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CONCEPTS FOR A BOTTOM-MOUNTED BUOYANT, STAB-IN COLD
WATER PIPE FOR THE OTEC PROGRAM

MASTER

Technical Report No. 1485

By
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Joe W. Key

January 1979

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ORI, Inc.
Silver Spring, Maryland

U.S. Department of Energy

Solar Energy

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ABSTRACT

A conceptual design for a bottom-mounted, stab-in cold water pipe (CWP) for OTEC is presented. The design concepts used are based on experience gained in the design of marine risers for offshore petroleum production. After a detailed description of the system envisioned and the installation scenario, the status of the major components in the system is discussed relative to the present state of the art in the oil industry. From preliminary structural analyses and cost projections, a comparison is then drawn between the bottom-mounted pipe and free-hanging CWP designs. The comparison shows the bottom-mounted concept to be technically and economically sound, utilizing present oil industry design practices. Finally, recommendations are made for further work to integrate the bottom-mounted CWP concept into the OTEC program.

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I. INTRODUCTION

This report describes a design concept for the OTEC Cold-Water Pipe (CWP) based on experience gained by the offshore petroleum industry in the design of Marine Risers for application to very deep water. The purpose of the report is to provide an assessment of the concept of a bottom-mounted pipe as a viable alternative to free hanging pipes and to present information on the relative state of development of the various components that comprise this type of CWP system.

Section II of this report presents details of recent oil industry experiences in the development and deployment of Marine Risers for application to depths ranging up to 4300 feet. A detailed conceptual design of the bottom-mounted system and a scenario for the method of installation are presented in the succeeding three sections. Section VI reviews the status of the major components of the system relative to the present state-of-the-art in the offshore petroleum industry. Preliminary structural analyses for comparison to stress, deflections and pipe characteristics envisioned for free-hanging CWP designs are presented in Section VII; followed by cost projections and a technical comparison with free-handling concepts. The final two sections summarize the major conclusions of the study and make recommendations for integration of a bottom-mounted CWP concept into the overall OTEC program.

The technical portion of this program was conducted by Ocean Resources Engineering, Inc. of Houston, Texas under subcontract to ORI, Inc. The subcontractor has demonstrated experience and expertise in the design and deployment of large Marine Risers for very deep-water application, bordering on the limitations of the present technology.

The calculations presented in Section VII are preliminary in nature, developed in order to compare orders of magnitude of stress and deflection to those computed for free-hanging pipes. As such, a number of simplified methods and approximations (such as the current velocity profiles presented in Figures

7.1 and 7.4) were utilized in order to remain within the cost limitations of a preliminary conceptual design. Thus, these calculations should not be considered as design numbers.

It is felt that the present report adequately illustrates the viability and cost-effectiveness of a bottom-mounted, stab-in design for the OTEC cold-water pipe and that such a design concept should be investigated in greater detail for possible integration into the OTEC program.

II. BACKGROUND ON MARINE RISER TECHNOLOGY

Commerical exploratory drilling has recently been conducted in water depths of 4300 feet. This drilling is conducted through a riser pipe approximately twenty inches in diameter; the outside diameter of the pipe including bouyancy is approximately four feet. Systems have been designed and components are being designed and tested to produce oil in these water depths. The systems include on-bottom production facilities, pipelines and the production riser systems used to bring the produced fluids to the surface. Riser pipes for some of these systems are three to five feet in diameter with an outside diameter, including bouyancy, of six to ten feet. The practical upper limits on diameter depends on the type of floating vessel connected to the riser at the surface, the weather window in which the system operates while connected, the survival environment when the floating vessel is not connected to the riser, and the characteristics of the system which couples the riser to the floating vessel. As a result of detailed design and testing work, a production riser/tanker mooring system has been fabricated and should be installed next summer in Santa Barbara Channel in 500 feet of water to connect to a fixed offshore platform installed in 875 feet of water. A three part platform with subsea assembly of major structural components has recently been installed in the Gulf of Mexico in 1,000 feet of water. Detailed design of moored towers and tension leg platforms have been completed for locations with water depths greater than 1,000 feet. Information describing some of the recent developments by the petroleum industry is included in the appendix to this report. Details of the most advanced systems are not available in public sources, due to the proprietary nature of the designs.

The concept of the free-standing riser has been developed by the petroleum industry and proven suitable for drilling in very deep water and for production risers in shallow water depths. Production risers have been designed for very deep water locations, but have not been needed to date. Generally this concept is used to allow quick disconnection near the surface so the ship can leave location or to limit surface environmental conditions to which the lower riser is subjected. A paper entitled: "Exxon's New Deepwater Production

Riser" by R.H. Gunderson of Exxon Production Research Company and P.A. Lunde of Ocean Resources Engineering, Inc. is included in Appendix A.

An application of this technology to the OTEC Project appears meaningful in developing viable options for the design, construction and installation of the Cold Water Pipe (CWP).

III. DESIGN PARAMETERS

The site selected by DOE for this study is an area off Punta Tuna, Puerto Rico as shown on Figure 2.1. It is located at 17° 57' N 65° 52' W where approximate water depth is 4,000 feet. The gross bottom conditions are described as silt and sand high in carbonate content. The slope of the bottom is approximately 1:3 at the site.

Environmental data and vessel characteristics and motions used in the design are included in Appendix B to this report.

The size of the CWP will be thirty (30) feet inside diameter. The material choice will be steel, because it is the material exclusively being used by the petroleum industry in structures of this type and because it has high strength, uniform properties and is easily fabricated using common techniques. It is possible that other materials will be acceptable or possibly preferable, but the scope of this study has been limited to consideration of steel.

IV. DESCRIPTION OF BOTTOM-MOUNTED CWP SYSTEM

GENERAL

A bottom-mounted, buoyant CWP is illustrated on Figure 4.1, which shows the system in operation with the OTEC power plant vessel attached to the CWP. The major components include:

- (a) Fluid Swivel
- (b) Upper Flexible Joint
- (c) Quick-Disconnect from Ship
- (d) Slip Joint
- (e) CWP, with Flexible Joint near Ocean Surface
- (f) Water Intake
- (g) Connector Link from CWP to Base
- (h) Universal Joint
- (i) Base Connector
- (j) Base
- (k) Heave Compensation.

Additional details of these components are shown on Figures 4.2, 4.3, 4.4, 4.5 and 4.6. The fluid swivel allows the power plant vessel to weathervane about the base. The two flexible joints limit the stresses and effectively isolate much of the vessel motion from the CWP.

FIGURE 4.1

General Configuration of Bottom-Mounted Cold Water Pipe (C.W.P.)

FIGURE 4.2 UPPER CWP CONFIGURATION

FIGURE 4.3 MID CWP CONFIGURATION

FIGURE 4.4 LOWER CWP CONFIGURATION
GRAVITY BASE ALTERNATE

FIGURE 4.5 LOWER CWP CONFIGURATION
PILE BASE ALTERNATE

- 1 ELASTOMER ELEMENT - Made up of an inner housing, outer ring and rubber/metal laminate. The laminated portion, bonded to both the inner housing and outer ring, is constructed of alternate spherical elements of rubber and metal. The radius of all elements passes through a common center. The elastomer element subassembly rests on the guide ring/wear bushing under static and initial installation conditions.
- 2 GUIDE RING/WEAR BUSHING - In addition to the support function noted above, the guide ring/wear bushing absorbs wear occurring during normal operations, thus protecting the elastomer and bottom portion of the main housing.
- 3 HOUSING - This part of the sub-sea flexible joint is a holding fixture for the elastomer element and guide ring/wear bushing.
- 4 RETAINER RING - This part, bolted only to the housing, constrains the elastomer element within the housing.

Figure 4.6: Special Components Flexible Joint

The slip joint serves as an aid in connecting/disconnecting the CWP and the power plant vessel and works as a heave compensator to isolate the CWP from forces imposed by the vessel heave.

The CWP can be disconnected at the vessel and a short section of pipe is lowered by wire-line into the permanent riser. This feature greatly decreases the possibility of exposure of the vessel and CWP to severe environmental forces. It also provides the capability to have planned outages for essential maintenance or repairs.

The lower u-joint reduces the stresses in the connector link and allows efficient utilization of materials. The lower, remotely operated disconnect (Figure 4.7) is used during the construction phase and for possible relocation, while the upper quick-disconnect is used only for temporary curtailment of operations.

In order to provide stability during free-standing conditions, buoyancy is distributed along the length of the CWP. This is accomplished by having a buoyance chamber surround the CWP, with compressed air between the CWP and the shell of the buoyance chamber. By having a closed top and open bottom in the buoyancy chamber, the compressed air can be achieved passively by lowering the combined unit into the water (see Figure 4.8).

If greater buoyancy is desired, an external source can be used to further displace the water which enters the bottom of the buoyancy chamber. This minimizes the differential head encountered by the CWP, and is a feasible method of controlling the CWP during installation and operation. Preliminary calculations indicate that the bottom-mounted CWP designed in this manner can have a wall thickness of one inch to 1.50 inches. The shell of the buoyancy chamber can be limited to a thickness of about 0.375 inches.

The buoyancy chamber around the CWP can incorporate a conduit for running the power cable from the power plant to the ocean floor. This feature may obviate many problems associated with safe installation of the power cable.

We have selected a pipe 15 feet in diameter as the connecting link to the base. This is considered preferable to a special chain or similar unit due to installation and maintenance costs. Additionally, the connector link can be filled with a suitable ballast material to detune the motions of the CWP, reduce the excursion of the power plant vessel or to optimize the stresses in the structural components. This may be helpful in reducing the adverse effects of vortex shedding.

The base can be filled with ballast and operate as a gravity base or be pile-supported.

OPERATIONAL FEATURES OF THE SYSTEM

The operation of the system after connection to the bottom-mounted CWP will be essentially the same as for the free-hanging CWP. Due to the heave compensation and flexible joints built into the CWP system, the vessel mooring requirements will be minimized. The flexible joints at the vessel and at -450

FIGURE 4.7 SPECIAL COMPONENTS - UNIVERSAL JOINT
AND BASE CONNECTOR

FIGURE 4.8 BUOYANT CWP SECTION DETAILS

feet elevation will be designed to allow an angle of more than +10 degrees. This will allow vessel excursion of more than 600 feet in any direction from the base.

The buoyancy of the CWP is designed to limit the lateral displacement of the top of the CWP to approximately 590 feet under maximum storm and tide conditions when disconnected from the vessel.

Preliminary dynamic analyses of the CWP and vessel for both operation conditions (14 foot significant waves) and survival storm conditions (45 foot significant waves) show that the system is suitable for both conditions. The analytical method used follows that given in Young and Fowler (1978)*. The results of this analysis are presented in Section 7.

QUICK-DISCONNECT FEATURE OF THE SYSTEM

The predictability of environmental conditions and the vessel/CWP responses to these conditions is on the outer limits of the state-of-the-art of design. It appears prudent to have the capability of rapidly moving the vessel off location in the event of extreme weather conditions or for other special circumstances, such as major maintenance or repairs due to deterioration or obsolescence of system components, catastrophic failure of the system, or for general relocation to a more desirable location.

The vessel can be easily disconnected from the CWP. The CWP can also be disconnected from the base and relocated to other sites where a new base has been installed to receive the CWP.

The capability of quickly disconnecting the CWP without the necessity of retrieving any CWP segments provides a greater contingency against damage or costly moves required for the various reasons described above.

HEAVE COMPENSATION

There are a number of mechanical and material problems inherent to the design of the slip joint which, in order to insure operation over a long time period must be resistant to fouling and binding and must not wear excessively. Thus, a number of alternative means of heave compensation are proposed. Figure 4-9 shows a system utilizing a mechanical damping device near the base connector. Figure 4-10 shows a system utilizing a large diameter synthetic line connecting the CWP to the base and providing very flexible restraint.

* Reference listed in Part B of Appendix B.

FIGURE 4.9 HEAVE COMPENSATION ALTERNATE A
MECHANICAL DAMPING AT BASE

FIGURE 4.10 HEAVE COMPENSATION - ALTERNATE B
SYNTHETIC LINE CONNECTOR LINK

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4-14

V. INSTALLATION METHODS

GENERAL

The following discussion of installation methods will describe the basic equipment, components and operations required for installation of the bottom-mounted CWP system. Sketches of the installation procedures have been included on Figures 5.1, 5.2, and 5.3.

BASE INSTALLATION

Two basic design alternates have been reviewed for the base design. The primary system considered is a gravity type base (Figure 4.4). The alternate system considered is a base fixed to the sea floor by piling (Figure 4.5).

The gravity base on a normally firm bottom and minimum bottom slope should be more economical to install in this range of water depth. However, due to the steep bottom slope (1:3) the installation of a pile supported base may be advisable.

Both systems can be installed using crane barges with 1000 tons or greater crane capacity. Deep water drilling equipment may be required to install pilings.

As shown in Figure 5.1 the base will be lowered to its position on the bottom and ballasted. If the pile-base alternate is selected the piling will be installed at this time.

COLD WATER PIPE INSTALLATION

It is proposed that the CWP be installed using a self-propelled semi-submersible crane vessel with two revolving cranes. Similar equipment with crane capacities of 2000 and 3000 tons are currently operating in the offshore petroleum industry.

FIGURE 5.1 CONSTRUCTION METHOD BASE INSTALLATION

As shown in Figure 5.2, a guide must be installed on the crane vessel for make-up of the CWP. CWP segments up to 200 feet long will be "made-up" in the guide.

The first CWP segment will include the base connector, universal joint and approximately 1000 feet of the connecting link which is about 15 feet in diameter. The CWP sections will continue to be added and the CWP lowered into the water. Wire lines will be attached to the base connector and run through a sheave on the base, and controlled by winches at the surface. This will guide the bottom of the riser connector link, significantly relieve stresses during installation and minimize risks during this critical operation.

As the CWP is completed, the base connector will be pulled and guided into position on the base, and hydraulic jacks on the base will be activated to drive wedges into the connector. This will complete the connection of the CWP to the base. If desired, the process can be reversed, and the CWP can be disconnected from the base and moved to another location.

VESSEL CONNECTION TO THE CWP

After the CWP has been secured, complete with the surface connector pipe telescoped into the CWP, the power plant vessel will be positioned over the CWP. A wire line will be attached to the surface connector pipe which will be raised and connected to the vessel CWP (Figure 5.3).

The telescoping surface connector will form a slip joint which will provide the required heave compensation for the vessel. The vessel must be equipped with position control to the extent that it will remain within a radius of excursion of less than 600 feet.

QUICK-DISCONNECT

The connection to the vessel will be accomplished utilizing a connector device which will basically incorporate the principles of various quick-connect (disconnect) devices presently used on drilling and production risers and on deep water pipeline connectors.

The connector can be operated hydraulically and will be pulled by the wire line and stabbing guides to a position where the connector can be actuated and the connection secured.

When this connection between the CWP and the power vessel is completed, the OTEC system will be ready for operation.

FIGURE 5.2 CONSTRUCTION METHODS CWP INSTALLATION

Raising Surface C.W.P. by Wire Line

FIGURE 5.3 CONSTRUCTION METHOD POWER PLANT VESSEL CONNECT TO CWP

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VI. COMPONENT STATUS

GENERAL

The following discussion covers the status of the various CWP components with regard to the relative complexity of design and requirement for R & D efforts.

BASE

The base structure should be designed in accordance with present structural design practice for hull type construction. The structure will be designed to remain at or near ambient pressures during erection, (i.e. will utilize controlled flooding). Similar structures have been designed and installed in water depths of several hundred feet. The installation aspects which are water depth sensitive have been developed and used for many years in water depths comparable to the OTEC program. Therefore, the base is considered to be state-of-the-art, requiring only careful design and control during installation.

BASE CONNECTOR AND UNIVERSAL JOINT

The base connector is within the scope of existing design methods and similar systems have been designed and fabricated for loads and conditions similar to those anticipated for the CWP riser system. Therefore, this also is considered to be state-of-the-art, requiring only extensive engineering analyses and design.

CONNECTOR LINK FROM BASE TO CWP

This section can be designed to withstand calculated design stresses with verification of loadings with ship model-basin testing, as required by the overall CWP system. This is considered to be a challenging design effort, but major R & D efforts will not be required. Extensive analyses will be required to avoid problems during installation and to minimize possible difficulties with vortex shedding.

CWP INLET

The inlet will be designed in accordance with existing water intake systems. Further study may be required to determine feasible systems for maintaining and/or replacement of the intake screens.

BUOYANT CWP SECTION

Standard structural design practice coupled with an extensive program of computer simulation and model basin testing will be required to determine the static and dynamic behavior of the CWP system during installation and during sustained operation.

The buoyancy system presented in the report utilizes buoyancy chambers with bottoms open to the hydrostatic pressure of the sea. Similar concepts have been proven with drilling in water depths of several thousand feet.

Firms experienced in the design of deep-water production risers can accomplish this critical design without an extensive R & D effort, assuming that problems associated with vortex shedding can be obviated in a straight-forward manner.

FLEXIBLE JOINTS

Figure 4.6 shows the conceptual design of the flexible underwater CWP joints located at -450' elevation and at the vessel tie-in. Conceptual design is based on similar joints developed for drilling risers with inside diameter of about five feet.

Extensive research, development and testing may be required prior to the design and construction of a flexible joint of the size required for the OTEC program. Whether or not a bottom-mounted CWP is utilized, it appears prudent to have a flexible joint in the CWP to reduce stresses, minimize the weight of steel, and improve the probability of success. Therefore, high priority should be given to the development of a flexible joint. This probably can be best accomplished by current manufacturers of the smaller flexible joints currently in use in the offshore industry.

TURNTABLE (SWIVEL JOINT)

To provide for vessel movements required to maintain proper headings for weather and sea state conditions and for general positioning, a turntable (swivel joint) will be required just above the flexible joint at the vessel, as shown in Figure 4.2.

Existing swivel joint connections have been developed for pipe sizes up to four feet in diameter.

As with the flexible joints, much research, development and testing may be required to develop a suitable swivel 30 feet in diameter, as required for the OTEC program. It may be possible to incorporate this with the slip joint, rather than have a separate component.

QUICK-DISCONNECT

Several systems of remote connectors have been developed. Existing connector sizes range up to 8 feet in diameter. These connectors do not seem to be sensitive to the pipe diameter, but rather to the axial and shear loads encountered.

Connector design probably will require additional development, but this component will not have the complexity of development associated with the two previously discussed components (Flexible Joint and Swivel).

VESSEL HEAVE COMPENSATION

For exploration drilling, heave compensation normally is accomplished by installing constant tensioning devices to the riser and allowing the vessel to move independently with respect to the riser.

The conventional drilling riser tensioning systems are not desirable for the OTEC heave compensation because this would require a system of flexible connections to the pumping system.

Two basic concepts for heave compensation have been proposed in this study.

System 1 involves the use of a slip joint in the surface connector pipe. Much design, development and testing will be required to construct a functional slip joint for these conditions.

System 2 incorporates a system of heave compensation devices near the sea floor, as shown previously on Figures 4.9 and 3.10. These systems will require extensive analytical and model testing programs to determine the response of the vessel/riser system when connected to the base in this manner.

The slip-joint seems to have the most promise for providing heave compensation and probably should be given priority over the use of the near-bottom heave compensation.

POWER CABLE

The power cable probably should be integrated with the CWP and the connecting link to the base. This makes the power cable installation more complex but reduces the risks of damage to the power cable. If integrated with the CWP, several areas of development and testing will be required for the power cable installation. One problem will be the underwater junction required just below the lower flexible joint at elevation -450 feet. Underwater connectors for large power cables have been developed and tested for the petroleum industry. Those connectors may be adaptable to the OTEC conditions. Another problem will be the development of an electrical connection at the swivel joint connection. This

probably will be a quantum jump in the state-of-the-art. A method of junctioning at the quick-disconnect just below the keel of the power vessel must also be provided.

The laying and installation of the power cable to shore can be accomplished using standard submarine cable construction methods.

VII. PRELIMINARY ANALYSES

Several static cases were considered for the free-standing CWP (without the power plant vessel attached) to determine the approximate weights, buoyancy, and displacement of the system. Preliminary dynamic analyses were accomplished to determine the approximate stresses, moments and deflections. Sufficient work was done to assure the concept is feasible and to have input data for future analyses.

Figures 7.1 and 7.4 show the current profiles which were utilized in our analyses for the survival mode and the operating mode, respectively. The other environmental data is included in Appendix B.

Figures 7.2 and 7.5 show the deflected shape of the CWP during the survival condition and operating condition, respectively. In both cases, the deflection from the base is essentially linear, with a maximum excursion of about 600 feet at the top.

Figures 7.3 and 7.6 show the bending moment diagrams for the survival condition and operating condition, respectively. The irregular shapes indicate that the optimum distribution of weights and buoyancy has not been achieved.

The maximum moments are about 200,000 kip-feet for survival loads and about 120,000 kip-feet for the operating conditions. This is significantly lower than the moments of 1,400,000 kip-feet which are encountered with a free-hanging CWP.

With a wall thickness of 1.5 inches for the CWP, the maximum combined stresses (axial and bending) are less than 20 ksi for the survival condition or less than 14 ksi in the operating environment.

It appears obvious that serious consideration should be given to the use of a bottom-mounted CWP in lieu of a free-hanging CWP.

FIGURE 7.1. SURVIVAL CONDITION - CURRENT PROFILE

FIGURE 7.2 SURVIVAL CONDITION - CWP DEFLECTED SHAPE

FIGURE 7.3 SURVIVAL CONDITION - BENDING MOMENT DIAGRAM

FIGURE 7.4 OPERATING CONDITION - CURRENT PROFILE

FIGURE 7.5 OPERATING CONDITION - CWP DEFLECTED SHAPE

FIGURE 7.6 OPERATING CONDITION - BENDING MOMENT DIAGRAM

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VIII. COST PROJECTIONS AND TECHNICAL COMPARISON

An order of magnitude cost estimate has been developed for the system. No accurate cost data is available for the special connectors, flexible joints, swivels, etc. Fabrication and installation cost data for the basic riser system and base structure are based on present day costs, i.e. 1978-1979. No escalation has been included.

The estimated cost is based on the complete installation of the riser and connection to the power plant vessel. A cost of \$75 million has been developed for the design, construction and installation of the basic CWP system including the quick-connect unit on the keel of the power vessel and all components to the ocean floor. It is not anticipated that significant changes in the order of magnitude cost would result in using any combination of the various design alternatives noted in the report. This cost is 25 to 40 percent of our estimated costs for the free-hanging CWP.

Apparently, the free-hanging CWP requires steel thickness of at least 5 inches, with dynamic bending stress levels to 31 ksi for storm conditions. Design reports for the free-hanging CWP indicate a typical wall thickness of nine inches of steel.

This thickness will be very expensive to procure, difficult to fabricate, cumbersome to handle and costly during erection. The free-hanging CWP could weigh as much as 35,500 pounds per foot, or a total weight of 53,000 short tons for 3,000 feet of CWP.

This compares to a bottom-mounted CWP with a wall thickness of only 1.50 inches with ring stiffeners, and an outer buoyancy chamber wall thickness of 0.375 inches. Estimated weight of this bottom-mounted CWP is only 7,600 pounds per foot, or a total of about 15,000 short tons of steel for all components, including the base and connecting link.

Stress levels in the bottom-mounted, buoyant CWP are approximately 20 ksi for the survival condition, and only 14 ksi for the operating condition, greatly improving the safety of the CWP and significantly increasing the fatigue life of the CWP.

The bottom-mounted, buoyant CWP system studied in the report is within the state-of-the-art of present technology, although several components will require much additional development effort. We do not consider the free-hanging CWP to be within the state-of-the-art of present technology.

IX. CONCLUSIONS

As a result of the preliminary analyses, it appears that the use of a bottom-mounted, buoyant CWP has many significant advantages over the free-hanging CWP.

Some of the advantages of the bottom-mounted CWP are:

- (a) Bending moments are only one-tenth of those of the free-hanging CWP.
- (b) CWP wall thicknesses can be reduced from six or eight inches to about one or 1.50 inches. This makes the basic fabrication of the CWP within the state-of-the-art and allows greater competitiveness in construction bidding.
- (c) Weight of the CWP can be lowered from about 53,000 short tons to about 15,000 short tons. This has a marked impact on the ability to handle the components during the installation of the CWP.
- (d) Primary mooring of the power plant vessel is achieved with the bottom-mounted CWP system. During the operating environment, an auxiliary mooring system is not required, reducing the initial investment for moorings or reducing the operating cost for dynamic station-keeping. When the 100 year storm is anticipated, the power plant vessel can be disconnected from the CWP, or power can be diverted for dynamic station-keeping.
- (e) Electrical power cable can be protected from the environment, greatly improving the reliability of the total OTEC unit.
- (f) Fabrication can be accomplished at existing U.S. yards and installation schemes are achievable with currently available offshore construction and drilling equipment.

- (g) Power plant vessel can be disconnected from the CWP during storm conditions, minimizing the risk of catastrophic failures.
- (h) Power plant vessel can be disconnected from the CWP for scheduled maintenance, repair or upgrading of the energy conversion plant. This makes it feasible to design many components for a ten year life, with major savings in initial investment costs. Also, it minimizes adverse impacts resulting from future obsolescence of the initial equipment.
- (i) CWP can be retrieved and relocated to a more desirable location in the event of potential unrest or similar situations. Eliminating the requirement to stay in water depths greater than 3,000 feet enhances the logistics and related costs for a major relocation.
- (j) Investment costs can be reduced by about 200 to 500 million dollars.
- (k) Many of the major components are within the state-of-the-art of current technology and require only sound engineering analyses and design.
- (l) Problems associated with vortex shedding can be minimized since the primary stresses are reduced significantly and some detuning is possible.

Extensive engineering will be required before the CWP can become operational. However, the base, universal joint, base connector, connecting link, water inlet, and the basic CWP with compressed air buoyancy chambers, and the quick-disconnect unit can be designed now and are well within the state-of-the-art of current technology. Developmental effort, design and testing will be required for the fluid swivel, slip joint (or other heave compensation) and the flexible joints.

X. RECOMMENDATIONS

It is strongly recommended that a viable program be developed to integrate a bottom-mounted CWP into the overall OTEC program. This program should include:

- (a) Analyses and preliminary design of the overall system, including testing at a suitable model test basin. This probably will require about 18 months and cost about \$1.0 million.
- (b) Development and testing of flexible joints to minimize bending stresses in the CWP. This probably will require about 18-24 months and cost about \$2.0 million.
- (c) Development and testing of a slip-joint or other heave compensation device. This should take about 15-18 months and cost about \$1.5 million.
- (d) Development and testing of a fluid swivel so the power plant vessel can weathervane around the base, if a barge-shaped power plant is used. This should take 12-15 months and cost about \$0.5 million.
- (e) Preparation of a comprehensive plan for the fabrication and installation of the bottom-mounted CWP system. This should take about 9 months and cost about \$0.5 million.
- (f) Final design and preparation of fabrication specifications for the base, universal joint, base connector, connector link, CWP, power cable support conduit, quick-disconnect unit and other system components. This will require about 24 months and cost about \$4.0 million.
- (g) Obtain competitive bids for all components of the bottom-mounted CWP system, and provide construction management and quality control inspection during the fabrication or manufacture of the components. This will continue over a period of about three years and should cost about \$3.0 million.

- (h) Coordinate the assembly and installation of the bottom-mounted CWP system. This cost will depend on the type of contract and the amount of responsibility assigned to the installation contractors.

Additionally, consideration should be given to any new options which may have been created for the heat transfer and energy conversion components by having a bottom-mounted CWP connected to the ocean floor. Those possibilities are far beyond the scope of this feasibility study.

APPENDIX A
TECHNICAL PAPER ON PRODUCTION RISERS

Exxon's new deepwater production riser

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Exxon's deepwater production terminal, applicable for use in water depths to over 5,000 ft in rough water environments, consists of a SALM (Single Anchor Leg Mooring) production riser and a floating storage tanker with production facilities on board. The separated gas and water are reinjected into the formation, and shuttle tankers offload the crude oil by tandem mooring to the storage tanker.

The riser serves three main functions: (1) it moors the storage vessel, (2) serves as a support for the fluid lines, and (3) serves as a support for communication lines to subsea production equipment.

Exxon has conducted extensive model tests and analyses on the new riser system to assess its feasibility and has designed several SALM systems for various parts of the world. The Exxon riser system design criteria has been developed using established codes and emerging code requirements for offshore loading terminals modified to fit the functional and structural characteristics of the Exxon SALM. In fact, many of the design features of the deepwater riser are evident in the Santa Ynez SALM that was installed in the Santa Barbara Channel in 490 ft of water during the summer.

Description of the riser system

Exxon's new production riser system (Fig. 1) uses an above-water hinged rigid arm to permanently moor a storage tanker to the SALM. The multiline fluid swivels and electrical swivels are located above water and are accessible via the rigid arm for inspection and maintenance. In addition, the rigid arm itself can be easily inspected and maintained.

The main structural components of the SALM system are:

- Base (pile-founded or gravity)
- Lower universal joint
- Riser
- Upper universal joint
- Buoy

- Mooring turntable and pitch pin
- Roll pin
- Rigid mooring arm
- Hinge connection to tanker

The base may be either a pile-founded or a gravity base (Fig. 2). It serves as an anchor to resist the large, vertical buoyancy forces, the water particle forces along the length of the riser, and forces at the top caused by motion of and loads on the ship. The base also houses the pipe line connection hardware for connection of flowlines from Exxon's sea-floor production system (SPS).¹ A large structural connector attaches the riser to the base just below the lower universal joint. A multiline fluid connector is housed within the structural connector but carries no structural loads. The structural and flowline connectors at the base are remotely operated during installation.

The universal joints (Fig. 3) allow the riser to deflect in any azimuthal direction under the applied wave and mooring loads. The yokes of the universal joints are very stiff; this minimizes relative distortions between bearings on either side of the yoke, thereby minimizing wear and prolonging bearing life. The self-lubricated aluminum-bronze bearings use specially formulated lubricants designed for seawater service. The bearings are designed to load levels of about one-fifth of their rated operational compressive strength, which insures an essentially "zero wear" design and a long service life.

The cross member of the universal joint is a large, fabricated structure that provides a convenient path for the flowlines to follow in traversing the universal joint. Smaller versions of the multiline fluid swivel may be used instead of in-line swivels if more than one line must go through each half of the cross (Fig. 3).

The riser portion (Fig. 4) is essentially a cylindrical steel pipe approximately 3 ft in diameter. Buoyancy is provided by double-walled, open-bottom steel air cans. The air cans provide lift to but are not structurally attached to the riser and therefore do not carry any of the riser tension or bending loads. Foam buoyancy can also be used. Guides installed within the riser assist installation of riser

FIG. 1—Deepwater production riser system.

FIG. 2—Base structure and riser connector.

FIG. 3—Universal joint with multiline fluid bypasses.

flowlines and prevent buckling of the bottom-supported piping.

The cylindrical spar-shaped buoy provides the restoring force needed to hold the tankers on location. The primary buoyancy comes from the enlarged sec-

FIG. 4—Typical riser section.

FIG. 5—Mooring turntable and swivel stack.

FIG. 6—Rigid mooring arm.

tion situated below the trough of the largest waves. The enlarged section near the bottom of the buoy is partially filled with water and serves two functions: (1) to provide reserve buoyancy for adjustments of riser tension, and (2) to provide a large inertia mass on the lower portion of the buoy. This mass lowers the center of roll of the buoy and reduces the motions of the upper universal joint. Most of the bending in the riser below the universal joint is caused by the horizontal motion of the universal joint, so any decrease in this motion increases the fatigue life of the riser.

The SALM riser system is compliant enough to allow short-period ship motions while providing the necessary long-

term drift restraint. The buoy configuration can be optimized to minimize the imposed wave loadings. The buoy and riser can be adapted quite easily to varying water depths and environmental conditions by adjusting the buoyancy can diameters and inertia can dimensions.

The rigid arm is coupled to the top of the buoy through a roll pin and pitch pin (Fig. 5). These components allow roll and pitch degrees of freedom for the arm and uncouple its motion from that of the buoy. The entire assembly is mounted on a mooring turntable to let the tanker weathervane 360 degrees around the buoy.

The rigid arm is a tubular-member truss structure connected to the tanker by hinges that provide a pitch degree of freedom of the arm with respect to the tanker (Fig. 6). The arm length can vary from 150 to 200 ft and the arm width at the ship can vary from 50 to 100 ft, the exact dimensions depend on the tanker size, buoy size, water depth and environmental conditions.

Riser flowlines

One of the main purposes of the riser is to provide a flowpath between the sea floor and the surface. Very special attention was given to selecting a piping system in which all parts are reliable and together make up a reliable system. Maintenance of deepwater risers will be extremely expensive and downtime, including lost production, may run into millions of dollars a day.

For these reasons hard piping is used for riser flowlines and components throughout the system, and the hard piping is protected as much as possible. Replaceable hose segments are used for the pump down tool bypasses around the universal joints.

A submersible maintenance vehicle is being developed that can replace critical components on the riser. (A similar vehicle has already been developed and used to service the SPS³).

The flow path for fluid coming from an SPS goes through a seafloor pipe line to the base of the riser, through the pipe line connector in the pipe line porch, through piping to the fluid connector between the base and the riser (Fig. 2), and up to the first fluid swivel at the universal joint. The path then goes through an elbow in the cross and out through a fluid swivel at 90 degrees from the first swivel, up through and into the transition section just above the universal joint, and into the piping within the riser. At the top of the riser, the fluid travels through an expansion loop, then traverses the upper universal joint and enters the fluid lines within the buoy. There are various valves and expansion loops within the buoy that the fluid passes through before reaching the multilane structural/fluid connector at the mooring swivel. It then goes up and out through one of the outlets of the multilane fluid swivel at the top of the buoy. An in-line fluid swivel is used to bring the fluid around each of the hinges on the arm and, finally, it reaches the ship.

Installation

The installation procedure for the deepwater riser system relies heavily upon a drilling vessel. The reasons for choosing a drilling vessel as the principal construction platform were: (1) a drilling vessel may be on site for installation of the SPS template and to drill the wells, (2) the riser base can be transported on a barge, suspended below the vessel, and lowered into place in a manner similar to that employed in the installation of the SPS template,¹⁰ (3) the riser can be handled in segments and joined together in a manner similar to drilling risers, (4) a drilling vessel that uses air cans for buoyancy on the drilling riser will have the air compressors required to fill the production riser air cans, (5) the vessel's riser tensioners and motion-compensated derrick can be used to provide a heave-decoupled support for the riser during the riser-to-base connection, and (6) the vessel is capable of drilling and grouting the foundation piles.

Because the method of installation strongly impacts the design, the installation procedure was developed in some detail during the early stages of the design project. The following discussion briefly outlines the steps in the installation:

The base is loaded onto a barge and towed to the site. It is launched on the lee side of the drilling vessel and floats in the water while rigging lines are attached. Some of the members are then filled with water to submerge the base. Auxiliary vessels hold the base away from the drilling vessel as it swings into a position directly below the drilling vessel; the base is now suspended by the rigging lines. The base is then gradually lowered, using the vessel's winches, until it is near the bottom. The final orientation is done by the auxiliary vessels, tugging on lines attached to the outer edges of the base. Once the base is on bottom, the lines are released by acoustically operated devices and all members are flooded. The drill vessel then drills the holes, sets the piles, levels the base, and grouts the piles in place.

The lower universal joint, complete with bypass piping, is brought into position in the moonpool and the first riser section attached to it. The riser is constructed in sections about 50 ft long; these sections can be brought in through the Vee door of the derrick and handled in a manner similar to a drilling riser. Succeeding riser sections are connected one by one as the assembly is lowered into the water, much like drilling risers are now run. As the riser is run, the hook load is controlled by injecting air into the buoyancy cans. Follower riser sections between the ship and the top of the free standing riser are used to lower the riser to the base. After the connection has been made at the base and the riser flowlines have been installed, the follower sections are removed. The structural and flowline connectors at the base are tested prior to buoy installation.

The riser flowlines stand on end within the riser. Guides within the riser assist in the installation of the pipes and prevent

buckling of the flowlines under their own weight. The flowlines are assembled using threaded tool joints and are lowered into the riser just like tubing into a wellbore. The flowline connection at a point just above the lower universal joint is made remotely with a modified well-head tubing connector. After the flowlines have been installed, connections are made at the upper end to preinstalled thermal expansion loops. The riser is neutrally buoyant along most of its length, but it has sufficient additional buoyancy near the top to insure that it stands upright after the drill vessel has set it in place and prior to the installation of the buoy.

The buoy is floated out to location on its side and is upended by controlled flooding of selected internal tanks. The buoy is positioned over the riser, and pull-down cables are attached. The buoy is brought into contact with the riser by controlled flooding and pulling with constant-tension winches on auxiliary vessels. The connection is made between the riser and the buoy at a point just below the upper universal joint, using a remotely operated structural connector. Ballast water is now pumped out of all tanks except those designated as inertia/reserve buoyancy tanks.

Before the storage vessel leaves port, the rigid arm is attached, complete with all piping and the swivel stack, including the multiline fluid swivel and the electrical swivels. The end of the arm is supported on a barge or auxiliary buoyancy as the ship is towed to location. The tip of the arm is raised to a position initially higher than the top of the buoy, and it is then drawn down to the top of the buoy and connected with a combination structural/flowline connector like the one used on the SPS test riser base.³ During this operation, the ship and the riser are held in place by lines to several auxiliary vessels.

Analyses

Two basic analytical programs were used to design the riser: (1) RISDYN, a large-deflection special-purpose riser dynamic analysis program,¹⁰ and (2) RCYCLO, a fatigue analysis program. Initial sizing is based on design forces developed for the maximum design storm (usually, the 100-year storm). These forces include the wind, wave and current forces on the ship.

The initial buoyancy and configuration is selected based on that required to restrain the forces applied in a static fashion and to limit the angles and excursions to desired levels (Fig. 7). Subsequent analyses are performed using the dynamic program RISDYN to arrive at the final riser configuration and solve for stresses, angles, displacements, stress ranges, member forces and reactions.

The philosophy used in the analysis and design of the production riser system components is to treat the structure as a normal offshore design but to use conservative allowable stresses for survival loading conditions of critical items. Critical items are those which are not easily accessible or are nonredundant.

There have not been any codes written explicitly for this type of structure so the most applicable codes were selected for use in the design of each component of the riser. The codes employed in the deepwater riser design were: API RP-2A,¹¹ ANSI/AIME BPV-VIII-1,¹² AWS D1.1,¹³ DNV¹⁴ and rules of classification agencies developed for offshore loading terminals (DNV¹⁵ and ABS¹⁶).

Rigid mooring arm. The mooring arm is a tubular truss structure very similar to that of an offshore platform or pipe-laying stinger. The arm is analyzed using a standard frame analysis program along with a preprocessor that generates wave and current loadings. The sources of loading are: (a) weight and buoyancy, (b) reaction load from the buoy caused by wave, current and ship-induced motions, (c) wave and current loads on the arm, (d) motion of the arm relative to the water resulting from vessel and buoy motions. Both the wave and current load and the reaction load from the buoy depend on the orientation of the ship relative to the wave direction. Measured forces from model tests at the buoy end of the rigid arm are of the form shown in Fig. 8.

Load conditions that maximize both horizontal and vertical resultant loads on the arm must be considered, including possible locations of the arm relative to the water surface. The arm is designed in accordance with allowable stresses determined by API RP-2A.¹¹ For survival loading conditions, the allowable stresses are increased by one-third in accordance with the code.

Buoy. The buoy structure is a ring and longitudinally stiffened shell with compartments for ballast and damage control. The loading conditions imposed on the buoy include: (a) hydrostatic pressure from the static depth of submergence, tilt of the buoy, and waves and tides, and (b) bending and axial loads resulting from the mooring forces, wave and current loads, and buoy motion. The axial load and moment distribution are calculated by the program RISDYN. Because of damage conditions and ballast control requirements, each deck must be designed for the same pressure as the shell in the compartment below.

Both stress and buckling conditions are analyzed for operational and survival conditions, using ASME¹² and DNV¹⁴ rules as applicable. Transitions and special attachments are analyzed using detailed finite element analyses. For survival loading conditions, the allowable stresses in the buoy are increased by one-third.

Riser. The riser structure is a uniform pipe with mechanical connectors at intervals. Buoyancy cans are attached to the outside of the riser sections, but are designed so as not to limit the flexibility of the riser core. Such a bending limitation would cause an excess of curvature at the connectors between sections. Loads and stresses are determined directly from the RISDYN dynamic analyses. Because the riser is a nonredundant structure, the allowable stresses for the survival condition are conservatively limited to 60 percent of the yield stress.

FIG. 7—Preliminary design guidelines for riser deflections.

FIG. 8—Horizontal force components on rigid arm.

Universal joints. The universal joints are fabricated plate structures with permanently lubricated bronze bearings. Final design of the universal joints is based on a detailed finite element analysis of each component of the structure to determine its stresses and deformations. Because the thrust loading on the universal joints is carried by one flange only and because the load can be applied in any compass direction, several models are required to evaluate all loading conditions. Because the universal joints are nonredundant, the maximum stress is limited to 60 percent of the yield stress based on von Mises criteria. Deformations predicted by the analysis are used to determine required machining clearances and tolerances for the various components.

Base. The base structure is a tubular frame with several large-diameter members designed as pressure compartments to control buoyancy during installation. The primary load on the base structure is the riser reaction at the lower universal joint. In addition, loading conditions during launch and lowering of the base structure are considered. The in-place base structure is analyzed as a pile-founded truss with pile-structure interaction considered. Separate frame analyses are performed for the various conditions the structure is subjected to during launch and lowering. The large, stiffened members serve as buoyancy tanks during this time and are designed as pressure vessels. When the base structure is submerged near the surface, the large members are pressur-

FIG. 9—Static force displacement curve.

FIG. 10—Static offset/wave height curve.

FIG. 11—Ship motions/wave height curves.

ized to help offset the external pressure on the base as it is lowered. When the base structure is on the bottom, the buoyancy members are subjected to a net external force. After installation is complete, all members are flooded so the full strength of the members can be used to resist operating loads.

The design of the base structure and piles is based on API RP-2A,¹¹ ASME¹² and DNV¹⁴ rules as applicable. Allowable stresses are increased by one-third for the survival conditions. For installation considerations and the design of pressurized members, normal allowables are used without the one-third increase.

Fatigue analyses

The general procedures for a spectral fatigue analysis of offshore structures has been previously presented by Maddox and Wildenstein.¹⁵ This technique has become the accepted method for fatigue analysis of fixed offshore structures. The primary difference in applying

this method to the analysis of production riser systems is in the determination of the response operators for stress range and in the methods for inclusion of the effects of wind and wave direction.

Three basic sets of data are required for spectral fatigue analysis: stress range response operators, environmental data and S-N data. The EPR computer program RCYCLO performs the large amount of numerical manipulation required to perform the spectral analysis and cycle counting for each point analyzed.

The *stress range response operator* is determined through a combination of stress analyses and dynamic analyses of the riser system. The response operator curve is the ratio of stress range divided by wave amplitude over a range of periods.

The dynamic response of the riser system is determined using the computer program RISDYN. A series of computer analyses are run for a range of wave periods varying from small to periods larger than those which contain significant wave energy. Computer simulations have been used rather than model test data, because the cost is prohibitive to perform tests for the large number of data points required.

Because of nonlinear effects of velocity on the forcing function, it is important to select for the dynamic analyses input parameters that are representative of sea states occurring at the period being analyzed. For most sites, a constant can be determined which adequately relates significant wave height to the dominant period squared:

$$H_s = \sigma T_D^2$$

Using this relationship, wave heights are selected corresponding to the array of selected periods. This wave is input to RISDYN as a sinusoidal wave with the selected period.

The static offset of the vessel and the vessel motions must also be selected to be consistent with the period and wave amplitude. Knowing the static offset behavior shown in Fig. 9, the static offset versus wave height curve shown in Fig. 10 can be determined by calculating the equivalent static force from long-term wave drift, current and wind for various wave heights. From this figure, the static offset of the vessel can be selected for each significant wave height being considered. In addition, data such as shown in Fig. 11 is developed for the vessel bow heave and surge motions as a function of significant wave height. This data can come from either model test results or from computer simulations. For each analysis, vessel motions and phasing are selected corresponding to the assumed wave height.

The result of the series of RISDYN analyses is values of standard deviation for stresses calculated directly by the program for simple components and for values of internal forces and reaction loads within the system for each period considered. Because the input to RISDYN for the fatigue analyses is in the

form of sinusoidal motions and wave heights, the response range can be determined for each variable by multiplying the standard deviation by 2×1.41 . The response operator value for range at a given period is therefore:

$$RO = \frac{2 \times 1.41 \times STDV}{\text{Wave Amplitude}} \quad (2)$$

For points at which stress is not directly calculated by RISDYN, such as in the mooring arm, mooring hinges, mooring swivel, and universal joints, the values of stress are determined from the stress analyses as a function of characteristic loads. For example, the stress at a particular point in the mooring arm is primarily a function of the longitudinal and lateral loads applied to the end of the mooring arm as a reaction force from the buoy. Knowing these relationships, the load range response operator can be transformed into stress range response operator data. This transformation can be done after RISDYN runs have been made if the phase relationship between various characteristic loads affecting the stress can be neglected, or the calculation can be done internally within RISDYN if phasing is to be considered.

The relative angle between the wind and waves adds an additional complexity to the fatigue analysis of SALM production riser systems. When the wind direction differs from the predominant direction of the seas, the vessel and mooring arm will be oriented at an angle relative to the waves. This will result in a component of the reaction from the buoy being applied as a lateral load to the mooring arm. From the model test data, relationships can be developed, such as those illustrated in Fig. 8, which relate values of the longitudinal and lateral arm load components of the resultant buoy reaction to the relative angle between the wind and the waves. Using this data, the load range response operator for the resultant reaction at the buoy can be transformed into a series of stress range response operator curves for various relative wind angles for any point at which stress is known as a function of longitudinal and lateral loads at the end of the mooring arm. Therefore, these points will have a series of response operator curves corresponding to various relative wind angles rather than just one curve per point. Each of these response operator curves will apply for a given percent of time.

The *environmental data* required as input for the fatigue analysis program RCYCLO is the usual data which relates sea state to percent of occurrences over the life of the structure and a specified wave energy spectrum. In addition, wind rosette data and data for percent of occurrence of various wind to wave angles may be required. Local variation in wind direction with respect to the waves occurs because of the time-varying nature of wind fields. At the present time, data on relative wind to wave angles is normally not readily available. One technique for determining this data is through the use of weather simulation programs such as the one that has been

written for the Gulf of Mexico to simulate hurricane storm passage.¹⁸ It is probable that for some time, the determination of such data will be based on educated estimates by oceanographers.

The S-N data normally used to predict life of the material for various stress ranges is taken from the AWS-X curve.¹³ This curve may be modified to reflect the effect of submergence in salt water.¹⁹ This data is for the peak calculated or measured stress at the point being considered. Therefore, the stress concentration factor at the point must either be included in the original stress calculations and in the RCYCLO input data or considered in an after-the-fact evaluation of the calculated allowable stress concentration factor.

The results of RCYCLO are presented as a predicted life for the stress concentration factor assumed in the input data, as an allowable stress concentration factor which can be applied to the stress values assumed in the input data and results in the desired life, or as resulting damage ratios at various stress concentration factor levels for the selected life.

For the moderate environment cases that have been considered in detailed fatigue analyses, fatigue life does not

impose a major design problem. Predicted lives have been in the range of several times the design life of the structure. For more severe environmental conditions or for sites which have unusual wind behavior, fatigue considerations may become a significant design consideration.

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APPENDIX B

ENVIRONMENTAL DATA, VESSEL MOTIONS
AND ANALYTICAL RESULTS

APPENDIX B

A. DESIGN PARAMETERS

1. Sea States

a. Survival Conditions

Significant Waves	- 45.2 ft.
Wind	- 92.8 knots
Significant Period	- 13.0 seconds
Average Period	- 11.8 seconds
Max. Spectral	
Density Period	- 13.8 seconds

b. Operating Condition

Significant Waves	- 12.0 ft.
Wind	- 25.5 knots
Significant Period	- 7.52 seconds
Average Period	- 6.77 seconds
Max. Spectral	
Density Period	- 7.95 seconds

Note: Wind, current and waves assumed acting colinear.

2. Vessel Motion

a. Survival Condition (Double Amplitude)

Roll	65.0°
Pitch	19.5°
Yaw	10.0°
Heave	50.2 ft.
Surge	29.7 ft.
Sway	32.5 ft.

b. Operating Condition (Double Amplitude)

Roll	4.0°
Pitch	4.2°
Yaw	3.9°
Heave	5.0 ft.
Surge	2.2 ft.
Sway	4.9 ft.

3. CWP designed for 40 ft. differential static head.

4. Survival current as shown on Figure 6.1.

5. Vessel Properties

Length	620 ft.
Beam	300 ft.
Depth	85 ft.
Draft	45 ft.
Operating Displacement	310,000 L.T.
Principle Hull - Mild Steel	

6. Cold Water Pipe System

Inside Diameter	30 ft.
Material	Mild Steel
Base Connection	Pinned

B. DESIGN METHODS

1. Static and dynamic riser (CWP) analysis, Ref. R. D. Young and J. R. Fowler, "Mathematics of the Marine Riser" November 1978, unpublished.
2. Structural steel design in accordance with ASME Pressure Vessel and Boiler Code, Section VIII, 1977.
3. Design for Buckling of Cylindrical Shell in accordance with DNV "Rules for the Design, Construction and Inspection of Offshore Structures, Appendix C, Steel Structures", 1977.

C. SUMMARY OF RESULTS

1. Survival condition produced a static offset of 620 ft. with a maximum angular offset in the upper flexible joint of 10.2°. Top tension is 1,000 kips and universal joint/base tension is 6,000 kips. Current profile, CWP deflected shape and bending moments are shown on Figures 7.1, 7.2 and 7.3 respectively for the maximum load conditions.

2. The operating condition produces a static offset of 600 ft. with a maximum angular off set in the upper flexible joint of 7.2° . Top tension is 1,000 kips and bottom universal joint/base tension is 5,800 kips. Figure 7.4, 7.5 and 7.6 show current profile, deflected shape and bending moment.