the array.

Pinger. A recall-type buoy, which pops to the surface when released acoustically, was considered a simple way of finding the subsurface array. However, once this type of system is triggered, the line must be recoiled, the release reset, and the buoy redeployed. This was considered too time-consuming and uneconomical for periodic monitoring of the array. Therefore, instead of recall buoys, a pinger which could be located with a diver-operated listening device was mounted in the array. This method was used with partial success. A 40-kHz pinger with sufficient battery capacity to last 1 year was fabricated at CEL and did operate successfully on this first installation.

Current Meters. The current meters were self-contained digitizing meters set to record data for 1 minute every 30 minutes. Two meters recorded the data on photographic film and one on magnetic tape. The film meters were placed at the top and bottom of the array and the magnetic tape unit at mid-depth. Although the meters are designed to be placed in-line, they were mounted in a bracket to lessen the chances of losing part of the array should a meter fail mechanically and pull apart during retrieval.

Concrete Block. A concrete block anchor was fabricated after all buoyancy calculations were made. The block was 2 x 2 x 3 feet, weighing 1,783 pounds in air and 1,015 pounds in water. A sample of concrete impregnated with an antifouling material was tied to the eye in the top of the block to evaluate a 6-month exposure at this depth.

Miscellaneous Equipment. Three-eighths-inch-diameter, 6 x 19 bright steel wire with a heavy grease coating was used. Eyes with thimbles were put in the ends of the two 260-foot lengths. Three-ton swivels were placed in the arrays, as shown in Figures 2.2.1 and 2.2.2. These permitted the buoy to rotate and the block to spin free when lowered without kinking any of the wire lengths.

Array Number Two

On 28 August 1970 the second array was deployed 1,000 feet from the site of the first array. Figure 2.2.3 shows the location of this array and the other two. This array was basically the same design as array number one, with a subsurface buoy, anchor weight, and the three current meters; however, after

Figure 2.2.2. Bottom current meter of array no. 2 connected to the anchor block by 3-ton swivel.

consultation with the current meter manufacturer, several steps were taken to improve its design.

Subsurface Buoy. One of the changes incorporated into the second array was to paint the subsurface aluminum buoy with zinc powder paint. Because gray is difficult to distinguish by divers, two 6-inch-wide (152.4-mm) white stripes were painted around the buoy.

Pinger. The CEL-fabricated pinger used on array number one was reinstalled on array number two (Figure 2.2.4). One month after the deployment of array number two, the pinger was inoperative; it was replaced by a 40-kHz Burnett pinger with sufficient battery capacity to last 1 year.

Current Meters. Severe corrosion to the current meters during the deployment of array number one prompted several changes to the design of array number two. The galvanic corrosion was so severe during the first 6-month deployment that various parts of the current meters had to be replaced and all of the other parts had to be refurbished. The steel mounting brackets and steel shackles that supported the aluminum current meter cases proved to be detrimental. The meters had small screw-in anodes installed, but they were ineffective against the galvanic corrosion set up between the case and the brackets (Figure 2.2.5).

Two approaches to the problem were incorporated in the later deployments. First, nonmetallic isolators were placed in the supporting eyes at the ends of the current meters, thereby preventing metal-to-metal contact between the current meters and the shackles. In addition, 4 x 1-1/2 x 1-inch military specification zinc anodes were screwed onto aluminum bars which, in turn, were bolted to the two end plates of the current meters providing added protection to the aluminum meter cases. These are shown in Figure 2.2.4. All external metallic components of the meter had to be in contact for the anode to work properly; therefore, paint and anodizing coatings were removed from the mating surfaces.

A strong copper base antifouling paint was used on the rotor and vane of the two upper meters to be deployed in array number two. The antifouling paint was added to the brackets around the rotor and vane of the top meter only.

Concrete Block. In array number two, brackets were added to the sides of the block so that additional samples of wood and acrylic materials could be attached.

Miscellaneous Equipment. The wire used in array number one was determined to be in adequate condition for re-use in array number two. Some growth was evident on the cable, but the corrosion was negligible. The 3-ton swivels were cleaned, greased, and reinstalled on array number two.

Array Number Three

The acquisition of a new digitizing instrument capable of recording current speed and direction, conductivity, temperature, and depth (CCTD) influenced the design of array number three. This time the changes were minor because of the good results obtained from array number two. The new meter was placed at the bottom of the array to obtain

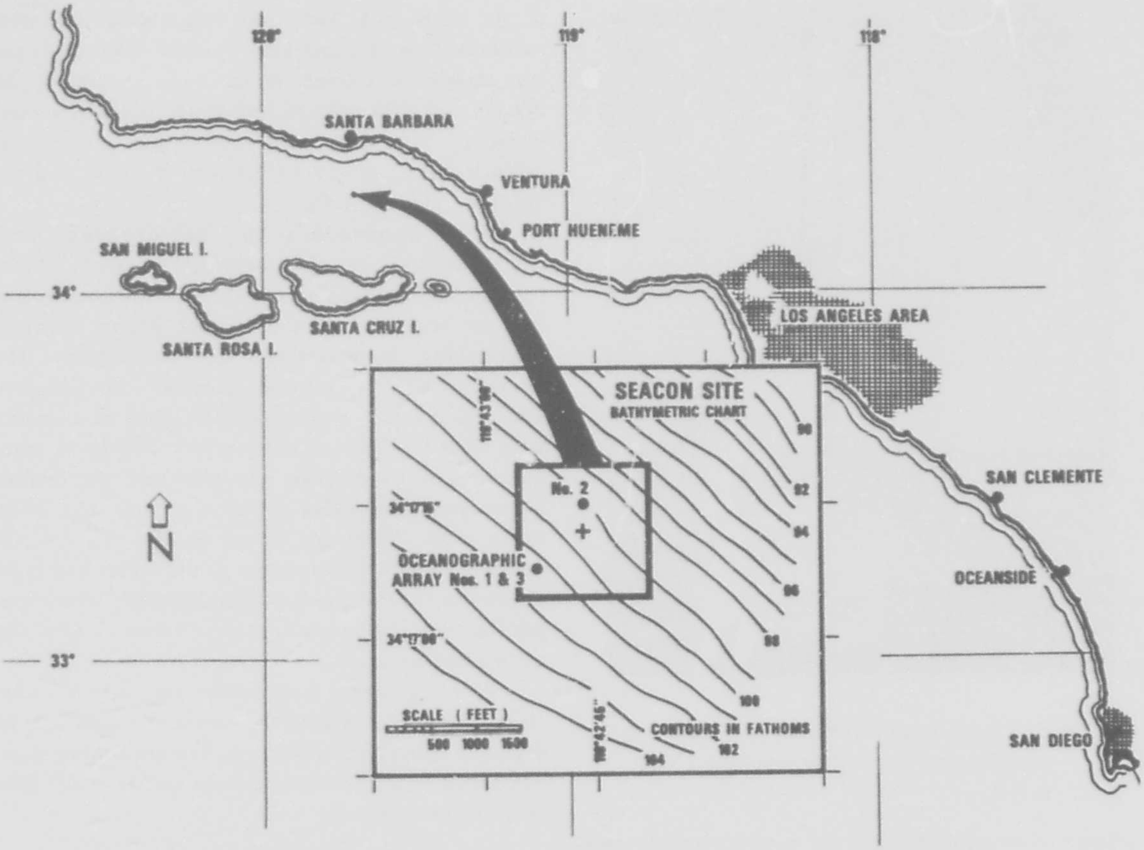


Figure 2.2.3. Map showing location of the three oceanographic arrays deployed in support of SEACON I experiments.

the additional parameters that would be of more value at this level. This meter was delivered with an anode mounted on one end of the meter; anodes were also attached to the ends of the stainless steel tie rods. The use of anodes on the tie rods is questionable, especially if they are designed to protect the tie rods from crevice corrosion failures under rubber standoffs. This meter was not mounted in the special bracket for the deployment, but the isolators were used to separate it from the steel hardware and wire.

The mid-depth and top meters were the same ones used previously. The two top meters were programmed to record data at 30-minute intervals for 208 days, and the new meter at 15-minute intervals for 240 days. The meters and the buoy needed no refurbishment other than a washing to remove the previous biological growth. Test panels of wood, ropes, plastic, acrylic, and concrete were again attached to the bottom concrete anchor block.

SEA OPERATIONS

Emplacement

The arrays were placed within the 1,500-foot-square SEACON I site so as not to interfere with the other sea operations at the site. The first array was placed at 34°17'08"N, 119°42'53"W on 28 January 1970 from the *USNS BARTLETT* (T-AGOR-13) and was not disturbed during the 6-month period. The array was checked periodically by divers locating the pinger and swimming to the

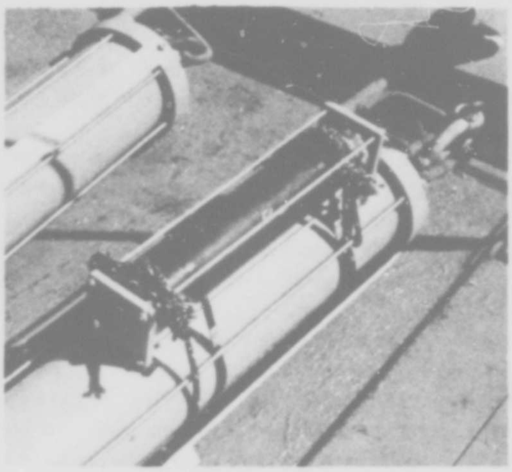


Figure 2.2.4. Location pinger fastened to the shallow current meter of oceanographic array no. 1.

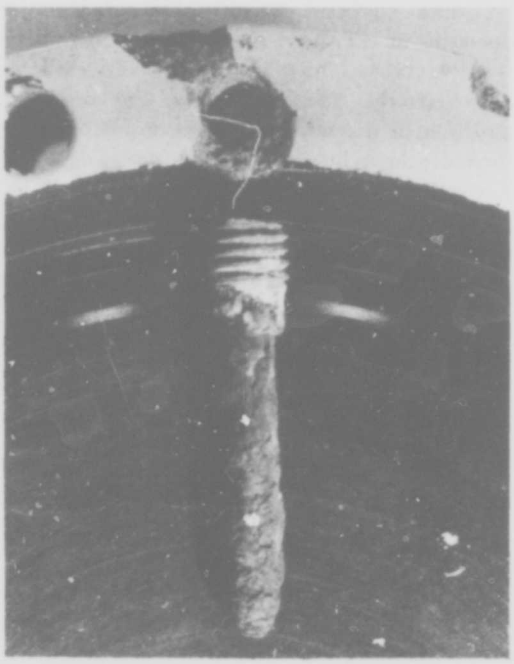


Figure 2.2.5. Impurities in sacrificial anode of oceanographic array no. 1 reversed the galvanic cell and caused severe corrosion of aluminum parts.

subsurface buoy. Some difficulties were experienced in the initial attempts to locate the pinger, but after the divers obtained more practice using the locator, the operation went smoothly.

Array number two was placed within the SEACON site on 28 August 1970 from the CEL warping tug. The array was placed at 34°17'15.5"N, 119°42'47.5"W, as shown in Figure 2.2.3. The array was not disturbed during its deployment except to change the pinger. The original intent was to leave the array for a 6-month period, but its location prompted early retrieval so as not to interfere with scheduled operations which were upcoming within the last 2 months of its deployment.

Since the emplacement of the SEACON I concrete structure was delayed, array number three was not deployed until 28 August 1971; it was deployed from the CEL diving boat (LCM-8) at 34°17'18"N, 119°42'53"W. A spar buoy of PVC pipe sections was installed which stood 5 feet above the surface. It was used as an aid for locating the array.

Recovery

Array number one was retrieved on 23 July 1970 after 181 days in the ocean. The CEL diving boat with a small 5-ton crane was used for the recovery. The entire array was retrieved, thereby providing valuable information about the environmental effects on materials as well as current data.

Array number two was retrieved with the CEL diving boat on 30 December 1970 after 124 days of operation. The entire array was retrieved, including the concrete block with the material samples.

Array number three was retrieved on 25 February 1972, 186 days after implant. Earlier attempts to retrieve the array were unsuccessful because divers could not locate the array by homing on the pinger.

RESULTS AND DISCUSSION

Corrosion and fouling data were obtained directly from the sample materials attached to the anchor block and indirectly from the meters.

Corrosion was a serious problem on the first array. All three meters experienced deep pitting due to the galvanic cell set-up between the steel brackets, wire, and array hardware and the aluminum meter cases. The screw-in anodes supplied with these meters failed to function. An analysis of the composition of these anodes showed them to be standard zinc castings with impurities rather than pure zinc, which may account for their poor performance. After properly isolating and cathodically protecting these meters they were essentially free of corrosion after being used on arrays two and three. The only other corrosion problems experienced were on the new CCTD. Upon retrieval, the rotor was found to be loose in its housing. A closer examination disclosed that the bearing on one end plate was missing. In spite of an anode being mounted on the outer side of this end plate, the area around the bearing corroded and the bearing fell out.

Fouling was detrimental to array number one as it caused the top meter's rotor and vane to stop rotating after 54 days. The application of antifouling paints on the rotors, vanes, and housings eliminated the fouling problem on arrays number two and three.

The meters at the bottom and at mid-depth recorded current data for approximately 169 and 176 days, respectively, on array number one. The top meter recorded direction information indirectly for 108 days and speed data for only 44 days. The short records are a result of the rotor and vane fouling rendering them immovable. The indirect data for the current direction is a result of the offset orientation of the deployed meters (Figure 2.2.2). Although the vane could not turn, the whole meter could turn with a change in the direction of the current, and the resultant current direction was reduced from the compass data alone. Normally, the compass and vane data are added algebraically to obtain the resultant current direction.

Figure 2.2.6 shows the distribution of current speed and direction of the first 6-month deployment. The similarity of the three direction curves indicates the subsurface current to be generally to the northwest, coinciding with the direction of the bottom contours at this station (Figure 2.2.3). The data at the bottom show a greater variability of direction, but this is attributed to the very low velocity flow. (The direction vane on these meters acts erratically and tends to oscillate in low velocity regimes; on the other hand, in flows of 0.3 knot or greater, the vane will remain relatively steady in the flow direction.)

Figure 2.2.7 shows the distribution of current speed and direction of the second deployment. The data are similar in speed and direction to array number one. The rotor on the bottom meter failed to function, so no speed data were recovered for this instrument.

No current data were obtained from the CCTD on array number three because of problems encountered with the recording head of the self-contained magnetic tape recorder. As stated earlier, the rotor was found to be loose in its mount as a result of corrosion around the bearing which eventually fell out. The temperature and conductivity data from this instrument are shown in Table 2.2.1. Data for the upper two instruments in array number three are shown in Figure 2.2.8.

The surface current, observed from ships operating at the site during the deployment periods, was variable, but generally set easterly or southeasterly. The data show the predominant direction of the subsurface current measured at the three depths to be northwesterly. The surface current is wind driven from the west or southwest in the morning and west or northwest in the afternoon. This was the case during most of the on-site observations and is the usual wind pattern throughout the year [2.2.3].

Table 2.2.1. Temperature and Salinity at the 182-Meter Depth for a 6-Month Period

Month (1971)	Temperature Range (°C)	Salinity (°/oo)
September	9.15 to 9.55	34.65
October	8.95 to 9.65	34.75
November	8.75 to 9.55	34.50
December	8.45 to 9.45	34.55
January	8.45 to 9.75	34.50
February	5.15 to 9.45	37.0

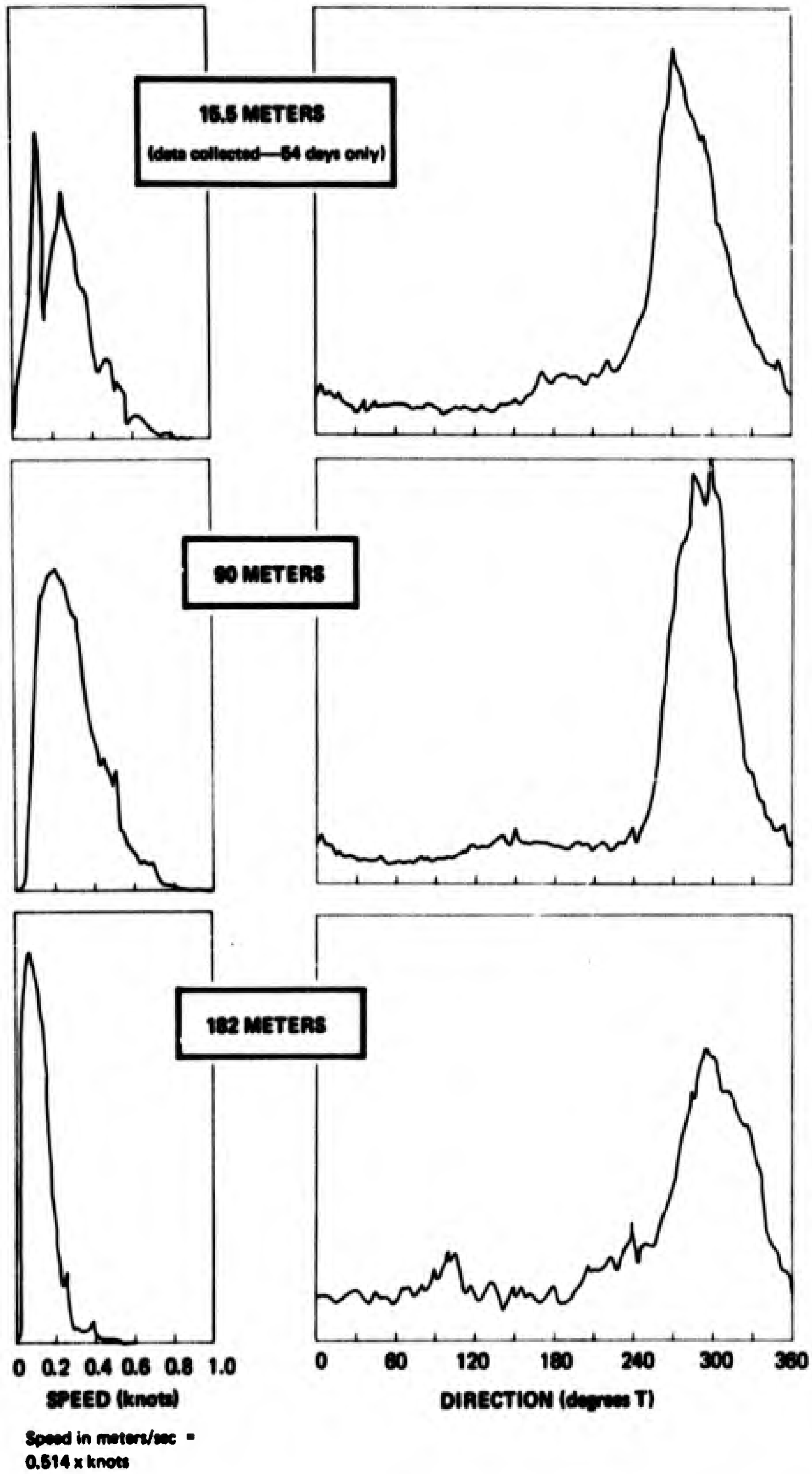


Figure 2.2.6. Relative frequency of current speed and direction values for three meters deployed for 176 days on array no. 1.

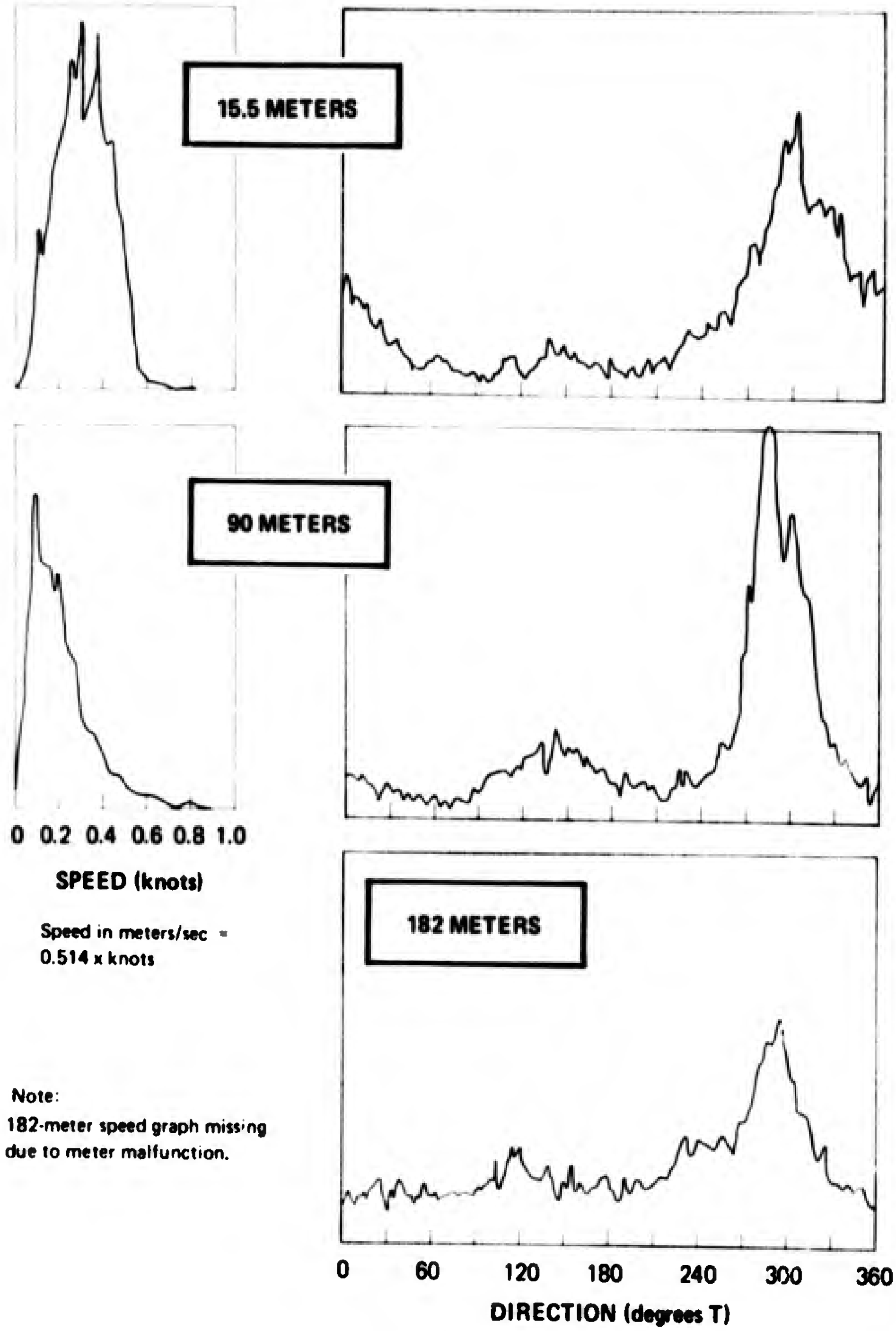
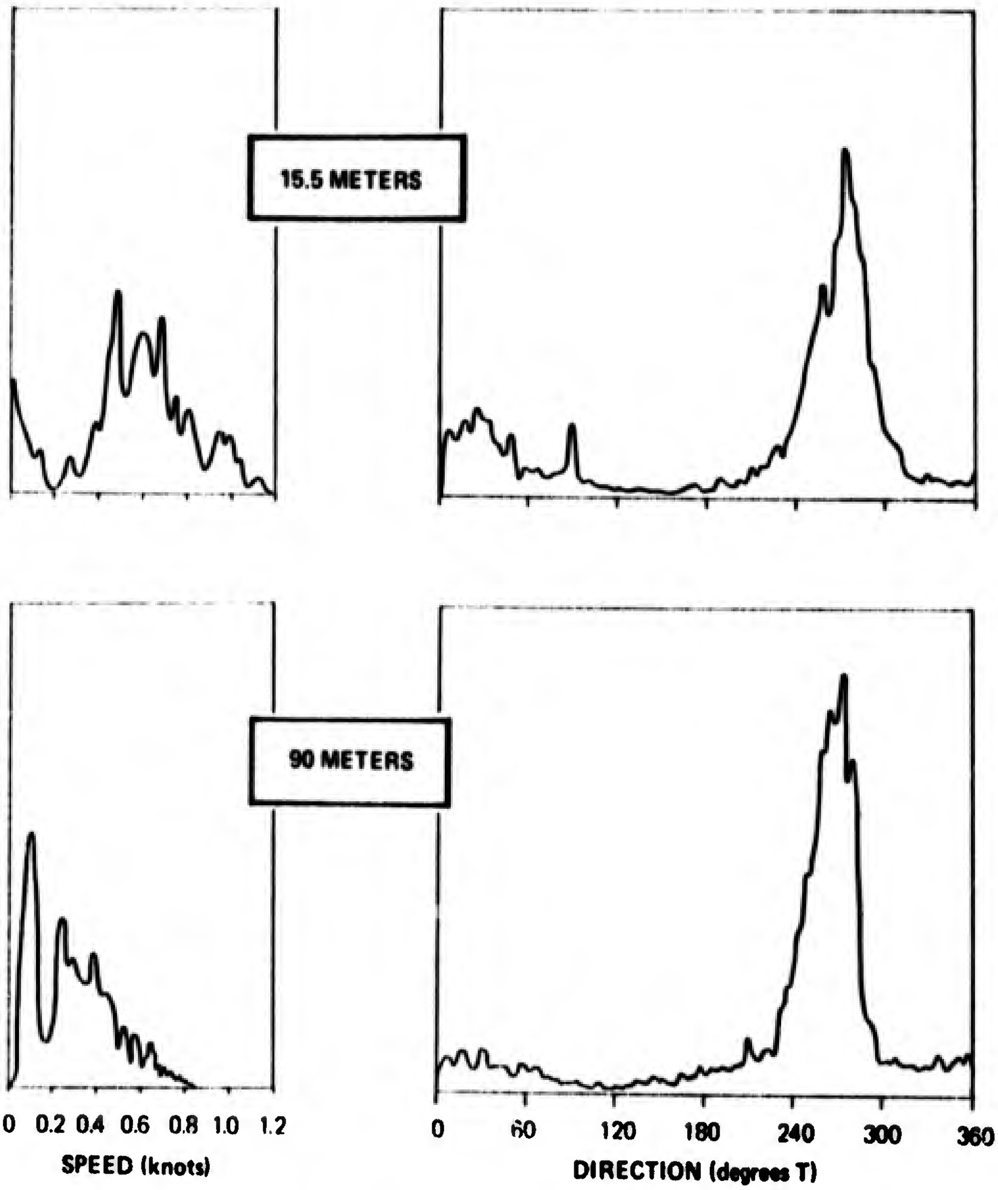


Figure 2.2.7. Relative frequency of current speed and direction values for three meters deployed 128 days at site no. 2, 8 August to 30 December 1970



Speed in meters/sec
0.514 x knots

NOTE: 182 meter speed graphs missing due to meter malfunction

Figure 2.-.8. Relative frequency of current speed and direction values for two meters deployed 185 days on array no. 2, 28 August 1971 to 25 February 1972.

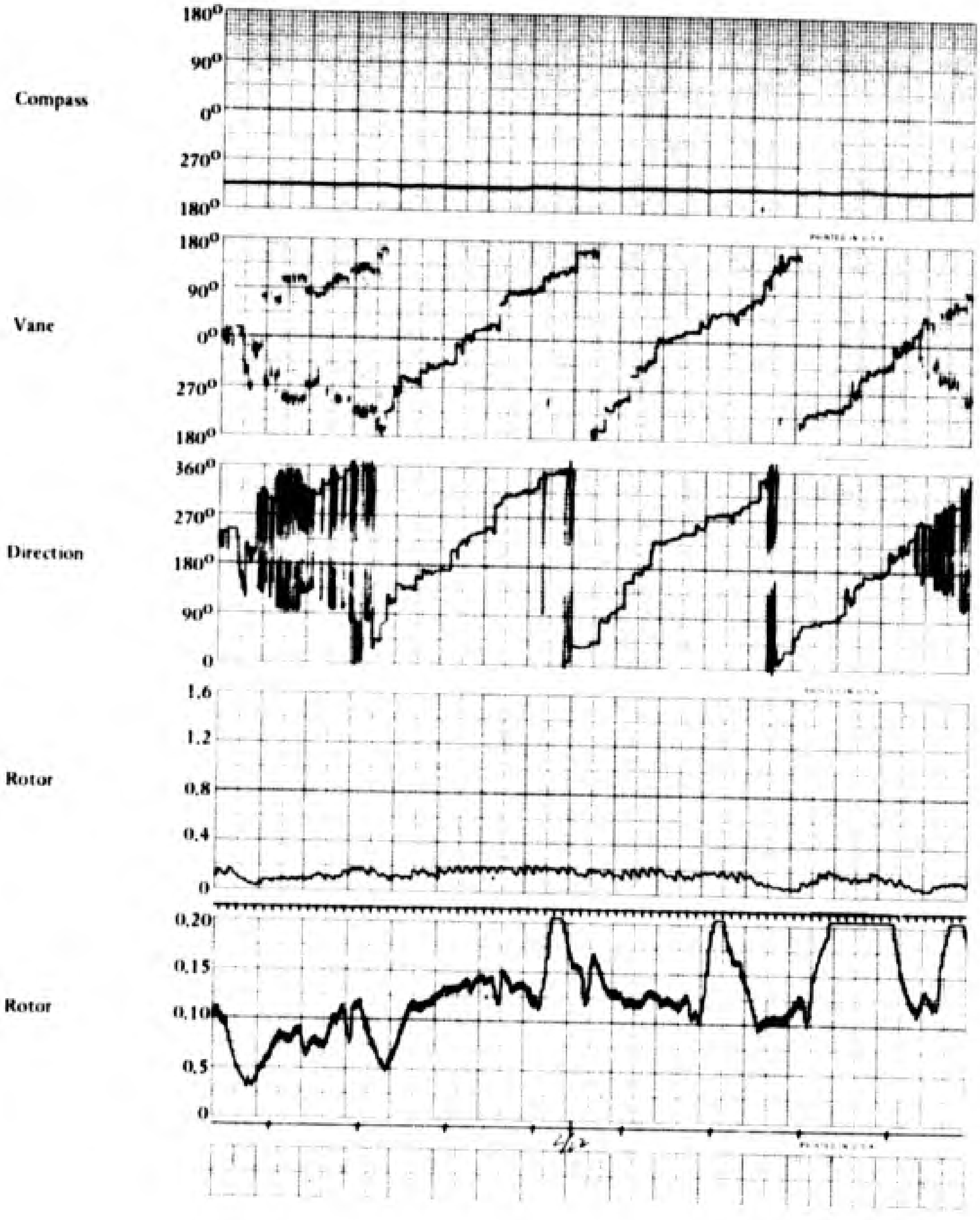


Figure 2.2.9. Strip charts of data from 182-meter instrument showing clockwise current rotation with 12-hour periods. Timing marks inked beneath rotor data are exposed at 1/2-hour and 5-hour intervals.

The strength and the duration of the wind-induced surface current are a possible explanation for the multipeaked velocity data for the top meter. The higher velocity peak is nearly coincident with the velocity peak at the mid-depth meter. The lower velocity peak could be the result of the flow being acted upon by the friction of the water above moving in the opposite direction. The bottom meter indicates a very low velocity flow, which is substantiated by the fine bottom material and the observation of suspended matter via TV and submersibles.

Another flow pattern is shown in Figure 2.2.9; it was taken from strip charts of the data for a bottom instrument. The direction data indicate movement of the current in a clockwise rotation with a 12-hour period. This phenomenon does not appear to occur regularly or for any specific length of time. It may, therefore, be a reflection of the juncture of the two main currents that enter the Santa Barbara Channel, further complicated by the 12-hour tidal period. One of the currents enters the Channel between Point Conception and San Miguel Island and establishes a fairly stable counterclockwise circulation cell in the western half of the Channel [2.2.4]. Another current enters the Channel between Anacapa Island and the mainland. This current sets northwesterly and extends a few miles west of the SEACON site; however, its nearby juncture with the counterclockwise circulation at the western end of the Channel probably complicates the current patterns at the SEACON I site.

The clockwise current rotation shown in Figure 2.2.9 may be in part inertial, but the repetition of periods of rotation approximating a one-half pendulum day (25 hours) is not apparent in the data.

CONCLUSIONS

1. The long-term measurement of oceanographic environmental parameters by a taut moor requires systems oriented design techniques.

2. Although current speed and direction data were the most important parameters measured, the information collected relating to corrosion and fouling proved to be useful, and it was collected at very little additional expense.

RECOMMENDATIONS

1. All long-term oceanographic moors should include corrosion prevention in their design.

2. Development research should be continued to improve the reliability of long-term current meter arrays.

SECTION 3

CONSTRUCTION SITE SURVEY WITH UNDERSEA VEHICLES

by John B. Ciani and R. J. Malloy

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OBJECTIVE

The purpose of this experiment was to evaluate the use of the undersea vehicles *DEEP QUEST*, *CURV II*, *NEMO*, and *TELEPROBE* for surveying the SEACON I construction site.

INTRODUCTION

Both manned and unmanned undersea vehicles have been suggested for surveying sites for seafloor construction [2.3.1]. Some deep-ocean research vehicles have as part of their standard equipment devices for mapping, observing, testing soil, and measuring oceanographic parameters [2.3.2]. Manned vehicles in particular have demonstrated their capability in survey operations [2.3.3].

Undersea vehicles were used in the SEACON I experiment to select a site, identify significant seafloor features, profile the unconsolidated sediment, measure oceanographic parameters, and determine the microrelief. These data were compared with those gathered by conventional surface techniques. Comparison was also made between types of vehicles.

The *CURV II*, shown in Figure 2.3.1, was the first undersea vehicle used in a survey capacity for SEACON I. It was supported by a medium yard tug (YTM 759) that handled the 13-foot unmanned vehicle over the side and also carried the van from which the *CURV II* was monitored and controlled. *CURV II* made the preliminary selection of the SEACON I site in June 1969. *TELEPROBE*, the 18-foot unmanned vehicle shown in Figure 2.3.2, was later employed at the same site in September 1969 to conduct site survey operations, including side-scan sonar and stereo photography. It was supported by an oceanographic research ship, the T-AGOR 12, *USNS DE STEIGER*. Early in 1970 the preliminary SEACON I site was abandoned because of impending oil drilling operations nearby, and a conventional surface ship survey was conducted at a new site 3 miles north. The *DEEP QUEST*, 40-foot-long manned submersible, was employed to survey the new site on the seafloor; it was supported by the surface vessel *TRANSQUEST* (Figure 2.3.3).

UNDERSEA VEHICLE SURVEYS

CURV II

Based on surface ship surveys, an area extending 6 miles along the 100-fathom isobath about 10 miles south of Santa Barbara was chosen within which a 1,500-foot-square site was to be selected using the *CURV II*. Seven dives were made between 11 June and 13 June 1969. The average length of each dive was 2-1/2 hours surface to surface for a total time underwater of 17-1/2 hours. Descent and ascent took approximately 15 minutes each for a total time on the bottom of 14 hours.

The operational equipment on *CURV II* included a crude nonrecording system to identify the location of *CURV II* during operations. A 37-kHz pinger was mounted on *CURV II*, and a directional hydrophone on the YTM was manually tilted in the vertical plane and panned horizontally until the strongest signal was heard through a pair of earphones and also read on a meter. The bearing (±10 degrees) and the vertical angle (±10 degrees) to *CURV II* from the YTM were read from the hydrophone control rod. It was estimated by the operators that the location of *CURV II* relative to the YTM could be determined within 100 feet.

Readings from a depth sensor mounted on *CURV II* were transmitted to the surface and read topside; the altitude of *CURV II* above the bottom was measured with a fathometer on the vehicle and read on the surface with an accuracy of ±1 foot. The water depth at the site was measured by the ship's

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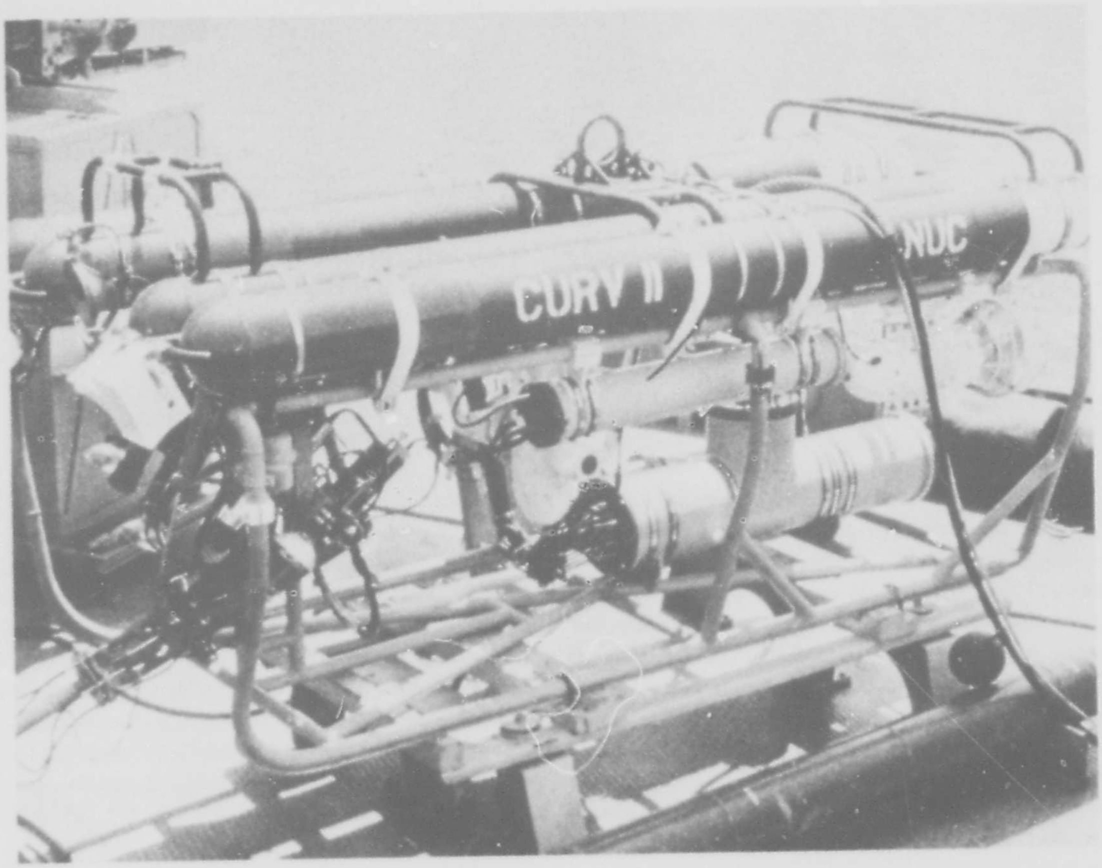

Figure 2.3.1. *CURV II* submersible vehicle.

depth sounder, and the length (usually twice the depth) of *CURV II* cable was measured as it was payed out. Small buoys were attached at appropriate intervals to the cable near *CURV II* for a given length (usually one half of that to be payed out).

If a target (active or passive) were used, a continuous transmission frequency modulated (CTFM) sonar (9 or 45 kHz) on *CURV II* would pick out the target, and its range and bearing from *CURV II* would be displayed on a cathode ray tube (CRT) topside. The television cameras on *CURV II* served as navigational aids by visually identifying the height of the vehicle above the bottom or its distance from a target.

Additional site survey equipment were added to the instrument complement on *CURV II*. Included were sediment corers and two types of sediment penetrometers, one cylindrical and one conical, carried in the claw. A LORAC positioning set was put on the YTM to determine position.

During the first four dives of this operation *CURV II* visited the seafloor between latitudes 34°14'N and 34°16'N, and between longitudes 119°40'W and 119°46'W to pick a site. Visual observations with the television, sonar search with the CTFM, and soil testing and sampling with the cylindrical penetrometer and the soil corer were made and photographs taken. It was found during these dives that the eastern part of this area had poor visibility and the middle part was partially rocky. The western part, which was finally picked, was found to offer the good visibility and cohesive sediment that

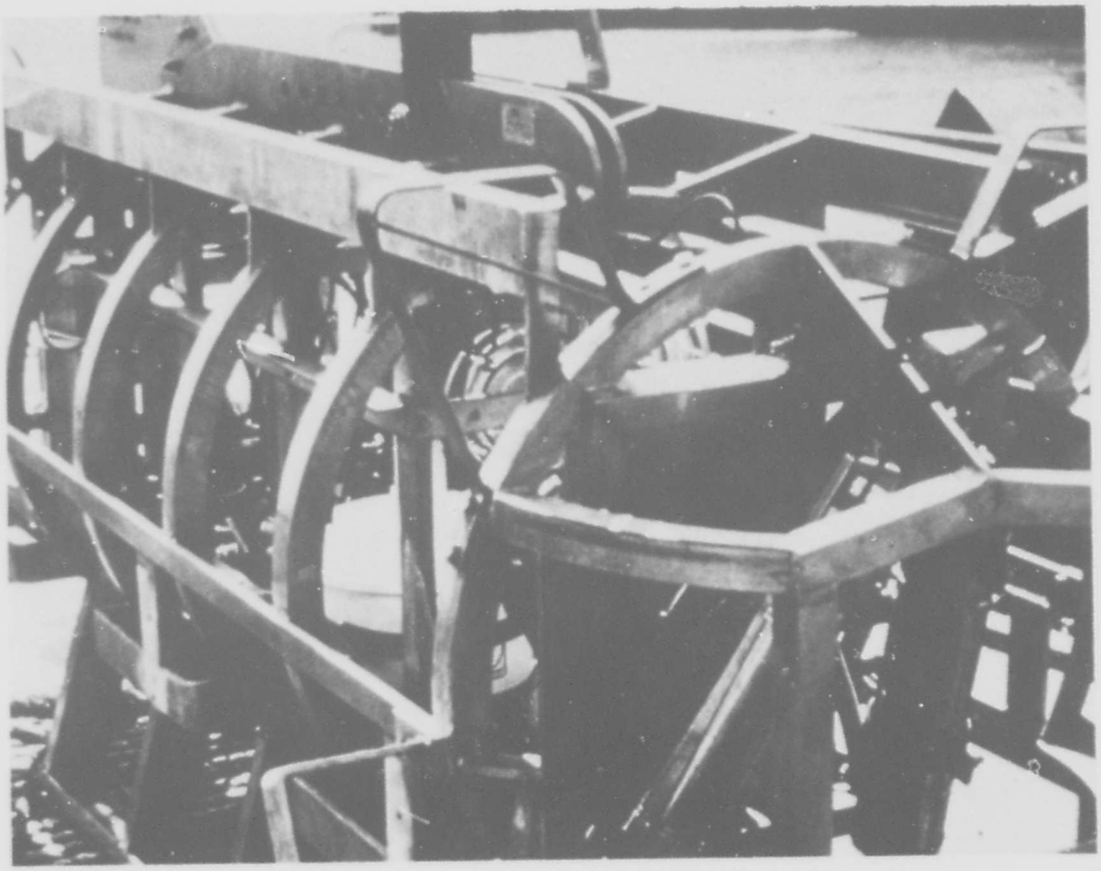

Figure 2.3.2. *TELEPROBE*, a near-bottom, towed vehicle.

were desired. The site selected was at 34°14'53"N, 119°44'25"W, and was marked with a passive marker made of two oxygen tanks welded together end to end. This marker, shown in Figure 2.3.4 was dropped from the YTM.

The next two dives involved surveying the 300-foot-radius area around the marker; this was done primarily with television and sonar. Penetrometer tests with the cylindrical device were made, and a sediment core was taken. The entire 1,500-foot-square area was then surveyed by television and sonar during the seventh dive. The cone penetrometer was also employed on this last dive.

These survey dives revealed that the 600-foot-diameter area surrounding the marker remained reasonably clear of turbidity in spite of all the *CURV II* movements. No features except for small depressions up to 1 foot in diameter and 2 inches in depth were detected by sonar or television, and the area was quite flat. Animal life consisted of equal numbers of urchins and sea pens at an average of 10 feet between individuals and occasional crabs and small fish, which probably produced the small depressions. There was very little trash (tires, cans, etc.) on the bottom. The 1,500-foot-square area centered on the marker was as featureless as the 600-foot-diameter part, except that some rocks were exposed with attending animal life near the southwest corner, and that some small knolls were found near the northeast corner. Turbidity and reduced visibility were noticed when *CURV II* passed over a course for a second time.

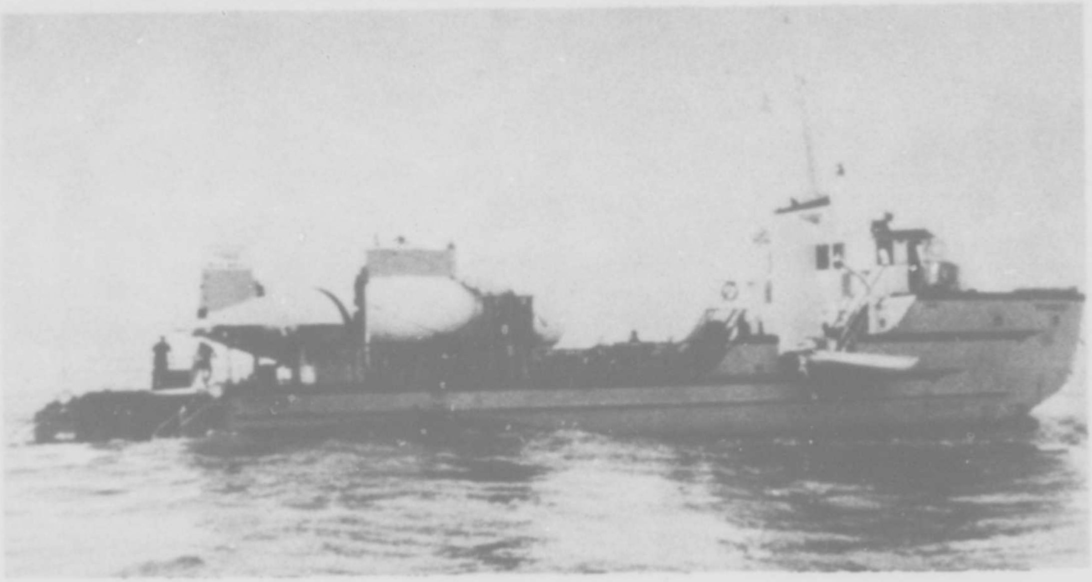

Figure 2.3.3. *DEEP QUEST* aboard *TRANS QUEST*.

Figure 2.3.4. SEACON I site marker viewed from *CURV II*.

TELEPROBE

The *TELEPROBE* vehicle was undergoing sea trials in Southern California at the time of the SEACON I site survey. Therefore, it was convenient for the *TELEPROBE* to try its side-scan sonar and stereo-photography capabilities at the SEACON site. Since it was an excellent opportunity for CEL to compare *TELEPROBE's* site survey capability with *CURV II's*, it was used at the preliminary SEACON site. It made six dives between 9 September 1969 (when the support ship arrived on site) and 18 September 1969 (when the support ship departed the SEACON I site) after spending 10-16 September in port for repairs. The average length of each dive was 4 hours surface to surface for a total underwater time of 24 hours. Descent and ascent took about 15 minutes each for a total bottom time of 21 hours.

The *TELEPROBE* equipment used for this operation was the side-scan sonar and the stereo-photography instruments. The *TELEPROBE* concentrated on the preliminary site selected after the *CURV II* operation. It made dives when the approximate location of the can marker was reached on the surface as determined by LORAC.

The dives confirmed that the preliminary SEACON I site was virtually featureless. The photographs showed the same sparsely populated flat seafloor found by *CURV II*. The side-scan sonar records showed larger depressions than *CURV II* revealed; these appeared to be up to 20 feet in diameter.

DEEP QUEST

The site finally selected for SEACON was surveyed by *DEEP QUEST* as part of an operation planned by the Naval Oceanographic Office to demonstrate the surveying capability of a completely instrumented, manned submersible as described by Busby [2.3.4]. Twelve dives were made between 10 April and 16 May 1970 with an 18-day interruption for submersible and instrumentation repair. The total underwater time logged by *DEEP QUEST* during the actual surveying operation was about 73 hours for an approximate average length of dive of 6 hours surface to surface. Weather conditions on six dive days prevented *TRANSQUEST* from recovering *DEEP QUEST* at the SEACON I site; the submersible had to be towed or travel under its own power toward Santa Barbara so that it could be retrieved.

Unlike *CURV II* and *TELEPROBE*, most of the information gathered by *DEEP QUEST* was read by the four men (pilot, navigator, and two observers) in the submersible. Only submersible position was monitored topside with an over-the-side hydrophone which received signals from a 37-kHz pinger on the submersible. The position of the surface vessel was determined by LORAC. A two transponder navigation net allowed the *DEEP QUEST* to monitor its own position relative to established points on the seafloor using CTFM sonar. With this navigation system survey grids were run and data were taken at points of known relative position.

The *DEEP QUEST* was equipped with many site survey devices. Television was unnecessary because the observers were on site, but records were made using two 35-mm and two 70-mm cameras and strobes. Side-scan and subbottom profile sonar systems were also on board. Instruments to record oceanographic parameters included a water sensor pod, which displayed and recorded temperature, salinity, sound velocity, and depth; an ambient light meter; a light transmissometer which measured water clarity; dissolved oxygen sensor; and a current velocity meter. Although bad weather, poor visibility, and equipment failures plagued this operation, the flexible survey team obtained valuable data and demonstrated the unique capability of manned submersible surveying.

Figure 2.3.5. Seafloor at SEACON I site viewed from *DEEP QUEST*.

Figure 2.3.5 is one of the 3,600 photographs taken at SEACON I by the 35-mm cameras that were operated on dives 3, 4, and 5. The 70-mm cameras were operated only on dive 2. These photographs and observations revealed abundant animal life: brown and pink sea urchins, 2 to 3 inches across; orange and red sea cucumbers; pens; white anemones 1 to 2 feet high; 3- to 4-inch-long shrimp; and fish including eel-like fish (2 to 3 inches long), members of the Plaice family (2 to 6 inches long), bastoides (4 to 5 inches), dark gray and white rat-tailed sharks (1 to 1-1/2 feet), and smaller red and white fish resembling Bahamian squirrel fish which burrowed their tails into the soft sediment. The salinity on the bottom was determined to be 34.06 $^{0}/oo$; temperature, 8.5^{0}C; current, from the southeast at 0.05 to 0.1 knot; and sound velocity, 1,489.7 mps. Although the transmissometer never functioned, the observed visibility ranged from 3 to 12 feet on the bottom. The ambient light measurements were quite

Figure 2.3.6. Subbottom trace recorded by *DEEP QUEST*.

dependent on the hour of observation, but, in general, it can be said that light extinction at SEACON I was greater than that observed near San Clemente Island with the same equipment.

The photographs revealed no natural topographic relief greater than the tracks, burrows, and mounds made by the animal life. The side-scan sonar records showed very little except the 4- to 5-inch-deep skeg marks made by the submersible. Data on sediment strength was expected from photographs of concrete blocks placed at the site, but unfortunately oblique photos were impossible, and the downward shots could not show the amount of settlement. It was observed, however, that the sample foundation blocks which were not all level had settled 2 or 3 inches. The sediment, which was a light tan clay with some silt, was easily disturbed by the smallest organism, causing sediment clouds.

The subbottom records showed the soil to be approximately 50 feet thick (Figure 2.3.6). The 50-foot reflector had no dip unconformity, but this is expected in this Continental Slope province where bedrock strata typically conform to the overlying unconsolidated sediments. The differential pressure device, necessary for proper photo-interpretation, operated only on dives 2, 8, and 10. It was clear from these observations of the seafloor that the SEACON I site is composed of a planar surface of cohesive sediments which are thick enough to undergo long-term settlement.

FINDINGS

The site surveys conducted at SEACON I by submersibles were very valuable–first in selecting a site, then in making a detailed survey. A comparison of the site information acquired by submersibles and conventional surface ships reveals specific advantages for both data collection methods. The surface ship survey approach seems optimum for: (1) Large area topographic information, e.g., slope, obtained only from the surface using the datum of sea level. Obtaining this sort of information on the seafloor at this gradually sloping site was deemed inappropriate for submersibles; (2) Geologic profile data which were obtained both from surface ship surveys and by submersible. The surface ship data corroborated the depth to bedrock that the submersible records showed; (3) Oceanographic parameter measurement, although the spot measurements by the *DEEP QUEST* compared reasonably well with conventional surface ship measurement. These parameters, including temperature, salinity, dissolved oxygen, and sound velocity, vary only slightly between adjacent water masses. Submersibles may have an advantage for measuring the oceanographic parameters of current and light since these cannot be measured very well from the surface but are easily measured by a submersible with the proper equipment; (4) Reliability, which is improving for conventional surface ship measurement devices (the experimental submersible equipment used in the SEACON I surveys require more development and experimentation).

The submersible survey approach appears a better alternative for: (1) Photographic coverage–the submersible photographs taken at specially selected points were an excellent means of determining in-situ conditions within a few feet of marked points. Camera racks suspended from the surface provided only unselective and scattered shots, good only for making sample assessments of large areas; (2) Microtopography–this cannot be resolved by surface fathometers, but can be accurately observed and recorded from submersibles. The utility of the side-scan sonar was demonstrated by its ability to detect even the very small skeg marks on the seafloor; (3) Biological identification of the seafloor and near-bottom animal life–this was easy for trained oceanographers in the submersible viewing these creatures in their own environment. This work from surface ships would require either capturing the animals or obtaining their images on film, which has been described as being easier from submersibles than from surface-ship-suspended cameras; (4) Seafloor soil mechanics observations; these were accurately positioned with the submersible, although in-situ vehicle-assisted testing is not yet perfected.

A comparison of the costs of the submersibles used in the SEACON I surveying operations as a function of their capabilities is not possible because each vehicle was equipped differently to accomplish different tasks. Another reason that cost effectiveness cannot be determined on the basis of the SEACON I surveys is that much of the survey equipment used was under development and thus was not fully effective at the time.

CONCLUSIONS

1. The surface-ship survey was appropriate at SEACON I for determining large-scale topography, geologic subbottom features, water temperature, salinity, dissolved oxygen, and sound velocity.

2. The submersible survey was appropriate at SEACON I for photographic coverage, microtopography, biology, seafloor soil mechanics observations, water current, ambient light, and light transmissibility.

3. Surface-ship survey equipment is currently more reliable than submersible equipment.

4. Visual and sonar reconnaissance with unmanned submersibles like *CURV II* and *TELEPROBE* can be used for selecting a seafloor construction site once a general site area had been chosen.

5. Manned subemrsibles are a good means for thoroughly surveying a seafloor construction site.

SECTION 4

IN-PLACE SOIL TESTING AND SAMPLING FOR NAVAL SEAFLOOR CONSTRUCTION

by Robert J. Taylor

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OBJECTIVE

The objective of this experiment was to determine the applicability of a variety of techniques for obtaining and analyzing information on the engineering properties of marine sediments. These techniques will be employed to generate data for improving the Navy's ability to design and construct foundations for seafloor construction sites.

INTRODUCTION

Knowledge of the engineering properties of sediments at a construction site is essential for evaluating the mass stability of the area, for designing reliable foundations, and for devising construction procedures at the site. Equipment has been or is being developed that is capable of obtaining the needed information.

In-place tests were performed at the 600-foot-deep SEACON I site with the CEL-developed plate bearing device, the DOTIPOS-mounted stationary-piston core sampler, and the DOTIPOS-mounted vane shear and cone penetrometer devices. In addition, friction plate tests were performed with the plate bearing device. The in-place test data were reduced and analyzed, and laboratory analyses were performed on the stationary-piston core samples.

TEST APPARATUS

The Deep Ocean Test In-Place and Observation System (DOTIPOS) [2.4.1] was equipped with a stationary-piston core sampler and a vane shear and cone penetrometer tower to obtain in-place soil strength data to a depth of 10 feet. Plate bearing tests and friction plate tests were performed on the surface sediments with the plate bearing device [2.4.2].

DOTIPOS System

The DOTIPOS system is a remotely controlled bottom platform that has a lifting/transmission cable, command and readout components, and a winch system. Attached to the DOTIPOS platform are the stationary-piston coring subsystem and the vane shear and cone penetrometer subsystem.

Core samples up to 10 feet in length can be obtained with the stationary-piston core sampler. A polyvinyl chloride (PVC) coring tube was used; this reasonably meets Hvorslev's criteria [2.4.3] for an undisturbed soil sampler. The coring tube has a 4.50-inch outside diameter, a 4.05-inch inside diameter, and a double-beveled cutting edge. The area ratio is approximately 25%, which is close to Hvorslev's maximum allowable value. Penetration is achieved by mechanically pressing the coring tube into the soil at a rate of 2 ips with an electric motor and chain drive system.

The vane shear and cone penetrometer also has a sediment penetration capability of 10 feet [2.4.4]. A 2-inch-diameter steel rod is mechanically pressed into or withdrawn from the soil at a rate of 10 ipm by a jack screw and electric motor system; either a cone or vane may be attached to the end of the steel rod. For vane shear testing, an electric motor and transmission system rotates the steel rod at a rate of either 10 rpm or 1 revolution per hour (6 deg/min). Potentiometers are used to graphically and visually monitor displacement and rotation. A load cell is coupled to the bottom of the penetration rod to measure axial load or torque for the cone penetrometer or vane shear tools, respectively [2.4.4].

Plate Bearing System

The plate bearing device consists of a movable weight that presses a bearing plate or friction plate into the soil [2.4.2]. The movable weight is

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Table 2.4.1. Program for Core Samples and In-Place Tests at SEACON I Site

Core Samples

Sample No.	Core Embedment (in.)	Sample Length (in.)
600-C-1	108	96
600-C-2	108	72

Vane Shear Tests

Test No.	Soil Condition	Vane Width and Height (in.)	Maximum Depth of Vane Center (in.)
600-VS-1	Undisturbed	2-1/2 x 5	72
	Remolded		36
600-VS-2	Undisturbed	2 x 4	84
	Remolded		48

Cone Penetrometer Tests

Test No.	Total Embedment of Penetrometer (in.)
600-CP-1	100
600-CP-2	114
600-CP-3	113

Plate Bearing Tests

Test No.	Plate Diameter (ft)	Plate Area (ft^2)
600-PB-1	1.5	1.76
600-PB-2	1.5	1.76
600-PB-3	1.5	1.76
600-PB-4	1.0	0.787
600-PB-5	1.0	0.787
600-PB-6	1.0	0.787
600-PB-7	1.0	0.787
600-PB-8	0.5	0.196
600-PB-9	0.5	0.196
600-PB-10	0.5	0.196

Friction Plate Tests

Test No.	Plate Thickness (in.)	Bottom Width (in.)	Bearing Area ($in.^2$)
600-FP-1	0.75	0.75	18
600-FP-2	0.75	0.75	18
600-FP-3	0.75	0.75	18
600-FP-4	0.25	0.75	18
600-FP-5	0.25	0.75	18
600-FP-6	0.25	0.75	18
600-FP-7	0.25	0.75	18
600-FP-8	0.25	0.25	6
600-FP-9	0.25	0.25	6
600-FP-10	0.25	0.25	6
600-FP-11	0.25	0.25	6

supported and guided by a tripod frame with support pads. Vertical displacement is limited to 11 inches, and the displacement rate is controlled by three hydraulic cylinders. The equipment is operable to 14,000 feet and can apply a maximum load of 6,000 pounds to bearing plates up to 1.5 feet in diameter. Plate bearing resistance, plate displacement, and attitude of the device are sensed by transducers mounted to the tripod. This information is transmitted acoustically from the device to a hydrophone sensor mounted on the support ship. When a test is complete, the movable weight is reset automatically by lifting the device to a new position.

Three circular bearing plates and three friction plates were used in this test program; all were fabricated of structural steel. The bearing plates were 0.5, 1.0, and 1.5 feet in diameter and 1/2 inch thick. The friction plates resembled a vane shear tool with a diameter and height of 1 foot. However, the thickness of the friction plates varied significantly (one each at 0.25 and 0.75 inch, and one at 0.25 inch with a bottom lip 0.75 inch wide).

GENERAL TEST PROGRAM

At the 600-foot-deep SEACON I site two core samples were taken, and two sets of vane shear tests, three cone penetrometer tests, eleven plate bearing tests, and eleven friction plate tests were performed.

A program for core samples and sets of vane shear tests and cone penetrometer tests is presented in Table 2.4.1. The core recovery ratio (ratio of sample length to core embedment) was less than one for both samples. Since the piston was preset to function at or slightly below the soil-water interface, this ratio was due to a poor gasket seal between the piston and core barrel. (This was verified by the presence of water between the piston and the top of the core sample for both cores.) Vane shear data were obtained to a soil depth of only about 90 inches. This was caused by faulty welds on the vane shear tools, which caused the vanes to bend in the stiffer sediments. Fortunately, no difficulties were encountered with the cone penetrometer, and the problems with the piston cores and vane shear tools were easily corrected for future seafloor operations.

Cone penetrometer tests involve continuous penetration through 10 feet of soil; vane shear tests are performed at incremented depths (increment depending upon vane size and desired coverage). At each depth, the vane is rotated at 6 deg/min until failure. After peak shear, the soil is remolded by one revolution of the vane (10 rpm for 6 sec), and a remolded strength value is obtained by rotating the vane at 6 deg/min. A core sample was taken after each set of vane tests or series of cone tests, and DOTIPOS was returned to the ship's deck.

Information from the tests performed with the plate bearing device is also presented in Table 2.4.1. The displacement rate was adjusted to approximately 1 ipm for the plate bearing tests and 3 ipm for the friction plate tests. No equipment problems developed during the at-sea test trials. A detailed description of the operation and handling of the device is provided in Reference 2.4.2.

TEST RESULTS

Soil Properties

An olive-gray, clayey-silt exists at the 600-foot SEACON I site. According to the Unified Soil Classification System, the soil is predominantly ML; however, two test increments had a marginal classification of MH and CL. Data from the laboratory analysis of core number 600-C-1 are presented in Figure 2.4.1. Between 12 and 36 inches the soil is nonplastic. The vane shear strength increases approximately linearly with depth except for an erratic weak shear value of 0.2 psi at a depth of 17 inches. Sensitivities of 3 to 4 predominate, which indicates a material of medium sensitivity.

The ratio of undrained shear strength to effective overburden pressure (c/p) decreases sharply to a depth of approximately 15 inches and then continues to decrease gradually to a depth of 84 inches. This behavior is typical of loosely deposited seafloor soils.

Vane Shear and Cone Penetration Tests

Only two sets of vane shear tests were performed at SEACON I, and the incremental test depths are not the same for both tests (Figure 2.4.2).

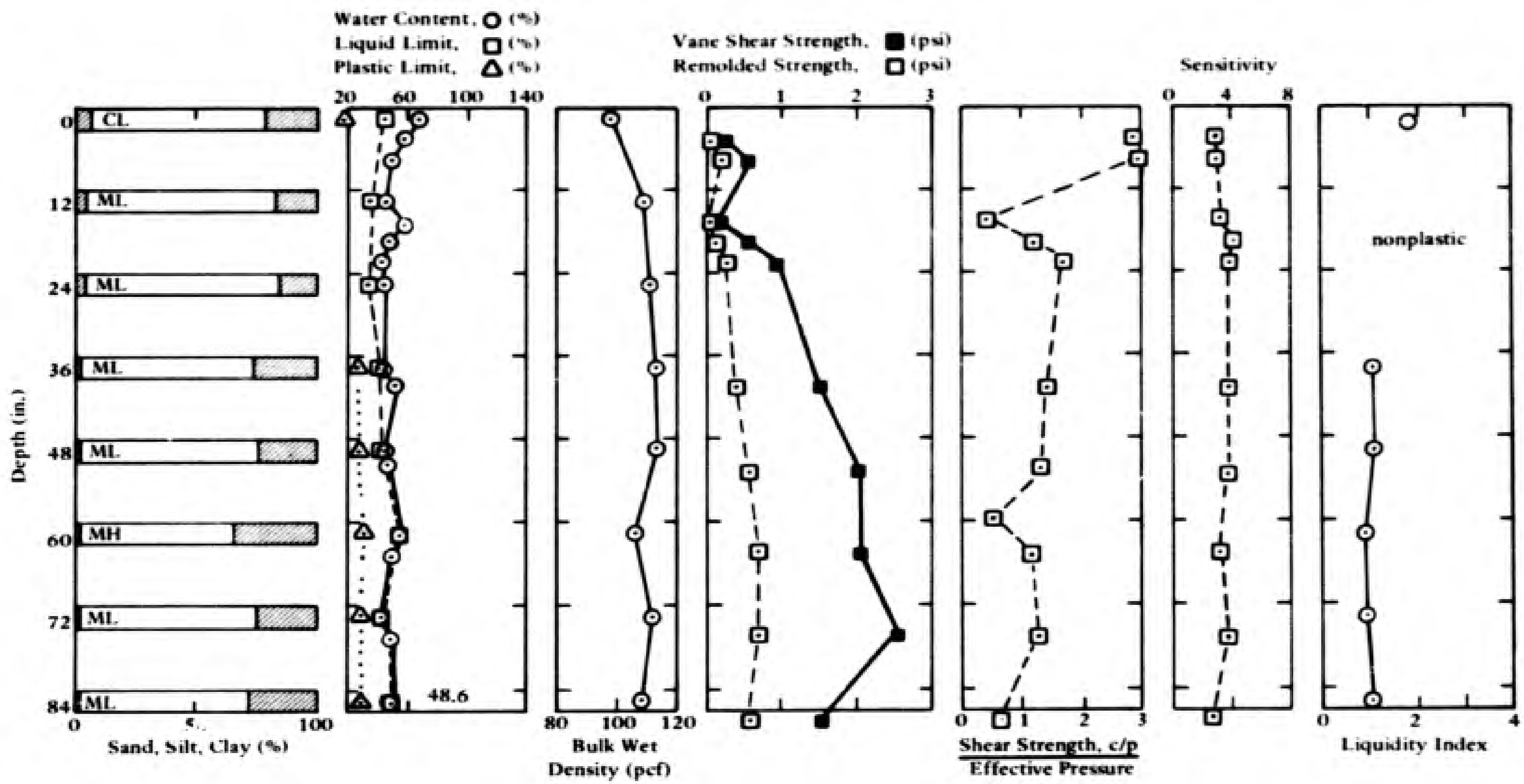

Figure 2.4.1. Soil properties for SEACON I, core 600-C-1 [2.4.4].

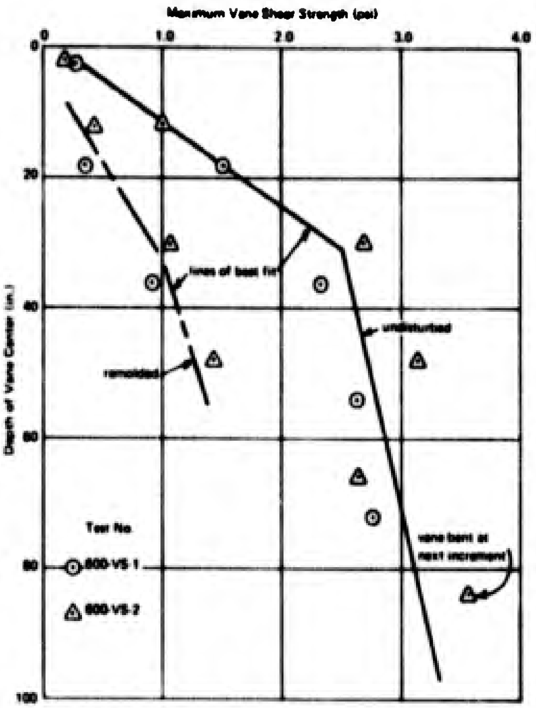

Figure 2.4.2. In-place vane shear soil strength versus depth for SEACON I.

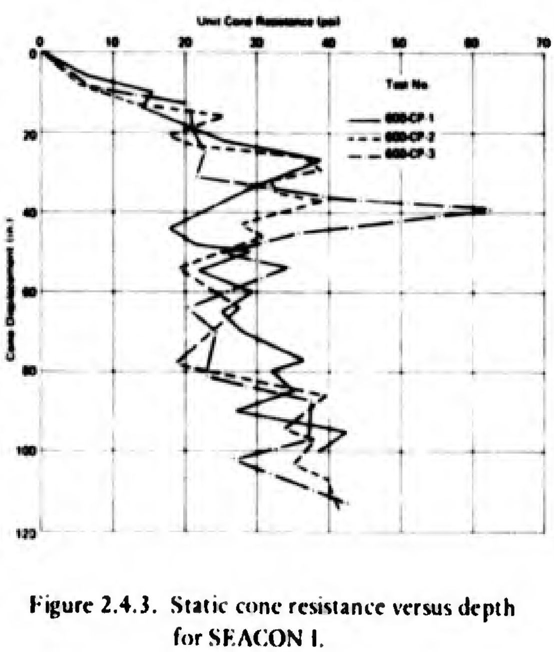

Figure 2.4.3. Static cone resistance versus depth for SEACON I.

By staggering the test depths, it was possible to achieve a more detailed picture of the soil strength profile. The lines of best fit for the undisturbed and remolded tests show a trend for a rapid linear increase in strength to about 30 inches. Beyond 30 inches, the vane shear strength tends to increase, but at a rate less than the increase in the first 30 inches of soil.

The results of the three cone penetrometer tests, shown in Figure 2.4.3, present a rather erratic soil profile; however, this is considered typical of the penetration test. Disregarding the gross discontinuities, definite trends are apparent. The cone resistance appears to increase to about 30 inches, decrease to 70 inches, and continue to increase beyond 70 inches. Variations between the general vane shear and cone penetrometer profiles may be attributed to the sketchy vane shear data, to the erratic discontinuities in the cone resistance profile, or, more probably, to the paucity of information concerning the relationship between vane shear and cone penetration test results.

Plate Bearing Tests

Bearing pressure-settlement curves for the tests performed with the 0.5-, 1-, and 1.5-foot-diameter plates are presented in Figure 2.4.4. An average relationship was eye-fitted for each test series. Binding occurred between the weight holder and supporting frame during SCN 10 (0.5-foot-diameter plate), thereby preventing the bearing plate from completing its penetration. Data scatter tends to decrease as plate size increases [note proximity of tests SCN 1, 2, and 3 (1.5-foot-diameter plates)]. The smaller the plate the more its behavior is controlled by the softer and more variable surficial sediments.

Friction Plate Tests

Friction plate resistance versus settlement curves for the tests performed with the 1/4-inch, the 3/4-inch, and the 1/4-inch plate with a 3/4-inch-wide bottom lip are presented in Figure 2.4.5. The data are somewhat scattered; this is probably due to the friction plate, also shown in Figure 2.4.5, becoming clogged with soil after the first test in each series. Since each series of tests was performed continuously, without returning to the surface, the

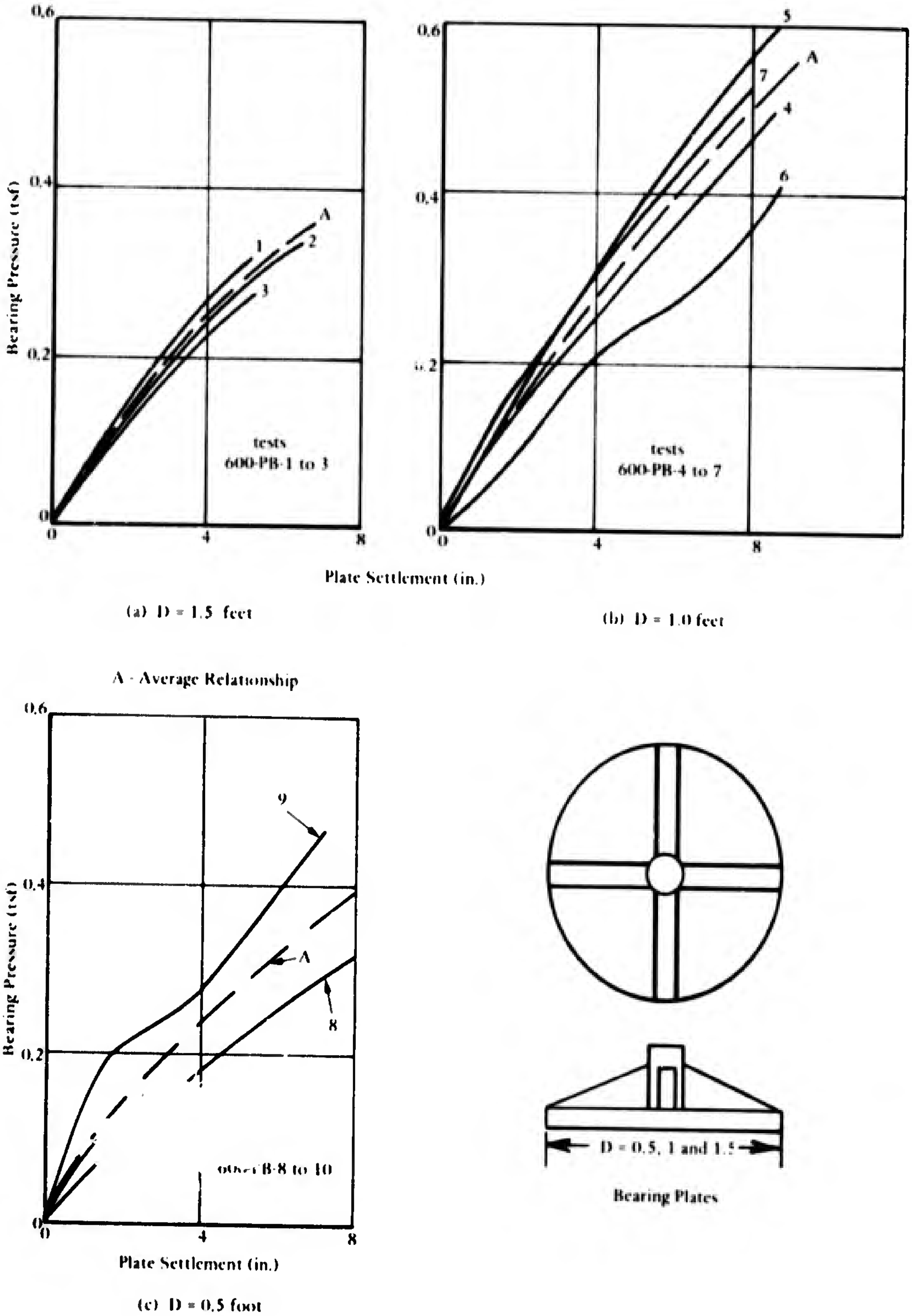

Figure 2.4.4. Bearing pressure versus settlement at SEACON I site for 6-inch, 12-inch, and 18-inch diameter plates.

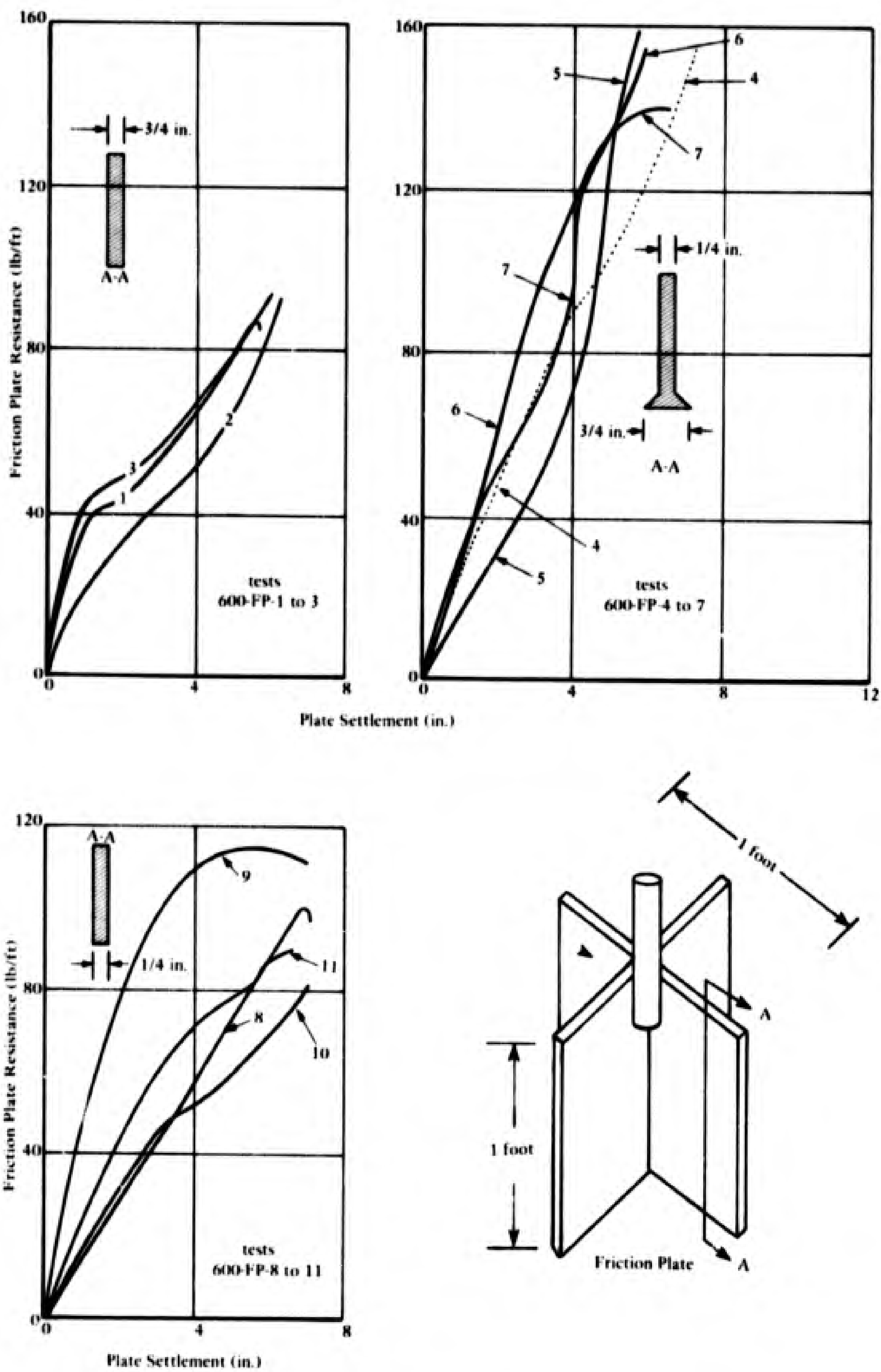

Figure 2.4.5. Friction plate resistance versus settlement at SEACON I site.

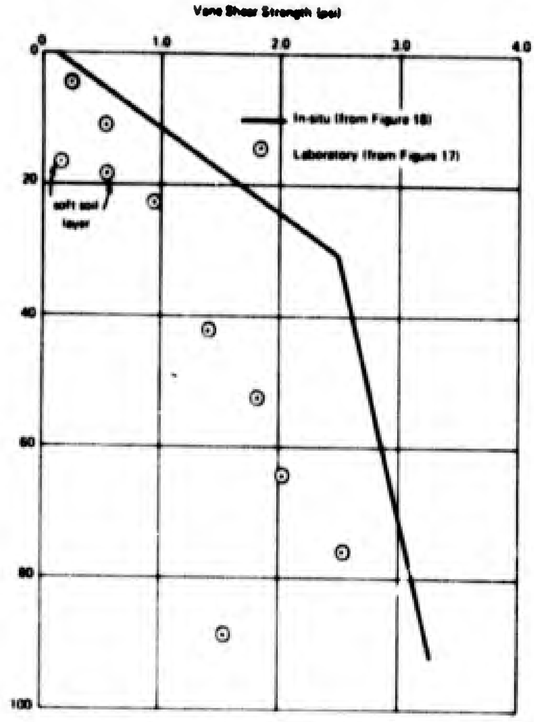

Figure 2.4.6. Comparison of laboratory and in-place vane shear soil strengths for SEACON I site.

assumption that the plate became clogged after the first test is based upon the fact that the plates were clogged upon return to the surface. It is possible that intermediate tests are valid; however, only tests SCN-FP-1, 4, and 8 will be considered further.

ANALYSIS

Laboratory and In-Place Vane Data

The laboratory and in-place vane shear strength versus depth relationships for the SEACON I site are presented in Figure 2.4.6. This figure indicates that laboratory vane shear values are less than the in-place vane shear values for this site. (This relationship also holds for remolded strengths.) Friction on the torque rod, shear rates, and disturbance may have caused this discrepancy; however, only disturbance is considered to be of significance. Disturbance effects are more severe during laboratory testing because of sampling disturbance, sample handling, and vane insertion, while in-place testing is limited to disturbance by vane insertion.

Disturbance by vane insertion was minimized by designing the vane so that the ratio of the cross-sectional area of the vane to the area of the cylinder generated by the vane being rotated about its axis is less than 0.15 [2.4.5]. The soils sampled are most likely disturbed during sampling and sample preparation in the laboratory. In another comparison of in-place vane shear data and laboratory vane shear data from thick-walled gravity cores [2.4.6], the in-place shear strengths were higher than laboratory values by approximately 25%.

Since the SEACON soil is comprised primarily of silt-sized particles, it is believed that the core sample was disturbed considerably during handling and sample preparation. A hand saw was used to cut the samples into 3-inch lengths for the laboratory vane shear tests. Although the vibrations from sawing did not appear to be significant, they were probably of a sufficient magnitude to disturb the silt sample. During the remolding process, the laboratory vane was rotated twice as opposed to once in the field, which may have accounted for the low disturbed laboratory vane shear values. Effects of sample handling in and outside the laboratory appear to be of first order significance. Scale effects may also be significant for different size vanes in silt.

Correlation of Vane and Cone Data

The ratio of average unit cone resistance to average vane shear strength versus depth is presented in Figure 2.4.7. The ratios fall between 9 and 12 to a depth of 90 inches. These data agree with the results of Skempton [2.4.7] and Begemann [2.4.8] and lend credibility to the SEACON I data. The trend in the data, which shows a decrease in the ratio of cone to vane strengths at about 40 inches, agrees with the increase in plasticity at 40 inches (refer to Figure 2.4.1). Soils with lower plasticity (the more granular soils) should exhibit a higher ratio of cone resistance to vane shear strength. Vane failure surfaces will be similar for all soils; however, the sliding surface produced by the static cone increases with increasing soil friction angle. It appears probable that cone penetration resistance data, in conjunction with a simply determined soil index, plasticity index, can be

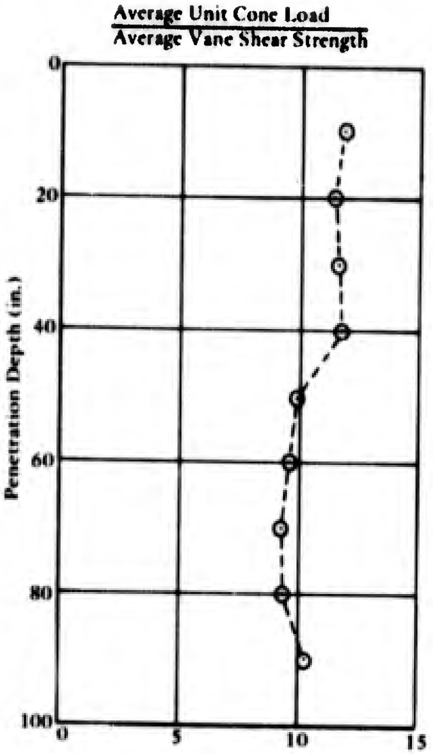

Figure 2.4.7. Relationship between ratio of average unit cone load and average vane shear strength versus penetration depth for SEACON I.

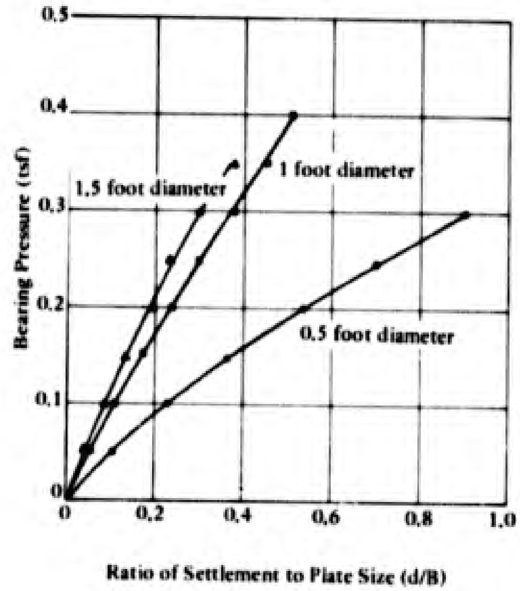

Figure 2.4.8. Bearing pressure versus ratio of settlement-to-plate size (d/B) for SEACON I.

used to predict accurately shear strength in most seafloor soils. This is important because the cone penetration test is quicker, simpler, and more economical than a vane shear test; in addition, the cone test yields a continuous record of cone resistance versus depth.

Plate Bearing Tests

The analysis of the plate bearing data is based upon Taylor's analysis [2.4.9] of the settlement of footings in homogeneous cohesive soils. Taylor states that two footings loaded to the same bearing pressure will settle in direct proportion to their widths.

Utilizing the average bearing pressure versus settlement relationships from Figure 2.4.4, the curves of bearing pressure versus the ratio of settlement to plate size (Figure 2.4.8) were derived. If these curves were to behave according to Taylor's relationship, then the curves should be superimposed. This disagreement can be explained by examining Taylor's assumption that shear strength is constant with depth. Figure 2.4.2 clearly indicates that at the SEACON I site, vane shear strength rapidly increases to a 30-inch depth and then gradually increases to 90 inches. Since plates derive support from depths directly proportional to their size, it is apparent tthat the behavior exhibited in Figure 2.4.8 is qualitatively correct.

The data from Figure 2.4.8, which were derived from circular plate tests, are also applicable to square plates [2.4.2] and can be used to formulate design curves for surface footings. Design curves of total load versus the ratio of settlement to plate sizes, d/B, plotted in Figure 2.4.9 for various footing widths from 1.5 to 6 feet, were developed from the relationship for the 1.5-foot-diameter footing in Figure 2.4.8. If the in-place soil strength continues to increase with depth, and indications are that it will continue, and if the trend shown in Figure 2.4.8 by the small plates continues for larger footings, then Figure 2.4.9 should have provided conservative design data.

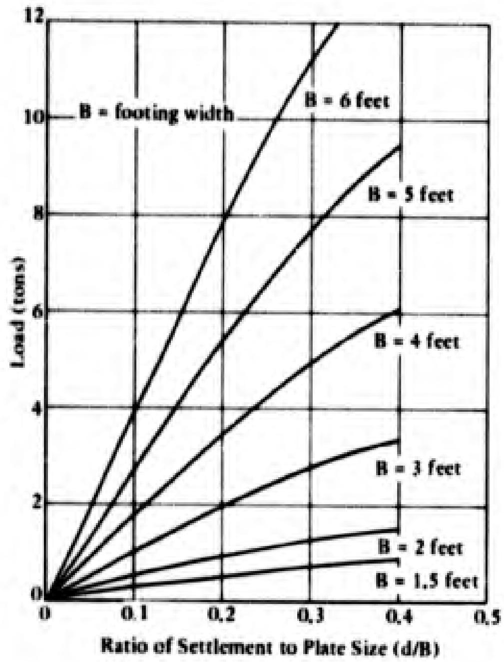

Figure 2.4.9. Possible SEACON design curves based on 1.5-foot-diameter plate in Figure 2.4.8.

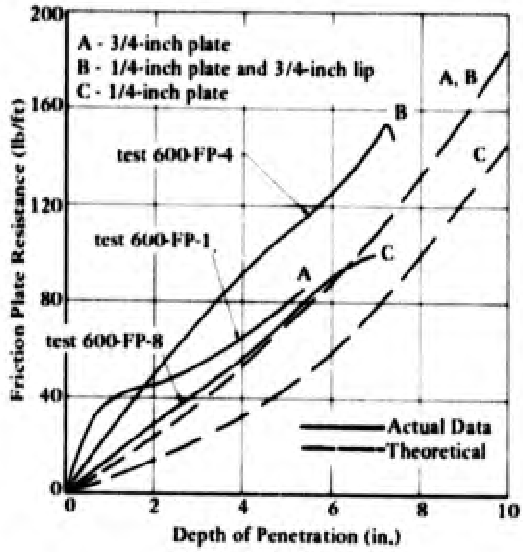

Figure 2.4.10. Friction plate resistance versus depth for SEACON I, using only first test in each series.

Friction Plate Tests

The results of the first test in each series of tests with the three friction plate configurations are plotted in Figure 2.4.10. For comparison, penetration resistances for the three plates were calculated using bearing capacity theory and undisturbed vane shear strengths from Figure 2.4.2; they are shown dotted in Figure 2.4.10. It appears that the required force to cause penetration could be 50% greater than the theoretical value. This is somewhat surprising because undisturbed vane shear strengths were used in the calculations. Using undisturbed shear strength to predict soil adhesion resulted in practically identical curves for the 3/4-inch plate and the 1/4-inch plate with the 3/4-inch lip. Soil disturbance undoubtedly occurs during penetration, thereby reducing soil adhesion to the plate sides; this is particularly so for the 1/4-inch plate with 3/4-inch lip. The use of remolded strengths would have magnified this discrepancy. In any event, predicted penetration resistance is less than observed.

Several circumstances could have produced this effect. First, the SEACON I soil is composed of some granular material (silt and sand). Since it was not feasible to account theoretically for the increased resistance due to soil friction, this effect was neglected. Second and probably more important, shear strength data in the variable surficial sediment profile (top 12 inches) were limited.

The direction plate tests were performed close to the site of the SEACON I foundation; therefore, it is prudent and, in this case, conservative to use the actual test data, which predict higher penetration resistances, than to use the theoretical penetration resistances.

FINDINGS

1. The vane shear and cone penetrometer devices and the piston corer, all subsystems of DOTIPOS, operated satisfactorily.

2. The piston-corer functioned satisfactorily, although the recovery ratio was somewhat less than one, due to a poor gasket seal; this problem has been corrected.

3. Vane shear and cone penetrometer data appeared to be of good quality; their relationship agrees with previous experimental data.

4. Laboratory vane shear strengths were up to 70% less than in-place strengths for the SEACON I sediment. This is attributed to disturbances caused by sample handling and laboratory preparation.

5. The plate bearing device performed efficiently and reliably at the 600-foot SEACON I site.

6. The bearing pressure versus ratio of plate size to settlement relationship for the 1.5-foot-diameter plate can be conservatively used to formulate design curves for larger footings for the SEACON I site.

7. The required force to cause penetration of a friction plate (keying edge) may be as much as 50% higher than the theoretical prediction. This difference is probably due to the presence of granular material, which would increase resistance, and second and possibly more important is the fact that strength data in the variable surficial sediment were extremely limited.

RECOMMENDATIONS

1. In-situ tests should be performed and undisturbed cores taken whenever possible at prospective seafloor construction sites.

2. High quality "undisturbed" piston cores should be supplemented with lesser quality gravity cores to more thoroughly evaluate areal variability.

3. Care should be exercised to properly evaluate the more variable, soft, surficial sediments at a seafloor construction site since this material contributes significantly to foundation behavior.

SECTION 1

SHIP MOORING SYSTEM FOR SEAFLOOR CONSTRUCTION

by J. R. Padilla

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OBJECTIVE

The purpose of the ship moor was to permit surface vessels to position very precisely within the SEACON I site and maintain a position very accurately while operations were being conducted.

INTRODUCTION

The requirements for lowering the SEACON I structure to its foundation by a guideline system demanded a surface positioning accuracy which could be obtained only through a three- or four-point ship moor. The surface mooring capability was originally intended to be of a mixed type; that is, to consist of a conventional anchor, an experimental explosive anchor, and an experimental vibratory anchor. The inability to obtain mooring legs with the explosive anchor or the vibratory anchor resulted in the use of three conventional anchors for the ship mooring.

MOOR POSITION

The orientation of the moor was determined by the wind and seas, which are predominately from the west northwest, and by the configuration of the CEL warping tug, the primary user of the moor. To position the tug with the seas on the stern quarter with two mooring lines from the bow and one from the stern required one anchor to be north of the site and the other two anchors to be positioned southeast and southwest of the site.

MOOR DESCRIPTION

Since the surface mooring buoys were intended to last 2 years, they were constructed to withstand extreme environmental conditions, the use of the moor in normal operation, and vandalism. The Mark T-6 mooring buoy (Figure 3.1.1) is of sufficient size to withstand normal operational use and environmental hazards. To prevent the loss of the moor from vandalism, the buoys were filled with a foam that would provide sufficient buoyancy to keep the buoys on the surface if their skin were to be penetrated. The Mark T-6 mooring buoy is 7 feet long, 5 feet high, and 5 feet wide. Six-by-six-inch timbers surround the buoy approximately 1 foot down from the top. The top of the buoy down to the timbers was painted white for good visibility, and the bottom of the buoy was painted with a black anti-fouling paint. A four-pound zinc anode was bolted to the base of each mooring buoy. A quick-flashing white light was attached to the top of each buoy for the initial installation.

The legs extending from the mooring buoys to the anchors were configured as shown in Figure 3.1.2. The wire rope in leg 1, which was laid at a bearing of 70 degrees true to the center of the SEACON I site, was 1,800 feet long and consisted of 1-1/4-inch 6 x 37 nongalvanized wire rope with a fibercore. Leg 2 was laid at a bearing of 190 degrees true to the center of the SEACON I site, was 1,480 feet long, and consisted of 1-1/4-inch 6 x 19 wire rope. The same construction wire was used in leg 3 which was 1,770 feet long and was laid at a position southeast of the center of the SEACON site at a bearing of 310 degrees true.

MOOR INSTALLATION

The moor was installed on 27 August 1970 from the CEL Warping Tug. The three lengths of wire rope were stored on the center drum of a warping tug winch. The wire was led over the A-frame on the warping tug, attached to the chain and anchor, and lowered into the water. The warping tug was maneuvered to the drop sites, and the anchor was lowered to the bottom. The wire was then paid out, and the anchors were set by pulling on the wire. The

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Figure 3.1.1. Navy Mark T-6 mooring buoy as originally installed at SEACON I site.

mooring buoys were then attached to the upper chain, and the shackles were welded shut.

The moor was recovered with the CEL Warping Tug on 10 April 1973 after nearly 3 years of service. During that time the only maintenance required was on the lights. Inspection of the mooring hardware after recovery indicated legs 2 and 3 were very near failure while leg 1 was in reasonably good condition. The 1-1/4-inch 6 x 19 wire was badly corroded and slightly birdcaged near the middle. The 1-1/4-inch 6 x 19 wire eye splice at the buoy end of leg 3 was badly corroded and frayed.

DISCUSSION

During the SEACON I experiment, the CEL warping tug, the *USNS Gear*, a YTM (*CURV* support vessel), and the Scripps Oceanographic Research Buoy/RUM moored within this system. The usual mooring procedure was to come up to one of the buoys, usually the west buoy, attach the stern line, and then proceed beyond the center of the SEACON I site; small boats would then take the remaining two mooring lines to the southeast and northeast buoy. The only exception to this procedure was with the *USNS Gear*, which moved with the bow to the west buoy.

The major problem with this moor was the maintenance of the lights. Many trips had to be made to the SEACON I site to replace batteries in the lights or to replace the entire light which either had been damaged or was completely missing. Approximately 10 months after deployment it was decided that maintenance of lights could be improved if each light were to be placed within a pad locked sheet metal box on top of a 5-foot pole. This was done, and the damage from vandalism was stopped and deterioration from sea splash was significantly reduced.

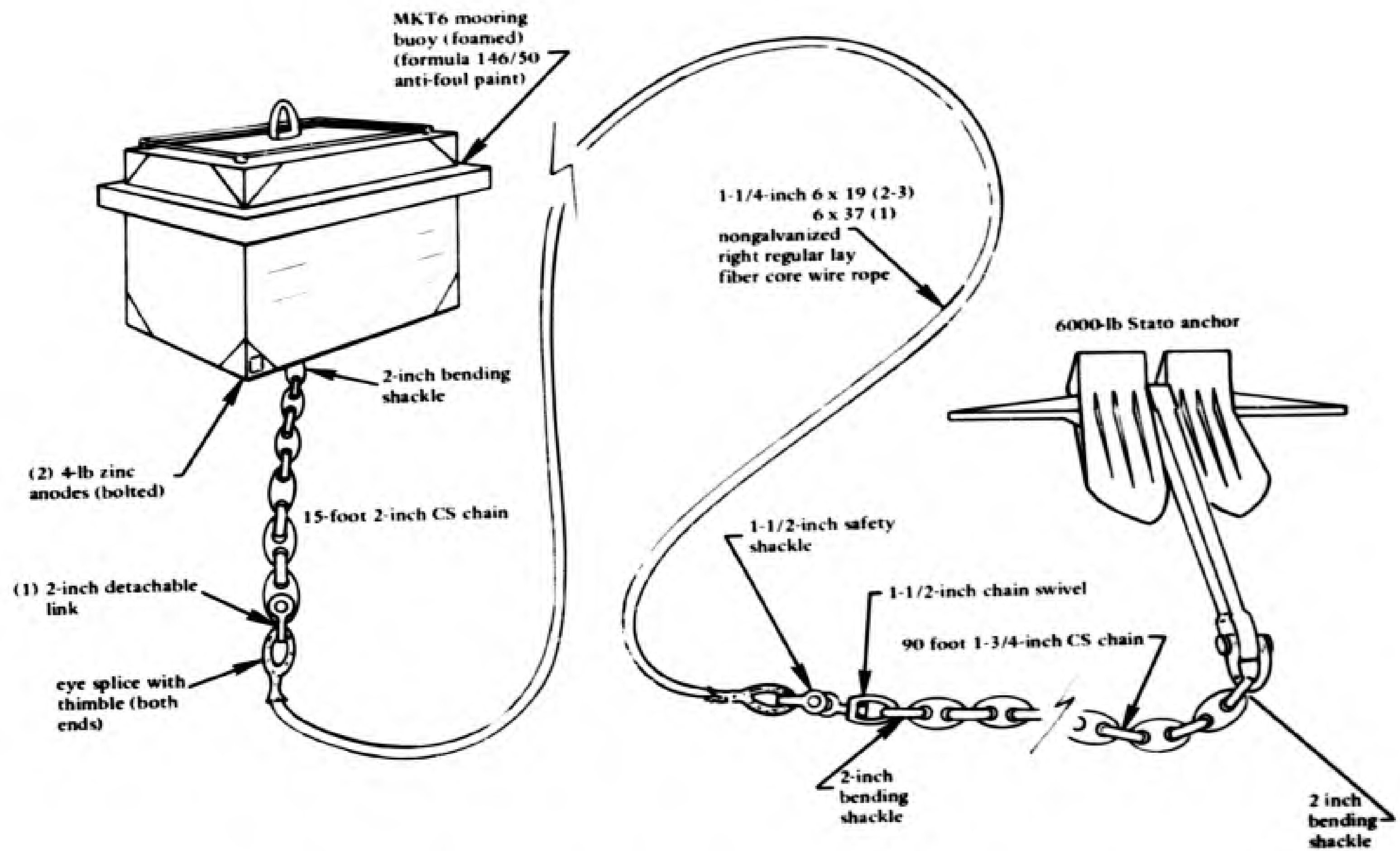

Figure 3.1.2. Mooring legs installed at SEACON I site.

The near failure of leg 2 may have been caused by working of the cable near its intersection with the sea bottom. Leg 2 was shorter than the other two legs; therefore, it would be more affected by surface actions on the buoy being transmitted to its intersection with the bottom. The cause of the accelerated corrosion of the eye splice in leg 3 is unknown.

CONCLUSIONS

1. With the exception of the lights, the mooring system met or exceeded performance specifications.

2. The availability of the stable mooring greatly facilitated the seafloor construction activities by (a) providing controlled maneuverability, (b) providing a horizontally stationary platform, and (c) dampening vertical motion by pulling the ship down into the moor.

RECOMMENDATION

An effective, low cost, low maintenance vandal-proof buoy light needs to be developed.

SECTION 2

TRANSPONDER NAVIGATION SYSTEM FOR SEAFLOOR POSITION CONTROL

by R. D. Hitchcock and J. R. Mittleman

OBJECTIVE

The purpose of this experiment was to devise and evaluate procedures and equipment for accurately positioning equipment and structures on the seafloor during a seafloor construction operation.

INTRODUCTION

A three-unit acoustic transponder network installed at the SEACON I construction site was used to control the relative positioning of the foundation and superstructure as well as other submerged objects for the SEACON I experiment. The main purpose of the transponder network was to provide a local reference frame in which the relative positions of all SEACON I seafloor and above-bottom objects could be determined with high precision as compared to that provided by a shore-based electronic navigation system. The unattended life of the transponders was estimated to be 2 years.

This section gives details on the transponder equipment and the emplacement procedure. Also given is a description of the operational and analytical procedures for determining the relative positions of the three seafloor transponders.

EQUIPMENT

The SEACON I transponder navigation system was furnished under Navy Contract N00123-71-B-0752, with InterOcean Systems Corporation, San Diego, California. The system is the long-baseline range–range type which measures the time for a sound pulse to travel from the interrogating transducer to the transponder and return.

The InterOcean Model 1079 Transponder System consists of three battery-powered subsurface units and six portable shipboard units powered by 120 volts, 60 Hertz. The six surface units can be set onto a horizontal surface or be rack mounted; in the horizontal set-up they occupy a space approximately 6 feet by 3 feet. The assembled surface system is shown in Figure 3.2.1.

Two interrogating transducers are connected to the surface equipment; one transducer is attached via a 200-foot cable, the other, via a 1,000-foot cable. Interrogation of the three submerged transponders is made from one transducer at a time by means of a two-position switch on the transmitter unit. The transducer on the 200-foot cable is submerged about 10 feet below the water surface to determine ship-transponder range. The transducer on the 1,000-foot cable is attached to the object being positioned on the seafloor to determine load-transponder range.

Each subsurface unit consists of an acoustic transponder packaged together with a motor-driven release assembly operated acoustically from the surface. The subsurface unit is shown in Figure 3.2.2. Figure 3.2.3 is a schematic of the entire subsurface assembly: transponder, buoy, and anchor.

The component sub-assemblies of the transponder system are listed below:

Surface Equipment (Figure 3.2.1)

- Model 1100 Acoustic Command Transmitter
- Model 1300 Acoustic Range Indicator (three each)
- Model 1079 Acoustic Receiver
- Model 1079 Power Supply
- Model 1120 Transducer with 200-Foot Cable
- Model 1120 Transducer with 1,000-Foot Cable

Subsurface Equipment (Figure 3.2.2)

- Model 1000 Acoustic Command/Transponder Release (three each)

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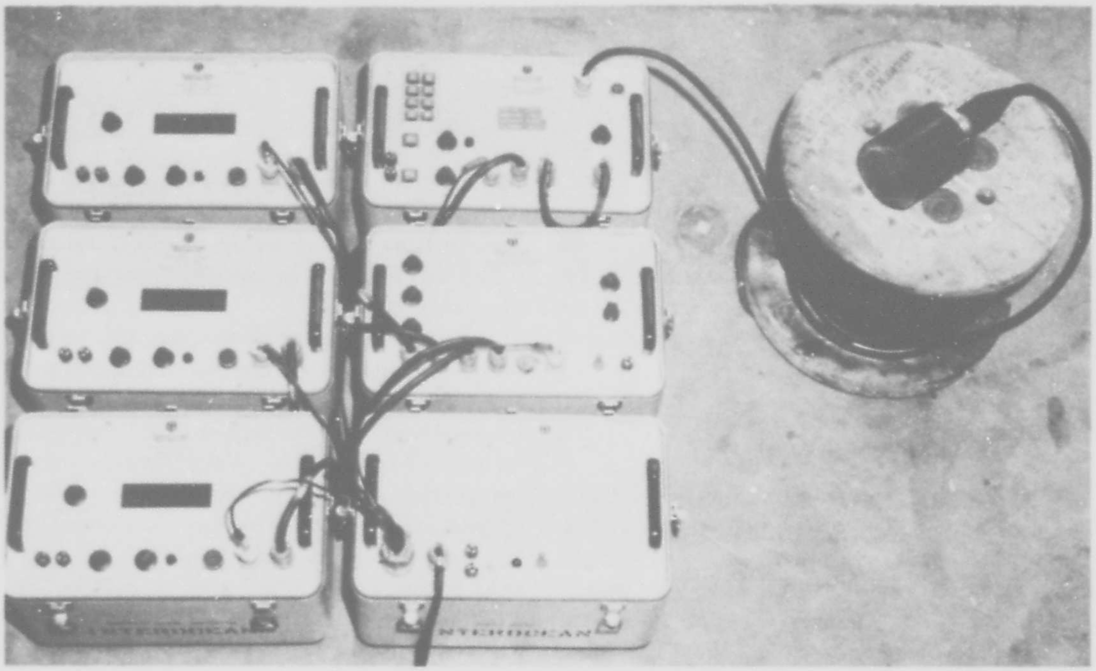


Figure 3.2.1. Surface equipment for SEACON I transponder navigation system.

PRINCIPLES OF OPERATION

Measurement of transducer–transponder range is made by transmitting a 12-kHz omnidirectional pulse, 10 to 20 msec in length, from the transducer. At the time this pulse is initiated, a gate pulse is sent to all three range indicators, resetting and restarting the range indicator counters. Upon receipt of the return pulses, each surface receiver channel generates a gate pulse which stops the counter in the corresponding range indicator. A single transmit pulse generates a single omnidirectional return pulse in each transponder, 4 msec in length, and at one of the three frequencies—8.00 kHz, 9.12 kHz, or 10.40 kHz. The received pulses are separated by conventional filtering circuitry in the receiver unit.

The range is read in feet on a digital incandescent display. This range reading requires two separate corrections. The major correction is the subtracting of a systematic turn-around error (16.75 feet) which is the same for each transponder. A minor correction is the multiplying factor (close to unity) which is the result of computing the average velocity of sound over the one-way ray path. The sound velocity switch on the front panel of each range indicator is adjustable in increments of 50 fps from 4,800 fps to 5,100 fps. In general, the average velocity over the ray path is different from any of the selectable velocity settings; hence, a correction factor is required that is based on temperature-salinity-depth data taken previously at the site. Both of these corrections are handled by the computer program for determining transponder positions.

OPTIMUM BASELINE LENGTH

Optimum baseline is that which maximizes the precision of the ship position. An estimate of the optimum baseline length was made by computing a mathematical relationship between baseline, **b**, and the error, σ_x, associated with lateral ship position at the centroid of a two-dimensional transponder network. A plot of σ_x versus **b** is shown in Figure

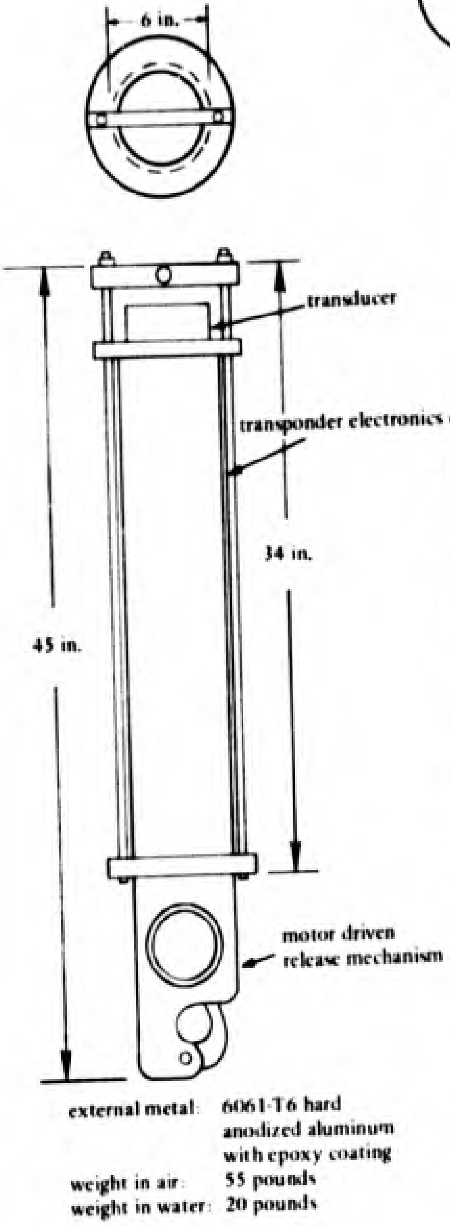


Figure 3.2.2. SEACON I transponder.

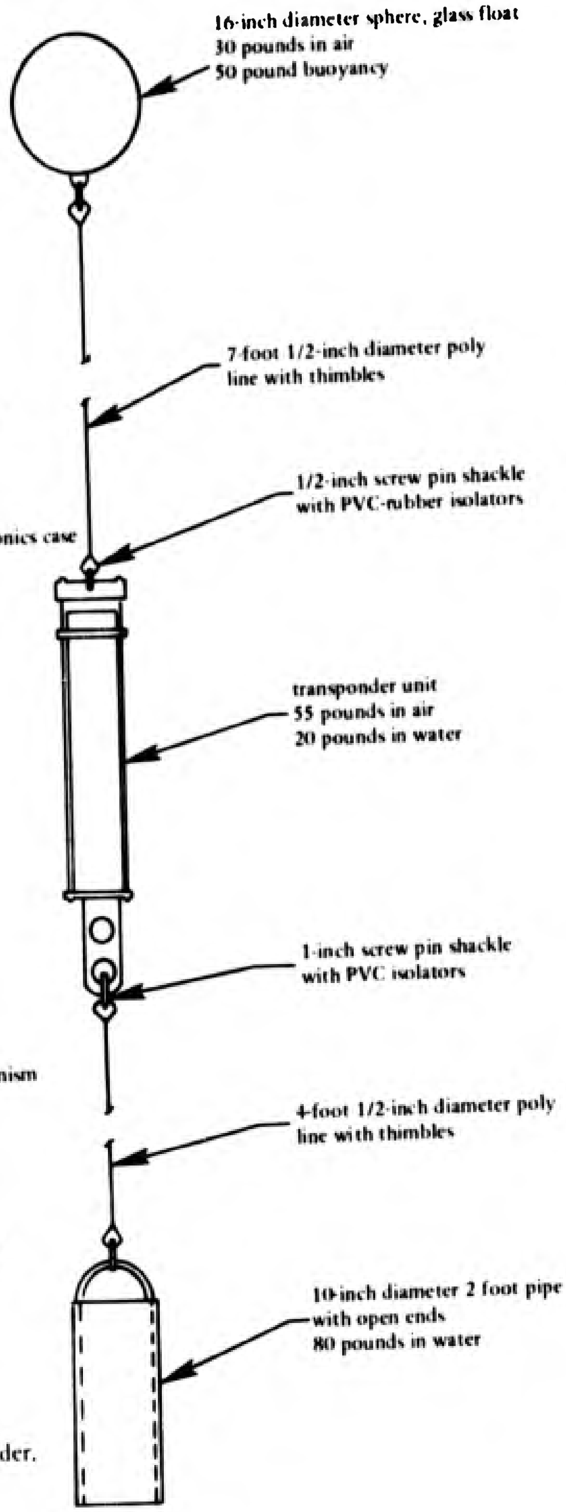


Figure 3.2.3. SEACON I transponder, buoy, and anchor.

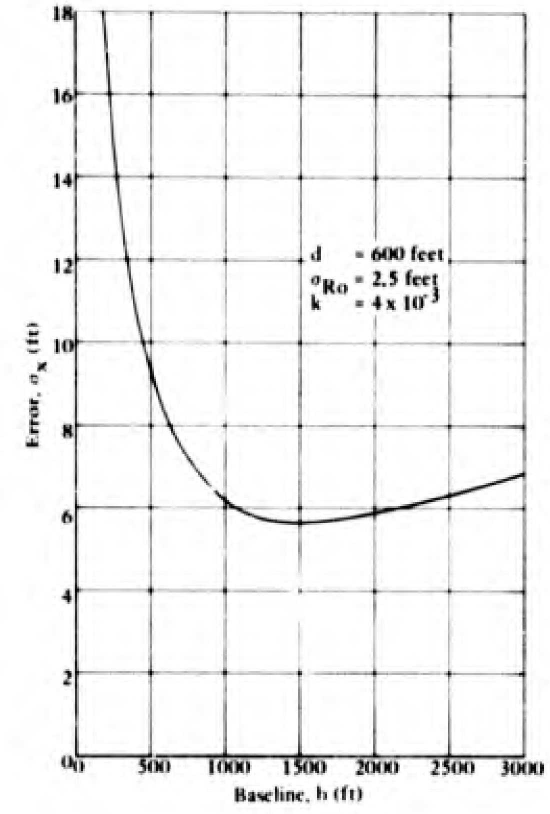


Figure 3.2.4. Plot of error versus baseline length for determining optimum baseline length.

3.2.4. The minimum point of this plot defines the optimum baseline which turns out to be around 1,500 feet for a 600-foot depth and a minimum travel-time error, σ_{R_0}, of 2.5 feet.

The minimum travel-time error was determined by calibrating the transponders at dockside. A distance of about 200 feet was taped off between transponder and interrogating transducer, and then the transponder was interrogated repeatedly until enough range data were taken to plot a distribution curve. This curve was roughly Gaussian and had a standard deviation of 2.5 feet.

The equation giving σ_x as a function of b was derived by assuming:

$$\sigma_x = \sqrt{2}\left(\frac{\partial x}{\partial R}\right)\sigma_R \qquad (3.2.1)$$

where R is the ship-to-transponder range and σ_R is the error associated with the measurement of R. The quantity $\partial x/\partial R$ can be obtained analytically, and σ_R can be expressed as a linear function of R:

$$\sigma_R = \sigma_{R_0} + kR \qquad (3.2.2)$$

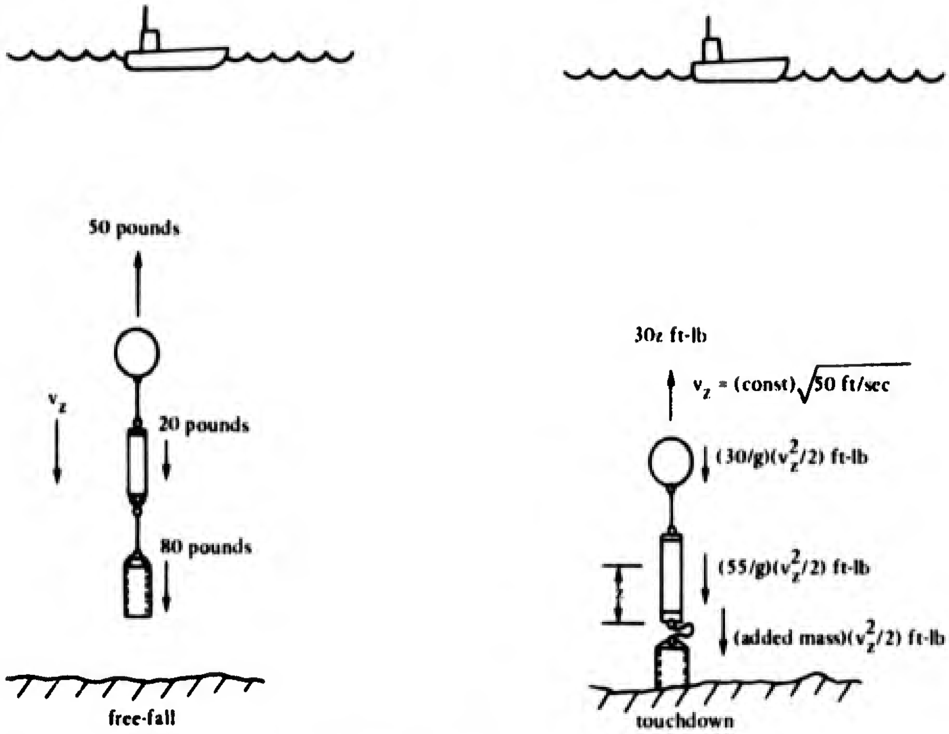
The plot in Figure 3.2.4 is based on a value of $k = 4 \times 10^{-3}$. The magnitude of k depends on the signal-to-noise ratio and the receiver bandwidth among other things; the value chosen for Figure 3.2.4 is a worst-case estimate based on standard sonar equations.

FREE-FALL EMPLACEMENT

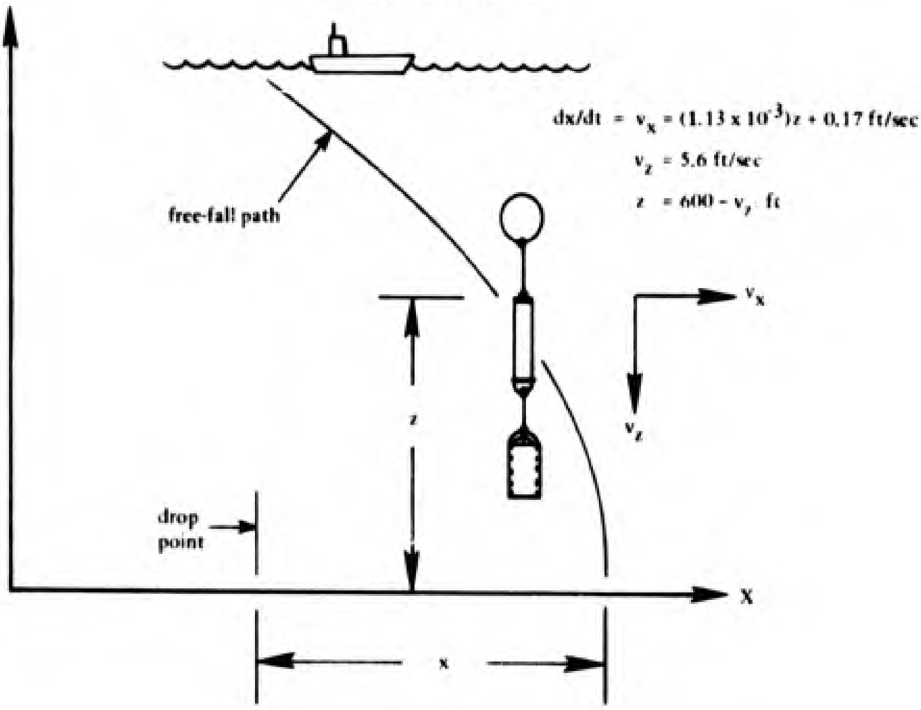
In planning the free-fall emplacement of the three transponders, a simplified analysis of the touchdown dynamics was made to determine the length of the transponder-to-anchor line needed to prevent impact between transponder and anchor. The line should be long enough to prevent impact and short enough to prevent large offsets caused by bottom currents.

Figure 3.2.5a is a schematic of the transponder assembly at touchdown. The vertical distance traveled by the transponder, after the anchor reaches the bottom, was computed by equating the kinetic energy of the buoy-transponder assembly to the work performed by the buoyant force acting on the buoy-transponder assembly. To prevent impact between transponder and anchor, a lower limit of 2.4 feet was computed for the length of line between transponder and anchor.

An analysis was also made to determine the maximum lateral displacement of the transponder assembly from the drop point at the surface. To make this calculation, it was assumed that the ocean current vector lies in a horizontal plane and that its magnitude, v_x, varies linearly from 0.5 knot at the surface to 0.1 knot at the seafloor. Figure 3.2.5b is a schematic of the transponder assembly during free-fall to the bottom. In computing lateral displacement at touchdown, it is assumed that the lateral velocity of the transponder on the way down is equal to the current velocity, v_x, at the depth of the transponder. If the velocity of descent, v_z, is

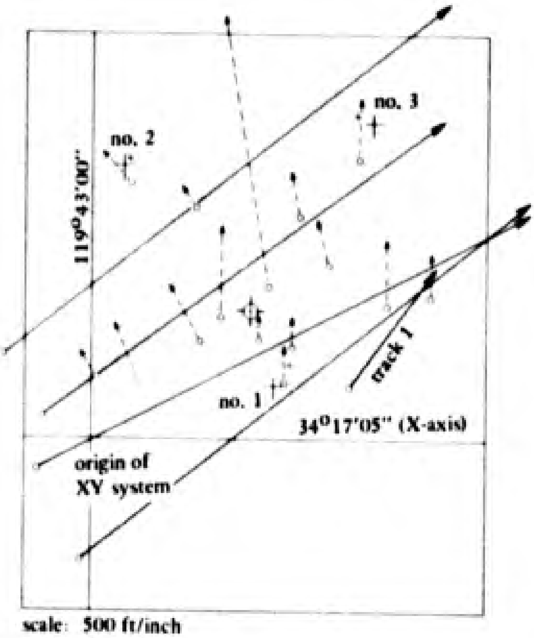


a. Touchdown Dynamics



b. Lateral Displacement

Figure 3.2.5. Transponder free-fall emplacement dynamics.



scale: 500 ft/inch

6/1/71
5/3/71 track relative to transponder

computed position of transponder

drop point relative to transponder

center of SEACON I site

Figure 3.2.6. Survey of track lines.

assumed constant (5.6 fps, as computed from the drag-force equation), then integration of the lateral-displacement equation yields a maximum lateral displacement, x, of 54.7 feet.

The three transponder assemblies were dropped from a surface vessel (LCM-8) to the ocean floor. The positions of the drop points were determined by LORAC B, the three points having been established on the LORAC B chart so as to form a roughly equilateral triangle with each leg equal to approximately 1,500 feet. The positions of the three drop points were selected in an effort to make one transponder land at a point about 300 feet south of the center of the SEACON I site, and to make the other two transponders land at points north of the center of the site at roughly the same latitude. Figure 3.2.6 shows the drop points and relative seafloor positions of the three transponders as determined by computer and the track lines (relative to the transponders) of the surface vessel made during the two survey operations.

DETERMINATION OF TRANSPONDER POSITIONS

The touchdown positions of the three transponder assemblies were determined relative to the LORAC B coordinate system by obtaining transponder-to-ship ranges at many points over the SEACON I site and its vicinity. The data were later processed on shore by computer to yield transponder positions and the error associated with each position determination.

Two surveys were conducted for the purpose of computing the baseline lengths of the network and seafloor positions of the three transponders. The first survey was carried out from the LCM-8 immediately after the free-fall emplacement was completed on the morning of 3 May 1971. The second survey was conducted on 1 June 1971 from the AVR-9. The same basic procedure was used during each survey operation; that is, the ship was moved to some position from which the ship drifted along a desired track line and, at points along the drift path, LORAC B and transponder-range data were obtained.

During the first survey with the LCM-8, each LORAC B position (Red, Green) was read aloud from the dials at the same time that the corresponding set of three transponder-to-ship ranges was displayed. Each set of five numbers was recorded by hand. During the second survey, a LORAC B recorder was used and a mark was put onto the time axis at the same instant the transponder button was pressed. The two LORAC B coordinates were read off the chart paper at a later time. Use of the recorder, during the second survey, yielded transponder position errors about half the magnitude of the errors obtained with the data of the first survey.

Figure 3.2.7 is a schematic of the SEACON I transponder network showing the three ship-to-transponder ranges,* R_1, R_2 and R_3, and the relative positions of the interrogating transducer and the LORAC B antenna. Because of the impossibility of pointing the ship at a constant heading during the

* The sound path is assumed to be a straight line.

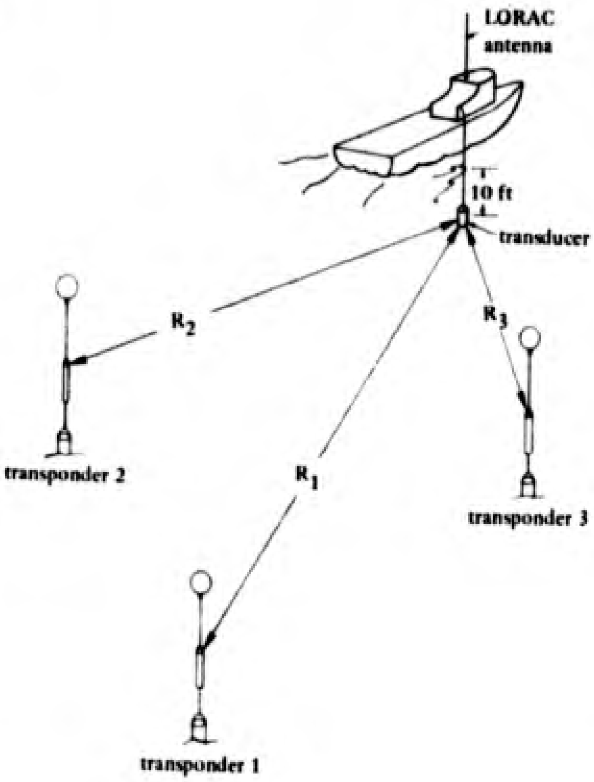


Figure 3.2.7. SEACON I transponder network.

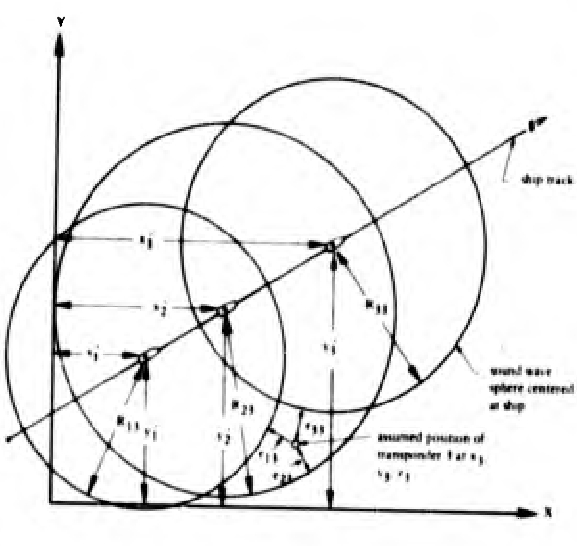


Figure 3.2.8. Errors in ship-to-transponder ranges.

entire survey, it can be presumed that the horizontal projection of the vector between transducer and LORAC B antenna had an azimuth which ranged over 360 degrees. The average value of the magnitude of the horizontal vector was around 10 feet for the LCM-8 and 6 feet for the AVR-9.

The position of each transponder was computed by assuming an xyz position in an arbitrary rectangular coordinate system and then adjusting the assumed position to minimize the sum of the squares of the error distance, e_{ij}, defined as the minimum increment of distance from the assumed position to the sphere whose radius is the measured transponder range. The error distances, e_{ij}, are shown schematically in Figure 3.2.8; the rms error, E_j, is defined as follows:

$$E_j^2 = \frac{1}{N} \sum_{i=1}^{N} (R_{ij} - r_{ij})^2 \qquad (3.2.3)$$

where j = transponder number 1, 2, or 3

N = number of five-number data sets taken during survey*

r_{ij} = ith measured range to transponder j

$$R_{ij} = [(x_i' - x_j)^2 + (y_i' - y_j)^2 + (z_i' - z_j)^2]^{1/2} \qquad (3.2.4)$$

x_i', y_i', z_i' = ship position in xyz coordinate system

x_j, y_j, z_j = assumed position of transponder, j, in xyz coordinate system

The origin of the xyz coordinate system was made to coincide with the seafloor projection of the geographic position: 119°43'00"W, 34°17'05"N. Figures 3.2.9 and 3.2.10 are positioning charts for use with the SEACON I transponder system. The numbers identifying the coordinate circles are transponder ranges in feet, that is, indicated range less 16.75 feet.

The computer program is written in Fortran IV, and the minimum value of E_j is computed by the machine-language subroutine, AMINI.** A set of E_j is computed for the initial assumed transponder

* See Table 3.2.1.

** This subroutine selects the smallest number from a set of numbers.

Table 3.2.1. Baseline Lengths for SEACON I Transponder Network

(Unit of Length = 1 foot)

Survey	N	Criterion for N	b_{12}*	Δb_{12}	b_{23}*	Δb_{23}	b_{31}*	Δb_{31}
No. 4	169	$R_{ij max} \leq 3935$	1624.8	9.0	1636.6	6.7	1721.4	1.0
No. 2	137	Distance from Centroid $\leq$ 1800	1633.8		1643.3		1722.4	

* b_{ij} = baseline length between transponder i and j.

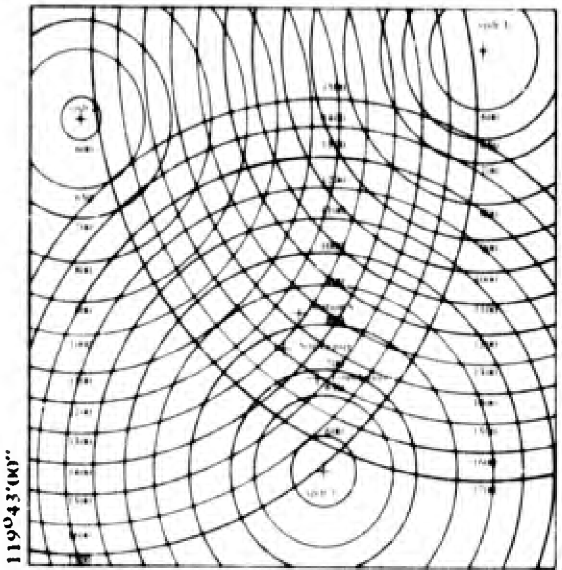


Figure 3.2.9. Transponder surface positioning chart.

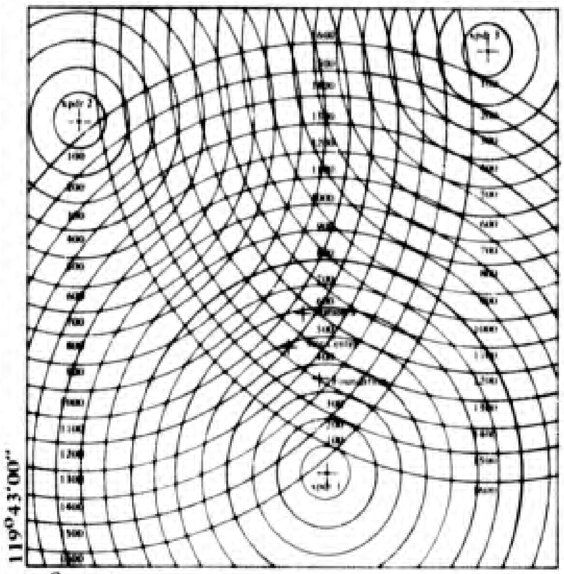


Figure 3.2.10. Transponder seafloor positioning chart.

position, $x_j y_j z_j$, and 26 other xyz positions lying on the six surfaces of a cube centered at $x_j y_j z_j$. These 26 positions are computed by selecting an increment of distance, SIZE, and then multiplying the increment by 0, +1, -1 to produce 27 distinct three-number sets. The 26 positions are generated by algebraic addition of the elements of each of these three-number sets (excluding the 000 set) to the corresponding elements of the initial (central) point set.

The computer picks out the minimum E_j from the 26 values computed as outlined above, and then computes 26 new positions lying on a cube centered at the position which minimized E_j in the first computation. This process is repeated until the position which minimizes E_j turns out to be the center of the cube; the computer then stops and prints out the coordinates of this center point as the transponder position.

E_j is a well-behaved function of x, y, and z, and the technique of computing E_{jmin} by using the subroutine, AMINI, is equivalent to finding E_{jmin} by computing the gradient,* ∇E_j, and multiplying by SIZE. Since ∇E_j is the maximum rate of change of E_j per unit change in direction, then E_j will tend to follow the gradient in going from the center of the cube to a peripheral point which makes E_j have

* Gradient of $E_j = \nabla E_j = \frac{i\,\partial E_j}{\partial x} + \frac{j\,\partial E_j}{\partial y} + \frac{k\,\partial E_j}{\partial z}$

minimum value. The smaller the value of SIZE, the more closely E_j will follow the gradient.

Baseline lengths for the transponder network were computed and are listed in Table 3.2.1. The magnitude of the baseline is given by

$$b_{\ell m} = [(x_\ell - x_m)^2 + (y_\ell - y_m)^2 + (z_\ell - z_m)^2]^{1/2} \qquad (3.2.5)$$

where x_ℓ, y_ℓ, z_ℓ = computed position of transponder, ℓ

x_m, y_m, z_m = computed position of transponder, m

As shown in Table 3.2.1, the computed baseline lengths from one survey differ from the corresponding baselines from the other survey by less than 10 feet, the average difference being approximately 5.6 feet. This result indicates that the precision of baseline measurement is considerably better–possibly, by a factor of 3 or more–than the precision of transponder-position measurement relative to the LORAC B coordinate system. The average E_{jmin} is 35.8 feet for the first survey and 17.7 feet for the second survey.

CONCLUSIONS

1. From the data taken on two separate surveys, baseline lengths on the order of 1,500 feet can be determined with an average error less than 6 feet (depth = 600 feet; three-transponder network).

2. LORAC B and transducer-offset errors are largely canceled out in the determination of baseline length.

3. Transponder positions, relative to the LORAC B coordinate system, can be determined with rms errors, E_{jmin}, around 18 feet.

RECOMMENDATIONS

A work unit should be established to determine optimum techniques for surveying a seafloor long-baseline transponder system at depths up to 6,000 feet. For a near-shore network, shore-based navigation should be employed. In deep water, the baseline-crossing technique should be used. Results of the investigation would yield procedures for minimizing the ship time required to determine relative transponder positions with a given accuracy.

SECTION 3

EMPLACEMENT AND RECOVERY OF THE SEACON SYSTEM

by F. C. Liu

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OBJECTIVE

The objective of this work was to demonstrate the technology available in the design of ocean lift systems for handling and placing structures and equipment on the seafloor.

INTRODUCTION

Construction, whether on land or at sea, involves the lifting and transporting of heavy equipment and bulky materials. Although on-land load-handling technology is highly sophisticated, at-sea technology is not. The on-land technology cannot be transferred directly because of the sea's adverse environmental conditions such as the dynamic sea surface and the lack of direct observation in positioning objects on the seafloor. Motion-compensation lift systems have been developed to reduce the effect of work platform motion on the forces in the handling equipment. Also, guideline systems are used to assure tolerable final payload position.

In order to demonstrate the state of at-sea load-handling technology, the SEACON I experiment involved (1) positioning a concrete hull on a preplaced foundation by means of a double-guideline system and (2) the retrieval of the hull through use of a counterweight system to minimize dynamic tensions in the lift line.

In this section, the definition of the SEACON I load-handling experiment, the design of the handling systems, and the conduct of the experiments are discussed. In addition, the effectiveness of the load-handling systems is evaluated, and recommendations are given for future design of similar systems.

PROBLEM DEFINITION

A concrete hull and foundation were to be emplaced on the seafloor at a depth of 600 feet for 1 year, and then retrieved. The concrete hull was cylindrical with hemispherical end closures. It was 10 feet in diameter and had an overall length of 20 feet; the cylindrical portion was 10 feet long. The hull weighed 95,000 pounds in air and 11,000 pounds when fully ballasted in seawater. The foundation was 14 feet square and weighed 25,000 pounds in air and 15,000 pounds in seawater.

At the outset, it was decided that the foundation and hull would be lowered separately to minimize the loads handled by the lift system as well as to provide an opportunity for an underwater structural mating experiment.

SYSTEM DESIGN

Emplacement Lift System

The parameter which dominates the design and performance of an ocean lift system is the dynamic line tension. The total lift line tension consists of static and dynamic forces. The static force (or load) equals the dead weight of the payload and cable. The dynamic tension is more difficult to compute as it depends upon the surface platform motions, the cable properties (modulus of elasticity, diameter, dry and submerged weights), and the payload properties (mass and hydrodynamic drag). It is also a function of the period of suspension if random excitation is considered. With these input data, a computer program, LILIAN (Lift Line Analysis), was written [3.3.1] to predict the peak dynamic tension at selected suspension depths. This program is based on an analytical solution developed by A. D. Little, Inc. [3.3.2].

By means of program LILIAN, the total tension can be compared with the breaking strength of the cable to determine the factor of safety. If the cable is not adequate, another cable is selected and the new system is analyzed in the same manner as before. The procedure is described in detail in Reference 3.3.3, and the computer program is available on loan from CEL.

For the SEACON I operation, sea state 3 was selected as the upper limit for performing load-handling operations. The CEL warping tug was selected for the surface support platform on the basis of its stability, availability, and load-handling capability. A design motion spectrum to represent the expected motion of the warping tug in sea state 3 was derived from acceleration records which were obtained during several sea cruises with the warping tug. The physical properties of the hull and the foundation were supplied by the SEACON I structure designers.

The lift system was designed using the SEACON I hull as the primary payload. Although the foundation has a higher in-water weight than the hull, the hull's mass is almost four times greater than that of the foundation. Therefore, the dynamic loads in handling the hull would be greater than those in handling the foundation.

To complete the computer program input requirements, a 2-inch-diameter nylon braided rope was selected as the lift line. This rope was expected to act as a soft spring and to reduce the dynamic tension and motion. The computer analysis confirmed the selection of this rope. The main advantage is that the hull motions are reduced to one-tenth of the surface excitation when the hull is near the foundation on the seafloor. The maximum dynamic line tension occurs when the hull is near the surface. In this near-surface position, the analysis showed the maximum total tension expected to be one-half of the nylon line's rated strength. Wire ropes of comparable strength were also analyzed. However, with wire rope, the payload motion at the 600-foot depth would be excessive, and the dynamic tensions would be high.

With 2-inch-diameter nylon braided rope, there was no need for motion compensation at the winch. Therefore, a hydraulic traction winch with a steady line pull of 25,000 pounds was selected. A support sheave 24 inches in diameter was used to transfer the vertical line tension to the horizontal winch load.

Guideline System

The main purpose of the guideline system is to assure proper mating and positioning of the hull on the foundation. In addition, it restricts rotation of the hull during lowering.

Although little information is available on how to design a double-guideline system, it is known that guidelines must be kept in tension at all times to prevent entanglement with other lines. The magnitude of the required guideline tension depends on the moment needed to restrict the rotating motion of the hull during lowering and to restore the hull to the correct position [3.3.4]. A tension of 5,000 pounds was applied to the guidelines during the lowering of the hull. As the hull is forced to rotate under any external forces, the guidelines are deformed. The horizontal components of the guideline tension form a torque to restore the position of the hull. The restoring torque is minimum when the hull is suspended at mid-depth. The equation for the guideline restoring moment at mid-depth is:

$$M = \frac{4 T d^2 \sin \frac{\phi}{2} \cos \frac{\phi}{2}}{\sqrt{D^2 + 4 d^2 \sin^2 \frac{\phi}{2}}}$$

where T = guideline tension

ϕ = payload rotation

D = guideline length

d = guideline spacing

This restoring moment, M, must be larger than the exciting moment caused by the current drag forces. A similar analysis applies to the design of the subsurface guideline buoy. The buoyancy must be large enough to provide enough line tension to prevent excessive rotation of the spreader bar connected to the upper ends of the guidelines. The restoring moment for this case is:

$$M = \frac{T d^2 \sin \frac{\phi}{2} \cos \frac{\phi}{2}}{\sqrt{D^2 + d^2 \sin^2 \frac{\phi}{2}}}$$

The SEACON I guideline system consisted of two 1/2-inch 6 by 9 wire ropes spaced 12 feet apart. The size of the guidelines was determined by the required maximum tension. One of the wire ropes was of regular lay construction and the other one was of left lay construction. With this approach, tension-induced torques in either line would balance each other to minimize the chance of entanglement. The lower ends were attached to the foundation guideposts, which were 5 feet high and 8 inches in diameter. The upper ends were supported by air tuggers having a maximum line pull up to 7,000 pounds. An air tugger is an air-operated winch with relatively fast response. When set at a desired pressure, it will maintain nearly constant line tension regardless of ship motion. To effect proper mating of the hull to the foundation, a pair of guide cones was installed on the hull support-frame. As the hull reached the foundation guideline posts, the guide cones were to slide over the guideposts to assure proper alignment of the hull. The guidelines were to be attached to a buoyed spreader bar for long-term deployment.

Recovery Lift System

Because the outer braid of the 2-inch nylon rope failed during the emplacement (details are presented later), it was decided that a steel wire rope should be used for the recovery. However, an analysis of the line tensions using program LILIAN showed that excessively high tensions would be induced in the simple lift system. Motion compensation would definitely be required for the recovery lift system. Many methods of motion compensation were considered; the most simple and effective one was the counterweight system similar to the one successfully used in handling the SEALAB II Hull [3.3.5]. In general, the winch line passes a fixed support sheave before it is attached to the payload. The position of the counterweight changes as the line tension varies. The change in counterweight position adjusts the vertical distance between the support sheaves and the payload to compensate the platform motion. In short, it acts like a nonlinear soft spring. The spring stiffness increases as the tension increases, and decreases as the tension decreases. The design method is described by Carpenter in Reference 3.3.5. However, he does not consider the dynamics of the whole lift system, which would be a major task.

Since an estimate of the dynamic tensions was needed, a semidynamic analysis was used to predict the dynamic tension in the lift line. This approach utilized the static method to calculate the tension–displacement relationship. An equivalent spring constant of the counterweight system was determined. Neglecting the motion of the counterweight, the dynamic line tension was calculated by program LILIAN using the counterweight system spring constant and the cable spring constant.

The final design of the recovery system included a traction winch, a 10-ton steel ship anchor as counterweight, a 1-1/8-inch-diameter wire rope, and four 4-foot-diameter sheaves. The large-diameter sheaves were required to prevent bending fatigue of the wire rope.

DATA ACQUISITION

A log was maintained to document the observations during all sea cruises. This information was later analyzed to evaluate the performances of the transport method and the load-handling systems.

Quantitative data were obtained for the lift systems by measuring the ship motions and the lift line tensions during the emplacement and recovery of the SEACON hull. An accelerometer having a range of 0 to 1.5g was mounted on deck at the lift point. A strain gage load cell having a range of 0 to 30,000 pounds was mounted between the platform and the support sheave. The vertical acceleration and line tension signals were fed through a signal conditioner and amplifier before being displayed on a dual channel strip chart recorder. The depth of hull suspension was measured by a sonar depth sounder which continuously recorded the position of the hull to an accuracy of ±5 feet. The position of the lift point was determined by interrogating the three transponders previously planted on the seafloor.

SEA OPERATIONS

The CEL warping tug was used as the main surface support platform for all the SEACON I cruises (Figure 3.3.1). A three-point mooring system, installed prior to the emplacement cruises, enabled the crew to spread-moor the warping tug over the

Figure 3.3.1. CEL warping tug, the work platform for SEACON I emplacement and recovery.

SEACON I site. This moor also stablized the warping tug during the sea operation.

Cruise I – Foundation and Guideline Emplacement

The foundation was transported to the site on the deck of the warping tug under the bow A frame. After the warping tug was spread-moored over the site, its position was adjusted using a transponder navigation system, which consisted of three seafloor transponders and a surface hydrophone transducer.

The foundation was lifted from the deck and eased into the water by a BU 140 winch (Figure 3.3.2). The winch has three drums and two capstans. Due to the poor response of the winch, control of the foundation was lost for a split second. The shock, resulting when force was reapplied, damaged the automatic emplacement frame for the settlement monitoring instrument. The damaged parts were removed. The foundation was then successfully lowered into the water and transferred to the lifting sheave at the starboard side of the warping tug (Figure 3.3.3). There were three lines attached to the foundation: one 2-inch nylon braided rope as the main lift line and two 1/2-inch wire ropes, on opposite sides, as guidelines. The bow guideline became entangled with the lift line during the transfer; it was untangled by divers. The foundation was then lowered to the seafloor with both guidelines in tension. No further entanglement occurred. Before landing on the seafloor, the position of the foundation was checked by the transponder navigation system. After placement on the seafloor, the foundation's inclination was checked. The main lift line was then removed from the foundation by activating a hard-wired electric release hook. The two guidelines remained attached to the foundation guideposts. A buoy with a spreader bar was installed 50 feet below the surface to support and tension the guidelines (Figure 3.3.4).

Cruise II – Hull Emplacement

Three months after the emplacement of the foundation, the hull was ready for deployment. It was towed about 25 miles to the site. Two 8.4-ton inflatable salvage pontoons were attached to the hull to provide buoyancy in case of emergency. The warping tug was positioned and moored over the foundation (Figure 3.3.1). The hull was moored between the warping tug and an auxiliary mooring buoy about 800 feet from the tug. The guideline buoy and both guidelines were retrieved to the deck. After a complete check of the hull's monitoring systems, the hull ballast was flooded and eased to the lowering position 50 feet under the support sheave. At this position, divers passed guidelines through the guide cones on the hull. The sea state was increasing; there were 5-foot swells and 12-knot winds. The operation with the hull suspended at the 50-foot depth had consumed about 1 hour. At this point it was found that the bow guideline had been passed through the guide cone in the wrong direction. Shortly thereafter, the outer braid of the nylon lift line parted at the support sheave. A decision was made to release the bow guideline and to lower the hull with the core braid along the remaining guideline. The hull was placed on top of the foundation without further incident, but was misaligned 30 degrees in azimuth. The remaining guideline was secured to a small subsurface buoy 50 feet under the surface. The lift line and the two

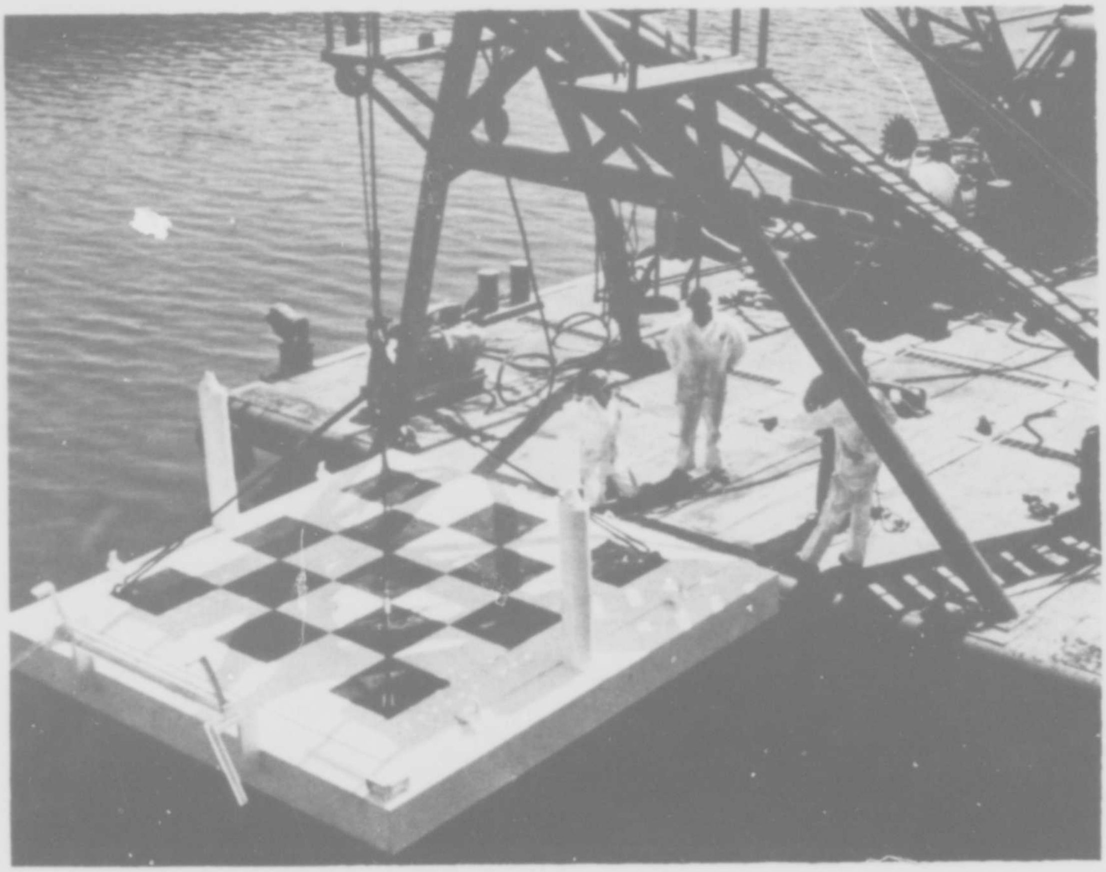

Figure 3.3.2. Fourteen-foot-square, 25,000-pound SEACON foundation is readied for emplacement.

SEACON I power/data cables were supported under the station B buoy, which was spread-moored 50 feet below surface (Figure 3.3.5).

Cruise III – Hull Recovery

Ten months after the hull was deployed, a sea cruise was made to recover the hull from the seafloor. A new lift line, a 1-1/8-inch wire rope, had been attached to the hull prior to the sea cruise. The stern guideline had also been removed. After positioning and spread-mooring the warping tug, the lift line was rigged on the counterweight motion-compensation system (Figure 3.3.6). An auxiliary mooring buoy was deployed about 800 feet from the starboard side of the warping tug. The hull was successfully raised to a depth of 80 feet, where it was deballasted and allowed to float to the surface while the auxiliary buoy maintained a steady pull on the hull. The cruise was concluded by towing the hull to Port Hueneme.

EVALUATION OF LIFT SYSTEMS

Computer program LILIAN was used to compute the line tensions based upon the measured ship accelerations. By comparing the computed tensions with the measured tensions, the effectiveness of computer program LILIAN as a design tool could be evaluated. Also, small dynamic tensions would

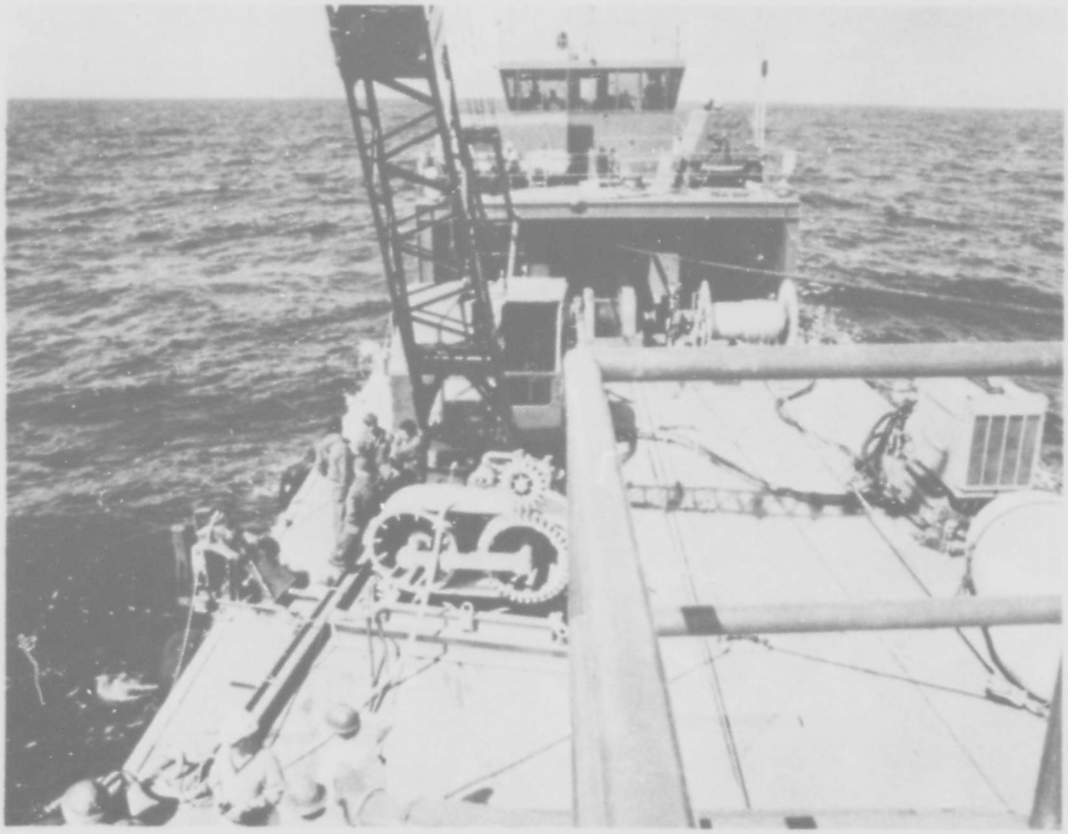

Figure 3.3.3. Equipment setup on warping tug during foundation emplacement cruise.

indicate that the lift system design is adequate. The guideline system evaluation was based on its effectiveness as a guidance system and its ease of handling.

Simple Lift System

Figure 3.3.7 shows the measured and calculated dynamic tension traces when the SEACON I hull was suspended at a depth of 50 feet. Although these two traces do not match exactly due to the random nature of the tension, the calculated peak tensions are within 20% of the measured peak tensions. This error is considered tolerable for the purpose of lift system design. The dynamic tensions were considered high as compared to the static weight of the payload. However, the measured total line tension never exceeded 30,000 pounds, which is only one-third of the lift line's breaking strength.

The effectiveness of the soft-spring lift system is clearly demonstrated in Figure 3.3.8. The hull was suspended 50 feet above the seafloor, near where the danger of a hard landing on the concrete foundation was of primary concern. The measured dynamic tension was only 2,000 pounds. The vertical peak-to-peak motion of the hull was estimated to be only 0.6 foot. The spring constant of the lift line was slightly lower than the design value due to the breakage of the outer braid. The nylon rope was effective in reducing tension and motion when the hull was near the foundation.

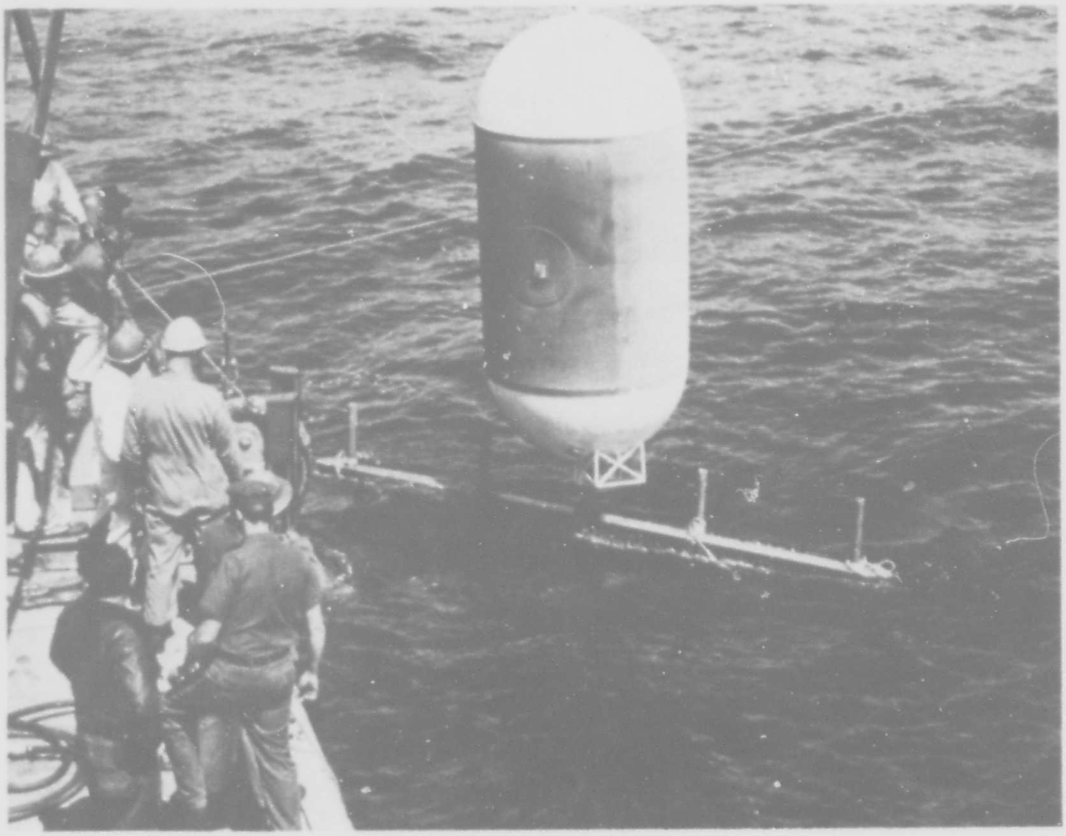

Figure 3.3.4. Guideline buoy and spreader bar assembly being lowered into water. Guidelines, secured to vertical bars, were attached after assembly was 50 feet down.

The parting of the outer braided cover (Figures 3.3.9 and 3.3.10) occurred after the SEACON I hull had been suspended under the warping tug at the 50-foot depth for about an hour. The rope was supported by a sheave 24 inches in diameter having a bell shaped groove 1-3/4 inches wide. The sheave had been hard-surfaced with chromium-nickle and this had partially chipped off. Since the lift line was a 2-inch-diameter Samson 2-in-1 braided nylon rope, the sheave groove was slightly undersized. At the time of the selection, it was expected that the rope would deform under tension to conform with the steel groove. The lift line was powered by a double-drum traction winch. Based on consultation with several specialists, the possible sources of failure are wear, heat generation, and fatigue, but not overstressing. After the line was recovered during the hull retrieval, a visual examination was made to identify the cause of failure. Based on this visual examination, it was concluded that the line failed due to nonuniform distribution of load between the core and the outer braids. Frictional wear against the undersized sheave, and stress creep under long-term loading also contributed to the failure.

It is hypothesized that the nonuniform stress distribution between the inner and outer braids was caused by slippage between the braids. Slippage results because the lift line is reeled on/off the storage drum by a traction winch which develops line pull by friction between the traction winch drums and the

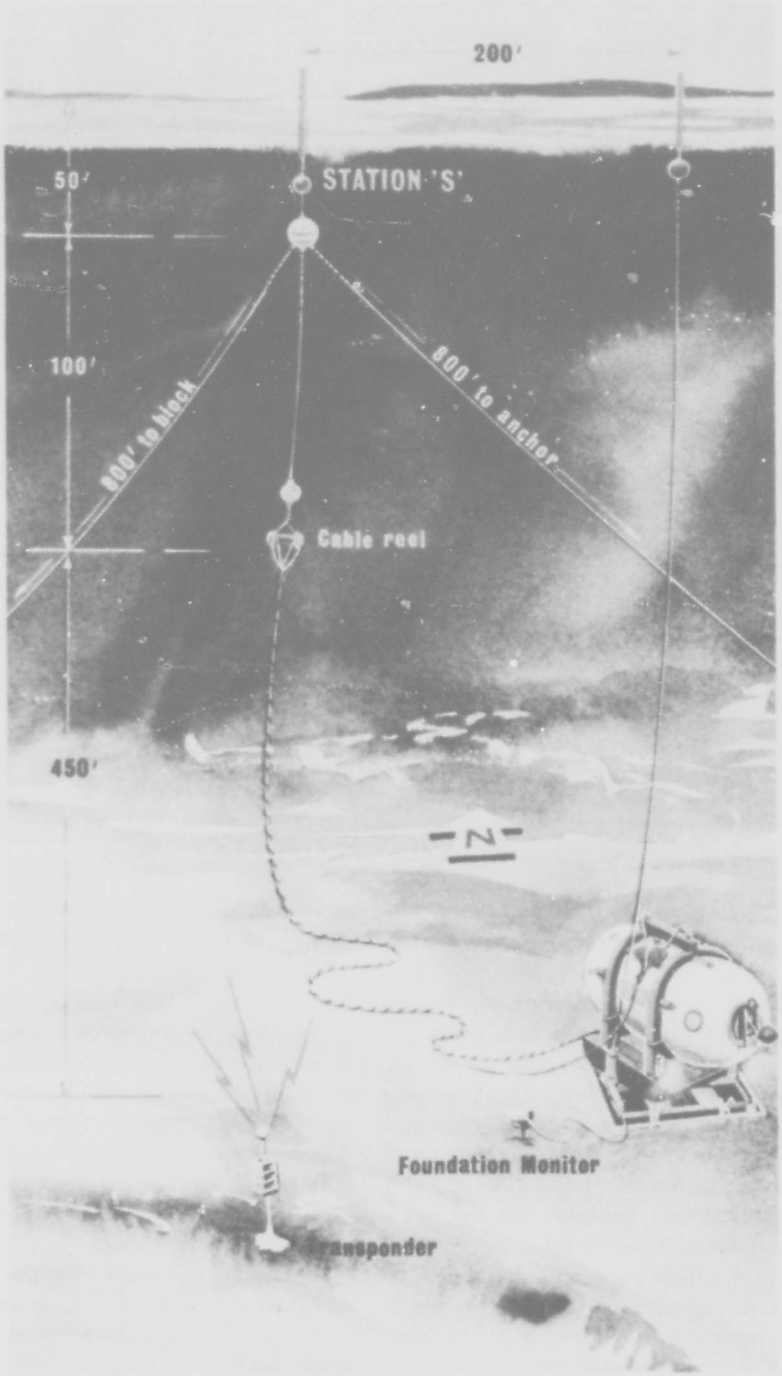

Figure 3.3.5. Completed SEACON I installation.

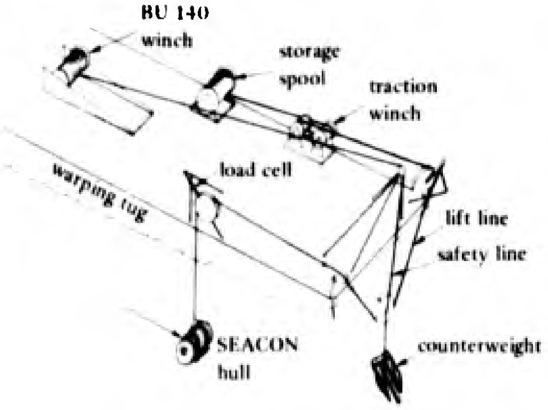

Figure 3.3.6. SEACON motion compensation system.

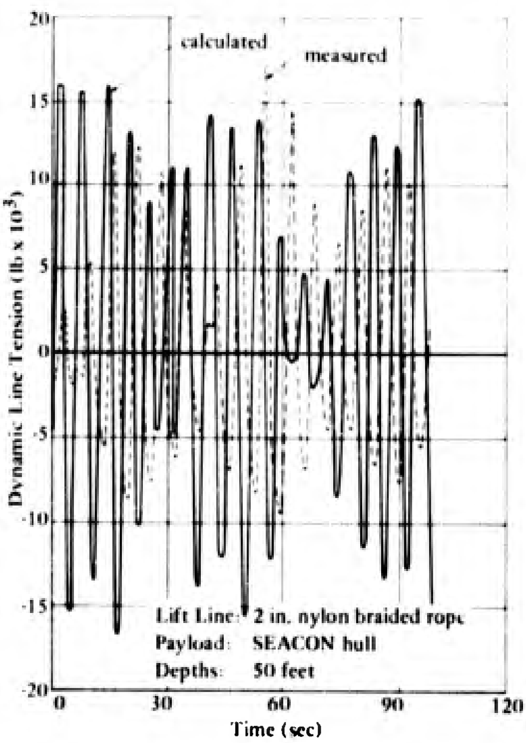

Figure 3.3.7. Comparison of measured dynamic line tensions with values calculated by Program LILIAN.

outer braid of the nylon rope. In this operation, the nylon double-braided rope was wrapped around the 36-inch double-traction drums seven times. As slippage progressed under the continual dynamic loadings, the outer braid continued to take a greater share of the load. The slippage, plus a reduction of fiber strength from mechanical abrasion of the outer braid against the metallic sheave and time-dependent effects, caused the outer braid to part after 1 hour with the hull at 50 feet.

Counterweight Motion-Compensation System

The measured and calculated dynamic tension traces are presented in Figure 3.3.11. These traces show that the counterweight system is effective in reducing the dynamic tension. The peak dynamic load was less than 2,000 pounds, which is only 1/5 of the static load. The computer program using an equivalent spring constant to represent the counterweight system yields a lower magnitude of tension because of the linearization of the highly nonlinear stress-strain relationship.

The disadvantages of this system are the higher hardware costs and the greater handling requirements. Large suspended sheaves were required to minimize the bend fatigue of large wire rope. A forty-to-one sheave-to-rope diameter ratio is required. Because of the large sheave size and the high line tension, large frameworks were required to support the load. The counterweight should weigh approximately twice the submerged weight of the payload. When such a weight is not available, fabrication of a heavy weight out of steel or lead is required and adds to the expense of the operation. Furthermore, suspended large sheaves are awkward to handle, and there is a danger that the lift line might jump the groove and jam between the sheave and the sheave cheeks.

Guideline System

The method of remotely placing a structure on top of another by means of guidelines proved effective. With the bow guideline inactivated, the SEACON I hull was successfully placed on the foundation; one guide cone properly matched over the corresponding guidepost. The hull was positioned about 30 degrees from the intended orientation. Had it been lowered with double guidelines there should

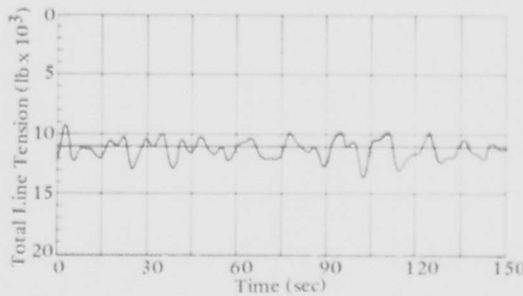

Figure 3.3.8. Record of line tension obtained when hull was suspended at 550 feet with nylon line (peak dynamic tension less than 2,500 lbs).

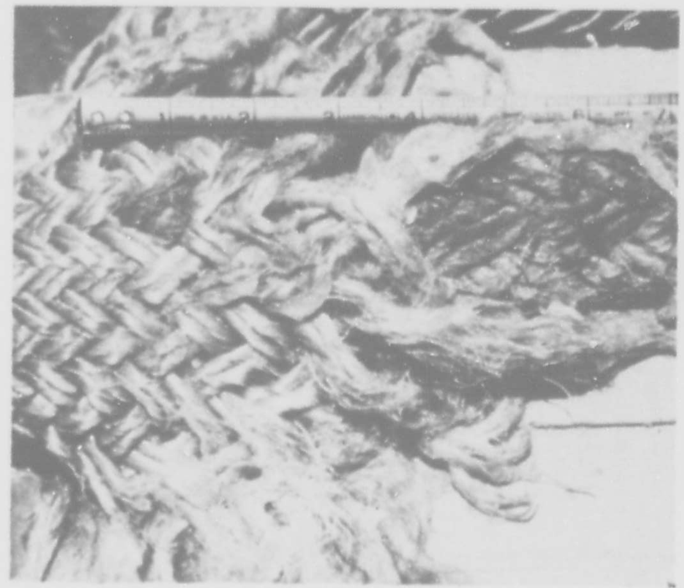

Figure 3.3.9. Upper end of parted nylon rope showing exposed core braid.

Figure 3.3.10. Lower end of parted nylon rope.

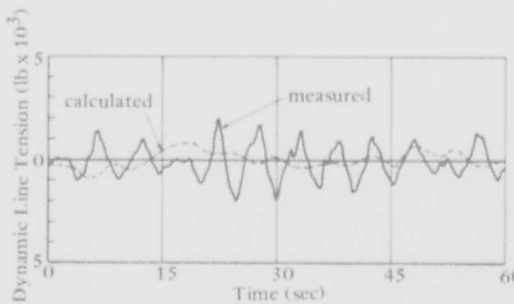

Figure 3.3.11. Comparison of calculated and measured dynamic tension showing lack of agreement due to oversimplification of dynamic model for counterweight system.

have been no misalignment. The stern guideline was deployed at the site for 1 year. During this period, it served as a guideline for lowering an underwater television, which was used to inspect the exterior condition of the hull and to guide the NEMO submersible to a position near the SEACON I structure.

The primary deficiencies of this system involve the deployment technique and the attachment hardware. The SEACON I guidelines were deployed with the foundation. Three lines were attached to the foundation as it was being lowered to the seafloor. One incident of line entanglement was caused by an error in rigging. No entanglement was observed during the lowering operation. Continuous tensioning of guidelines by air winches was the key for the successful deployment. For greater depths, this method is not adequate because the rotation tendency and chance of line entanglement increase with depth.

The design of the hull guide cones required the guideline ends to pass through the guide cones when the foundation was in water. Divers' assistance is needed for this operation. By modifying the design of the guide cones the guidelines could be attached to the payload on the support platform to save time. For example, a latch could be installed on the guide cones with an opening to allow quick engagement of the guidelines. With guidelines in the guide cones before the payload is placed in the water the payload could be lowered without a long period of suspension at a shallow depth, thereby minimizing the danger of high dynamic tension in the lift line. Such an arrangement, however, requires specially designed ship-to-sea transfer equipment as will be discussed next.

Payload Transportation and Ingress/Egress

Information is lacking on how to transport heavy payloads to an ocean site and how to place them into water. The SEACON I foundation was carried on deck by the warping tug under the bow A frame and was lowered into the water by a combination of dragging and lifting. The operation was performed by a lift line through the A frame roller and a tag line attached to the payload for the control of its motion. This method was crude, and it was difficult to maintain uniform control of the lift line. A component mounted on the foundation was lost due to shock loads generated by the winch.

Transporting the hull to the site was considered much more difficult than transporting the foundation until a trial tow was performed in the harbor. The towing indicated that the hull was stable, and that it could be towed safely. Other methods considered included air-to-sea transfer, and transporting by a small barge and then lowering into the water by a crane barge at the site. The cost of the latter method was too high, and the crane barge was not available to work in deep water. Air-to-sea load transfer is a difficult problem, and this method of load handling should be avoided if possible. By towing the hull to the site, air-to-sea transfer and associated problems were eliminated. The hull was placed in its ready-to-lower position quickly and without problems.

When it is necessary to move a large payload from shipdeck to sea, specially designed handling equipment, preferably with motion compensation, should be used to assure safe load ingress. Other special equipment could include stern elevator hinged ramp, hinged A frame, gentry crane, center well, etc.

Support Platform Stability and Station Keeping

A stable platform with station keeping capability is a prerequisite for successful at-sea load-handling operations. The CEL warping tug is an excellent work platform for load handling. When it is oriented heading or tailing the sea, there is minimum roll and pitch. Since it is a shallow flat-bottom barge, it follows the long waves in heave. When spread-moored with two mooring lines at the bow and one at the stern, the motions are further stabilized. For the SEACON I operations, a three-point mooring system was deployed at the site prior to the emplacement cruises. This mooring system was able to minimize the surface excursions of the warping tug. With the transponder/navigation system, the position of the tug was adjusted by lengthening or shortening the three mooring lines with an accuracy of approximately 10 feet.

CONCLUSIONS AND RECOMMENDATIONS

1. Deep-ocean technology for the emplacement and recovery of a heavy (50-ton) payload, at shallow (600-foot) offshore (7-mile) sites, 25 miles from port, has been demonstrated. A heavy payload, supported by a flexible lift system, can be properly positioned on a predeployed foundation by means of a guideline system.

2. The simple lift system using a 2-in-1 braided nylon rope was effective in reducing line and motion when the payload was near the bottom. High line tension was encountered when the payload was near the surface.

3. Although 2-in-1 braided synthetic ropes are effective in reducing dynamic and snap loads, their use in prolonged lifts at sea should be made only after an in-depth study of the behavior of such ropes over sheaves and traction drums.

4. The counterweight motion-compensation lift system utilizing a steel wire rope was effective in reducing dynamic line tension and payload motion through the depth range of the payload.

5. A guideline system is useful in positioning a payload over a preplaced foundation or anchor. Line entanglement is not a serious threat to the guideline system so long as the guidelines are properly tensioned. Hardware improvements and field data are needed for better guideline design and performance.

6. Specially designed load-handling equipment is recommended for safe payload ingress into the sea.

7. Prolonged suspension of a payload near the surface (50 feet) should be avoided. The handling procedure should be designed to allow the completion of most of the rigging and other mechanical and electrical connections on deck of the support platform or at the surface before the lift line is subjected to the dynamic loading.

SECTION 4

DEMONSTRATION TESTING OF AN EQUIPMENT TEST TRACK IN COMBINATION WITH A SOIL CUTTER-PUMP SYSTEM

by E. J. Beck

OBJECTIVE

The purpose of this experiment was to demonstrate the functioning of the combined equipment test track and soil cutter-pump equipment to 600-foot depths, thus extending the results of the shallow-water experimental work.

INTRODUCTION

This test was conducted to obtain some experience with a track designed for operation on submerged, saturated soils under actual deep-ocean conditions. The track (Figure 3.4.1) had previously been extensively tested in shallow water in Maryland [3.4.1] and off Port Hueneme, California [3.4.2]. The soil at those two locations did not approach the claylike material available at the SEACON I site off Santa Barbara, California, considered to be more typical of deep-ocean bottoms than what the shallow-water sites provided.

Because of the long time required to lower the assembled equipment and instrumentation with a number of hoses and control wires to the bottom, only one test was conducted. Track loading and retardation were set at values which would develop significant shear in the soil but not a high rate of slip. The maximum drawbar pull was, therefore, not developed, but an intermediate pull, considered useful in the eventual design of bottom-crawling construction equipment, was used.

The equipment as shown schematically in Figure 3.4.2 was modified in several respects from its original fitting for shallow-water use [3.4.2]. First, it was not possible at 600 feet to observe the exact position of the track or its cable with time to obtain its velocity, as in the shallow-water tests. Second, while the hydraulic dynamometer originally used to measure drawbar pull was retained, the direct reading hydraulic gage was replaced with a hydraulic strain gage unit. It was impractical with limited controls and only two hydraulic hoses from the surface to retard the progress of the track with a hydraulic winch. A heavy slide was dragged along the ways (Figure 3.4.1), and the friction was adjusted for the conditions to produce the desired drag. Also, it was not possible at the 600-foot depth to observe the position of either the track or drag with respect to time to obtain its velocity. A multiturn precision potentiometer in a pressure housing was fitted to the drag, and as the drag moved along a taut wire the potentiometer gave its exact position. Plotted against a known chart speed at the surface, the location of the drag at any moment was known. For shallow-water a hydraulic dynamometer with a direct reading gage was used to obtain the drawbar pull. To avoid the 600-foot-long pressure tube and possible errors introduced by uncertain fluid density, the gage was replaced with a hydraulic dynamometer utilizing strain gages, and the force was recorded on the same strip chart as was the potentiometer readout indicating the drag's position.

To allow direct observation of the track, a movable TV camera was mounted adjacent to the position-indicating potentiometer. The camera's tilt and pan was controlled through the same cable that carried the TV signal and electric power for site lighting. The track was connected to the retarding drag by a 1/4-inch steel cable. The cable was useful only in tension, so the track could be tested for only one run.

OPERATION

The conductor-cable-conduit system consisted of a 1-1/2-inch nylon lifting rope, two 3/4-inch-ID high-pressure hydraulic hoses, two electrical cables each 3/8 inch in diameter, the television cable about 5/8 inch in diameter, and a cable to the positioning transponder for determining the unit's location on the bottom with respect to the CEL warping tug. The hydraulic hoses were spooled as a pair on a large

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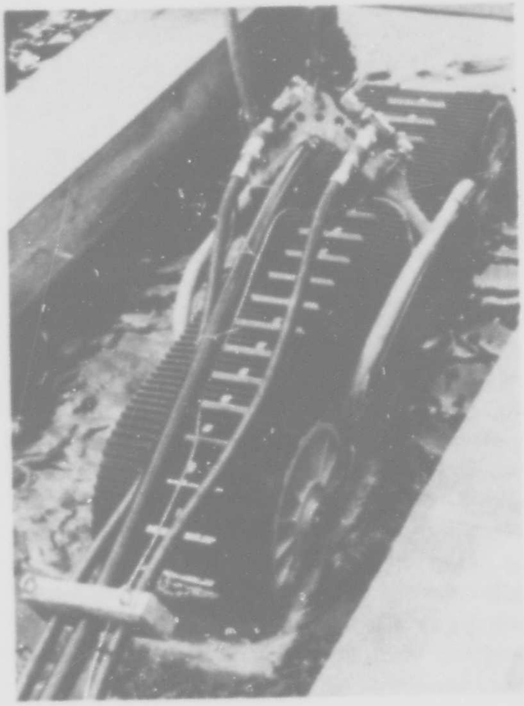

Figure 3.4.1. Experimental equipment test track designed for use on submerged, saturated soils on the seafloor.

electrical hydraulic winch. Each of the other components was individually spooled or stored, and all were mated after passing through the fixed sheave on the starboard side of the CEL warping tug. They were taped and tied at about 12-foot intervals over the entire length of the assembly, just under 700 feet. Upon raising the test assembly, the CEL riggers removed the ties before the bundle of lines was brought over the sheave. While this required the riggers to work over the side part time, it did allow orderly storage of the individual lines and hoses in their respective reels. This time-consuming process was accomplished without incident.

Because the warping tug was moored, it was expected that the test unit could be landed almost directly below. A limited amount of extra hydraulic hose was available beyond the 600 feet necessary to reach the bottom. Even though the test assembly was fairly heavy, its sail area and that of the hose and line bundle caused it to drift in the current in the water column. With about 670 feet of line out, the test assembly would just touch bottom. A position check with a three-transponder system showed that indeed all the available scope was utilized in landing the unit on the bottom. Once landed, the test unit was not moved during the test run.

During transit to the bottom, the test track was setting on a plywood platform at one end of the test frame, and it had been planned to lower it to the bottom without retention on the platform other than gravity and friction. On the particular day of the test, a brisk westerly wind created considerable surge and some small breaking waves; it was elected to lash the track to the platform during lowering through this rough surface down to about 40 feet below the surface, at which point it was cut loose by a diver.

Just at the end of the test run, which was limited by the length of the track guiding the drag, both channels of information failed. Although the television camera was working, water had entered the housing for the pan and tilt motors before it touched bottom, so the track and its operation could not be observed. When the track was operated, a great deal of fine debris was thrown up into the current, and essentially nothing could be seen except this debris drifting by. The failure of the pan and tilt prevented observation of the track, but it did not interfere with the taking of test data.

Following the test run, the track was operated long enough to return it to the wood platform for raising. It could not be determined whether the track returned to the platform and fell off shortly after lifting started (which seems probable), or did not return to the platform. There was mud in the front sprocket and the track was suspended from the towing cable when retrieved.

One other problem which, while anticipated, was not fully appreciated, was an increase in line pressure loss in hydraulic lines due to cooling. The actual increase in pressure loss in 1,400 feet of 3/4-inch line was about 40% higher than anticipated, indicating a lower average temperature of the water column. The hydraulic power unit capacity was far greater than required (both in pressure/capability and volume) so that the operation was not hindered. Without this excess capacity, the operation of the

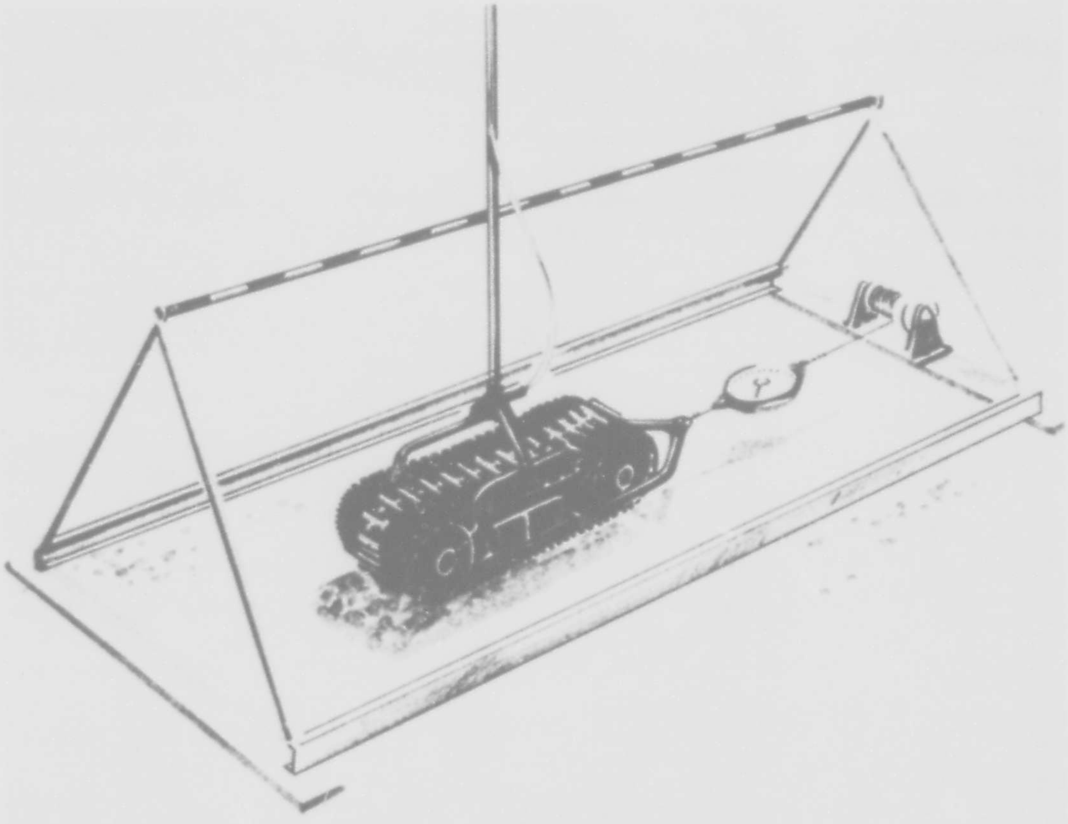

Figure 3.4.2. View of equipment test track showing hydraulic dynamometer.

track would have been marginal or unsatisfactory. This would indicate a need for precise temperature information for deep operation of hydraulic equipment with marginal motor and pump capacities. The operation of the hydraulic motors in the test track, on the other hand, was undoubtedly enhanced by the increased viscosity, as the lightweight oil (Military Specification 5606B) was somewhat less viscous and lighter than the industrial oils normally recommended for this type of motor.

CONCLUSIONS

1. From an operational standpoint the tests were adequate but marginal, in that failure could easily have occurred.

2. With the exception of observation of the track, the data acquisition was adequate.

3. With minor modifications the system as lowered could be made capable of repeated test runs without raising the unit to the surface.

4. The handling system, which involved pairing a large number of hoses, lines, and electrical cables, was adequate and cost effective; a system combining the many parts in a single cable capable of spooling and paying out through a sheave would be very expensive.

5. The hydraulic system utilized, while involving heavy hoses, was very reliable; all the failures incurred in the testing were electrical. The efficacy of using hydraulic power to a depth of 600 feet is well demonstrated in these tests.

RECOMMENDATIONS

For similar operations in the future, several modifications based on results from this test might be made. First, an alternate drag method using pulleys and weights might be devised. The weight would be raised as the cable was pulled out and would lower as the track was reversed. This would allow repeated tests without raising the unit to the surface.

SECTION 5

EVALUATION OF NEMO FOR CONSTRUCTION INSPECTION

by P. K. Rockwell

OBJECTIVE

NEMO (Naval Experimental Manned Observatory), Figure 3.5.1, is an acrylic hulled submersible with an anchor/winch system for moving vertically in the water column (the principal mode of operation). In the SEACON I experiment NEMO was evaluated with respect to visibility, maneuverability, operational requirements, turn-around time on dives, and the efficiency of its documentation and communication systems.

INTRODUCTION

In the SEACON I experiment the goal was to evaluate the in-situ capability of a transparent hull submersible for observing ocean engineering experiments. Further description and a general operational evaluation of NEMO are contained in References 3.5.1 and 3.5.2.

TEST PLAN

NEMO's anchor must be lowered prior to beginning a dive. Also, the translation capabilities of NEMO are difficult to control and are limited to 50 to 100 feet horizontally. In order to get NEMO close to SEACON I and also avoid hitting the SEACON I structure with NEMO's anchor, a system was devised to prelocate NEMO's anchor at the desired location. The anchor lowering system (Figure 3.5.2) was a spreader bar attached to the anchor at one end and to one SEACON I guideline at the other. After the anchor location was determined to be correct via a TV camera the other equipment was retrieved. NEMO could then proceed to the preselected location, and the occupants could inspect and photograph SEACON I.

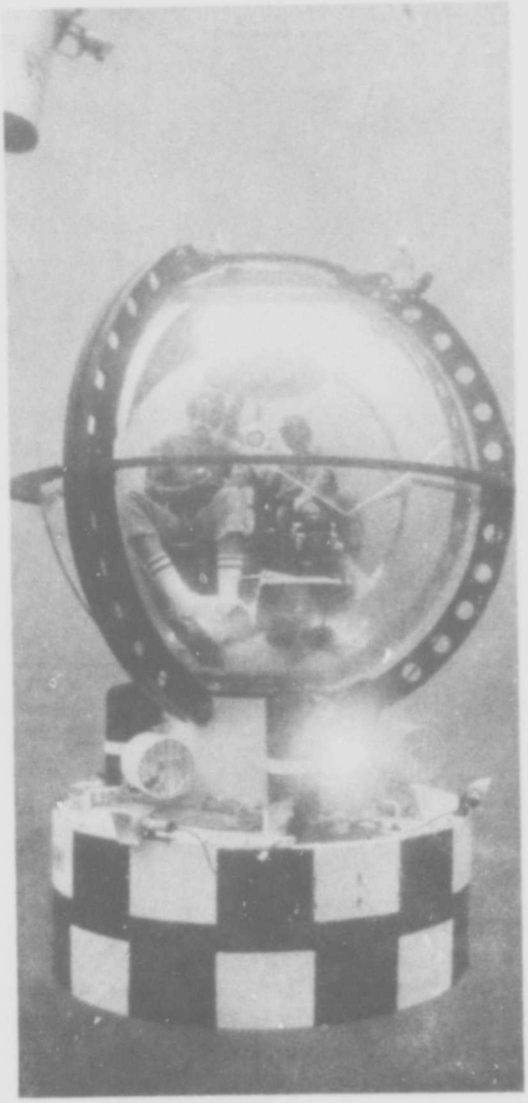

Figure 3.5.1. Navy Experimental Manned Observatory (NEMO).

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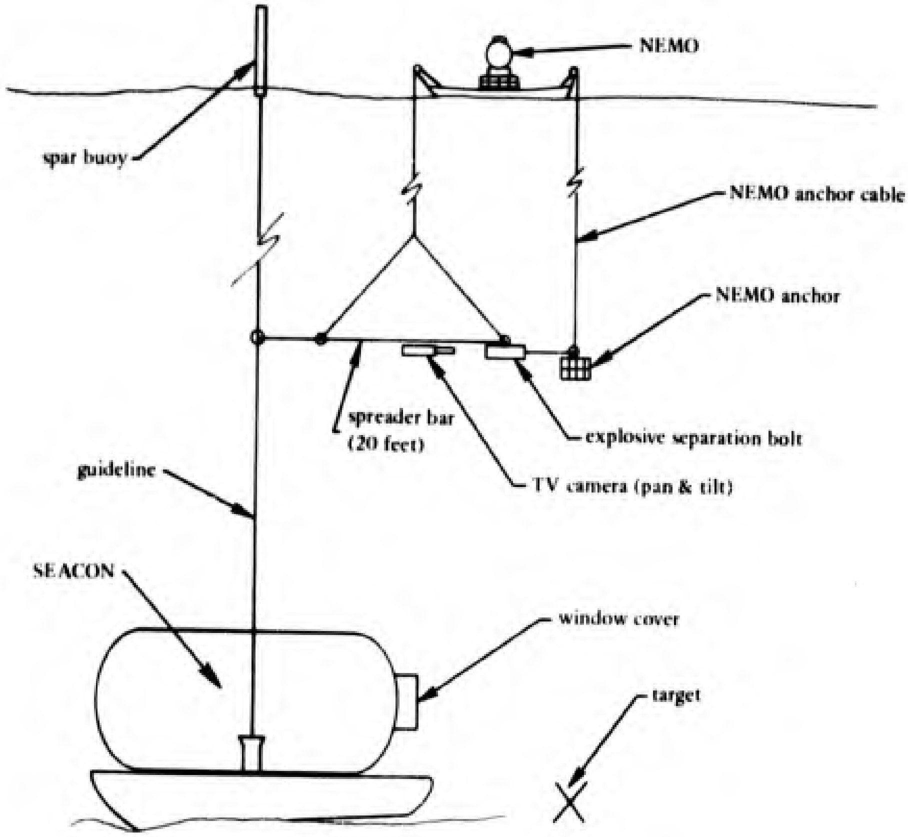

Figure 3.5.2. Deployment of NEMO anchoring system.

RESULTS

On 3 February 1972, the anchor was placed about 12 feet from the window end of SEACON I using the system diagrammed in Figure 3.5.2. On the morning of 4 February 1972, NEMO started its dive, stopping approximately every 100 feet to take data and check equipment operation. The SEACON I lights were turned on when NEMO reached 450 feet. NEMO personnel reported seeing a faint glow from the light at the 500-foot level, and then proceeded to 600 feet. The visibility was so poor at 600 feet that neither the bottom nor SEACON I could be seen (except for the SEACON lights). In order to translate, visual contact with the bottom must be maintained. Since the bottom was not visible, a translation was not attempted. Therefore, visual contact with SEACON I was never achieved.

Upon surfacing, it was apparent that NEMO was about 50 to 60 feet from the point of descent. Apparently, the anchor had moved during descent.

CONCLUSION

Overall, the anchor emplacement operation and the actual NEMO dive were successful. Failure to make visual contact can be attributed to three factors:

1. The poor visibility at the bottom (*CURV III* operators later estimated 5-foot visibility).

2. The fact that NEMO's anchor moved out of posi- while NEMO descended.

3. The lack of a true translation capability with NEMO.

RECOMMENDATIONS

Several recommendations can be made to assure a better probability of success for in-situ inspection of bottom structures with acrylic-hulled submersibles similar to NEMO.

1. Prior determination of bottom conditions, especially current and visibility, is important. No matter how well submersible personnel can see out their vehicle, if the current is such that they cannot hold position, or if turbidity limits visibility to only a few feet, effective inspections cannot be made. A device, located in the target area, which can send current and turbidity data to the surface on command is required.

2. NEMO's anchor/winch system needs improvement. The anchor jerks from the bottom when the winch is started, allowing the current to carry NEMO and its anchor away from the desired location. A proportional control valve would allow smooth starts and stops during winching, thus eliminating the jerk loads applied to the anchor.

3. An inspection and observation vehicle, with or without a transparent hull, needs an effective near-bottom translation capability. Automatic or semiautomatic buoyancy controls or a vertical thruster are required, as visual contact with the bottom cannot be relied upon. Efficient thrusters and a directional control system are also needed for near-bottom excursions.

SECTION 1

EXPERIMENTAL EMBEDMENT ANCHOR TESTS

by J. E. Smith and R. M. Beard

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OBJECTIVE

Two types of direct-embedment anchors under development by the Civil Engineering Laboratory are the vibratory anchor and the explosive salvage anchor. SEACON I objectives were: (1) examine the equipment, procedures, and methods necessary to effect proper deployment of the anchors and the preciseness of the positioning achieved; (2) document the in-service use and performance of the anchors over an extended time period, and (3) gain needed operational experience in installing anchors at a water depth considered to be the threshold of deep-water anchoring problems.

INTRODUCTION

Anchors are an important but previously neglected area of development in deep-sea technology. There are requirements for sophisticated structures and instrument arrays to be reliably held in position on and under the sea in depths and at locations not normally associated with anchoring. Plans for such ocean construction usually call for using deadweights and/or conventional drag anchors. Deadweight anchors have a low holding-capacity-to-weight ratio, and are unreliable on sloping seafloors. Drag anchors require large scopes of line to hold effectively and then resist loading strongly from only one direction. Only recently have anchors that would overcome these deficiencies been under development. These anchors, referred to as direct-embedment anchors, penetrate directly into the seafloor without a preset pull. They have high holding-capacity-to-weight ratios because their resistance to movement is derived from the strength of the soil or rock into which they are embedded. They can hold on sloping seafloors and can resist loading effectively from any direction because their flukes are buried deep into the seafloor directly under the load line.

DESCRIPTION

The vibratory anchor, Figure 4.1.1, is an assembly comprising four major components: a vibrator power unit, a shaft with a specially designed quick rotating fluke attached, a support frame, and a lead-acid battery pack. The vibratory anchor is driven by a 10,000-pound-capacity electric vibrator powered by the battery pack. The quick-rotating fluke minimizes penetration resistance then engages the fluke at its deepest penetration. The anchor stands about 20 feet high and weighs about 1,800 pounds.

The explosive salvage anchor, Figure 4.1.2, is also composed of four major components: a launch vehicle, an anchor-projectile, a propulsion package, and a safe-and-arm (S/A) device. The launch vehicle itself is composed of three circular hull sections, three struts, and a gun barrel. The salvage anchor utilizes a single-pulse propellant burn in the gun barrel to drive the anchor-projectile at high velocity into the seafloor. Different anchor-projectiles are used for sand, clay, and coral seafloors. The salvage anchor weighs about 12,000 pounds, is 12 feet high, and is 10 feet in diameter at the base.

TEST PROGRAM

The test program planned included three phases: (1) installation, (2) long-term performance monitoring, and (3) extraction after long-term service. Installation of the anchors was to be accomplished using the CEL warping tug as the work platform. One prototype vibratory anchor and one prototype explosive salvage anchor were to be placed. A single-riser mooring system, consisting of a foam-filled subsurface buoy, a foam-filled surface buoy, and appropriate connective gear, was devised for each anchor.

Once the anchors and moorings were installed, the program called for documentation of the service loads applied and the consequent performance of the

Figure 4.1.1. Vibratory anchor is deployed by support vessel.

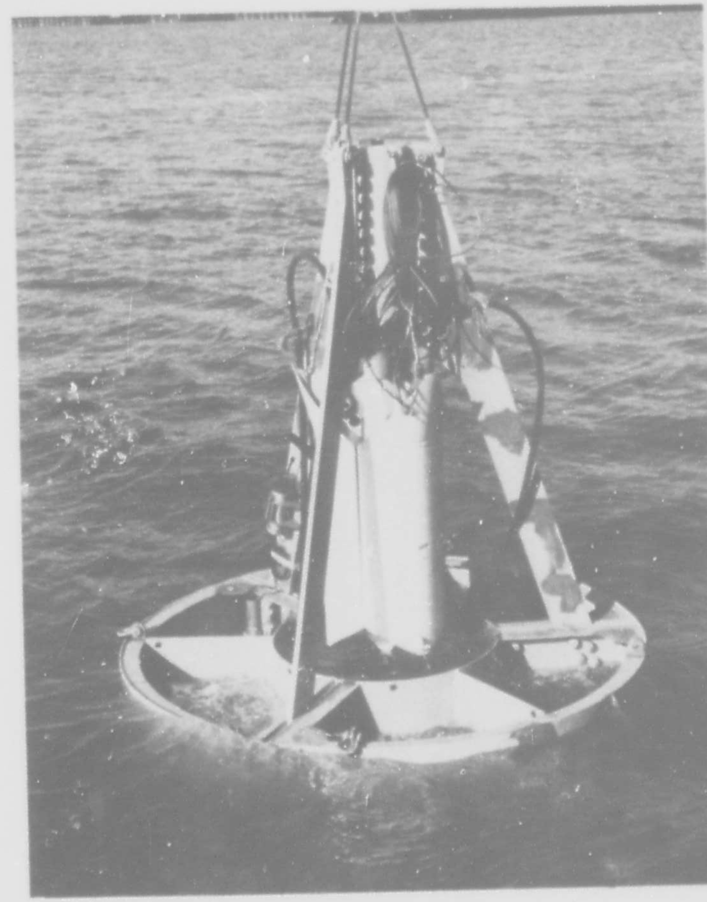

Figure 4.1.2. Lowering explosive salvage anchor.

anchors. Whenever arrangements could be made with users of the mooring, load measurements were to be obtained, and ship characteristics and environmental conditions were to be noted. Upon completion of the in-service period, extraction was to be accomplished using the CEL warping tug as a work platform. Pullout loads were to be measured.

RESULTS

Two separate attempts were made to emplace the anchors. The first, in June 1970, ended with neither mooring installed. Installation of the vibratory anchor was thwarted by an electrical short at a bulkhead connection on the circuitry interconnecting the battery boxes. An immediate repair could not be effected because the batteries were totally discharged as a result of the short. Deployment of the salvage anchor was terminated when a mishap occurred to the deck crane while handling the anchor at the air-water interface. A large amount of water contained in the tub-like hull section of the salvage anchor increased the load suddenly and caused the crane's roller bed to fail.

The second installation attempt was made in July 1970. Again neither mooring was installed, though the vibratory anchor was successfully embedded. Deployment of the explosive salvage anchor was attempted, but the anchor fired prematurely at a depth of 100 feet. The premature ignition occurred because the riser mooring line struck the bottom-contact firing mechanism which then triggered the safe-and-arm device. The riser line had been faked onto the deck of an auxiliary boat and hauled off to a distance of about 200 feet. After the anchor had been lowered to 100 feet the faked riser line was released preparatory to lowering the anchor the remaining distance to the seafloor. It was during this action that the bottom-contact release mechanism was activated. There was no hazard to personnel and equipment because the safe-and-arm device employed three safety features to prevent ignition too near the surface: a lanyard pin release, a pressure valve, and an in-line-out-of-line feature. Nevertheless, this operation in conjunction with other testing indicated that a simpler safe-and-arm device that permitted a more direct control of the firing process was needed.

The vibratory anchor was lowered, and after reaching the seafloor the vibrator unit functioned in excess of 1 hour as determined by monitoring the sound of the vibrator using the warping tug's precision depth recorder. However, when test loads were applied no load build-up occurred. The vibrator unit of the anchor assembly was subsequently pulled onboard minus the remainder of the anchor. Inspection of the vibrator revealed that the bolts that held the vibrator to the top of the anchor shaft had suffered fatigue failures. The anchor was presumed to have been driven into the seafloor. On a cruise in January 1971 the vibratory anchor was observed with a *CURV* vehicle. It appeared that the fluke was embedded about 6 feet; its holding capacity was estimated to be about 12,000 to 15,000 pounds. On another cruise 9 months after the embedment, the *CURV* vehicle attached a line to the anchor and it was pulled free of the bottom with a peak line tension of 16,000 pounds. It was determined that corrosion sufficient to affect the structural strength of the vibratory anchor had not occurred. No further efforts were made to install either a vibratory or salvage anchor.

CONCLUSIONS

1. The vibratory anchor is easy to deploy and can be accurately placed on the seafloor at a depth of 600 feet from a stable work platform.

2. Considerable care is required in preparing the prototype vibratory anchor. Particular attention should be given (1) to the electrical connections, because of high voltages, and (2) to the structural connections, because of the great number of cyclic stress reversals that are experienced during embedment.

3. More operational experience with the vibratory anchor is required before it can be considered an operational piece of hardware.

4. The loss of structural strength of the vibratory anchor by corrosion should not be a factor for periods of 3 to 5 years.

5. The holding capacity of the vibratory anchor, if the embedment depth and the sediment strength are known, can be reasonably estimated.

6. Had a mooring been connected to the vibratory anchor it would have served well for anchoring small work boats.

7. The weight of the salvage anchor complicates its deployment.

8. The water trapped in the salvage anchor reaction vessel when it is lifted through the air-water interface is a handicap.

9. The safe-and-arm design used for the salvage anchor is inadequate.

RECOMMENDATIONS

1. Take advantage of all opportunities to use the vibratory anchor to gain additional operational experience.

2. Redesign the launch vehicle of the salvage anchor to reduce its weight and eliminate the use of hull sections that trap water.

3. Redesign the explosive salvage anchor's safe-and-arm device.

SECTION 2

A FOUNDATION FOR THE SEACON STRUCTURE

by K. Rocker, Jr. and H. G. Herrmann

OBJECTIVE

This experiment had multiple purposes: (a) to evaluate a test device designed to obtain data on in-situ settlement/compressibility soil characteristics, (b) to evaluate a developmental foundation performance monitoring device, (c) to provide a foundation to reliably support the SEACON I structure, and (d) to provide a detailed case history on the design and performance of a spread-footing foundation.

INTRODUCTION

This section summarizes the design procedures and performance monitoring of the SEACON I foundation. The foundation was designed as the supporting base for the SEACON I structure to insure that all experiments could be conducted without problems related to orientation or instability. It is significant that very few spread-footing foundations have been attempted for deep-water structures on compressible soils. And even fewer have had the data base provided by a relatively extensive sediment exploration program.

DESIGN OF THE SEACON FOUNDATION

General Requirements

In order to perform its multitude of experiments, the SEACON I structure required emplacement on the desired seafloor site in an acceptable and stable orientation. The overall SEACON I goals also specified placing the foundation and the structure in a two-stage operation. This procedure gave, as a by-product, increased stability and reduced initial settlement, since it allowed consolidation to occur under the load of the foundation alone.

Design of the foundation superstructure was, thus, greatly influenced by the need for this remote linkup and by the limited capabilities for handling and positioning such large structures. This placement technique and the hardware configurations necessary to accomplish it are described elsewhere in this report.

Foundation Loading

Sizing of the foundation was initially based on the anticipated structure and foundation static loads. The empty foundation was expected to weigh 10,000 to 15,000 pounds submerged. The structure's submerged weight was taken as 6,000 pounds, although this value was subsequently revised upward. A considerably larger load of approximately 61,000 pounds would be applied were the structure to flood completely. Occurrence of flooding immediately following structure placement became the critical case in the actual foundation design. Figure 4.2.1 shows the loads discussed in terms of average bearing pressure applied on the sediment over a 14-foot-square footing, the eventual size. The design procedure was iterative and involved considering these and other loads simultaneously applied to footings which were varied in both size and shape during the design procedure. The separation, in this report, of settlement and stability computations for many footing sizes is done for clarity of presentation and is not intended as a synopsis of the step-by-step procedure. Steps are discussed out of their actual sequence in the complex design procedure.

Other Loading

Earthquake, current, and surge-generated forces of a significant level have a reasonable chance for occurrence in the Santa Barbara Channel. The effect of ground accelerations likely to be induced by even moderate earthquakes was large and is discussed subsequently with respect to stability problems. The

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total current surge-induced lateral force was calculated to be a maximum of 20 pounds per square foot, live load, based on estimated extreme water motion at the chosen site. This is not always considered to be applied in excess of the other critical loading conditions; for example, the lateral forces may not necessarily be critical under flooded structure conditions.

Other factors, including scour and animal undermining, could reasonably be expected to influence foundation behavior if they occurred at a significant level. Their influence on footing shape and appurtenances was large, although their influence on footing size was minimal.

In-Situ Engineering Properties

In order to analyze sediment response to anticipated loadings, a determination of sediment properties in the zone affected by those loadings was required. An extensive site selection investigation was made. A site was selected which would satisfy other project criteria and which appeared to offer a suitably level and relatively firm seafloor. This site was further investigated by in-place testing and laboratory analysis of sampled sediment. Plate bearing, vane shear, cone penetrometer, and friction plate tests were run in-situ, and stationary-piston corer samples were taken to a soil depth of 108 inches. Results of the in situ tests are presented in an earlier section of this report. Laboratory testing included consolidation properties, vane shear strength, specific gravity, Atterberg Limits, water content, grain size, and bulk wet density. Results of this investigation are summarized in an earlier section of this report and in Reference 4.2.1.

Settlement

Settlement and stability are the two factors most heavily influencing foundation size. The primary reason for settlement analysis for design purposes is to keep differential structure settlement, or tilting in the case of a single spread footing, within tolerable limits, and to do this with reasonable reliability. An increase in foundation size increases reliability, and the incremental fabrication costs are low. However, the complexity and cost of the deployment operation increase much more rapidly as foundation size and weight increase.

For a structure of this type a total settlement of several inches is not a disastrous condition. A differential settlement of this magnitude, however, can compound stability problems and may even contribute to a rotational failure. For small foundations where sediment variability over the foundation plan area is unknown, differential settlement is typically estimated as a percentage of the computed total settlement. Foundations on soft marine sediments may be subjected to differential settlements as large as the predicted total settlement. The inability to remove very soft local irregularities of surface material and the likelihood of nonlevel initial placement contribute to these large predictions of differential settlement for marine foundations. The initial settlement of the footing at 71 psf bearing pressure was expected to be a negligible amount due to high sediment resistance to skirt penetration. The resistance mobilized should be approximately equal to the submerged foundation weight, resulting in a very low applied base pressure.

The estimated force required for penetration was 10,100 pounds. The foundation was expected to apply about 13,000 pounds due to its static weight. Predictions of immediate settlement were made on the basis of plate bearing tests and friction plate tests performed in-situ. The prediction for immediate settlement of the footing and structure (pressure = 102 psf) was 0.9 inch. If the structure flooded immediately (pressure = 398 psf) the immediate settlement would be 3.0 inches. Consolidation settlements were estimated by classical Terzaghi consolidation theory using Boussinesq pressure distribution and an idealized void ratio-pressure diagram from laboratory tests. The maximum predicted settlement due to consolidation was 14 inches under one corner of a differentially loaded footing where pressure = 1,077 psf. Secondary compression was not considered important due to the short design life of the structure and the relatively low value of the coefficient of secondary consolidation [4.2.1].

Computations were made for a number of footing sizes for the flooded-structure loading condition. For a 14-foot-square foundation, differential settlement, equivalent to total consolidation settlement, was computed to be as large as 14 inches if the structure flooded immediately after placement with an initial foundation tilt of 4.4 degrees from the horizontal and a final stable

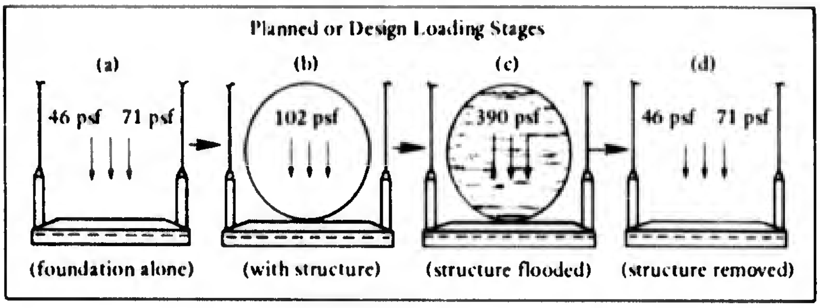

Figure 4.2.1. Foundation loading.

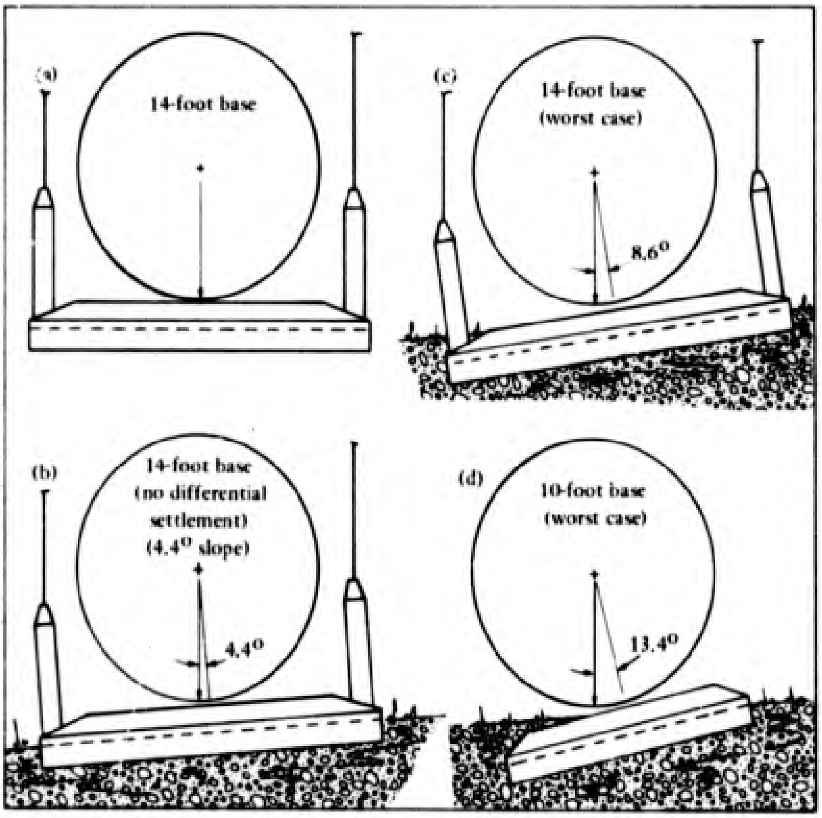

Figure 4.2.2. Stability design considerations.

inclination of 8.6 degrees. A 4.4 degree tilt, which was considered the worst likely case for the site based on topographic data, was set as a criterion for the maximum allowable initial inclination of the foundation alone. A larger initial inclination would lead to significant differential loading and possible overturning as a result of this and the resulting larger differential settlement.

Stability

The design process revealed stability to be the most critical factor in determining foundation size. This is primarily because of the high center of gravity of the structure and its large mass, in comparison to the foundation mass, under the critical flooded condition. The previous section on settlement revealed the important interrelationship of differential settlement with stability. The specific critical conditions that determined foundation size were an initial tilt of 4.4 degrees, a flooded structure immediately after placement, development of large differential settlements prior to structure retrieval, and maximum current force acting downslope on the structure. This would result in a total tilt on the order of 8.6 degrees on a 14-foot-square footing. This gave a minimum factor of safety against a bearing capacity failure under the downslope side of 1.15. Similar conditions with a 10-foot-square footing would result in a total tilt on the order of 13.4 degrees, almost certainly causing rotational failure due to overstressing of the soil under the downslope side of the foundation. These conditions are depicted in Figure 4.2.2.

Stability computations were based on the previously outlined static loading conditions and the sediment's supporting capability developed through shear resistance mobilized along active and passive wedges. A more detailed analysis for the critical case was not justified because of the assumptions included in the differential settlement estimates. These computations were made on a range of footing sizes to determine the 14-foot-square chosen size.

Analysis of lateral loads indicated a maximum expected lateral load of 8,900 pounds. The resistance to lateral loads which can be mobilized by the foundation with a 10-inch perimeter key was 8,900 pounds. This resistance is based on the remolded strength of the sediment rather than its undisturbed strength. Thus, the resulting factor of safety of 1.0 is considered adequate under this extreme loading condition.

Earthquake Effects

Consideration was given to the effects of earthquake-generated ground and water motion on the SEACON I structure because of its seismically active location. A survey of recorded earthquakes in the vicinity of the Santa Barbara Channel area revealed that a significant number of earthquakes have occurred in the site vicinity. A study [4.2.2] was made to determine the probability of various levels of severe ground motions at the site, and the effects on structures based on spread-footings. Assuming the water mass moves with respect to the sediment in response to the generated acceleration-velocity-displacement spectrum, forces as high as 36,000 to 57,000 pounds may be applied horizontally to the structure. Although the forces are transient, this would be sufficient to cause extreme differential settlements or overturning in both normal and flooded structure situations. As a result of these studies, it was determined that it would be impractical, if not impossible, to prevent overturning or severe movements during a significant earthquake. The probability of such a significant earthquake occurring close enough to the site to cause each severe ground motions was estimated to be 5% during the 1-year lifetime of the SEACON I structure.

Design for Other Factors

Subsequent to determining the necessary foundation size and weight, consideration was given to determining a best shape for the foundation base. Scour, animal undermining, and lateral movement determined the other design features shown in Figure 4.2.3, principally the skirt and low profile. Scour and undermining from local animal acitivity have been noted as being major contributors to excessive long-term differential settlements of small spread footings [4.2.1].

Preventative measures were taken to keep unwanted sediment removal or buildup to a minimum. Although photographs at this site and

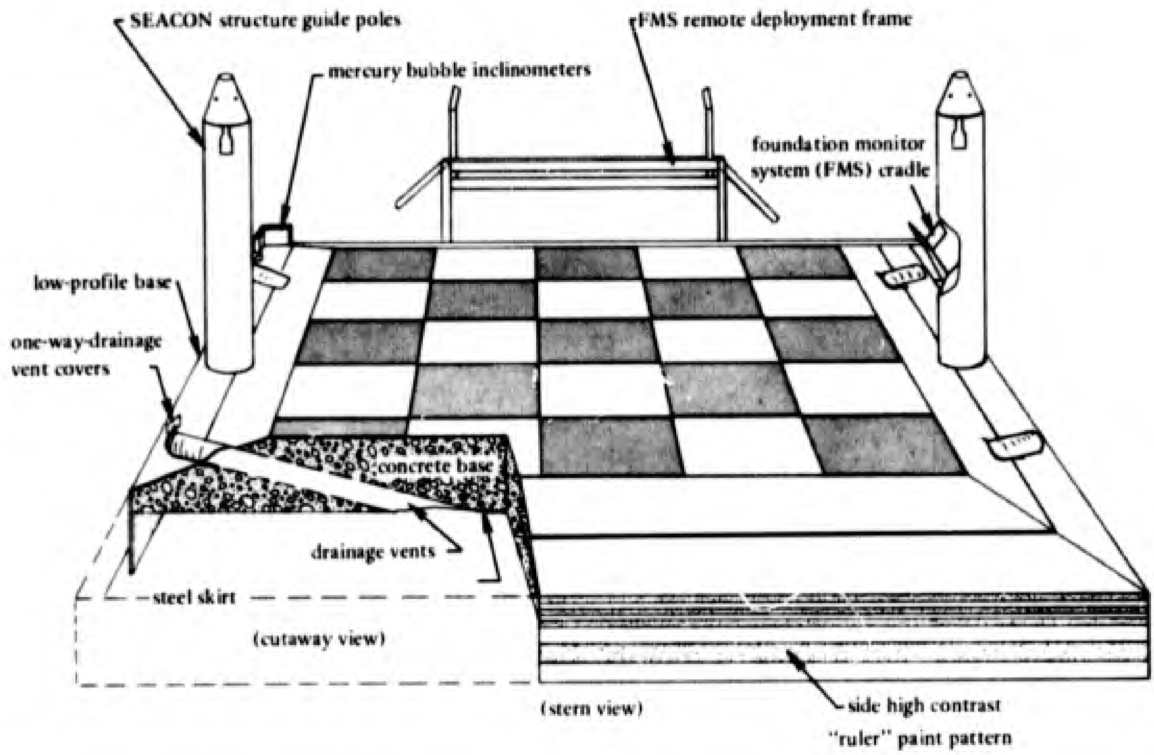

Figure 4.2.3. SEACON foundation.

others in the Santa Barbara Channel show constant fish activity around small footing bases, no attempt was made to discourage their presence. Mechanical means of doing this would likely be only partially successful, and chemical means were considered inappropriate. Prevention of sediment scour and buildup from current could not be totally achieved but could be influenced by the shape of the foundation which interacts with the water flow patterns. The foundation base was sculptured to taper from an 11-inch-thick concrete center to a 4-inch-thick edge over the outer 2 feet. In addition, a 1/4-inch-thick steel skirt was added to all edges of the foundation, extending 10 inches below the concrete base. These measures help to alleviate the three problems previously mentioned. The streamlined, low profile base reduces the turbulence of the bottom currents which initiate sediment scour. The low profile also provides a smaller vertical face, considered to be less attractive to moderate-sized fish. The skirt is designed primarily to key the foundation to the soil and, thus, to resist lateral loads. In addition, it prevents what current and animal scour that does take place along the foundation base from undermining the foundation. The "trapped" sediment also creates a partially anaerobic environment which discourages other animals from living beneath the footing.

Two problems became evident with use of a foundation skirt. One of these, the entrapment of water under its base during foundation placement, was largely eliminated by a simple means: drainage was allowed through four pipe channels in the concrete base as shown in Figure 4.2.3. One-way valves capped these pipes to maintain the desired base environment after drainage and to prevent easy entry by marine organisms. The second problem, interference of the skirt with foundation embedment, was more difficult to overcome. The skirt resists foundation embedment by mobilizing shear resistance along its sides and penetration resistance at its leading edge. Friction plate tests (forcing of a thin plate on edge into the sediment) were performed to get a better estimate of the forces required. Results of these tests indicated that a force as much as 50% larger than that predicted by basic theory would be necessary to embed the plates. Several explanations for this are plausible. The most likely is that the upper 1 foot of soil at this site contains a layer of nonplastic material. If this material is actually granular, then the resulting resistance to penetration would be higher than predicted by theory for a cohesive soil.

IN-SITU MODEL FOOTING TESTS

Long-term model footing tests were planned at the site as part of the design effort to complement, and in some respects confirm, laboratory computations. This model testing was integrated into studies at several sites in the Santa Barbara Channel to take advantage of the resulting additional information. Three footings were planned for placement at the SEACON I site for continuous monitoring of tilt and settlement. Two of these were instrumented LOBSTER footings [4.2.1] with diameters of 4.0 and 3.0 feet and bearing pressures of 100 psf and 200 psf, respectively. The other was a test foundation 6.0 feet in diameter with a bearing pressure of 150 psf. The Foundation Monitor System (FMS) was deployed on this footing following its placement [4.2.1]. These tests confirmed that animal undermining and/or scour have large effects on the behavior of a small footing. Based on observations of these footings it appears likely that the importance of these effects decreases with increasing foundation size under a given set of conditions.

It was anticipated that these model footing tests would provide a foundation record sufficient to confirm settlement predictions. However, problems with both LOBSTER deployments prevented obtaining usable settlement data from these tests. From visual observations on the 100-psf LOBSTER footing, it appeared that a small settlement (less than a few inches) took place almost immediately, with subsequent settlement not discernible. Considerable animal activity and slight current-induced scour and fill were noted, but no undermining was visible, and it was not possible to judge if settlements were affected.

The test foundation incorporated a low-profile design and skirt similar to the SEACON I foundation, but the anaerobic environment was not duplicated. An excellent record was obtained of tilt and settlement for a period of 56 days until the Foundation Monitor System was removed. The record began several days following footing placement and shows settlement proceeding at a relatively constant logarithmic rate close to that predicted for about 2 weeks, followed by an increased logarithmic rate until FMS removal. This is the only foundation of the large series studied where settlement proceeded at a larger rate than expected. Periodic remote visual inspection of this foundation indicated that this increase was not attributable to animal or current-induced problems. Differential settlements were considerably less than total values and did not increase when the latter did as would be the likely case for scour or undermining. Settlements measured approximately 3 inches over the period monitored, with all settlements prior to automated monitoring, both initial and consolidation, estimated by visual means at less than 2 inches.

It is difficult to compare predicted with observed behavior without knowledge as to whether the large rate of settlement at the time of FMS removal would continue. However, the overall behavior of this foundation and that of the 100-psf LOBSTER footing tend to confirm design steps taken to reduce footing scour and undermining.

In addition to these three model studies, four other foundation blocks were deployed in conjunction with other SEACON experiments. Subsequent observations of two of these blocks demonstrated the possible effectiveness of a low-profile footing, and the feasibility of embedding a properly designed perimeter keying edge with water vents.

FOUNDATION BEHAVIOR

Foundation Performance Monitoring

Three methods were employed to monitor the foundation's performance while on the seafloor. During the foundation placement operation, tilting considered critical would be reported immediately by a pinger signal actuated by an inclinometer attached to the foundation. Following placement, the Foundation Monitoring System (FMS) would continuously record settlement and tilt of the foundation. The third method was periodic visual inspection of the foundation itself and of two inclinometers attached to a foundation corner. Although the FMS would record continuously and more accurately on total and differential settlement, these data would not become available until after FMS retrieval and data reduction. The visual inspections were expected to reveal any major scour and undermining problems and give an immediate estimate of tilt and settlement.

The tilt-activated pinger was set to signal if an inclination of greater than 4.4 degrees was encountered. This would provide an alert during installation that the foundation was tilted more than allowed, thus requiring recovery and redeployment of the foundation in a more level attitude.

The FMS was to be deployed immediately upon touchdown of the foundation. This system requires one large component firmly attached to the foundation, and a smaller reference module to be rigidly embedded in sediment away from the zone of foundation-applied stress. The remote deployment method chosen was successfully tested on a model footing placed at 1,200 feet in the Santa Barbara Channel [4.2.1]. It utilized gravity to emplace the reference module and was triggered by detachment of the cable used to lower the foundation into place. The reference module is gripped in a scissors-like fashion by two 14-foot steel arms in a near vertical position. Following release the arms swing away from the foundation edge and emplant the reference module, then fall away from both module and foundation. This allows immediate gathering of settlement information and eliminates the need for a separate remote vehicle to place the system. FMS monitoring was planned in two stages with removal and replacement after 6 months to refurbish its batteries and to examine the instrument and data.

Visual monitoring of the foundation was to be aided by a high-contrast painted pattern on the foundation sides, as shown in Figure 4.2.3. The pattern was, in effect, a ruler to measure how far sediment came up the foundation sides. Black and white stripes were alternated in 1-inch or 3-inch layers, with lettered codings given to each side for identification.

Foundation Performance

The foundation appeared to behave according to expected criteria before and after placement of the SEACON I structure. Two factors largely influenced the evaluation of this behavior by making it more difficult. First, the empty foundation was considerably lighter than expected due to very high buoyancy forces applied through guidelines attached for structure placement. Actual submerged weight was only 7,700 pounds compared to the planned 13,000 pounds. Secondly, the FMS was unable to gather any exact settlement data necessary to carefully evaluate loading response.

The foundation was placed in an alignment with the 4.4 degrees tilt restriction imposed by design considerations. Although sporadic signals were received from the inclinometer-activated pinger during the placement operation, these ceased when the foundation was released in its final position. The signals were apparently in response to surface-induced ship motions translated to the foundation through the lift lines. Visual monitoring of the foundation several days after placement showed no unusual tilting, although the bubble inclinometers could not be read due to poor visibility and vehicle maneuvering problems resulting in poor camera angles. Photographs did reveal a microtopography with significantly larger variation than previous visual site observations. Considerable disturbance in the immediate foundation vicinity was evident, with one small trench approaching one of the foundation corners. It appeared that the foundation had itself disturbed the seafloor before its final touchdown and release in the position photographed.

The foundation initial settlement could not be established by these photographs, as sediment level against the foundation is not considered a reliable indicator, and the entire perimeter was not photographed. The sediment level on the foundation skirt was below the level of the concrete base over most of the photographed perimeter. This supports the possibility that skirt embedment and concrete base contact with the sediment were both incomplete.

Several problems acting together or independently prevented the FMS from obtaining data. Shipboard damage of a portion of the remote deployment system prevented its being used to place the reference module. The module was then properly placed several days after foundation deployment at the same time a visual inspection was made. The next inspection, following structure emplacement, revealed that both the reference module and the secured larger instrument piece were pulled out of their positions and deposited next to each other beside the foundation. The connecting umbilical cord was strung over the foundation and fouled on the remote deployment frame. A slackened wire rope may have entangled the FMS; when this rope was retensioned, the FMS was picked up and moved. In addition to these problems, the FMS recorded few data on tape due to an internal malfunction.

Visual observation was, thus, the only means of measuring foundation performance. Photographs and video tapes were made during three visits of *CURV* [4.2.1] vehicles to the SEACON I site. Two of these occurred several months following placement of the SEACON I structure. Good readings on the bubble inclinometers were made at this time, and revealed existing inclinations of less than 1 degree to the horizontal in the two principal planes monitored. A smaller and slightly different percentage of the foundation perimeter was viewed. However, the small trench had been largely filled in and no longer was at a level below the skirt base. Analysis of the mudline before and after structure placement indicated a settlement of approximately 2 inches.

No major problems with sediment buildup or scour were evident. Currents did produce small amounts of contouring around the foundation, most evident at corners. In one photograph, the buildup at one side of the skirt corner was 6 inches lower than the buildup only a few inches around the corner. Some of the unusual topography suspected to have been generated during foundation placement is less dramatic in the later photographs.

Comparison of Theoretical and Observed Data

Comparison of predicted foundation behavior with observed behavior was difficult due to lack of quantitative data. Based on visual observations, however, it appears that all foundation settlements were of the same magnitude as those predicted. The unexpectedly low submerged foundation weight should have reduced settlements prior to structure placement, and increased initial settlement when the structure was placed. However, the predicted foundation initial settlements were very small, and observed settlement may well have been "negative" – a reflection of incomplete skirt embedment. Predicted displacements from structure placement include 0.9 inch maximum immediate settlement, and 1.5 inches of consolidation settlement. The observed sediment level change of approximately 2.0 inches is in this range and may reflect final skirt embedment as well as these settlements.

CONCLUSIONS

1. The foundation satisfactorily supported the SEACON I structure and allowed all experiments to be carried out in the intended stable position. No indications of lateral motion, excessive settlement, or a tendency to overturn were evident throughout the duration of structure placement.

2. Although reliability of the partial visual foundation inspections is questionable, the foundation appeared to experience very small initial settlement after placement. In fact, the foundation could have had only partial base-area-to-sediment contact due to light loading and mobilized skirt resistance. Based on a similar reliable observation, the foundation appears to have settled when viewed 5 months after structure placement. These values compare reasonably with settlement predictions of negligible and 2-1/2 inches, respectively.

3. No animal undermining, major scouring, or sediment buildup was evident at the foundation, a likely reflection on the ability of the keying edge and profiled footing to discourage these phenomena. Quantitative effectiveness of these measures is difficult to assess because the magnitude of the problem at the SEACON I site is not well established.

4. The design procedure revealed particular difficulty in assessing the liklihood of structure overturn due to instability. Tilt, resulting differential loading, and settlements are affected by each other, and must be evaluated by an involved iterative procedure.

5. Visual foundation performance monitoring was adequate for the evaluation of SEACON I project

experiments but would likely have been inadequate from a quantitative standpoint had a foundation problem developed.

6. Exact large foundation total settlement characteristics are difficult to establish by visual means alone. Initial settlement of a skirted foundation is very difficult to measure by visual means.

7. Emplacement is likely to be the most critical moment for a well-designed foundation, regardless of the load level at that time. Foundation performance can be heavily influenced by emplacement technique. Maximum care appears justified to prevent multiple sediment contact by the foundation during emplacement. Multiple contacts caused by ship motions could result in an unsatisfactory placement.

RECOMMENDATIONS

1. Design of seafloor structures should emphasize low-profile and low-center-of-gravity structures to minimize problems from over-turning forces.

2. Placement of seafloor foundations should be accomplished with maximum care, and with minimal site disturbance from the foundation being emplaced. Surface-induced motion of the tethered foundation is the major problem.

3. All possible foundation loading conditions must be considered in the foundation design. Overturning forces from current- or surge-induced drag, earthquakes, and off-center loading caused by slope or tilt may be more critical to the design process than classical settlement or bearing capacity considerations alone and are more difficult to analyze.

4. Sufficient information on local topography (microtopography) to evaluate possible initial foundation inclinations must be made available to the design engineer.

5. Foundation orientation should be monitored to evaluate performance of the structure and its equipment. Coarse measurements of tilt and of initial and subsequent settlements should suffice. High-contrast painted patterns should be used on all surfaces, as they could become invaluable to visual monitoring if mechanical methods fail.

6. Foundation performance should be monitored to evaluate foundation-sediment interaction and improve future design reliability. Tilt, initial settlement, and subsequent settlements should be measured to an accuracy dependent on foundation size and on knowledge of sediment engineering properties.

SECTION 3

EVALUATION OF A PRESSURE-RESISTANT CONCRETE STRUCTURE

by H. H. Haynes

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OBJECTIVE

The objective of the test was to determine the strain behavior and watertight integrity of a concrete pressure-resistant structure under long-term hydrostatic loading. Other secondary objectives were to advance the state of technology in hull penetrations and joining of concrete structural members with epoxy adhesive.

INTRODUCTION

The use of concrete as a construction material for deep-ocean, pressure-resistant structures originated at CEL in 1964 [4.3.1]. Since that time, experimental studies have generated a considerable amount of technology on undersea concrete structures. The SEACON I experiment offered the opportunity to design, fabricate, and test a prototype-size reinforced concrete cylindrical structure (Figure 4.3.1).

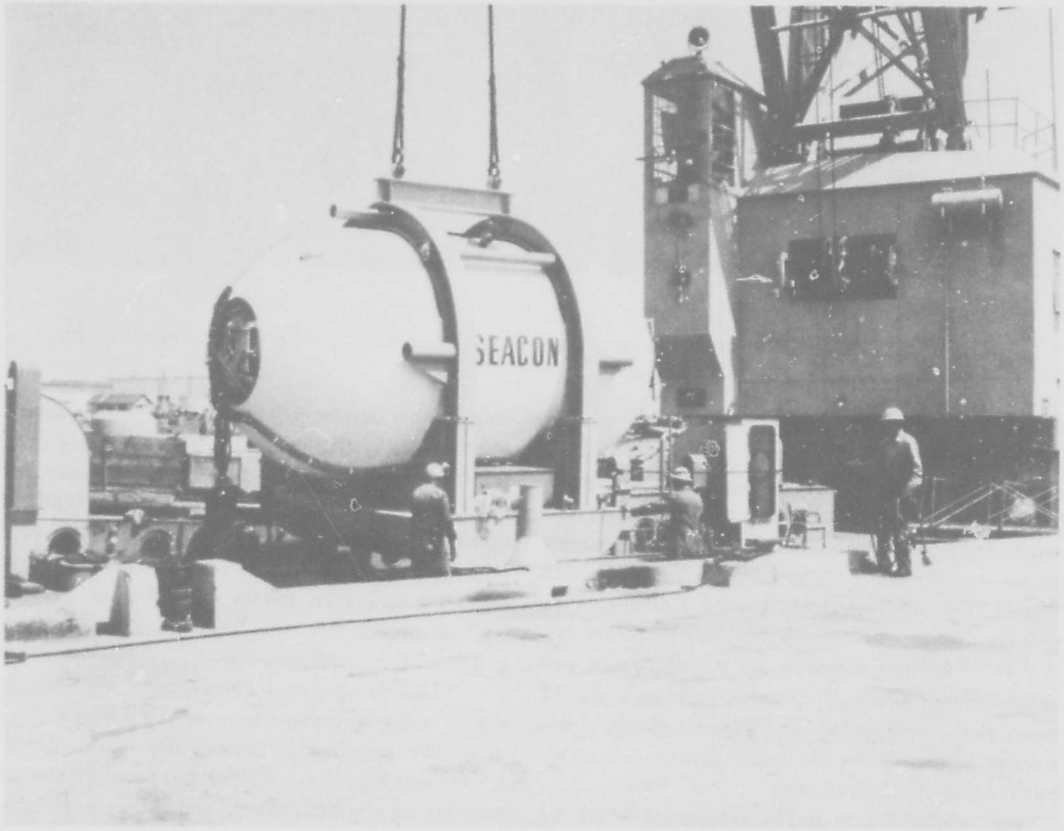

Figure 4.3.1. SEACON, cylindrical concrete structure with 10.1-foot outside diameter, 20-foot overall length, and 9.5-inch wall thickness.

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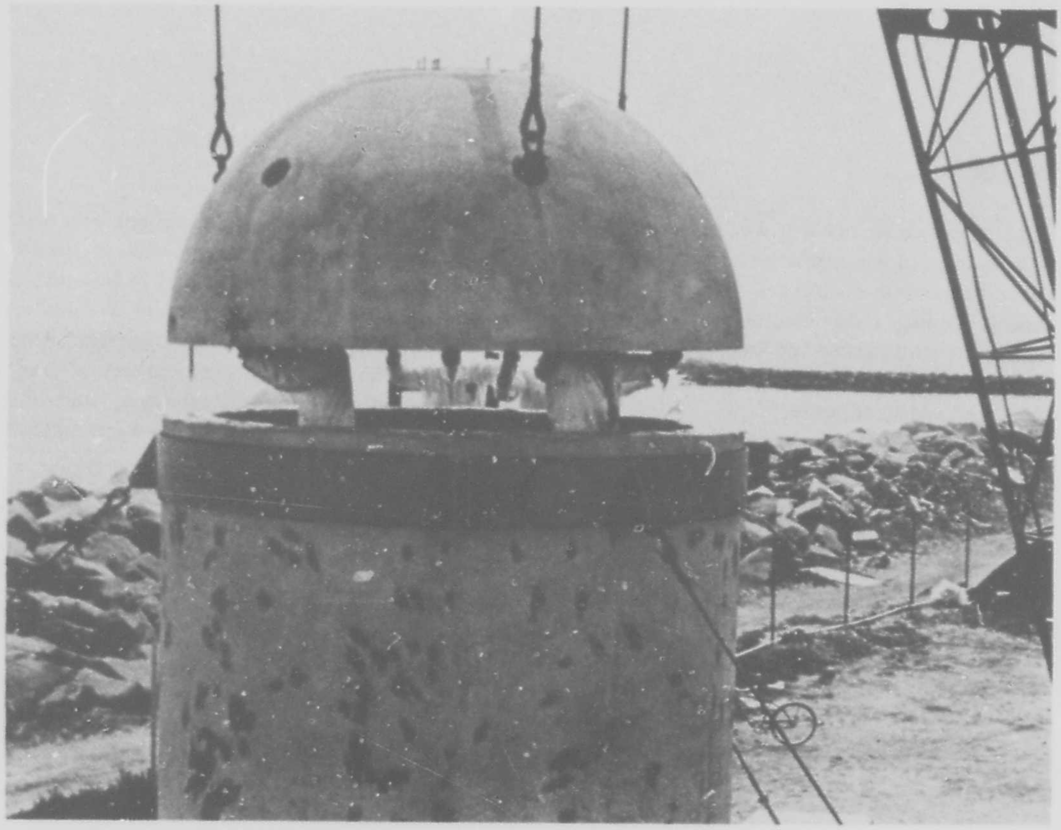


Figure 4.3.2. Lowering hemispherical end closure for bonding to cylinder with epoxy adhesive.

DESCRIPTION OF SEACON

The cylindrical structure was assembled from three precast, reinforced concrete sections. The straight cylinder section, 10.1 feet in outside diameter by 10 feet in length by 9.5 inches in wall thickness, was fabricated by United Concrete Pipe Corporation. The concrete hemisphere end-closures, 10.1 feet in outside diameter by 9.5 inches in wall thickness, were fabricated in-house. Tolerances on the sections conformed to concrete pipe standards of not to exceed ±3/4 inch for the inside diameter or minus 1/2 inch for the wall thickness.

Steel reinforcement in the amount of 0.70% by area was used in both the axial and hoop direction for resisting temperature and handling stresses. Reinforcing bars of 5/8-inch diameter were employed throughout the structure. A double circular reinforcement cage was fabricated for each precast section; the concrete on the outside and inside reinforcing cage was 1 inch thick. For the cylinder section, hoop rebars had a center-to-center spacing of 6 inches and axial rebars a spacing of 27-1/4 and 31-1/4 inches for the inside and outside cages, respectively.

The hemispherical end-closures were bonded to the cylinder section with an epoxy adhesive [4.3.2], no other attachment besides the epoxy bond was employed (Figure 4.3.2). The gap between the mating surfaces of the hemisphere and the cylinder was less than 1/8 inch for over 75% of the contact area; however, the gap was as great as 1/2 inch for certain

Figure 4.3.3. Hatch penetrator (top) and hull penetrator in hemisphere.

localized areas. Prior to epoxy bonding, the concrete surfaces were prepared by sandblasting and washing with acetone.

A large hull penetration, major diameter of 50-1/4 inches and minor diameter of 42-3/8 inches, was located at the apex of each hemisphere. This size of penetration was equivalent to 40% of the hemisphere diameter. The design philosophy for the penetrator was to make the penetrator stiffer than the concrete material it replaced so that the hemisphere was "unaware" of the large hole [4.3.3]. The steel penetrator (Figure 4.3.3) was epoxy bonded to the concrete using the surface preparation method described above for the joint. Six smaller penetrations, major diameter of 6 inches and minor diameter of 5 inches, were included in one of the hemispheres; these penetrations were part of a seals and gasket study discussed in a later section. Two small penetrations, major diameter of 4.5 inches and minor diameter of 4.0 inches, were also included near the center of the cylinder section to accommodate pressure relief valves.

The exterior of the concrete structure was coated with an epoxy waterproofing system.* After lightly sandblasting the concrete, an epoxy primer and topcoat (phenoline No. 300) were sprayed onto the concrete and each coating was dabbed with a brush to coat the recessed air pockets. Many air pockets were not coated so that approximately one pin hole per 2 square inches existed in the final waterproof coating.

The concrete structure was instrumented with a total of 40 electrical resistance strain gages to monitor hull response under long-term loading. Half of the gages were placed diametrically opposed to each other on the structure. The data were stored on magnetic tape inside the structure and were recovered when the structure was retrieved. At approximately 2-month intervals the data were interrogated from a surface ship.

The concrete material for the cylinder portion of the structure consisted of portland cement type II, sand, and coarse aggregate in the proportions of 1.0 to 1.4 to 2.5 by weight, respectively. The water-to-cement ratio was 0.40 by weight, and a water-reducing admixture was used; the slump was 1-1/4 inches. The average compressive strength at 28 days was 7,800 psi. A mix design of different proportions was used for the hemispheres; the cement-to-sand-to-coarse-aggregate ratio was 1.0 to 1.95 to 2.3 by weight, the water-to-cement ratio was 0.38 by weight, and a water-reducing admixture was used. The slump was also 1-1/4 inches. The average compressive strength at 28 days was 8,170 psi.

RESULTS AND ANALYSIS

Concrete Compressive Strength

The compressive strength of the concrete was obtained from uniaxial compressive tests on 6 x 12-inch cylinders. Figure 4.3.4 shows the compressive strength as a function of age of the concrete. The structure was on the seafloor between the ages of 294 and 608 days.

* A limited evaluation study was performed on eight off-the-shelf epoxies to determine their relative ability to retard water absorption by concrete under hydrostatic load and to resist abrasion.

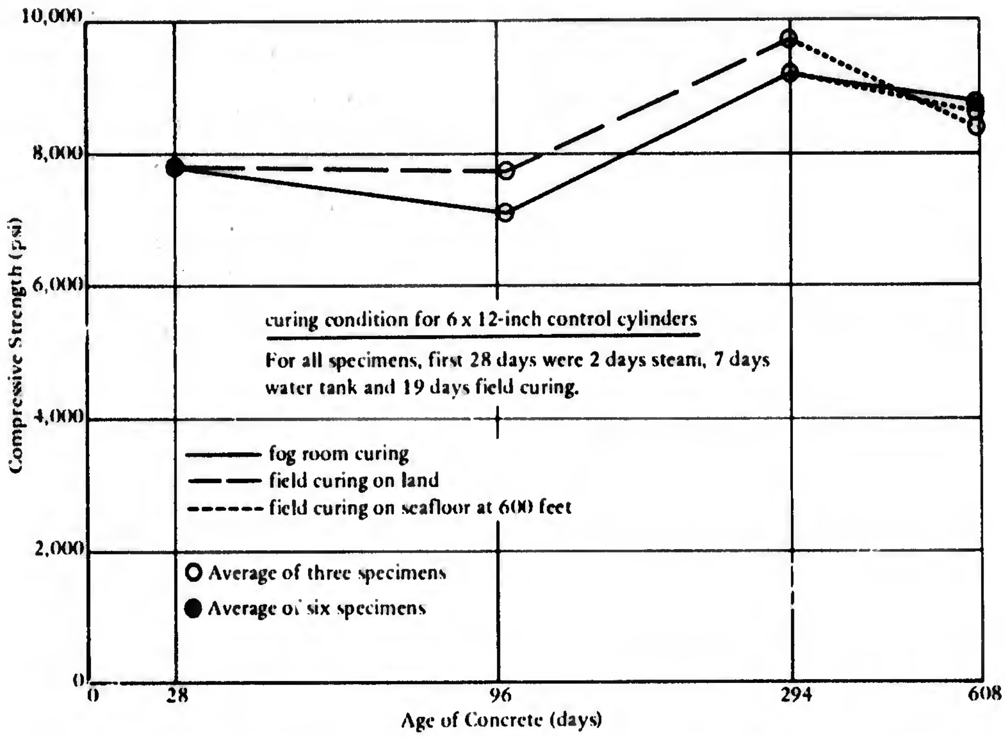


Figure 4.3.4. Compressive strength of concrete test specimens from batch used to fabricate SEACON.

The control cylinders which were field-cured with the structure on land and then with the structure on the seafloor showed a decrease in strength of 14%; this strength reduction was due to the "dry" on-land concrete becoming saturated at the ocean depth of 600 feet. Previous CEL experiments showed that control cylinders saturated with seawater (by subjecting the specimens to a simulated depth of 1,100 feet for a period of 7 days) decreased in compressive strength by 10% [4.3.4]. Some experiments performed in Russia have shown a decrease in strength of 27%; however, the details of the test procedure are not known [4.3.5].

Prediction of Implosion Depth

A prediction of implosion depth can be made for the structure by using an empirical equation developed from model cylindrical structures having an outside diameter of 16 inches [4.3.6]:

$$P_{im} = \phi f'_c [2.05 (t/D_o) - 0.028] \qquad (4.3.1)$$

where P_{im} = implosion pressure, psi

ϕ = long-term loading factor

f'_c = concrete compressive strength, psi

t = wall thickness, in.

D_o = outside diameter, in.

For the structure, f'_c was 8,370 psi (weakest strength), t/D_o was 0.0785, and ϕ was 0.70 [4.3.4]. The predicted implosion pressure was 780 psi or an implosion depth of 1,750 feet. With the structure at an operational depth of 600 feet, the factor of safety was 2.9.

Strain Behavior

The short-term strain response of the structure (Figure 4.3.5) showed lower values of strain, by 30%, than were estimated from model studies. On the inner concrete surface the strains averaged 370 μin./in. while 16-inch-OD models gave an estimated strain of 2,520 μin./in.

At the beginning of the test, the structure was subjected to a sustained pressure load of 21%, the short-term implosion strength ($f_c' =$ 9,710 psi and $\phi = 0$ in Equation 4.3.1). From previous work [4.3.6, 7, 8], this low level of loading should not have produced any detectable strain variation along the length of the cylinder section due to the discontinuity of the cylinder/end-closure joint. The actual strains showed this to be true; therefore, the gages along the length were averaged together (Figure 4.3.5).

The difference in strain magnitude between the opposite sides of the structure was erratic, but in general, one side registered approximately 150 μin./in. greater strain. Out-of-roundness of the cylinder could have caused a strain difference of this magnitude [4.3.8].

The creep behavior of the concrete under sustained stress for 314 days is shown in Figure 4.3.5. The level of stresses in the concrete wall was calculated by using Lame's equations for thick-walled cylinders [4.3.9]; these stresses are listed in Figure 4.3.5. The average total creep strain in the hoop and axial direction was 120 and 80 μin./in., respectively; these values represent a 40% and 50% increase, respectively, over the short-term strain, which is not unusual for concrete. The data gave no indication that the creep strain was nearing termination.

The large penetration had little effect on the behavior of the hemisphere (Figure 4.3.6). Again, the low stress level in the concrete might not have been sufficient to produce a noticeable strain riser at the penetration. In any case, it was a significant finding to observe that the penetrator, equivalent to 40% of the structure's diameter, did not produce a harmful effect on the structure.

Epoxy Adhesive Joining Technique

From all appearances, the method of joining the end-closures to the cylinder section using epoxy adhesive worked well. The structure withstood handling stresses on land and in the water during tow, emplacement, and retrieval. No leaks or distress were visible around the joints in a post retrieval inspection. Similar findings applied to the method of bonding penetrators to the concrete hull. However, caution is recommended in utilizing the epoxy bonding method in manned undersea structures because tests have not been conducted to determine the strength of the joint after long-term submergence or under cyclic loading conditions.

Watertightness of Structure

Upon retrieval, the interior of the structure was found to be free from water that permeated the concrete walls.* There was no evidence of condensation or even damp concrete walls.

The waterproof coating provided an adequate barrier to retard permeation of seawater through the concrete for up to 314 days, even though the coating had pinhole openings. The expected quantity of water was predicted to be 1.6 cu ft; this prediction was made using Darcy's equation and a permeability coefficient of 0.13×10^{-12} ft/sec [4.3.4]. This test demonstrated that a concrete hull can remain watertight at 600 feet in the ocean.

FINDINGS

1. The compressive strength of the concrete decreased 14%, from 9,710 to 8,370 psi after 314 days at 600 feet in the ocean. This strength reduction was due to "dry" on-land field-cured concrete becoming saturated with seawater.

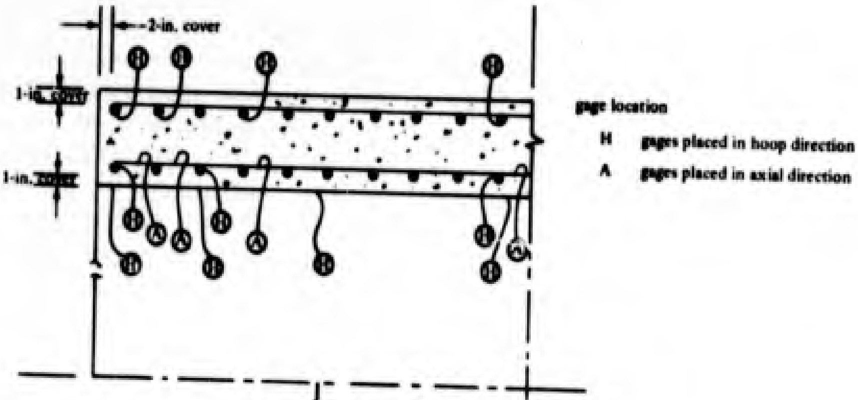
2. The magnitude of strains from the cylinder section was lower by 30% than that estimated from model studies.

3. The hull penetration for the window, which had a major diameter 40% of the hemisphere's diameter, had no detrimental effect on the behavior of the hemisphere.

4. The construction technique using epoxy adhesive to bond the hemisphere end-closures to the cylinder section and to bond steel penetrators to the hull worked well.

5. The structure remained completely watertight against seawater permeating the concrete.

* Three quarts of water were found inside the structure due to a leak in a check valve in one of the small penetrators under investigation.



Symbol	Direction	Location	No. of Gages	Wall Stress (psi)
•	hoop	outer rebar	7	1625
V	hoop	inner rebar	4	1805
□	hoop	inner concrete	7	1865
H	axial	inner rebar	8	935

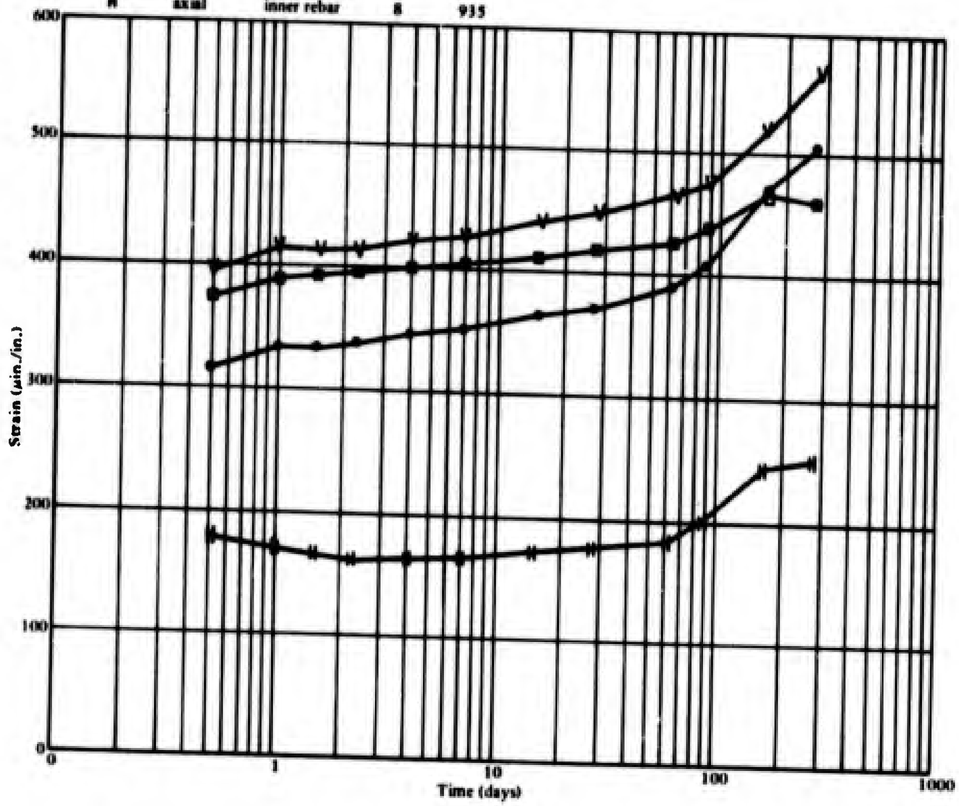


Figure 4.3.5. Strain behavior of cylinder section.

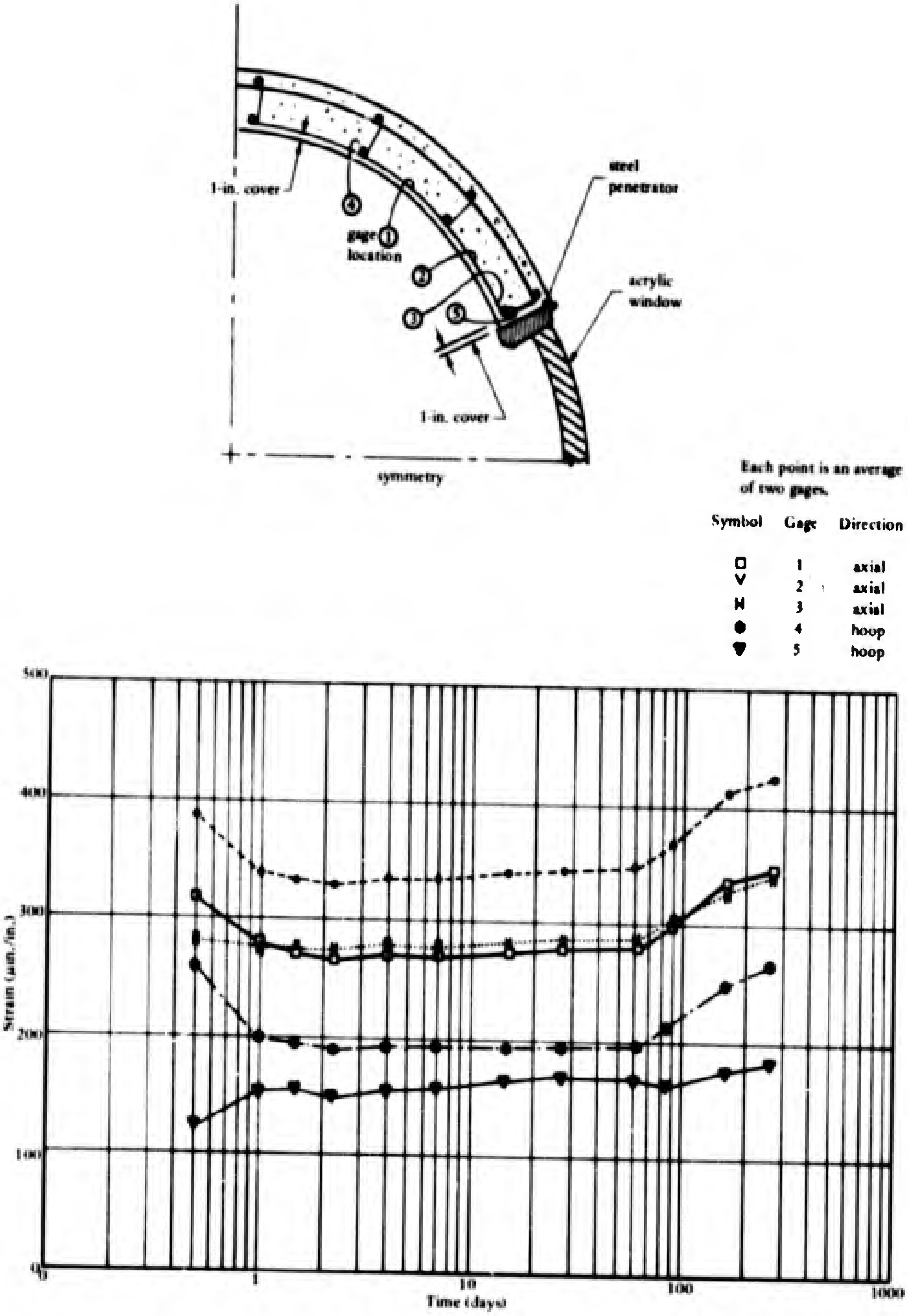


Figure 4.3.6. Strains on inner reinforcing bar cage of hemisphere.

SECTION 4

MAINTENANCE OF ACRYLIC WINDOW VISIBILITY AND LONG-TERM STRUCTURAL PERFORMANCE OF A SPHERICAL ACRYLIC WINDOW

by P. K. Rockwell, K. O. Gray, and W. J. Nordell

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OBJECTIVE

The objective of this experiment was to develop and evaluate a mechanical fouling prevention system for hydrospace windows under long-term submersion in the ocean. A second objective of the window experiment was to obtain data on the long-term structural performance of the spherical acrylic window.

INTRODUCTION

Unprotected acrylic windows become fouled with marine life after a few days of exposure. When coated with commercially available transparent antifouling compound, fouling is delayed by approximately 10 days; no antifouling agents for acrylic windows have been successful for more than 20 days. In order to maintain visibility for several months, a different antifouling system, or combination of systems, was required. The SEACON I structure's acrylic window provided a test bed for the fouling prevention system.

EXPERIMENTAL PLAN

The maintenance of visibility through a window installed in a pressure-resistant structure subjected to long-term submersion necessitates keeping both the external and internal surfaces of the window clean. For an uninhabited structure, such as SEACON I, the fouling prevention system must be actuated automatically or upon signal from the surface.

The internal surface of windows in inhabited structures is subjected principally to fogging due to high internal humidity. Therefore, a blower system or simple wiper mechanism will suffice. The internal surface cleaning operation need only be used when it is required to view through the window, since condensation buildup is not a problem.

The external surface presents a more severe cleaning problem, being exposed to colloidal depositions and biological fouling, both of which increase in density and become more difficult to clean as exposure time increases. Therefore, a means of preventing biological fouling buildup by continuously wiping deposits from a window is required. A description of the SEACON I window assembly is presented in Figure 4.4.1.

Fouling Prevention System Description

Internal. The blower system for removing condensation from the inside surface of the SEACON I acrylic window consisted of a heating element, blower, and ducts around the window circumference. The ducts were pierced at intervals, directing warm air radially toward the center of the window. The blower-heating element system was turned on upon command from the surface.

External. Figures 4.4.2 and 4.4.3 show the fouling prevention system for the window exterior. Several considerations influenced selection of the final configuration. A stagnant area around the window exterior was desired to inhibit growth of biological fouling; this was provided by the window cover. For viewing through the window, the lift bag assembly was used to lift the cover and wiper assembly. The lift bag is filled from two 300-SCF air bottles via a pressure regulator and a 3-way, 2-position solenoid valve (Figure 4.4.4). When the solenoid is activated, air at 10 psi above ambient is directed into the lift bag. As the bag, located inside a flooded fiberglass housing, fills with air, buoyancy raises the entire assembly. When the signal is removed from the solenoid valve, the air in the bag is directed to the air bleed atop the structure. Because the lift bag is deeper than the exhaust fitting, the external pressure on the bag is greater than the internal pressure, causing the air to bleed from the bag. With the buoyancy removed the assembly returns to its position with the brushes in contact with the window.

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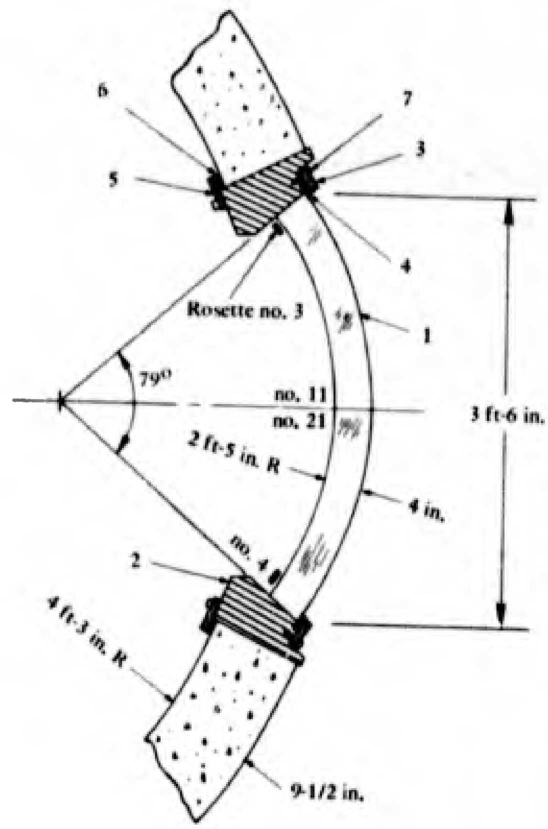

1 Spherical window of unshrunk acrylic plastic - Type "G" having a nominal thickness of 4.00 inches
2 Steel (A-36) window ring
3 Steel (A-36) retaining ring
4 Neoprene retaining ring gasket
5 Steel (A-36) retaining clips
6 Neoprene retaining clip gaskets
7 Titanium cap screws and nylon washers

Figure 4.4.1. SEACON window assembly.

The curved brushes (Figure 4.4.3) were rotated by a 1/10-hp DC motor which operated automatically for 2 minutes every 8 hours and on command from the surface.

An additional complication was imposed on the system by the need to resist the drag forces encountered during the tow to the SEACON I site and while lowering the structure to the seafloor. A camlock and handle mechanism was designed to lock the cover in the down position. The research vehicle *CURV II* was employed to grasp the handle and rotate it 90 degrees, thereby releasing the cam from its retainer and freeing the window cover.

In addition to the mechanical wiping motion, a chemical dispenser was installed in the cover to deter marine growth. The dispenser was a porous material containing 33.1 grams of 50:50 tri-n-butyltin oxide and cellulose powder. The chemical leaches through the porous container until the equilibrium concentration is reached in the stagnant area enclosed by the window cover. When the cover is opened and then closed, the chemical again leaches out until equilibrium is reached.

The experiment was divided into two phases:

Phase 1: The combination mechanical and chemical fouling deterrent systems was to be used for 3 months. Then, the chemical dispenser was to be removed by *CURV* via a large ring attached to the dispenser, and the window inspected.

Phase 2: For the remainder of the time, mechanical methods alone were to be used for fouling prevention.

Structural Performance of Spherical Acrylic Window

Four strain gage rosettes were attached to the window's interior surface at the locations shown in Figure 4.4.1. Each rosette consisted of two gages oriented at 90 degrees to one another. Therefore, at each point meridional and hoop strains were obtained.

The strain data were recorded in the same manner as the SEACON I structure strain data. The details of the instrumentation and data gathering and reduction are presented in the section dealing with the SEACON I structure and will not be repeated here.

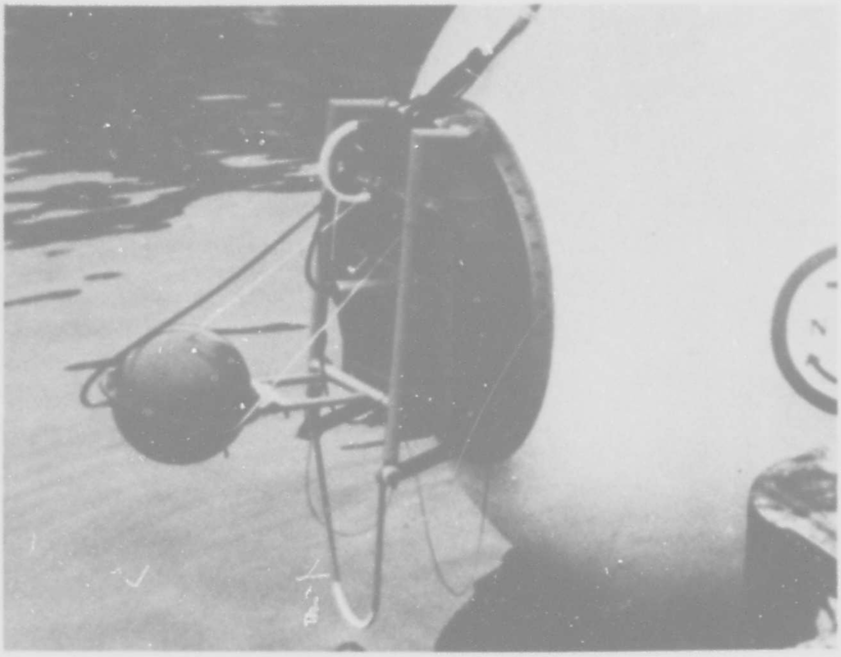

Figure 4.4.2. SEACON window fouling prevention system – external view.

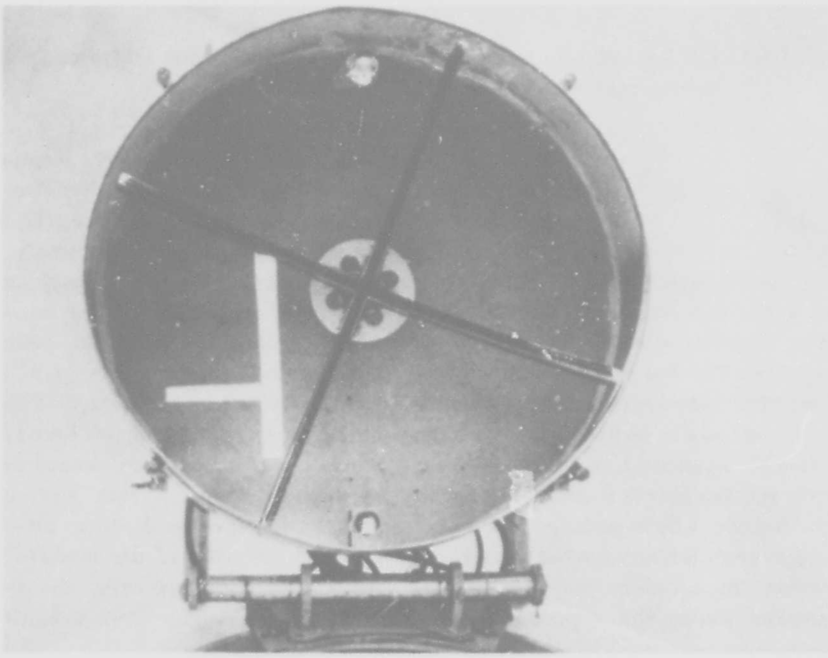

Figure 4.4.3. SEACON window fouling prevention system – internal view.

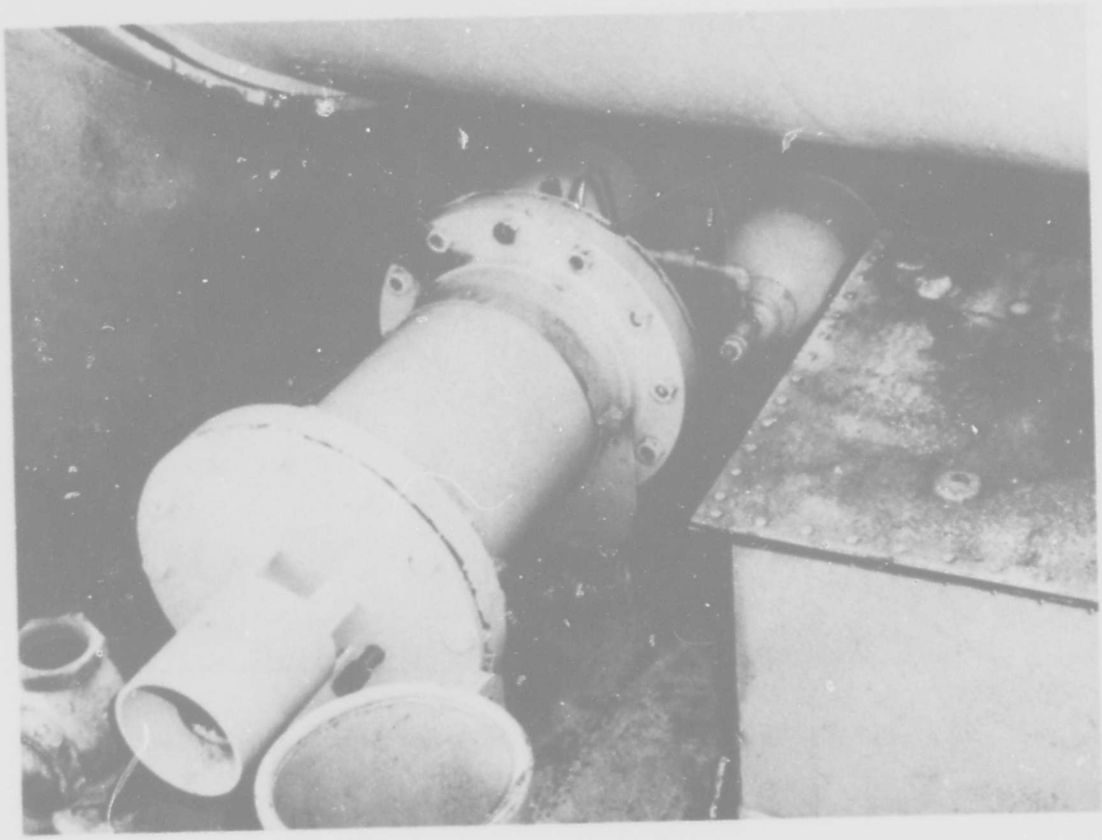

Figure 4.4.4. Lift bag inflation system: two 300-scf air bottles with pressure regulator and solenoid valve package.

RESULTS

Fouling Prevention

During the 10-1/2 months that SEACON I was emplaced, the window wiper cover assembly was opened 10 times. Each time the visibility through the window was excellent. The first time that the window cover was raised after submergence, the antitouling dispensing capsule fell to the seafloor. Therefore, no results were obtained for phase 1, which involved the mechanical wiper and the chemical antifouling agent. The automatic feature which actuated the wiper brush for 2 minutes every 8 hours worked throughout the entire mission. In addition, the window was wiped on command during the inspection cruises. During the 4 February 1972 inspection, the window cover closed unexpectedly. During SEACON I recovery, it was found that the fiberglass shroud which constrained the buoyancy bag had failed, leading to explosion of the buoyancy bag.

Final inspection of the window showed that several groups of branchlike colonies of hydroids (Endentrium californicum), 1/2 inch long, were found attached to the surface of the acrylic window at the upper edge. None was found on the area of the window which had been cleaned periodically by the mechanical wiper. A thin layer of primary slime growth together with fine silt also coated the unwiped perimeter of the window. The action of the wiper apparently prevented the spread of hydroids and a slime buildup from occurring on the wiped

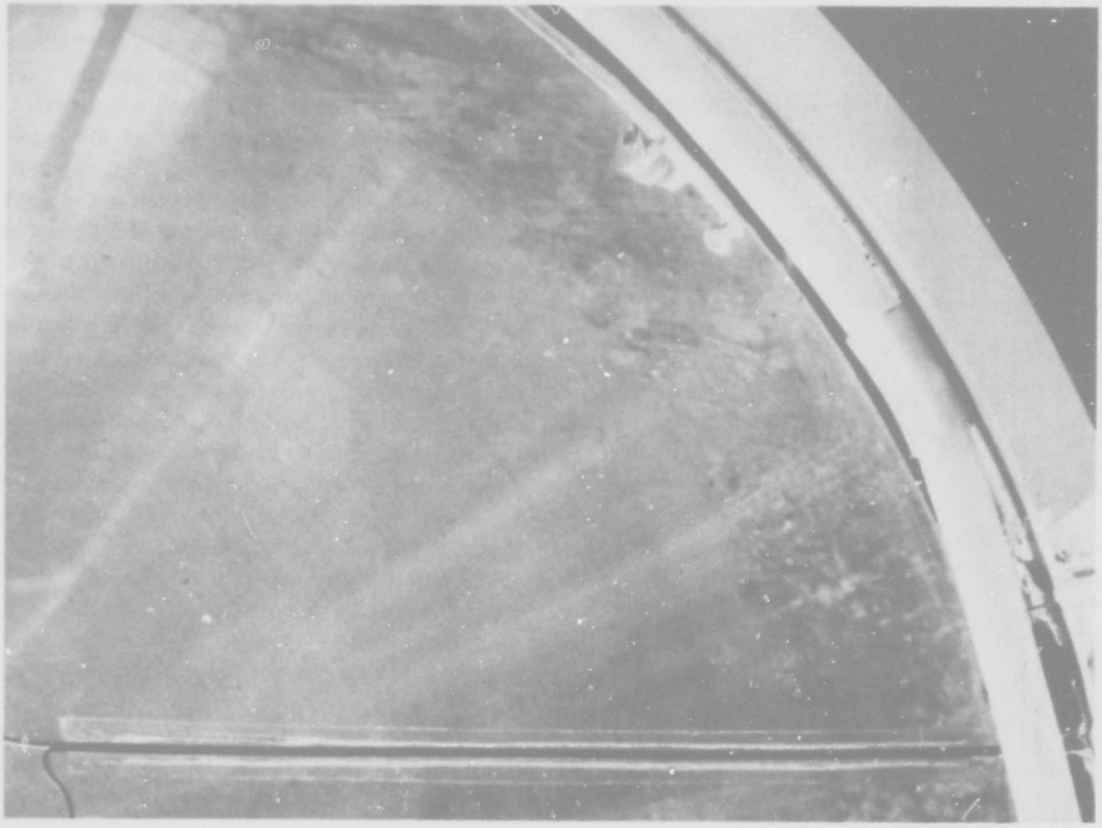

Figure 4.4.5. Scratches caused by window brush.

portion of the window. The wiper did introduce fine scratches onto the surface of the window (Figure 4.4.5). The scratches did not adversely affect the visibility through the window since they were in contact with water. No fogging was observed during the time that SEACON I was on the bottom.

Acrylic Window Strain Data

The strain data for the spherical acrylic window are presented in Figure 4.4.6. The meridional and hoop strains near the window apex, Figure 4.4.6a, agree to within 15% of the average value at a given time. The magnitude of strain computed using Lame's thick spherical shell theory is within 27% of all the measured strains at the apex during the first days of submergence; however, it is just 12% less than the average value of the measured strains for the same time period. The computed value was obtained using an elastic modulus equal to 450,000 psi, a Poisson's ratio equal to 0.35, and a pressure of 267 psi (depth, 600 feet). The computed strain corresponds to a stress in the acrylic equal to 1,115 psi, which is well within the material's strength capability. As shown in Figure 4.4.6c, the average meridional strain near the window-flange interface is approximately twice as great as the corresponding hoop strain, which is approximately equal to the meridional and hoop strains near the apex. Using the elastic modulus and Poisson's ratio noted previously, the strains at the interface correspond to meridional and hoop stresses equal to 2,060 psi and 1,510 psi, respectively. Similar results were obtained from tests on the Johnson-Sea-Link spherical acrylic hull, which is 4 inches thick and has an inside radius of 29 inches [4.4.1]. These dimensions are the same as those for the SEACON I window. This hull was instrumented so that the discontinuity stresses at the hatch-hull interface could be established. The experimental results indicated stress concentrations in the acrylic at the hatch-hull interface, and that the highest stress concentration was for inside, meridional stress. The same observations are true for the SEACON I window. The measured strains at the interface for the hull test, Reference 4.4.1, were reduced by the ratio of the SEACON I experiment pressure (267 psi) to the hull test procedure (900 psi) and are shown in Figure 4.4.6b. Because these strain measurements are from a region with a high strain gradient, close agreement is not to be expected. The comparison shown in Figure 4.4.6b indicates a similar edge effect in the hull and window. The differences in data may also be caused by fluctuations in the pressure bearing circumferentially around the interface due to mismatches between the acrylic and the flange or hull.

The meridional and hoop strains at the apex and the hoop strains near the window-flange interface remained relatively constant throughout the 10-1/2-month test. The meridional strains near the interface increased at the most rapid rate. However, by extrapolation, these strains should not exceed 5,000 μin./in. (a 25% increase over the initial value) in 25 years.

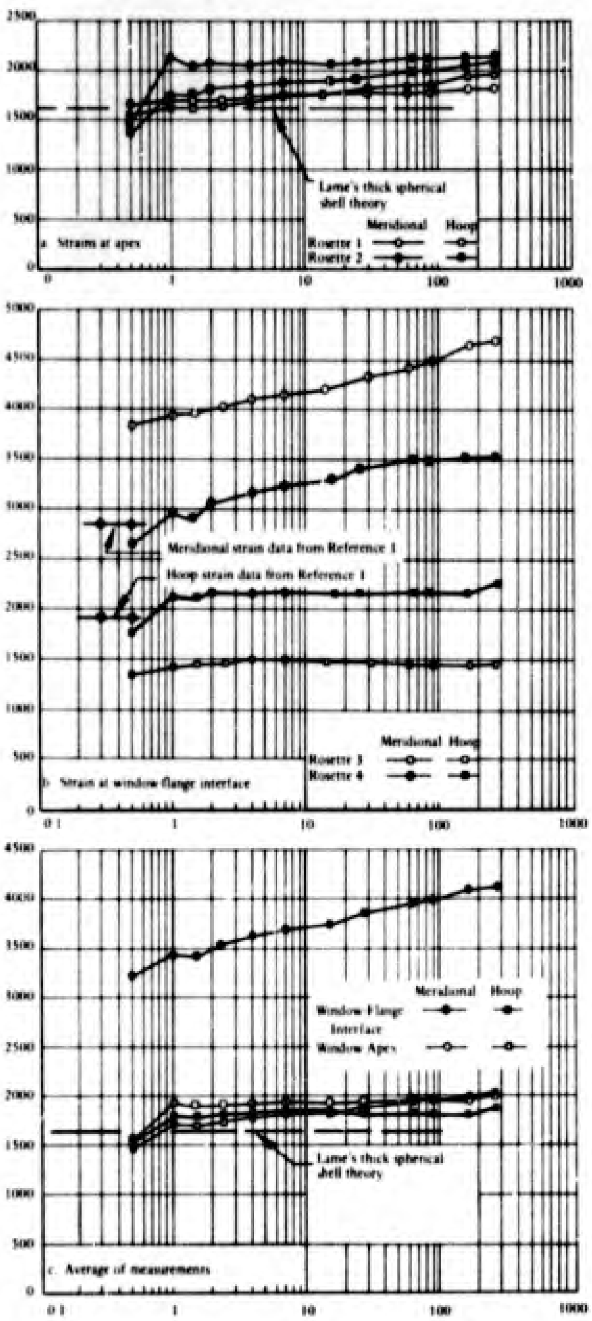

Figure 4.4.6. Spherical acrylic window strain data: strain versus time.

FINDINGS AND CONCLUSIONS

1. Intermittent brushing effectively eliminates the accumulation of slime and biological fouling on acrylic viewport surfaces.

2. The brushing action produces scratches in the acrylic plastic surface. However, the scratches do not measurably affect visibility while the scratched surface remains wetted.

3. The window cover lift/lower system, using air storage tanks for dewatering and ambient differential pressure for collapsing a buoyancy bag, is both reliable and effective.

4. Fogging of the viewport surface did not occur in this closed submerged structure.

5. No conclusions can be drawn regarding the effectiveness of the chemical fouling retardent system.

6. The structural performance of the spherical acrylic window was more than adequate for the SEACON I depth of 600 feet.

RECOMMENDATIONS

1. Chemical means of preventing fouling of acrylic windows should be tested again, since a passive chemical system is inherently less expensive and more reliable than mechanical means.

2. Brush material and configuration as well as other wiper systems should be investigated to reduce window scratching.

SECTION 5

PERFORMANCE TESTING OF THROUGH-HULL PENETRATORS

by J. F. Jenkins

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OBJECTIVE

This experiment had two major objectives: (1) to design and test a leak-resistant through-hull penetrator for use in thick-walled structures, and (2) to determine the resistance of such penetrators, fabricated from six materials, to corrosion-related leakage.

PROCEDURE

Design

A sleeve and plug penetrator design utilizing O-ring seals was chosen to meet mechanical and physical requirements for the hull penetrators. The basic design chosen is shown in Figure 4.5.1. The sleeve was designed to be cemented inside each of the six cast-in holes located in the hatch hemisphere. The plug with redundant O-ring seals was designed to fit in the upper half of the sleeve and be retained in the sleeve, utilizing a bolt through the 1/2 x 13 NC hole in the penetrator base as shown in Figure 4.5.1. The O-ring seals, as shown in Figure 4.5.2, were self-loading upon the application of external pressure; i.e., the external pressure tended to reduce the sleeve-plug clearance.

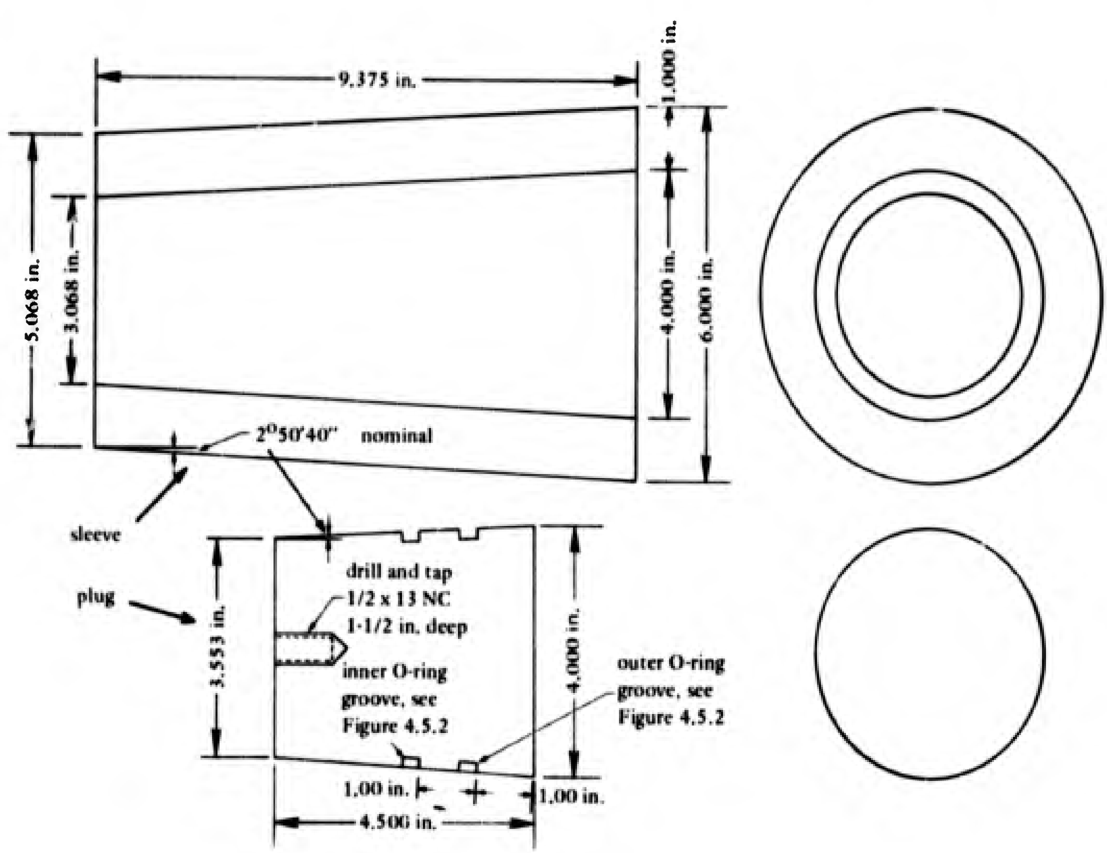
Materials Selection and Fabrication

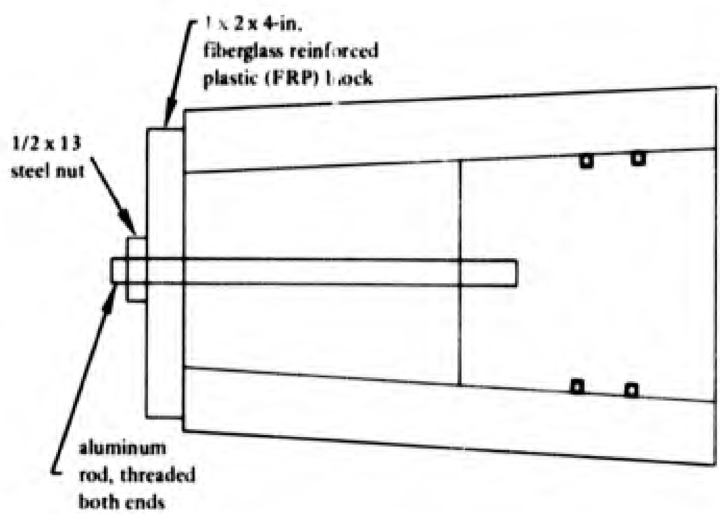
Six materials were chosen for fabrication of the penetrators. The selection was based primarily on the resistance of the material to nonuniform (e.g., pitting) and crevice type attack. Secondary considerations included: strength, fabricability, and cost. The six materials chosen were: carbon steel (AISI 1020), 70-30 cupro-nickel, nickel-copper alloy 400, nickel-molybdenum-chromium alloy "C", nickel-chromium-molybdenum alloy 625, and titanium alloy 6Al-4V. The chemical compositions and typical mechanical properties of these alloys are given in Table 4.5.1. The six sleeves and matching plugs were machined from forged billets. Three of the plugs were further modified for use as penetrators in conjunction with the sump-pump, pressure relief, and electrical systems. The carbon steel plug was modified as per Figure 4.5.3, the nickel-copper 400 alloy plug as per Figure 4.5.4, and the nickel-chromium-molybdenum alloy 625 as per Figure 4.5.5. These modified plugs were retained in their respective sleeves by three 1/4 x 20 bolts and a retaining ring as shown in Figure 4.5.6.

Installation

The six sleeves were installed in the concrete hemisphere in the locations shown in Figure 4.5.6, by the following procedure. The tapered holes in the hemisphere were cleaned with ethyl alcohol and dried with infrared heating lamps. The outside surfaces of the metallic sleeves were likewise cleaned and dried. A two-component furane cement was applied to the inside of a tapered hole in the concrete hemisphere in a layer approximately 3/8 inch thick. A metallic sleeve was then pressed into the tapered hole. Considerable force, applied utilizing a threaded rod and end plates, was used to pull the sleeves into the holes. As the final hull-to-sleeve clearance was approximately 1/8 inch, much cement was extruded; however, this procedure insured complete coverage of the sleeve-hull interface with cement and, therefore, a watertight joint. This procedure was repeated for each of the five remaining sleeves.

After the furane cement had cured, the sleeve-retaining fixtures were removed and any additional excess cement was removed from the sleeves and hull. The three unmodified penetrator plugs were then installed. The O-rings were lightly lubricated, utilizing a silicone grease compound, then emplaced in their respective grooves. The plugs were then placed in the sleeves and secured as shown in Figure 4.5.1.





assembled hull penetrator

Figure 4.5.1. SEACON hull penetrator.

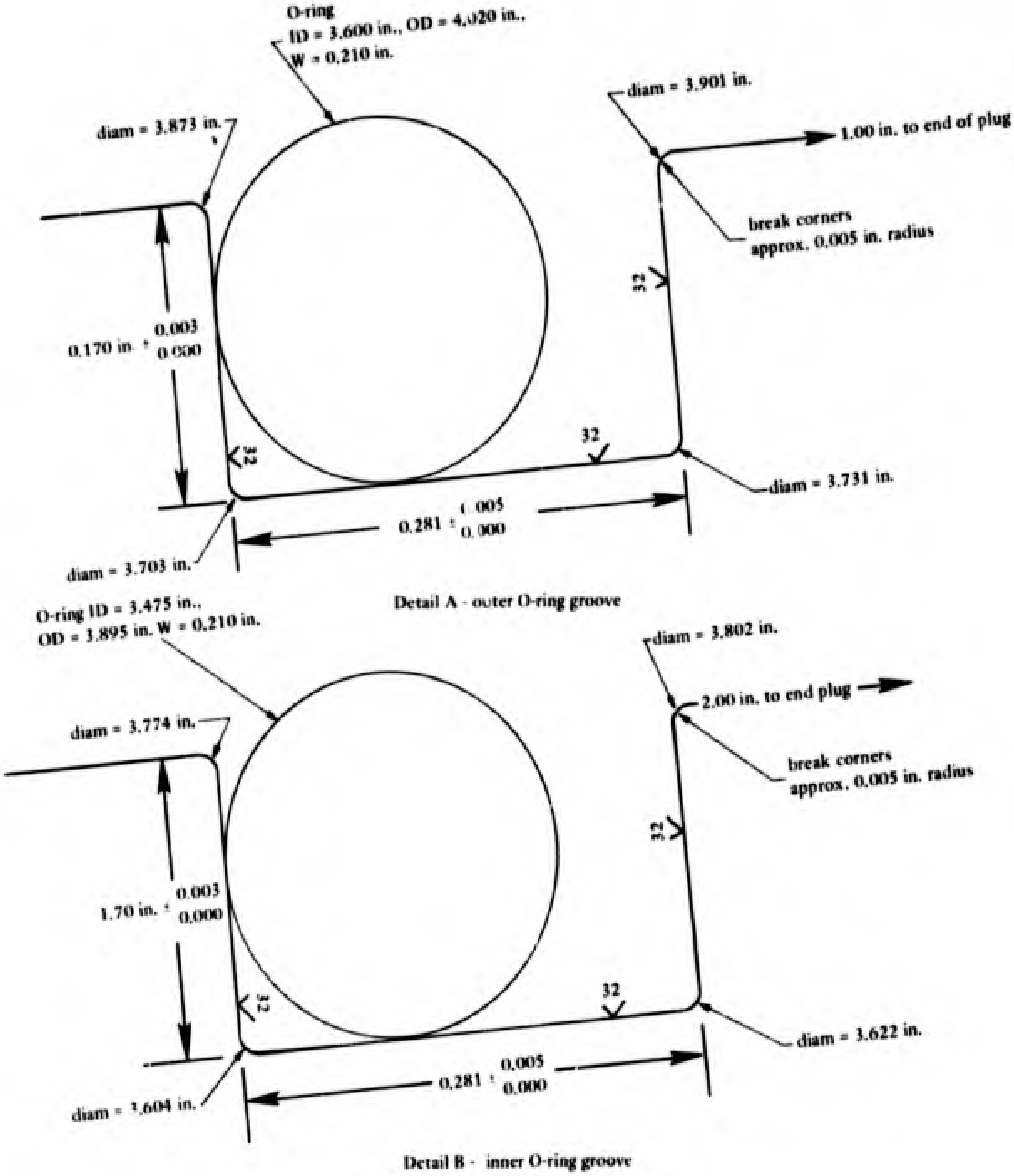


Figure 4.5.2. Seal details.

Table 4.5.1. Chemical Composition of Penetrator Alloys

Alloy Name	Chemical Composition (percent by weight)												
	C	Mn	P	S	Si	Cr	Ni	Mo	V	Ti	Al	Cu	Fe	Other
Carbon Steel	0.19	0.48	0.012	0.022	0.18	–	–	–	–	–	–	–	Bal	–
70-30 Cupro-Nickel	–	0.33	–	–	–	–	30.53	–	–	–	–	68.61	0.53	0.03 Pb 0.08 ZN
Nickel-Copper Alloy 400	0.20	1.12	–	0.009	0.24	–	64.00	–	–	–	0.009	32.49	1.91	–
Nickel-Molybdenum Chromium Alloy "C"	0.05	0.53	0.003	0.004	0.48	15.25	Bal	15.65	0.06	–	–	–	6.05	0.926 O 3.75 W
Nickel-Chromium Molybdenum Alloy 625	0.04	0.38	0.01	0.003	0.20	22.10	Bal	9.0	–	0.20	0.18	0.10	1.65	0.106 O 3.53 Cb+Ta 0.004 B
Titanium Alloy 6A1-4V	0.016	–	–	–	–	–	–	–	3.93	Bal	6.20	–	0.047	0.012 N 0.0008 H 0.085 O

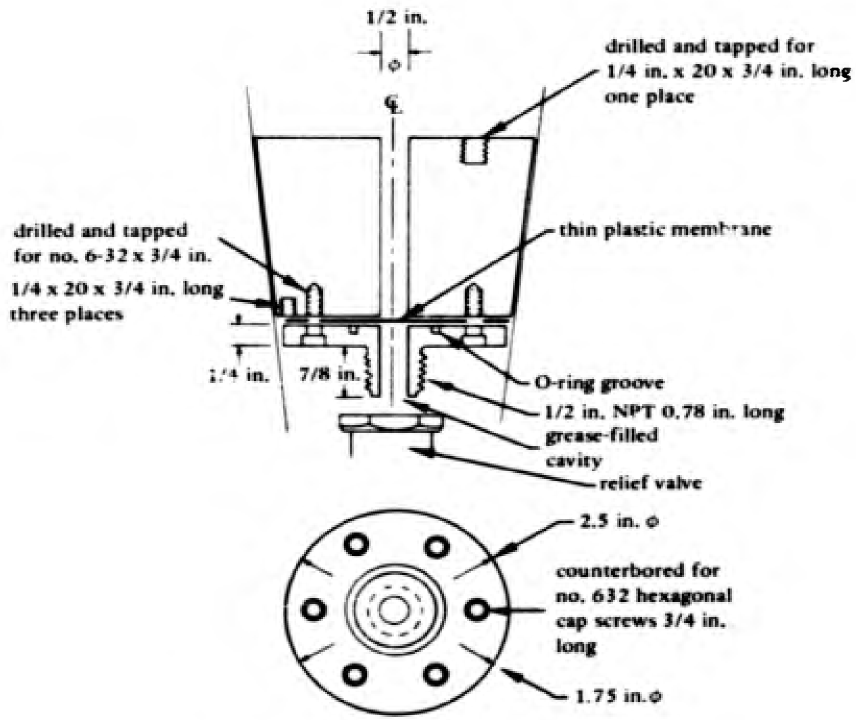


Figure 4.5.3. Modification of steel penetrator plug.

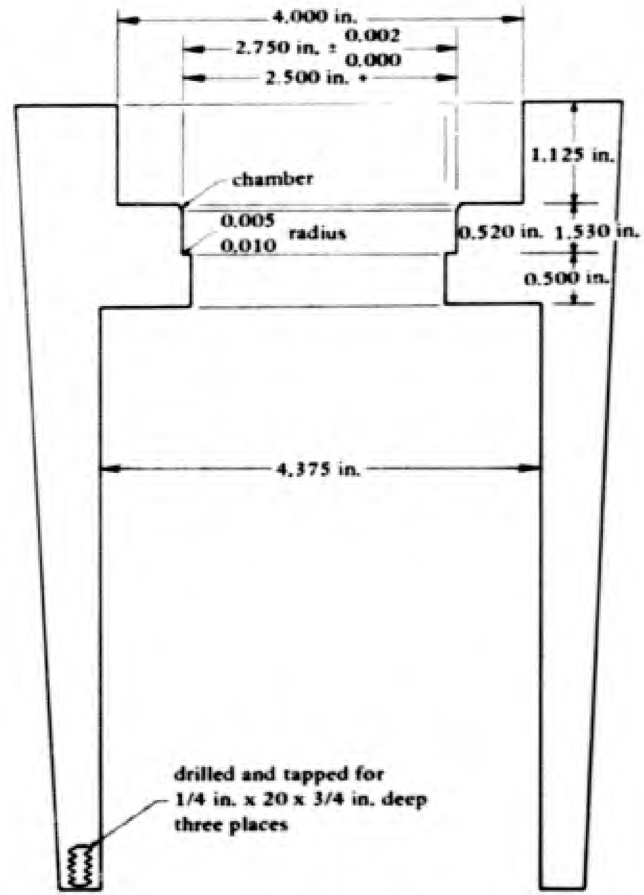


Figure 4.5.4. Modification of nickel-copper 400 alloy penetrator plug.

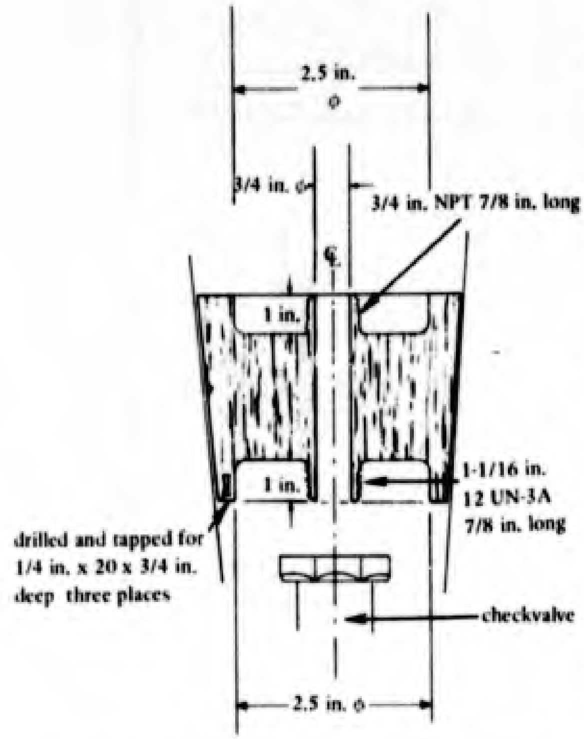


Figure 4.5.5. Modification of nickel-chromium-molybdenum alloy 625 penetrator plug.

The nickel-copper 400 alloy plug was fitted with a nickel-copper 400 alloy electrical connector. The plug-connector interface was sealed, utilizing redundant O-rings. The nickel-chromium-molybdenum alloy 625 plug was fitted with a type 316 stainless steel check valve. The valve-to-plug threads were sealed with a Teflon tape sealant. The connection between this check valve and the sump-pump tubing was made with an insulating nylon-lined fitting in order to eliminate potential galvanic corrosion between the sump-pump plumbing and the check valve/plug assembly.

The steel plug was fitted with a nickel-copper 400 alloy pressure relief valve as shown in Figure 4.5.3. The valve-to-plug threads were sealed with a Teflon tape sealant.

After assembling the three modified plugs, they were installed in their respective sleeves in essentially the same manner as the unmodified plugs. These plugs were, however, secured using a retaining plate and three 1/4 x 20 6-inch steel bolts as shown in Figure 4.5.6.

The zinc anode conforming to MIL-A-18001G Type ZEP was attached to the outside surface of the steel plug using a 1/4 x 20 steel bolt. This anode was attached in order to evaluate the efficacy of cathodic protection in mitigating the corrosion of steel in deep crevices.

Evaluation of Test Penetrators After Exposure

Upon recovery of the SEACON I structure, the condition of the through-hull penetrators was evaluated. This evaluation was based primarily upon visual observations. The external and internal condition of the plugs and sleeves before disassembly and the condition of their mating surfaces after disassembly are given below.

Steel Penetrator. The surface of the plug and sleeve exposed on the outside of the structure were free of corrosion immediately after recovery. However, a thin, adherent, rust film rapidly formed on these surfaces after they were removed from the seawater. The zinc anode was covered with a layer of white calcareous deposit approximately 1/8 inch thick. Upon removal, cleaning, and weighing the zinc anode was found to have lost 11% of its original weight. Viewed from the inside of the structure, a slight amount of rust staining was noted on one area of the relief valve attachment flange. The appearance of this stain indicated that a few drops of water had leaked from the relief valve to flange connection. However, subsequent chemical analysis failed to show any chloride present in the rust deposit, indicating that the rusting was probably the result of condensate water and not seawater leakage. The other surfaces of the plug and sleeve, as viewed from inside the structure, were corroded.

Upon removal of the penetrator plug from the sleeve, a thin layer of tightly adherent rust was found on the surfaces of the plug and sleeve to the outermost O-ring seal. No corrosion of the plug or sleeve was noted inside of the outermost O-ring seal. Upon removal of the O-ring seals a thin layer of tightly adherent rust was noted in the outer section of the outermost O-ring groove. No crevice-type corrosion was noted in either O-ring groove. The O-rings retained their original size, shape and hardness. Upon cleaning there was no significant corrosion of the plug or sleeve underlying the thin

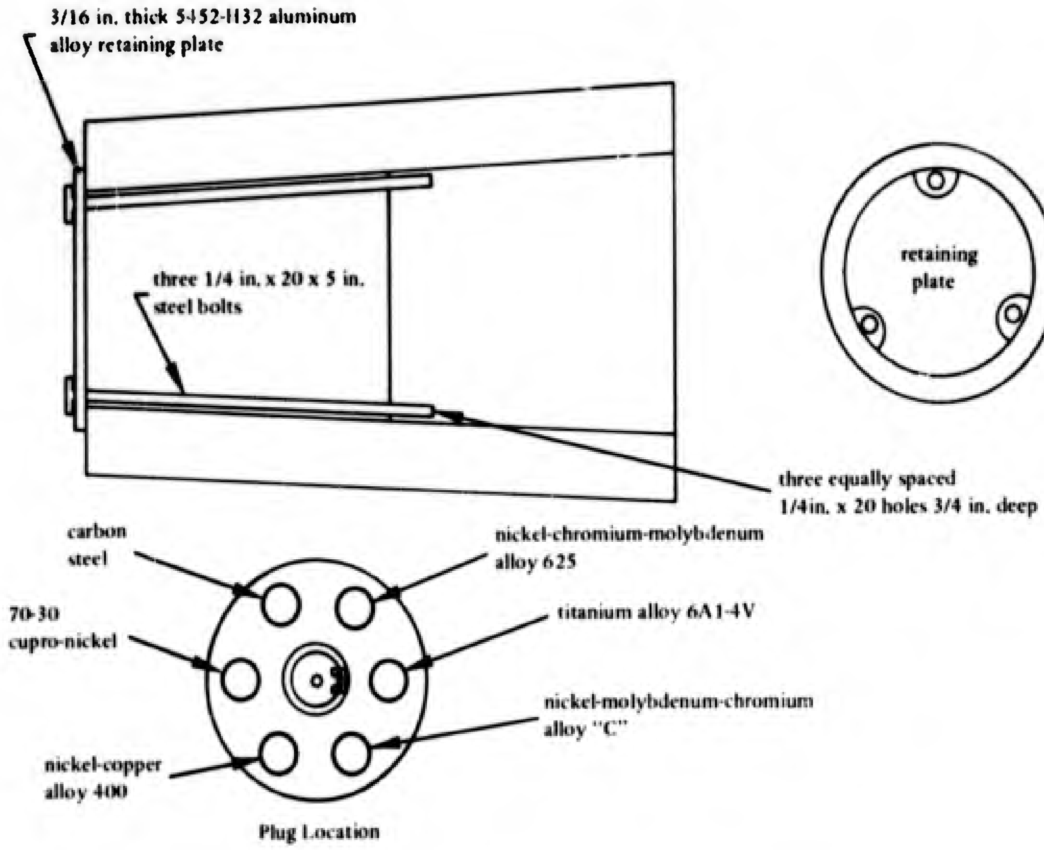


Figure 4.5.6. Retaining system for modified penetrators and location of penetrators.

layer of rust noted on the surfaces outside the outermost O-ring seal. The corrosion which had occurred was uniform and had resulted in the loss of less than 0.001 inch of material at the most severely attacked areas. The condition of the steel penetrator plug and retaining fixture upon removal from the structure is shown in Figure 4.5.7.

70-30 Cupro-Nickel Penetrator. The surfaces of the plug and sleeve exposed on the outside of the structure were covered with a thin, tightly adherent layer of green to brown corrosion products. Viewed from the inside of the structure there was no visible corrosion of the penetrator plug or sleeve.

Upon removal of the penetrator plug from the sleeve no corrosion of the plug or sleeve was noted. Upon removal of the O-ring seals, the O-ring grooves were also found to be free from corrosion. The O-rings retained their original size, shape, and hardness.

Nickel-Copper 400 Alloy Penetrator. The surfaces of the plug, sleeve, and electrical connector exposed on the outside of the structure were covered with a rust-colored stain with scattered areas of thin, tightly adherent green corrosion products. The rust staining was attributed to the carbon steel cap installed over this penetrator in conjunction with its use as an electrical connector. The other surfaces of the plug and sleeve, as viewed from inside the structure, were, in some areas, covered with a light rust staining. This was attributed to the corrosion of the steel bolts used to secure the penetrator plug. This penetrator was located in the lower section of the structure, and considerable condensate water was found inside the penetrator plug and sleeve. No corrosion of the surfaces of this penetration was noted when viewed from inside the structure.

Upon removal of the plug from the sleeve, slight staining of some areas of the plug and sleeve

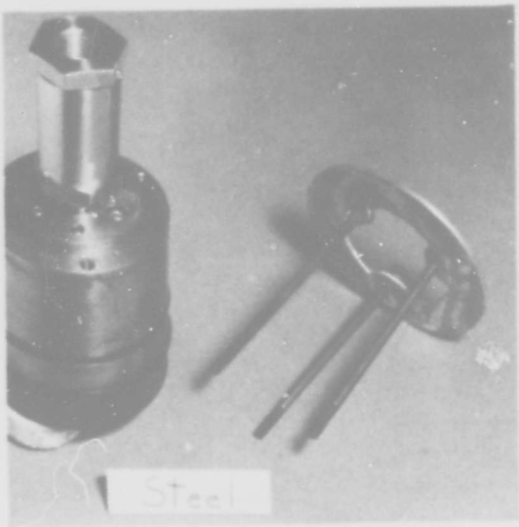


Figure 4.5.7. Carbon steel penetrator plug and pressure relief valve after exposure.

Figure 4.5.8. Nickel-chromium-molybdenum alloy 625 penetrator plug and sump-pump check valve after exposure.

extending to the outermost O-ring seal was noted. Only light etching of the surfaces underlying these stains was noted after cleaning. Upon removal of the O-ring seals, the O-ring grooves were found to be free from corrosion. The O-rings retained their original size, shape, and hardness. Upon removal of the electrical connector from the penetrator plug, no corrosion was noted on inside surfaces of the connector or plug.

Nickel-Molybdenum-Chromium Alloy "C" Penetrator. The surfaces of the plug and sleeve exposed on the outside of the structure were uncorroded. When viewed from the inside of the structure, voluminous white corrosion products were noted covering the plug and lower portions of the sleeve. The sleeve was also partially filled with saline water.

Upon removal of the plug from the sleeve, it was found that the aluminum rod used to retain the plug in the sleeve was severely corroded. However, the plug and sleeve were found to be free from attack. The corrosion of the aluminum rod which produced the voluminous white corrosion products was due to the partial filling of the interior of the sleeve with a mixture of condensate water and seawater from a leak in the penetrator assembly located above it. No evidence of leakage of this penetrator was noted. Upon removal of the O-ring seals the O-ring grooves were free from corrosion, and the O-rings had retained their original size, shape, and hardness.

Nickel-Chromium-Molybdenum Alloy 625 Penetrator. The surfaces of the plug and sleeve exposed on the outside of the structure were free of corrosion. When viewed from the inside of the structure, however, the lower portion of the sleeve and the aluminum alloy retaining ring were covered with voluminous white corrosion products which were found to contain considerable chloride ion. The lower surface of the insulating nylon-lined fitting used to connect the sump-pump discharge line to the check valve was corroded.

Upon disconnecting the sump-pump discharge line, the penetrator was removed from the sleeve. As shown in Figure 4.5.8, no corrosion of the plug or sleeve was noted upon removal of the white corrosion products. However, upon removal of the nylon-lined coupling from the check valve, damage of the nylon threads was noted. The leakage which had occurred at this penetrator was due to a fault in the check valve and damage to the nylon-lined coupling. No evidence of leakage at the penetrator seals was noted. No corrosion was noted in the O-ring grooves after removal of the O-ring seals. The O-rings retained their original size, shape, and hardness.

Titanium Alloy 6A1-4V Penetrator. No visible deterioration of the plug, sleeve, O-ring grooves, O-rings, or plug retaining devices was noted.

Furane Cement Joints. These cement joints showed no external signs of leakage or deterioration. The joints were not disassembled.

RESULTS

No leakage of the penetrator systems occurred due to either faulty penetrator design, fabrication, or deterioration. Penetrators fabricated from the following alloys showed no deterioration:

- nickel-molybdenum-chromium alloy "C"
- nickel-chromium-molybdenum alloy 625
- titanium alloy 6A1-4V

Penetrators fabricated from the following alloys showed no significant deterioration at sealing surfaces other than light staining:

- 70-30 cupro-nickel
- nickel-copper alloy 400

The carbon steel penetrator showed considerable corrosion even with cathodic protection but retained watertight integrity.

Plug-retaining systems utilized in this experiment were not satisfactory due to corrosion. Corrosion resistance had been anticipated to be a major factor as a dry structure interior was assumed.

The O-rings utilized in this experiment showed no deterioration from exposure.

RECOMMENDATIONS

1. The basic plug-in sleeve-type through-hull penetrator design tested in this experiment is suitable for thick-walled deep-ocean concrete structures.

2. Nickel-molybdenum-chromium alloy "C", nickel-chromium-molybdenum alloy 625, and titanium alloy 6A1-4V, based upon this and other deep-ocean tests, can be used as penetrator materials without deterioration for long periods of exposure.

3. 70-30 cupro-nickel and nickel copper alloy 400 are resistant to crevice-type attack and can be utilized as penetrator materials with reliable lifetimes of over 1 year.

4. Carbon steel is also resistant to severe attack in the critical O-ring seal areas of penetrators of this design and can be used, if cathodically protected, for periods of up to 1 year.

5. The plug retaining systems utilized in this experiment should be redesigned utilizing corrosion-resistant materials.

SECTION 6

CORROSION ANALYSIS OF THE SEACON I STRUCTURE AFTER 314 DAYS OF EXPOSURE AT 600 FEET

by J. F. Jenkins

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OBJECTIVE

This evaluation of the SEACON I structure after exposure is intended to serve as a general guide for the selection of materials for future similar ocean structures.

INTRODUCTION

One of the design considerations for components of the SEACON I structure was corrosion resistance. However, due to factors such as cost, availability, fabricability, etc., many noncritical components were fabricated from noncorrosion-resistant materials. Visual observations of the structure were made after recovery and upon partial disassembly of some subsystems to evaluate the corrosion which had occurred during exposure.

VISUAL OBSERVATION AND ANALYSIS

Main Pressure Hull, Including Hull Penetrations and Support Structure

The main pressure hull, fabricated from painted reinforced concrete, showed no deterioration. No signs of corrosion of the steel reinforcement, such as spalling or rust staining, were noted.

The spherical window seat, fabricated from painted mild steel, showed signs of rusting near the seat-hull interface as evidenced by rust stains on the hull originating at the interface. The screws used to secure the window retaining ring onto the window seat were painted after assembly. However, this paint coating failed to prevent rusting of the screws at their bases. The corrosion of the window seat and attaching screws did not result in system failure. The window assembly was not disassembled for further inspection.

The window scrubber attachment plates had also rusted at areas of paint failures, primarily evidenced by rust bleeding from the scrubber attachment plate–window seat faying surfaces. The amount of damage to the components was insignificant.

The chromium-plated steel window washer hinge bar was covered with a film of flaky red rust, especially near the carbon steel hinge plates. There were many areas of failure of the chromium plating on this hinge bar.

The 3/16-inch steel wire ropes used to secure the window washer assembly prior to deployment had been severed by corrosion. The pressed-on copper sleeves used to secure the eyes on these ropes had not corroded significantly. However, the wire rope immediately adjacent to these fittings had corroded at an accelerated rate due to the adverse effects of this copper-steel galvanic couple.

The pressure hull support structure was fabricated from mild steel and was painted. Immediately after retrieval the paint on these surfaces was covered with gas-filled blisters as shown in Figure 4.6.1. These blisters were much reduced in height 1 day after recovery and were virtually unnoticeable 1 week after recovery. There was no noticeable deterioration of the steel underneath these blisters. There were many other paint failures on the pressure hull support structure. Most of these failures were at welds or on exposed corners. No significant deterioration of the underlying material was noted at these paint failures. The bolts and nuts used to assemble the main support sections were covered with a moderately thick film of flaky red rust. Removal of this rust film revealed corrosion of the bolts and nuts underneath. This corrosion was not severe and although the amount of attack which had occurred would interfere with disassembly of the fasteners, their cross-sectional area was not significantly reduced.

The deterioration of the six through-hull penetrators in the hatch hemisphere is discussed in a separate section of this report.

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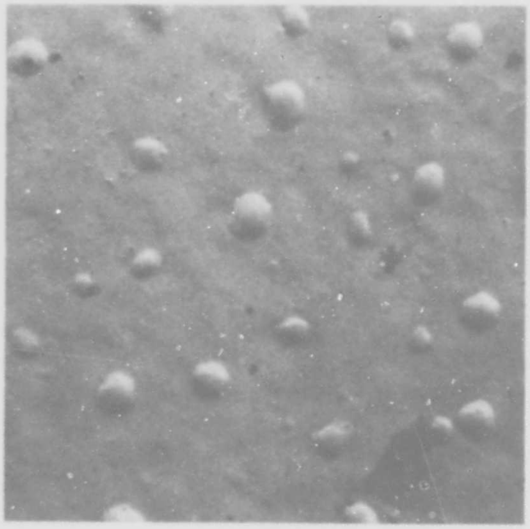

Figure 4.6.1. Paint blistering on steel structure upon recovery.

Figure 4.6.2. Rust bleeding at electrical penetrators in hatch seat.

The hatch seat and hatch were fabricated from carbon steel and painted. There were many areas of paint failure on the hatch seat. These were primarily located on the outside periphery of the seat where the paint coating was thin. The steel at these areas of paint failure was covered with a thin film of red rust but was not significantly corroded. There were several electrical penetrators in the hatch seat. There was rust bleeding from the crevices between these nonmetallic penetrators and the hatch seat, as shown in Figure 4.6.2. The surfaces of the holes in the hatch seat which accommodated these penetrators were unpainted. One penetrator was removed, and the corrosion of the hatch seat which had resulted in the rust bleeding was not severe and extended only into the area of the penetrator O-ring seal.

The chromium-plated hatch hinge was covered with a loosely adherent film of flaky red rust in many areas, as shown in Figure 4.6.3. In these areas the chromium plating had failed completely and was gone. At the edges of these areas of complete failure there was undercutting of the plating due to accelerated corrosion of the underlying steel. There was a loss of approximately 0.01 inch of material from the surfaces of areas of complete plating failure.

The hatch-locking hand wheel was uncorroded. The zinc anode attached to the hand-wheel was completely consumed. Upon extended exposure to the atmosphere after recovery the hand-wheel showed some rust staining indicating that the attached zinc anode was effective in preventing corrosion of the hand-wheel over a major portion of its immersed exposure.

The hatch-to-hatch-seat mating surfaces were unpainted. There was a thin film of red rust on these surfaces inward up to the outermost O-ring seal. The amount of corrosion associated with this rusting was minimal. No undercutting of the O-ring seal at either the seal seat or in the O-ring groove was noted.

The inside of the structure was virtually unaffected by its exposure except in three areas. There was a large amount of white, saline, corrosion products at the sump-pump check valve penetrator. This was a result of a combined failure of the check valve and an insulating nylon coupling utilized to prevent galvanic corrosion between the check valve and sump-pump plumbing. The small amount of seawater leakage at this point had resulted in the corrosion of the aluminum penetrator retaining plate. The retaining system of the through-hull penetrator below had also been damaged by water from this leak. Another through-hull penetrator retaining system was damaged by condensate water which had collected in the penetrator. This damage is covered in detail in the Through-Hull Penetrator section of this report.

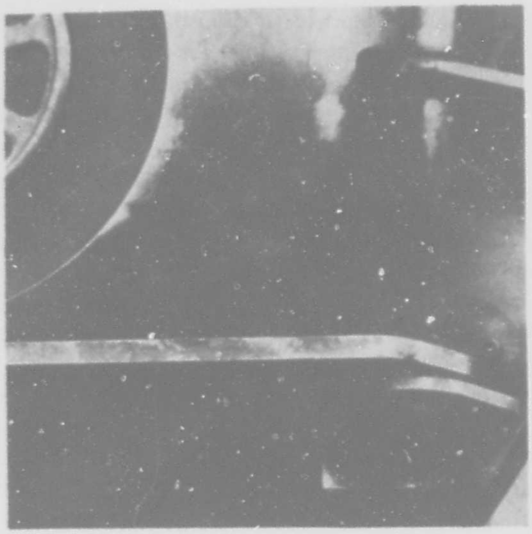

Figure 4.6.3. Failure of chromium plating on hatch hinge.

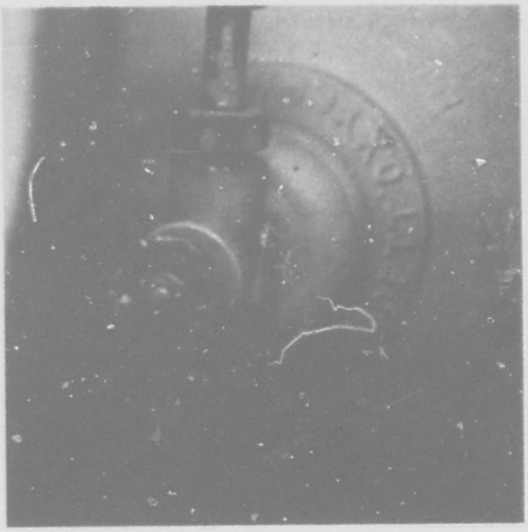

Figure 4.6.4. Condition of bronze ballast control valve after recovery.

Ballast System, Including Control Valves and Lowering Cable Guides

The main ballast tank system was fabricated from mild steel and was painted after fabrication. The paint on these surfaces was, like the paint on the hull-supporting structure, blistered upon recovery. These blisters did not cover any significant corrosion. Paint failures at welds and at areas of mechanical damage were associated with light rusting, but no significant corrosion of the underlying structure had occurred.

The bronze ballast control valves were uncorroded upon recovery (Figure 4.6.4). However, after recovery, a thin film of green corrosion products formed on these valves. This indicated that the valves received cathodic protection from the surrounding steel structure. This galvanic relationship was further confirmed by the accelerated corrosion of the steel and zinc handles attached to the valves. The ballast tank relief valves, fabricated from carbon steel, were covered with a moderately thick layer of red rust upon recovery. Light corrosion of the valves was evident upon removal of this rust. The valves, however, were operational.

The paint coating on the inside of the lowering cable guides attached to the ballast tank was, as expected, severely damaged. A thin layer of flaky red rust covered these surfaces, but no significant corrosion had occurred.

External Electrical Systems, Including Battery Box and Lights

The external cabling was attached to the structure utilizing cadmium-plated steel hardware. The cadmium plating had corroded away, and the steel hardware was covered with a thin film of red rust upon recovery. However, the hardware was not significantly corroded, and no corrosion related failures were noted.

The painted steel battery box was, like many other painted steel components, covered with blisters upon recovery. This blistering did not result in any significant corrosion of the underlying steel. The stainless steel nuts and bolts used to secure the battery box lid were not significantly corroded. However, signs of incipient crevice corrosion were noted on some of these fasteners.

The external lights attached to the structure near the spherical window were fabricated in part from painted aluminum alloy. The paint coating had not protected the aluminum, and pitting attack up to 1/8 inch deep was measured on these components at the areas of paint failure.

CONCLUSIONS AND RECOMMENDATIONS

No significant deterioration of the painted steel components of the structure was noted. The chromium and cadmium plating of the steel components was less effective than the paint coating in preventing corrosion. Zinc anodes can prevent corrosion of chromium-plated steel for up to 1 year.

O-ring seals in unprotected carbon steel flanges were not damaged significantly during this exposure. Corrosion occurred in the flanges, but did not result in seal failure.

Bronze valves used on the steel ballast tank were unattacked. They received cathodic protection from the surrounding structure, but due to the large area of structure involved, did not cause noticeable acceleration of corrosion on the large steel structure. Small areas of less noble materials (steel and zinc valve handles) attached to the valves corroded very rapidly due to the galvanic action. Relative area relationships are at least as important as galvanic potentials in the design of corrosion-resistant structures.

Painted aluminum alloys were not resistant to corrosion. Based upon this exposure and previous tests, aluminum alloys are not recommended for such components, especially when attached to large areas of more noble materials (steel). Should aluminum alloy components be used, they should be isolated from large areas of more noble materials.

In general, the corrosion noted on the SEACON I structure was insignificant and reflected good selection and utilization of materials for corrosion resistance and corrosion protection. The only significant corrosion noted was caused by galvanic corrosion. Such attack can be eliminated only by isolation of dissimilar metals when their use is necessary.

SECTION 7

FOULING AND BIODETERIORATION OF ANTIFOULING CONCRETE AND OTHER MATERIALS AT A DEPTH OF 600 FEET

by James S. Muraoka

OBJECTIVE

The objective of this study was to determine if concrete structures such as SEACON I, with a plastic viewport, would become fouled with marine growth during a 1-year submersion.

INTRODUCTION

Whenever man-made objects are placed in the sea, they soon become covered with marine growth. The attachment of sessile organisms on submerged objects occurs abundantly and rapidly on materials exposed near the surface of the sea. Before the SEACON I structure was emplaced on the seafloor in the Santa Barbara Channel at a depth of 600 feet for a period of 1 year, various materials such as wood, plastic, ropes, and antifouling concrete test specimens were exposed at the site. The test specimens were secured to an 1,800-pound, 2 x 3 x 3-foot concrete block, which served as an anchor block for the current meter array. The current meter array was used to obtain oceanographic data of the area. This large concrete block also served as a control specimen.

The concrete test specimens exposed at the SEACON I test site were made by saturating lightweight expanded shale aggregates with a chemical solution containing (1) creosote oil, (2) tributyltin oxide, (3) pentachlorophenol, and (4) malachite green (oil and water soluble). The chemically treated aggregates were mixed with appropriate amounts of water and cement to form a mortar and then placed in a 1 x 6 x 12-inch wood mold. The materials and method used to make the antifouling test panels and the results obtained on short-term exposure tests have been published in Reference 4.7.1. The study of fouling and biodeterioration of materials exposed at a depth of 600 feet in the Santa Barbara Channel was of interest because similar materials were exposed in the open sea at greater depths [4.7.2]. Reported herein are the results obtained on marine fouling and biodeterioration of materials from three exposure tests exposed on current meter arrays, and from an examination of the SEACON I structure when it was recovered.

RESULTS AND DISCUSSION

First Exposure Test (January to July, 1970)

Only antifouling concrete test panels were exposed during this test. Upon recovery, the test panels were found to be free of any fouling organisms after 6 months exposure at a depth of 600 feet. However, over 25 small goose barnacles were found attached to the 2 x 3 x 3-foot concrete mooring block which served as a control specimen. These goose barnacles have been identified as *Scalpellum osseum* by Dr. Dora Henry of the University of Washington.

Acorn barnacles, such as *Balanus tintinnabulum*, *Balanus concavus pacificus*, and *Balanus nubilus*, were found attached to a painted buoy submerged about 50 feet below the surface of the sea. The shells of several of these barnacles measuring about 1.5 inches at the base had penetrated the paint, severely damaging the protective coating (Figure 4.7.1). Current meters exposed at this depth were heavily fouled by hydroids and tube dwelling amphipods. Fouling of the rotor by hydroids and some barnacles resulted in malfunction of the instrument (Figure 4.7.2).

Second Exposure Test (August to December, 1970)

In addition to antifouling test panels, other materials, such as an acrylic plastic panel and a wood panel, were exposed for testing.

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Figure 4.7.1. Sharp edges of barnacle shell, cutting through and lifting paint coating on subsurface buoy.

Antifouling Concrete Panels. When recovered the panels were free of marine growth of any kind. The surfaces of the panels were covered with a thin layer of creosote oil which had oozed out from the interior of the concrete. Except for some scattered hydroid growth, the control block (2 x 3 x 3-foot block) was also free of marine growth. The goose barnacles which were found on this mooring block during the first exposure test were not present during this exposure period.

Acrylic Plastic (Plexiglas) Panel. Only a trace of hydroid growth was found on the panel. The surface of this 1/4-inch-thick, clear, transparent plastic was covered with a thin layer of fine silt and also with primary slime film composed of microorganisms. The visibility through the plastic was considered fair (Figure 4.7.3). Other varieties of fouling organisms, such as barnacles, mussels, bryozoans, and tubeworms, normally found attached to submerged materials at the surface of the sea were not found attached to the plastic test panel.

Wood Panel. Six deep-sea molluscan wood borers, *Xylophaga washingtona,* were found inside a 1/4 x 4 x 12-inch untreated fir panel. The shells of the largest borer measured about 1/4 inch in diameter and had penetrated over 1 inch deep into the wood.

Figure 4.7.2. Rotor of current meter, showing fouling by hydroids and barnacles at depth of 50 feet.

Numerous small amphipods (crustaceans) and annelid worms were found on the surface of the Douglas fir panel.

Third Exposure Test (September, 1971, to February, 1972)

Over 20 different kinds of materials (30 individual specimens) were evaluated for fouling and biodeterioration. The general condition of some of the test specimens soon after being recovered from the sea is shown in Figure 4.7.4.

Antifouling Concrete Panels. The antifouling concrete test panels were free of fouling attachment. The surface of the treated panels became heavily coated with creosote oil shortly after recovery (Figure 4.7.5). The oil had expanded and oozed out

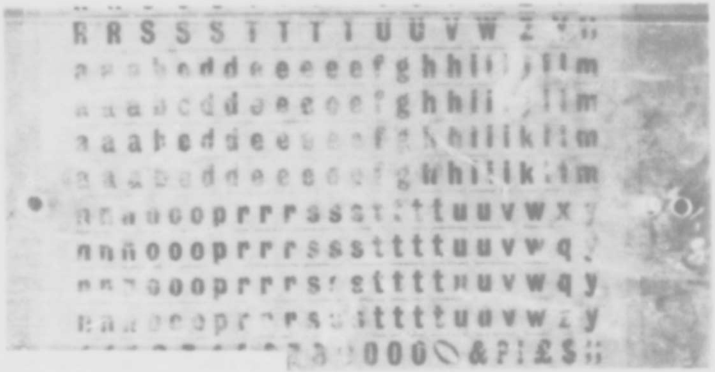

Figure 4.7.3. Acrylic (Plexiglas) panel exposed 4 months at SEACON I site (600 feet).

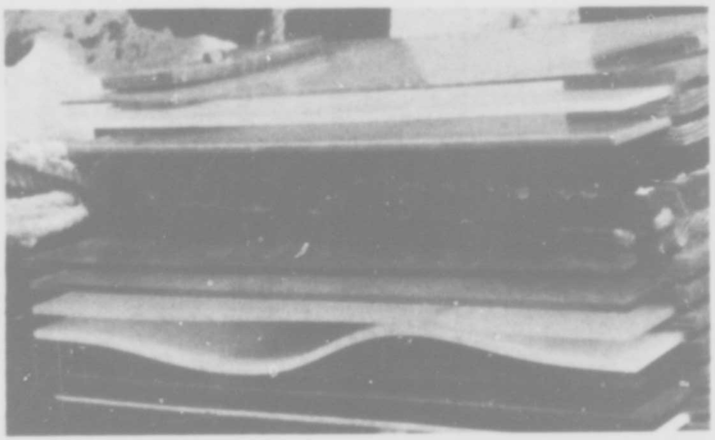

Figure 4.7.4. Test specimens after 6 months' exposure at SEACON I site (600 feet).

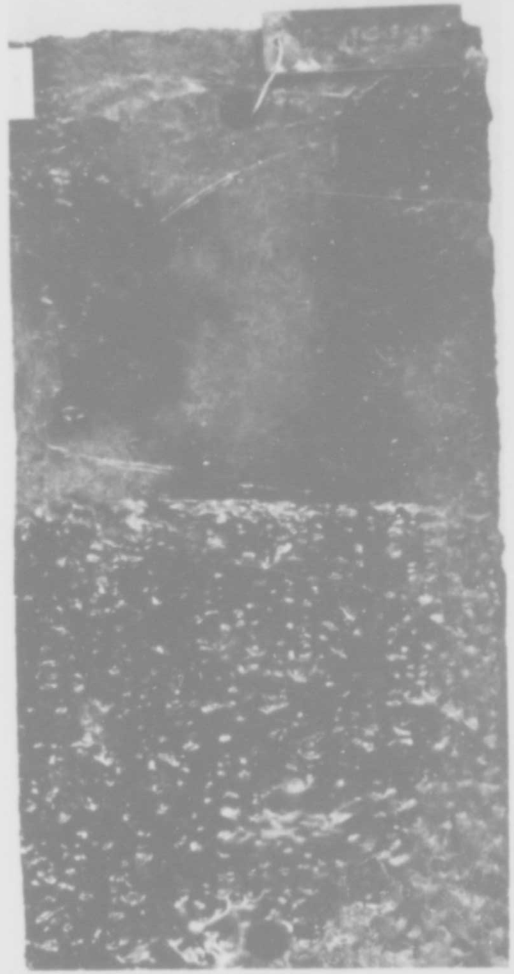

Figure 4.7.5. Antifouling concrete test panel after 6 months' exposure at SEACON I site (600 feet).

Table 4.7.1. Results of Tests on Plastic Panels Exposed at SEACON I Site[a]

Materials	Size (in.)	Hardness Test[b]		Biological Effects
		Before Exposure (dry)	After Exposure (wet)	
Acrylic, Plexiglas G	1/8 x 6 x 12	90.0	88.0	All of the panels were essentially free of marine growth except for deposits of primary film, fine silt and thin threadlike tentacles of hydroids. All of the test panels were damaged by borers under an area where a wood piece was in contact with the plastic.
Nylon, 6	1/8 x 6 x 12	79.3	63.0	
Polyethylene	1/8 x 6 x 12	47.6	47.6	
Polycarbonate	1/8 x 6 x 12	84.6	83.6	
Polypropylene	1/8 x 6 x 12	74.3	75.0	
Polyurethane	1/16 x 4 x 12	95.0[c]	94.0[c]	
Polyvinyl Chloride	1/8 x 6 x 12	85.0	85.0	
Polystyrene	1/8 x 6 x 12	84.0	83.0	
Phenolic Laminate, Grade XXX	1/8 x 6 x 12	94.6	92.0	
Tetrofluoroethylene	1/16 x 4 x 12	55.0	55.0	
Vinyl, black, pp, rigid	1/16 x 6 x 12	81.3	81.3	
Vinyl, pp, rigid	1/8 x 6 x 12	85.0	84.3	
Vinyl, pm, rigid				

[a] Third array test.

[b] Durometer "D" ASTM D1484.

[c] Durometer "A-2" ASTM D676.

of the interior of the panel when it was exposed to the warmer surface temperature. The untreated 2 x 3 x 3-inch concrete block which served as a control specimen was also free of marine growth except for traces of hydroid attachment. The goose barnacles which were found on this block during the first exposure test (January to July) were again not present on this block during this exposure period.

Plastic Panels. A list of various types of plastic materials which were exposed is presented in Table 4.7.1. When the panels were recovered and examined, they were found to be relatively free of marine growth. However, the surface of the plastic panels were lightly covered with branches of thin, threadlike tentacles of hydroids. A thin layer of primary slime growth together with fine silt covered the surface of these panels. The visibility through a 1/4-inch-thick acrylic (Plexiglas) panel was considered good. Although the plastic test panels were essentially free of marine growth, light to moderate marine wood borer damage was sustained by all of the panels under the area where a wood panel (serving as a spacer between the panels) was in contact with the plastic. The wood borers present inside the wood had continued to bore in the plastic, producing numerous pits over the surface as shown in Figure 4.7.6. The result of a hardness test conducted on the recovered plastic specimens is presented in Table 4.7.1. The hardness of the majority of the plastic specimens remained about the same except for the nylon panel. The nylon panel is much softer when wet than when dry.

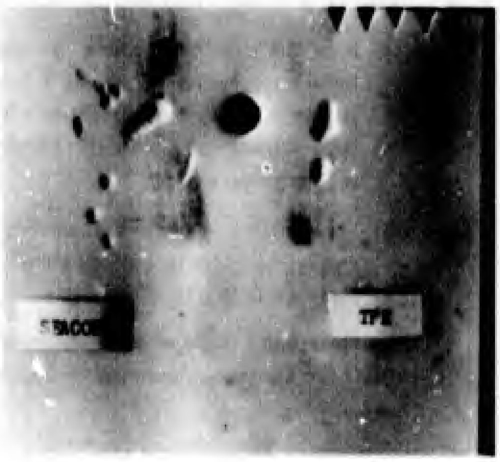

Figure 4.7.6. PTFE (Teflon) panel exposed at 600 feet, showing pitting produced by marine borers where wood was in contact with plastic panel.

Table 4.7.2. Results of Tests on Breaking Strength of Rope Specimens[a]

(All specimens 1/4-inch in diameter)

Rope Materials	Breaking Strength (lb)[b]	
	Unexposed Specimens	Exposed Specimens
Polypropylene	1,137	1,395
Polythylene	1,025	1,190
Polyester	1,535	1,500
Nylon	1,515	1,262

[a] Exposed for 186 days.
[b] Average of two ropes.

Wood Panels. The 1/4 x 2 x 4-inch Douglas fir panels that served as spacers between two plastic panels were riddled with two types of molluscan borers, *Xylophaga washingtona* and *Bankia setacea* (identified by Dr. Ruth Turner of Harvard University, Museum of Comparative Zoology). Finding *Bankia setaceaa* (normally found in shallow waters) in wood panels exposed at a depth of 600 feet was unexpected (Figure 4.7.7). The wood panels which were in contact with the antifouling concrete panels were free of borer damage. The wood had absorbed enough toxic chemicals from the antifouling concrete panels to render the wood immune to any borer attack.

Rope Specimens. The 1/4-inch-diameter rope specimens (nylon, polyethylene, polypropylene, and polyester) were essentially free of marine growth except for some slime growth over the ropes. A tensile strength test was conducted on the recovered rope specimens (wet) to determine the effects of the ocean environment on synthetic ropes. The results of this test are presented in Table 4.7.2. The breaking strength data on ropes which had not been exposed in seawater (control) are also presented for comparison. In general, the tensile strength of the exposed nylon ropes decreased; the polyester (Dacron) ropes remained about the same; and polyethylene and polypropylene ropes had increased in strength. Similar results were obtained on nylon, polyethylene, and polypropylene ropes exposed for a period of 6 months at a depth of 6,000 feet off the coast of Southern California [4.7.2]. Polyester (Dacron) rope was not tested at 6,000 feet.

Inspection of SEACON I Structure (September 1971 to June 1972)

When the SEACON I structure (coated with Phenoline 300 epoxy paint) was recovered and viewed from some distance, the surface of the concrete structure was exceptionally clean and seemed to be free of marine growth. Closer inspection of the structure for the presence of fouling attachment was conducted the following day when the structure was returned to the Laboratory. The following fouling animals (sessile forms) were found attached to the structure:

1. Goose barnacles (*Scalpellum osseum*). Four specimens about 1 inch in length.

2. Calcareous tubeworms. Numerous specimens attached to various parts of the structure.

3. Sea anemone. A single specimen about 1 inch in diameter found inside a pipe.

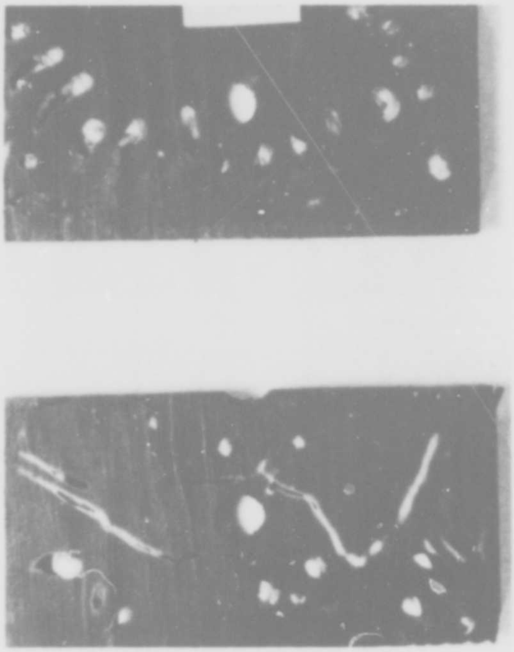

Figure 4.7.7. Untreated wood panels exposed at 600 feet for 6 months, showing damage caused by marine borers *Xylophaga washingtona* and *Bankia setacea* (elongated tunnels).

4. Small scallops (pectens). Several 1/2-inch-diameter specimens found in protected areas.

5. Hydroids (*Endentrium californicum*). These may easily be mistaken for one of the brown algae. Several groups of branch-like colonies (1/2 inch in length) were found attached to the surface of the acrylic (Plexiglas) window (upper edge). It is possible that these hydroids would have spread over the entire surface of the window if the surface had not been cleaned periodically with the mechanical wiper.

6. Primary slime. A thin layer of primary slime growth together with fine silt coated the unwiped area of the window.

In addition to the above fouling organisms, the following free-swimming (nonsessile) form of marine animals were found on the SEACON I structure:

a. Deep Sea Shrimps – two species

(1) *Pandalus gurneyi*. Sixteen live specimens each measuring about 5 inches in length. Several hundred could have been washed off during the SEACON recovery operation.

(2) *Spirontocaris* sp. More than 24 live specimens each measuring about 1.5 inches in length.

b. Isopods (related to wood boring crustacean, *Limnoria*). A single specimen of *Pentiodotea resecata*.

c. Lobster-like crustacean. Several specimens belonging to Family Galatheidae.

Other Materials Associated with SEACON I Structure

Red Plastic Float With Rubber Bladder. It was essentially free of marine growth when recovered. A few specimens of the following fouling organisms were found attached to the float. Hydroid colonies (*Endendrium californicum*), small scallops (pectens), and several calcareous tubeworms.

Braided Nylon Rope Attached to DOT High-Voltage Connector. Storage of about 100 feet of 2-inch-diameter tightly wound nylon rope on a steel drum 50 feet below the surface of the sea resulted in the formation of an anaerobic environment (stagnant condition) under the stored rope. Hydrogen sulfide was formed by the sulfate-reducing bacteria growing in an anaerobic environment. When recovered, the rope (bottom section) exposed in this environment was covered with black iron sulfide. The long-term effects of hydrogen sulfide on nylon rope fibers is not known.

Polyethylene and Polyurethane Cable Jacketing. The entire length of both cables (DOT electrical connectors) was covered with a thin layer of fine silt and light hydroid growth (*Obelia* sp) and few barnacles (*Balanus concavus pacificus*).

Concrete Cylinders. The concrete test cylinders secured to the side of the SEACON I structure were free of marine growth.

Burlap. The fibers of the burlap wrapping material were severely decayed by bacterial action and could easily be torn apart by one's fingers.

CONCLUSIONS

Materials and instruments exposed at the surface of the sea down to a depth of 50 feet will become heavily fouled primarily by hydroids, tube dwelling amphipods, and some barnacles. Fouling of the crucial parts of an oceanographic instrument will result in the malfunction of such instruments (fouling of the rotor of a current meter).

Materials (including concrete) exposed on the seafloor in the Santa Barbara Channel at a depth of 600 feet do not become heavily fouled by marine organisms even after 1 year of exposure. There are potential fouling organisms such as hydroids, pectens, tubeworms, sea anemones, and barnacles present at this location and depth. Marine wood borers are present at this depth in large numbers; therefore, plastics and other materials which are susceptible to borer damage should not be placed against any untreated wood pieces in the deep ocean.

Even a light fouling environment can pose a problem for viewports. Hydroid and slime/silt buildup on the viewing area of the window appeared to be prevented by the cleaning action of the mechanical wiper.

SECTION 1

ELECTRICAL SYSTEM FOR SEACON I

by G. A. Edgerton

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OBJECTIVE

The objective of the electrical power and telemetry system for the SEACON I Project was to provide a highly reliable, state-of-the-art system to power and retrieve data for the experiments of the project.

INTRODUCTION

The power, telemetry, and transmission system was designed not as one of the SEACON I experiments but as a support function. The approach was to use state-of-the-art, off-the-shelf components wherever possible. The power source, power storage elements, power equipment, and transmission cables were proven and highly reliable. Redundancy for subsystems was added whenever possible to assure success.

The electrical and electronic systems were built at CEL with the exception of the data acquisition system. Whenever possible during subsystem and system integration and testing, components and subsystem were both pressure- and cold-tested. The complete electrical system was designed to operate in the event the structure flooded.

ELECTRICAL POWER SYSTEMS

General Description

The electrical power system for SEACON I consisted of four broad system areas: the energy generation and storage system, the transmissions and distribution system, the power utilization system, and the telemetry system.

Energy Generation and Storage. To maximize the probability of success, SEACON I was designed so that the structure could be powered from either the surface support ship or from the submerged structure itself. The surface power was generated by a 3-kw generator located on a support ship. The subsurface power came from a 28-volt, 500-ampere-hour lead–acid storage battery. The cells were contained in a pressure-compensated housing filled with Primal 207 white oil.

When the structure was recovered, the battery was discharge tested at a 5-ampere rate. The total time of discharge was 67 hours (335 ampere-hours). At the 5-ampere discharge rate the manufacturer's specification for the cells was 392 ampere-hours. The test results show the batteries had 85% of their capacity remaining.

Power Transmission and Distribution. The power transmission from the surface to the structure was accomplished with two electromechanical cables. One cable system was 440 VAC while the second system was 4,160 VAC.

The 440-VAC, three-phase, three-wire system was comprised of the following: the generator, a 208/440-VAC step-up transformer, 750 feet of electromechanical cable, a step-down transformer, and distribution relays housed inside a waterproof container. The electrical distribution was made through high-pressure penetrators mounted in the main hatch ring.

The transformers were 10-kva, 440-VAC phase-to-phase primary, and 208-VAC phase-to-phase secondary. They were submerged in oil in pressure-compensated housings.

All cable supplied, other than the main cable, was neoprene jacketed cable, type SO with jute fill. The main cable consisted of one RG-8, three No. 6 AWG power leads (440 VAC, 60 Hz), and 25 No. 22 AWG conductors. An inner layer and an outer jacket of polyurethane enclosed a metal strength braid which provided fish bite protection. The main hull penetrator MS-2-19-BCR was machined of Monel 400. The contact wafer was transfer molded under high pressure and temperature utilizing fiberglass-reinforced epoxy. Some of the characteristics of this material are as follows: dielectric strength, 375

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volts/mil (dry); tensile strength, 11,000 psi; compressive strength, 28,000 psi. The main connector set consisted of 29 contacts: one RG-213, three No. 6 AWG, and 25 No. 20 AWG. The contacts were silver plate brass.

The mating connector to the above penetrator was also machined of Monel 400 and had a special adaptor on the back end for the termination of the braid armor. This connector housed the female sockets molded in fiberglass-reinforced epoxy (characteristics given in preceding paragraph). Polyurethane molding was used to bond the back shell and the main cable to form a solid, high-pressure water seal. Rigid epoxy was used to pot the interior of the connector body.

The twelve XSK-1/6-BCL-P/20 connectors consisted of one No. 6 AWG electrical contact. These connectors were fabricated of the same fiberglass-reinforced epoxy used in the manufacture of the contact inserts as described above. This nonmetallic material is compatible with all types of bulkhead materials. These connectors were supplied with a cable potted to withstand high pressures on the low-pressure side of the connector. This series of connectors contained one facial O-ring seal rated to 20,000 psi hydrostatic pressure.

Four connectors, type XSK-2/10-BCL-P/20, were supplied. The material used in the fabrication of these connectors was the same as described for the contact inserts and the connector in the above paragraph.

Twelve connectors, type RMS-1/6-FS, were supplied. Three types of rubber were used to manufacture this series of connectors: (1) a soft durometer, good flow, excellent electrical grade rubber for around the electrical contact and between contacts where more than one contact was involved, (2) a durable but yet soft durometer rubber where O-rings or O-ring grooves were involved, and (3) a tough, durable rubber for the connector exterior.

Four connectors, type RMS-2/10-FS, were supplied for mating to the XSK-2/10-BCL-P/20. These connectors were the same as described in the preceding paragraph except for the two No. 10 AWG contact arrangement.

The 4,160-VAC system is discussed in the next section.

Power Utilization

Sump Pump. A sump pump was included in SEACON I in case a relatively minor amount of water had to be removed from the structure. The sump pump did not operate automatically but was controlled from the surface in case the water level was found to be high. The sump pump was not waterproofed and, therefore, was mounted in a watertight housing on the floor of the structure. Flexible lines with appropriate fittings were provided leading from the sump area to the pump and from the pump to the hull penetration. The various components taken in order from the sump pump to the hull walls were: two fittings mounted on a tee; a piece of flexible tubing leading to the pump intake; the pump itself; a 700-psi, 4-gpm displacement pump; and a 10-foot length of flexible hose from the pump outlet to a Pescor nylon-lined insulating coupling that separated the stainless steel fitting on the hose from the next piece in the line. A check valve made out of Inconel 625 was mounted into the Inconel penetration. Failure of this valve caused a small amount of leakage (1 gallon) that was discovered when the structure was opened after recovery. The sump pump was not needed during the operations and was not turned on.

External Light. The external lights were mixed-vapor arc lamps which operated in conjunction with a high-voltage ballast transformer. The ballast transformer was mounted inside the structure. The reflector provided a solid cone of illumination exceeding 90 degrees in each dimension. One of the lamps was flooded at the time of retrieval.

Internal Light. There were five mercury-iodide lights mounted in the interior of the structure. The positioning of the lights was such as to give the best lighting for the TV reception. All of these lights operated with no failures.

The windshield scrubber and motor and window defogger unit are discussed in Chapter 4, Section 4.

System Sensors and Telemetry

Sensors within the structure included battery voltage, battery current, internal temperature, relative humidity, pressure, internal water height, strain gages, and sump pump operation.

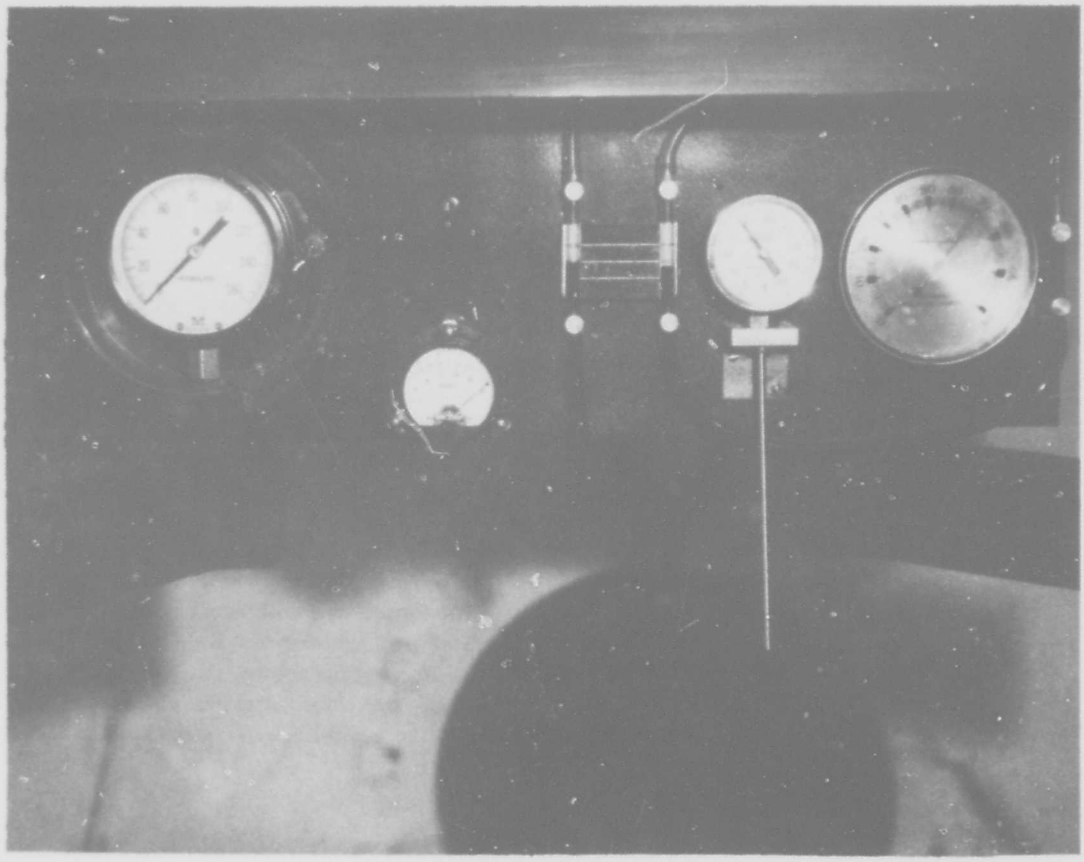

Figure 5.1.1. Instruments providing data on SEACON's internal environmental conditions. (l-r internal pressure, voltage/amperage, structure tilt, temperature, and relative humidity).

The system commands which were controlled from the surface were: internal lights, external lights, sump pump operation, window scrubber, TV, data acquisition system, window defogger, and lift bag inflation solenoid. In addition, the data acquisition system was timed to interrogate once each 8 hours and record all inputs. The window scrubber was timed to operate 2 minutes each 8 hours.

All sensor information and commands were telemetered using the electromechanical cable described above. Upon command, the data acquisition system displayed channel data sequentially on a digital readout. This information was then manually recorded at the surface.

The television was placed to allow visual display of the relative humidity, battery voltage and amperage, temperature, internal pressure, and structure tilt (see Figure 5.1.1).

Data Acquisition System

The data acquisition system, manufactured by the Montedaro Corporation, consisted of two complete self-contained, independent data acquisition systems; each could measure and record 30 channels of information. Each system was enclosed in a watertight pressure housing capable of withstanding a minimum of 400 psi.

Figure 5.1.2. Topside television and telemetry control console.

High-pressure bulkhead connectors were required to maintain watertight integrity in the instrumentation package. Care was taken in selecting compatible housing and bulkhead connector materials. Should the concrete structure have leaked the instrumentation package would have been surrounded by salt water and dissimilar metals would have caused corrosion. It was of vital importance to select connectors with an externally molded pigtail assembly. This eliminated electrical leakage problems inherent in mating pin-type connectors.

The power requirements were for separately regulated battery supplies; one for bridge excitation, the other to provide all other power requirements. Battery packs were arranged in sections so that diode isolation could be employed to insure that failure of one section would not drain the others. Battery power was provided to operate the equipment for 1 year.

Television System

The television system consisted of a KinTel Model 20/20 television camera and a topside control console (Figure 5.1.2). The topside remote control and monitor included electronic focus, sensitivity, beam, optical focus, zoom, and iris. A single coaxial cable (RG 8A/U) was used for both control and video signals. The telemetry signals were frequency multiplexed. The system used solid state circuitry throughout with the exception of the TV camera vidicon and video amplifier, and the TV monitor. The camera was supplied 115-VAC power from the power distribution relay housing.

The camera was set in the structure in such a position as to view the entire front hemisphere. The zoom had a maximum setting for view of the strain gage on the front window. The television operated with no mishaps during the year.

All control and switching circuits were installed in a watertight housing and mounted on the structure floor. These circuits allowed the selection of both the command and data retrieval channels from the surface. The components were mounted as shown in Figure 5.1.3.

CONCLUSIONS

All electrical and electronics systems and subsystems operated without failure* during the 1-year test period with the exception of the external hydroblaze lamp, which was broken during implant. This shows that when a definite objective is defined, reliable electronics and electrical systems can be designed, fabricated, and deployed in the ocean for extended periods of time.

* The Foundation Monitor failed due to a bad solder joint inside the instrument canister. The Foundation Monitor was not considered part of the electrical system tested in this section.

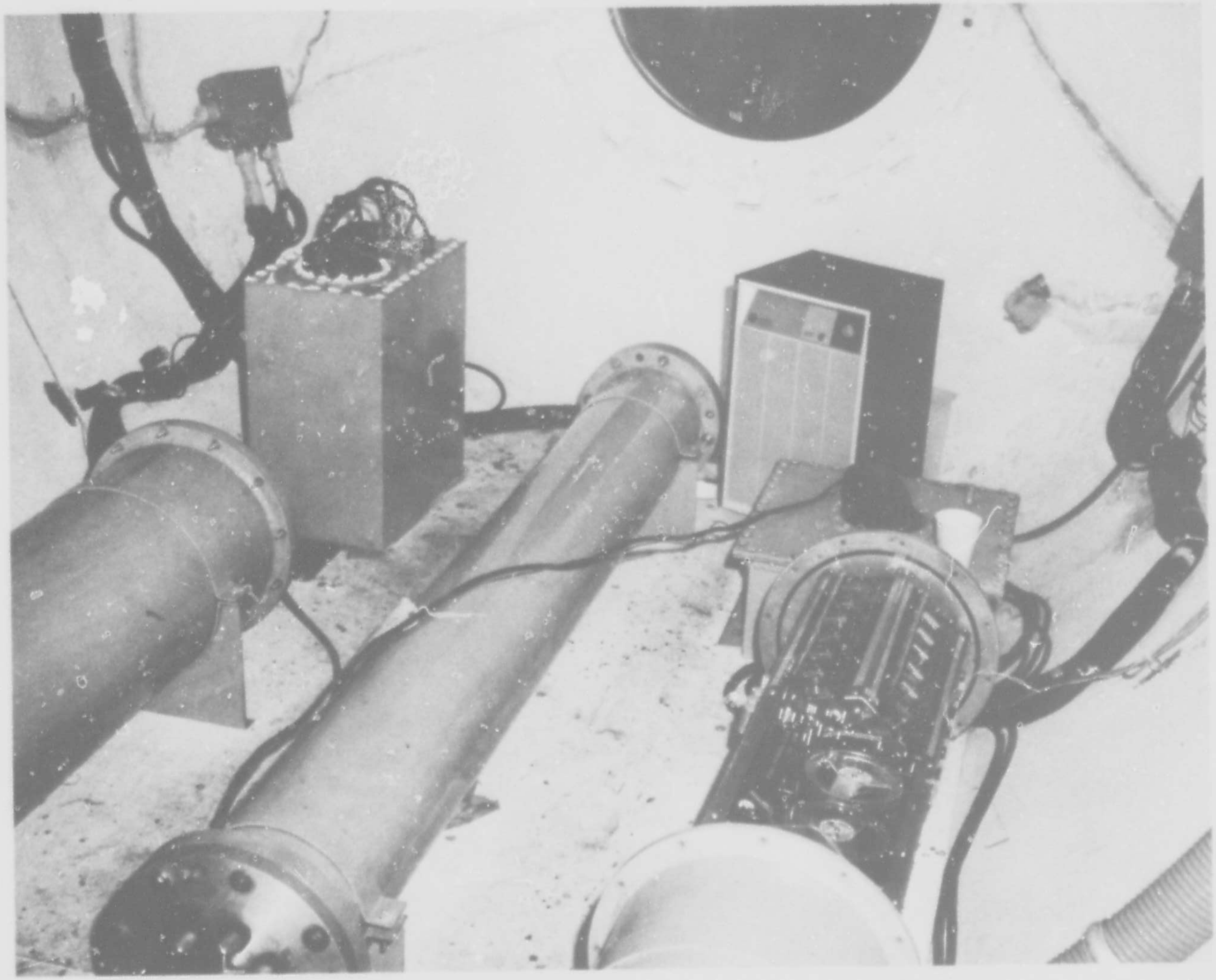

Figure 5.1.3. Internal component mounting and data acquisition system.

SECTION 2

PERFORMANCE TEST OF DOT 5,000-VOLT ELECTRICAL POWER CONNECTORS

by J. F. McCartney

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OBJECTIVE

In 1968 the Navy's Deep Ocean Technology Project began the development of connectors with air (dry) and underwater (wet) make/break capabilities to be used in power cable systems operable to a water depth of 6,000 feet, with a power capacity of 360 kw. It was the objective of the experiment described here to determine the electrical and mechanical performance of the DOT power connectors under the conditions and environment of SEACON I.

INTRODUCTION

The most versatile approach to providing high power to undersea facilities and equipment is transmission of power generated on shore or on the surface above the activity. Today, in the absence of integrally mounted seafloor power sources, transmission cables offer the only reliable long-term means of providing high power. In a study to determine the technical feasibility and technical limits of transmitting electrical power to deep-ocean installations and structures [5.2.1], it was concluded that the most serious limitation associated with obtaining usable power at deep-ocean depths was the absence of reliable watertight cable connectors. Mechanical and electrical problems were identified. The mechanical problems pertained to watertightness, material compatibility, strength, the capability of mechanical connection and disconnection submerged, and the ability to terminate effectively the armor wire for the type of cable considered in the study. The electrical problems involved meeting the current-carrying capacity at the required voltage with minimum connector contact resistance, dielectric breakdown, heat generation, and the manner of compensating for extreme voltage stress at the termination of the insulation.

DESIGN AND FABRICATION OF EXPERIMENTAL HARDWARE

In December 1968 a contract was awarded to Southwest Research Institute, San Antonio, Texas, for design, fabrication, and laboratory testing of an experimental high-power electrical connector system [5.2.2]. The following performance requirements were assigned:

(1) 360 kw of 60 Hz, three-phase power at 4,160 volts, 50 amperes per phase

(2) 100 mating operations without maintenance

(3) 5-year life

(4) Operation to 6,000 feet

Designs were required for a cable design, a dry connector concept, and a wet connector concept. Both the wet and dry connectors were to include pressure-resistant penetrator pins in their internal construction so that the connectors might be adapted to serve as hull penetrators.

Cable Concept

The concept initially selected for the cable included four quadconfigured No. 6 conductors, which were insulated, shielded, and cabled around jute filler. Around the polyethylene inner jacket were 48 round steel armor wires, and there was a polyethylene outer jacket to protect the armor from abrasion and corrosion. Because of difficulties encountered in cable procurement, the delivered cable shown in Figure 5.2.1 was considerably changed from the original design. The conductor configuration was changed to a triad with three separate neutral conductors for better structural and electrical balance. The cable armor was changed to stranded

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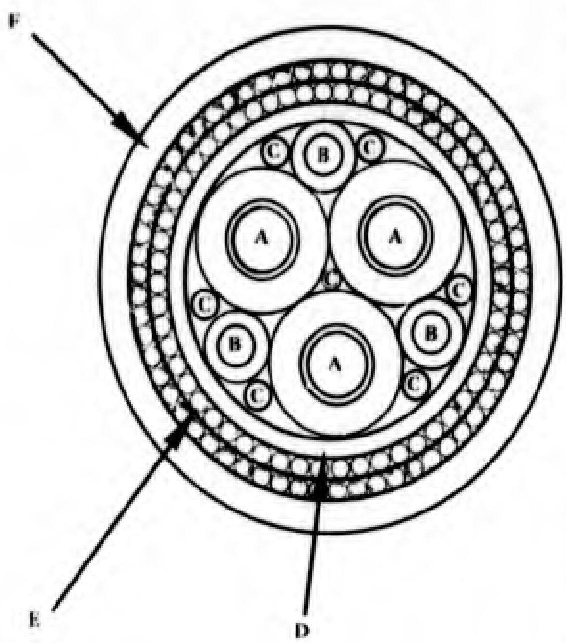

NOTES:

A. No. 6 awg. phase conductors with a 0.030 W conductive polyethylene insulation followed by a 0.150 W high molecular weight natural polyethylene insulation.

B. Three no. 10 awg. neutral conductors, insulation is high molecular weight green polyethylene.

C. Fillers, a polyethylene rod.

D. Inner jacket is 0.060 inch wall polyurethane.

E. Armor is 1/16 (1 x 7) stranded galvanized armor wire.

F. Outer jacket is high-density black polyethylene, 0.150 inch thick.

Cable interstices are filled with mastic blocking compound for crush resistance.

Minimum cable breaking strength is 14,500 pounds.

Figure 5.2.1. SEACON I armored cable configuration.

wires rather than solid. The inner jacket was changed to polyurethane (0.050 inch), and the outer polyethylene jacket was increased to a 0.160-inch thickness. The cable was not waterblocked, had no shielding, and had no bedding for the armor. As delivered, it weighed 2.14 pounds per foot in air (1.07 pounds per foot in water) and was very stiff. Although the basic configuration of the delivered cable was satisfactory, many refinements in shielding, waterblocking, jacket thickness, and armor configuration were lacking.

Dry Connector Concept

The dry connector concept (Figure 5.2.2) involved a stainless steel cylindrical body with one internal main bulkhead near each mating end. Fused-glass penetrator pins through this bulkhead extended back into the body toward the cable termination area and forward into an oil-filled, pressure-compensated chamber which was formed when the two connector halves were mated. The pins in the oil-filled chamber mated with an interference fit. The pins were solder-spliced to their respective phase leads, shielded with stainless steel sleeves, and completely potted in polyurethane. This potting included the entire interior of the connector body. The cable armor was terminated by flaring it and clamping it between two flat compression rings.

Wet Connector Concept

The wet connector concept (Figure 5.2.3) utilized the same urethane-potted cable termination and penetrator pin techniques as the dry connector. The design differences were primarily in the area of the mating ends of the penetrator pins.

The male half was fairly simple and had no moving parts. The penetrator pins employing diallylphthalate (DAP), silicon rubber (RTV), and fused-glass insulation extended out from the face of the connector about 4 inches with a ring contact about halfway back along their length.

The female half was much more complex. Each of the penetrator pins had an offset sleeve contact on the mating end and were completely potted in polyurethane except for a hole from the front of the connector through the urethane to the sleeve contact.

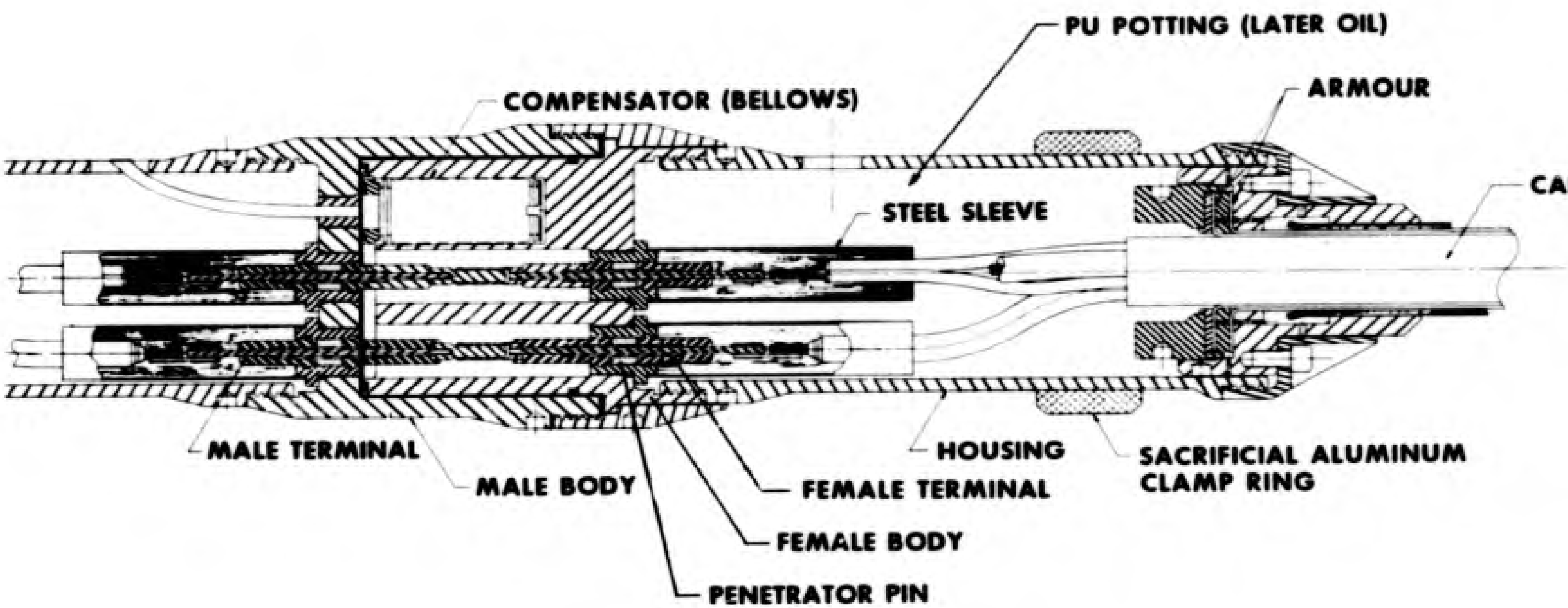

Figure 5.2.2. SEACON I dry connector concept.

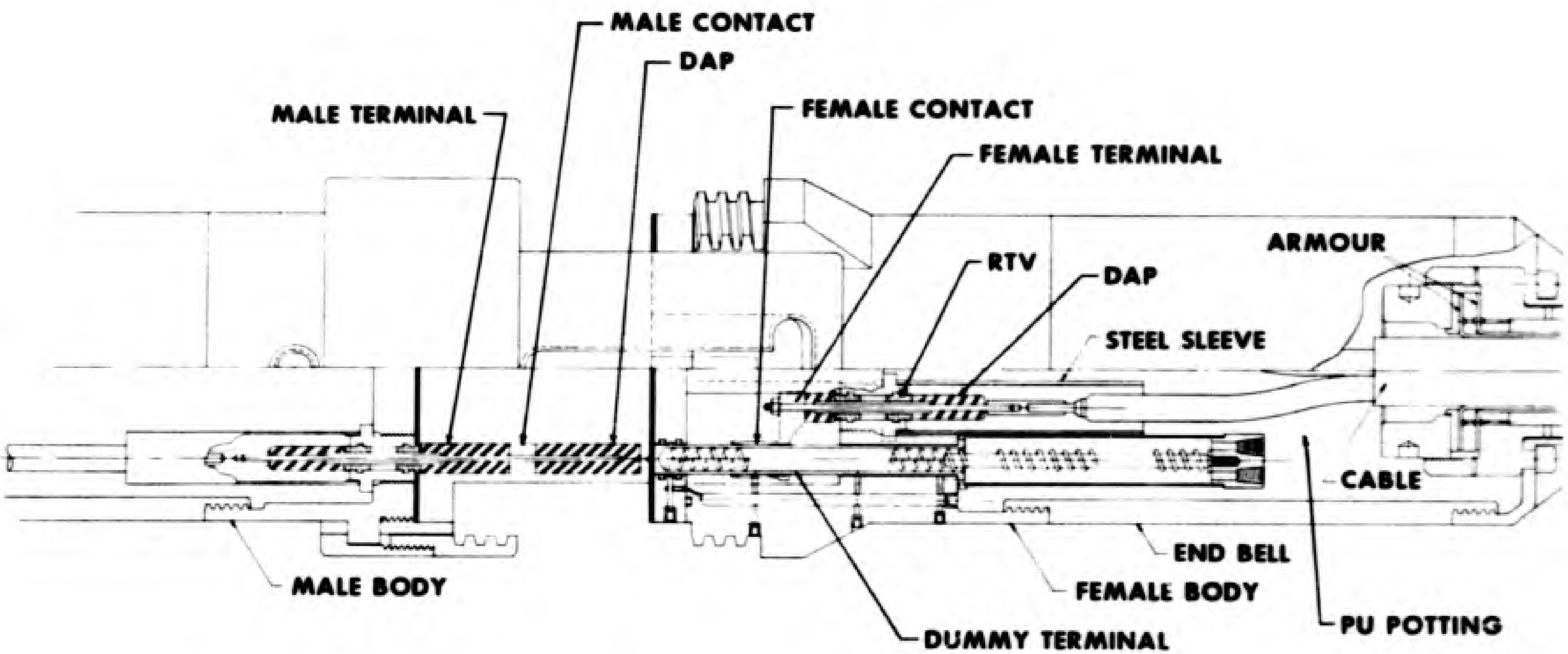

Figure 5.2.3. SEACON I wet connector concept.

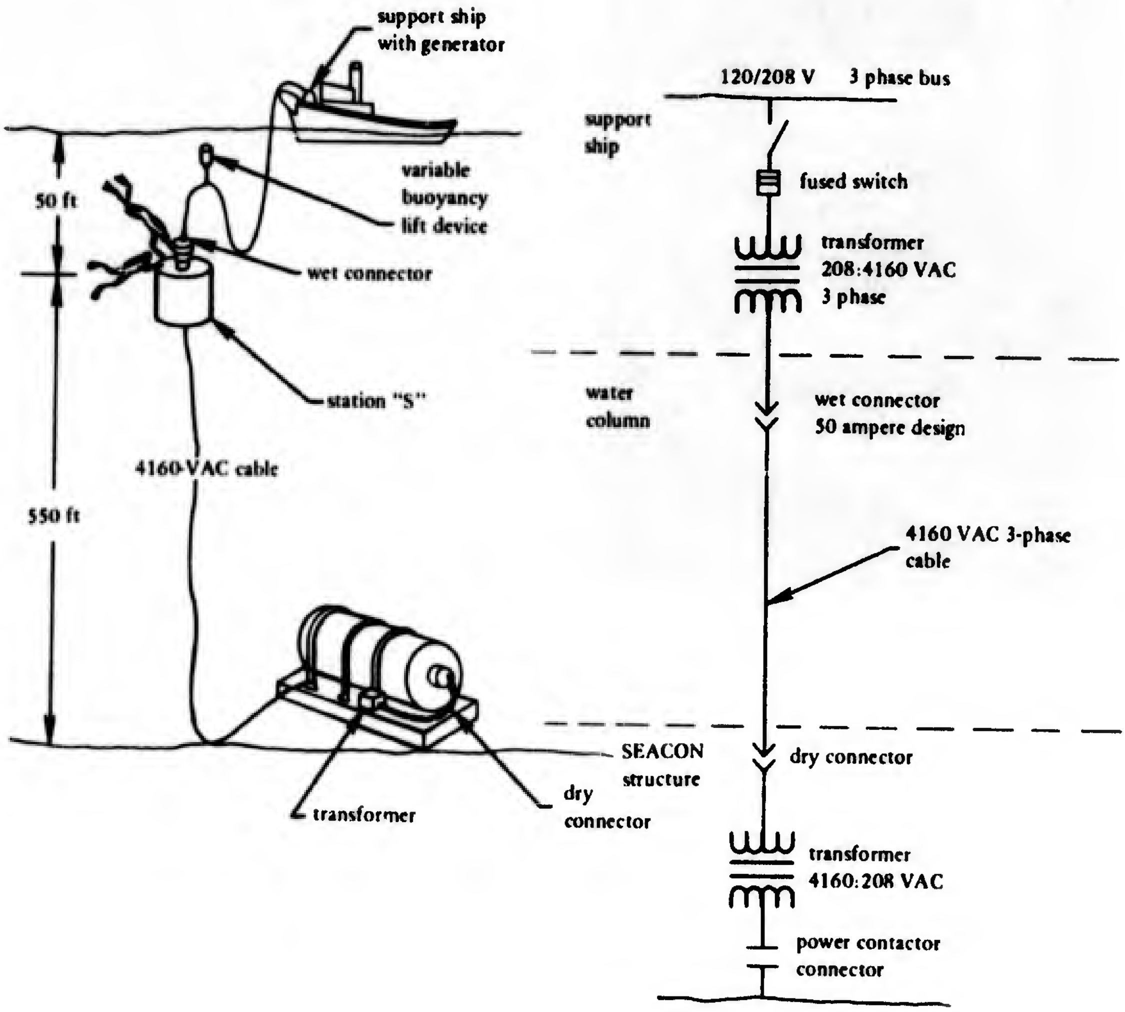

Figure 5.2.4. SEACON I high-voltage cable and connector concept.

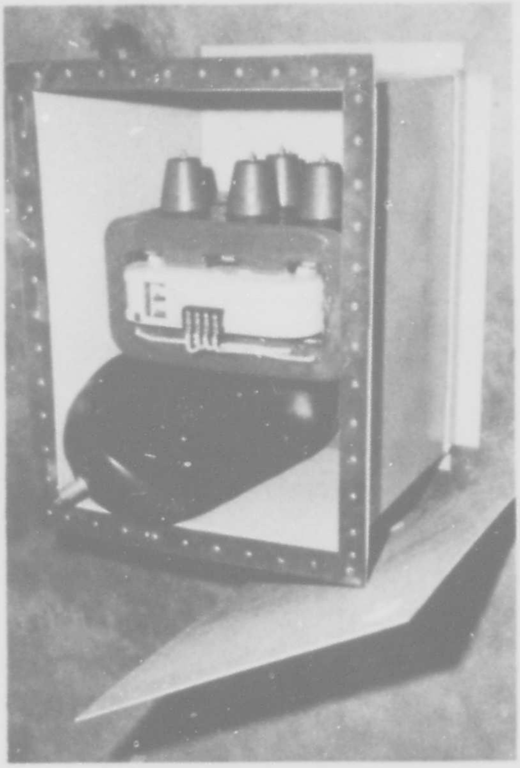

Figure 5.2.5. Pressure-equalized high-voltage transformer.

This hole was filled with a sliding dummy piston made of glass-filled Teflon. This piston was double O-ring sealed near the outer end, and the piston was spring-loaded and pressure-compensated via a small oil-filled chamber behind it. This provided for exclusion of seawater from the interior when the connectors were unmated.

During mating the two halves were held in alignment by two large projecting surfaces from the male half which acted as a guide cradle. The two halves were pulled together by a large single-throw lever linkage and as the male pins entered the female cavities they displaced the dummy pistons. The male pins were wiped clean of seawater by the two O-rings.

EXPERIMENT DESCRIPTION

The connectors, penetrators, and cable developed under the DOT connector program were used in fabricating a power transmission cable system for use between the SEACON I structure and the submerged buoy (Station S) as shown in Figure 5.2.4. The system was first subjected to a 600-foot depth, 150-kw, 3-hour submersion test and then was deployed at sea with the SEACON I structure. The cable system was used to periodically power various underwater equipment items mounted on the structure.

The cable system included both wet and dry connectors. The cable was terminated at the main transformer box (Figure 5.2.5) on the structure base and was led to a dry connector mounted on the hatch end of the structure as shown in Figure 5.2.6. The cable was then fastened at intervals to the telemetry cable and a 7/8-inch polypropylene lift line and then led to a subsurface buoy (Station S). The cable system was terminated at the upper (source) end in a wet female connector and was attached to the submerged buoy.

Periodically a support ship would anchor over the buoy, using the three-point mooring system. With diver-sided methods shown in Figure 5.2.7, a power cable from the ship terminating in a male wet connector was connected to the submerged female wet connector on the buoy. After resistance and continuity checks ensured integrity of the circuit, power was applied. The low-voltage power and telemetry cable system composed of off-the-shelf components was installed to power the structure in the event of a high-voltage connector failure.

At the conclusion of the SEACON I test the cable system was raised with the structure and examined for corrosion and deterioration. Data from this examination and from the operational performance of the system were evaluated to determine (1) satisfaction of the original DOT design objectives, and (2) need for further improvement.

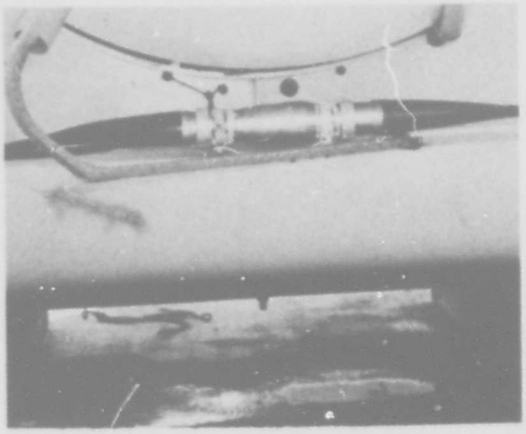

Figure 5.2.6. Dry connector installed on SEACON structure.

DISCUSSION

Six-Hundred-Foot Loop Test

Severe failures occurred during initial connector tests at the 6,000-foot depth, and further tests were required before deciding to include the high-power connectors and cable on the SEACON system. Plans were made to make a loop test to the SEACON I depth, 600 feet. To facilitate testing at 600 feet, CEL had the connectors delivered with two cable systems already assembled. Each was about 600 feet in length, and one system (for SEACON I) had a wet female half on one end and a dry male half on the other end. The other cable had a dry female and a wet male. With this arrangement one matching pair could be mated and suspended at 600 feet from the support vessel and power could be applied through the other ends at the surface. The upper ends were then wired to the transformers leading to the generator and load bank. The entire system was designed to apply full voltage and about half power (4,160 VAC phase-to-phase and 150 kws) through the connector/cable system.

Three cruises were made to test the connectors, one with the dry connector submerged, one with the wet connector submerged, and one to test the SEACON I transformer system. Power was applied for about 3 hours each time, and all the tests were successful.

SEACON I Installation

The major at-sea experiment with these connectors called for a continuing year-long operational demonstration in 600 feet of water with the SEACON structure. SEACON was towed 26 miles from Port Hueneme Harbor to the installation site. A 750-foot reel of high voltage cable with connectors attached was also towed behind the structure. At the site, the cable reel was recovered from the water and placed on the deck of the warping tug as shown in Figure 5.2.8. The structure then was lowered to its foundation, and at the same time the cables were payed out over the bow as shown in Figure 5.2.9. Within a few hours the cables were suspended between the cylinder and a float located 50 feet below the surface. The installation of the structure and associated cable systems was successful, and after an initial drop in insulation resistance the system steadied at about 70 kΩs and remained the same during the year of submergence.

Structure Powering Tests

About every 2 months the SEACON I site was visited for a powering-up and monitoring exercise to determine the long-term reliability and performance of the systems. Once the CEL warping tug was in the moor, divers would swim to Station S and make preparations to recover the cables suspended from Station S. The warping tug winch and deck crane were used to lift the buoy and cables aboard, which required about 1 hour to complete. After removing the protective boat from the wet female connector, electrical insulation measurements were made of the entire transmission system before any power was applied. It was usually necessary to flush the oil compensation system to assure that any seawater contamination that leaked through the connector pin seal was removed from the high-voltage contact areas. This was accomplished by pumping oil into the connector system while depressing the dummy pistons to vent oil past the O-ring seals.

Other than the low (70 kΩ) insulation resistance found in the transmission system following its installation and connection with the SEACON structure, the system performed as originally planned. In general, the structure equipment performed

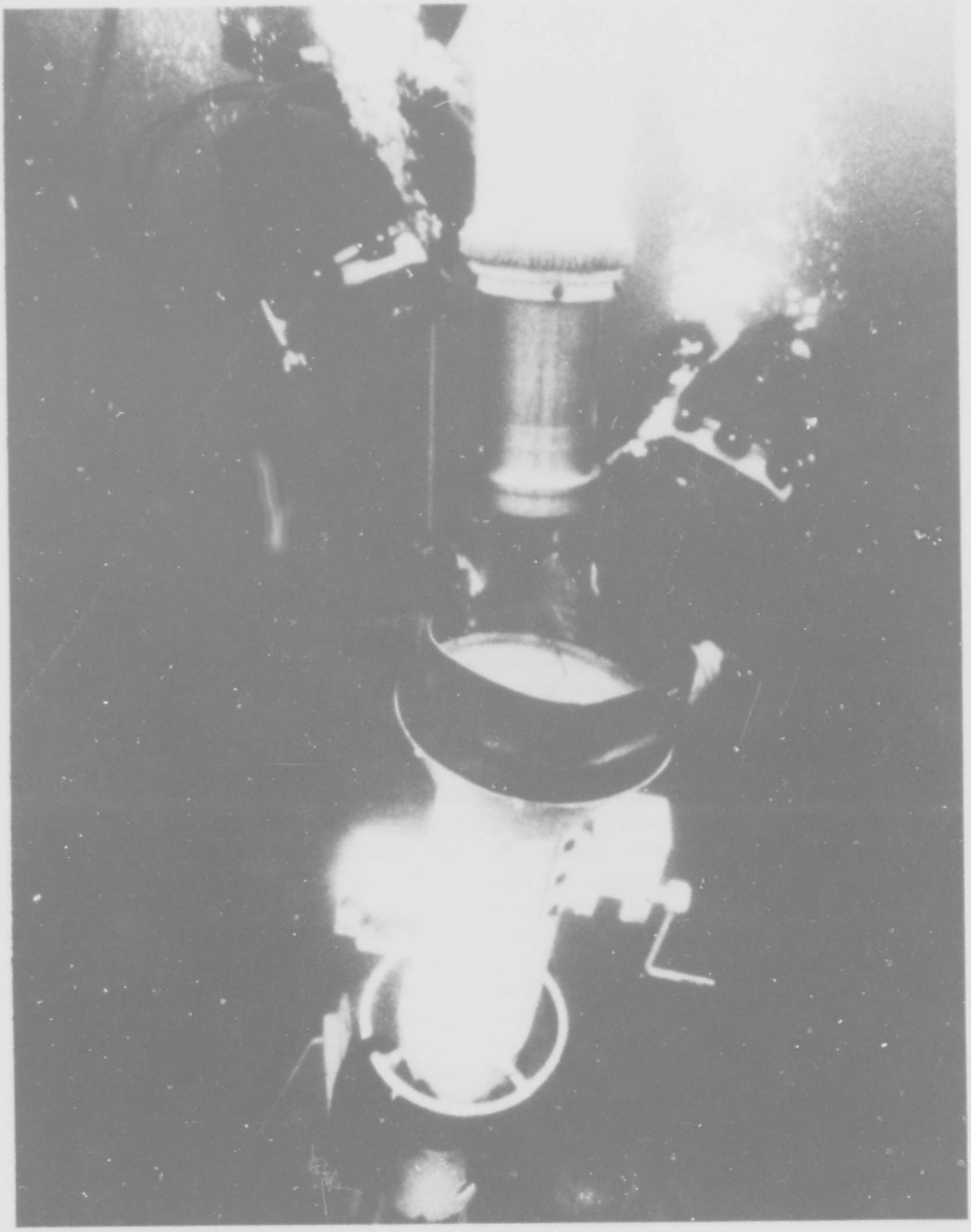

Figure 5.2.7. Wet connectors being mated by divers.

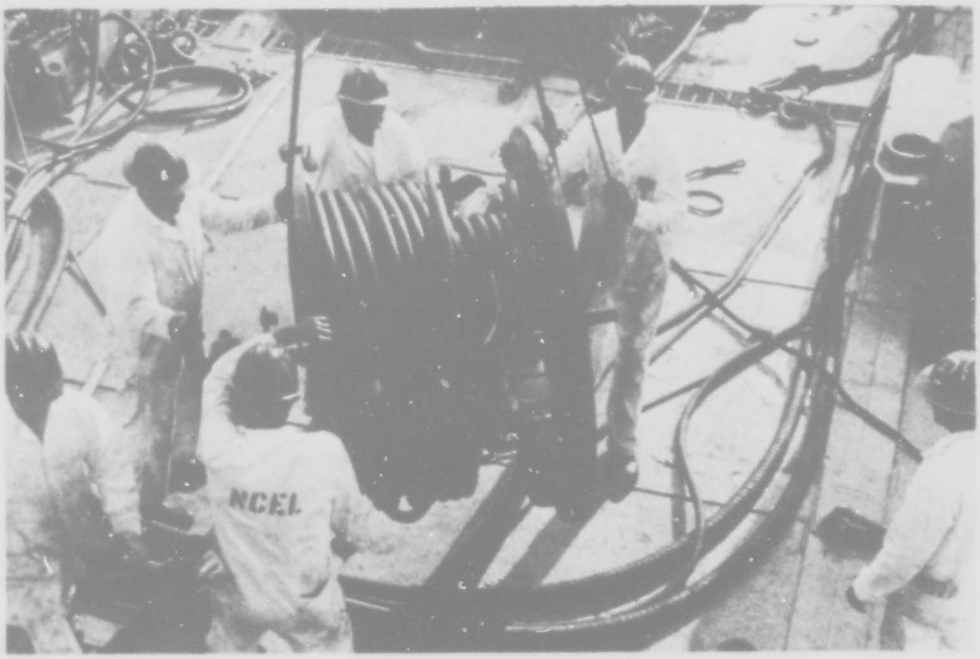

Figure 5.2.8. Handling high-voltage cable on support vessel.

Figure 5.2.9. Paying out cable during SEACON I installation.

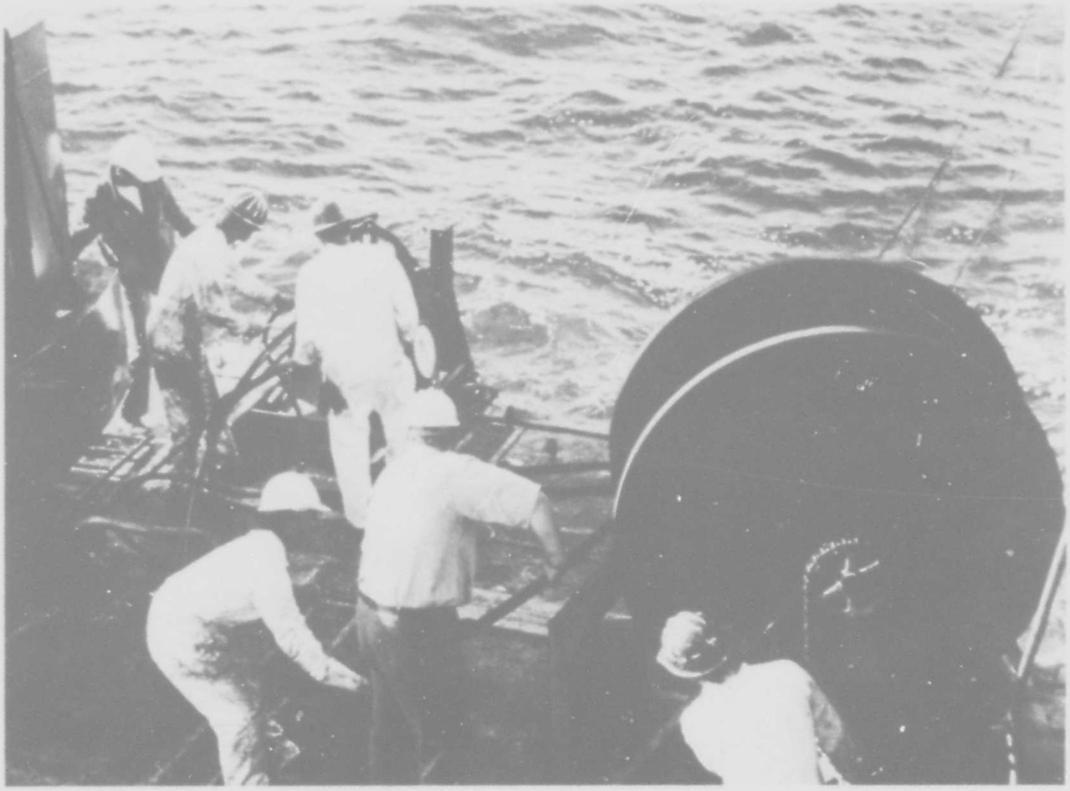

Figure 5.2.10. Cable handling during SEACON I recovery.

considerably better when powered with the high-voltage system than when powered with the 440-VAC main umbilical because the voltage regulation at this load was better with the low-loss, high-voltage system.

Mating Wet Connectors by Divers

The structure powering test described above demonstrated the need to develop a capability to mate the wet connectors underwater by divers. If the connector could be mated underwater it would no longer be necessary for the warping tug to complete a three-point moor and then recover the connector by winch and crane. Approximately 6 hours can be saved in a powering exercise with an underwater mating, and a small craft can be substituted for a large ship with a winch and crane.

A guide cone and positioning gear assembly was designed, fabricated, and tested to provide an easy and reliable capability for divers to mate the connectors. The gear system enabled the divers to rotate the male connector and to crank the halves together while the cone held them in alignment. As shown in Figure 5.2.7, the basic concept was to mount the cone on the female in a vertical position and attach the assembly to the submerged SEACON I Station S buoy. The male half was then lowered from the surface. A variable-buoyancy lift device was attached to the male half to provide a cable catenary and basic lift support for the connector.

The male connector was successfully mated underwater by divers, in a relatively strong current (0.75 to 1.0 knot). The system checked-out electrically, and the SEACON structure was powered through the just mated wet connector and the dry connector attached to the SEACON structure at 600 feet. The handling techniques for this operation should now be considered state-of-the-art.

SEACON I Recovery

After 1 year the SEACON structure was recovered from the seafloor and towed back to Port Hueneme. The power cables and lowering line were recovered as the structure was lifted. Handling of the cables proved to be the slowest and most difficult part of the lift operation. As shown in Figure 5.2.10 there were as many as nine men involved in recovering the cables. Fortunately, with only the 600 feet of cable there was never more than a few hundred pounds of tension on the cables. Otherwise the tangle of lines and cables on deck would have presented an operation impossible to complete safely.

The cable was observed to have a light growth of hydroids and barnacles and a thin layer of fine silt over its entire length. The slipperiness of the surface, the stiffness of the cable, and the several observed punctures in the jacket all indicate that an outer cable jacket is a handicap to deck handling and also a very poor waterblock. The difficulty of cable recovery illustrated the need for an underwater disconnectable connector that would separate the cables from the structure prior to recovery.

After SEACON was returned to port and lifted onto the dock, the dry connector was unmated. The low electrical resistance that had existed throughout the experiment was found to exist in two of the phases within the dry connector half on the long cable section. The section connected to the structure was in excellent condition.

The dry and wet connectors were both satisfactory for operations at the limited depths of 600 and 150 feet, respectively. Neither connector showed any appreciable corrosion or fouling after the 1-year exposure, and neither were damaged by the power transmitted through them. Other experiments in the connector test program, however, have shown a need for several modifications to obtain satisfactory operation at 6,000-foot depths.

CONCLUSIONS

In general, this Deep Ocean Technology Project task has demonstrated:

1. It is possible to design, fabricate, and operate in the ocean environment high-power, high-voltage transmission systems employing both dry and wet connectors.

2. As with most large-scale high-power equipment, it takes many years and several iterations of design, fabrication, and test to evolve long-life, reliable undersea power equipment.

3. Wet connectors can be mated in the open ocean by divers, but the compensation oil must be renewed after repeated underwater matings. Work in progress to upgrade this capability shows good potential for 40 or more reliable matings.

4. A need exists for remotely mating and unmating cable connectors to deep-ocean structures and equipment during their installation and recovery. The diver connector mating exercise will be of considerable value in developing a remote mating capability.

5. High-voltage power transmission to undersea systems improves the performance of the transmission equipment and the loads.

RECOMMENDATIONS

1. A capability should be developed to mate high-power wet connectors remotely using the manipulators of manned and unmanned deep submersibles.

2. Underwater cables and connectors should be developed for circuits other than high power including coaxial communication circuits.

3. High-voltage power transmission should be used for future undersea programs for improved performance of equipment.

CONCLUSIONS AND RECOMMENDATIONS

by T. R. Kretschmer

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PROJECT CONCLUSIONS AND RECOMMENDATIONS

SEACON I is the first major at-sea experiment conducted by this country to focus on evaluating seafloor construction technology. As such, it provided the first opportunity to evaluate at sea, as a system, numerous recent developments in ocean technology. Because the constructed system did not involve a manned structure, investigators were free to try technologically risky techniques. This freedom applied as long as the chance for success of other experiments was not seriously jeopardized and the experiments were performed within the bounds of good safety practices. This approach resulted in a large payoff for some of the experiments. It is recommended that future seafloor construction experiments retain this nonoperational, unmanned, mission approach because of its potential for making rapid strides in expanding the state of the art in seafloor construction technology.

The approach of integrating the various technologies into an operating system without allowing the failure of one to jeopardize the success of other experiments seems contradictory but was successfully accomplished in SEACON I. In several cases it was impossible to avoid one experiment potentially jeopardizing the success of others such as in the acrylic viewport and concrete structure experiments; if one failed catastrophically the other experiment would also fail. The risk of interference between experiments was reduced by using the best design data available and applying a factor-of-safety appropriate to a man-rated installation. Another way serious interference between experiments was reduced was by providing redundant methods for performing a function such as using conventional drag anchors if the experimental embedment anchors failed or obtaining site data using surface vessels in addition to the several different manned and unmanned submersibles. In summary, interference between experiments was controlled while the value gained from integrating the experiments to support a mission was retained by applying conservative factors of safety where necessary and providing redundancy. It is recommended that the concept of the focal project in which developing technologies can be integrated into a system be retained in ocean technology development.

The SEACON system approach proved to be a very cost effective means of performing ocean evaluations. Many of the sea tests performed as part of the SEACON I project also satisfied individual work unit requirements. SEACON I provided a well-documented site with a surface mooring facility and precision transponder navigation systems. Sea cruises were coordinated in such a way as to accommodate, in many instances, several different experiments on a given cruise resulting in cost-effective sea operations. It is recommended that future SEACON experiments continue to integrate planned evaluations into the SEACON framework and provide multiple missions for each cruise.

EXPERIMENTAL FINDINGS AND CONCLUSIONS

1. Site survey equipment to define the site parameters for the SEACON I installation was adequate except for sediment corers and transmissometers. Nearly all the instruments used in site survey, however, need improvement in reliability.

2. Control of corrosion and fouling of the current meters posed the largest obstacle to obtaining ocean current data at the site.

3. Knowledge of near-bottom current velocity and direction variations was found to be especially important for planning structure inspection and maintenance operations by submersible vehicles.

4. Submersible vehicles proved valuable in performing the detailed site survey and were

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especially appropriate for photographic coverage, microtopographic measurements, biological observations, and seafloor soil mechanics measurements.

5. A suite of instruments for obtaining good quality sediment cores at the SEACON I site and for performing in-place strength and model footing tests was demonstrated and produced valuable data for seafloor foundation design.

6. The SEACON I foundation satisfactorily supported the structure with no indications of excessive settlement, tendency to overturn, or lateral motion. Although the Foundation Monitor System did not obtain settlement data, visual observations indicate the foundation settled approximately as predicted.

7. The tendency of the structure foundation to overturn was found very difficult to assess analytically due to the interrelationships of tilt, differential loading, and settlements and the effect of possible earthquake loading.

8. The foundation emplacement technique can be a critical factor in foundation performance. Multiple contact with the seafloor due to ship motions can result in site disturbance and possible unsatisfactory performance of the foundation.

9. A three-transponder bottom navigation network was successfully used to accurately position work vessels and seafloor equipment during construction operations and to reacquire a surface position accurately enough for SCUBA divers to rapidly locate subsurface buoys.

10. Operation of an Equipment Test Track in soft sediments extended the data compiled during shallow-water evaluations to a depth of 600 feet in a representative cohesive seafloor sediment.

11. Neither the vibratory nor explosive-actuated embedment anchors could be installed properly. The installation attempts were very valuable, however, in bringing design problems to light that were rectified later.

12. The conventional three-point mooring system, installed for nearly 3 years, proved to be highly indispensable for conducting construction operations. The system was well-designed and maintenance-free except for keeping the buoys lighted.

13. The pressure-resistant concrete hull performed even better than predicted. The magnitude of strains on the cylinder section was 30% lower than that estimated from model studies. The window penetration, equivalant to 40% of the structure diameter, produced no harmful effect on the structure. Joining the structural elements with epoxy proved to be a very workable technique. The waterproof coating kept the structure completely free from seawater permeating the concrete.

14. A mechanical window wiper system using a brush that rotated periodically effectively eliminated biological fouling on the acrylic viewport surface. The brushing action did produce scratches in the acrylic plastic surface but these scratches did not measurably affect visibility. Due to premature removal of the antifoulant capsule in the window cover no results were obtained on chemical means of preventing biological fouling on the viewport.

15. The magnitude of strain on the acrylic viewport agreed very closely with analytical predictions and with test results on a similar viewport. The method of joining the window and steel frame worked well, producing a joint which did not leak during the installation period.

16. A plug-in sleeve-type through-hull penetrator was shown to be suitable for thick-walled concrete structures. Nickel-molybdenum-chromium alloy "C", nickel-chromium-molybdenum alloy 625, and titanium alloy GA1-4V can be used as penetrator materials without deterioration for long periods of time. Nickel-copper alloy 40 and 70-30 cupro-nickel are resistant to crevice-type attack and can be utilized as penetrator materials with reliable lifetimes of over 1 year. Carbon steel can be used in this penetrator design, if cathodically protected, for up to 1 year.

17. The corrosion of the SEACON structure system was insignificant and reflected good selection and utilization of materials for corrosion resistance and corrosion protection.

18. Marine fouling at depths to 50 feet below the surface was very severe and resulted in lost data and damage to hardware. Fouling at the 600-foot depth at the SEACON I site, even after 1 year, was light and caused no problems.

19. The 50-ton concrete structure was successfully towed a distance of over 50 miles, round trip. It was emplaced on a 14-foot-square pre-deployed foundation in 600 feet of water by means of a guideline system. Despite partial failure of the synthetic lowering line and one guideline, the structure was successfully installed. The *CURV III* submersible vehicle, using a synthetic guideline which it attached to the structure, was able to guide a new 1-1/8-inch-diameter wire rope lift line to the bottom and attach it to the structure by a snap hook. A counterweight motion-compensating lift system used for structure recovery reduced the dynamic loads and motion to insignificant levels.

20. A technique for precisely locating a submersible vehicle for construction inspection was demonstrated. Poor visibility and jerking action of the NEMO winch system which picked up the anchor and allowed NEMO to move laterally prevented visual contact to be made with the SEACON structure.

21. All electrical and electronics systems operated without failure during implant, demonstrating that when an objective is defined reliable electronics and electrical systems can be designed, fabricated, and deployed in the ocean for extended periods of time.

22. A high-voltage transmission system, employing both dry and wet connectors, operated successfully for nearly 1 year in the ocean. The wet connector was mated underwater by divers and then was used in transmitting power from the surface to the SEACON structure on the seafloor.

EXPERIMENT RECOMMENDATIONS

1. A transmissometer designed to make long-term measurements should be developed. Additional research should be done so predictions of underwater visibility can be made at seafloor construction sites.

2. A corrosion assessment should be made of all oceanographic instruments prior to their use. Special emphasis should be placed on corrosion prevention in the design of long-term oceanographic moors.

3. Reliability of both submersible vehicles and their surveying instruments needs improvement.

4. In-situ tests should be performed and undisturbed cores taken if possible at prospective seafloor construction sites. Special attention should be paid to obtaining data to assess lateral variation of sediment properties and to determine the properties of the surficial sediments which contribute most significantly to shallow foundation behavior.

5. The need to install foundations with minimal site disturbance must be considered a major goal in designing an installation system.

6. Seafloor foundation performance should be routinely monitored, at least visually, in order to provide a base for improving future design reliability.

7. Work should be initiated on determining optimum techniques for surveying seafloor, long-baseline, transponder navigation systems.

8. Both the vibratory and explosive-embedment anchors need extensive, operational use to point up further refinements in design and installation procedures and to gain additional data on holding capacities, especially what can be expected in the way of long-term service.

9. An effective, inexpensive, vandal-proof buoy light needs to be developed.

10. The SEACON I concrete structure should be reinstalled on the seafloor at a deeper depth (between 1,200 and 1,800 feet) to obtain data on its performance at stress levels near its short-term implosion strength.

11. Chemical means of preventing acrylic viewport fouling should be investigated since a passive chemical system can be made less expensive and more reliable than mechanical means.

12. Consultation and design review by an underwater materials expert should be done routinely for all hardware being installed in the ocean.

13. Material test specimens should be placed at a potential construction site for at least several months in order to provide data on the severity of marine fouling that is likely and on the types of organisms present.

14. Motion-compensating equipment should be used when handling heavy loads in the ocean. Because so

little is known about the effect of dynamic loads on flexible lift lines the solution now is to design the lift system to insure against significant dynamic loads.

15. The reaction of 2-in-1 braided synthetic rope to dynamic loads is an area which needs thorough investigation.

16. Installation procedures should be designed to allow completion of all rigging prior to subjecting the lowering line to dynamic loads.

17. An inspection vehicle such as NEMO needs effective near-bottom translation capability.

18. A wet connector should be developed for circuits other than high power, including coaxial communication circuits.

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