415
10-22-80

H. 1923

DOE/NOAA/OTEC-22

MASTER

**MODEL TESTS OF OTEC-1—TEST OF HMB WITH AND WITHOUT COLD
WATER PIPES**

By
Lewis R. Sheldon
Roderick A. Barr
John F. O'Dea

December 1977

Work Performed Under Contract No. EY-76-C-02-2681

HYDRONAUTICS, Incorporated
Laurel, Maryland

64

U.S. Department of Energy

Solar Energy

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$7.00
Microfiche \$3.50

HYDRONAUTICS, Incorporated

MODEL TESTS OF OTEC-1 -
TEST OF HMB WITH AND
WITHOUT COLD WATER PIPES

December, 1977

By

Lewis R. Sheldon

Roderick A. Barr

John F. O'Dea*

(HYDRONAUTICS, Incorporated Technical Report 7513-2)

Prepared Under

DOE (ERDA) Contract No. EY-76-C-02-2681

(Formerly ERDA Contract E-11-1-2681)

*Now at DWTNSRDC

mf

HYDRONAUTICS, Incorporated

INTRODUCTION

In early 1977, ERDA began an extensive study of various factors which could effect the early design and deployment of OTEC-1, a test platform for evaluation of one megawatt (1 MW) OTEC heat exchangers. The platform was to consist of the Hughes Mining Barge (HMB) and a 3000 foot deep cold water pipe (CWP). One of the factors to be considered was the motions of the HMB and the motions, loads and stresses of the CWP.

Several theoretical methods, including one developed at HYDRONAUTICS, Incorporated, Reference 1, were to be used to predict motions and CWP loads and stresses. There existed, however, no model tests or other validation of these theoretical methods. The lack of any validation of the theoretical methods was of some concern as early studies, such as Reference 2, indicated that high CWP bending stresses, in particular, could represent a significant design problem. In early May 1977, HYDRONAUTICS proposed to carry out, under a modification of existing ERDA Contract EY-76-C-02-2681 (E-11-1-2681), model tests of a one-fiftieth scale model of the HMB with several CWP models representing relatively rigid (steel) and flexible (glass reinforced plastic GRP) CWP's. This proposal was accepted by ERDA, and the model tests were carried out during June 1977. Preliminary results were provided to ERDA during June and July 1977. This report describes the work carried out and discusses the results, including a comparison of measured and predicted results.

DESCRIPTION OF TEST PROGRAM

The model test program was designed to provide a maximum amount of information in a short time. The tests were required to provide validation data for various cases including the HMB alone and with CWP's of widely varying flexibility and attachment flexibility or stiffness, for various HMB headings relative to incident regular and random waves. Tests were carried out for the following configurations in head and beam waves or seas:

1. HMB alone
2. HMB with stiff CWP rigidly attached to HMB
3. HMB with stiff CWP free in heave and rotation
(pitch and roll)
4. HMB with flexible CWP rigidly attached to HMB.

Table 1 presents the complete test matrix considered. The details of HMB, CWP and CWP attachment geometrics and characteristics are discussed in detail in the next section.

Tests were carried out for regular waves (10 waves with frequencies spanning the range of wave frequencies of interest) and for three sea states modeling random, long-crested (unidirectional) waves with significant (average of one-third highest) wave heights of 8, 12 and 16 feet. Characteristics of these waves are given in Table 1. All random wave motions spectra were used, together with wave energy spectra, to obtain motion response amplitude operators (RAO's) which give response

as a function of wave frequency. Such RAO's provide a far more meaningful basis for validating predictions than do the statistical values (RMS or significant motions usually derived from random wave tests. In this report, all comparisons are made for RAO's only.

Due to the high frequency wave content of the test sea states, it was not possible to fully reproduce the desired Bretschneider wave energy spectra for the 8, 12 and 16 foot significant wave heights specified by ERDA. Figure 9 shows a comparison of the desired spectra and the spectra used in the model tests. The differences in desired and actual spectra will effect statistical results for a given sea state but will have no significant effect on RAO's deduced from the tests.

The two 40 foot long CWP models represent 2000 foot long CWP's, although this proposed OTEC-1 CWP was to be 3000 foot long. It was only possible to test a 40 foot long CWP model in the tests and modeling a 3000 foot long CWP would have resulted in a scale ratio of 75 and in a HMB model size which was considered too small. As the tests were carried out to validate the theoretical predictions, the modeling of a 2000 foot long CWP was considered acceptable.

MODEL DESCRIPTION

Three models built to a linear scale ratio of 50 were used for this test program. The model of the 324 foot mining barge was built from plans for the HMB, Reference 3. The two cold water pipe (CWP) models were constructed from commercially available plastic tubing selected to match the desired diameter and stiffness ($E \times I$) as closely as possible.

The barge model was constructed from a composite of plywood and rigid closed cell foam. A well or "moon pool" 9.0 inches in diameter (37.5 foot prototype diameter) was provided in the model at amidships. The cold water pipe was suspended at the center of this moon pool. An apparatus for suspending the CWP's was provided above the moon pool. This apparatus was designed to provide for two modes of operation. One mode provided a fixed or "rigid" attachment point and the other mode provided a flexible or "free" attachment. This free attachment mode was free in heave, pitch and roll, but constrained in surge, sway and yaw. The apparatus also included transducers to measure relative heave, pitch and roll between the CWP and the barge for the "free" attachment mode. Figures 1 and 2 show the barge model without the cold water pipe suspension apparatus. Figure 3 shows the CWP suspension apparatus (in the free mode) in place on the barge model. Characteristics of the prototype HMB for use in OTEC-1 and the HMB model, as tested, are given in Table 2.

The two CWP models were constructed of commercially available grades and sizes of plastic tubing. The "stiff" pipe was two inches

schedule 40 rigid PVC pipe. The "flexible" pipe was 2.00" O.D. by 1.50" I.D. clear, flexible PVC tubing. Each of these models were provided with two strain gaged bending moment flexures. On each pipe, one flexure was placed one-third of the total pipe length up from the lower end and the other flexure was placed between the pipe and the barge attachment. Figures 4 and 5 show the geometry of the CWP model. It should be noted that during the tests with rigid CWP attachment, the pitch-roll gimbal was replaced with a spacer of equal dimensions and weight. Figure 6 shows a photograph of one of the bending moment flexures. These flexures were designed with four active element bridges in two perpendicular bending moment axes which corresponded to the transverse and longitudinal axes on the model. The geometry of the strain gages provides temperature compensation and eliminates interactions between the two bending moment axes or between bending moment and axial or torsional loading.

Figure 7 shows the details of the mooring array used to locate the barge model in the model basin. The apparatus (which can be seen in Figure 4) used to generate this mooring array consisting of a circular ring 16 feet in diameter with vertical posts reaching into the water with pulleys attached to the underwater end of the posts. The mooring lines ran from the barge to these pulleys and then up to the mooring spring units located above the water. The entire mooring ring can be rotated and changes in heading angle were made by rotating it.

TEST FACILITY DESCRIPTION

All tests were conducted in the HYDRONAUTICS Ship Model Basin which is equipped with a deep well which was used in these tests. The principal dimensions of the basin and deep well are:

Basin

Length	414 ft 11 in.
Width	24 ft 1 in.
Water Depth	11 ft 6 in.

Deep Well

Diameter	11 ft 0 in.
Depth (from water surface)	41 ft 6 in.
Distance from wavemaker	322 ft 5 in.
Distance from beach	92 ft 6 in.

The CWP was located at the center of the deep well for all tests.

TEST PROCEDURES

Determination of Cold Water Pipe Characteristics

In order to measure the stiffness (EI) of the two CWP models, bending tests were performed on representative samples of the two CWP materials. Because of the large difference in stiffness, somewhat different procedures were used for each pipe.

The stiffness of the stiff CWP was calculated from the slope of a load displacement curve generated from a simple beam experiment. A section of the pipe material was supported on rollers 144" apart. A series of known weights were applied midway between the support points. The resulting deflection was measured at the point of load application. The wet and dry weights for the "stiff" pipe material were determined by weighing a section of the material and carefully measuring its inside and outside diameter to determine its buoyancy per unit length.

The same general procedure was used to determine the characteristics of the "flexible" pipe material except that a section of the material was tested as a cantilever beam with an effective length of 15". Figure 8 summarizes the dimensions and characteristics of the CWP pipe model materials.

Natural Period Tests

Natural period tests in heave, pitch and roll were conducted for the barge without CWP and for the barge with the stiff CWP rigidly attached. The primary purpose of these tests was to

insure that the moorings would not effect measured motions by introducing a resonant frequency within the range of wave frequencies of interest. In addition, natural sway period was measured for the barge without CWP. The same basic procedure was used for all tests. In each case the output of the motion sensing transducer for the motions measured was recorded as a voltage analog on magnetic tape. This voltage analog was also used to produce a strip chart time history. The natural periods were determined by analyzing the response of the model after an initial offset was applied for the motion in question. Care was taken to achieve pure heave, pitch, roll or sway offsets, however, some offset in the other motions was unavoidable.

Seakeeping Tests

For the seakeeping tests 7 to 14 channels of data were recorded. All transducers produced a voltage analog of the quantity measured which was recorded on a magnetic tape recorder. For all seakeeping tests, wave height and the six motions (heave, pitch, roll, surge, sway, yaw) of the barge model were measured. The wave height transducer was a capacitance wave probe. The wave height probe was located 21'9" ahead of the model CG to minimize measurement of reflected waves from the model. The six motions of the barge model were measured with a light weight pantograph rig which can be seen in Figure 4. Potentiometers were used as transducers for the six motions measured. For tests with a CWP model either fixed or freely attached to the barge model, three more channels were added. They were longitudinal and transverse bending moment in the

cold water pipe at two locations. The transducers for these measurements were the bending moment flexure described previously. For tests with a freely attached CWP, three additional channels were measured; relative heave, pitch and roll between the CWP and the barge.

The following procedure was used to conduct all seakeeping tests. After waiting between 15 and 25 minutes after the preceding run to allow the waves from the preceding run to die out, "zeros" were recorded on the magnetic tape of each of the data channels. After this, the HSMB wavemaker was programmed to produce the desired regular or irregular wave and started. It was then necessary to wait for the regular wave or sea state to become fully developed over the deep well where these tests were conducted. This waiting period was calculated for each wave based on its progressive velocity or, in the case of the irregular waves, the velocity of its shortest component. At the end of this waiting period, the magnetic tape recorder was started and data was recorded for approximately 120 seconds. Approximately 100 seconds of these data were digitized.

Data Reduction Procedures

The magnetic tape recorder used to record the data has the capability of playing back the data being recorded with a short time delay. This allowed the data to be processed as each run was being made. For selected channels, strip chart time histories were made. The primary purpose of these was to verify the transducer outputs during the run.

The voltage analog of the data which was played back from the tape recorder was run through an analog to digital converter and into a computer. The A-D converter sampled the data at a rate of 5 Hz and these points were stored in a file by the computer. Because of the location of the moon pool and cold water pipe heave compensating mechanism on the barge, it was not possible to measure the barge motions at the barge center of gravity. For this reason the stored digital data was processed by a program that transformed the data to an axis system with origin at center of gravity and stored the resulting digital data in a separate file.

The transformed data was processed in one of two ways. For runs in regular waves the data were processed by a computer program that calculated the RMS value of each signal. The values were used to calculate response amplitude operators (RAO's) which were plotted as a function of wave frequency. For runs in irregular waves, the digital data were analyzed using a spectral analysis program which generated motions power density spectra. A second program was then used to calculate an RAO from each motion spectrum and the measured wave power density spectrum.

Accuracy of Measurements

In order to aid in the interpretation of the model test data, estimated instrumentation accuracy is provided in Table 3. This table deals separately with two distinct areas of the measurement accuracy problem. The first is the maximum possible error that can be expected in any measurement. This error arises from two sources. The first is the maximum observed

deviation from the best straight line fit to the calibration data. The second is the maximum error to be expected from the record/playback process using the magnetic FM tape recorder used to store the data. This latter value is provided by the tape recorder manufacturer.

The second type of error is signal threshold, or the smallest signal that can be measured. This threshold is a function of the tape recorder used for data storage and is supplied by the manufacturer. For each type of transducer used, Table 3 lists typical sensitivity, maximum calibration deviation, maximum tape recorder error, maximum error converted to physical units, tape recorder threshold and tape recorder threshold converted to physical units.

PRESENTATION OF RESULTS

The results of this study are presented in the form of response amplitude operators and significant (average of one-third highest) values for random waves. Test results are also compared with theoretical predictions made for the exact conditions of the model test.

Response amplitude operators (RAO's) for the four model configurations (HMB alone and with three CWP's cases described earlier) and for head and beam waves are given in Figures 10-23. Each figure presents the ratio of surge (sway) and heave amplitude to wave amplitude, pitch (roll) angle amplitude to wave slope and, except for the HMB above, CWP bending moment amplitude divided by wave amplitude. Each figure presents results for regular and random waves.

Figures 24-37 present comparisons of the measured and predicted RAO's. In these figures only curves representing the test data are shown. The theoretical predictions were made using methods described in Reference 1. These methods, which account for the flexibility of the CWP and the stiffness of the CWP attachment, are based on earlier work for rigid CWP's, Reference 3.

Tables 4-7 present measured and predicted significant (average of one-third highest) motion, CWP relative motion and CWP bending moment amplitudes (one-half peak-to-peak values) for the random wave tests with eight and sixteen foot significant wave heights. All results are given for prototype scale. It

HYDRONAUTICS, Incorporated

-13-

should be noted that the CWP bending moments are for the model CWP's, which do not represent proposed CWP designs for OTEC-1. The CWP bending moments, particularly for the stiff CWP model, are higher than expected for actual HMB CWP's due to the modeling of a 2000 foot long rather than a 3000 foot long CWP. CWP bending moments for a 2000 foot long CWP are significantly larger than those for a 3000 foot long CWP, Reference 1.

DISCUSSION OF RESULTS

Perhaps the most striking features of the model test results are the generally good agreement of the RAO's deduced from the tests in regular waves and from those in random waves or sea states, and the general absence in the data of scatter and clearly defined nonlinear effects. The regular wave results show considerably greater scatter than do the random wave results. Scatter and nonlinear effects are more apparent in CWP bending moments than in HMB motions and are more apparent in beam sea results than in head sea results.

Agreement of measured and predicted responses is generally good, with the largest differences occurring in sway motion and CWP bending moments. Differences in the measured and predicted significant responses in random waves are due largely to differences in response at high frequencies (prototype periods of less than five seconds).

Model Test Response Amplitude Operators (RAO's)

The results for the HMB alone in head seas, Figure 10, show excellent agreement between all data, indicated an absence of any significant nonlinearities in response. All motions are well damped. Results for beam seas, Figure 11, indicate significant scatter in the data for frequencies below about seven radians per second (prototype periods greater than about six seconds). The scatter is worse for roll response. All responses are characterized by multiple peaks of magnitude 1.4 (sway) to 2.34 (roll).

The hull is not highly damped in roll, and hence large peak roll response is not surprising, but the multiple peaks or broad-bandedness of maximum roll response is surprising. The sway and roll free decay test data for the moored HMB were analyzed, but the results provided no clues; sway was heavily damped with a natural frequency of about 1.25 radians per second while roll natural frequency was comparable to the calculated value of about six radians per second for the free floating HMB. The large, low frequency modulation of the roll motion observed in the tests, which is not correlated with the wave record, may be a factor.

The sway and pitch motions for the HMB with freely attached, stiff CWP, Figure 12, show good agreement between all data. The heave motions data are in good agreement except for the results for 16 foot significant height waves (hereafter called 16 foot waves). Heave motions for 16 foot waves are much larger than those for other waves. This is not a typical nonlinear effect, where response usually decreases with increasing wave height. Motions in beam seas, Figure 13, have scatter similar to that for the HMB above. Roll response is more typical than that for the HMB alone, with a resonant peak at a frequency of about six radians per second. A secondary roll peak, probably resulting from large sway motion and strong roll-sway coupling, appears to occur at a frequency near two radians per second (15 second prototype period). The large sway and roll motions at low frequencies may be an artifice due to the HMB mooring.

The CWP bending moments for the HMB with freely attached, stiff CWP in head seas, Figure 14, show generally good agreement between all data, but also show a clearly defined nonlinearity at the point of peak response, 4.5 radians per second or seven/second prototype period. Response increases with decreasing wave height, an indication of nonlinear damping. There appears to be secondary peaks at frequencies of about two and seven to nine radians per second. The CWP bending moments in beam seas, Figure 15, show somewhat greater scatter than those in head seas and also show strong nonlinearities at the four radian per second response peak. Secondary peaks appear to occur at frequencies below two and at about nine radians per second. Peak response magnitudes in head and beam seas are comparable.

Motions for the HMB with rigidly attached, stiff CWP, Figure 16, show good agreement between all data. Surge and heave motions are comparable to those for the HMB alone, while pitch response is less than that for the HMB alone. Motions in beam seas, Figure 17, show significant variations between data for different waves. Roll data, surprisingly, shows the least scatter. The multiple peaks in response may be due to CWP resonances. The largest measured responses are due to regular waves. There is a possibility that motions, particularly in regular waves, may be effected by reflected waves.

The CWP bending moments for the HMB with rigidly attached, stiff CWP in head seas, Figure 18, show good agreement between all data. There are minimal to moderate nonlinear effects at the 5.5 radian per second response peak. Secondary peaks appear

to occur at frequencies of about two to three and 7.5 radians per second. CWP bending moments in beam seas, Figure 19, show considerable scatter and strong nonlinear effects at the four and eight radian per second response peaks. The bending moments, particularly at the upper location, are significantly larger than those for the freely attached, stiff CWP.

The motions for the HMB with rigidly attached, flexible CWP, Figure 20, show good agreement between all data. Motions are very similar to those for the HMB without CWP. There appears to be a surge, and perhaps pitch, resonance, at a frequency below two radians per second. If a resonance does exist, it is probably due to the effect of the HMB mooring. The motions in beam seas, Figure 21, show moderate variations between data for different waves, and some indications of nonlinearities, particularly for sway motions. Response peaks occur at frequencies of about 2.5 and six radians per second.

The CWP bending moments for the HMB with rigidly attached, flexible CWP in head seas, Figure 22, show moderate scatter. The data for regular waves are not in good agreement with the other data. Bending moments are much smaller than those for the rigid CWP. Bending moments for beam seas, Figure 23, also show moderate scatter. Results for the upper location, where moments are largest, show less scatter and no significant nonlinearities. The results for the lower point do show nonlinear effects, but the moment magnitudes are very small (about one percent of the maximum moments measured in this study).

Comparison of Measured and Predicted RAO's

Figure 24 compares measured and predicted motions for the HMB alone in head seas. The measured and predicted responses are in generally good agreement, with measured motions smaller than predicted motions. This is probably due to underprediction of hull damping, a result that is not surprising considering the low length-beam ratio and large beam-draft ratio of the HMB. Figure 25 compares calculated and measured motions of the HMB in beam seas. Only two sea states have been shown for clarity. Local peaks, as described by single data points in Figure 13, have been eliminated. The agreement based on this "smoothed" data, is fairly good. The increasing sway response measured at low frequencies may be due to the sway resonance of the moored HMB, although the free oscillation tests indicate this motion was heavily damped.

Figure 26 compares measured and predicted motions for the HMB with a freely attached, stiff CWP in head seas. Agreement is generally good, although measured pitch motions are less than predicted pitch motions, probably for the same reason noted for the HMB alone. The behavior of heave for a 16 foot scaled significant wave height has already been noted. Figure 27 presents a comparison for the same model in beam seas. Agreement is good, although the theory does not predict the secondary roll motion peak at a frequency of about 2.5 radians per second (18 second prototype period) or the rising sway response at frequencies below 3.5 radians per second (13 second prototype period). Motions at these low frequencies are generally not important for OTEC-1 operating sea states.

Figure 28 compares measured and predicted CWP head sea bending moments, for the freely attached, stiff CWP. The moments at the lower point are in good overall agreement, although there are significant differences in measured maximum bending moments and the measured maxima occur at about 10 percent higher frequency than does the predicted maximum. The measured maximum bending moments at the upper point are much larger than the predicted value. This is probably due to the stiffness of the flexure section, which causes a large local increase in the stiffness of the CWP. The agreement between measured and predicted bending moments for beam seas, Figure 29, is not as good, although the frequencies for maxima and the general magnitude of the maxima are comparable. The theory, which is best suited to small amplitude motions, gives a lower point maximum bending moment which is similar to the measured results for the smallest sea state (eight foot significant wave height).

Figure 30 compares measured and predicted motions for the HMB with a rigidly attached, stiff CWP in head seas. Agreement for surge and heave is generally very good. Agreement for pitch is good for higher frequencies (greater than 4.5 radians per second), but only fair for lower frequencies. Figure 31 compares motions for beam seas. Again agreement is not as good as for head seas. The best agreement is, surprisingly, for roll. Measured and predicted heave motions agree well except for the large measured but unpredicted fluctuations at frequencies between four and seven radians per second. For all motions, the measured results for the 16 foot significant height random waves is in the best agreement with the predictions.

Figure 32 compares measured and predicted CWP head seas bending moments for the rigidly attached, stiff CWP. The measured maximum bending moments are 40 to 50 percent of the predicted maximum values; otherwise the results are in generally good agreement. Figure 33 compares bending moments for beam seas. Despite large differences in the measured values for different wave conditions, the measured and predicted results are in reasonably good agreement. The primary difference is at frequencies around 5.5 radians per second (5.7 second prototype period) where the measured response has a peak not found in the predictions. The measured peak bending moment, at the lower point, is about 10 percent greater than the predicted value.

Figure 34 compares measured and predicted motions for the HMB with a rigidly attached, flexible CWP in head seas. Agreement for surge and heave is very good. Agreement for pitch is fair, with measured motions being significantly less than predicted motion at frequencies below five radians per second. Figure 35 compares motions for beam seas. Agreement for sway and heave is generally good. Agreement for roll is fairly good, although the measured roll motions do have a much smaller peak than does the predicted roll for frequencies above six radians per second (5.2 second prototype period).

Figure 36 compares measured and predicted CWP head seas bending moments for the rigidly attached, flexible CWP. The measured and predicted bending moments for the upper and lower locations show generally the same behavior, but measured values are several times as large as predicted values. This is probably

due to the local increases in CWP stiffness due to the stiff flexure section. Figure 37 compares bending moments for beam seas. Measured results for the lower location are in reasonably good agreement with predicted bending moments. Measured and predicted results for the upper location show similar behavior, but measured values are approximately twice the predicted values. It is possible that the observed differences in bending moments are due to an inability to accurately determine model CWP modulus of elasticity, due to non-elastic behavior of the material, but the influence of the strain gage flexure sections on local CWP stiffness seems a more probable cause.

Significant Responses in Random Waves

Table 4 shows measured and predicted significant motions for the HMB without CWP. Motions in head seas are rather small. Agreement between measured and predicted motion is generally good except for surge and heave for the eight foot significant wave height, where measured values are about three times larger. This is due to the larger measured motions at frequencies greater than seven or eight radians per second, as shown in Figure 24. Motions in beam seas are much larger than those in head seas. Agreement between measured and predicted motions is good except for sway. Measured sway motions are two to three times larger predicted motions, again due to the much larger measured motions at high frequencies, as shown in Figure 25. Measured and predicted roll motions are in surprisingly good agreement.

Table 5 presents measured and predicted significant responses for the HMB with freely attached, stiff CWP. Motions

in head seas are quite similar to those for the HMB alone, except for surge for the 16 foot significant wave height. The differences between measured and predicted surge and heave are again due to the larger measured responses at high frequencies, Figure 26. Measured CWP bending moments for the lower point are larger than the predicted moments. The best agreement between measured and predicted bending moments is for the lower point in 16 foot waves, the case of largest bending moment. The large differences at the upper point are probably due to the local increase in model CWP stiffness due to the strain gage flexure section.

Two values are given for each CWP bending moment in Tables 5-7. The first value is the bending moment due to deflections in the direction of wave propagation and primary platform motions. The second value is the bending moment due to deflections in a direction normal to that of wave propagation. This latter bending moment, which is typically less than one-half the former value, is probably due to motions resulting from platform yawing.

The measured motions and the agreement between measured and predicted motions in beam seas are similar to those for the HMB alone. The measured heave and CWP relative heave for the 16 foot waves appear questionable and are not shown. Measured CWP bending moments are, typically, 50 percent greater than bending moments in head seas. The agreement between measured and predicted bending moments is quite good and much better than the agreement of bending moments in head seas. The

CWP relative motions (heave and roll of the CWP relative to the platform) are larger than those in head seas and are comparable to platform heave and roll, indicating small absolute motions of the CWP.

Table 6 presents measured and predicted significant responses for the HMB with rigidly attached or fixed, stiff CWP. Motions in head seas are somewhat different than those of the HMB alone. For the eight foot waves, surge is larger with the CWP. For the 16 foot waves, heave and pitch are smaller with the CWP. Measured and predicted motions are in reasonably good agreement except that measured surge and heave in eight foot waves are about three times predicted values. Bending moments are much larger than those with the freely attached, stiff CWP, particularly for the upper location. Bending moments at the upper and lower locations are nearly equal. Measured and predicted bending moments are comparable for eight foot waves, while measured bending moments are 40 to 50 percent of predicted values for 16 foot waves.

The measured motions in beam seas are, except for roll, similar to those for the HMB alone. The measured roll motions are 10 to 20 percent of those for the HMB alone. The measured and predicted heave and roll motions are in good agreement while measured sway is two to three times predicted sway, due to the differences in high frequency motions. Measured CWP bending moments in beam seas are similar to those in head seas, although bending moments at the lower location are 30 to 40 percent larger than those at the upper location. Measured and predicted bending moments are in generally good agreement.

Table 7 presents measured and predicted significant responses for the HMB with rigidly attached flexible CWP. Measured motions in head seas are similar to those for the HMB alone, although surge motions with the CWP are 30 to 50 percent larger than those for the HMB alone. Measured and predicted motions are in good agreement, except that measured surge and heave, for eight foot waves only, are much larger than predicted values. Measured CWP bending moments are much smaller than those for the stiff CWP. Predicted bending moments are much smaller than measured values, perhaps due to the effect of the stiff strain gage flexure sections.

The measured motions in beam seas are similar to those for the HMB alone. Measured and predicted heave and roll are in good agreement, while measured sway is two to three times predicted sway. Measured CWP bending moments are larger than those in head seas, but much smaller than those for the stiff CWP. Predicted bending moments are again much smaller than measured bending moments, but agreement is much better than that for head seas.

RECOMMENDATIONS FOR FUTURE STUDIES

Based on the results of this study, several recommendations for future model tests of OTEC plants seem in order. These include:

1. CWP bending moments should be measured at more than two positions along the length of the CWP.
2. Motions at the bottom of the CWP should be measured. It would be desirable to measure motions at other CWP locations, but the added cost must be considered.
3. In modeling rather flexible CWP's, a model pipe material which has a more elastic behavior than that of the present flexible CWP model would be desirable.
4. Testing only in random waves is considered satisfactory. Tests in random waves provide response amplitude operators which have less scatter than those determined from regular wave tests and which are in generally good agreement with regular wave results.

CONCLUSIONS

It is possible to draw a number of general conclusions from this study. Conclusions of particular note include:

1. Response amplitude operators determined from regular and random wave tests are in generally good agreement.
2. Nonlinear effects appear to exist only for limited cases of motions in beam seas and for CWP bending moments.
3. Measured and predicted motions are generally in good agreement, with measured motions tending to be less than predicted motions and with largest differences for sway and roll in beam seas.
4. Measured and predicted CWP bending moments are generally comparable, although agreement is not as good as that for motions.
5. It is feasible to conduct tests of OTEC plant models with CWP models up to 40 feet long using the methods employed and the HYDRONAUTICS Ship Model Basin or other test facility with a comparable deep section.

More specific conclusions will be found in the Discussion of Results Section.

TABLE 1
 Characteristics of Test Regular
 and Irregular Waves

I. Regular Waves

Wave	Wave Length Feet		Wave Height Feet	
	Model	Prototype	Model	Prototype
1	4.0	200	0.06	3.0
2	4.7	237	0.072	3.6
3	5.7	286	0.087	4.3
4	7.0	350	0.106	5.3
5	8.8	440	0.133	6.7
6	11.4	571	0.173	8.7
7	15.3	767	0.232	11.6
8	21.7	1086	0.329	16.5
9	33.0	1650	0.50	25.0
10	56.0	2800	0.583	29.2

II. Irregular Waves

Sea State	Significant Height-Feet		Peak Energy Frequency-1/sec	
	Model	Prototype	Model	Prototype
1	0.16	8	7.69	1.09
2	0.24	12	6.25	0.88
3	0.32	16	5.44	0.77

TABLE 2
Characteristics of HMB as Tested

Characteristic	Model	Prototype
Displacement	142.0 pounds (with 13.52 pound CWP)	7924 long tons (with CWP)
Draft	2.74 inches	11.4 feet
LCG	0.5 inches fwd.	2.1 feet fwd.
KG	6.91 inches	28.8 feet
Pitch gyradius	20.2 inches	84.2 feet
Yaw gyradius	20.2 inches	84.2 feet
Roll gyradius	10.6 inches	44.2 feet
Roll GM	19.85 inches	82.7 feet
Pitch GM	178.1 inches	742 feet
Length-overall	77.8 inches	324 feet
Beam	25.60 inches	106.7 feet

TABLE 3
Table of Instrumentation Accuracy

Quantity Measured	Transducers	Typical Sensitivity	Maximum Deviation of Calibration (millivolts)	Maximum Tape Recorder Error (millivolts)	Maximum Error in Millivolts	Maximum Error in Physical Units	Tape Recorder Threshold in Millivolts	Threshold in Physical Units
Wave Height	Capacitance Probe	2.083×10^{-4} ft/mv	20	4	24	5.00×10^{-3} ft	20	4.17×10^{-3} ft
Heave	Potentiometer	8.672×10^{-5} ft/mv	10	4	14	1.21×10^{-3} ft	20	1.73×10^{-3} ft
Pitch	Potentiometer	1.163×10^{-2} deg/mv	10	4	14	1.63×10^{-1} deg	20	2.33×10^{-1} deg
Roll	Potentiometer	1.176×10^{-2} deg/mv	5	4	9	1.06×10^{-1} deg	20	2.35×10^{-1} deg
Surge	Potentiometer	8.091×10^{-4} ft/mv	15	4	19	1.51×10^{-2} ft	20	1.62×10^{-2} ft
Sway	Potentiometer	8.091×10^{-4} ft/mv	15	4	19	1.51×10^{-2} ft	20	1.62×10^{-2} ft
Yaw	Potentiometer	9.091×10^{-3} deg/mv	30	4	34	3.09×10^{-1} deg	20	1.82×10^{-1} deg
Upper Transverse Bending Moment	Strain Gauge	2.500×10^{-2} ft lbs/mv	25	4	29	7.25×10^{-1} ft lbs	20	5.00×10^{-1} ft lbs
Upper Longitudinal Bending Moment	Strain Gauge	2.421×10^{-2} ft lbs/mv	25	4	29	7.02×10^{-1} ft lbs	20	4.84×10^{-1} ft lbs
Lower Transverse Bending Moment	Strain Gauge	2.427×10^{-2} ft lbs/mv	25	4	29	7.04×10^{-1} ft lbs	20	4.85×10^{-1} ft lbs
Lower Longitudinal Bending Moment	Strain Gauge	2.475×10^{-2} ft lbs/mv	25	4	29	7.18×10^{-1} ft lbs	20	4.95×10^{-1} ft lbs
Relative Heave	Potentiometer	8.418×10^{-5} ft/mv	10	4	14	1.18×10^{-3} ft	20	1.68×10^{-3} ft
Relative Pitch	Potentiometer	9.524×10^{-3} deg/mv	10	4	14	1.33×10^{-1} deg	20	1.90×10^{-1} deg
Relative Roll	Potentiometer	1.163×10^{-2} deg/mv	5	4	9	1.05×10^{-1} deg	20	2.33×10^{-1} deg

TABLE 4

Comparison of Measured and Predicted
Significant Response Amplitudes in Irregular
Waves for HMB Without CWP

Response	Measured	Predicted	Measured	Predicted
Head Seas	$H_{\frac{1}{3}} = 7.8'$	8.0'	$H_{\frac{1}{3}} = 14.3'$	16'
Surge, ft	1.5	0.5	3.4	3.0
Heave, ft	1.4	0.5	4.2	2.8
Pitch, deg	1.0	0.7	2.5	3.0
Upper B.M.	-	-	-	-
Lower B.M.	-	-	-	-
Beam Seas	$H_{\frac{1}{3}} = 8.0$	8.0	17.1	16.0
Sway, ft	4.8	1.7	10.2	5.5
Heave, ft	2.2	2.2	6.3	6.4
Roll, ft	5.4	6.6	11.1	11.6
Yaw, ft	0.7	0.5	1.4	0.7
Upper B.M.	-	-	-	-
Lower B.M.	-	-	-	-

TABLE 5

Comparison of Measured and Predicted
Significant Response Amplitudes in
Irregular Waves for Stiff CWP
with Free Attachment

Response Head Seas	Measured $H_{\frac{1}{3}} = 6.8'$	Predicted 8.0	Measured $H_{\frac{1}{3}} = 16.6'$	Predicted 16.0
Surge, ft	1.5	0.5	6.2	3.0
Heave, ft	1.1	0.5	4.6	2.8
Pitch, deg	0.6	0.7	3.1	3.2
Upper B.M./10 ⁶	2.5/10**	0.8	5.0/1.9	2.0
Lower B.M./10 ⁶	12.5/2.5	4.5	52/16	36.0
CWP heave*, ft	0.3	-	3.6	-
CWP pitch*, deg	1.8	-	1.6	-
Beam Seas	$H_{\frac{1}{3}} = 7.6$	8.0	18.2	16.0
Sway, ft	4.4	1.3	13.9	5.2
Heave, ft	2.3	2.2	-	6.3
Roll, deg	6.1	6.5	12.6	13.5
Yaw, deg	0.6	0.5	1.6	0.7
Upper B.M./10 ⁶	3.8/2.5	3.1	8.8/5.0	6.2
Lower B.M./10 ⁶	30/6.2	23.0	73/34	74.0
CWP heave*, ft	2.8	-	-	-
CWP roll*, deg	6.1	-	13.1	-

*Motion relative to HMB.

**

TABLE 6

Comparison of Measured and Predicted
Significant Response Amplitudes in
Irregular Waves for Stiff CWP
with Rigid Attachment

Response	Measured	Predicted	Measured	Predicted
Head Seas	$H_{\frac{1}{3}} = 8.0$	8.0	$H_{\frac{1}{3}} = 13.9$	16.0
Surge, ft	2.5	0.7	3.4	4.1
Heave, ft	1.6	0.5	2.3	3.0
Pitch, deg	0.9	0.5	1.7	2.4
Upper B.M./10 ⁶	51/4.4	62.0	96/7.5	251.0
Lower B.M./10 ⁶	54/7.5	32.0	103/20	208.0
Beam Seas	$H_{\frac{1}{3}} = 6.2$	8.0	18.0	16.0
Sway, ft	4.0	1.3	7.3	4.5
Heave, ft	2.3	2.1	6.5	6.6
Roll, ft	1.0	0.9	1.3	2.0
Yaw, ft	0.7	0.01	1.3	0.02
Upper B.M./10 ⁶	35/29	39.0	62/38	79.0
Lower B.M./10 ⁶	48/22	31.0	79/42	95.0

TABLE 7

Comparison of Measured and Predicted
Significant Response Amplitudes in
Irregular Waves for Flexible
CWP with Rigid Attachment

Response Head Seas	Measured $H_{\frac{1}{3}} = 8.4$	Predicted 8.0	Measured $H_{\frac{1}{3}} = 17.7$	Predicted 16.0
Surge, ft	2.1	0.5	5.4	3.1
Heave, ft	1.4	0.5	3.4	3.0
Pitch, deg	0.9	0.7	3.2	3.2
Upper B.M./10 ⁶	4.0/1.9	3.1	10.8/2.1	1.7
Lower B.M./10 ⁶	1.2/2.0	0.2	1.8/1.8	0.5
Beam Seas	$H_{\frac{1}{3}} = 8.5$	8.0	18.8	16.0
Sway, ft	4.7	1.6	14.2	5.5
Heave, ft	2.8	2.1	7.6	6.6
Roll, ft	4.1	5.9	9.1	11.5
Yaw, deg	0.6	0.5	1.5	0.7
Upper B.M.	11.6/4.2	4.1	24/5.3	7.3
Lower B.M.	1.7/2.1	1.1	1.9/2.5	2.2

FIGURE 1 - SIDE VIEW OF THE HMB MODEL

FIGURE 2 - BOW VIEW OF THE HMB MODEL

FIGURE 3 - HMB MODEL ATTACHED TO MOORING RING SHOWING COLD WATER PIPE SUSPENSION APPARATUS IN FREE MODE

FIGURE 4 - GEOMETRY OF STIFF COLD WATER PIPE

FIGURE 5 - GEOMETRY OF FLEXIBLE COLD WATER PIPE

FIGURE 6 - PHOTOGRAPH OF TYPICAL BENDING MOMENT FLEXURE

FIGURE 7 - DETAILS OF BARGE MOORING SYSTEM

FIGURE 8 - SUMMARY OF CWP CHARACTERISTICS

FIGURE 9 - COMPARISON OF TYPICAL MODEL TEST WAVE SPECTRA AND DESIRED BERTSCHNEIDER SPECTRA

FIGURE 10 - RESPONSE AMPLITUDE OPERATORS FOR MOTIONS AT THE HMB CG IN HEAD SEAS - NO CWP

FIGURE 11 - RESPONSE AMPLITUDE OPERATORS FOR MOTIONS AT THE HMB CG IN BEAM SEAS - NO CWP

FIGURE 12 - RESPONSE AMPLITUDE OPERATORS FOR MOTIONS AT THE HMB CG IN HEAD SEAS - STIFF CWP - FREE ATTACHMENT

FIGURE 13 - RESPONSE AMPLITUDE OPERATORS FOR MOTIONS OF THE HMB CG IN BEAM SEAS - STIFF CWP - FREE ATTACHMENT

FIGURE 14 - RESPONSE AMPLITUDE OPERATORS FOR CWP BENDING MOMENTS
IN HEAD SEAS - STIFF CWP - FREE ATTACHMENT.

FIGURE 15 - RESPONSE AMPLITUDE OPERATORS FOR CWP BENDING MOMENTS
IN BEAM SEAS - STIFF CWP - FREE ATTACHMENT

FIGURE 16 - RESPONSE AMPLITUDE OPERATORS FOR MOTIONS AT HMB
CG IN HEAD SEAS - STIFF CWP - RIGID ATTACHMENT

FIGURE 17 - RESPONSE AMPLITUDE OPERATORS FOR MOTIONS AT THE HMB CG IN BEAM SEAS - STIFF CWP - RIGID ATTACHMENT

FIGURE 18 - RESPONSE AMPLITUDE OPERATORS FOR CWP BENDING MOMENTS
IN HEAD SEAS - STIFF CWP - RIGID ATTACHMENT

FIGURE 19 - RESPONSE AMPLITUDE OPERATORS FOR CWP BENDING MOMENTS
IN BEAM SEAS - STIFF CWP - RIGID ATTACHEMNTS

FIGURE 20 - RESPONSE AMPLITUDE OPERATORS FOR MOTIONS AT THE HMB CG IN HEAD SEAS - FLEXIBLE CWP - RIGID ATTACHMENT

FIGURE 21 - RESPONSE AMPLITUDE OPERATORS FOR MOTIONS AT THE HMB CG IN BEAM SEAS - FLEXIBLE CWP - RIGID ATTACHEMENT

FIGURE 22 - RESPONSE AMPLITUDE OPERATORS FOR CWP BENDING MOMENTS
IN HEAD SEAS - FLEXIBLE CWP - RIGID ATTACHMENT

FIGURE 23 - RESPONSE AMPLITUDE OPERATORS FOR CWP BENDING MOMENTS
IN BEAM SEAS - FLEXIBLE CWP - RIGID ATTACHMENT

FIGURE 24 - COMPARISON OF MEASURED AND PREDICTED HMB CG MOTIONS IN HEAD SEAS - NO CWP

FIGURE 25 - COMPARISON OF MEASURED AND PREDICTED HMB CG MOTIONS IN BEAM SEAS - NO CWP

FIGURE 26 - COMPARISON OF MEASURED AND PREDICTED HMB CG MOTIONS IN HEAD SEAS - STIFF CWP - FREE ATTACHMENT

FIGURE 27 - COMPARISON OF MEASURED AND PREDICTED HMB CG MOTIONS IN BEAM SEAS - STIFF CWP - FREE ATTACHMENT

FIGURE 28 - COMPARISON OF MEASURED AND PREDICTED CWP BENDING MOMENTS IN HEAD SEAS - STIFF CWP - FREE ATTACHMENT

FIGURE 29 - COMPARISON OF MEASURED AND PREDICTED CWP BENDING MOMENTS IN BEAM SEAS - STIFF CWP - FREE ATTACHMENT

FIGURE 30 - COMPARISON OF MEASURED AND PREDICTED HMB CG MOTIONS IN HEAD SEAS - STIFF CWP - RIGID ATTACHMENT

FIGURE 31 - COMPARISON OF MEASURED AND PREDICTED HMB CG MOTIONS IN BEAM SEAS - STIFF CWP - RIGID ATTACHMENT

a. UPPER LOCATION

b. LOWER LOCATION

FIGURE 32 - COMPARISON OF MEASURED AND PREDICTED CWP BENDING MOMENTS IN HEAD SEAS - STIFF CWP - RIGID ATTACHMENT.

FIGURE 33 - COMPARISON OF MEASURED AND PREDICTED CWP BENDING MOMENTS IN BEAM SEAS - STIFF CWP - RIGID ATTACHMENT

FIGURE 34 - COMPARISON OF MEASURED AND PREDICTED HMB CG
MOTIONS IN HEAD SEAS - FLEXIBLE CWP - RIGID ATTACHMENT

FIGURE 35 - COMPARISON OF MEASURED AND PREDICTED HMB CG MOTIONS IN BEAM SEAS - FLEXIBLE CWP - RIGID ATTACHMENT

FIGURE 36 - COMPARISON OF MEASURED AND PREDICTED CWP BENDING MOMENTS IN HEAD SEAS - FLEXIBLE CWP - RIGID ATTACHMENT

a. UPPER LOCATION

b. LOWER LOCATION

FIGURE 37 - COMPARISON OF MEASURED AND PREDICTED CWP BENDING MOMENTS IN BEAM SEAS - FLEXIBLE CWP - RIGID ATTACHMENT