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AT-SEA TEST VALIDATION DATA NEEDED TO VERIFY THE NOAA/DOE CWP ANALYTIC CODE

By
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March 12, 1980

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By:

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PREPARED FOR:

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
OFFICE OF OCEAN ENGINEERING

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ABSTRACT

Test data requirements are developed in this memorandum for the one-third scale Ocean Thermal Energy Conversion (OTEC) cold water pipe (CWP) at-sea tests. A major goal of the at-sea tests is to collect sufficient data so that the National Oceanic and Atmospheric Administration (NOAA)/ Department of Energy (DOE) CWP Analytic Code can be validated. The code is examined to determine the individual responses requiring verification. The wave environment is then considered for prototype survival and the scaled test. The expected response of the OTEC CWP test article in the test environment is used to form a basis of the test plan. Requirements for the tests of standard configurations of the OTEC CWP test system are first planned followed by requirements for tests of alternate configurations and evolutions. The final product is a set of justified NOAA/CWP analytic code validation requirements.

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LIST OF SYMBOLS

e	exp, base of natural logarithm ($\ln$)
f	wave frequency sec^{-1} (hertz)
f_o^{-1}	modal period of frequency spectrum
H	wave height, feet (meters)
$\bar{H} = H_{\text{ave}}$	mean or average wave height
H_{max}	most probable maximum wave height
$H_s = H_{1/3}$	significant wave height, average heights of one-third highest waves
$S(f_o)$	maximum of $S(f)$ at f_o
T	wave period, seconds
$\bar{T} = T_{\text{ave}}$	mean or average wave period
T_o	modal period of period spectrum
T_s	significant wave period, average period of waves with highest one-third heights
U_s	surface wind speed, ten minute average at 10-meter anemometer level

1. OVERALL OBJECTIVES OF THE AT-SEA TESTS

The National Oceanic and Atmospheric Administration (NOAA) has been assisting the Department of Energy (DOE) in the development of a design methodology for Cold Water Pipes (CWPs). Figure 1.1 is a schematic diagram of the OTEC Cold Water Pipe Program Plan Elements. There are four elements that make up the data base which also is the corner stone of the design methodology for CWPs. The first part of the data base is the analytical portion. The analytical portion consists of analytical codes for system design and loading analysis. Analytical codes include those in the frequency domain such as Paulling's ROTEC and the NOAA/DOE CWP Analytic Code developed by Hydronautics. A time-based mathematical code is also under development. System Designs are preliminary designs of the prototype CWP, such as those of TRW and SAI. Loading Analysis is the evaluation of completed designs with several analytical codes and other methods to determine survivability of the proposed design.

The second phase of the methodology development is laboratory tests. Laboratory tests have included test of the complete system as well as individual tests on particular aspects of the design such as behavior of cylinders in various Reynolds number flows. Material tests have also been part of the laboratory test program. Some model scale tests of various operating procedures have been made to evaluate trade-offs in deployment and towing arrangements.

Figure 1.1 OTEC Cold Water Pipe Program Plan Elements

The third phase of the methodology development is the At-Sea Test of large cold water pipes to gather data in a real environment as near as possible to the prototype scale. Tests of a five foot diameter 500 foot long steel pipe and a 70 foot long polyvinyl chloride pipe have already been conducted. This present paper is concerned with the 10 foot diameter 1000 foot long fiberglass reinforced plastic CWP.^{1*} Finally, some qualitative experience is expected to come from the CWP on the OTEC-1 heat exchanger tests.

The fourth phase of the methodology development effort is the integration of the other three parts. This involves determination of input and outputs to each of the other phases. Determination of test design goals is for both laboratory and at-sea test programs, interfacing the plan for generation of new analytical tools, and ensuring that the results of laboratory and at-set tests contribute to the state-of-knowledge for full scale CWP desing in part of this phase. A Design Manual may be an end product of the integration effort.

The OTEC CWP At-Sea Test Program for a 1000 foot long diameter fiberglass CWP has four objectives. These objectives are displayed in Table 1.1. The first objective is to demonstrate fiberglass reinforced plastic technology for the OTEC CWP at sea in a real environment. Fiberglass reinforced plastic is a viable alternative to more highly developed steel pipes for the 10/40 MW Pilot Plant. There has already been an at-sea test program for a steel cold water pipe and much valuable data has been collected. In order for the state-of-are of fiberglass to be at the same or nearly the same level as steel, additional at-sea test data is requiried. Thus, the one-third scale At-Sea Test Program has been forced to use a fiberglass pipe in order to examine the behavior of this material at as close to the same scale as the 10/40 MW Pilot Plant as possible.

The second objective of the OTEC CWP At-Sea Test Program is to validate the NOAA/DOE CWP Analytic Code.² This is the premier code presently being used to examine the bending performance of code water pipes.

*References are listed in Section 6.

TABLE 1.1
OTEC CWP AT-SEA TEST PROGRAM

OBJECTIVES

- Demonstrate FRP Technology For The
OTEC CWP At-Sea
- Validate NOAA/DOE CWP Analytic
Codes
- Verify CWP Design Methodology
- Scale OTEC 10/40 MW Plant
 - CWP Design
 - Potential Environmental Site Data

This code was refined with the best available data from laboratory and field tests of platforms, and can generate the loads on any particular cold water pipe design. Nevertheless, particularly for fiberglass, the performance of this code when actual sea spectra is used and at the scale being used for the at-sea test program is currently open to question. It is the program director's hope that the data available from the at-sea test program can be used to upgrade the NOAA/DOE CWP Analytic Code to the point where it can be used with great confidence on cold water pipes for the Pilot Plant design. It is the purpose of this memorandum to determine the minimum quantity of data necessary from the at-sea test program to be used to fulfill this second goal.

The third objective of the OTEC CWP At-Sea Program is to verify cold water pipe methodology. The actual deployment, testing and recovery of a fiberglass pipe at sea will do much to ensure that all of the design calculations made in developing that pipe were both necessary and adequate.

The fourth objective of the at-sea test program is to scale the 10/40 MW Plant. In order for a pipe of 30 foot diameter to be built with confidence, all loadings on that pipe must be known and designs must be capable of performing under those loadings. The at-sea test program will be a 1/3 scale test of the 10/40 MW pipe. In addition to validating the use of mathematical tools, such as the analytic code, the test itself can be thought of as including a complete set of loadings, by conducting a test with all parameters properly scaled. Cost data from the at-sea test will also improve the accuracy of the Pilot Plant cost estimates and may also lead to reduced Pilot Plant costs through refinement of design. Finally, in the same vein of conducting a scaled test of a 10/40 MW Plant, it is hoped that some of the environmental data collected as part of the at-sea test program will be useful in describing potential OTEC deployment sites more fully.

2. DESCRIPTION OF THE MATHEMATICAL MODELS

2.1 THE NOAA/DOE CWP ANALYTIC CODE

The primary code to be verified with the CWP At-Sea Test Program is the NOAA/DOE CWP Analytic Code.² This code consists of four computer programs; CWPFLX, COTEC, XOTEC, and CWPEXT. This computer code has been distributed to all interested OTEC designers by NOAA and is continuously upgraded and updated by the NOAA Systems Support Contractor, ORI. Figure 2.1 is a flow chart for the NOAA/DOE CWP Analytic Code. There are essentially two parts to the analysis of any cold water pipe and platform system. These are indicated in Figure 2.1 by the dotted lines encircling first the upper portion of the flow chart and then the lower portion. The upper part of the flow chart covers the programs CWPFLX and CWPEXT in which the input is the cold water pipe properties. Program CWPFLX uses linear elastic beam theory to analyze pipe bending responses in the frequency domain. Program CWPEXT uses linear elastic theory for longitudinal and torsional analysis of the CWP and does not require the coupled motion analyzed in the remainder of the program. Program XOTEC computes the pipe/platform response amplitude operators (RAO) for regular waves and then uses spectral analysis to statistically analyze the motions in a given sea state. The program COTEC analyzes the hydrodynamic properties of the platform using strip theory. COTEC may be bypassed if model test data on the hydrodynamic coefficients are available from another source.

Figure 2.1 Flow Chart For NOAA/DOE CWP Analytic Code
(Reference 3)

The first three programs are used in sequence to determine the responses of the coupled platform/CWP system to wave loading. All programs operate in the frequency domain. First CWPFLX uses the line solution transfer matrix method to calculate the pipe responses through unit motion of the surface platform. Superposition of pipe natural mode shape is used to obtain the response due to a given loading condition. Next, COTEC computes the sectional added mass, damping and wave loading in sway, heave, and roll for each specified exciting frequency and at 0 forward speed. This program delivers its output of hydrodynamic coefficients for each frequency to 3 transfer files for later use by XOTEC. Finally, program XOTEC solves the linear simultaneous equations of ship motion in regular waves and computes the response amplitude operators (RAOs) for each frequency composing a spectral domain. A statistical analysis is then performed for each sea state. XOTEC uses the CWP transfer file to first modify the equations of motion and then to solve for the pipe response after the ship motions have been computed. The output of XOTEC consists of a statistical summary of ship and pipe motion and pipe loading for each sea state.

2.2 INDIVIDUAL LOADINGS AND RESPONSES TO BE VERIFIED

For the purpose of validating the design methodology used to develop cold water pipes for OTEC plants it is necessary that all loadings that are significant in a design process be measured on the at-sea test article. Nevertheless, only part of these loadings will be useful in validating the NOAA/DOE CWP Analytic Code. These are the responses shown in Table 2.1. These responses are all presently now handled by the code using a unidirectional wave spectrum. The primary purpose of the code was to examine the wave induced bending stresses. This requires the complexity of the code as it now exists in order to be properly determined. The response of the platform mooring and pipe and their coupling all goes into the determination of wave induced bending stresses. Simultaneous measurement of the environmental conditions, particularly the wave spectrum but also things that effect the wave spectrum such as wind and current, as well as the motions and stresses in the pipe and platform are necessary to verify the NOAA/DOE CWP Analytic Code.

TABLE 2.1
CODE RESPONSES TO BE VALIDATED

- Wave-Induced Bending
- Vortex-Excited Vibration
- Heave-Induced Longitudinal Stresses
- Torsional Vibration
- Coupling Of Pipe, Platform, And Mooring

A second response to be validated is the vortex excited vibration of cold water pipe. The code presently handles this method of exciting the pipe through imposition of point loadings on the cold water pipe having a sinusoidal time history. The at-sea test will be the first large scale cylinder to be exposed to this type of loading.

The program CWPEXT predicts the longitudinal stress and torsional stresses which will occur as the pipe is in operation. Helical vortex suppressors may excite torsional vibration. These stresses need to be verified through collection of actual data including variation with time as the pipe is in operation.

Finally, it is the intermediate values of motions and RAOs of the platform and mooring to waves and the pipe to the platform induced motions which will completely verify that the CWP Analytic Code has converted the existing currents and waves into correct stresses in the wall of the cold water pipe.

Although the development of the NOAA/DOE CWP Analytic Code involved collection of the very latest available data on performance of ocean engineering systems at the time of its formulation, certain assumptions were necessary in order to obtain a solution and to shorten the solution to a reasonable period of time. It is the purpose of the validation effort to ensure that the assumptions made do not significantly reduce the accuracy of the results of the code over the ranges to be expected in both the 10/40 MW Pilot Plant and the commercial plant, the ultimate goal of OTEC development program.

3. EXPECTED PERFORMANCE OF THE 1/3 SCALE MODEL

3.1 DESCRIPTION OF THE TEST ENVIRONMENT

The Department of Energy has an ongoing program to take environmental data for OTEC sites as it becomes available and to publish it to the OTEC community. Reference 3 is the latest available environmental data package from DOE. This package contains a description of the survival environment which the prototype 10/40 MW Pilot Plant can be expected to see at either the Puerto Rico or Hawaii OTEC sites. It can also be used to get a general appreciation of the test site environmental conditions although the test site has not been firmly selected as yet. For the purpose of this memorandum, the data for the Hawaii OTEC has been used as representative of typical 1/3 scale test site condition. The most significant mismodelling present at the Hawaii test site is in the current profile which exists which is neither a model of the survival currents or the operational currents for the pilot plant.

Figure 3.1 is a frequency spectrum for the 100 year return interval or survival conditions at the Hawaii OTEC site. Along the bottom of the figure are plotted the frequency of the individual waves while the ordinate of each frequency corresponds to the energy at that particular wave length and frequency. A tabulation of the curve is contained in the small box to the right of the figure. For Froude scaling the frequencies should be

Figure 3.1 Keahole Point, Hawaii OTEC Site 100-year Two Parameter Wave Spectrum
(Reference 2)

scaled by the square root of the scale factor or the square root of three. The spectral density or energy content of the individual waves would be scaled by $3^{3/2}$. Nevertheless, it will probably not be possible to find a test site which contains the exact scaled frequency spectrum for the survival conditions. The survival sea spectra at 1/3 scale will approximately be as shown in Figure 3.2 in which significant wave height has been scaled by a factor of 3. Since the spectra shown in Figure 3.1 and 3.2 are both idealized spectra as envisioned by Bretschneider, the scaling is perfect. What figure 3.2 shows is an idealized spectrum for the conditions that would occur when the significant wave height is 10 feet. The spectral density of waves at heights different than 10 feet or for larger waves to the left of the peak and smaller waves to the right of the peak is given in the corresponding Bretschneider formula tabulated at the bottom of the figure. This is a good indication of which modes of vibration for the cold water pipe 1/3 scale model will be excited in 10 foot sea, even though the actual spectrum will not be as smooth as shown in this figure.

The next questions to be answered as to the test environment for the 1/3 scale model is the frequency of occurrence of the survival conditions for the test article, and whether conditions more severe than survival of the prototype might be incurred. This can be seen by examining the figures in Table 3.1. For the expected test months of December, January, February, and March the annual percentage of occurrence of waves in excess of 10 feet in height is 18.1 percent at the most. There have been only a small number of observations of ships passing by the OTEC test site in Hawaii, making the data quite crude. Since conditions in excess of the design survival capabilities of the cold water pipe attached to the platform might be experienced, the design of the test article must take this possibility into consideration and procedures for decoupling the platform and cold water pipe must be included in its design.

To achieve loading conditions nearly those of the survival of the prototype, wave heights would have to be at least 8 feet in height in order to generate the same order of magnitude forces as the prototype is expected to see. The combined percentage for above 8 feet (about 2.5 meters) is

Frequency $f = (\text{sec}^{-1})$	Spectral Density $S(f) = (\text{ft}^2 \text{ sec})$	Frequency $f = (\text{sec}^{-1})$	Spectral Density $S(f) = (\text{ft}^2 \text{ sec})$
0.0050	0.118955	0.380	1.135774
0.0060	2.016229	0.390	1.022132
0.100	12.35471	0.400	1.07311
0.110	32.39896	0.410	0.98447
0.120	51.69261	0.420	0.88736
0.130	62.73313	0.430	0.79299
0.140	64.88592	0.440	0.70319
0.150	60.89679	0.450	0.60823
0.160	53.97209	0.460	0.50006
0.170	46.20143	0.470	0.40000
0.180	38.75241	0.480	0.30000
0.190	32.14082	0.490	0.20000
0.200	26.81257	0.500	0.10000
0.210	21.83397	0.510	0.05000
0.220	17.99516	0.520	0.02000
0.230	14.66630	0.530	0.01000
0.240	12.32265	0.540	0.00500
0.250	10.25668	0.550	0.00250
0.260	8.57059	0.560	0.00125
0.270	7.14520	0.570	0.00062
0.280	6.06798	0.580	0.00031
0.290	5.14047	0.590	0.00016
0.300	4.37407	0.600	0.00008
0.310	3.73305	0.610	0.00004
0.320	3.20793	0.620	0.00002
0.330	2.76414	0.630	0.00001
0.340	2.39104	0.640	0.00000
0.350	2.07607	0.650	0.00000
0.360	1.80907	0.660	0.00000
0.370	1.58185	0.670	0.00000

Figure 3.2 Sea State 5 Spectrum for $U_s = 22.0$ knots
 $H_s = 10.0$ ft. and $f_0^{-1} = 7.26$ seconds
 (Reference 2)

Table 3.1
WAVE HEIGHT
Probability Distribution for Keahole Point
(Reference 2)

	Wave Height (Meters)					Number of Observations
	0 - .5	1.0 - 1.5	2.0 - 2.5	3.0 - 3.5	4.0 - 6.5	
January	12.6	53.9	25.0	8.7	0	104
February	8.7	52.2	26.1	10.1	2.9	69
March	30.5	50.5	17.9	0	1.1	95
April	14.6	56.4	23.6	3.6	1.8	55
May	13.6	56.8	22.7	6.8	0	44
June	27.4	56.5	11.3	4.8	0	62
July	36.0	40.4	21.9	0.9	0.9	114
August	19.7	66.9	11.8	1.6	0	127
September	34.2	46.8	13.9	3.8	1.3	79
October	27.9	52.9	17.3	1.0	1.0	104
November	32.0	37.3	20.0	6.7	4.0	75
December	9.7	38.7	35.5	12.9	3.2	62
Annual	23.3	51.1	19.9	4.4	1.2	990
Cumulative	23.33	74.44	94.34	98.78	99.99	

about 25 percent of the time. This occurrence is therefore common and indicates that it will be easy to take the required data with weekday, eight-hour shifts.

Other figures in Table 3.1 can be used to assist in planning the remainder of the tests. For example, it appears that the wave height is less than 3 feet about 15 percent of the time; which might be necessary for deployment, towing, and recovery. The majority of the time will see waves of a height between 3 and 5 feet.

Table 3.2 can be used to determine the possibility of exciting different modes away from the significant wave for different significant wave heights. It shows the shape of the curve of wave height and period. For example, this table shows that for waves from 2.2 to 2.4 times the significant wave height, the total probability of occurrence is only .04 of 1 percent. This probability is broken down in four steps, the first step being very short waves having a period of 0.5 to 0.7 times the period of significant wave, with the last step maximum height longer waves having 1.1 to 1.3 times the period of the significant wave. Table 3.2 really shows the relationship of the random heights and periods in a sea as characterized by a Bretschneider spectrum to the significant wave height and the period of the significant wave. This figure shows that there is a wide range of waves in sizes and intervals of encounter that will be seen by the cold water pipe platform.

3.2 BENDING MODES OF THE TEST ARTICLE

Figure 3.3 is a sketch of the design details in the fiberglass sandwich wall construction cold water pipe developed by Science Applications from their 10/40 MW Pilot Plant design⁴. This design has probably not had the degree of refinement which will be found in the actual cold water pipe used for the At-Sea Tests. The wall of this pipe consists of two fiberglass skins .3 of an inch thick separated by a syntactic-foam core which tapers from the top where it is 1.84 inches between the skins. The fiberglass skins are made up using a transverse filament tape wound onto a mandrel. By use of this process, 90 percent of the fibers in the reinforcement are

Table 3.2

Joint Probability Distribution of Wave Height and Period (for Zero Correlation)
 Number of Waves per 1000 Consecutive Waves and Ranges in Relative Heights and Periods
 (Reference 2)

Range in Relative Height H/H_s	R A N G E S I N R E L A T I V E P E R I O D											Sum	Cumula- tive
	0- 0.1	0.1- 0.3	0.3- 0.5	0.5- 0.7	0.7- 0.9	0.9- 1.1	1.1- 1.3	1.3- 1.5	1.5- 1.7	1.7- 1.9	1.9- 2.0		
0-0-0.2	.01	0.46	3.06	9.15	17.21	21.36	16.61	7.30	1.50	.14	0	76.88	76.88
0.2-0.4	.02	1.10	7.83	23.44	44.09	54.73	42.56	18.71	4.05	.36	.01	196.98	273.86
0.4-0.6	.02	1.43	9.51	28.49	53.59	66.51	51.73	22.74	4.92	.44	.02	239.40	513.26
0.6-0.8	.02	1.25	8.29	24.84	46.72	57.99	45.10	19.82	4.29	.39	.01	208.72	721.98
0.8-1.0	.01	0.85	5.67	16.98	31.94	39.65	30.84	13.55	2.93	.26	.01	142.69	864.67
1.0-1.2	.01	0.47	3.15	9.42	17.73	22.01	17.12	7.52	1.63	.15	-	79.21	943.88
1.2-1.4	-	0.22	1.44	4.32	8.12	10.08	7.84	3.45	.75	.07	-	36.29	980.17
1.4-1.6	-	0.08	0.55	1.65	3.10	3.85	3.00	1.32	.28	.03	-	13.86	994.03
1.6-1.8	-	0.03	0.18	.53	.99	1.23	.96	.42	.09	.01	-	4.44	998.47
1.8-2.0	-	0.01	0.05	.14	.27	.33	.26	.11	.03	-	-	1.20	999.67
2.0-2.2	-	-	0.01	.03	.06	.08	.06	.03	.01	-	-	0.28	999.95
2.2-2.4	-	-	-	.01	.01	.01	.01	-	-	-	-	0.04	999.99
Sum	.09	5.98	39.74	119.00	223.83	277.83	216.09	94.97	20.56	1.85	.05	999.99	
Cumula- live	.09	6.07	45.81	164.81	388.64	666.47	882.56	977.53	998.09	999.94	999.99		

oriented in the longitudinal direction while only 10 percent are in the hoop direction. Properties of the fiberglass are indicated at the upper right hand corner of this figure. A spherical bearing located at the top of the upper end cap will suspend the pipe below the test platform and allow decoupling of the pitch and roll of the platform from the upper portion of the pipe. The elastic modulus obtained through this particular laminate design is much higher in the axial direction of the pipe than the elastic modulus of comparable alternate designs. This is due to the relatively large percentage of glass by volume, 65 percent, in the fiberglass skins, and also to the large portion of fibers in the longitudinal direction.

Figure 3.4 shown an arrangement sketch for CWP connection to the platform and the bottom weight. The fiberglass sandwich pipe has two end caps which are used to form a transition between the fiberglass and both the concrete-filled steel bottom weight or spherical-bearing support for connection to the platform. The spherical-bearing has been designed for a total travel of 31 degrees from the vertical in any direction. This travel is necessary to compensate for both the angle of the pipe in the current and the roll of the platform caused by waves. The bottom weight has been sized to make the pipe angle 6 degrees from the vertical in a uniform 2 foot-per-second current. A uniform 2 foot-per-second current is not a scaled representation of the survival conditions in the 100 year storm on the 10/40 MW Pilot Plant pipe. Rather, it is what is expected to be seen during 12 foot seas at either Puerto Rico or Hawaii OTEC sites should these be chosen for the tests. Calculations have shown that the maximum rotation in a 12 foot sea is expected to be 16 degrees from the vertical counting both the roll of a 1/3 scale Johns Hopkins University/Applied Physics Laboratory platform design and the static angle of the pipe due to current. Should the contractor for the At-Sea Test Program be able to find a more favorable current regime which scales the maximum survival currents and has the necessary skew from bottom to top to represent the profile currents over a 3000 foot depth found at the OTEC sites for 10/40 MW plants, then the bottom weight size could probably be reduced substantially.

The NOAA/DOE CWP Analytic Code has been run for the design shown in Figures 3.3 and 3.4. Table 3.3 contains the results of the run of the first portion of the code, CWPFLX. The first 9 modes of vibration and their natural frequencies and corresponding periods are tabulated in this table. The first 3 modes of vibration are substantially longer than even the longest period waves which will be seen in 12 foot seas. Only a very small portion of the seas' energy spectrum is located at the frequencies represented by the 7th, 8th, and 9th mode of vibration even for very small waves and also, for these frequencies, exciting energy is much smaller anyway. Thus, for this particular design it appears the 4th, 5th, and 6th mode of vibration will receive the greatest amount of excitation during testing, particularly at the survival condition where the most severe strains are expected. If we drop 1 additional mode lower than the modes which are expected to receive the greatest excitation, to the 3rd mode of vibration, then the longest period of interest is 33.3 seconds.

3.3 EXPECTED RESPONSES TO THE TEST ARTICLE DURING TESTS

By combining the results in Figure 3.2 with the natural frequencies of Table 3.2 we can determine which natural frequencies will be excited by a standard sea state. The indications of this analysis are that modes of vibration less than the 4th mode and below will not receive a sufficient excitation to exhibit any strains. The 9th mode and above will also probably not be excited. For the 5th through 8th mode the results of the comparison of the wave energy near the CWP point design natural frequencies are contained in Table 3.4. The four modes that will be excited are tabulated in the first column under mode. In the second column are the natural frequencies adjacent the mode and for the nearest tabulated values from Reference 3. For example, the natural frequencies of 0.164 hertz for the 6th mode has a tabulated value at 0.170 for the 10 foot spectrum in Reference 3 and a tabulated value of 0.160 as the next adjacent lower value of frequencies in the table. Values have been extracted and are displayed in the last two columns of Table 3.4 for both 10 and 6 foot significant wave heights. In order to find the spectral density of a Bretschneider spectrum expected at the natural frequencies one would have

Figure 3.4 Arrangement Sketch for Connection to Platform and Bottom Weight
(Reference 4)

TABLE 3.3
RUN OF CWPFLX FOR POINT DESIGN

<u>Mode of Vibration</u>	<u>Natural Frequency, Hertz</u>	<u>Period, Seconds</u>
1	0.0024	416.7 (6.94 min.)
2	0.0116	86.0 (1.44 min.)
3	0.0320	33.3
4	0.0643	15.6
5	0.108	9.26
6	0.164	6.10
7	0.232	4.31
8	0.311	3.2
9	0.400	2.5

TABLE 3.4
WAVE ENERGY NEAR POINT DESIGN
NATURAL FREQUENCIES

Mode	Natural Frequency	Spectral Density $H_3 = 10$ ft.	Spectral Density $H_5 = 6$ ft.
	<u>Hertz</u>	<u>ft.² sec.</u>	<u>ft.² sec.</u>
	.100	12.55	
	.106		0.0528
5	.108		
	.110	32.40	0.150
	.160	53.97	16.1
6	.164	(50.96)	
	.170	46.20	17.8
	.230	14.87	11.1
7	.232		
	.240	12.32	9.62
	.310	3.74	3.40
8	.311		
	.320	3.21	2.94

to interpolate between these two tabulated values. This interpolation results in a value of 50.96 feet squared seconds as indicated in parenthesis in Table 3.4. The other values in this table could be obtained likewise. This value of 50.96 is fairly high in comparison to the peak energy located at the center of the spectrum of 65.0 feet squared seconds. Thus the 6th mode of vibration will receive heavy excitation during the 10 foot sea provided that the sea is nearly represented by a Bretschneider spectrum. A similar mode of vibration will be excited in a 6 foot sea but only one-third as much energy will be present in the waves.

The preceeding analysis will hold for other designs of cold water pipes even if it is different modes of vibration which are the primarily excited components of pipe motion. For example, if the contractor for the at-sea test program can locate a much more favorable current regime and thus reduce this bottom weight, the natrua frequencies of the pipe will go up considerably from those which occur when the bottom weight is nearly 3 times the weight of the entire pipe in water. For lower bottom weight, lower natural frequencies, such as the 3rd and 4th modes of vibration, will be excited. However, these actual frequencies will be close to those for the 5th and 6th modes in the point design studied above. Thus the correspondence between the wave frequencies and the pipe natural frequencies will still result in vibration of approximately the frequencies given above. For example, in the point design the 4th natural frequency is too low to receive any excitation by the seas which are to be expected at the Hawaii OTEC site. Although, a cold water pipe design with low bottom weight may have the 4th or even 3rd modes excited, the frequency of the 3rd mode of vibration in this case may correspond to the 5th mode for the point design. Thus despite potential design changes, the natrua frequencies of interest will still be on the order of 10 seconds.

4. DEVELOPMENT OF THE VALIDATION REQUIREMENTS

4.1 VARIATIONS OF STANDARD OPERATIONS TO VERIFY THE CODE

The Cold Water Pipe will respond to surge and sway loading on the test platform by vibrating in several modes as was discussed in the previous section. Each mode of vibration corresponds to a natural frequency of the beam formed by the cold water pipe. Previous analyses have shown that a typical sea spectrum as idealized by Bretschneider will normally excite the 1/3 scale cold water pipe with measurable components of natural frequency in the 5th, 6th, 7th, and 8th modes. Higher and lower modes of vibration are not expected to be important as there is little energy in open sea waves at these frequencies. The highest mode excited determines the sampling rate for the digitizing system. The 8th mode of the point design has a period of 3.2 seconds; thus, if the digitizing system makes approximately 3 samples per second, there will be 10 samples for a complete cycle in the record which will determine the shape and peaks of the vibration wave. Likewise, it is the lowest mode of vibration which determines the length of the total record. For the 5th mode of vibration of the point design this period is 9.26 seconds. Thus there are approximately 6 periods to a minute, 60 periods per 10 minutes, and 120 periods in a 20 minute continuous series recording. For the structural response of the cold water pipe a continuous recording of 20 minutes of data is probably sufficient to determine the frequency

components of the cold water pipe modes of vibration and peak stress which would be seen for continuous operation in that particular sea state.

Discussion with experts in recording open sea wave conditions have indicated that a period approximately 1/2 hour of continuous data is necessary to determine the complete frequency spectrum of open sea waves. This is because waves are much more irregular than structural vibrations. The first mode of vibration of the cold water pipe point design is a 7 minute period. A 30 minute period of continuous data would contain 4 complete periods of even the lowest mode of vibration. In discussions between NOAA/DOE and NOAA's Systems Support Contractor, the conclusion was reached that a period equal to double the minimum required, or one hour, for each particular condition of sea state and platform configuration should be obtained to ensure that at least one-half of that record could be used for analysis.

When conducting tests in a natural environment the ability of the test team to vary parameters of interest is severely constrained. The primary variable of interest during the at-sea data collection effort is the waves. Waves are characterized by directional spectra and amplitude. The spectra content will change from day to day and even hour by hour as surface winds change speed and direction with the passing of distant storms. From the standpoint of the major loadings on the platform, pipe, and SKSS the wave height of the 1/3 highest wave and its direction relative to the platform are most important. These two parameters have been selected to characterize the data sets to the exclusion of other spectral components, winds, and current.

The most important part of the at-sea program is to determine the performance of a cold water pipe in its operating configuration and at the highest loads which could be expected under that configuration. A range of wave heights and directions is needed to characterize variations in structural responses with variations in the environment. This range should cover all the expected environmental conditions on the prototype. The least-severe prototype 10/40 MW OTEC site is Keahole Point, Hawaii. At

TABLE 4.1
VERIFICATION OF OPERATIONAL
USE OF THE NOAA/DOE CODE

Direction of of Wave Incidence	Wave Heights Percent of Survival			
	Calm	30	60	90
Bow $\pm 20^\circ$	-	3	2	1
Beam $\pm 20^\circ$	-	3	2	1
Quartering $\pm 20^\circ$	-	3	2	
Unspecified	2			
Total	2	9	6	2

this site, the 100 year storm has a significant wave height of 27.6 feet. Since the prototype moorings for large waterplane platforms are multiple leg designs, which makes the platform fixed in direction, the platform must be able to take oncoming waves from any direction.

Ideally, tests would consist of a range of heights of oncoming waves toward the bow (head seas), the beam (beam seas), and quarter (quartering seas) if the bow and stern of the platform are similar in shape. With a platform essentially fixed, it is not practical to wait for the ideal validation data. Therefore, a tolerance on the ideal situation was developed to allow data collection over a greater period while still assuring that the range of data collected would validate all conditions.

The scaled survival wave is $27.6/3$ or 9.2 feet. Four increments of wave height are desired to cover the operational range. The increments selected were calm, 30%, 60%, and 90% of survival. Table 4.2 shows the operational data desired. The center of the range contains waves most readily available. Thus, more data has been required at these wave heights to make statistical validation. A tolerance of plus or minus one foot on the target wave height seems reasonable to ensure the ability cross check results without unduly restricting data collection because of improper conditions. For the 9.2 feet survival wave, 30% = 2.8 feet, 60% = 5.5 feet, and 90% = 8.3 feet.

4.2 NON-STANDARD OPERATING CONDITIONS AND THEIR EFFECTS

The NOAA/DOE CWP Analytic Code has the capability to model various interfaces for the CWP with the platform. This could include sliding sleeves for a bottom-mounted pipe, restricted hinges to simulate a bad bearing, or a fixed mounting of the CWP to the platform, perhaps for gimbal repair. In addition, the SAI prototype design contemplated detaching the CWP in heavy seas for survival. It is desirable that the CWP At-Sea Test Program collect data under these conditions to verify that the code routines correctly simulate these configurations.

The locked-gimbal exercise may severely stress the pipe and must be done near calm. However, the seas must not be completely calm, or else no strain data will be collected. Likewise, the braked-gimbal test must be done in less severe seas than the free-gimbal tests. For these, the restraining force must be known, and a constant-tension winch with multi-part blocks may be required.

4.3 DEPLOYMENT, RETRIEVAL, AND TOWING

Most of the work on CWP design has addressed the ability to survive on-station and function properly up to the practical limiting sea-state for the OTEC plant housed on the platform. However, in spite of their short duration; the stages of tow-out from the protected assembly site, mounting of the pipe to the platform, and safe demobilization also require data collection. In fact, one of the key positive features of the At-Sea Test Program is the ability to examine these phases of the test in detail where they are done in open-sea conditions to verify that they could be accomplished on a pipe three times as large. Multiple strain gauges will be in place for the operational tests. Some of these gauges must be monitored during each phase of the deployment and retrieval to:

- be sure design strains are not exceeded
- relate environmental conditions during that phase to pipe loads.

If possible, tow-out and return should be conducted in two possible modes for the prototype 10/40 MW Pilot Plant. For example, the tow-out could be with the CWP breaking the surface while tow-in could be with auxiliary buoyancy holding the CWP submerged. During deployment and retrieval, a complete record is necessary of pipe strains, the environment, and pipe position, all coordinated in time so that hazardous operations can be eliminated for the Pilot Plant CWP and the deployment and retrieval performance more fully understood.

4.4 PRECAUTIONS FOR SURVIVAL

In the detached or decoupled survival condition, it would be ideal to have waves equalizing or exceeding prototype survival conditions. However, reaching this point should be carefully approached in a step-by-step process, as working with loads as heavy as the At-Sea Test CWP will be a dangerous operation. These three steps are proposed; first near calm, then at approximately 50% of survival wave (4.6 feet) and then at the maximum wave available at the test site.

5. SUMMARY OF REQUIRED TESTS

The complete listing of Validation Data Requirements is contained in Table 5.1. Data has been arranged chronologically as it would be encountered during the test program.

TABLE 5.1

VALIDATION DATA REQUIREMENTS

Complete time-series data is required from all applicable instruments under the following test conditions:

- Platform without CWP
 - Head sea Response Amplitude Operators (RAOs) without SKSS
 - Beam sea RAOs without SKSS
 - Quartering sea RAOs without SKSS
 - Head sea RAOs with SKSS
 - Beam sea RAOs with SKSS
 - Quartering sea RAOs with SKSS

- CWP Tow (Tow-out breaking surface) - Continuous record

- CWO Deployment - Continuous record

- Complete At-Sea Test Program

- Gimble Free (19 sets of one-hour continuous data)

Sufficient Wave (plus or minus 1 foot)	Sea Direction from bow	Repetitions
Calm	-	2 each
30% of survival	3 angles differing by 45 degrees	3 each
60% of survival	3 angles differing by 45 degrees	2 each
90% of survival	3 angles differing by 45 degrees	1 each

If practical, the following additional tests shall be run

- Gimble Locked (one set of one-hour continuous data near calm)
- Gimble Braked (one set of one-hour continuous data near calm with known restraint)
- Survival Condition (3 sets of one-hour continuous data with decoupled CWP) - Significant Wave (plus or minus 1 foot) of:

- Calm
- 50% of survival
- Greater than survival

- CWP Recovery - Continuous record

- CWP Tow (Tow-in submerge) - Continuous record

6. REFERENCES

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