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NOAA Technical Report OOE 4

Design and Analysis of OTEC's Cold Water Pipe

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CONTENTS

FIGURES

TABLES

DESIGN AND ANALYSIS OF OTEC'S COLD WATER PIPE

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ABSTRACT. The Ocean Thermal Energy Conversion (OTEC) Program of the Department of Energy (DOE) is developing an engineering design manual for the OTEC Cold Water Pipe (CWP). Nominal dimensions of the pipes now under study have lengths to 1,000 meters, diameters of 9 meters and thicknesses ranging from 0.07 to 0.6 meters, depending on materials. Under the action of unsteady, three-dimensional hydrodynamic loads, as well as loads due to coupled surface platform motions, the CWP is subject to a combination of bending, torsional, and ovaling modes of oscillation. The CWP Engineering Design Manual will contain essential information and analytical models for CWP design and design assessment. This paper focuses on the problem of CWP structural analysis and describes CWP hydrodynamic loading forces and existing linear elastic beam CWP structural models. Sample calculations are presented which illustrate structural response predictions for the CWP in typical seas and demonstrate tentative agreement for a limited range of parameters between the three most widely used CWP structural models and the scant existing experimental data.

Introduction

The ocean thermal energy conversion (OTEC) concept is a process for recovering useful energy from vertical temperature gradients that exist in tropical oceans. Warm water from surface layers and cool water from layers about 1,000 meters below the surface provide renewable thermal resources for operation of a heat engine. (See figure 1.) The available temperature differences, however, are only about 22°C so that very large quantities of water must be moved through an OTEC plant for significant energy production. For example, a 100 MW_e OTEC powerplant requires a combined cold and warm water flow of about 2×10^5 gallons per second. Cool condenser water is withdrawn through a long cold water pipe (CWP) about 30 meters in diameter and 1,000 meters long, suspended from the OTEC platform. (See figure 2 for representative OTEC plant configurations.) The CWP has been recognized as one of the most important OTEC technology problems.

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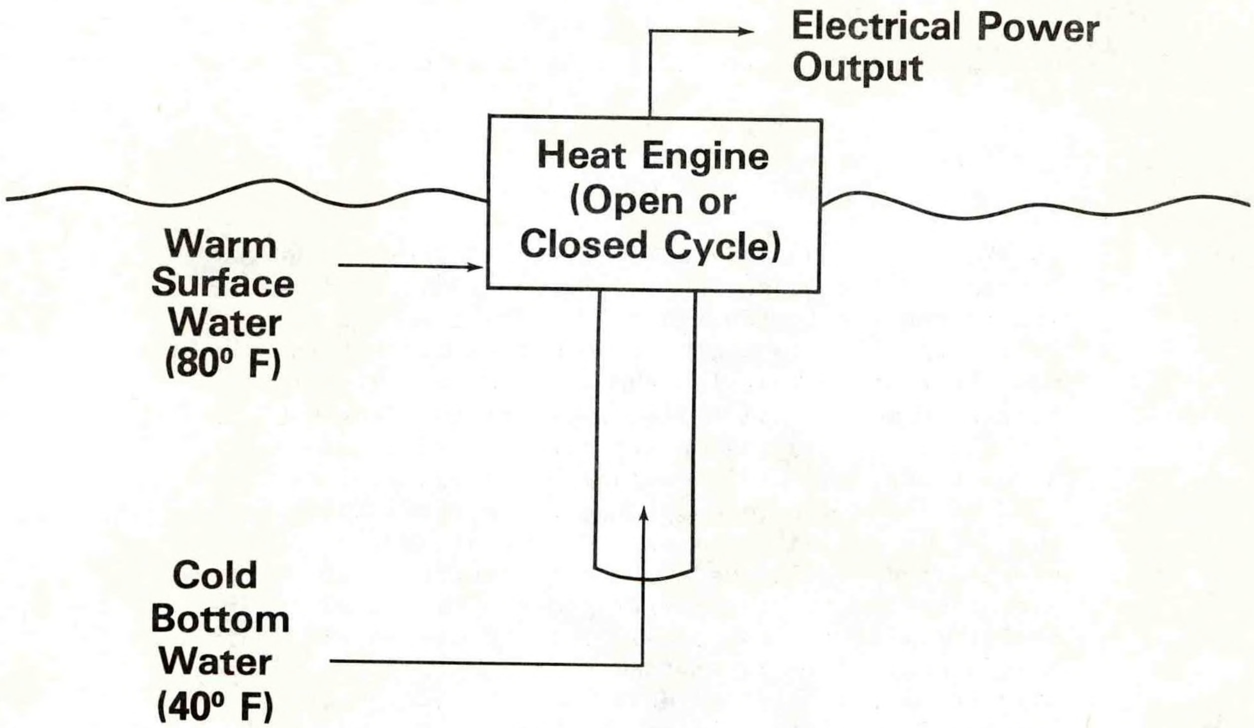

Figure 1.--Ocean thermal energy conversion principles.

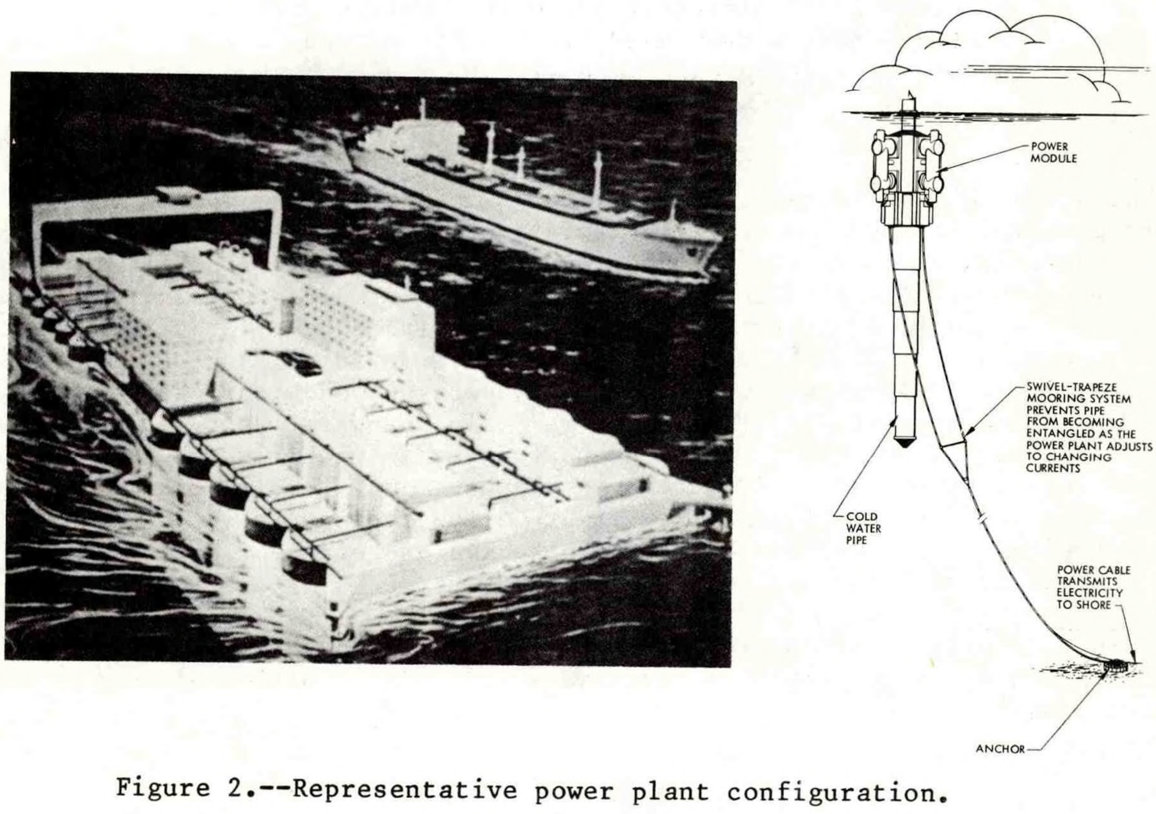

Figure 2.--Representative power plant configuration.

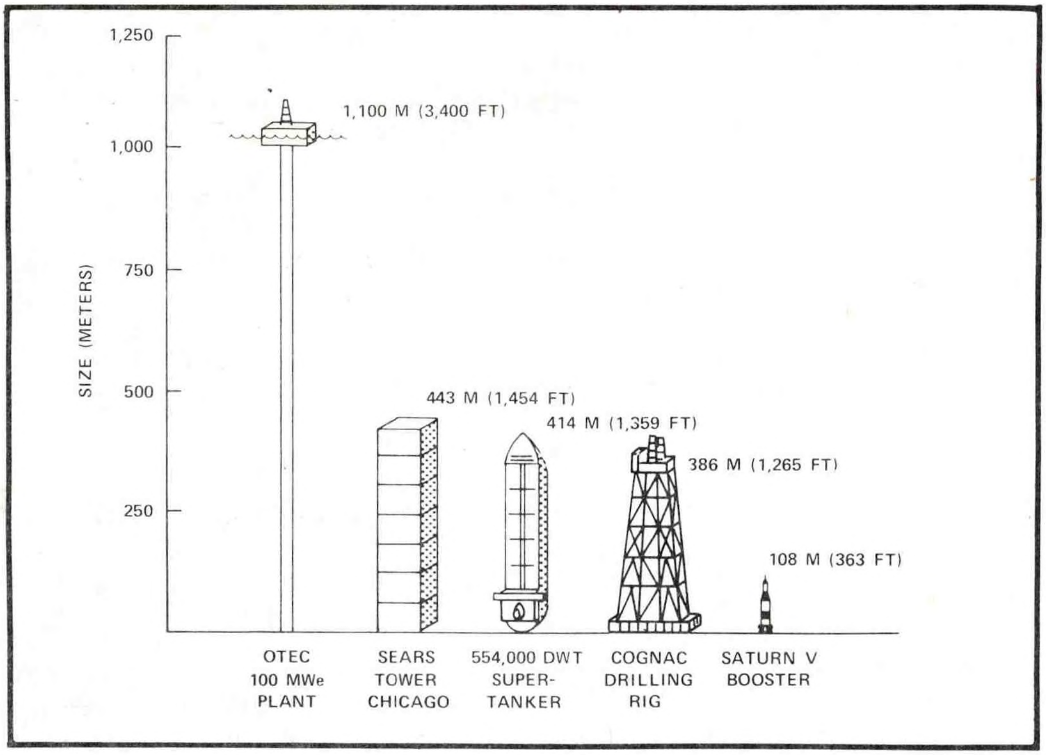

Figure 3.--Physical relationship of OTEC to other large structures.

The technical viability of OTEC is being demonstrated at the present time by the "MINI OTEC" experiment being conducted off the coast of Hawaii by a consortium of organizations including: University of Hawaii, Dillingham Construction and Dredging Co., and Lockheed Missiles and Space Co. MINI OTEC is designed for 50 kw of electrical output and has a 0.5 meter diameter by 630-meter-long CWP.

When deployed in the ocean environment, the OTEC CWP experiences a variety of forces and may respond in both beam and thin-shell modes of oscillation. Moreover, for such a large, flexible structure as the CWP, construction and deployment loads can exceed operational loads. Detailed design and structural response analyses must, therefore, be carried out for each phase of a CWP's life and represent formidable engineering problems. The OTEC CWP is unique among the world's largest manmade structures in that it is the longest, moveable, flexible structure ever to be designed. (See figure 3.) Construction and deployment of the first 9-meter-diameter by 1,000-meter-long CWP is now planned for 1983-84. A 30-meter-diameter by 1,000-meter-long CWP is a goal for the late 80's.

The Office of Ocean Engineering (OOE) of the National Oceanic and Atmospheric Administation (NOAA) under agreement with the Department of Energy, is developing an OTEC CWP engineering design manual (EDM). This manual will be useful both to commercial organizations interested in designing, building, and operating the first large-scale OTEC powerplant(s), and to the government (or other sponsoring organizations) in selecting the best CWP design(s). The first edition of the EDM will be available as public information by the end of 1980 and will include the following elements which are essential for successful translation of CWP concepts into reality:

- o Detailed engineering properties of candidate CWP materials
- o Specification in engineering terms of CWP hydrodynamic loads during installations and operations
- o CWP structural response analytical models and computer codes for construction, deployment, and operational scenarios
- o A laboratory and at-sea test data base
- o Economics of construction, deployment, and maintenance of the CWP
- o Sample CWP designs, including: fabrication, deployment, and maintenance procedures, and stress and economic analyses.

The purpose of this paper is to present a brief overview of the OTEC CWP and its structural analysis and of the development of a CWP engineering design manual. CWP hydrodynamic forces, linear elastic beam structural analysis, and economics are also described.

A large number of design concepts have been proposed for the CWP and span the full range from a massive gravity structure to a ring-stiffened, very thin and flexible fabric structure. Recent design studies carried out for NOAA/OOE by TRW and SAI (Ref. 1 and 2) have defined the most viable of these within the constraints of existing technology and the plan to construct and deploy a 9-meter-diameter by 1,000-meter-long CWP by 1983-84. The "best" CWP design concepts are those which promise safe stresses under all pipe loadings, low cost, low maintenance, and high probability of long life (30 years). Constructability is, of course, a crucial factor and is included under cost.

The CWP design concepts selected by TRW and SAI are of the following four generic types and are listed in Table 1:

- o Rigid pipe with or without articulated joints
- o Compliant pipe
- o Bottom-mounted pipe
- o Multiple pipes (with hydraulic radius equivalent to a single pipe).

The most promising pipe materials at present include: steel, concrete, fiber-reinforced plastic (FRP), thermoplastics, and elastomers/fabrics.

Structural analysis of the CWP to assess expected pipe stresses requires a complete specification of all environmental, operational, and platform-induced loading to be experienced by the CWP.

Table 1 – Baseline CWP Design Concepts*

SAI	TRW
1. Steel; thin-shell, tee-stiffened pipe with articulated joints	1. FRP, sandwich wall pipe without articulated joints
2. FRP; sandwich wall pipe without articulated joints	2. Elastomer; synthetic fabric and/or steel cable reinforced, ring stiffened, rubber pipe without articulated joints
3. Steel; bottom-mounted buoyant pipe, attached to platform as a tension leg	3. Polyethylene or FRP; multiple pipe bundle without articulated joints

* All concepts are gimballed to OTEC platforms.

CWP Loading Forces

For purpose of design, OTEC tropical site environmental conditions have been specified both for normal operations and for the 100-year storm (ref. 3). Wind speeds as large as 95 knots with gusts up to 150 knots are anticipated. A moored OTEC powerplant will experience ocean currents that vary in both magnitude and direction with both depth and time, as driven by geostrophic, tidal, and wind forces. Currents as large as 1.8 meter/s at the ocean surface and 0.2 meter/s at a depth of 100 meters are anticipated. For a grazing OTEC plant, the additional effects of a 0.25 meter/s plant grazing motion must also be taken into account. Surface waves with a maximum significant wave height of 10.5 meters at a period of 12.5 s are predicted for the 100-year storm at several of the sites.

The above environmental effects produce unsteady, three-dimensional loading on the CWP both directly through hydrodynamic forces due to waves and currents and indirectly through platform/CWP coupling forces and platform-induced CWP motions. Earlier analytical studies and model basin tests (ref. 4 and 5) have demonstrated the necessity of analyzing the OTEC platform and CWP as a coupled system. In addition, the following effects of internal pipe flow during operations (e.g., about 2 meters/s) must also be considered for realistic analysis of the CWP:

- Pipe wall frictional resistance
- Static pressure differences due to fluid speed and to fluid density differences
- Centripetal forces
- Coriolis forces
- Inlet reactive effects.

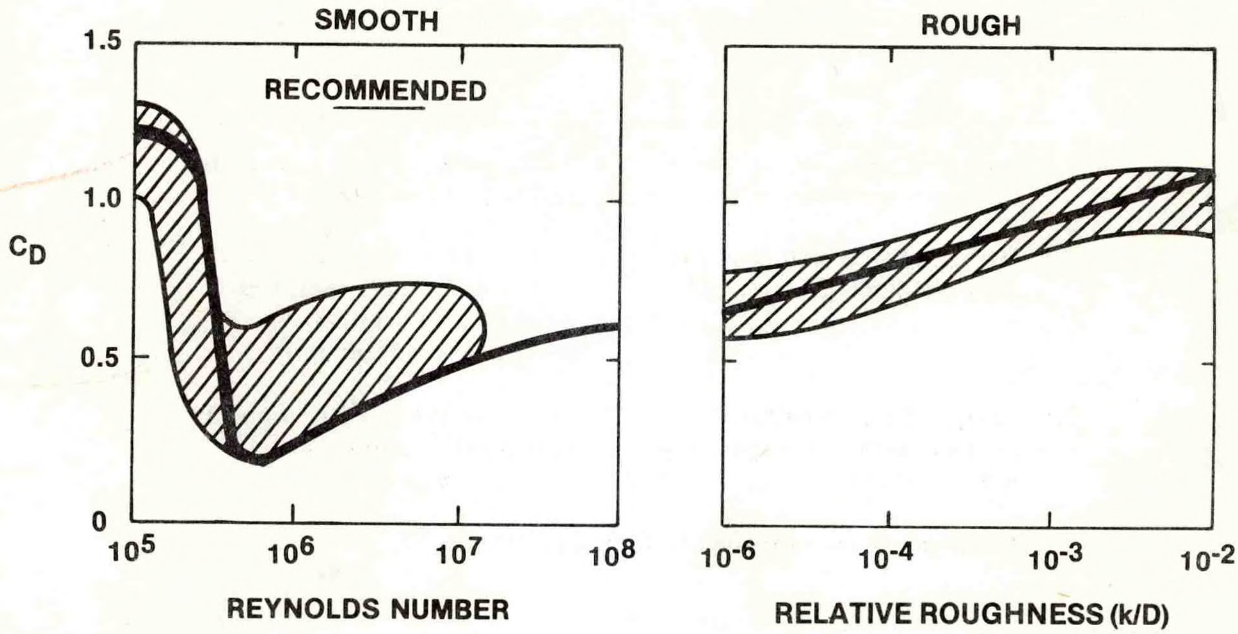

Figure 4.--Cylinder mean drag coefficients (ref. 6).

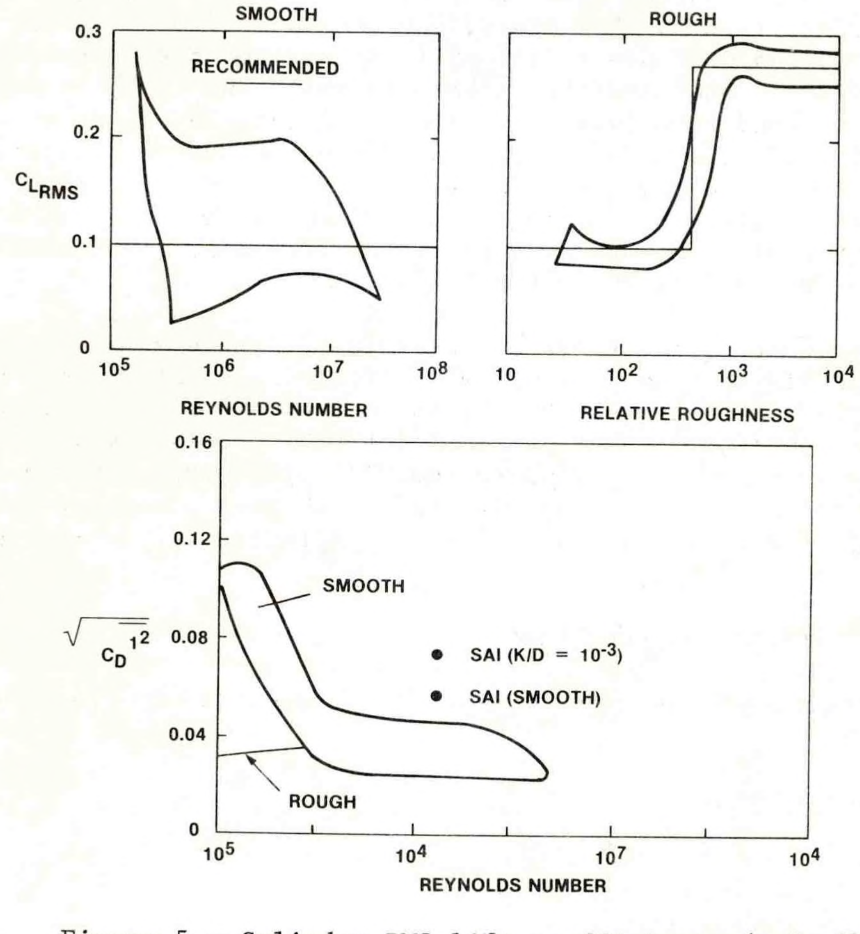

Figure 5.--Cylinder RMS lift coefficients (ref. 6).

The situation is complicated by the probability of organized vortex shedding from and attendant unsteady loading on the CWP in the OTEC environment. For a 9-meter-diameter CWP, maximum expected Reynolds and Keulegan-Carpenter numbers are on the order of 10^7 and 10, respectively, which characterize a "super critical" and an "inertia-dominated" flow field.

Specification of the CWP hydrodynamic forces in engineering terms has been carried out recently by SAI (ref. 6) using analytical flow models and available empirical data. The effects on CWP loading of vortex shedding and of resonance or "lock-on" between CWP beam natural modes of oscillation and vortex shedding have also been described in detail by Griffin (ref. 7).

Figure 4 and 5 (taken from reference 6) provide the hydrodynamic force data necessary for the analysis of the CWP as a linear elastic beam in a current field (without lock-on). The critical parameters in this case are Reynolds number (UD/ν) and surface roughness ratio (k/D); where D is CWP diameter, U is current speed, ν is kinematic viscosity, and k is CWP surface roughness height. Figures 6 and 7 (taken from reference 7) shows the effects of lock-on for in-line and cross flow, vortex-excited CWP oscillations. The critical parameters in the case of lock-on are the reduced velocity, $V_r = U/f_nD$, and the reduced damping, $k_s = 2m\delta/\rho D^2$, where f_n is the frequency of the n^{th} pipe natural bending mode; $m/\rho D^2$ is the structural-fluid mass ratio; and is the logarithmic decrement. These results indicate that oscillation amplitudes as large as 0.12 D and 0.72 D can be produced by vortex-excited in-line and cross flow modes, respectively. As pointed out by Giannotti (ref. 8), cyclic loading due to vortex loading (with lock-on) could drastically reduce CWP life expectancy by promoting fatigue failure and, therefore, deserves careful attention.

Analysis of the CWP as a thin-shell requires that the loading over its entire surface be specified rather than along its center line, as in the case of a beam model. Both steady and unsteady hydrodynamic CWP surface pressure distribution are specified in reference 6. The effects of current shear and ambient turbulence and of CWP distortion on surface pressure distribution are, however, not yet fully resolved. The relationship between current shear and vortex shedding correlation along the length of the CWP and the hydroelasticity of a flexible structure in a fluid flow field are two areas under further study (ref. 9 and 10, respectively).

CWP Structural Response

A number of theoretical methods have been developed for analyzing the structural response of the coupled platform/CWP system to wave and current induced loads. These methods treat the CWP as a linear elastic beam coupled to a rigid platform. (See figure 8.) The three most widely known and successfully used in the OTEC community are:

1. A linear model in the frequency domain developed for NOAA (the "NOAA/DOE model") by Hydronautics, Inc. reference 11), which uses the transfer matrix method for solution.

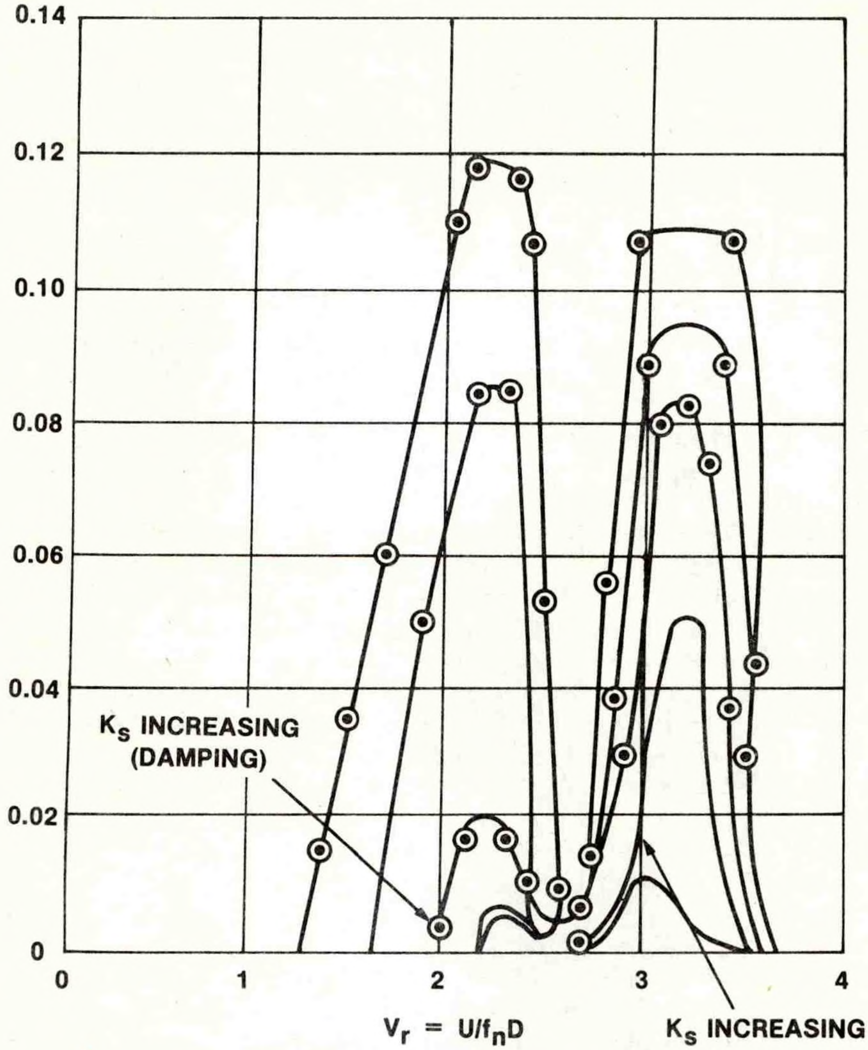

Figure 6.--Vortex-excited displacement of a flexible cantilever (from equilibrium) in the in-line direction plotted against the reduced velocity $V_r = U/f_nD$ (ref. 7).

2. A linear model in the frequency domain, developed for the Department of Energy by J. R. Paulling (ref. 12), which uses finite element solution methods.

3. A nonlinear model in the time domain, developed in-house by TRW (ref. 13), which uses finite difference solution techniques.

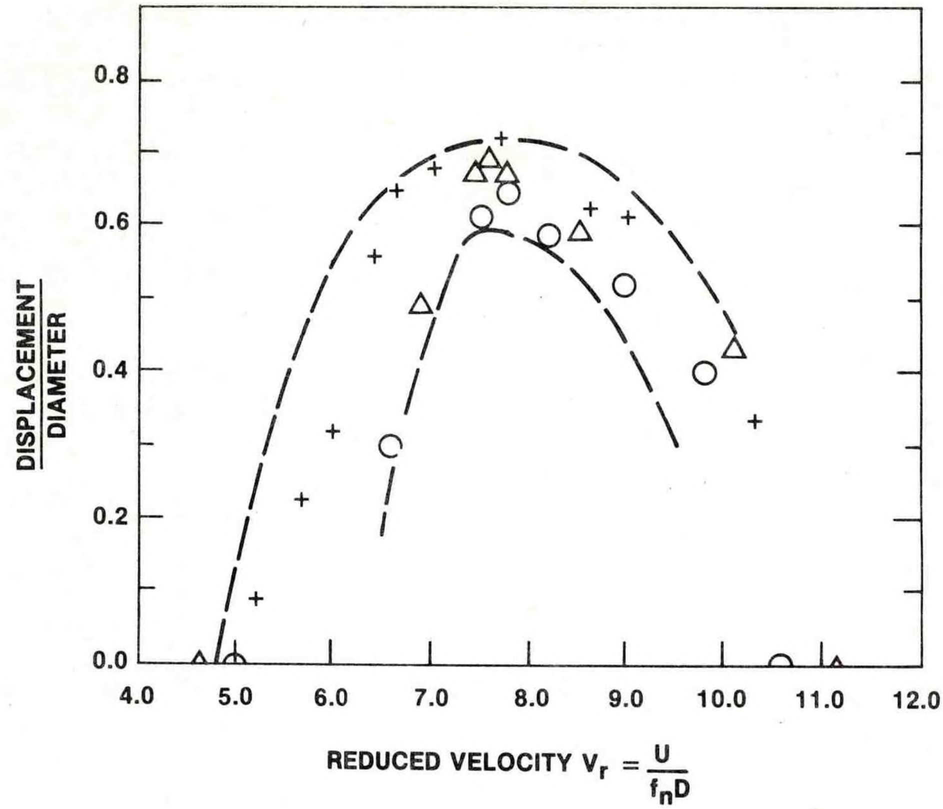

Figure 7.--Cross flow-induced displacement amplitude plotted against the reduced velocity (ref. 7).

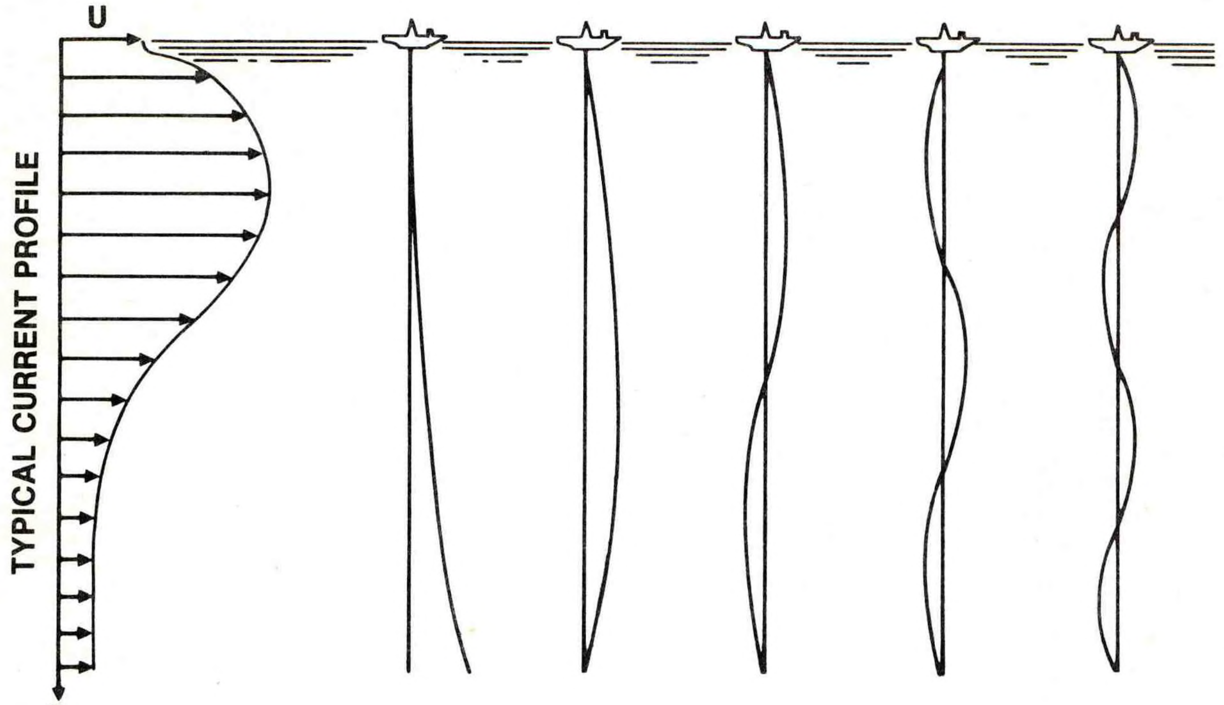

Figure 8.--Structural analysis of cold water pipe (elastic beam).

In general, all three methods are capable of treating a variety or rigid and articulated CWPs attached to OTEC platforms in wave and current fields. Computer source decks and detailed User's Manuals are generally available for 1 and 2 through NOAA. A comparison of these three methods as well as an evaluation of experimental methods for obtaining model validation data is presented in reference 14. Table 2 (from reference 14) provides further general information for each method. The TRW time domain method is the most adaptable and realistic of the three models for flexible CWPs, in that it can treat nonlinearities and retains the phase information between loads and displacements. However, the platform is assumed to have frequency independent hydrodynamic forces which might cause significant errors for some platforms (ref. 14). In terms of operating costs, the NOAA/DOE and TRW methods are about equal and Paulling's is somewhat more expensive. A comparison of the pipe stresses calculated by all three methods for a sample OTEC platform/CWP scenario is presented in figure 9 (from reference 13) and shows fairly good agreement.

The validation of these analytical models with experimental data is a crucial factor in the OTEC CWP program. Unfortunately, very little suitable test data are now available, but it is expected that ongoing and future OTEC projects will supply the necessary data base for analytical model validations during 1979-81. Recent preliminary comparisons between CWP linear elastic beam analytical model predictions and existing model basin (ref. 14) and at-sea (ref. 15) test results have indicated fairly good agreement. However, some discrepancies were noted (refs. 4, 13, and 16). Further work is planned for a thorough validation of the existing analytical tools.

Table II – Comparison of Capabilities of Theoretical CWP Analysis Methods

Feature/Capability	NOAA/DOE	Paulling	TRW
Loadings			
Uni-directional Waves	Yes	Yes	Yes
Directional Waves	No	IP	Yes
Steady Current	Yes	IP	Yes
Vortex Shedding	Yes	No	Yes
Arbitrary Loads	Yes	No	Yes
Internal Flow	Yes	No	Yes
CWP Geometry			
Joints	Yes	Yes	Yes
Non-Linear Damping	AP	AP	Yes
Wave/Current Interaction	No	IP	Yes
Moorings, etc.	Yes	No	No
Platform			
Frequency Dependence	Yes	Yes	No
Full CWP Coupling	Yes	Yes	Yes

Where – IP denotes work in progress
AP denotes approximate treatment

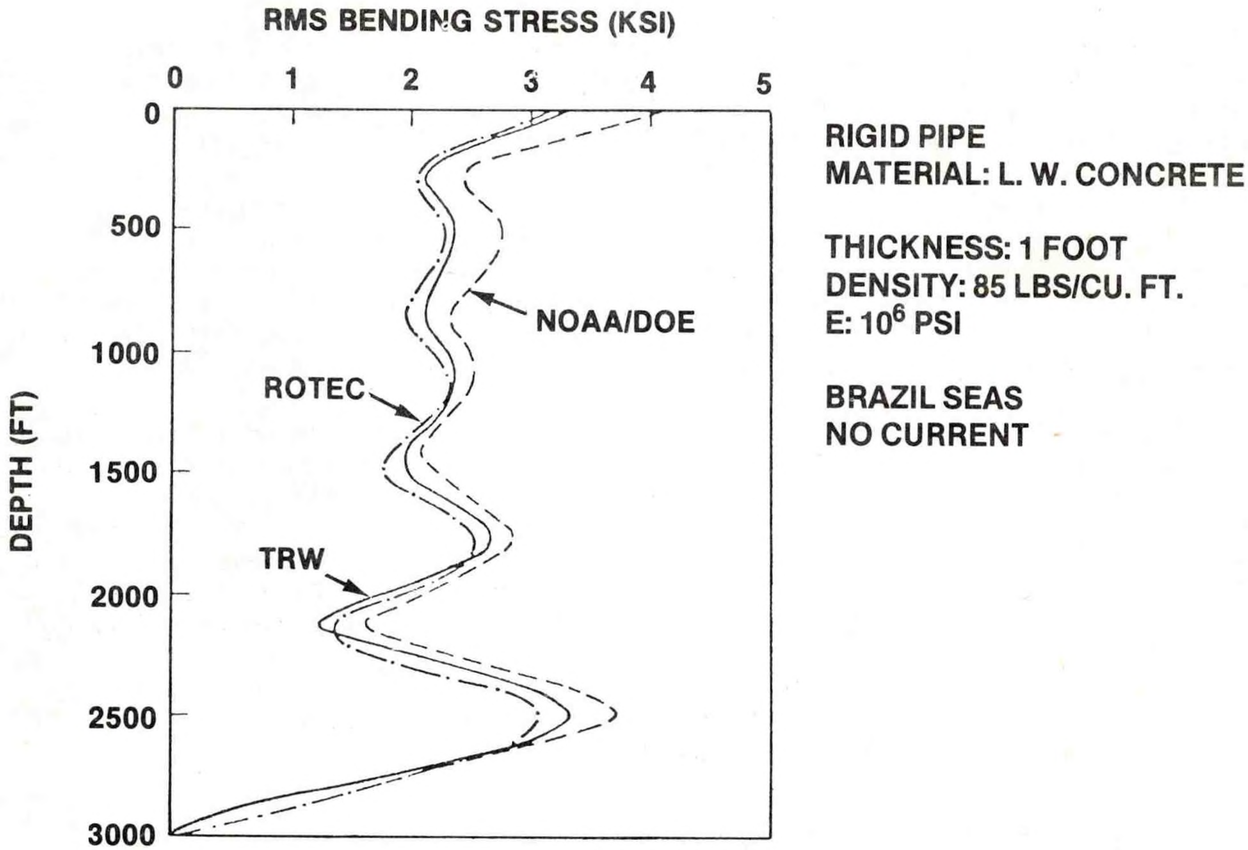

Figure 9.--Comparison of TRW, NOAA/DOE, ROTEC (Paulling) CWP model results (ref. 13).

The CWP design concepts currently under study have thickness-to-diameter ratios and cross sectional stiffnesses which are small enough to characterize the pipe as a thin-shell, particularly for the flexible materials; e.g., elastomers and polyethylene. (See references 1 and 2.) The environmental loading on the CWP, especially that due to currents and vortex shedding, is basically three-dimensional and unsteady so that excitation of shell ovalling and torsional modes is probable. Resonance between CWP shell modes and loading can produce high stresses or cyclic fatigue failures and, therefore, are crucial to a complete structural analysis of thin walled, flexible CWPs. Earlier investigations (ref. 6) using sample ring and hoop models suggested that such such structural problems can be avoided by judicious CWP design.

A NOAA-funded study (see reference 10) is underway to develop analytical models to predict the three-dimensional, nonlinear structural response of OTEC CWPs to all loading for a realistic assessment of CWP designs. The results of this study are expected by spring of 1980 for inclusion into the CWP EDM.

The remaining elements of the EDM (described above) are now being developed simultaneously for inclusion into a preliminary version of the EDM by the summer of 1980.

CWP COST ESTIMATES

An essential and usually the most controversial consideration during the early phases of a structural design and development program is cost. Preliminary cost estimates are being generated along with CWP designs, and the present discussion would be incomplete without some mention of costs.

The most costly aspects of the CWP are materials and construction/fabrication/deployment operations, due primarily to its enormous size. Of these the deployment process represents the most expensive (and risky) operation of the entire task of design, construction, and attachment of a CWP to an OTEC powerplant. Maintenance and repair costs over a pipe's useful life are design/material dependent and are highly speculative at present.

Cost estimates for the following two CWP designs are presented in Table 3: an articulated thin-shell, tee-reinforced steel CWP by SAI and Brown and Root, Inc. ($39.0M, ref. 2) and a nonarticulated sandwich wall FRP (balsa wood interior layer) CWP by TRW and Global Marine Development, Inc. ($19.7M, ref. 1). Costs include acquisition and construction of the CWPs at a construction site in the northeastern United States and deployment of the CWPs at the OTEC site off Puerto Rico. Full details for each cost scenario are given in references 1 and 2.

Table III— Preliminary CWP System cost estimates
(Acquisition/construction/deployment)

ITEM	COST	($M)
	Steel Thin-Shell and Tee Concept	FRP-Sandwich Wall Concept
Cold Water Pipe	16.9	7.4
Inlet Screens	0.7	0.1
CWP/Platform Coupling	1.5	1.6
Bio/Corrosion Control	3.0	0.0
Acceptance Testing	0.6	0.0
Deployment	12.0	6.5
Facilities	3.1	2.3
Engineering/Detail Design	1.2	1.8
Total	39.0	19.7

FINAL REMARKS

The many and unique criteria imposed on OTEC's CWP have produced designs which are probably more realistically treated as thin-shells than as beams. However, economy and expediency have dictated that structural analysis of the CWP be developed from simplier beam to thin-shell structural models. Recently developed beam models are giving results which are apparently consistent between different models for a limited range of parameters and with limited, existing experimental data.

One objective of the Government's OTEC CWP program is to develop fully validated CWP structural model(s) for inclusion into a CWP engineering design manual. This manual, which will contain a broad range of information essential to the design of an OTEC CWP, will be available for general distribution by the end of 1980.

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