MASTER

DOE/NOAA/OTEC-15(Summary)

OTEC MODULAR EXPERIMENT PLANT COLD WATER PIPE SYSTEM DESIGN STUDY

Executive Summary

December 1979

Work Performed Under Contract No. EG-77-A-29-1078

Science Applications, Inc.
El Segundo, California

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE.

**It has been reproduced from the best
available copy to permit the broadest
possible availability.**

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.

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.

Science Applications, Inc.

One Continental Plaza, Suite 310
101 Continental Boulevard
El Segundo, California 90245

OTEC MODULAR EXPERIMENT PLANT
COLD WATER PIPE SYSTEM DESIGN STUDY^{###}
EXECUTIVE SUMMARY

DECEMBER 1979

SAI-063-80R-071-LA

PREPARED FOR:

OFFICE OF OCEAN ENGINEERING
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

UNDER CONTRACT:

MO-A01-78-00-4142

ALBUQUERQUE • ANN ARBOR • ARLINGTON • BOSTON • CHICAGO • DENVER
HUNTSVILLE • LA JOLLA • LOS ANGELES • McLEAN • PALO ALTO • SANTA ANA

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1
1.1 Objectives	2
1.2 Scope	2
1.3 Performing Organizations	3
2.0 PROJECT SUMMARY	4
2.1 System Requirements	4
2.2 System Design Approach	5
2.3 Rejected Approaches	7
2.4 Recommended Approaches	8
3.0 BASELINE CWP SYSTEM DESIGN	11
3.1 Stiffened Steel Shell CWP	11
3.2 Fiberglass Sandwich CWP	19
3.3 Bottom Mounted Stiffened Steel Shell CWP	28
4.0 SUBSYSTEM DESIGN CONSIDERATIONS	39
5.0 RECOMMENDATIONS	55

1.0 INTRODUCTION

The Department of Energy has undertaken a program to demonstrate the technical and economic viability of Ocean Thermal Energy Conversion (OTEC) plants as rapidly as possible. To achieve this goal a 10/40 MWe Modular Experiment Plant (MEP) will be deployed in 1984. The NOAA Office of Ocean Engineering has responsibility for developing the MEP cold water pipe (CWP), and parallel prime contracts were awarded by NOAA to SAI and TRW to screen candidate CWP concepts and provide three baseline system designs. Puerto Rico and Brazil were the two sites selected for the study, and both a stationary spar platform and a grazing barge platform were considered.

At the outset of this study the various concepts suggested for the CWP were in different states of development; one had been through design reviews (the APL concrete pipe) while others consisted of little more than an idea (e.g., compliant walls with bottom mounted pumps). In almost all instances fabrication/construction/installation plans had not been developed; yet these processes often strongly influence system design. Cost estimates were incomplete since fully integrated designs were almost nonexistent.

The OTEC CWP is more than just a tubular structure. Subsystem components consist of flexible joints, vortex suppressors, buoyancy pods, platform interface, pump/plenum arrangement, intake, screens and (if bottom mounted) the mooring system. Also associated with the design are any fabrication, transportation/handling and maintenance equipment. All of the subsystems had to be considered in developing acceptable CWP designs.

1.1 Objectives

The OTEC Cold Water Pipe System Design Study was undertaken to evaluate the diverse CWP concepts, recommend the most viable alternatives for a 1984 deployment of the 10/40 MWe MEP, and develop selected designs. Specific objectives of the study were to prepare candidate CWP concepts for stationary and grazing mode OTEC plants along with fabrication/construction/installation plans and cost estimates. CWP designs were to be integrated with the relevant subsystems, have a thirty year design life, meet the imposed performance criteria and be cost effective. Three concepts selected by the government were then to be developed through baseline design.

1.2 Scope

In the first phase of the study a systems analysis was performed to evaluate alternative concepts. Baseline configurations were proposed, and significant engineering development was expended to bring the concepts to a sufficient design state such that technical feasibility, schedule, and cost judgments could be made rationally. Those concepts which faced overwhelming technical and/or scheduling problems were rejected. Those which were found to be unviable due to crucial technical and/or scheduling problems for which a technical development may reverse the decisions were deferred. Fabrication, construction, and installation plans were developed for successful concepts, and costs were determined in a WBS format. Evaluations were performed on the basis of technical and cost risk.

Baseline designs, along with fabrication/construction/installation plans, were developed for three concepts in the remainder of the study. Additional design requirements

assigned after the concept selection phase were incorporated into the concept development. Dynamic response of the platform/CWP systems was assessed with the Government furnished design tool referred to as the NOAA/DOE code. Fabrication techniques studies emphasized the use of existing facilities; scale up from a 30 foot diameter pipe to 100 foot diameter was briefly reviewed.

1.3 Performing Organizations

Science Applications, Inc. (SAI) was the prime contractor for the present study. In addition to managing the project, SAI established the hydrodynamic loads, developed the composite wall pipe concepts, performed the design concept selection, recommended flexible joint, inlet and vortex strumming suppressor subsystems, and developed the fiberglass sandwich CWP baseline design.

Brown and Root Development, Inc. (BRDI) was the major subcontractor to SAI. BRDI developed the steel and concrete CWP concepts, aided in the concept selection, recommended the corrosion protection subsystem design, suggested alternative bearing and seal concepts and developed two stiffened steel shell CWP baseline designs.

SAI and BRDI were assisted by several subcontractors and consultants. Hydronautics, Inc. provided computations and advice on the implementation of the NOAA/DOE code. Campenon Bernard Cetra reviewed the APL concrete CWP design and offered improvements. Structural Composites Industries, Inc. prepared fabrication/construction plans for the fiberglass sandwich CWP baseline concept and provided advice on fiberglass design. Corrosion Consulting Service Corporation prepared the corrosion protection analyses.

2.0 PROJECT SUMMARY

A twelve month study was conducted by SAI and its subcontractors for NOAA to establish baseline CWP designs for the 10/40 MEP. Results of the concept tradeoffs are documented in an interim report (SAI-063-80-R-008-LA), and the baseline designs are presented in the final report (SAI-057-79-845-LJ). Design drawings have been provided to the NOAA Office of Ocean Engineering.

2.1 System Requirements

For the purpose of this study the 10/40 MEP cold water pipe was taken to be 3280 feet long with a thirty foot internal diameter. The cold water flow rate was 6.5 ft/sec, and the water temperature rise was restricted to less than 1°F. Head losses were estimated to be 15 percent of the plant output.

A design lifetime of thirty years was required. The environmental specifications derived from the "OTEC Demonstration Plant Environmental package" included a Sea State 5 operating condition (12 foot significant waves) and a severe storm survival condition (36 foot significant waves at Puerto Rico and 29 foot significant waves at Brazil). For the stationary plant at Puerto Rico an operating current profile with a 2.0 fps surface current was specified, and for the grazing plant a uniform imposed current of 1.6 fps was employed. Severe storm currents had surface velocities on the order of 5 fps.

For the baseline designs additional system requirements were to be satisfied:

- Define failsafe devices and procedures for recovery of the pipe or section of the pipe lost during deployment.

- detach for routine maintenance in benign seas.
- remain attached during hurricanes.
- consider detaching the CWP and stationing it near the platform in 20 ft. significant wave height conditions.

2.2 System Design Approach

Proposed CWP concepts were analyzed to determine if they met system requirements for technical feasibility, performance (delivering cold water), availability, and deployment schedule (Figure 1). Uncertainties and design issues were identified and addressed through design studies until the system concept was judged to meet the system requirements on a best estimate basis. In any conceptual design there remain uncertainties if only because of lack of experience with similar systems or lack of appropriate test data. Given that the nominal design meets the system requirements, it is the technical and cost uncertainties that are assessed in the evaluation process to provide rational comparison of alternative concepts.

In addition to crosssection configuration, the methods of fabrication, construction, installation, and maintenance were included (Figure 2). Configurations cannot be sized just for the operating loads. In some instances fabrication or installation loads can exceed the operating loads, and fatigue life may be greatly affected by installation procedures. Subsystems interact with the configuration in terms of loads induced on each other and the interfaces required. Maintenance is another key item in designing and costing a cold water pipe. Thus, concept synthesis required consideration of all phases of the design process.

Figure 1. Conceptual Design Approach

Figure 2. Concept Definition Process

2.3 Rejected Approaches

Major decisions need to be made early in conceptual design studies to avoid expending resources on design approaches which cannot satisfy program technical or schedule goals. That is, certain approaches may be rejected due to construction difficulties, deployment difficulties, availability of material or fabrication facilities within schedule constraints, or engineering judgment as to the performance and survivability of the system. Such judgments are not lightly made as they allow the possibility of excluding an attractive approach. However, they are necessary for the program to move forward.

Multiple pipes were rejected because of the increased pumping power required to overcome frictional losses, and the difficulty in securing a bundle of pipes in a dynamic environment. Slip forming concrete pipes at sea was rejected because the long time required for production leads to exposure to severe environments coupled with the fact that operations at sea are more difficult and expensive than operations on shore. Stockade pipes were rejected because of the difficulties of construction and the potential for leakage and corrosion. Alternatives to the APL lightweight concrete pipe with bayonet joints were explored but none proved satisfactory.

Mounting the pumps at the CWP bottom would reduce CWP structural requirements by providing a positive internal pressure. However, this concept was deferred until such time as pump reliability and maintenance can be established for pumps of the required size operating at 3500 foot depths.

2.4 Recommended Approaches

Ten baseline concepts which appeared feasible were developed in the first phase of the design study (Table 1). The concepts were categorized in terms of rigid walls, compliant walls, and bottom-mounted designs as required by the contract. Each design was further defined in terms of the material most predominantly used in the design, the deployment mode, screen, mooring (if any) and bearings. Each of these concepts were developed to the point where rational decisions could be made regarding their relative merit.

Candidate CWP concepts were evaluated within the categories specified, and then the top two candidates from each category were evaluated together. Rigid wall concepts recommended were a stiffened steel shell design and a fiberglass corrugated wall design; compliant wall recommended candidates were of polyethelene and elastomer construction. Two bottom mounted approaches were suggested--slack moored and taut moored.

Three individual criteria were most important in ranking the remaining CWP concepts. These were schedule, technical feasibility, and cost. Concept rankings were performed on the basis of probability of meeting a 1984 deployment date, probability of meeting the DOE risk criteria number 5, and probability of meeting an acquisition cost of \$50M. A risk factor of 5 was selected as necessary for a prudent investment of research and development funds to return payoff in the specified period. An acquisition cost of \$50M was selected as an average of the cost ranges presented. It is noted that the bottom mounted designs incorporate the mooring function for the platform, and thus future cost criteria should include this aspect.

Table 1. Baseline Concept Alternatives

CATEGORY	RIGID					COMPLIANT			BOTTOM MOUNTED BUOYANT	
	Steel	Steel	Concrete	Fiber Glass	Fiber Glass	Elasto-mer	Fabric	Plastic	Steel	FRP
Material										
Deployment Mode	V	V	V	H	H	V	V	H	V	H
Screens	1	1	1	1	1	1	1	1	1	1
Mooring									1	2
Bearings	1	1	2	3	3	-	-	3	4	3

H = Horizontal; V = Vertical; Numbers indicate different design approaches

Most concepts had little trouble meeting a four year deployment period. In the category of technical risk the preferred candidate is the stiffened steel shell concept based on the historical experience with steel in offshore structures. With regard to cost the polyethelene concept proved least expensive by a substantial margin.

As a method of combining the evaluation criteria, a final ranking of these initial ten baselines was performed on the basis of the probability of meeting the technical feasibility requirement and not exceeding a \$50M acquisition cost. The combined ranking was accomplished by multiplying the respective probabilities since the criteria are independent. This final ranking of baseline concepts indicated that the stiffened steel shell concept was preferred, followed by the corrugated fiberglass, polyethelene, bottom mounted-slack elastomer, and bottom mounted-taut. Again, the mooring cost contributed to this ranking.

3.0 BASELINE CWP SYSTEM DESIGNS

Three CWP concepts were selected by the Government for further baseline development. Direction was given to proceed with a stiffened steel shell concept (formerly called shell and tee) for attachment to the APL barge off Brazil, a fiberglass reinforced plastic sandwich concept for attachment to the APL barge off Puerto Rico and a bottom mounted concept for attachment to the Gibbs and Cox spar located off Puerto Rico. The final phase of the CWP System Design Study sought to bring the selected concepts to an improved level of development. In that regard significant design evolutions occurred both through design innovations and due to the additional design requirements levied after the conceptual design phase. Notable features of the baseline designs are presented here including a description of the CWP design, the fabrication/construction/installation process, schedule through deployment, and estimated costs in the DOE W.B.S. format.

3.1 Stiffened Steel Shell Design

Due to the extensive offshore experience with steel, this material was an obvious candidate for the CWP. Since steel is corrosive in seawater, a corrosion protection system is included in the design. Steel structures have existed for over thirty years in the ocean, so there is ample design experience. Early design studies had indicated a requirement for extremely heavy steel pipes if a monolithic wall was employed. However, during the conceptual design phase the elements of a stiffened thin shell with flexible joints were defined and the advantages shown.

3.1.1 Design Description

The stiffened steel shell CWP design for the APL barge is a five segmented pipe connected by compression block bearing flexible joints (Figure 3). The basic cross section is a half inch thick A36 steel shell with 13.5 inch bulbflat longitudinal stiffeners and T section ring stiffeners cut from S24 x 105.9 tees. A buoyancy pod attached to the exterior of the upper segment of the pipe is used as a work platform during deployment and provides a flotation capability for CWP disconnect. The total weight of the CWP is 14,250 kips.

Disconnection for routine maintenance or repair was a requirement for the baseline designs. Some consideration was given to emergency disconnect for severe storm conditions, but specific systems were not developed. Detachment will be achieved with the use of hydraulically actuated shoes that lock the CWP into a conical-shaped opening inside the bottom of the platform hull; twelve shoes utilize eight-inch hydraulic cylinders to provide a locking force capable of handling 5000 tons.

Disconnection procedures initiate by ballasting the platform to release the load on the shoes. The shoes are withdrawn and the platform deballasted. As the platform moves off the CWP a buoy attached to the CWP by a heavy length of wire rope is released providing a surface attachment point. Reattachment is accomplished by releasing a "lead-in" buoy out of the platform moon-pool. A light wire rope connects this buoy to a winching system inside the platform. The surface connection is made, and the buoys are pulled back inside the platform thus positioning the platform over the CWP. Finally, the platform is ballasted, and the shoes are locked into place terminating the reattachment procedure.

FIGURE 3. Stiffened Steel Shell

The stiffened steel shell design procedure was based on AISC and DNV recommendations. Buckling stability checks included bending, torsion, shear, external pressure and axial tension. Buckling modes considered were buckling of the shell wall, buckling of the stiffened wall and local stiffener buckling. Dynamic response of the CWP was dictated by minimum critical length segments designed to cause the pipe motions to decay with depth and not be in resonance within the wave energy spectrum. The maximum survival stress due to combined bending, shear and tension was 22,000 psi. Operating stresses due to waves and currents (vortex shedding) were low such that a CWP wall fatigue life well in excess of 30 years was assured. Bearing performance will likely dictate system life.

3.1.2 Fabrication/Construction/Installation

The scenario developed for the stiffened steel shell is to fabricate 100 foot long CWP segments in a Gulf Coast fabrication yard and barge the segments to the mid-Atlantic for installation off the coast of Brazil. All material is readily available from a variety of suppliers (although lead times of a year are not uncommon), and several Gulf coast fabrication yards are already adequately developed.

Fabrication of the CWP will proceed as outlined in Figure 4. Steel plate segments will be rolled to form a circle prior to the installation of ring stiffeners. The vertical seams will be welded with upwelding equipment, and the structural tees will be welded to the shell exterior by semi-automatic welding equipment. Two stiffened courses will be stacked and the radial seam welded with a 3 o'clock sub-arc-welder to form a 20-foot segment. This piece will then be upended and transported to horizontal rollers where a total

Figure 4

REVISION NO. 1 DATE 10/1/79 BY J. W. KENN CHECKED BY J. W. KENN DATE 10/1/79 BY J. W. KENN	APPROVED J. W. KENN DATE 10/1/79 BY J. W. KENN	TITLE OF DRAWING FABRICATION METHOD FOR 100-FOOT FIELD JOINTS-SCALLOPED QTEC-COLD WATER PIPE DEPARTMENT OF ENERGY UNITED STATES OF AMERICA	CONTRACT NO. ER-0925 DRAWING NO.
---	---	--	--

Brown & Root, Inc.

HOUSTON, TEXAS

of five pieces will be joined to form a 100-foot CWP segment. External welding will be performed by sub-arc-welders on a boom, while the interior welds are accomplished by a tractor-mounted sub-arc-welder. Longitudinal stiffeners in the form of bulb flats (or bulb plates) are then inserted on the exterior and welded to the shell with tractor-mounted sub-arc-welders. Anodes are installed as required. The 100 foot CWP segments are then loaded onto a transporter and moved to storage. CWP sections will be transported to the Brazil site by barge; a 250' x 75' x 16' barge can accommodate four 100 foot sections.

The stiffened steel shell CWP deployment procedure is illustrated in Figure 5. Since the buoyancy tanks required for CWP detachment could not be deployed through the APL barge moonpool, it was decided to use the buoyancy tanks as a work platform. A crane from the barge will be used to upend the buoyancy tanks and install the jacking frame. Individual CWP sections will be lowered into place and swarm welded to the previous sections. When the final pipe section and the interface joint are in place, the buoyancy tanks will be partially flooded and the CWP keel hauled for attachment. After all connections are made the ballast tanks will be flooded for operation. CWP detach/reattach and CWP recovery will use the same procedures.

3.1.3 Schedule

Starting with the present baseline design, a period of 31 months will be required to complete and install the CWP (Figure 6). This includes a two year final design period covering detailed engineering design and certain development tests. Model tests will be required as will the development

Figure 5

Brown & Root, Inc.

HOUSTON, TEXAS

DATE OF DESIGN: 11
DATE OF CONSTRUCTION: 11
DATE OF COMPLETION: 11
SCALE: 1/4" = 1'-0"

APPROVED

APPROVED

STIFFENED STEEL SHELL-CWP INSTALLATION PROCESS, OTEC-COLD WATER PIPE
DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

CONTRACT NO. ER-092
DRAWING NO. S-847-2
SHEET 1 OF 1

Figure 6. Stiffened Steel Shell CWP Schedule

and large scale testing of flexible bearings and seals. Fabrication and segment construction will take about seven months while installation can be accomplished in two months.

3.1.4 Cost

Nominal cost estimates (in constant 1978 dollars) for the elements of the DOE work breakdown structure (WBS) applicable to the CWP are presented in Table 2. WBS element 1.0, 2.0 and 4.0 costs were based on a one year contract design period, a one year final design period, and a 30 year lifetime. Model tests were included in the contract design costs, but large scale tests were not. Acquisition costs are \$61.9M, and the life cycle costs are \$107.1M.

3.2 Fiberglass Sandwich Design

Fiberglass composite wall CWP structures have been recommended since the earliest NSF sponsored OTEC system studies because of their high strength to weight ratio, their ability to achieve tailored material properties and their lack of corrosion or electrochemical interaction with other system components. Although composite structures have met some resistance for offshore application, technical and cost advantages make the FRP sandwich design extremely attractive. The pipe can be installed in a single section, and a single set of equipment and procedures is used to deploy the CWP, maintain the bearing in air, perform detachment/reattachment, secure the CWP for hurricane survival and recover the CWP.

3.2.1 Design Description

The FRP sandwich concept is composed of inner and outer FRP skins of constant thickness ($\frac{1}{2}$ inch) and a neutrally buoyant syntactic foam core (Figure 7). The ceramic microsphere

Table 2. Stiffened Steel Shell CWP Cost (\$M)

WBS Number	Title	Element Cost	Total
1.0	GENERAL MANAGEMENT		
1.1	Design	0.6	
1.2	Acquisition/Deployment	1.3	3.0
1.3	Operation	1.1	
2.0	CONTRACT DESIGN	3.4	3.4
3.0	ACQUISITION/CONSTRUCTION/DEPLOYMENT		
3.3	Cold Water Pipe System		
3.3.1	Pipe System	24.3	
3.3.2	Screen	3.8	
3.3.3	CWP/Hull Transition	1.2	56.6
3.3.4	Bio/Corrosion Control	3.0	
3.3.5	Mooring/Flotation	3.0	
3.8	Acceptance Testing	1.1	
3.9	Deployment	13.7	
3.10	Facilities	3.1	
3.11	Engineering/Detail Design	3.0	
4.0	SYSTEMS OPERATION		
4.1	Offshore	28.3	
4.2	Onshore	0.1	
4.3	Test	2.5	44.1
4.4	Refit/Mod	8.2	
4.5	Disposal	5.0	
			107.1

PRINCIPLE COMPOSITE CHARACTERISTICS

E_{WALL} : 2.41E+05
 E_{CORE} : 5.1E+05
 E_{CORE} : 1.5E+05
 ρ_{CORE} : 64.4 lb/ft³
 ρ_{WALL} : 129 lb/ft³
 ρ_{WALL} : .35
 ρ_{WALL} : .12
 ρ_{CORE} : 70.65 lb/ft³
 ρ_{SPECS} : 37.4 lb/ft³
 PIPE WEIGHT:
 AIR : 8.4X10⁻⁶ LBS.
 SEA WATER : 1.71X10⁻⁶ LBS.
 ULTIMATE TENSILE STG.
 AXIAL : 12000 PSI
 HOOP : 31000 PSI

PRINCIPLE DESIGN PROPERTIES

LENGTH	AVERAGE AXIAL PROPERTIES			AVERAGE HOOP PROPERTIES			AVERAGE BENDING STIFFNESS		
	AS WALL	AS CORE	SHORE A	ES WALL	ES CORE	SHORE A	ES WALL	ES CORE	COMPOSITE ES
0-500	2.3X10 ⁹	2.7X10 ⁹	5.1X10 ⁹	3.7X10 ⁹	4.75X10 ⁹	4.75X10 ⁹	3.7X10 ¹³	4.44X10 ¹³	8.1X10 ¹³
500-2000	2.3X10 ⁹	1.95X10 ⁹	4.25X10 ⁹	2.4X10 ⁹	1.81X10 ⁹	2.18X10 ⁹	3.7X10 ¹³	3.2X10 ¹³	6.9X10 ¹³
2000-3280	2.3X10 ⁹	1.5X10 ⁹	3.8X10 ⁹	1.51X10 ⁹	1.16X10 ⁹	1.42X10 ⁹	3.7X10 ¹³	2.5X10 ¹³	6.2X10 ¹³

ITEM NO.	PART NO.	NEXT ASSY.	USED ON	APPLICATION
PREPARED BY: C. GUARD CHECKED BY: [] APPROVED BY: [] DATE: 11/9/79 TITLE: CONCEPTUAL ARRANGEMENT OF 30 FT. DIA. GLASS REINFORCED PLASTIC CWP SCALE: NONE SHEET: 1 OF 1				

and polyester resin core thickness is tapered from 5 inches at the top to $1\frac{1}{2}$ inches at the bottom to accommodate the hydrodynamic load distribution. Because the skins are denser than seawater, the CWP has a net weight in water (1.7×10^6 lbs) sufficient to maintain the pipe at an acceptable angle from the vertical. No bottom weight is required.

A single spherical bearing connects the CWP to the platform, so long term performance of multiple flexible joints is not an issue. State of the art design practice suggests a bearing life of more than 30 years. However, the bearing is supported by a platform mounted on a jacking system which can raise the bearing and CWP to the main deck for maintenance, if required. The spherical bearing also performs the sealing function, so the installation, inspection and maintenance of exterior seals is avoided.

A survival mode has been developed which minimizes the platform and wave induced bending stresses during severe storms (Figure 8). The CWP is capped, the upper 34 feet pressurized with air at 26.5 psig and the CWP lowered 236 feet below the platform on a constant tension (300 kips) wire rope attached to the bridge crane. Suspending the CWP below the platform reduces the angular motion of the tension line, and pressurizing the top of the CWP reduces the magnitude of the tension. Taken together these two effects minimize platform surge and sway inputs to the CWP. The procedure of rigging the CWP for survival can be performed in significant wave heights in excess of 12 feet and should take about four hours. Based on the environmental data package, this procedure will not unduly affect system availability.

1. WITH CWP SUPPORTED BY SPHERICAL BEG, PRESS 3\"/>

2. SECURE PRESSURE CAP, ATTACH HANDLING RING, OPEN SEAWATER VALVE, INFLATE PLUG TO 2 PSIG.

3. LOWER END OF PIPE USING SPHERICAL BEG TO OPERATING POSITION 36' ABL.

4. COMMENCE FILLING WITH BRACKISH WATER ($\gamma = 63.24 \text{ lb/ft}^3$) UNTIL PIPE HEIGHT IN WATER $\sim 300 \text{ KIPS}$. AT THIS POINT PIPE ANGLE SHOULD BE $\sim 6.7^\circ$ FROM VERTICAL AND LENGTH OF REMAINING S.W. COLUMN 575'.

1. ATTACH TAG LINE FROM BODY TO SERVICE TUG.
2. TAKE UP PIPE WEIGHT ON DEPLOYMENT WINCH.
3. CLOSE SEA WATER VALVE.
4. RELEASE LATCH RING & LOWER AWAY UNTIL CLEAR OF MOONPOOL.
5. RESUME PUMPING & OPEN S.W. VALVE.
6. CONTINUE PUMPING UNTIL PIPE ANGLE $6 \sim 40^\circ$.
7. TAKE UP TENSION ON AUXILIARY WINCH, SLOWLY SLACK LINE FROM DEPLOYMENT WINCH.
8. PIPE IS FULLY SUPPORTED BY AUXILIARY WINCH.
9. CONTINUE PUMPING UNTIL PIPE REACHES SURFACE.
10. DISCONNECT LINES & RIG FOR TUNING.

NOTES

- (1) SCREEN NEUTRALLY BUOYANT
- (2) PIPE WT. IN S.W. $\sim 1.71 \times 10^6 \text{ LBS}$
- (3) ALLOWABLE MOMENT $\sim 2 \times 10^6 \text{ FT LBS}$
- (4) DEPLOYMENT PROCESS IS REVERSE OF RECOVERY PROCEDURE SHOWN

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES ARE		CONTRACT NUMBER		DATE	
DECIMALS	ANGLES	PREPARED	DATE	TITLE	
1/16	1/2	6.6.1	11-10-79	CWP RECOVERY/DEPLOYMENT ARRANGEMENT	
MATERIAL		APPROVED			
FINISH		QA			
		REL			
SCALE: ACP/E		CODE IDENT NO.		DWG. NO.	
		E		SAI-111979-005	
		SHEET		OF	

OFFSHORE TECHNOLOGY DIV.
A DIVISION OF SCIENCE APPLICATIONS, INC.

3.2.2 Fabrication/Construction/Installation

The scenario developed for the FRP Sandwich CWP is to fabricate the entire pipe in a single section at a shore based facility and float the CWP to the nearby OTEC site for upending and connection to the platform.. There is ample precedent for custom fabrication of continuous FRP structures although not at this scale. All materials are readily available, and numerous fabricators have indicated a capability to transport fabrication equipment to the site.

The pipe fabrication begins with the fiberglass inner skin wound onto a 30 foot diameter stationary mandrel by a circumferentially rotating ring containing spools of uncured composite tape. The tape has an appropriate biaxial distribution of fibers impregnated with resin, and overlapping the edges of the tape by fifty percent produces a 100 percent strength continuous structure in a greatly simplified operation. Prefabricated strips of core will be applied in the same manner. Finally, the outer skin will be wound over the core under tension, and the entire composite section cured by heating.

Each segment of the CWP is partially ejected leaving the 15 foot tapered splice area on the mandrel. The winding equipment starts the inner skin at the previous termination continuing to the end of the exposed mandrel. Successive increments of inner skin, core and outer skin complete the segment. Staggering the individual layer terminations in this tapered fashion develops the full strength of the joint. As multiple pipe sections are added, the upper end of the CWP is ejected over a pneumatic conveyor into a flotation channel (Figure 9) where the CWP is stored prior to deployment. The upper end of the CWP will be fitted with a transition ring and a pressure cap to be used for flotation, towing, rigging for severe storms and CWP recovery.

Figure 9. Fabrication Facility

The CWP towout procedure begins by towing the airfilled CWP out of the flotation channel to a shallow location where it is filled with a brackish water mixture sufficient to float the CWP awash. Since the air/sea interface transition is the most difficult, it is accomplished in protected shallow waters where recovery is simplified. Towing awash removes the wind loads on the pipe. A single tug will provide the primary towing power with a standby tug connected to the CWP towing fixture by a slack line ready to take over in case of failure. Towing to the site should be accomplished in as benign seas as possible with the CWP heading into the seas. However, dynamic analyses indicate the requirements are not severe as 50 degree headings can be accommodated in 10 foot waves.

When the CWP arrives at the operating site, the upper end of the CWP will be headed against the current which will keep the CWP away from the platform. Brackish water is pumped out of the top of the CWP to initiate deployment, and the pipe begins to upend. CWP rotation is resisted by the ambient current depending on the length of the pipe flooded with seawater. The deployment process can be reversed at any stage, and in fact, the recovery process is just the reverse of deployment (Figure 10).

It is noted that once deployment is initiated the seawater density difference creates positive pressure at the top of the pipe, and deployment angle can be controlled by a valve. The graph in Figure 10 shows the bending moments for a quasi-steady deployment; the corresponding bending stresses are approximately 500 psi. If the CWP is allowed to rotate downward at a few feet per minute, the parabolically distributed drag force decreases the bending stresses.

3.2.3 Schedule

The FRP sandwich CWP can be designed and deployed in less than four years (Figure 11). Included are two years for contract and final design. Facility development near the operational site would require eighteen months to establish, and long lead items need to be ordered early. One year is estimated to fabricate the CWP.

3.2.4 Cost

Nominal cost estimates (in constant 1978 dollars) for the elements of the DOE WBS applicable to the CWP are presented in Table 3. WBS elements 1.0, 2.0 and 4.0 costs were based on a one year contract design period, a one year final design period and a 30 year lifetime. Model tests were included in the contract design costs but large scale tests were not. Acquisition costs are \$26.4M, and the life cycle costs are estimated to be \$45.4M.

3.3 Bottom Mounted Stiffened Steel Shell CWP

As an alternative to the CWP hanging freely from the surface plantship, a bottom mounted design is under consideration for application near shore. This allows the CWP to perform both the cold water transport function as well as the plant mooring function thus providing potentially large cost savings. The present study developed a stiffened steel shell CWP for the Gibbs and Cox spar located in 4000 feet of water off Puerto Rico. The ocean bottom was specified as sandy silt with a thirty degree slope.

3.3.1 Design Description

The bottom mounted CWP design is a six segment pipe connected by compression block bearing flexible joints (Figure 12).

Figure 11. FRP Sandwich CWP Schedule

Table 3. CWP FRP Cost (\$M)

WBS Number	Title	Element	Total \$
1.0	GENERAL MANAGEMENT		
1.1	Design	.6	
1.2	Acquisition/Deployment	1.3	3.
1.3	Operation	1.1	
2.0	CONTRACT DESIGN	3.4	3.4
3.0	ACQUISITION/CONSTRUCTION/ DEPLOYMENT		
3.3	CWP System		
3.3.1	Pipe System	7.92	
3.3.2	Screen	.6	
3.3.3	CWP/Hull Transition	2.5	
3.3.4	Bio/Corrosion Control	.5	
3.3.5	Mooring/Flotation	N/A	
3.8	Acceptance Testing	.44	21.1
3.9	Deployment	1.3	
3.10	Facilities	4.8	
3.11	Engineering/Detail Design	3.0	
4.0	SYSTEM OPERATION		
4.1	Offshore	8.	
4.2	Onshore	.1	
4.3	Test	2.5	17.9
4.4	Refit/Mod	6.8	
4.5	Disposal	.5	
			45.4

Figure 12. Bottom-Mounted CWP Design

The basic crosssection is the same as the stiffened steel shell concept described in Section 3.1, but tension legs have been added to tie the pipe bottom to piles driven into the sea floor. Piles were selected over a deadweight anchor to prevent slipping down the slope in earthquakes or severe storms. The eight tension legs are 24 inch diameter API-5LX or ASTM A-618 steel pipes with a one inch wall. Buoyancy tanks and the spar provide the necessary buoyancy to keep the CWP in tension (5000 kip design value). The net pipe weight in water is approximately 16,000 kips.

The template consists of guides for the piling, sleeves for the tension legs and bracing (Figure 13). It is estimated that seventeen piles of 24 inch diameter, one inch wall A36 pipe drilled and grouted to a depth of 200 feet will be adequate. If further soils data indicate less favorable conditions, the number of piles may be extended easily to twenty-nine.

Dynamic analyses of the bottom mounted CWP design were far more difficult than for the hanging pipes because of problems with the NOAA/DOE code. Continuing efforts finally produced a working code which demonstrated that the six segment pipe could survive the Puerto Rico severe storm conditions. Although a complete fatigue analysis was not performed, it is believed by analogy to the previous stiffened steel shell design that the operating stresses in the CWP wall will be very low. Again, the CWP system lifetime will probably be dictated by bearing performance.

3.3.2 Fabrication/Construction/Installation

The scenario developed for the bottom mounted stiffened steel shell design is quite similar to that for the previous steel design with the addition of the tension legs and

Figure 13. 17 Pile Template

template. All materials are readily available, and several Gulf coast facilities are available.

Fabrication of the pipe sections will proceed as for the hanging steel CWP (Figure 4). Tension leg sections will be fabricated horizontally by welding spacer retainer plates to the 24 inch pipes making up the crosssection. Similar sections are welded to each other to form 100 foot sections for barge delivery.

The installation process for the bottom mounted concept is illustrated in Figure 14. Before the CWP and tension leg sections are brought to the construction site, a subsea template is installed on the sea floor using a derrick barge. Depending on the soil, the piles may be driven by a pile driver or (more probably) drilled and grouted in place by a drill ship. This exact type of installation has never been performed at this water depth and will require development. Subsea templates have been placed in shallower water, and drilling has been done in deeper water.

The template connecting joint will be attached to the first 100-foot section of the tension legs which will be stabbed through (or keel hauled into) the jacking frame in the buoyancy tank work platform. Locking pins in the buoyancy-pod-work-platform will secure the position of the tension leg section. The jacks are then lowered to a resting position on the lower locking pins, the next section is stabbed through the jacking frame, the upper locking pins are affixed, the sections are aligned and the joint is welded. This procedure continues until the full length of the tension leg is deployed. The inlet screen and the CWP sections follow in a similar manner.

When the CWP assembly is complete, the jacking frame and work platform are removed from the buoyancy tanks, and

Figure 14

PREPARED BY DATE CHECKED BY DATE SCALE		REVIEWED BY DATE APPROVED DATE SCALE		TITLE OF DRAWING BMB SWP INSTALLATION PROCESS DTIC-COLD WATER PIPE DEPARTMENT OF COMMERCE OFFICE OF NAVAL ARCHITECTURE UNITED STATES OF AMERICA		CONTRACT NO. ER-0825 DRAWING NO. S-847-116 SHEET 1 OF 1	
--	--	--	--	--	--	---	--

Brown & Root, Inc.

HOUSTON, TEXAS

the tanks are partially flooded. The CWP is then attached to the spar by keelhauling. To complete the connection to the subsea template, the spar and the buoyancy tanks are deballasted and the tension legs guided into the template sleeves by a guide wire and guide slots on the mating cone. When the tension legs are in position the final connection is made by explosive forming (e.g., Brown and Root Jet Lock) or hydraulically accuated pins.

3.3.3 Schedule

Starting with the present baseline design just over three years will be required to complete the install the CWP and template (Figure 15). This includes a two year final design period along with 21 months of development tests (including methods for placing the piles). Fabrication and construction will take about one year, and final installation will require 2½ months.

2.2.3 Cost

Nominal cost estimates (in constant 1978 dollars) for the elements of the DOE work breakdown structure applicable to the CWP are presented in Table 4. WBS elements 1.0, 2.0 and 4.0 were based on a one year contract design period, a one year final design period and a thirty year life. Acquisition costs were \$74.1M, and the life cycle costs were \$133.2M.

ITEM \ SCHEDULE	YEARS FROM PRELIMINARY DESIGN				
	1	2	3	4	5
FINAL DESIGN		2 YRS			
DEVELOPMENT TESTS		21 MONS.			
LONG LEAD ITEMS		1½ YRS			
FABRICATION		173 DAYS			
CONSTRUCTION			173 DAYS		
INSTALLATION			77 DAYS		
ACCEPTANCE				45 DAYS	

Figure 15. Bottom-Mounted Stiffened Steel Shell
CWP Schedule

Table 4. Bottom Mounted CWP Cost (\$M)

WBS Number	Title	Element Cost	Total
1.0	GENERAL MANAGEMENT		
1.1	Design	0.6	
1.2	Acquisition/Deployment	1.3	3.0
1.3	Operation	1.1	
2.0	CONTRACT DESIGN	4.0	4.0
3.0	ACQUISITION/CONSTRUCTION/DEPLOYMENT		
3.3	Cold Water Pipe System		
3.3.1	Pipe System	28.6	
3.3.2	Screen	1.8	
3.3.3	CWP/Hull Transition	1.2	68.2
3.3.4	Bio/Corrosion Control	3.5	
3.3.5	Mooring/Flotation	4.5	
3.8	Acceptance Testing	1.2	
3.9	Deployment	20.9	
3.10	Facilities	3.5	
3.11	Engineering/Detail Design	3.0	
4.0	SYSTEMS OPERATION		
4.1	Offshore	37.2	
4.2	Onshore	0.1	
4.3	Test	2.5	59.0
4.4	Refit/Mod	9.2	
4.5	Disposal	10.0	
			133.2

4.0 SUBSYSTEM DESIGN CONSIDERATIONS

Although components of the OTEC plant must be integrated into a single configuration, various subsystems are somewhat independent of CWP design. Included here are summaries of brief studies of flexible joints, inlets, plenum arrangements, corrosion protection and vortex suppressors. For each subsystem, preliminary designs have been outlined, but significant engineering development remains to be performed.

4.1 Flexible Joints

Generally all CWP designs require at least one flexible joint. A two degree of freedom rotational bearing at the platform interface most effectively reduces the platform input roll and pitch motions which tend to bend the CWP. Platform input sway and surge motion effects are reduced by adding additional flexible joints further down the CWP. In addition, the joints are required to seal the articulation from the admission of exterior water which will degrade the thermal resource. Separating these two functions allows wider options to be considered (Tables 5 and 6).

Based on its low cost and still high reliability, the compression block is recommended as the favored two dimensional joint concept (Figure 16). The crossed cylinders should be eliminated from further detailed consideration. Because of its potential for reducing input sway and possible maintainability when used at the platform interface, the hyperbolic cable joint is recommended for further design study.

The elastomeric bellows seal has a lower cost than the other options because of the simplicity of its interfacing requirements. In addition, the bellows provides high sealing capability and can be designed to not adversely contribute to

Table 5. Joint Design Comments

Criterion	Compression Block	Classical Cross Universal Joint	External Hyperbolic	Internal Hyperbolic
1. Manufacturability/fabricability	Readily fabricable in conventional materials scale not excessive.	Readily fabricable in conventional materials scale not excessive.	Readily fabricable in conventional materials scale not excessive.	Readily fabricable in conventional materials scale not excessive.
2. Compatibility/integrability	Interfaces with heavy ring which readily interfaces with all seals. Minimal flow obstruction.	Interface is the same as compression block. Significant flow obstruction.	Interfaces with ring, load can be distributed very uniformly, reducing load concentrations. Compatible with bellows seals, however imposes a shear requirement. No flow obstruction.	Interface is the same as compression block. Does not significantly obstruct flow. Compatible with bellows seal and imposes shear requirement.
3. Functional Performance				
3.1. Operational	Can be designed for articulations up to 25° . Bearing loads can be made small by increasing size--low PV. Can be deployed as a pipe section when vertically deployed, requires keeper for horizontal tow.	Large articulation possible. Small bearing loads. Deployed as a pipe section vertically. No problem in horizontal tow.	Not desirable for joints other than platform interface because of sway. Compatible with either vertical or horizontal deployment.	Not desirable for joints other than platform interface because of sway. Compatible with either vertical or horizontal deployment.
3.2. Reliability	Highly reliable.	May be more reliable than compression block because of built-in redundancy. Lift-off possibly eliminated.	Reliability depends on abrasion and bending at anchor points, and degradation of cable material which may be nylon.	Reliability depends on abrasion and bending at anchor points, and degradation of cable material which may be nylon. Cables are subject to abrasion by rubbing.
3.3. Maintainability/Repairability	Not repairable unless recovered.	Not repairable unless recovered.	Cables can be replaced, especially when used at platform in interface.	Cables can be replaced, especially when used at platform in interface.
4. Cost	$\$.5 \cdot 10^6$ for 10^7 lb capacity joint	$\$2 \cdot 10^6$ for 10^7 lb capacity joint	$\$.5 \cdot 10^6 - \$1 \cdot 10^7$ lb capacity joint	$\$.5 \cdot 10^6 - \$1 \cdot 10^6$ for 10^7 lb capacity joint

Table 6. Seal Design Concepts

Criterion	Bellows Seal	Lip Seal	Draped Seal
1. Manufacturability/ fabricability	Fabricable with conventional elastomers and fabrication techniques	Fabricable using conventional elastomers and fabrication techniques	Fabricable using conventional elastomers and fabrication techniques
2. Compatibility/ Integrability	Compatible with all joints. Little or no adverse effects on flow.	Incompatible with external hyperbolic, requires hemisphere and internal elastomer cylinder for flow continuity. Increased outer diameter increases requirements on pipe handling during vertical deployment.	Incompatible with external hyperbolic, requires hemisphere and internal elastomer cylinder for flow continuity.
3. Functional Performance			
3.1 Operational	High sealing capability feasible	May leak at low wear rates	High sealing capability feasible
3.2 Reliability	Highly reliable owing to elastomer experience	Could be reliable if leaky. May be adversely effected by fouling.	Subject to shear through differential rolling motion, may accumulate debris. High reliability possible.
3.3 Maintainability/ Repairability	Would require recovery of pipe. Most feasible at platform interface. Could be raised above pipe support point w/o increasing latch plate diameter requirements.	May be maintainable or replaceable.	Debris can be blown out of recess area. Would require recovery of pipe to replace
4. Cost.	$\$1 \times 10^6 - .25 \times 10^6$	$\$.2 \times 10^6 - .4 \times 10^6$	$\$.2 \times 10^6 - .4 \times 10^6$

Figure 16. Compression Block Articulation (10^7 lb Design Load)

flow losses. In view of these considerations, the elastomeric bellows seal is recommended for further design development.

4.2 Inlets

The inlet section of the cold water pipe performs two functions: to prevent fish and marine organisms from being ingested by the CWP and to guide the flow into the pipe and cancel out inlet disturbances caused by geometry or by relative motion of the pipe and surrounding ocean water. The former objective is achieved by screens either at the inlet or at the cold water plenum; the latter objective is achieved by proper inlet configuration/turning vane design.

Initial screen investigations for the inlet considered a grid of shaped bars with a 0.375 inch spacing; however, no credible means of keeping the screens clean was found. Instead, it is proposed to put heavy widely spaced bars around the opening to keep out large animals and to employ finer screens at a serviceable location on the platform. Traveling screens are often employed in power plants where a portion of the screen is exposed to backflushing. However the screens are cleaned, disposition of the material must be included in the seawater system design.

For the stationary platform, flow into the inlet is assumed circumferentially symmetric (currents are low at 1,000 meter depth). Requirements for horizontal inflow of less than 1.5 fps dictate that the inlet openings be along the side of the CWP and that the inlet area be at least 4.3 times the CWP crosssection. A proposed inlet design employs a series of concentric curved circular inlet plates to direct the flow into the pipe (Figure 17). Primarily, the flow dividers provide an equal head loss of flow potential along the length

Figure 17. Inlet Design for Stationary Platform

of the inlet to prevent most of the inlet flow from occurring in the region uppermost in the inlet. Their secondary but important function is to uniformly direct the flow vertically in the pipe. Vertical vanes are also required to support the horizontal turning vanes and suppress whirl about the longitudinal axis of the pipe. Radial vanes will be required above the inlet to prevent whirl; one diameter of length (30 feet) is suggested. Also the vertical lips of the curved vanes may be extended in the vertical direction in a short series of concentric tubes to assure smooth flow transition.

For the grazing plant, complications in inlet design arise since the forward motion is a sizable portion of the allowed inlet velocity. Flow into a circular inlet would be severely altered: inlet flow would go from a maximum at the CWP leading edge to zero at the trailing edge causing distortions in the pipe flow and possible crossflow from front to back of the inlet. The net result would be large flow losses for a circular inlet. A forward facing (pitot type) of inlet is one way to overcome the losses; these inlets have a high efficiency in recovering dynamic head from the fluid motion but have little tolerance for misalignment. Design details for a grazing plant inlet were not pursued beyond the conceptual stage because of the difficulties encountered. It is recommended that the design criteria be examined in light of technical and cost impacts.

4.3 Plenum Arrangements

The cold water supply system brings seawater from approximately 1000 meter depths, passes the water through the condensers and returns the water to the ocean at a location selected not to interfere with the warm water intakes. Multiple cold water pumps are suggested to keep pump size down

and allow individual maintenance. The total pumping requirements have been estimated to be 15 percent of the net power plant output.

The pumping arrangement should be laid out so that there is maximum efficiency of the circuit. Turns and area changes should be minimal and gradual. Pumps should be designed to run at constant speed since any off design perturbation results in a system loss. Experience with valves, pumps and drive motors has shown that these items require periodic maintenance. Replacement of a pump or motor is a major operation even on stationary installations on land. The design should allow installation and removal to be made in a vertical lift; horizontal installation is extremely difficult. There must be access to the surface of the platform for the large parts, and there must be sufficient clearance to prevent damage from ship motion. The pumps and motor must be capable of being isolated from the hydraulic circuit for shutdown, maintenance, inspection, and repair.

The cold water pipe terminates in a moon pool or plenum in which average velocity of the water is slowed from 6.5 fps to the order of 1 fps. This water is channelled to at least four pumps which should be located around the periphery of the plenum. Before the water enters the pump inlet, it must pass through screens to filter fish and debris which clear the bottom screens. Practice has shown that screen openings should be on the order of 0.375 inches to prevent clogging of condenser tubes. A continuous loop traveling screen can be used. If the top edge of the screen exits the water into the air, jets of high pressure water can clean the screen and flush debris away from the water inlet. If the screen is to be cleaned underwater, a baffle will have to be used to separate debris from the inlet water reservoir. It is

probably necessary to dispose of collected debris, in which case a large grinder is required to pulverize the debris before the waste pump throws it overboard.

Pressure fluctuations arising from platform motions and/or passing waves can be deleterious to pump and power system operation. Pumps will surge to meet the changing head requirements which affects the plant power regulation and leads to fatigue problems in the motors, drives, pumps, controls, and hydraulic components. These problems can be overcome by appropriately designed surge arrestors.

Proposed 10/40 MWe Modular Experiment platforms require widely differing pump/plenum arrangements. The Gibbs and Cox spar concept has a capped plenum located 200 feet below mean sea level with the cold water pumps located in external modules. APL recommended an open moon pool for the barge with pumps mounted in the top of the cold water pipe. System requirements suggest improvements to these designs.

The present Gibbs and Cox design apparently has no provision for surge arrestors, isolation valves, and fine mesh screens with associated cleaning equipment. If it cannot be shown that platform motion and wave passing pressure oscillations are below pump acceptable levels, surge chambers and/or active inlet controls will be required. Isolation valves are required for maintenance and replacement. Provision must be made for screen cleaning and debris disposal. Additional attention needs to be paid to minimizing rapid turns which cause flow losses.

The APL arrangement with the pumps located in the pipe is not satisfactory. There is no access for maintenance short of removing an entire module. If one pump is down there must be a way to isolate the others so that they won't be driven as a turbine and cause a loss. Also, the pumps would be

adversely affected by pressure surges, and screens can not be placed in front of the pumps easily in this design. Provision needs to be made for surge arrestors, isolation valves, screen cleaning and debris disposal.

4.4 Cathodic Protection System

The cathodic protection system is designed to provide state of the art anti-corrosion capability for steel CWP components. These include: the CWP internal, the CWP external, the buoyancy tanks, and for the bottom-mounted design; the area of tension legs in seawater, the subsea template, and the tension legs in mud. Ten anti-corrosion system alternatives were analyzed for the protection of the cold water pipe exterior and other external appendages (Table 7). The internal area of the cold water pipe is difficult and not all approaches are applicable--provisions for allowing corrosion to occur were analyzed as an alternative. Cost estimates were based on having longitudinal stiffeners interior, subsequent design modifications moved the stiffeners to the exterior resulting in significant savings.

Impressed current systems are the most widely used form of cathodic protection on large ships and mobile offshore drilling platforms. These systems have definite installation advantages over the sacrificial systems, particularly for the external appendages of the cold water pipe. Sacrificial anode cathodic protection has been used on approximately 90 percent of all fixed offshore oil production platforms world-wide and is therefore a well proven method. However, on the CWP exterior appendages, handling and jacking techniques limit the location of the sacrificial anodes.

Table 7. Anti-Corrosion Systems

SYSTEM NO.	SYSTEM
1	Sacrificial Anode Cathodic Protection of Bare Steel
2	Initial High Current Density Using Sacrificial Anodes
3	Impressed Current on Bare Steel
4	Initial High Current Density Using Impressed Current
5	Coal Tar Epoxy Plus Aluminum Anodes
6	Coal Tar Epoxy Plus Impressed Current
7	100% Solids Urethane Plus Aluminum Anodes
8	100% Solids Urethane Plus Impressed Current
9	Metallizing Plus Seal Coat
10	Alloy 5454 Sheet Aluminum 0.250 Inches Thick Over Steel

Another less feasible alternative to protection systems is to allow the CWP internal surface to corrode. Average internal corrosion rates of about 33 mils per year are estimated for smooth surfaces, and this amounts to 0.99 inches of steel over a thirty year life. Corrosion rates of two to three times these values are expected in areas of turbulent flow (i.e., welded seams, reinforcement rings, doublers, gussets). Such a corrosion allowance is too high a price to pay in view of the alternative schemes available for corrosion protection.

There are several variables which must be weighed against each corrosion protection system in order to achieve the most efficient and cost-effective method. In order of importance, these criteria are:

- a proven track record in a similar environment
- no undesirable side effects
- availability of a feasible alternative for effecting a repair
- the system must be economical.

The system that best meets the above criteria for the external CWP is impressed current on bare steel. This system has a proven track record, is compatible with the operator's capabilities and can be replaced without the use of divers or submersibles. Any major or minor current distribution problems with this system can be augmented by placement of small sacrificial anodes in the problem areas. The hardware consisting of multiple anodes stapled to the CWP exterior is commercially available, and qualified contractors exist to insure proper installation.

For internal protection of the CWP the 100 percent solids urethanes plus impressed current should be used in the first 300 feet followed by the 100 percent solids urethane plus aluminum anodes. It should be understood that there are a number of modern coatings equally as suitable as the hot applied 100 percent solids urethane. This coating system was used because of its thickness, excellent abrasion resistance and low cathodic protection current requirement. The main advantages of this urethane system are field touch up of welded seams and cost.

4.5 Vortex Strumming Suppression

An OTEC CWP will experience oscillatory hydrodynamic loads in a steady ocean current due to the periodic shedding of vortices as the flow separates in an alternating fashion from opposite sides of the pipe. Both in line and lateral oscillating forces are produced with the lateral forces (referred to as lift) being much larger. For a flexible CWP a dynamic resonance can occur if the frequency of vortex shedding is sufficiently close (± 30 percent) to a CWP natural frequency. This flow/structure interaction phenomenon referred to as vortex strumming leads to enhancements in both the mean and oscillatory loads. Persistent cyclical motions due to vortex shedding could seriously degrade CWP lifetime through fatigue, create surges on the pumps and induce additional loads on the platform interface.

The problem of calculating CWP response to vortex shedding is centered around a description of the loads and the adequacy of the codes to predict CWP motions. Empirical models indicate pipe deflections on the order of one to two diameters, although there is scant evidence that this occurs

at higher modes. The NOAA/DOE code was used here to calculate the vortex strumming induced stresses. Two CWP designs were considered--the FRP pipe attached to the APL barge off Puerto Rico and Brazil and a stiffened steel shell pipe attached to the APL barge grazing off Brazil. For an ocean current shear flow such as present in the Puerto Rico operating environment there is considerable disagreement over the vortex shedding correlation length. The approach used here was to assume fully correlated loads over the nodal lengths and is thought to be conservative. For the grazing plant there is little doubt that the loads are correlated since both surface roughness and pipe motion tend to increase the correlation length.

If vortex induced strumming occurs for the FRP cold water pipe as indicated by a comparison of CWP bending frequencies with the vortex shedding frequency, low level (~ 2500 psi) cyclical bending stresses would shorten the FRP design life to about 15 years. Furthermore, these calculations may not be conservative since the NOAA/DOE code does not predict the one to two diameter bending deflections implied by empirical data.

A continuous stiffened steel shell CWP would face severe fatigue problems due to vortex induced strumming. However, very low stresses are experienced by the segmented pipe considered here. Wall bending stresses did not exceed 1000 psi due to the multiple flexible joints which relieve the bending stresses. However, joint and seal reliability become the governing design issue.

The present calculations have indicated a requirement to relieve the vortex loads on the FRP pipe but not on the segmented steel pipe. Based on historical precedent, prudent engineering design practice dictates that vortex

induced strumming suppressors be considered for both types. Additional experimental data are required on the effects of higher mode flow/structure interactions, articulated pipes and correlation lengths in shear flows. Of great importance is the validation of the NOAA/DOE code used to perform these calculations. Should the need for a vortex suppression system be demonstrated, the spiral strake approach is judged most attractive.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

5.0 CONCLUSIONS AND RECOMMENDATIONS

The Cold Water Pipe System Design Studies sponsored by the NOAA Office of Ocean Engineering represent the first attempt to systematically analyze the multitude of cold water pipe concepts suggested by various sources. At the completion of the concept ranking phase, three candidate CWP system designs were selected from a number of viable alternatives for further development. As is usual with any new engineering venture, design problems were encountered, gaps in the available engineering data were identified and requirements for additional testing and analysis were defined.

5.1 Conclusions

The major conclusion of the present study is that a CWP system can be deployed by 1984. There appear to be no outstanding technical issues which cannot be overcome by appropriate R&D programs. Design, fabrication, construction and installation schedule requirements are not overwhelming. Furthermore, several technically and economically feasible CWP options exist.

Three viable CWP designs have been developed in this study. Barring unseen difficulties, the FRP design is superior to the stiffened steel shell design for a hanging CWP because it is lighter weight, has only one joint, can be installed in a single operation and its acquisition cost is 60 percent lower. For near shore OTEC sites the bottom mounted design is attractive because it combines the mooring function with the cold water transport function resulting in large cost savings. Further attention should be given to bottom mounting an FRP pipe.

A great deal of progress has been made in CWP designs over the past year by eliminating unworkable concepts and focusing attention on the more viable approaches. For example, CWP wall thicknesses are being discussed in terms of inches as opposed to feet. This progress has come about as a result of a planned Government approach to developing viable CWP concepts, reducing technological uncertainties and providing a design methodology. Technical issues which remain to be resolved include:

- long term material performance under cyclical loading in seawater
- CWP dynamic response including flow/structure interaction
- performance of large scale flexible joints
- environmental conditions at operating sites and between construction and operating sites
- deployment operation details
- internal flow transient effects
- ocean floor properties.

Research programs can resolve these issues within the MEP development schedule.

5.2 Recommendations

A vigorous research and development program is recommended to provide CWP design information. OTEC studies have systematically identified key engineering design issues for each major subsystem and provided solutions through appropriate developmental programs. Successful solutions to the CWP subsystem technical issues are equally promising.

Recommendations arising out of the CWP system design study are:

- pursue detailed design of selected CWP concepts including hanging and bottom mounted alternatives
- emphasize integration of platform/CWP/mooring
- improve dynamic analysis codes
- initiate material test/verification programs
- perform design and development tests of critical CWP components (e.g., flexible joints)
- investigate horizontal deployment details
- update environmental/design criteria
- complete dynamic model tests for code validation
- complete programs aimed at vortex induced strumming suppression and internal flow transient analyses
- conduct at-sea test to validate design methodology and gain experience.

It is recognized that some of the recommendations are already being pursued by NOAA/DOE.