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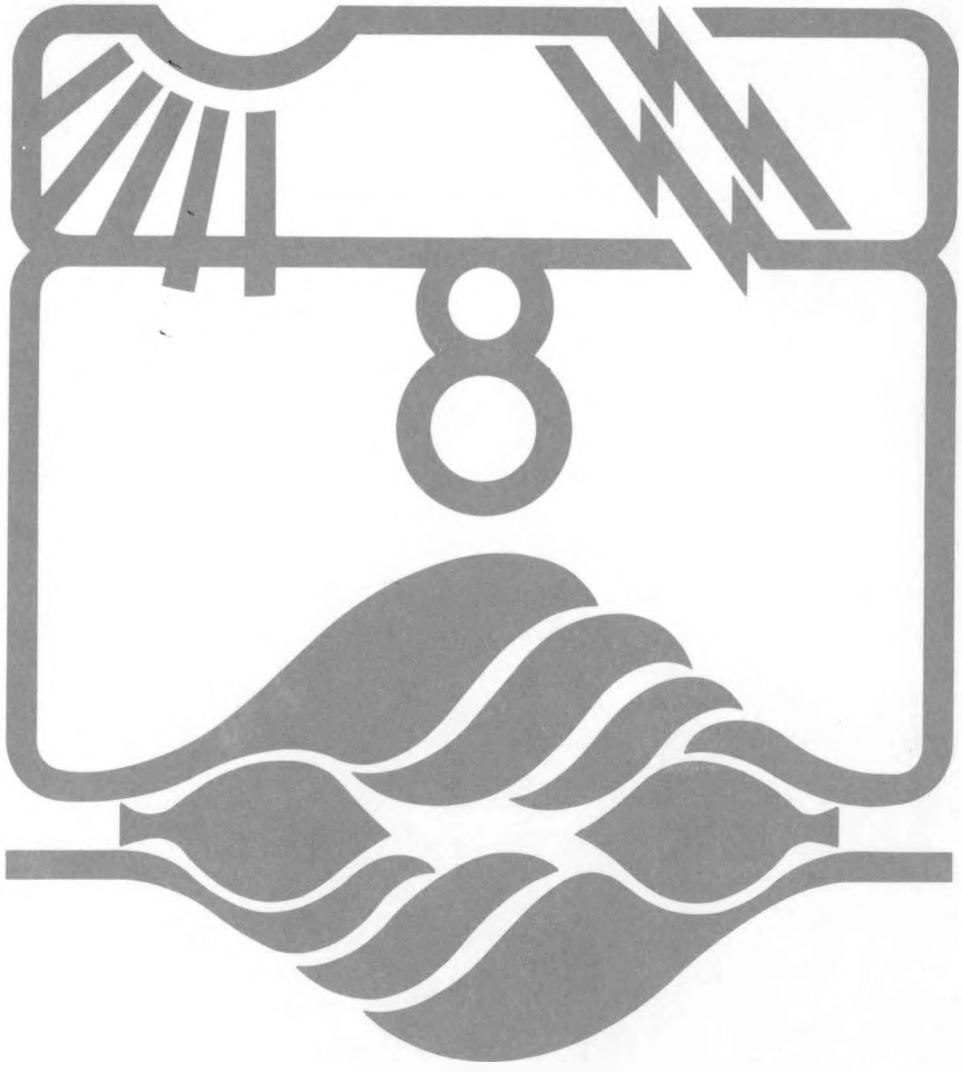
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Assistant Secretary, Conservation and Renewable Energy
Director of Ocean Energy Technology
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Proceedings of the 8th Ocean Energy Conference

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PREFACE

The Eighth Ocean Energy Conference benefited from the technical foundation and administrative experience of seven preceeding conferences. This was fortunate because its unique environment was a challenge to managers and contributors alike. Their reward from the Conference was the fine attendance in spite of uncertain prospects for future Government support of the program. More than 550 people attended the meetings, with additional people attending the luncheon, banquet and exhibits. The good attendance, under the prevailing circumstances, signified a strong and wide-spread interest in and dedication to the potential of ocean energy conversion technologies.

As Co-chairman of the Conference, Dr. Robert Cohen, of the Department of Energy, participated in every aspect of the conference administration. His purposeful dedication to ocean energy technology and tireless effort to create an effective information exchange by means of the Conference were examples of public service at its best. Additional credit goes to Mr. William Richards who helped to guide and support the Conference through confused budgetary seas.

The Conference Organizing Committee listed in these Proceedings, was in fact the Conference Management team. This team did an outstanding job in the severely limited time. As coordinator of the administrative activities, Ms. Lora Bernabei deserves special recognition. Mr. Robert Stiefel of the Department of Energy, whose magic produced the required publications on impossible schedules deserves special mention. The third special mention is to Mrs. Jean MacCutcheon for her essential assistance with the post-conference activities and the editing of these Proceedings.

Probably the most impressive feature of the whole effort was the large number of people who contributed substantial time, effort and resources in the roles of authors, speakers, workshop leaders, session chairmen or committee members. More than 350 volunteers provided these essential functions in support of the 8th Ocean Energy Conference.

The final camera-ready copy of these proceedings was delivered to the Department of Energy in May 1982, matching the budget schedule. In June we were informed that the entire final copy had been lost somewhere in the printing process. The credit for managing the construction of a replacement camera-ready copy goes to Professor Charles Cochran of the U.S. Naval Academy and to the 29 authors who provided 100 replacement half-tone illustrations.



E. M. MacCutcheon
Chairman, 8th Ocean
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DRALEY, J. E.
IIC1 371

DUGGER, Gordon L.
IE1 217

DUNBAR, Lyle E.
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EATON, Russel
IVA5 607

ERICKSON, Edward L.
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ESKANDER, Samir S.
VIC4 879

FANNING, Kent A.
IIIC5 537

FINK, Lloyd
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FJELD, Sven
IA7 51

FORNSHELL, John A.
IIIC11 565

FOUST, Harry D.
VA3 717

FRANCIS, Evans J.
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FRY, David J.
IIIB1 467

FRYDENLUND, A.
VIA9 841

FRYE, D.
VIIA7 1003

FULLER, Roger D.
VB1 775

GANTZ, Donald T.
VIA4 821

GARDY, David
VIA8 833

GAVIN, A. P.
IIC4 389

GAY, Forrest T., III
VIB4 859

GENENS, L.
IIC6 399

GEORGE, James
IB2 77

GERSHUNOV, Evgeny M.
IA9 69
VIIA4 991

GIANNOTTI, Julio G.
IIIC10 551

GILBERT, Barbara Jean
VIC1 867

GOETZ, Ted E.
VIIA5 997

GOLSHANI, Abie
IIA6 311

GONZALES, Juan G.
IIIC11 565

GRANNEMANN, G. M.
IIC4 389

GREEN, Herbert Jim
IIA5 303

GREEN, William L.
IA6 45
IVB2 633

GREENLAND, Arnold
VIA4 821

GRIFFIN, Owen M.
IA5 35

GRITTON, E. C.
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GROTE, Phillip B.
IA3 31
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GUILD, Donald H.
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GUNTER, G.
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HAGERMAN, G. M.
IC1 133

HALLANGER, Lawrence W.
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HAMMOND, R. Philip
IIA3 291

HARMS, Volker W.
IIIC12 575

HARRISON, G. E.
IA6 45

HARTWIG, Eric
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IIIC2 507
IIIC4 527
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HENDERSON, R. W.
IVC1 665

HESS, R. W.
VIC2 873

HILLER, Michele
VIB3 857

HILLIS, David
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HIRABAYASHI, M.
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HOGBOM, Thomas
IC3 155

HOLM, John
VA8 753

HOVE, Duane T.
IA3 31

HOWARD, P. A.
VIIA3 977

HUDON, Thomas J.
IC6 175
ID2 183

HUGHART, David
VIE7 963

HUMPHREYS, Adrian H., III
IIIB5 495

IMAN, S.
IID1 403
IID2 409

ISO, Shunya
IA8 61

JANSON, Jan Erik
IC3 155

JAWISH, William K., III
IA2 25

JIRKA, Gerhard H.
IIIB2 475

JOHNSON, D. H.
IIA5 303

JONES, Anthony
IIIC3 519

JONES, J. M.
IIIB2 475

JONES, Malcolm S., Jr.
IVB2 633
IVB6 643

KAJIKAWA, Takenobu
IC5 167
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KAMOGAWA, HIROSHI
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KATO, Hiroharu
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KEITH, Kent M.
VIB6 863
VID2 919

KINCAIDE, William C.
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KING, Raymond W.
IID6 431

KLINE, Jeffrey E.
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KNAUER, George A.
IIIC5 537

KRATZ, J. L.
IIB3 335

KUBIAK, David A.
IIIB1 467

KURT, Jeffrey P.
IVA2 595
IVA4 603

KUSUDA, H.
VB8 803

KUZAY, T. M.
IIC4 389

LAKSHMI, G. J.
IIIC4 527

LARSEN-BASSE, Jorn
IID4 421

LAVI, Abrahim
IIB2 329
VIC7 899

LAWRENCE, Michael F.
VIA3 815

LAWSON, J. E.
IVA3 599

LEAVITT, K.
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LEE, Theodore T.
IA3 31

LEWIS, Richard O.
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LIBBY, D.O.
IVA6 617

LIEBERT, Bruce E.
IID4 421

LINDMANN, Ross
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LOPEZ, Jose Manuel
IIIC11 565

LORENZ, J. J.
IIB1 319
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LOTKER, Michael
VIC1 867

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IIB5 355

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IVB2 633

MAEDA, N.
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MANLEY, Richard N.
IVB7 649
VIC6 889

MARINA, Jose
VIA6 827
VID4 927

MARTIN, Lowell F.
VIB1 849

McCLUNEY, Ross
VID3 923

McCORMICK, Michael
ID2 183

McGUINNESS, Terence
IA1 19

McNERNEY, N.E.
IV4 599

MEGGIT, Dallas
IB5 107

MELLOR, George L.
IIIB4 483

MENCHER, Frederick M.
IVC5 695

MEYER, A. E.
IID6 431

MICHEL, John W.
IIB4 347

MIDBOE, Eric
ID2 183

MIDORIKAWA, Koki
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MILES, John B.
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MILLER, Eugene P.
VIC8 909

MIYATA, H.
IE6 253

MOAK, Kevin E.
IC1 133

MONDE, Masanori
VB8 803

MORELLO, Aldo S.
VA7 747

MORGAN, Thomas O.
IID1 403
IID2 409
IID3 415

MORRISON, Todd A.
VIA3 815

MURRAY, John N.
IVC4 685

MYERS, Edward P.
IIIA3 453

NAKAMOTO, Yasunobu
IC4 161

NAKAOKA, T.
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NEUMAN, Lawrence D.
VIE2 957

NODA, E. K
VIIA7 1003

NORIEGA, Jaime P.
IIA4 297

NORLING, Richard D.
VID1 915

NORMARK, W. R.
IIIC7 547

NORTH, Wheeler J.
IE5 249

NUNN, Geoffrey N.
IVA7 625

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OHTA, T.
IE6 253

OLSON, D. A.
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OSOFSKY, Irving
IA3 31

O'SULLIVAN, J. B.
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OZUDOGRU, Yilmaz H.
IA9 69
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PADDISON, Fletcher C.
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PATTISON, John
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PEI, Richard Y
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PENNY, Terry R.
ID3 189
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PICHA, Kenneth G., Jr.
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QUINBY-HUNT, Mary S.
IIIA1 439
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RABAS, T. J.
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REVUELTA, R.
IID1 403
IID2 409

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VA6 741

RICHARDS, Dennis
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IVC1 665
VA10 769

RIDGEWAY, John R., Jr.
VIA6 827

RIDGWAY, Stuart L.
IIA3 291

RIVERA, C. J.
IID3 415

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IVA4 603

ROGALSKI, William W.
IC6 175
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ROGERS, John D.
IIA2 277

ROSENBLATT, Joel A.
VIC1 867

ROSS, Jonathan M.
IB3 85

ROTUNDO, Louis C.
VID3 923

RYAN, Constance J.
IIIC3 519

ST. ONGE, Hugh
IVA3 599

SANDS, M. Dale
IIIA4 461

SARGENT, F. E.
IIIB2 475

SASSCER, Donald S.
IID1 403
IID2 409
IID3 415

SATHER, Norman
IIB1 319

SATHJANARAYNA, K.
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SCHULTZ, Jeffrey A.
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IVA5 607

SCOTTI, Richard S.
IA2 25

SEREN, L.
IIB1 319

SHEETS, Herman E.
IIB7 361

SHELPUK, Benjamin
IIA1 271

SHEPHERD, Richard F.
VIA4 821

SHERBURNE, Clinton, P.
ID5 199

SHIMOGO, T.
IA8 61

SHIPMAN, Holton B., Jr.
VIA4 821

SINGARELLA, Paul N.
IIIB1 467

SNYDER, J. Edward
VA4 723

SODEN, James E.
IVA6 617

SOTELO, J.
VIA9 841

SPENCER, R. B.
IVC5 695

SPILLER, J. Robert
IVA6 617

STETTNER, Roger
ID6 205

STEVENS, H. C.
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SULLIVAN, S. Mack
IIIA1 439
IIIA3 453

TAKAHASHI, Kenichi
ID7 211

THIAGARAJAN, V. V.
IVB6 643

THOMAS, Anthony
IIB1 319

THOMPSON, David F.
IIA2 277

TOSTESON, Thomas R.
IID1 403
IID2 409

TOTH, Csanad
VIE3 961

TRIMBLE, Lloyd
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UEHARA, Haruo
VB8 803

UEMURA, K.
IE6 253

UMANS, S. D.
VIA9 841

VEGA, Luis A.
IB4 95
IE3 235
IIIC10 551

VENKATARAMIAH, A.
IIIC4 527

WALENTOWICZ, Richard
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WALSH, Ted W.
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WANG, Dong-Ping
IIIB6 503

WATTS-FITZGERALD, Thomas A.
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WERNER, Edgar
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WILDE, Pat
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WILSON, James L.
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WOOD, William A.
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YAMANE, Kazuo
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IA8 61

YARDEN, Abraham
VA4 723

YOSHIDA, K.
IA8 61

YOSHIOKA, Paul M.
IIIC11 565

YOUNG, M. I.
IIA2 277

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IIB2 329

ZAIDI, B. R.
IID1 403
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ZENER, Clarence
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Session Group IV

ENERGY TRANSFER AND UTILIZATION

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METHODS OF PREDICTING LOADING AND BENDING INDUCED IN AN OTEC RISER CABLE

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INTRODUCTION

One of the key elements in the successful design of a power transmission riser cable for the OTEC program is the ability to predict dynamic tension and bending. The riser cable must be able to withstand variations in tension and bending imposed on it from the motions of an OTEC platform and its environment. In addition to being able to withstand extreme loading conditions the cable must be designed so as not to fail due to mechanical fatigue of its structural components.

Two methods of predicting dynamic tension and bending are presented. One method uses a discrete lumped mass system to model the cable, while the other uses energy techniques to provide a continuous solution. Both methods are used to develop a set of cable transfer functions for tension and bending. Statistical techniques are then employed to develop predicted yearly tension and bending histories. These are used to predict fatigue in specific cable components.

The lumped mass model has been used to provide a predicted static tension with the cable loaded only by its own weight and steady-state current conditions.

STATIC TENSION

For the purpose of calculating static tension a continuous cable system is replaced by an equivalent discrete system composed of a finite number of straight, weightless segments connected at nodal points (See Figure 1). All external forces acting on the cable system are considered to act at these points. The external forces applied to the system can include the cable's weight, current drag and any other steady-state forces.

The method of solution used for the equilibrium cable configuration is the "method of imaginary reactions". To begin the analysis an initial estimate of the reaction forces at the top of the cable system is made (See Figure 2).

Since the resultant of all external forces acting at either end of a cable segment must be equal, opposite and colinear it is possible to use this

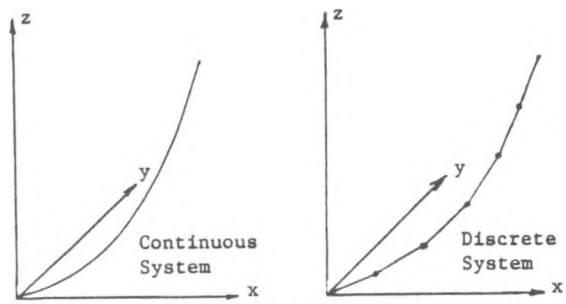


Figure 1

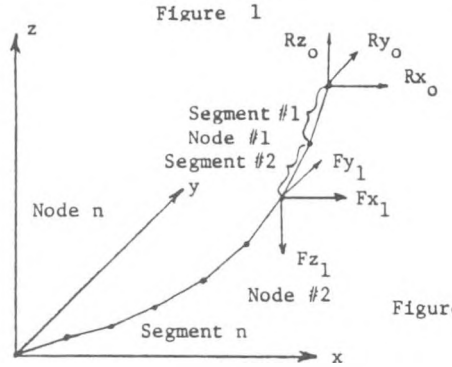


Figure 2

initial estimate to make a first cut at the reaction forces in each cable segment. If Rx_0, Ry_0, and Rz_0 are the reaction forces at the cable termination point, then the reaction forces at the first node below the termination can be found by:

$$Rx_1 = Rx_0 - Fx_0$$

$$Ry_1 = Ry_0 - Fy_0$$

$$Rz_1 = Rz_0 - Rz_0$$

Likewise the reaction forces at the second node below the cable termination point are:

$$Rx_2 = Rx_0 - Fx_0 - Fx_1$$

$$Ry_2 = Ry_0 - Fy_0 - Fy_1$$

$$Rz_2 = Rz_0 - Fz_0 - Fz_1$$

This continues down the cable with the reaction forces at any node n being found by:

$$Rx_n = Rx_0 - \sum_{i=0}^{n} Fx_i$$

$$Ry_n = Ry_0 - \sum_{i=0}^{n} Fy_i$$

$$Rz_n = Rz_0 - \sum_{i=0}^{n} Fz_i$$

Using these calculated reaction forces at each node the tension in cable segment n is found by:

$$T_n = \sqrt{(Rx_{(n-1)})^2 + (Ry_{(n-1)})^2 + (Rz_{(n-1)})^2}$$

Using the reaction forces at each node and the tension in each cable segment it is now possible to begin at the end of the cable on the seafloor and proceed up the cable calculating the coordinates of each node point. If the coordinates of node n are known to be (Xn, Yn, Zn) then the coordinates of node (n-1) are found by:

$$X_{(n-1)} = X_n + (L * \frac{Rx_{(n-1)}}{T_n})$$

$$Y_{(n-1)} = Y_n + (L * \frac{Ry_{(n-1)}}{T_n})$$

$$Z_{(n-1)} = Z_n + (L * \frac{Rz_{(n-1)}}{T_n})$$

where

L = Cable segment length.

In this manner the positions of each node are calculated based on an initial estimate of the reaction forces at the top of the cable. The position of the top node is calculated based on this estimate and compared with the desired coordinates for this point. If the calculated position is beyond some acceptable error bounds from the desired position, the initial estimate of the reaction forces is incremented and the whole procedure repeated. In this manner, an iterative procedure is carried out until an equilibrium configuration satisfying the specified boundary conditions is found.

DYNAMIC TENSION

A. Energy Method

This analysis, described more fully in Reference 1, considers one end of a cable which is subjected to random displacements $u_p(t)$ and $v_p(t)$, as shown in Figure 3. The resulting quasistatic response at any point along the cable is denoted by $q_n(s,t)$ and $q_t(s,t)$, which are measured normal to and along the cable axis respectively, and are described by:

$$q_n(s,t) = \frac{\partial q_n}{\partial u_p} u_p + \frac{\partial q_n}{\partial v_p} v_p + \Delta q_n$$

$$q_t(s,t) = \frac{\partial q_t}{\partial u_p} u_p + \frac{\partial q_t}{\partial v_p} v_p + \Delta q_t$$

Δq_n and Δq_t are displacements due to oscillatory deformation modes and are described by:

$$\Delta q_n = \sum_{i=1}^{\infty} \phi n_i(s) \quad \xi_i(t)$$

$$\Delta q_t = \sum_{i=1}^{\infty} \phi t_i(s) \quad \xi_i(t)$$

Where $\phi_{ni}(s)$ and $\phi_{ti}(s)$ are eigenfunctions

$\xi_i(t)$ is the normal coordinate of i^{th} oscillatory mode.

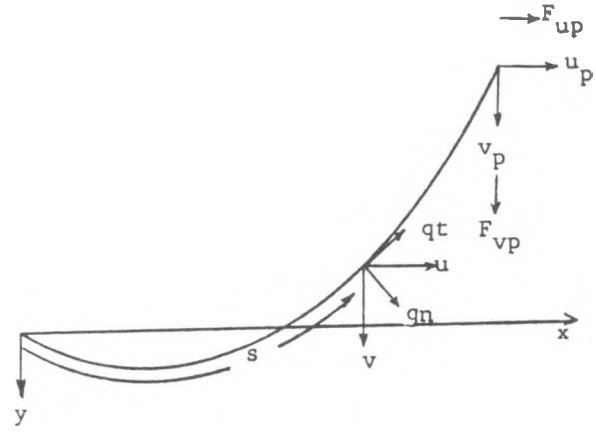


Figure 3 - Axis System for Cable Dynamics

By first describing the kinetic and potential energy of the cable and then applying Lagrange's equation to the n + 2 degrees of freedom, Up, Vp, ξ_1, ξ_2, .., ξ_n, the equations of motion may be found. The vertical component of tension constitutes most of the total tension. The equation of motion for the vertical component of tension is:

$$\begin{aligned}
&\ddot{V}_p \int_0^s \left[\left(\frac{\partial q_n}{\partial v_p}\right) + \left(\frac{\partial q_t}{\partial v_p}\right)^2\right] m\,ds \\
&+ \ddot{U}_p \int_0^s \left[\frac{\partial q_n}{\partial u_p}\frac{\partial q_n}{\partial v_p} + \frac{\partial q_t}{\partial u_p}\frac{\partial q_t}{\partial v_p}\right] m\,ds \\
&+ \int_0^s \left[\ddot{\Delta q}_n \frac{\partial q_n}{\partial v_p} + \ddot{\Delta q}_t \frac{\partial q_t}{\partial v_p}\right] m\,ds \\
&+ 2m\omega\zeta \dot{u}_p \int_0^s \frac{\partial q_n}{\partial u_p}\frac{\partial q_n}{\partial v_p}\,ds \qquad (1) \\
&+ 2m\omega\zeta \dot{v}_p \int_0^s \left(\frac{\partial q_n}{\partial v_p}\right)^2 ds
\end{aligned}$$

$$+ 2m\omega^2 \zeta \sum_{i=1}^{\infty} \int_{o}^{s} \phi n_i \frac{\partial q_n}{\partial v_p} \dot{\xi}_i \, ds \qquad (1)$$

$$= F_{yp}$$

Where m is the mass per unit length and ζ is the damping coefficient.

Equation (1) is used to find the mechanical admittance function, $H_F(\omega)$, defined by:

$$F(t) = H_F(\omega) \quad v(t)$$

Where v(t) is the displacement function in the time domain. The transfer function $Y(\omega)$ is related to the mechanical admittance function by the expression:

$$Y(\omega) = [H_F(\omega)]^2$$

The dynamic tension spectrum, S_T, can then be related to the platform response spectrum, S_R, by the relation:

$$S_T(\omega) = Y(\omega) \quad S_R(\omega)$$

It follows that the mean square value of the vertical component of dynamic tension $\overline{F_{yp}}$ is:

$$\overline{F_{yp}}^2 = \int_{o}^{\infty} [H_{Fyp}]^2 \, S_y(\omega) \, d\omega$$

B. Lumped Mass Method

The dynamic component of cable tension for a lumped mass system is found through solution of the equations of motion using the impedance method. The general form of the equations of motion system with viscous damping is:

$$M\{\ddot{q}\} + C\{\dot{q}\} + K\{q\} = \{Q(t)\} \qquad (2)$$

where

M	=	n x n	Mass Matrix
C	=	n x n	Damping Matrix
K	=	n x n	Stiffness Matrix
$\{\ddot{q}\}$	=	n x 1	Acceleration Vector Matrix
$\{\dot{q}\}$	=	n x 1	Velocity Vector Matrix
$\{q\}$	=	n x 1	Displacement Vector Matrix
$\{Q(t)\}$	=	n x 1	External Forcing Function Vector Matrix

The number of degrees of freedom the system will have corresponds to the number of generalized coordinates required to describe it. A discrete cable system represented by m masses will have n = 3 x m number of degrees of freedom since each mass may translate in all three orthagonal directions.

In solving the equations of motions using the impedance method the first task is to develop the three major matrices used in the equations of motion. These are the mass matrix, the damping matrix, and the stiffness matrix.

The mass matrix is a diagonal n x n matrix made up of elements that are the product of segment length times the mass per unit length of the cable times an appropriate coefficient of added mass. This matrix is formed in local coordinates with the cable element mass in the axial direction unchanged from the actual mass and the cable element mass in the normal direction accounting for entrained water. It is assumed that each node carries the mass of one cable segment. The two exceptions to this are the two nodes at the ends of the cable, each of these is assumed to carry only one-half of a cable segment.

In order to develop the stiffness matrix K, it is first necessary to develop a flexibility matrix D. The flexibility matrix is developed by using the method of imaginary reactions, (described in the section on static tension), to solve for the equilibrium configuration of the cable. After this an influence force (U) is applied at each node, one node at a time. With the influence force applied at one node the deflected positions of each node from the equilibrium configuration are calculated. This systematic application and removal of the influence force (U) at each node provides a set of influence coefficients, which define the static elastic characteristics of the system. The quantity d_{ij} is the deflection at station i due to the application of the influence force (U) at station j when this is the only force applied. The influence coefficients, which are the actual node displacements from the initial equilibrium configuration, form n column vectors of length n which make up the flexibility matrix shown in Figure 4.

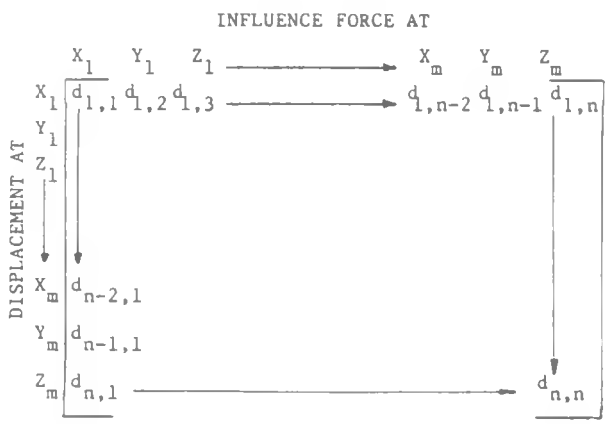


Figure 4 Flexibility Matrix

The flexibility matrix will be symmetric in keeping with Maxwell's reciprocity theorem because the solution is constrained to small deflections, linear analysis. Once the flexibility matrix has been completed it is inverted and postmultiplied

by the influence force ($\hat{U}$) in order to obtain the stiffness matrix. Normally, it is very convenient to treat the hydrodynamic forces as either normal or tangent to the cable axis. For this reason the equations of motion are solved in local coordinates and the stiffness matrix, which has been developed in global coordinates, is transformed to local coordinates.

In this analysis the only damping considered is from viscous fluid drag. Normally, viscous fluid drag is described as a quadratic function of relative normal velocity between the cable and the fluid. For the purposes of this effort the quadratic drag force will be replaced by an equivalent linear drag force. This linear drag force is defined to provide a rate of dissipation of energy equal to that of the quadratic drag force. The damping matrix is made up of linear drag coefficients multiplied by cable segment length. The relationship between the quadratic drag coefficients and the equivalent linear coefficients is:

$$C_L = \frac{8\omega a}{3\pi} C_D$$

where

C_L = Linear Drag Coefficient

C_D = Quadratic Drag Coefficient

a = Amplitude of Regular Harmonic Motion

ω = Frequency

If the cable motion is a Gaussian random motion having an RMS relative velocity given by σ_v then the linear drag coefficient can be found by:

$$C_L = \left(\frac{8}{\pi}\right)^{\frac{1}{2}} \sigma_v C_D$$

In order to solve this relationship it is necessary to know either the amplitude or RMS amplitude of cable motion. Presently, an initial value is assumed for C_L and the motion equation is solved to obtain a new amplitude. The new amplitude is used to find a new value for C_L. In this manner, an iterative process is continued until there is little change in the values computed for C_L.

The general form of the equations of motion for an n - degree-of-freedom system was shown in equation (2). In this analysis the harmonic forcing vector $\{Q\}$ is zero except for the top node. The magnitude of this force vector is chosen to provide a one foot displacement at the cable termination in each axis. This motion at the top node of the cable is what drives the cable.

Using the impedance method (described more fully in Reference (2)), to solve Equation (2), we substitute a harmonic force vector $\{F\}$ for the generalized force $\{Q(t)\}$ where $\{F\} = \{\bar{F}e^{j\omega t}\}$ and the n x 1 matrix $\{\bar{F}\}$ is the phasor of $\{F\}$. Let $\{X\}$ be the harmonic response, where $\{X\} = \{\bar{X}e^{j\omega t}\} = \{\bar{X}e^{j\omega t}\}$ and $\{\bar{X}\}$ is the phasor of $\{X\}$. Applying the impedance method and factoring out $e^{j\omega t}$ Equation (2) becomes:

$$-\omega^2 M\{\bar{X}\} + j\omega C\{\bar{X}\} + K\{\bar{X}\} = \{\bar{F}\} \qquad (3)$$

or

$$[K - \omega^2 M + j\omega C]\{\bar{X}\} = \{\bar{F}\} \qquad (4)$$

This equation may alternately be written as:

$$\begin{bmatrix} k_{11} - \omega^2 m_{11} + j\omega C_{11} & \cdots & k_{1n} - \omega^2 m_{1n} + j\omega C_{1n} \\ \downarrow & & \downarrow \\ k_{n1} - \omega^2 m_{n1} + j\omega C_{n1} & \cdots & k_{nn} - \omega^2 m_{nn} + j\omega C_{nn} \end{bmatrix} \begin{bmatrix} \bar{X}_1 \\ \downarrow \\ \bar{X}_n \end{bmatrix} = \begin{bmatrix} \bar{F}_1 \\ \downarrow \\ \bar{F}_n \end{bmatrix}$$

Equation (5)

If $z_{iy} = (k_{iy} - m_{iy} + j\, C_{ij})$, then Equation (5) may be written as:

$$\begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \downarrow & & \downarrow \\ z_{n1} & \cdots & z_{nn} \end{bmatrix} \begin{bmatrix} \bar{X}_1 \\ \downarrow \\ \bar{X}_n \end{bmatrix} = \begin{bmatrix} \bar{F}_1 \\ \downarrow \\ \bar{F}_n \end{bmatrix} \qquad (6)$$

or

$$Z(\omega)\ \{\bar{X}\} = \{\bar{F}\} \qquad (7)$$

where $Z(\omega)$ is the impedance matrix. The cable response is found by:

$$\{\bar{X}\} = Z(\omega)^{-1}\{\bar{F}\} \qquad (8)$$

By repeating the above solution for each frequency of interest the response of the system to a unit amplitude motion of a given frequency at the cable termination is found. The forces in each segment in local coordinates are found by multiplying the impedance matrix by the solution vector $\{\bar{X}\}$. The force in the axial direction is the cable tension.

C. Tension Predictions

Table 1 presents the calculated root-mean-square tension using both the energy method and the lumped mass method for several significant wave heights.

Wave Height	rms Tension (lbs.) Energy Method	Lumped Mass Method
2	1	65
4	40	110
6	150	196
7	250	301
8	500	575
10	1100	1605
12	1800	3060
16	4400	6070
18	5900	7325
20	7300	8417

Table 1
Comparison of rms Tensions for Direct Riser

Rayleigh statistics are employed to reasonably distribute the tension. The Rayleigh probability density, $p(\Delta T)$, is given by:

$$p(\Delta T) = \frac{2\Delta T}{\overline{\Delta T^2}} \exp\left(-(\Delta T)^2 / \Delta T^2\right) \qquad (9)$$

where $\overline{\Delta T^2}$ is the mean square tension.

A tension history may be formed by integrating Equation (9) and multiplying the curve by the expected number of cycles of tension. Figure 5 shows two tension histories of the riser cable for 30 years of service based on Table 1.

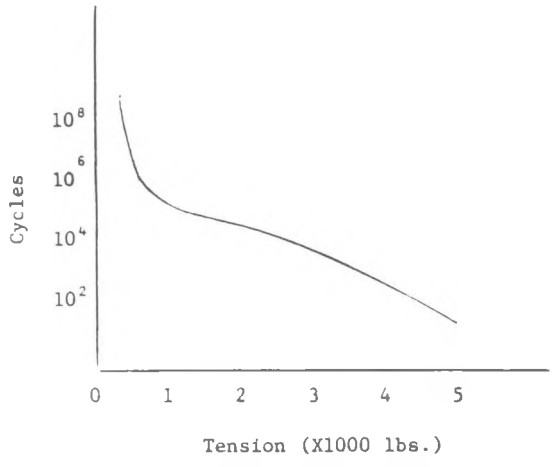


Figure 5 - Tension History of Riser Cable

D. Fatigue Predictions

The armor wire is the component of the cable which carries the load of the cable and is the component of concern when considering fatigue due to spectrum loading. This fatigue analysis is based on Miner's fatigue damage criteria (Ref. 2). The fraction of life of the material, D_i, is expressed by:

$$D_i = \frac{n_i}{N_i} \qquad (10)$$

When n_i is the number of cycles experienced at stress level σ_i, and N_i is the number of cycles to failure at σ_i. It is hypothesized that failure occurs when the cumulative damage, D, becomes unity.

The expected number of cycles, n_i, at stress level σ_i, is given by:

$$n_i = N_c p(\sigma) d\sigma$$

where N is the total number of expected cycles and $p(\sigma)^c$ is the probability density. The expected damage, E[D], is then found by summing the damage at each stress level as is expressed by:

$$E[D] = N_c \int \frac{p(\sigma)d\sigma}{N(\sigma)} \qquad (11)$$

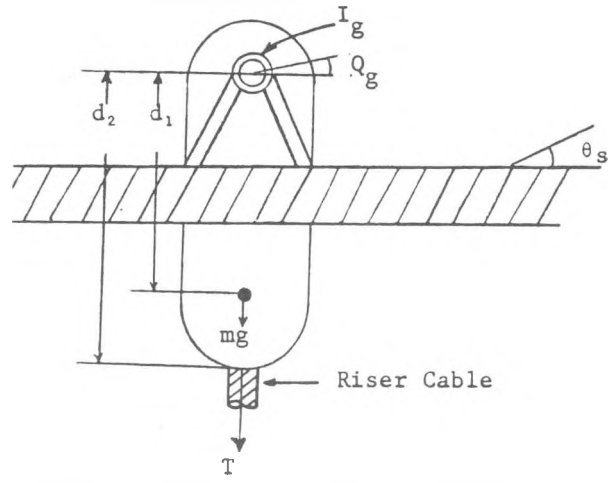
$N(\sigma)$ may be found from a fatigue curve of the material.

The expected damage for the armor wire for the sample case using Equation (11) was found to be 0.00017 for 30 years using the energy method and using the lumped mass method.

DYNAMIC BENDING

A. Gimbal Response

The most critical location for bending of the lead sheath in the OTEC riser cable is at the attachment point to the platform. The cable is attached to the platform via a gimbal which is interposed to reduce the bending on the cable. Figure 6 shows the gimbal being forced to rotate θ_g as the ship rotates θ_s.



Gimbal Response to Plantship Motions

Figure 6

The equation describing the motion of the gimbal is obtained by summing the moments about its pivot point. For small angles of θ_g, the equation may be written:

$$I_g \ddot{\theta}G + c\dot{\theta}g + (mgd_1 + T\,d_2)\,\theta g = c\omega\theta_{so} \sin \omega t$$

Where I_g is the inertia of the gimbal
c is a friction constant
mg is the weight of the gimbal
d_1 is the distance from the pivot to the center
T is the tension in the cable
d_2 is the distance from the pivot to the cable tension vector
θ_{so} is the amplitude of ship rotation

Assuming the steady state solution is of the form:

$$\theta_g(t) = A \sin \omega t + B \cos \omega t$$

the constants A and B can then be determined.

The gimbal amplitude, θ_{go}, is then related to the ship response amplitude by the expression:

$$\frac{\Theta go}{\Theta so} = \frac{c}{\sqrt{\left[Ig - \frac{1}{Ig}(mgd_1 + Td_2) - \omega^2\right]^2 + c^2\omega^2}} \qquad (12)$$

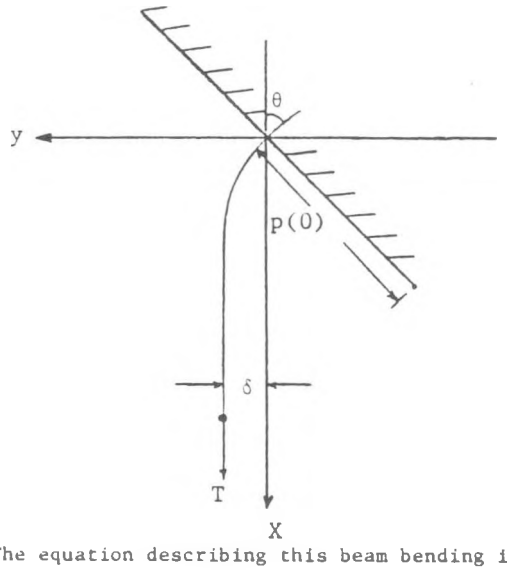
Equation 12 is used as a transfer function to generate a gimbal rotation spectrum from the ship motion spectrum in the following way:

$$S_{\Theta_g}(\omega) = \left[\frac{\Theta go}{\Theta so}(\omega)\right]^2 S_{\Theta_s}(\omega) \qquad (13)$$

B. Curvature of Cable End

This analysis models the end of the cable as a massless beam which has a stiffness, EI, equal to the properties of the riser cable. This beam is fixed to a gimbal at one end and pinned to a catenary at the other end. Figure 7 shows the bending of this massless beam between the gimbal and the cable catenary as the gimbal rotates, Θ, about its axis.

Figure 7 - Bending of Cable End



The equation describing this beam bending is:

$$\frac{d^2y}{dx^2} = \frac{M(y)}{EI} = \frac{1}{\rho} = \kappa \qquad (14)$$

Where

M(y) is the bending moment
EI is the cable stiffness
ρ is the radius of curvature
κ is the curvature

The beam is pinned to a catenary by matching the slope of the beam to meet the slope of the catenary. Solving Equation 7 and applying the proper boundary conditions yields the curvature, κ, for small angles at the attachment point to be:

$$\kappa = \sqrt{\frac{T}{EI}}\,\Theta \qquad (15)$$

Where

T is the tension of the cable
Θ is the gimbal rotation in radians

Since the plantship response is given in terms of response spectra, Equation 15 is rewritten as:

$$\kappa_{rms} = \sqrt{\frac{T}{EI}}\,\Theta_{rms}$$

Where

$$\Theta_{rms} = 2\sqrt{2\int_0^\infty S_\Theta(\omega)d\omega}$$

$S_\Theta(\omega)$ is the gimbal pitch or roll response spectrum

C. Predictions

As an example, the riser cable attached to the plantship platform in 4,000 feet of water is analyzed. Using parameters which are typical of this system, Table 2 presents a comparison of the curvature and radius of curvature for 20 foot significant wave height in head seas. Miner's damage in the lead sheath of the riser cable is also calculated for the two cases from Equation 11.

Table 2
Plantship and Gimbal Motion Comparison

	Plantship	Gimbal
Single Amplitude Θ_{rms} (deg.)	3.22°	.076°
Curvature (ft.$^{-1}$)	.0502	.00119
Radius of Curvature (ft.)	19.9	843
Miner's damage (30 years)	960	.011

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TESTING OF OTEC RISER CABLE COMPONENTS AND MODELS

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The OTEC riser cable application places new demands on traditional high voltage cable materials and requires the use of materials not historically utilized by submarine power cable. To indicate the suitability of the material selections for the prototype cable designs, a series of tests on riser cable components and riser cable models were performed. These tests focused on two elements of the prototype riser cable: the external strength member and the sheath.

The external strength member must support the entire weight of the OTEC riser cable. The prototype cable designs use a torque-balanced double armor of the austenitic stainless steel AL-6X* as the strength member. In order to meet the thirty year life, the primary design concerns for the strength member are corrosion and corrosion fatigue of the armor wire.

To study corrosion of the cable, eight different 15-inch long full-scale models of the "wet" section of the cable were deployed at depths of 25 feet and 200 feet at two potential OTEC sites: off Punta Tuna, Puerto Rico, and off Keahole Point, Hawaii. These models are based on sections of 2-inch diameter high density polyethylene pipe to which layers of jute, AL-6X armor, nylon roving, tar and 715 copper nickel sheathing have been applied in various combinations typical of potential OTEC riser cable designs. The Punta Tuna samples were removed after nine months of exposure. Only a thin layer of fouling developed over this time period, consisting of mainly algae and hydroids. The armor wires are in the process of cleaning to check for corrosion. A one-year immersion is planned for the Keahole Point samples, which should end in early 1982.

Nearly 100 samples of commercially-produced, 180,000 psi ultimate strength, 15-inch diameter AL-6X were fatigued in natural seawater at four different laboratories, LaQue Center for Corrosion Technology (LCCT), Battelle Columbus, Dr. Wm. Hartt of Florida Atlantic U., and Simplex Wire & Cable Co. Roughly 40 of these samples broke without grip failure. The tests were performed with a nominal mean stress of 75,000 psi, cycling rate of 30 Hz, and alternating stresses ranging from 13,000 psi to 60,000 psi. The resulting failures of the wire ranged from 10^4 to 10^7 cycles, and are plotted in Figure 1. A full logarithmic curve was fit to the data as shown in Figure 1, and is used as the design S-N curve. The equation of the least squares fit fatigue curve generated in this way is given below:

$$N = 2.99 \times 10^{24}\ S^{-4.3} \qquad (1)$$

N = number of cycles to failure

S = stress amplitude in psi

Additional tests were run at mean stresses of 30,000 psi and 0 psi. These tests indicate that with the sample in continuous tension, the effect of mean stress on fatigue life is insignificant. However, the fully-reversed stress loading indicated an increased life over the tests at 30 and 75 psi mean stress.

Tests at a 75 ksi mean stress were run at cycling rates of 3.5 and 0.0083 Hz in addition to the tests at 30 Hz to provide a range of total test times from a fraction of an hour to approximately 1300 hours. No effect of cycling speed was noted under these conditions.

Using the fatigue curve of equation (1), the Miner fatigue damage in the armor for a direct riser cable to an OTEC pilot plantship over 30 years is predicted to be below .005.

The main function of the sheath is to protect the insulation from moisture ingress. Fatigue of the sheath in the dynamic riser cable environment is one of the principal concerns in maintaining the hermetic seal over the insulation. Therefore, the sheath tests focused on fatigue.

* Trade name of Al Tech Specialty Steel Corp.

An extruded lead alloy covering is the traditional sheath for high voltage power cable, and the prototype cables use an arsenical lead sheath. The first step in evaluation of the arsenical lead sheathing material was the generation of an S-N curve for samples of removed cable sheaths in the range of 10^5 to 10^7 to failure. This data complements existing lead sheathing alloy fatigue data which normally extends to roughly 10^5 cycles to failure. The lead fatigue points were generated at a cycling rate of 30 Hz in room temperature air with a stress ratio of 0.1, with the samples in tension. The resulting data, along with literature data on similar lead alloys, is plotted in Figure 2. The best fit S-N curve to the generated fatigue data is a full logarithmic curve as given below:

$$N = 942\ S^{-3.05} \qquad (2)$$

N = number of cycles to failure

S = strain range in %

Since each decade of the arsenical lead fatigue data maintains a constant average slope, an endurance limit cannot be assumed.

A Miner's damage of 0.04 is predicted in the sheath of a direct riser cable to an OTEC pilot plantship over 30 years of service using Equation (2). This cumulative damage estimate assumes the riser cable is isolated from the angular motions of the OTEC plantship through a gimbal. If rigidly attached to the hull, the Miner damage in the sheath will go to unity in one or two years of service.

Further sheath fatigue tests using six different half-scale model cables were completed to act as a bridge between material data and the observed behavior of cable sheaths. The model cables are based on a common 15 kV XLPE power core covered with six different sheaths, including two arsenical lead sheaths, a copper bearing lead sheath, an extruded corrugated aluminum sheath, and seam welded, corrugated copper and aluminum sheaths. Two fatigue tests were applied to these model cables: a high cycle bending fatigue test and a low cycle bending fatigue test.

In the high cycle bending test the model cables were exposed to a 0.2% nominal strain range cycle in a rotating beam fatigue test. The cycling rate was 10 RPM. The relative sheath lives to fracture in the high cycle bend test are shown in Figure 3. In general, the results of this test could be predicted from the material S-N curves within about 40%.

In order to simulate the bends that a cable must endure during manufacturing, storage and handling, the low cycle fatigue test was completed. Sections of the model cable were flexed in fully-reversed bending over 3 foot and 5 foot radius bending guides at 12 cycles per minute. The relative lives to fracture in this test are shown in Figure 4. A plastic covering for the arsenical lead sheaths makes an improvement of two to three times in fatigue life in this test. With a plastic covering, the size of the buckles formed in the sheath prior to fracture is lessened. The smaller buckles act as less severe stress concentrations, allowing for longer fatigue lives.

The results of the OTEC riser cable have lead to a second series of materials tests. These tests will fatigue the AL-6X wire under variable amplitude loading, subject the lead to variable amplitude loading under fully-reversed stresses and at operating temperatures. The model arsenical lead cables will undergo a combination low cycle/high cycle bend test to study how a few tight bends affect the long term behavior of the cable. In addition to the sheath and armor wire, this second set of tests will begin to study the bending fatigue of a self-contained oil-filled laminated insulation.

Figure 1. FATIGUE OF AL-6X IN SEAWATER

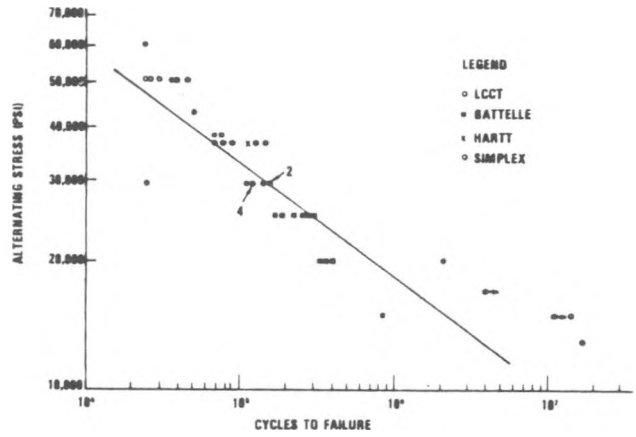


Figure 2. FATIGUE OF HABIRLOY C ARSENICAL LEAD

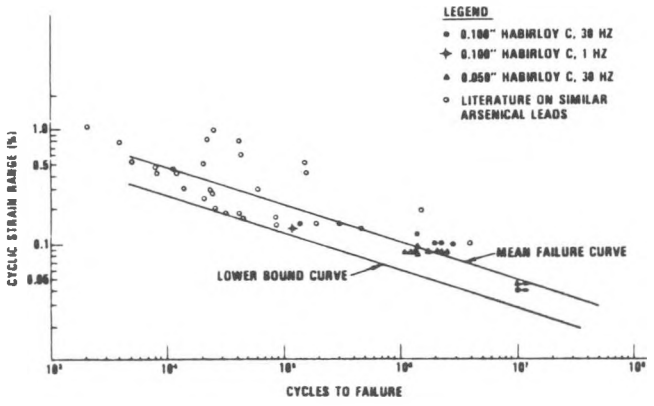


Figure 4. RELATIVE FATIGUE LIVES OF MODE C CABLE AT A 3 FT. BEND RADIUS

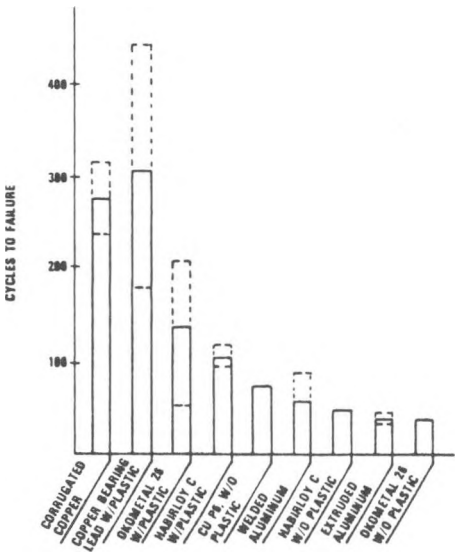
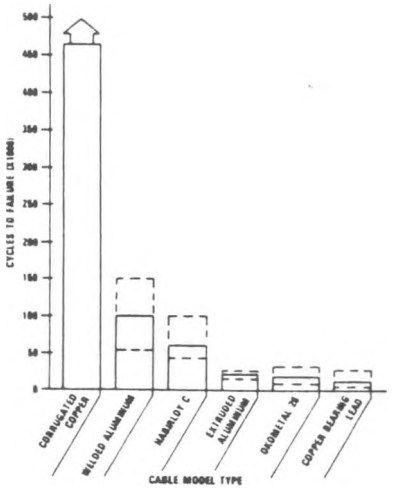


Figure 3. RELATIVE FATIGUE LIVES OD MODEL CABLES IN HIGH CYCLE BEND TEST



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ELECTRICAL/MECHANICAL CABLE TEST MACHINE DESIGN AND OPERATION

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ABSTRACT

This paper describes the design and operation of an electrical/mechanical (E/M) testing machine that is used to evaluate the performance of prototype OTEC riser cable designs. The E/M testing machine subjects samples of test cables to simultaneous dynamic tension, dynamic bending, voltage stress and current while the cable samples are in a seawater environment.

INTRODUCTION

OTEC riser cables will convey energy from a moored OTEC plant to a sea bottom cable. These riser cables are required to operate at depths of 6,000 feet while subjected to unprecedented static and dynamic loads for a power cable (Reference 1 and 2).

The riser cable test program includes a cable life simulation by an Electrical/Mechanical (E/M) testing machine designed and assembled by Simplex Wire and Cable Company and operated by Hydro Quebec Institute de Recherche (IREQ). This E/M testing machine subjects a riser cable sample to simultaneous cyclic tension, cyclic bending, voltage stress and current while the cable is in a seawater environment. Thus, the E/M testing program provides a unique opportunity to evaluate the performance of the riser cable designs being developed.

CABLE DESCRIPTION

Two riser cable designs have been manufactured for testing. One design utilizes an extruded cross-linked polyethylene (XLPE) dielectric (Figure 1), the other design utilizes a self-contained oil-filled (SCOF) dielectric (Figure 2). These two dielectrics were selected for their potential life expectancy in the OTEC application and because they can be utilized in riser cables with a reasonable extension of present power cable technology (Reference 3).

Both cable designs utilize a hermetic lead sheath. A hermetic sheath is required for the SCOF design as a fluid barrier and for the XLPE design to prevent ingress of water and water vapor to the dielectric (Reference 3).

The SCOF test cable utilizes a 1,250 kcmil copper keystone conductor with a .5 inch diameter oil channel. A 550 kcmil copper keystone conductor was originally called for in this design, but was unavailable during the time frame of cable manufacturing. The XLPE test cable utilizes a 350 kcmil round copper wire conductor.

Both cable designs have two layers of torque balanced AL6X armor wires as an external strength member. AL6X is an austenitic stainless steel which contains chrome and molybdenum. AL6X has an acceptable ultimate tensile strength for use in OTEC riser cables and has proven fatigue and corrosion resistance properties in seawater (Reference 3).

E/M TEST MACHINE DESIGN

The E/M testing machine is thirty-three and a half feet long, fifteen feet wide, and weighs approximately fourteen tons. The E/M testing machine subjects a riser cable sample to the levels of dynamic tension, dynamic bending, voltage and current expected during service.

The cable is mechanically terminated at each end of the machine with the electrical core of the cable continuing out of the terminations (See Figure 3 and 4). The length of cable between the terminations is 24 feet. Both terminations are wedged cone armor terminations, one of which is mounted to a hydraulic cylinder.

This hydraulic cylinder is connected to a separate hydraulic pump with an oil reservoir. The amount of tension exerted on the cable is controlled by an adjustable valve which controls the flow of hydraulic fluid from the cylinder. Hydraulic fluid returning from the cylinder to the reservoir

passes through a heat exchanger.

The length of cable between the terminations is surrounded by natural seawater. The seawater is continuously circulated in a closed system which includes two reservoirs. One reservoir is utilized as a main holding tank from which seawater is pumped through a heat exchanger to the second reservoir. Water from the second reservoir, which is one foot above the E/M tester, flows to the testing machine. The water temperature inside the E/M tester is maintained at 19°C, which is the average surface water temperature at the Punta Tuna OTEC site.

Cable bending is induced by a bending form located at the center of the machine (See Figures 3 and 4). The bending form induces bends in the cable as it transverses from side to side, moving a line of rollers with a 100-foot bend radius against the cable. Rollers on each side of the cable allow two opposite bends to be induced for each cycle of bending. The bending form is moved by an arm attached to an eccentric which is driven at 1 Hz by a 25 hp motor.

Bend restrictors prevent unacceptable bend radii at the terminations. These bend restrictors, like the bending form, utilize two lines of rollers with a 100-foot bend radius. Utilizing rollers to induce the bends minimizes cable chafing. All of the rollers are coated with plastic to prevent possible metal contact with the outer armor wires.

The electrical core of the cable that continues from the mechanical terminations is electrically terminated for 200 kV (2.5 times the rated phase to ground voltage). The testing protocol requires that the cable be energized to 200 kV during the test. Induced conductor current is required to bring the conductor temperature to the maximum predicted temperature at a mechanically stressed location during service.

ELECTRICAL/MECHANICAL TEST MACHINE OPERATION

The riser cable will experience maximum tensions at the OTEC plant during service with the static tension being the mean about which dynamic tensions cycle. This static tension can range from 50,000 to 100,000 lbs. for a direct riser cable, depending on the plantship position in the watch circle and the ocean current. The dynamic tension spectrum has been calculated for both operational and 100-year storm sea states (Reference 4), and will range to 40,000 lbs.

The hydraulic cylinder of E/M testing machine is programmed to tension the cable to nine different load levels above a base tension. Currently, six of these loads are being used to represent tensions during operational sea conditions and three load levels are used to represent tensions during the 100-year storm sea conditions (Reference 5). Each cable sample is mechanically tested for a period of one month, during which time 115 years of dynamic mechanical loads are modelled by the following sequence of tension spectra:

	1 - Five-year operational sea spectrum
11	1 - 100-year storm sea spectrum
repeats	1 - Five-year operational sea spectrum

The bending radius of the machine is constant, the frequency of bending is variable. The damage to the lead sheaths caused by actual service bending of the cable during the number of years simulated by the E/M testing has been established by Miner damage criteria. The number of cycles required to produce the same amount of sheath damage with a bending radius of 100 feet has also been established using Miner damage criteria. The bending frequency established for the E/M test provides the number of cycles required to produce equivalent damage at a 100-foot bend radius during the testing time period.

The cable is energized to 200 kV throughout the test and the service current is induced in the cable for 16 hours on, 8 hours off during the last half of the E/M testing period. Each cable sample is electrically tested before the E/M test and every five days during the test. Partial discharge and dissipation factor/capacitance measurements are made on the XLPE cable, dissipation factor/capacitance measurements are made on the SCOF cable and the ionization factor is determined. The electrical tests allow changes in the electrical portion of the core to be monitored during different stages of E/M testing.

The operation and monitoring of the E/M machine is performed by test personnel from a control station. From this station the valve on the hydraulic cylinder is automatically controlled. The water temperature, hydraulic fluid temperature and cable sheath temperature are continuously monitored. The number of bending and loading cycles are automatically recorded.

CONCLUSION

The E/M testing machine is giving cable engineers a unique opportunity to evaluate the performance of a power cable for utilization in a dynamic environment. The E/M testing machine is a critical part in the evaluation program of OTEC riser cable designs because of its capability of simultaneously bending the cable and dynamically tensioning it to loads of 200,000 lbs. while the cable is energized to 200 kV and loaded to realistic conductor temperatures.

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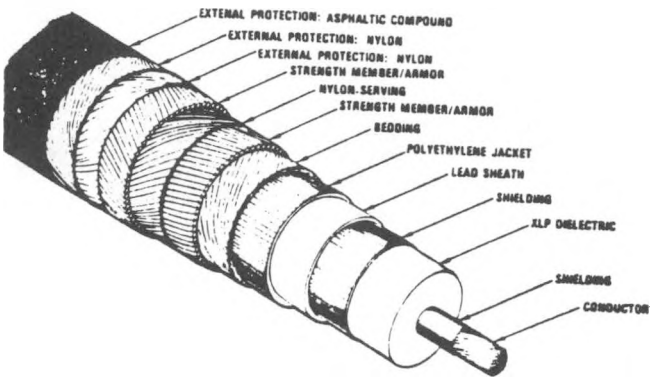


FIGURE 1

DESIGN OF THE CROSS-LINKED POLYETHYLENE RISER CABLE MANUFACTURED FOR THE OTEC TESTING PROGRAM

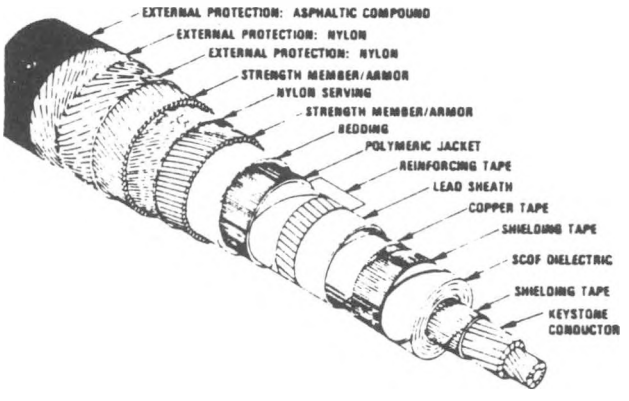


FIGURE 2

DESIGN OF THE SELF-CONTAINED OIL-FILLED RISER CABLE MANUFACTURED FOR THE OTEC TESTING PROGRAM

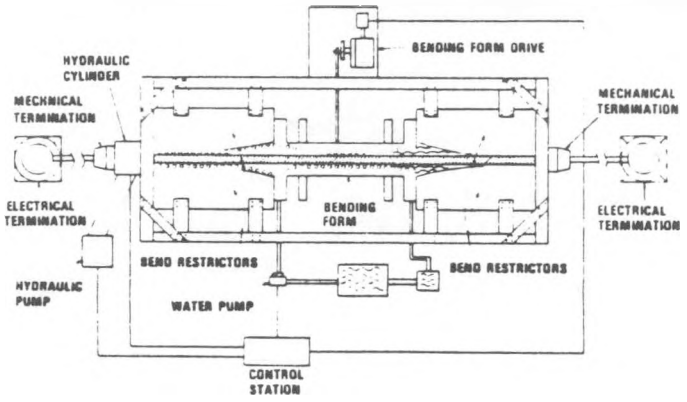


FIGURE 3
DESIGN OF THE ELECTRICAL/MECHANICAL TEST MACHINE

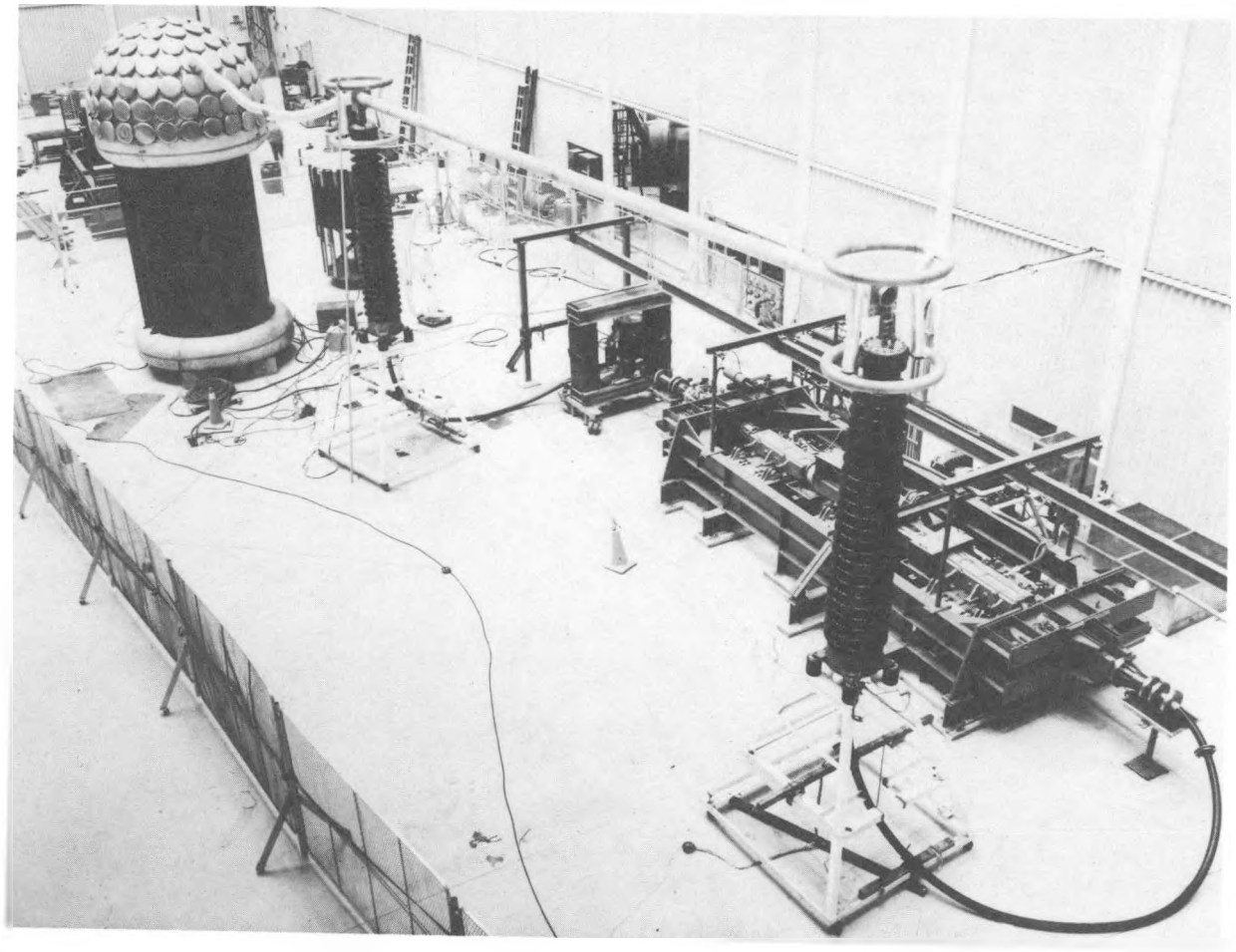


FIGURE 4
OUT OF THE ELECTRICAL/MECHANICAL TEST MACHINE AT IREQ

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TESTING OF FULL SCALE PROTOTYPE OTEC RISER CABLES

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1. INTRODUCTION

Two lengths of full-scale 100 MW prototype OTEC riser cable have been manufactured and will be exposed to the series of tests described in this paper. The object of these tests is threefold: to measure basic electrical and mechanical properties of the prototype OTEC riser cable, to determine if the prototype cables can meet the performance requirements for OTEC riser cable use, and to provide the background for the development of performance criteria for the pilot plant OTEC riser cables.

The prototype OTEC risers use two different insulations - a cross-linked polyethylene (XLPE) insulation and a self-contained oil-filled (SCOF) laminated paper insulation. The prototype cable constructions are shown in Figures 1 and 2. The two cables are insulated at a suitable level for 138 kV, three-phase service. Over the insulation both cables are similar. Both cables have an arsenical lead sheath. For the XLPE cable, the sheath is protected by a neoprene jacket reinforced by stainless steel tapes. The strength member of both cables is a torque-balanced double armor of special stainless steel wire.

2. MECHANICAL TESTS

The object of the mechanical tests is to measure the basic mechanical properties of the prototype OTEC riser cables. The mechanical properties of the cables are essential in describing the behavior of a riser cable system. In addition, the mechanical tests will yield information to relate the loads on the cable to local stresses within the cable construction. This information will allow better predictions of the strength and fatigue lives of the riser cable components.

Tension-elongation tests will be made for the copper conductor, the insulated, sheathed electrical core, and the complete armored cable. Tension-elongation curves and breaking strengths, along with tension-local strain curves, will be determined for each cable component. The completed cables will also have measurements made of cable tension-elongation, tension-twist, and tension-torque both with and without free rotating ends. These measurements will be made with cable loads up to 200,000 lbs., the full range of expected tensions on the cable.

An OTEC riser cable can be considered perfectly flexible over most of its length. However, at the ends which will endure the most severe service, bending must be considered. Bending stiffness tests have been performed on the two completed cables and cores to better describe the bending at the cable end. In the bending stiffness test, 3 meter lengths of cable have known moments placed on their ends and the resulting deflection is measured at ten points along the cable. A curvature is calculated from the deflection points. The bending stiffness is then found by relating the bending moments and their associated cable curvatures. The measured bending stiffness of the two cables to a 125 foot radius of curvature was measured to be approximately 3×10^{9} in.^{2}-lb.

Any submarine cable must be able to endure the bending encountered during manufacturing, handling, storage and installation. To simulate this sort of handling, the prototype OTEC cables will be shuttled between 15-foot diameter sheaves a total of 25 times with a tension of 3,000 lbs. The cables will be dissected following this test to check for damage.

The OTEC application requires that electrical transmission cables be operational to depths of 6,000 feet, far deeper than any existing high-voltage submarine cable. To verify that the prototype designs can withstand the hydrostatic pressures at these depths, a hydrostatic pressure withstand was included in the program. Three-foot long sections of each core were capped

and placed in a pressure chamber. The XLPE cable is tested at 3200 psi, 120% of the hydrostatic pressure at 6,000 feet, for 96 hours. The external pressure on an oil-filled cable is partially balanced by the oil head within the cable. The SCOF cable is tested at 400 psi, 120% of the difference between the seawater head and oil head at 6,000 feet. The XLPE cable withstood the pressures without observable change. The SCOF cores deformed to an oval shape under pressure (see Figure 3), the effect of which is still under study.

Sidewall pressures are introduced by many sources during the laying operations: the weight of the spooled cable on itself, the fleeting knives at the drum (if applicable), and the weight of the cable against the overboarding sheave. Due to the great depths of installation and weight of the OTEC riser cables, the sidewall pressures will be unusually severe for this application. As a first look at the crushing resistance of the prototype OTEC riser cables, cable samples will be pressed between two flat plates. Samples three feet in length will be placed between 8-inch long plates in a tensile machine. The cable samples have been loaded in from 2,000 lbs. to 40,000 lbs. The results to date indicate that the cables will be injured at sidewall pressures on the order of 10,000 to 15,000 lbs. However, testing is still underway to study the performance of the prototype riser cables under a crushing load.

The final mechanical test will be a sleeving test, where the load to push or pull the conductor out of the SCOF cable will be measured. Foot-long samples of the SCOF core will have their conductors pushed out in a tensile machine. Then, 30-foot long sections of the complete SCOF cable will have their conductors pulled out while the cable is under tensions realistic of OTEC riser service. The object of the sleeving test is to measure the shear forces that can be developed across the insulation.

3. ELECTRICAL/MECHANICAL FATIGUE TESTS

The most elaborate test in the prototype OTEC riser cable test program is the electrical/mechanical fatigue test which attempts to simulate electrical and mechanical service on an OTEC riser cable. The test conditions simulate service to an APL pilot plantship in 4,000 feet of water via a direct catenary. The sea conditions used for this simulation are modelled as those off the south coast of Puerto Rico.

A special test machine was designed and built by Simplex to simultaneously bend and tension an energized length of prototype OTEC riser cable in a natural seawater environment. A layout of this machine is given in Figure 4. The electrical/mechanical fatigue test uses a 100-foot length of cable, 16 feet of which is exposed to all the mechanical and electrical loads superposed. This 16-foot length of cable is in a natural seawater bath.

The month-long electrical/mechanical test begins with the cable sample being energized. The SCOF cable is energized to 160 kV and the XLPE cable is energized to 200 kV. These voltages produce the equivalent damage over the one-month test period as 80 kV (the rated line to ground voltage) would over a 115 year period. During the last fifteen days of the test period, the rated current of 465 amperes will be cycled for 16 hours on, and 8 hours off.

The mechanical loads are composed of a variable amplitude cyclic tension and a constant amplitude bending cycle. The tension spectrum, shown in Table I, represents all loads creating more than 6000 psi alternating stress in the wire over 115 years, including the passage of a 100-year storm every decade. Over the month-long test period the cable will be subjected to 150,000 bends over a 100-foot radius bending guide. This represents the Miner fatigue damage equivalent in the sheath of 115 years of service.

At the end of the test, the cable will be electrically broken down to see if any changes in the strength of the insulation have occurred. How the combination of electrical and mechanical stresses affects high voltage insulation is one of the unknowns of OTEC riser cable service. Following electrical breakdown, the cables will be dissected to check the condition of all of the components of the fatigued cable.

The full-scale prototype testing is expected to be complete, except for the electrical/mechanical fatigue testing, in the Summer of 1981. The electrical/mechanical tests will be complete in early 1982.

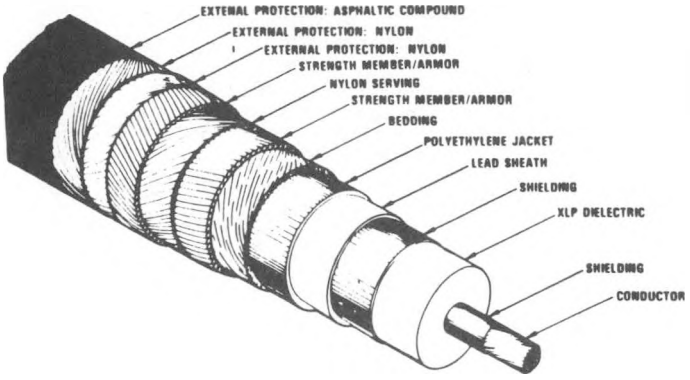


FIGURE 1

DESIGN OF THE CROSS-LINKED POLYETHYLENE RISER CABLE MANUFACTURED FOR THE OTEC TESTING PROGRAM

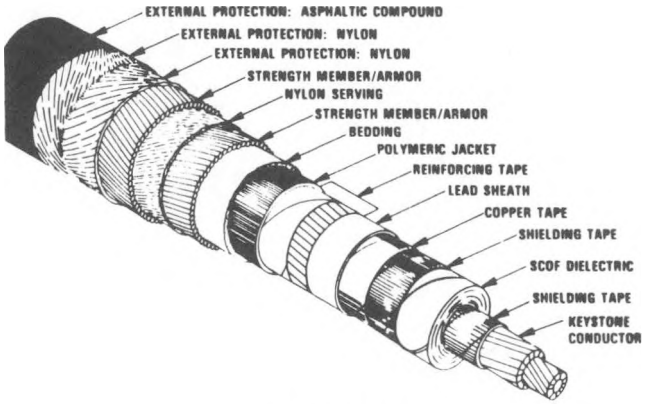


FIGURE 2

DESIGN OF THE SELF-CONTAINED OIL-FILLED RISER CABLE MANUFACTURED FOR THE OTEC TESTING PROGRAM

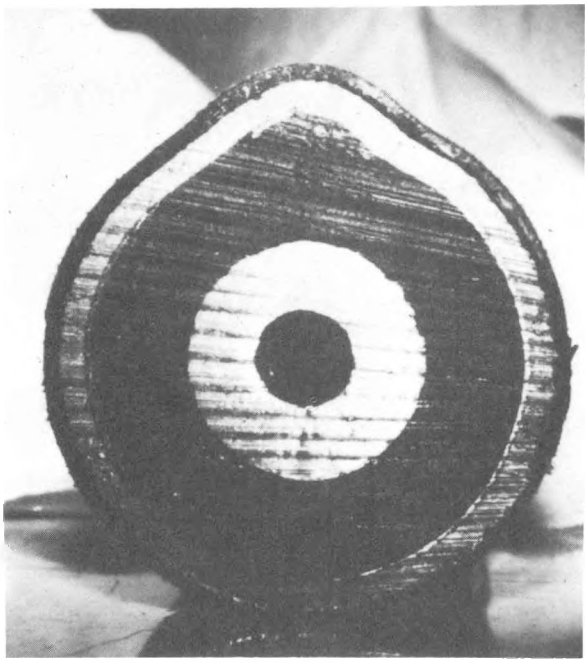


FIGURE 3 - Deformed SCOF Cable Core

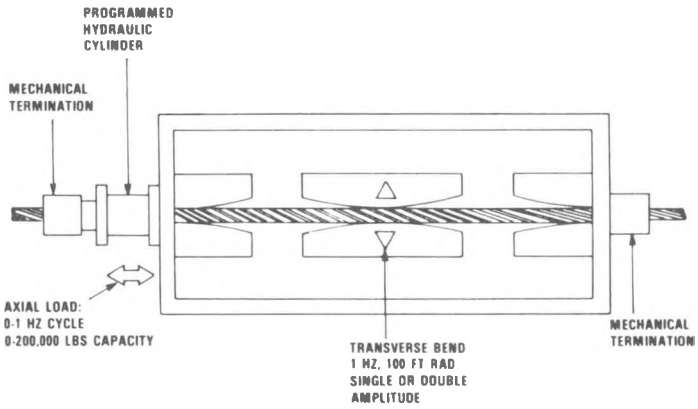


FIGURE 4 - Schematic of Electrical/ Mechanical Fatigue Machine

8th Ocean Energy Conference
Washington, DC
June 1981

THE DEVELOPMENTAL DESIGN STATUS OF RISER CABLE SYSTEMS FOR OTEC PILOT PLANTS

J. A. Schultz
Simplex Wire & Cable Co.

T. C. Dalton
Gibbs & Cox, Inc.

R. Eaton
U.S. Dept. Of Energy

ABSTRACT

This paper presents the three basic design concepts of riser cable systems for 40 MW floating OTEC pilot plants and describes the various items of hardware and cables which comprise the riser cable system. Particular references are made to the 40 MW spar and plantship platforms designed for specific sites off Puerto Rico. Further discussions on spar and plantship riser cable system designs concern comparisons of their key aspects and review of their conceptual deployment schemes. Conclusions from the spar and plantship riser cable system designs are reviewed with parametric analyses. Recommendations present future developmental efforts necessary to ensure successful riser cable system designs for 40 MW pilot plants.

INTRODUCTION

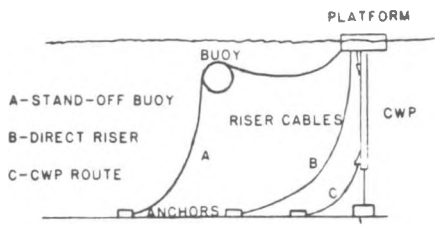
The success of OTEC as a source of energy depends on the dependable delivery of electric power. One of the principal challenges for electric energy delivery is a cost effective riser cable system which can accept the stresses of 30 years in OTEC service. This discussion presents the conceptual designs of riser cable systems developed for 40 MW floating OTEC pilot plants. To date, detailed analysis of floating pilot plants center upon plantship and spar platform configurations. Specific riser cable system designs will be described that have been developed for each of these platforms at potential sites off Puerto Rico. Although other pilot plant platform designs may yet evolve, these two platforms typify many unique engineering and hardware facets associated with an AC riser cable system design, which is suited to island sites or other short transmission lengths under 30 miles.

RISER CABLE SYSTEMS

Riser cable systems must accommodate platform motions of yaw, heave pitch, roll, sway, surge and excursions during operational conditions. Ideally, the riser cable system will also survive extreme platform motions caused by hurricane storm seas. There are three basic configurations for attachment of riser cable systems to floating platforms (Figure 1) as follows:

- o direct riser cables from seabed to platform
- o stand-off buoy arrangement with riser cables routed from platform to stand-off buoy to seabed
- o CWP arrangement with riser cables routed along CWP as they transit from platform to seabed

The direct riser cable may be deployed conventionally, but remains vulnerable to relatively large platform motions. The excessive motions may cause cable tensions to exceed the (423,000 pounds for present 40 MW AC riser cable designs) breaking strength of the cable support members. The stand-off buoy arrangement possesses the highly desirable advantages of significantly reducing riser cable responses due to platform motions, but allows larger platform excursions and relatively conventional deployment. Of the three schemes, the CWP attachment reduces the riser cable dynamic loads to the lowest total mechanical stress, but requires unconventional deployment. Riser cable systems for transmitting AC power from floating pilot plants consist of three active single phase cables and one spare cable as a minimal reliability consideration.

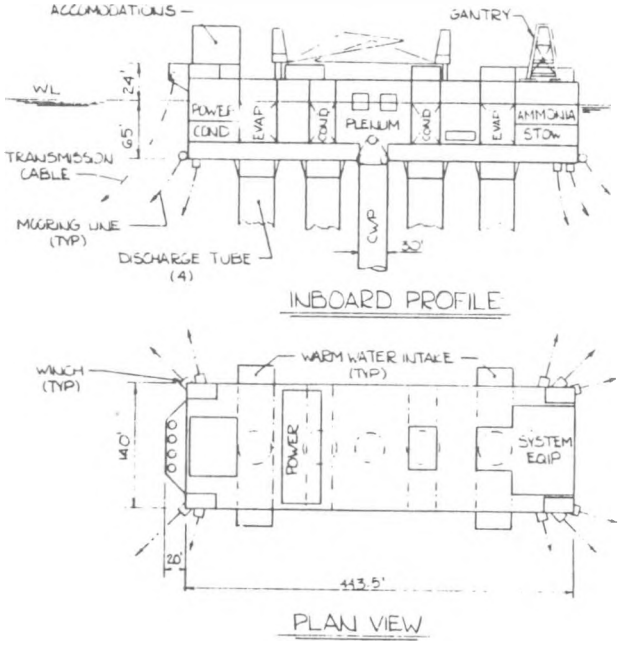


RISER CABLE SYSTEM CONFIGURATIONS

FIGURE 1

FLOATING PILOT PLANT PLATFORMS

The plantship (Figure 2) utilizes a concrete rectangular shaped hull form and floats as a typical surface vessel (References 2 and 3). The spar (Figure 3) however, floats as a semi-submersible as a consequence of its cylindrical geometry and steel construction (Reference 4). A typical multiple anchor leg mooring for the plantship (Figure 4) allows an operational watch circle radius of approximately 400 feet (120 meters). The spar employs a cold water pipe (CWP) tension leg mooring (Figure 5) that innovatively integrates platform mooring and cold water piping structures to reduce the operational watch circle radius to approximately 200 feet (60 meters). Floating pilot plants must be located in depths ranging from 4,000 to 6,000 feet (1,200 to 1,800 meters) with a minimum CWP length of 3,000 feet (900 meters). These extreme depths, along with the dynamic motions of the platforms, present severe engineering constraints for the development of the riser cable system.



PLANTSHIP GENERAL ARRANGEMENT

FIGURE 2

PLANTSHIP RISER CABLE SYSTEM

The plantship will preferentially employ a direct riser arrangement, but a stand-off buoy arrangement (Figures 6 and 7) minimizes riser cable motions caused by the plantship's relatively large watch circle. The plantship is moored with the stern facing the shore and the bow facing the direction of predominant seas. The riser cables enter the platform through a sponson cantelivered off the stern of the hull. This entry method minimizes the possible interference between the riser cables and the mooring lines, the sponson minimizes the watertight integrity required of the gimbal at the hull penetration and allows the riser cables to enter the water sheltered from the wave action under the lee of the platform.

The cold water pipe construction of the plantship does not allow attachment of the riser cable to the cold water pipe since relative movement between CWP and platform is possible. Thus, only the direct riser cable system and the standoff buoy/catenary riser cable system can be utilized with the plantship platform.

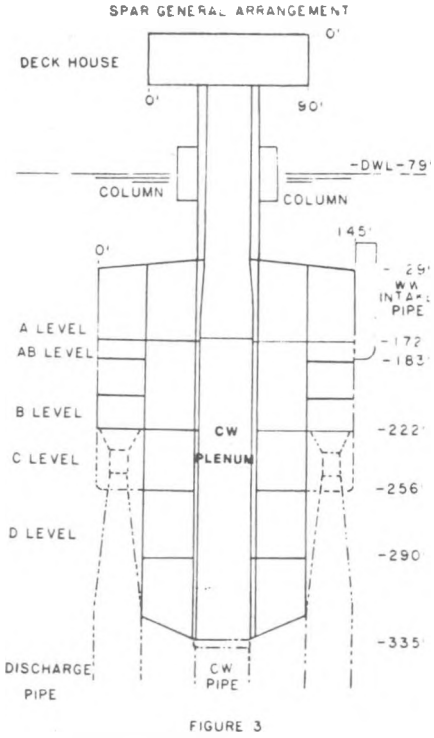
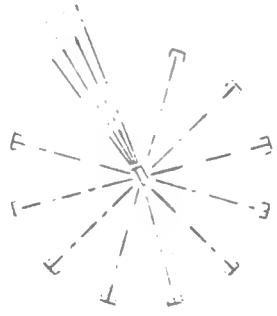


FIGURE 3

4 RISER CABLES



10 MOORING LINES

PLANTSHIP STATION KEEPING SYSTEM

FIGURE 4

SPAR RISER CABLE / MOORING ARRANGEMENTS

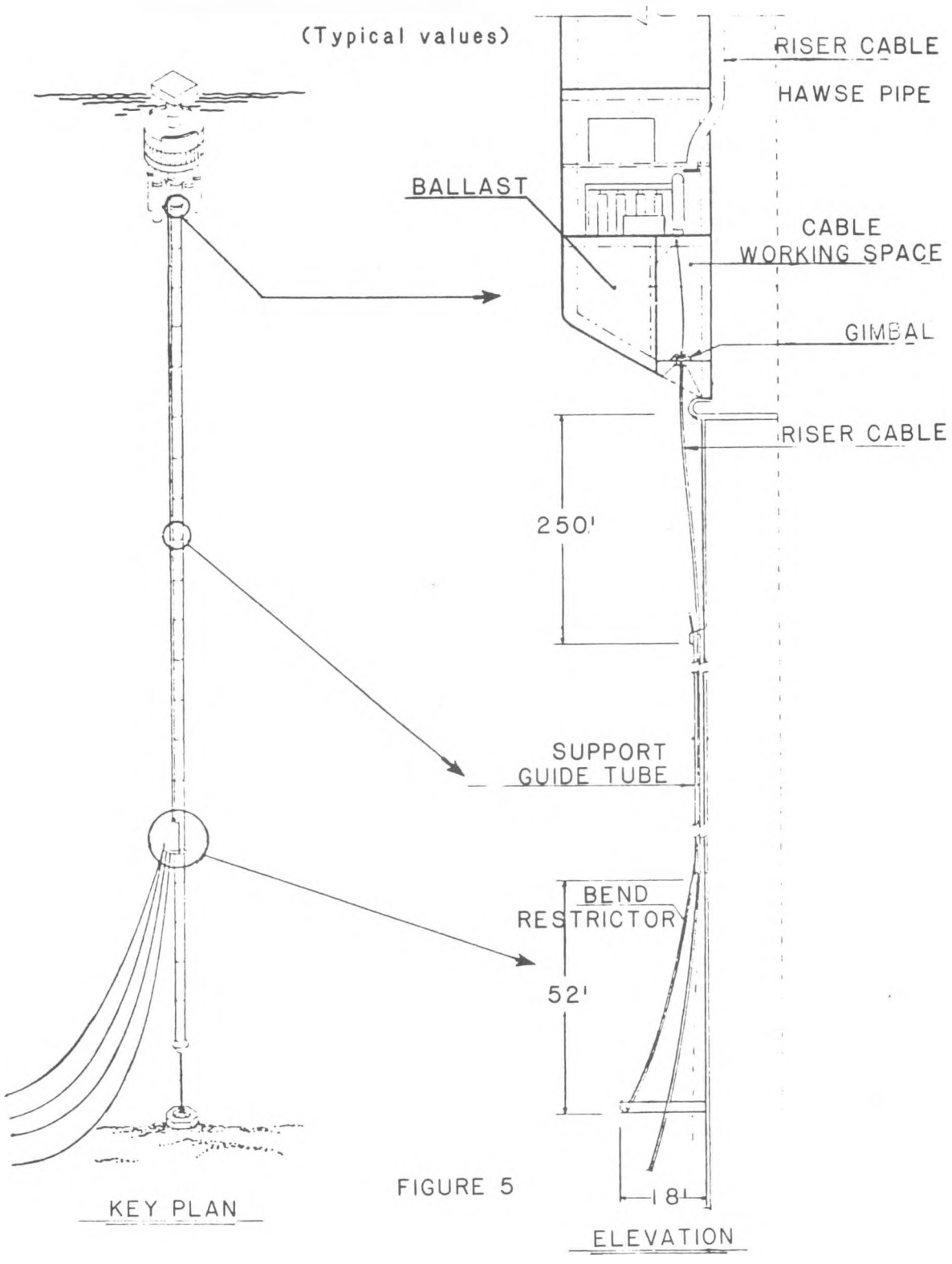


FIGURE 5

SINGLE CABLE PROFILE FOR PLANTSHIP

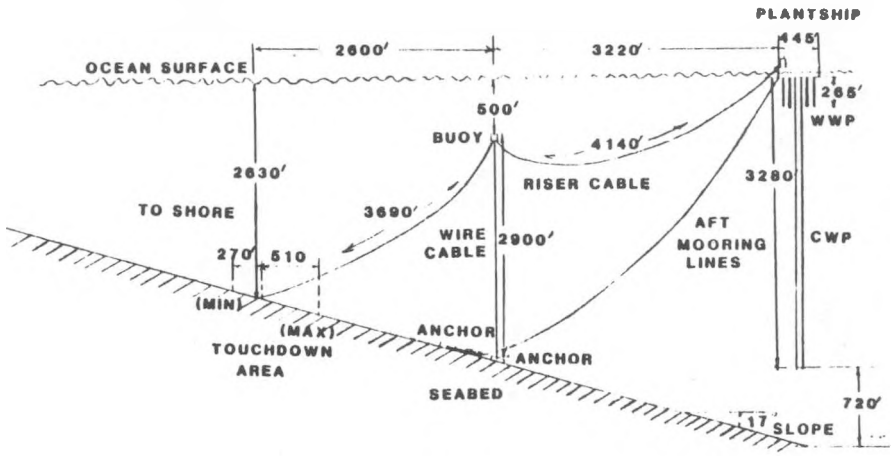


FIGURE 6 scale 1 in.=1000 ft.

RISER CABLE LAYOUT FOR PLANTSHIP

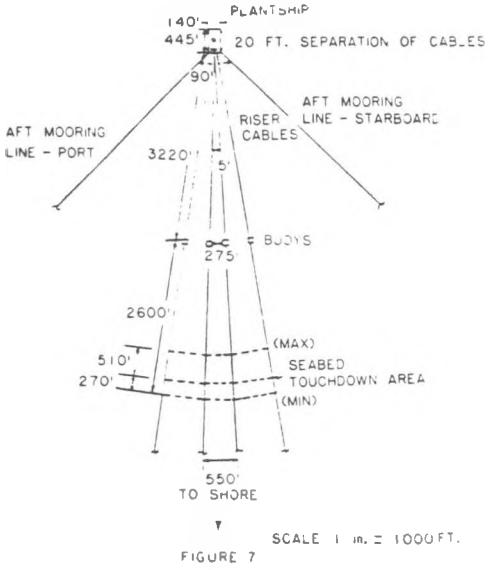


FIGURE 7

SPAR RISER CABLE SYSTEM

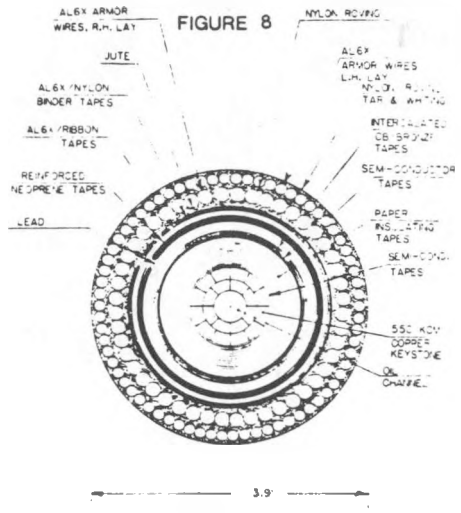
The restricted watch circle of the spar and its CWP lends itself most readily to the CWP routing (Figure 5) to minimize riser cable motions. This CWP routing extends down one quadrant of the CWP.

Interference between the warm water discharge pipes and the riser cables must be avoided. The excursion of the warm water pipes are such that the riser cables must be attached to the cold water pipe soon after the cable departs from the platform. The cable departs from the CWP route about 1,000 feet off the seabed to accommodate deployment considerations.

RISER CABLE SYSTEM HARDWARE

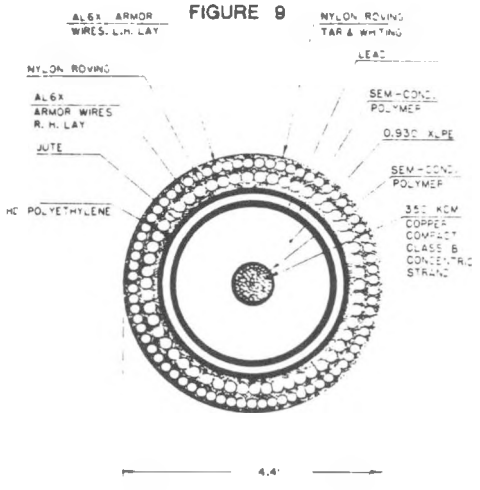
The various cable systems share several common subsystems; the riser cable itself, the cable bottom anchor, cable bend restriction devices, cable mechanical terminations, cable electrical terminations, gimbal device, cable disconnects, and where applicable, cold water pipe attachments and subsurface buoy. The riser cable for both the plantship and spar will require individual riser cable mechanical terminations on the external hull of each platform and electrical terminations within the hull body of each platform.

The riser cable itself is rated for 40 MW at 138 KV. The insulation could be either self-contained oil-filled paper (SCOF) or cross-linked polyethylene (XLPE). Both dielectrics would be similar in dimension and weight at approximately 3.9 and 4.4 inches and 13.1 and 13.7 pounds, respectively. The SCOF cable (Figure 8) consists of a 550 Kcmil copper keystone conductor, kraft paper and mineral oil dielectric, lead alloy hermetic sheath, external stainless steel alloy (AL6X) armor strength member (torque-balanced reverse double lay) and expendable asphaltic outer covering. The XLPE (Figure 9) cable is constructed of compact stranded 350 Kcmil copper conductor, extruded cross-linked polyethylene dielectric, lead alloy hermetic sheath with stainless steel alloy sheath reinforcement and external stainless steel alloy (AL6X) armor strength member (torque-balanced reverse double lay) and expendable asphaltic outer covering.



SELF-CONTAINED OIL-FILLED (SCOF) CABLE
13.1 LBS IN SEAWATER

FIGURE 9



CROSS-LINKED POLYETHYLENE (XLPE) CABLE
13.7 LBS IN SEAWATER

The gimbal device decouples the riser cable from pitch and roll motions of the pilot plant. The device is designed to be as frictionless as possible by using one of two bearing types, rolling element bearings or hydrostatic bearings (Figures 10 and 11). The proper function of a gimbal remains essential in the reduction of bending fatigue of the riser cable hermetic sheath at the hull penetration to ensure the desired cable life of 30 years will be maintained. The gimbal also functions as a watertight seal (up to 240 pounds/square inch) and transfers the cable load from the mechanical termination to the hull. This application requires a significant extension of the state of the art through additional design development.

A subsurface buoy (Figure 12) further decouples platform motions and provides a point of positive buoyancy in the catenary of the standoff buoy/catenary riser system. This buoy is designed for service at a depth of approximately 500 feet and consists of two coupled buoyancy modules of syntactic foam providing a net buoyancy of 150,000 pounds. This application requires a slight extension of the state of the art through additional design development.

Two concepts of cable disconnect devices are developed: a mechanical cutting device (Figure 13) which severs the cable below the gimbal, and an explosively-separated member (Figure 14) to which attached electrical and mechanical terminations. The function of these devices would be to provide instant separation of the riser cable in the event of high tensions caused by severe storms or other imminent catastrophies. Although provisions for retrieval and reconnection of the cable is considered an important aspect of the design of these devices, this remains a conceptual aspect that requires additional design development.

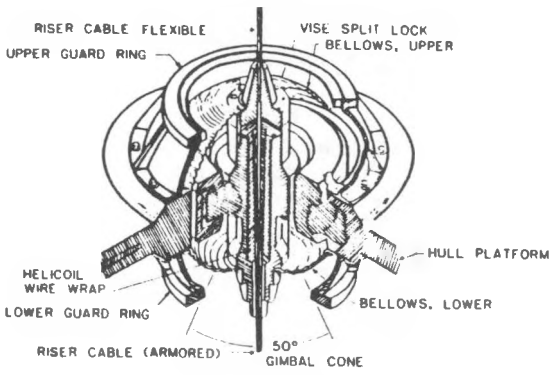
A mechanical termination (Figure 15) supports the riser cable and transmits the cable load up into the OTEC platform hull through the gimbal by gripping the armor wires together. This device is a reasonable extension of the existing state of the art, but requires tailoring to this application from normal mechanical cable useage.

A bend restriction device (Figure 15) is required at the points of cable attachment to the gimbal, buoy, or bottom anchor. This device will reinforce the cable against local bending at the attachment point to minimize premature bending fatigue. As such it can be made as part of the mechanical termination or a separate assembly. This device is within the existing state of the art.

A bottom anchor (Figure 16) for the riser cable is provided in all riser cable systems. This anchor is required to provide attachment of the cable to the seabed so that cable migration does not occur. This bottom anchor is a deadweight device and is within the current state of the art.

Electrical termination (Figure 17) of the riser cable in the platform will be by conventional cable potheads to provide an electrical interface between the riser cable and SF6 gas insulated bus of the power conditioning equipment. Routing of the cable through the platform in a cable conduit is also conventional utility of fiberglass.

On the cold water pipe routed riser cable system, the conduit which constrains the riser cable must be carefully integratd into the cold water pipe. The approach and departure points of the cable on the pipe are locations of bend restrictions guides or bellmouth type devices (Figure 18). These guides limit the bending of the cable at these points so that premature bending fatigue of the cable components will be minimized.

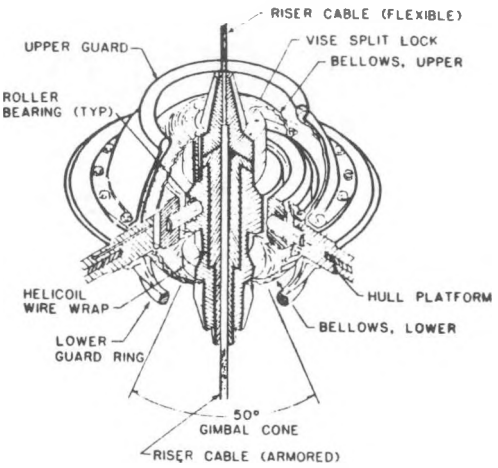


WEIGHT 70,000 LBS. DIAMETER - 14 FT

FRICTION COEFFICIENT - .0001 HEIGHT - 16 FT

HYDROSTATIC BEARING GIMBAL CONCEPT

FIGURE 11

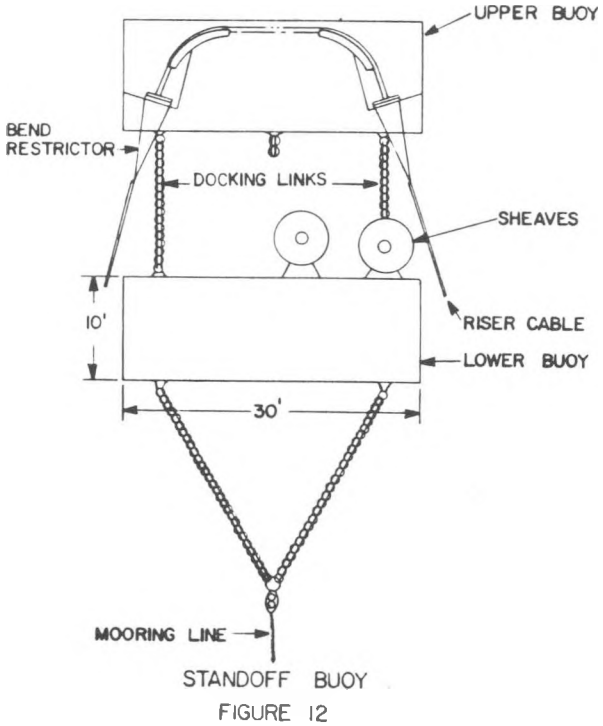


WEIGHT - 60,000 LBS. DIAMETER - 12 FT

FRICTION COEFFICIENT-.0015 HEIGHT - 14 FT

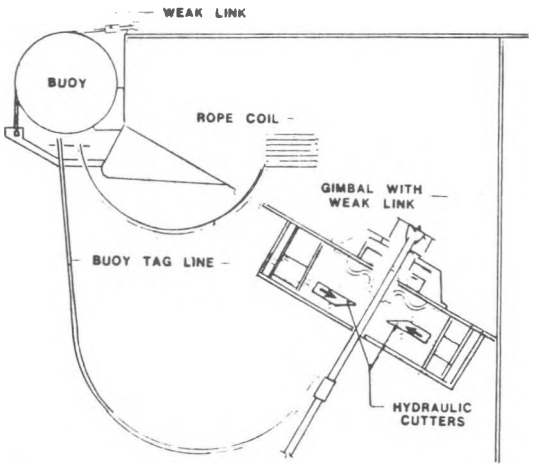
ROLLER BEARING GIMBAL CONCEPT

FIGURE 10



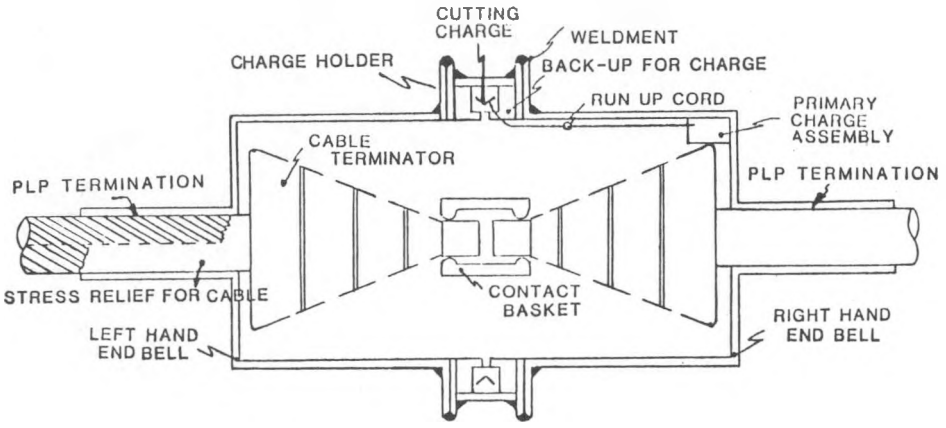
STANDOFF BUOY

FIGURE 12



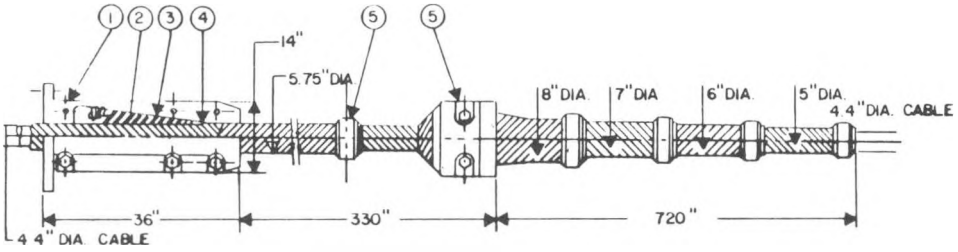
PROPOSED DISCONNECT SCHEME

FIGURE 13



CABLE DISCONNECT DEVICE - EXPLOSIVE CHARGE CONCEPT

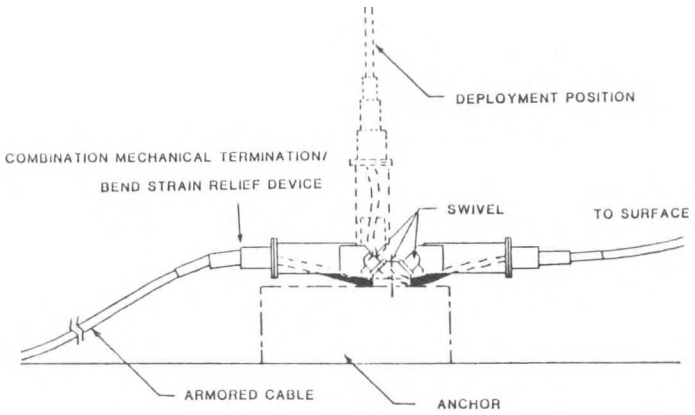
FIGURE 14



ARMOR GRIPPING VIA
MECHANICAL TERMINATION/BEND RESTRICTOR/HELICAL WIRE WRAP CONCEPT

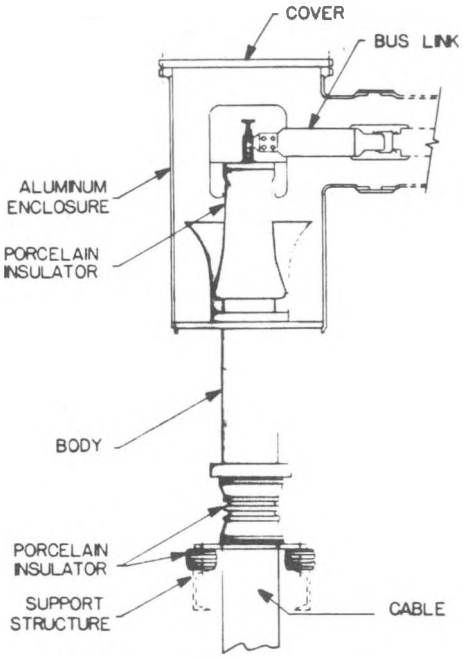
1 HOUSING WITH FLANGE ADAPTER
2 WEDGE INSERT ASSEMBLY
3 OUTER HELICAL FLEX RODS
4 INNER HELICAL FLEX RODS
5 CLAMP ASSEMBLY

FIGURE 15



CABLE BOTTOM ANCHOR ASSEMBLY

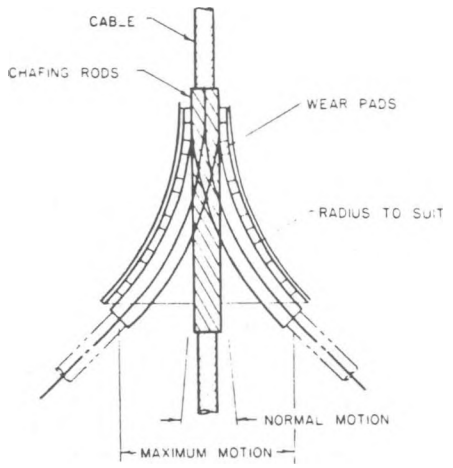
FIGURE 16



CABLE/SF6 POTHEAD FIGURE 17

PARAMETRIC RISER CABLE SYSTEM STUDIES

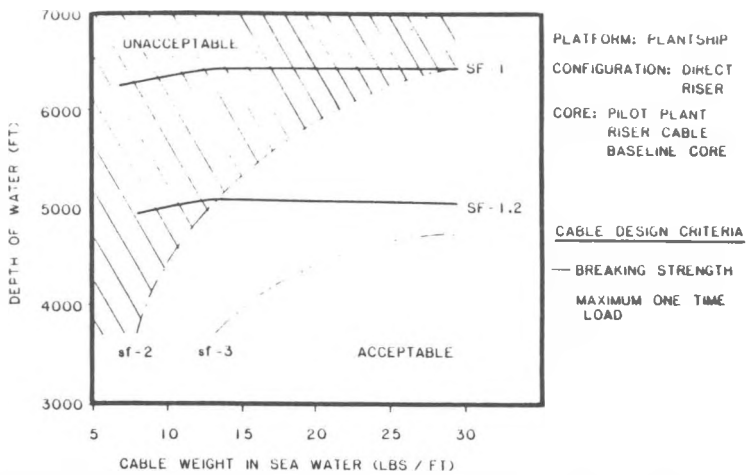
Parametric studies of the riser cable system were accomplished to evaluate the effect of various cable design and system application parameters. These studies have led to the definition of a design graph which shows the relationship between riser cable weight (as affected by placing different amounts of armoring on a constant cable core) and depth of water, given the need to achieve specified design criteria. The parametric analyses indicated that desired factors of safety can be achieved through the addition of armor to the riser cable core, but that these factors of safety asymptotically approach a limit with depth of water. For the case of the direct riser cable system on the plantship pilot plant, application of the identified riser cable (Figure 19) cannot be extended beyond a depth of 6,000 feet with a safety factor of two regardless of the amount of armor added. A standoff buoy analysis has also been developed, and it may be extended beyond 6,000 feet with a safety factor of two. However, in a standoff buoy configuration the breaking strength of the cable no longer remains the limiting function, since the conductor (copper) elongation and ratio of maximum working load to breaking strength become critical factors as well.



MINIMUM 125 FT RADIUS

BEND RESTRICTOR - BELLMOUTH CONCEPT

FIGURE 18



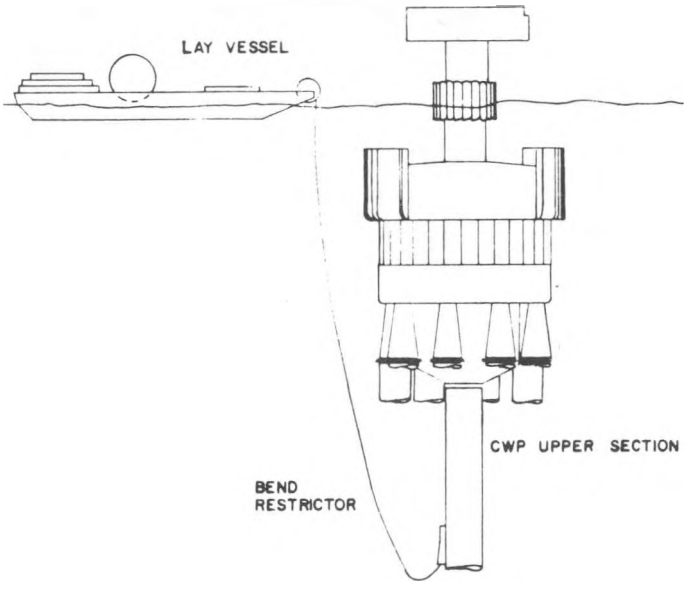
DESIGN COMBINATIONS OF WATER DEPTH AND CABLE WEIGHT

FIGURE 19

RISER CABLE SYSTEM DEPLOYMENT

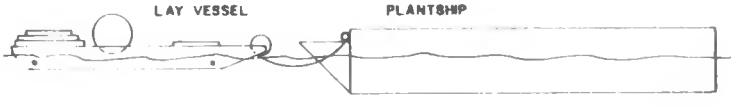
The plantship arrangement for riser cable systems allows conventional cable deployment methods and machinery (Figure 20). This conventional cable deployment will require the riser cables to be laid singularly from the plantship to shore via cable laying vessel. The cable laying vessel will attach the riser cable to the plantship, pay out riser cable in a catenary to the seabed (or to buoy to seabed) and then proceed toward shore until the bitterend must be transferred via other means to shore.

The spar arrangement for a CWP routed riser cable system does not permit conventional deployment methods and requires special machinery (Figure 21). This unconventional cable deployment will also require the cable to be laid singularly from the spar to shore via cable laying vessel. However, the cable laying vessel will attach the riser cable to the spar via the limited catenary necessary for the CWP routing. This stage requires particularly sophisticated coordination between the cable laying vessel's payout and the spar's hauling in, submarine monitoring, compartment pressurization and personnel decompression chamnbers. The remaining cable deployment is conventional and parallels that for the plantship.



SPAR CWP ROUTED RISER
CABLE SYSTEM DEPLOYMENT

FIGURE 21



PLANTSHIP CATENARY RISER SYSTEM
CABLE DEPLOYMENT

← TO SUBSURFACE
STANDOFF BUOY

FIGURE 20

RISER CABLE SYSTEM COMPARISONS

Table 1 depicts the primary characteristics of the riser cable systems of both plantship and spar 40 MW pilot plants.

The capital costs include the costs for the design, fabrication and deployment of the riser cable system and annual Operational and Maintenance costs include the costs for inspection and periodic maintenance of the riser cable system plus costs for instruction of operational personnel.

The cost of the refit is the cost of replacing the portion of the riser cable between the bottom anchor and the platform, the cable to shore being reused. Also included in the refit cost are an allowance for the replacement of required items of hardware as well as the costs of handling and redeployment of the system.

The refit period is somewhat undetermined, being based on the predicted life of the riser cable. Studies to further define cable life, and thus the refit period, are still under development. A period of ten years is presently assumed, but a 30-year life is anticipated.

TABLE I

OTEC RISER CABLE SYSTEM CONCEPT COMPARISONS

	PLANTSHIP PLATFORM		SPAR PLATFORM		
	DIRECT RISER	STANDOFF BUOY/ CATENARY RISER	DIRECT RISER	STANDOFF BUOY/ CATENARY RISER	VERTICAL RISER
30 YEAR LIFE	YES	YES	YES	YES	YES
EXTREME SEA STATE SURVIVAL	YES	YES	YES	YES	YES
TOTAL MAXIMUM TENSION (LBS.)	139,000 (SEE TABLE S-3)	82,000 (SEE TABLE S-3)	87,000 (SEE TABLE S-4)	52,000 (SEE TABLE S-4)	68,000 (SEE TABLE S-4)
DEVELOPMENT RISK	LOWER	HIGHER	LEAST	HIGHEST	MODERATE
CAPITAL COST (1980 $M)	27.4 (SEE TABLE S-5)	32.8 (SEE TABLE S-5)	26.3	32.0 (SEE TABLE S-5)	26.0
ANNUAL OPERATION & MAINTENANCE COST (1980 $M)	.57	.83	.58	.83	.64

CONCLUSIONS

The following items depict the conclusions derived from the design of riser cable systems for 40 MW spar and plantship pilot plants.

- Direct riser cable system remains limited in application by platform arrangements, site depth and platform motions, but applicable for most 40 MW OTEC pilot plants
- CWP routed riser cable system suffers a complex and unconventional means of cable deployment that implies a higher risk but less cost
- Stand-off buoy riser cable system provides the capability to support riser cable systems for 40 MW pilot plants beyond 6,000 feet or to most any site selected
- All riser cable system components are expected to be capable of enduring 30 years in service without a scheduled refit
- Majority of the riser cable system hardware consists of reasonable extensions of the state of the art devices and deployment requirements

RECOMMENDATIONS

The following items recommend the additional developmental efforts necessary to ensure successful designs for riser cable systems of 40 MW pilot plants.

- Development of preliminary design of gimbal and determine which type of bearing concept performs best in the pilot plant riser cable application
- Development of preliminary design of disconnection devices, subsurface buoys and cable bottom anchors for pilot plants
- Obtain hydrographic survey data of proposed pilot plant sites
- Development of preliminary deployment plans with each of the three conceptual riser cable systems for pilot plants
- Determination of refit periods for riser cable system hardware of pilot plants via further testing and modeling efforts
- Assessment of cable laying vessel capability and availability for riser cable system deployment of pilot plants in the Gulf and Pacific islands

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A STUDY OF OCEAN CABLESHIPS APPLIED TO SUBMARINE POWER CABLE INSTALLATION

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ABSTRACT

Existing ocean cableships are reviewed against a background of increasing need for capability to install heavy power cables in deep water. Applications to 7,000 feet are considered. Current practice is examined through a review of major underwater power cable installations around the world. Vessels engaged in cable laying are examined and their adaptability to deep water power cable installation discussed. Significant potential exists in this regard. Advantages and disadvantages of all purpose power and communication cableships are discussed and options for incorporating a dual function in future vessels considered. The approach is in large part through changes in power cable design which would more easily enable both power and communications cable laying functions to be incorporated in future cableships.

1. INTRODUCTION

The use of ocean cableships for the installation and repair of deep-water power cables provides potential advantages to both the submarine telecommunications and power cable industries. The telecommunications industry could benefit from increased usage of their cableships and the power cable industry could avoid the necessity of specially constructing additional vessels suitable for power cable lay in deep water.

The application of ocean cableships to power cable lay is not a novel concept. In 1956 the cableship Ocean Layer, a converted cargo vessel, was used to lay the first British Columbia-Vancouver Island power cable, and in 1965, the Marcel Bayard was used to lay the Sardinia-Corsica-Italy cable. Other power cable installations have been accomplished using cargo vessels specifically adapted for a particular job. Cables laid by these vessels have all had a single layer of armor, which permitted coiling in existing cable tanks.

The extension of power cable installation depths to 1,800 feet and beyond has typically resulted in the specification of torque-balanced double-armored cable designs, largely to provide required strength and to reduce the problem of hockling during installation. Such cables are not coilable, a fact which makes the adaptation of existing cableships to deep water power cable lay difficult. A simpler course of action may, in fact, be to modify cable designs to suit the loading and handling capabilities of the cableship itself.

2. EXISTING SUBMARINE POWER CABLE INSTALLATIONS

Submarine power cables to date have been installed in water depths to 1,800 feet. The deepest installation involving a communications cableship was the Sardinia-Corsica-Italy cable, installed in 1965 in 1,500 feet of water by the French cableship Marcel Bayard (1). The state-of-the-art in power cable installation is represented by the Skagerrak HVDC power cables, installed in 1976 and 1977 in 1,800 feet of water by a specially constructed lay barge, C/S Skagerrak (2).

Table 1 details maximum installation tensions and other characteristics of typical submarine power cable installations. The first two installations listed were accomplished by conventional cableships and share two common characteristics: the cables were single armored, which permits coiling, and maximum installation tensions were no more than about 15,000 pounds, well within the capabilities of any number of cableships existing in the world today. The New Zealand and Japan cables are also single armored and were installed at tensions slightly greater than the previous two. These latter installations were conducted by converted cargo vessels.

The Skagerrak cables, also listed in Table 1, were installed to a maximum tension approximately twice any of the others. The Skagerrak cable is double armored and cannot be coiled. This combination of charac-

teristics, plus the requirement to install continuous lengths of approximately 67 n mi resulted in the construction of a specially equipped lay vessel, C/S Skagerrak.

3. PROPOSED POWER CABLE INSTALLATIONS

A new generation of power cable installations is now being proposed. These cables are proposed to be installed to depths of up to 6,900 feet. Selected characteristics of several proposed cable installations are listed in Table 2.

The most ambitious of the proposed installations, in terms of length and installation depth, is the Hawaiian Intertie Cable (Figure 1). These cables would provide links between the islands of Hawaii and Oahu, Oahu-Molokai, Molokai-Lanai, and Lanai-Maui. Route lengths and installation depths as presently conceived would vary between 122 n mi and 6,900 feet (Hawaii-Oahu) and nine n mi and 220 feet (Lanai-Maui). Maximum installation tensions would range from 150,000 pounds for the Hawaii-Oahu link to 11,000 pounds for the Lanai-Maui link.

Each of the cables identified in Table 2 is expected to be double armored and, therefore, non-coilable. In the deeper installations double armoring will serve not only to provide the strength necessary to withstand cable tensions during installation, but also to reduce the potential for cable buckling at high installation tensions.

In order for existing cableships to be used for deep water power cable lay, either coilable cables must be designed which have required anti-twist characteristics, or existing cableships must be modified to handle non-coilable cable. Other characteristics of the vessel, such as cable engine tension capability, overboarding sheave diameter, and tank capacity must also be satisfactory.

4. DESIGN OF COILABLE, TORQUE-BALANCED CABLE

A prerequisite for use of existing cableships in deep water power cable installations is that either the cables be designed to be coilable or that the cableships themselves be modified to handle non-coilable cables through the inclusion of turntable arrangements in the bottom of cable tanks. Successful development of a coilable, torque-balanced cable will make the use of existing communications cableships in deep water power cable lay feasible and more easily enable the design of dual-purpose communications/power cableships in the future.

A concept for a coilable, torque-balanced cable has been developed and is presented in Figure 2, which details a design built around a 250 KVDC cable core, such as that proposed for the Hawaiian Intertie. The coilable, torque-balanced design consists of a set of rope-like armor units stranded around the single conductor power core. Each of the individual armor units consists of a core of a compliant material, such as rubber or polyethylene, surrounded by a series of wires. The individual wire strands over the armored rods are right hand lay; the armored rods are applied to the main core with left hand lay. The torques generated by the individual strands of the generated rods counter the torque generated by the armored rods around the main core.

The conceptual design which has been developed around the proposed Hawaiian Intertie core has a weight in air of about 29 pounds per foot and a weight in seawater of slightly over 20 pounds per foot. Outside diameter of the cable would be approximately 5.75 inches. A comparable design, conventionally torque-balanced using a double layer of galvanized round wire armor, has a weight in seawater of 18.2 pounds per foot and an outside diameter of 4.2 inches.

It is anticipated that the coilable, torque-balanced cable would have a minimum coiling diameter of perhaps 20 feet, and a minimum bending diameter during handling of approximately 10 feet. Verification of these values, however, depends on further development of the concept and testing in accordance with CIGRE recommended mechanical tests on submarine power cables (6).

5. EXISTING CABLESHIPS AND APPLICABILITY TO DEEP WATER POWER CABLE INSTALLATION

To analyze the potential of existing cableships for deep water power cable installation, an analysis of the cable installation capabilities and tank capacities of Long Lines has been conducted, with particular reference to the characteristics of the proposed Hawaiian Intertie route. The availability of a coilable, torque-balanced cable similar in concept to that presented in Section 4 is presumed. Long Lines is a good choice for this analysis as it has the greatest bow cable engine capacity and sheave diameters of any commercial cableship in existence today.

The installation of cables in deep water, such as those proposed for the Hawaiian Intertie, places certain specific demands upon the vessel which is to accomplish the lay. Among these are the following:

• Cable engine tension capability. Cable engines are typically operated at approximately 65 percent of rated capacity. Thus, if 50,000 pound installation tensions are expected, rated cable engine capacity should be in excess of approximately 77,000 pounds. Table 3 details variations in cable engine capability requirements as a function of maximum installation tension.

• Overboarding sheave and cable engine drum diameter. These diameters must be large enough to allow installation of cable without causing crushing of the cable over the drum or sheave. Typical crush forces experienced at the overboarding sheaves during power cable installation have ranged to the vicinity of 3,000 pounds per foot. A somewhat similar phenomenon, sidewall crushing due to fleeting knife squeeze, has resulted in crush forces on lead sheathed, paper/oil insulated cables in the range of 6,000 to 8,000 pounds per foot. Maximum acceptable sidewall crush from fleeting knives was estimated at 13,500 pounds per foot for the Sardinia-Corsica-Italy cable, with paper rupture occurring during tests at 33,000 to 66,000 pounds per foot (7).

Acceptable sheave and drum diameters can be calculated as a function of installation tension if one accepts the 13,500 pound per foot figure as a guide to the selection of sheave and cable drum diameters, and calculates sidewall crush force using the equation P = T/R (where P = crush force, lbs/ft; T = installation tension, lbs; R = sheave or drum radius, ft.). These values are given in Table 3. Actual requirements can only be verified through the conduct of a tensile bending test such as that required by CIGRE (6).

• Adequate cable storage and handling capability, taking into account minimum coiling and bending radii of cable. Potential cable route lengths for the Hawaiian Intertie range from nine nautical miles to 122 nautical miles. Cableship tank coiling capacity must be sufficient to store this in one continuous length in order to avoid the necessity of field splices on the power cable, a time-consuming and risky operation from the point of view of cable integrity. In addition, cable loading, storage and handling facilities must be compatible with minimum bending and coiling radii of cable being installed. This may require modification of existing vessels.

To see how existing cableships match the listed installation requirements, Table 4 has been developed. Table 4 lists key characteristics of the largest cableships in existence today. Rated bow cable engine capability of these vessels runs from 67,000 to 100,000 pounds. Sheave and drum diameters are all in the vicinity of 10 to 12 feet. As the table shows, Long Lines has the greatest cable engine capacity (100,000 pounds), drum diameter (12 feet) and sheave diameter (11 feet) of the vessels listed. In addition, Long Lines has the second largest coiling capacity of vessels listed, 168,000 cubic feet. These characteristics make Long Lines an immediate candidate for use in installations where maximum tensions are on the order of 65,000 pounds, which would allow it to install a 20 pound per foot cable to depths in excess of 2,500 feet. Many of the Hawaiian Intertie links fall within this range.

Development of novel installation techniques, such as the simultaneous use of both of Long Lines' bow cable engines, one to lower the cable and the other to simultaneously lower a support rope which takes up a portion of the installation tension, may increase the effective capability of Long Lines, but not enough to install cables in waters 7,000 feet deep. Preliminary analysis of the dual cable engine concept (a microprocessor ensures simultaneous payout of cable and support rope) reveals that a cable weighing 20 pounds per foot in seawater could be installed to depths of 4,000 feet or more. See Figure 3. Further increases in depth capability of Long Lines could be achieved through the provision of larger capacity cable capstans or through the development of lighter weight cables. Substitution of corrugated copper sheathing for the lead in the proposed cable design appears to have significant potential for reducing cable weight, though further definition of this concept is required.

Long Lines has the cable tank capacity to allow installation of significant lengths of submarine power cable, though the tanks are not configured to handle conventional torque-balanced cable. Table 5 details single tank cable coiling capacity for cables of varying diameter, assuming a 20 foot minimum coiling radius. Capacities of the largest of Long Lines tanks range from 123 n mi for a three inch diameter cable to 30 n mi for a six inch diameter cable. Due to the requirement for no field splices, and the anticipated difficulty in maintaining a continuous length of cable across more than one storage tank, the lengths noted effectively set maximum route lengths for power cables to be installed using Long Lines. These tank capacities would be sufficient to handle a 5.75 inch diameter coilable cable for all segments of the Hawaiian Interties route except the Hawaii-Oahu link. By eliminating the 122 n mi route, in effect island-hopping from

Hawaii to Oahu, a maximum route length of 30 n mi could be achieved, which is near the limitations of Long Lines tanks for a 5.75 inch cable.

An additional concern in this regard is the ease with which a large diameter cable can be handled during loading and installation activities. Long Lines has access ports built in for overhead loading of power cables into each of its main tanks. Some modification of handling arrangements beyond this may be necessary in order to successfully coil the cable in the tanks, and to provide for smooth cable passage during installation, but verification of these requirements awaits further development of the cableship installation concept.

b. DUAL PURPOSE POWER AND COMMUNICATIONS CABLESHIPS

Existing cableships such as Long Lines can be successfully adapted to lay power cables in moderately deep water. The vessels are limited however by existing bow cable engine capacity, bow sheave and cable engine drum diameters, and existing arrangements for handling of cables during the cable laying operation. Modifications in equipment, cable design, and installation techniques can likely overcome these limitations, but it is prudent to analyze the requirements for a purpose-built power cable/communications cableship with required equipment and handling capabilities built in.

The concept for a dual purpose vessel is similar to that for a combined high speed layer and repair vessel. The following characteristics are typical of those which would be required for a dual purpose vessel capable of communications cable installation as well as deep water (up to 7,000 feet) power cable installation. Verification of these requirements would, of course, depend on further analysis and testing.

- General arrangements to include provision for high-speed (6-8 knots) communications cable installation from the stern with a continuous cable working deck.

- Capstan-type cable engine at bow with tension capability in excess of 230,000 pounds. Drum diameter to be in the vicinity of 20 to 30 feet. Cable handling arrangements suitable for bow installation at slow speeds in the vicinity of 1-2 knots.

- Bow sheave diameter of approximately 20 to 30 feet.

- Cable tank arrangements suitable for storage and handling of long lengths of communications cable and power cable. This includes provision for loading of power cables with relatively large bending and coiling radii. Provision for coiling torque-balanced power cable can be through use of coilable designs or provision of turntable handling capability in one or more of the tanks.

- Provision of dynamic positioning capability to hold station for extended periods of time while operating in the depths contemplated.

With the exception of cable engine and overboarding sheave sizing and placement, the general arrangement of existing laying/repair vessels such as Long Lines provides an excellent reference for any proposed power/communications cableship.

Perhaps the largest conflict between power and communications cable missions will come with the provision of a large diameter bow sheave. This sheave, if left exposed, would be subject to slamming during high speed communications cable runs. It is anticipated that appropriate sheave placement and protection would reduce the potential for slamming, but it appears that reduced speeds for communications cable installation are a distinct possibility. Further, the large area which the sheave and cable engines themselves will take up within the vessel will likely result in some increases in overall length of a dual purpose vessel as compared to a purpose-built communications cableship. An additional complication in the proposed design is that drum type cable engines have only been built to 100,000 pounds capacity. Doubling of this will likely result in a significant development effort.

7. DISCUSSION

Ocean cableships have successfully been applied to submarine power cable installation in the past. Extreme installation depths and the non-coilable nature of proposed power cables, however, mitigate against the use of cableships in their installation unless significant changes in cable design are made.

A new concept for a torque-balanced cable has been presented. This cable, consisting of rope-like armor units stranded around the power cable core, can be coiled in a cable tank and makes possible the use of communications cableships in deep water power cable lay.

An analysis of the characteristics of Long Lines has been conducted to determine its suitability for deep water power cable installation using the coilable cable concept. Existing installation equipment and

tank capacities of Long Lines limit it to depths of about 2,500 feet and route lengths of approximately 33 n mi with a 5-3/4 inch coilable cable weighing 20 pounds per foot in seawater. Installation depths of 4,000 feet might conceivably be achieved using novel installation techniques.

The above considerations make feasible the concept of deep water power cable installations using large communications cableships such as Long Lines. Further investigation and trials in the areas of cable mechanical characteristics, installation techniques, and onboard handling and storage capabilities of large cableships must be conducted. These activities are not expected, however, to uncover any unsurmountable barriers to the concepts presented in this paper.

Required characteristics of a combined power/communications cable installation and repair vessel, capable of installing the coilable cable to depths of 7,000 feet have also been proposed. The vessel would be similar in nature to existing lay/repair vessels, with equipment modifications and cable storage and handling capabilities modified to handle large diameter power cable. Such a vessel appears likewise feasible.

ACKNOWLEDGEMENT

The authors appreciate the assistance provided to them by Mr. Thomas B. Bamford of Lincolnville, Maine. Mr. Bamford provided significant insights into the problems to be encountered in power cable installation and served as a sounding board throughout the preparation of the paper.

Note:

Tables and Figures on following pages.

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TABLE 1. TYPICAL SUBMARINE POWER CABLE INSTALLATIONS

Location	Cable Type	Lay Vessel	Max. Tension (lbs.-Approx.)	Ref.
Sardinia-Corsica-Italy	200 KVDC, Single Armor	Marcel Bayard	15,000	(1)
British Columbia-Vancouver (1956)	138 KVAC, Single Armor	Ocean Layer	15,000	(3)a
North-South Island, NZ	250 KVDC, Single Armor	Photinia	21,000	(4)a
Hokkaido-Honshu, Japan	250 KVDC, Single Armor	Hoshomaru	24,000	(5)
Skagerrak	250 KVDC, Double Armor	Skagerrak	52,000	(2)a

Notes:

a. Using CIGRE Formula for Installation Tension, T = 1.15 wh + 6750 pounds

T = Tension; w = Cable Weight per Foot in Seawater; h = Installation Depth

TABLE 2. PROPOSED SUBMARINE POWER CABLE INSTALLATIONS

Location	Anticipated Cable Type	Length (n mi)	Max. Depth (ft.)	Installation Tension (lbs)
Belle Isle Strait Newfoundland	400 KVDC, Double Armored	10.8	230	16,000
Florida-Bahamas	300 KVDC, Double	56	2,400	97,000
British Columbia-Vancouver Island	500 KVDC, Double Armored	16	1,300	58,000
Hawaiian Intertie:	250 KVDC, Double Armored			
Hawaii-Oahu		122	6,900 3,000 (ave.)	150,000 69,000
Oahu-Molokai		22	2,200	53,000
Lanai-Maui		9	220	11,000
Hawaii-Maui (Alternate)		30	6,900	150,000

Notes:

a. Using CIGRE Formula for Installation Tension, T = 1.15 wh + 6750 pounds

T = Tension; w = Cable Weight per Foot in Seawater; h = Installation Depth

TABLE 3. CABLE INSTALLATION EQUIPMENT REQUIREMENTS AS A FUNCTION OF MAXIMUM TENSION

Maximum Installation Tension (pounds)	Required Cable Engine Capability (pounds)[a]	Sheave and Drum Diameter Requirements (feet)[b]
50,000	77,000	7.5
100,000	154,000	15
150,000	231,000	22.5
200,000	308,000	30

Notes:

a. $T_{max} = 0.65 \times T_{rated}$

b. Assuming Crush $Force_{max} = \frac{T_{max}}{R_{drum}} = 13,500$ pounds per foot. Based on reported acceptable fleeting knife squeeze load on lead sheathed cable (7).

TABLE 4. SELECTED CABLESHIP CHARACTERISTICS

VESSEL	BOW CABLE ENGINES NUMBER	BOW CABLE ENGINES CAPACITY (lbs)	DRUM DIAMETER (feet)	BOW SHEAVE DIAMETER (feet)	TOTAL COILING CAPACITY (cu. ft.)
Long Lines (USA)	2	100,000 @ 1Kt	12	10 (two), 11	168,000
Alert (G.B.)	2	100,000 @ 0.25Kt	9.8	9.8 (three)	56,000
Cable Venture (G.B.)	2	67,000 @ 1Kt	9.8	9.8 (three)	222,000
Mercury (G.B.)	2	67,000 @ 0.5Kt	10	10 (three)	92,000
Vercors (Fr.)	2	67,000 @ 0.5Kt	9.8	9.8 (three)	90,000

Source: Underseas Cable Engineers, Inc., Cableship Characteristics (8).

TABLE 5. LONG LINES COILING CAPACITY BY TANK

CABLE OD (inches)	TANK CAPACITY[a] (n mi) NO. 1	NO. 2 & 3
3	66	123
4	37	69
5	24	44
5.75	18	33
6	16	31

Notes:

a. Assume 20 foot cable minimum coiling diameter, 24 foot depth of stack, cable coiling coefficient of 1.35.

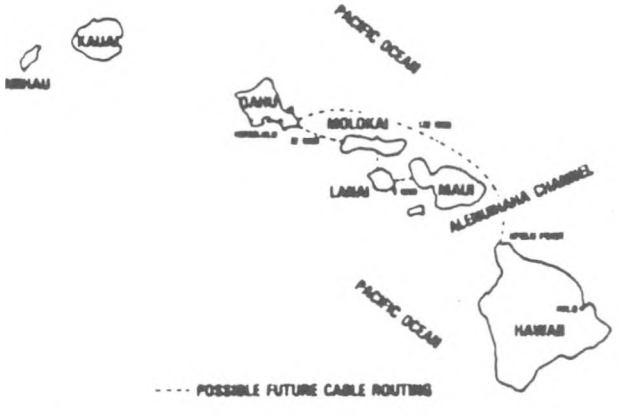


Figure 1. HAWAIIAN INTERTIE ROUTE

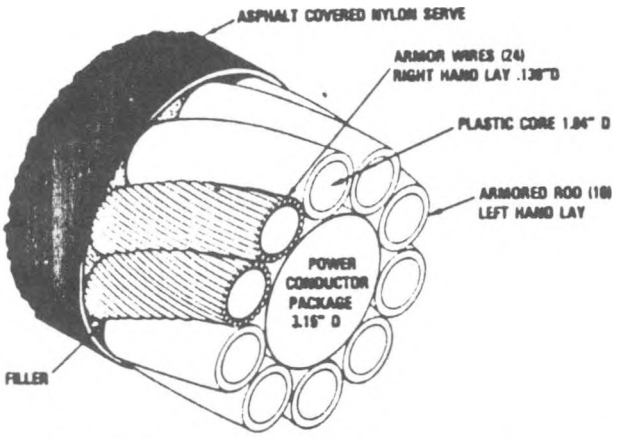


Figure 2. COILABLE, TORQUE-BALANCED CABLE

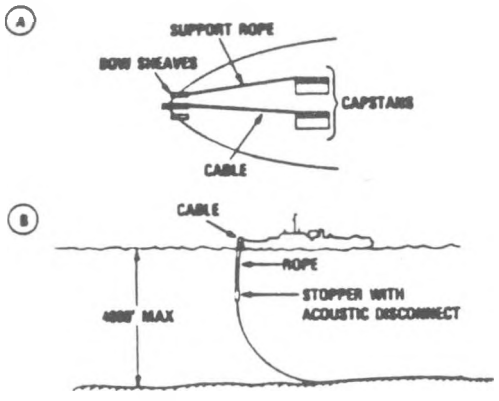


Figure 3. TWO-CAPSTAN INSTALLATION

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OTEC SUBSEA ELECTRICAL POWER CABLE PROTECTION SYSTEMS AND TECHNOLOGY

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ABSTRACT

Under contract to the Civil Engineering Laboratory, Brown & Root Development, Inc. is performing a study of existing technology for the protection of subsea OTEC cables. The systems are being considered for application anywhere from the shoreline to the deep ocean. The systems include trenching/burial systems as well as other not so familiar systems.

The survey has shown that several cable trenching/burial systems can be adapted for use in the protection of OTEC electric power cables from OTEC plants to a utility grid on shore.

The variation of design and operational parameters at different potential OTEC plant sites appears to exclude any expectation for the development of an all purpose system for all OTEC installations. If existing equipment does not satisfy the requirements of a given site's route, the conventional approach is to develop a combination of methods which will meet the needs of the present project.

1 INTRODUCTION

The primary means for transmitting power generated by OTEC plants will be through subsea electrical cables. The electrical power cables must extend from the OTEC plant down to the sea floor, then travel along the bottom to an onshore distribution network. Since the OTEC plant may be located in areas where the water depth is as great as 1524 m and located up to several hundred kilometers offshore, there is reasonable concern that the cable may be subject to damage.

In order to meet OTEC goals, a minimum life of 30 years has been specified for the cables. Past experience has shown that unprotected subsea power cables and other subsea transmission lines such as pipelines and communications cables are vulnerable to several types of damage as follows:

- o Fishing vessel trawl boards
- o Ship anchors
- o Abrasion due to motion on the bottom
- o Mud slides

Most authorities agree that up to 90% of cable damage occurs in coastal and shelf water and is due to fishing and ship anchors. However, trawler damage has occurred in 1326 m. Therefore, the question of protection requirements and methods must be addressed for the entire cable length.

The present accepted method for protecting subsea transmission line is by trenching/burial. This is done by excavating a trench into which the transmission line is placed. Backfilling the trench is usually left to normal bottom scour caused by bottom currents.

2 TRENCHING SYSTEM DESIGN PARAMETERS

The concept of a multipurpose trenching machine to be used in the burial of any subsea transmission line under all conditions can only be considered as an idea at this time. A review of the constraints placed on the hardware by the configuration of the transmission line, the operational environment, and the available support equipment will serve to clarify this point.

2.1 Configuration of the Line

The configuration of the line to be buried will affect the surface and subsea installation hardware. One aspect of the configuration, the line flexibility, strongly impacts the basic approach to handling. The most straightforward method for guiding a burial machine, to allow it to follow the line, is not generally possible with cables because the flexibility of the line does not provide sufficient reaction force for guiding. Most pipe burial machines such as sleds, plows, and some mechanical trenchers use the line as a guide while performing post lay burial. Equipment for the burial of cables, on the other hand, usually perform a simultaneous lay and bury.

In the simultaneous lay and bury technique generally used with cables, the vessel that tows the trenching machine also carries and lays the cable. The cable is guided from the surface to the sea floor and through the trenching machine. Cable, which is generally more fragile than pipe, is handled in a much different fashion as it is placed in the trench. For this

operation, the trencher is guided along the route by surface navigation and tracking equipment on the trencher. Operational differences stemming out of basic differences in line flexibility tend to restrict most cable burial systems to cable and pipe burial systems to pipe.

Size is an obvious aspect of line configuration that influences the design of transmission line trenching equipment. Most subsea cables range in diameter from 1 to 13 cm. Subsea pipelines, on the other hand, usually run from 15 to 92 cm. This provides a convenient separation point for the design of cable trenching and pipe trenching systems. The majority of experience with cable burying has been with communications lines, not power lines. The former are smaller and more easily handled; the latter are still generally smaller than the majority of the smallest pipes. The line size difference has a straight forward effect on the size of the trenching machine. It also influences the power required for trenching.

The power required to excavate a trench is a direct function of the cross-section of soil to be removed (which is related to the diameter of the line and the burial depth) and the speed at which the trencher moves across the bottom. Thus, for the same bottom speed, the power required for cable trenching and pipe trenching can vary significantly. Trenches may run from 0.372 m^2 cross section for 13 cm cable to well over 10 times that cross section for large diameter pipe. A vehicle large enough and powerful enough to handle a 92 cm pipe would be overkill for a 13 cm diameter cable even with proper cable handling capability.

2.2 Operational Environment

The operational environment, particularly the soil strengths and water depth impose significant impact on the design of trenching machines. The soil strengths affect the power required for cutting and the bearing support available for bottom crawling equipment.

Trenchers presently can work in soil strengths from about 0.14 Kg/cm^2 compressive strength (which just supports the equipment weight) to 82 Kg/cm^2 shear strength (which requires cutting). Water depth affects all aspects of system design from tether cable length, to wall thickness of hardcans to volumes of compensators. Most trenching systems available today are designed for relatively shallow water. The water depth capability for most systems is less than 305 meters.

The soil strength like the volume of soil removed affect the power requirement. The need to trench hard bottom such as chalky limestone will generally dictate a need for a great deal of system power. The size of the hardware to provide and transmit this power, along with the large and heavy characteristics of rock cutting equipment will result in a large and heavy trencher. This trend, however, is opposite to the design trend for soft soils where the power required is less and the bottom support available to the trencher is similarly less. Thus, the extremes of soil conditions contribute to opposites in design.

The choice of cutting device is also a function of the soil strength. Different techniques have been devised for the trenching of soils varying from unconsolidated sands to hard clays and chalky limestone. These techniques do not always effectively cross the boundary from one type of soil to another. For example, the most efficient trenching machine for the hardest bottom is the mechanical cutter type. These cutters are very inefficient in very soft bottoms of unconsolitdated soils. In such soils, a fluidization system can be used effectively but it will not work in clays.

Water depth has the most far reaching effect on trenching systems of any of the factors of the operational environment. The present operational depth of all cable trenching machines is less than the 1524 meters requirement specified by the possible OTEC sites. Only Sea Plow IV comes close, with a 914 meter capability. In order to extend the capabilities of the systems a total redesign of most hardware would be required. Some of the areas of present design limitations are pressure vessel working depth, line losses in tethers, and control of the system at depth. For many of the systems, particularly those with tethers providing fluids from the surface, extension of their capabilities to work at 1524 meters would be totally impractical.

The cumulative impact of line flexibility and size of soil strengths and water depth, prohibits the cost effective realization of an all purpose vehicle. The best methods for handling flexible lines and pipes are different. Line sizes for cables and pipes tend to divide into two distinct ranges. The extremes of soil strengths lead to very different trench cutting methods. Water depth, particularly due to a need for long tethers, tends to eliminate some systems that are very effective in shallow water such as air lifts and fluidization systems. The result is a number of different systems used for different lines under different conditions.

The wide range of different systems is reflected in past and present development of hardware for transmission line burial. Most systems that have been built have been developed with a particular crossing in mind. Prior to any crossing, detailed planning is undertaken to select a route that would cause the least problem for trenching and protection. In these planning stages the crossing is surveyed and the equipment is often built or modified based on

the requirements of that crossing. This in turn tends to establish upper and lower limits on the vehicle's capabilities

3 AVAILABLE SYSTEMS

An extensive literature review identified companies with systems which were potentially suitable for OTEC cable burial. Contacting these companies to obtain detailed information on cost, scheduling, experience, and status of the potential systems resulted in the identification of 37 suitable cable burial systems and 31 pipe burial systems.

There are essentially three types of systems available for burial/trenching of transmission lines:

- o Water jetting and eduction
- o Plowing
- o Mechanical cutting

In the early years of marine pipeline burial, water jetting with eduction was the primary method for excavating the trench. It is still an effective and widely used method. Recently, plowing and mechanical cutting methods have emerged as suitable alternates. The primary reasons for the development of the plowing and mechanical cutting systems were improved efficiency and harder soils encountered, respectively. Plowing has been a primary means for burying communications cables because it is faster and excavation requirements (trench cross section) are less than for pipeline trenching.

Jetting has several disadvantages. Jetting systems usually require considerable horsepower. The jetting action has a tendency to alter the mechanical characteristics of unconsolidated sands so that a trench in such soil has little stability and affords little protection. The depth capability of jetting systems is severely limited by the length of the fluid umbilical. Line pressure losses in long fluid umbilicals reach unacceptable limits, and such umbilicals become hard to manage and may cause the trencher to wander off course.

Plowing in unconsolidated sands offers a distinct advantage over jetting because it does not severely alter the surrounding soil characteristics. Plowing in many soils, however, requires excessive towing forces, making it an impractical method. A plow is often harder to steer in deep water because of the lengthy tow cable. It may have a tendency to ride up out of the trench due to the fluctuating plowing forces and the elasticity of the tow cable.

Mechanical trenchers excavate a good trench profile of relatively constant depth; however, they must crawl along the sea floor by using a powered propulsion system. As a result, they are relatively slow in comparison to the plows. Like the jet system, they require an umbilical but in most cases it carries electrical power and multiplexed control signals. The multiplex cable permits a smaller, lighter cable, and allows a greater water depth capability. The main disadvantage of mechanical systems is that they are more complex than the other systems.

3.1 General Capabilities

Soil shear strength is the primary variable for selecting a particular trenching system. Figure 1 was constructed from data supplied by the trenching system companies. In almost all cases, the soil strengths were indicated by soil types. Soil strengths described in terms of soil types have great ambiguity. For example, limestone varies from 50 Kg/cm^2 to 250 Kg/cm^2 shear strength and clays from .07 Kg/cm^2 to 70 Kg/cm^2 shear strength. In light of poorly defined data points the following approximation of trenching capabilities by soil type is presented.

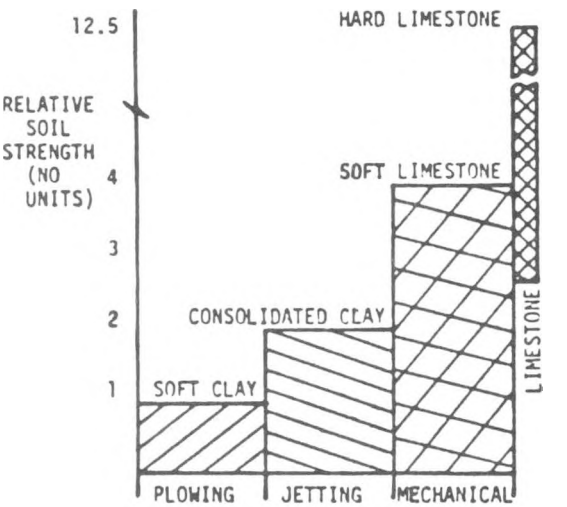


FIGURE 1

TYPICAL CABLE BURIAL SYSTEMS PRESENT CUTTING CAPABILITIES

Plowing may be employed in soil types up to a medium soft clay at which point a change to either a jetting or mechanical trenching system must be made. If a jetting system is selected it may be used in soil types up to and including overconsolidated or morainic clays. Then a change must be made to a mechanical trencher.

These generalizations are made in terms of relative working capabilities. This is not to imply that one system is more or less cost

effective than another. Many other factors must be considered to evaluate the systems for cost effective operation.

Figure 2 indicates the present definite trend in depth capability for each of the three systems. The graph indicates that the greatest overall depth capability is presently possessed by the jetting systems. This is probably because, up to now, they have enjoyed the widest usage.

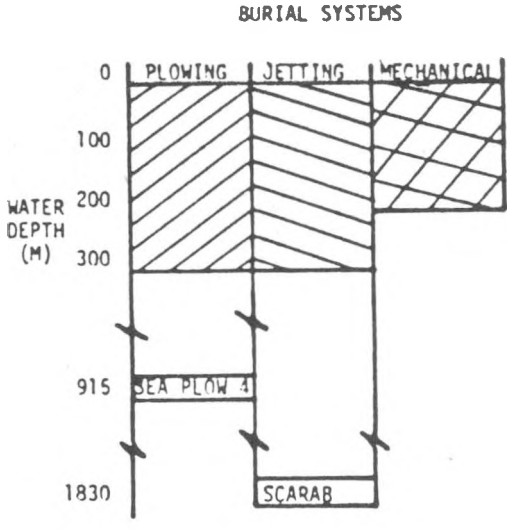


FIGURE 2

TYPICAL CABLE BURIAL SYSTEMS PRESENT DEPTH CAPABILITIES

4 PREMIER SYSTEMS

There are a considerable number of cable burial/trenching systems available. However, some of these systems are antiquated, no longer in use, or not suitable for burial of the OTEC cables. Suitability of a system is determined by judging whether or not the system has a viable trenching and propulsion system. The greatest measure of suitability is the system's past performance. Table 1 provides a brief description of cable burial systems which have been built and tested and which appear to be suitable for burying the OTEC subsea power cables.

5 ONGOING R&D - ADDRESSING DESIGN PROBLEMS BY JOB

Research is being done in a number of technical areas, and generally with a particular job in mind. A review of the ongoing research as a whole suggests a trend toward an improved capability for trenching harder soils, a more positive assurance of burial, and development of new control and propulsion systems.

One significant project in cable burial technlogy development is in progress in France and the UK. For this job, all aspects of the crossing were researched from the type of cable, to the method of protection, leading to the design of new hardware to provide for the protection of the cable.

In preparation for this crossing, considerable concern was shown for the route of the cable to determine bottom soil conditions and contour.
The optimum burial depth based on cost and risk of damage was also analyzed. With the bottom conditions, cable type, and the burial depth defined, and with awareness that no trenching equipment was available, design of systems for burying four crossings of two cables each was started. Two systems, the RTM II and Clem II, and the Travocean Trencher are under development in the UK and France respectively. These systems are being designed initially for a specific crossing with defined operational environment and cable configuration.

The approach of the French/UK project is common in present development of cable burial and trenching machines. The design of the KS-1 plow for the Japan-China submarine signal cable project went through a similar survey of the operational environment for the burial system. In this case the capability of the cable laying vessel was such that considerable design effort was required to reduce the tow force on the plow to match the capability of the vessel. This involved a unique application of multiple blades and extensive consideration of the blade configuration.

Much of the first work done in the design of cable burial equipment was for the Sea Plows designed by the Bell Laboratories. The systems were built or upgraded based on new lines to be laid. The Sea Plow II was redesigned for the TAT-5 line. "Surveys made of the proposed TAT-5 (Rhode Island to Spain) and MAT-1 (Spain to Italy) burying routes during the summer of 1968 showed a need for additional changes. The plow had to be modified to operate in very soft bottom and in conditions of zero TV visability. The resulting Sea Plow III was used to bury two TAT-5 shore sections and two MAT-1 shore sections. [2]"*

Although Sea Plow III was designed for TAT-5 it was not used for the whole line. "In the shallower and rocky shore approach the embedment requirment was increased to 4 feet (1.2m) and 6 feet (1.8m) through the surf area, therefore, requiring specialized cable embedment equipment.[3]" The Harmstorf plow was used in this shallow water shore approach. On the CANTAT 2 line the Sea Plow III was assisted by a

*Numbers in parenthesis refer to References listed at the end of the paper.

TABLE 1
PREMIER SYSTEMS

SYSTEM NAME	OWNER/BUILDER	YEAR BUILT	TYPE OF SYSTEM	MAX. DEPTH	SEA FLOOR TYPES	STATUS
Drum Cutter	Coflexip	1981	Mechanical	N/A	Hard offshore soils including coral	Land Testing
Flexiservice	Flexiservice	Unkwn.	Plow	200m	Variety of soil conditions	Last Report Working ('79)
Gopher MK2	Lyntech Corp.	1970	Mechanical	120m	All except coral	In Storage
KS-1	KDD	1976	Plow	Unkwn.	Fine Sands, Silts and mud	Unknown
Mark III	Sumitomo Electric Ind	1974	Plow	200m	Soft Sands to Soft Clay	Unknown
Mud Bug 6	Lyntech Corp.	1979	Mechanical	60m	All except coral and Sugar Sand	Operational
RTM II	Land & Marine Eng.	1979	Mechanical	100m	Chalk/Limestone/Sand stone/Ragstone/Clays	Completed Sea Trials
SCARAB II	Ocean Search, Inc.	1977	Jetting	1800m	Sands and soft clay	Operational
Sea Plow IV	A.T. & T.	1975	Plow	914m	Sands to Rocky Soils	Operational
SOFIE	Elsam/Svitzer	1977	Jetting	300m	Sand/Silt, Soft Clay	
Submarine Cable Burying Machine	Sumitomo	Unkwn.	Jetting	100m		Unknown
Submarine Cable Burying Machine	Sumitomo	Unkmw.	Plow	100m	Sand or Soft Mud	Unknown
Submarine Cable Burying Machine	Sumitomo	Unknwn.	Mechanical	200m		Unknown
TM-402	Tecnomare	1980	Mechanical	160m	Sand & Clay Rock up to 150 Kg/CM^2	Land & Sea Trials
Trencher	Travocean	1978	Mechanical	60m	Sand & Gravel Flint Cobble	Completed Sea Trials
UWAG I	Deutsche Babcock Anlagen	1980/81	Mechanical	100m	Sand/Clay/Marl/Chalk Limestone, Sandstone	Under Construction
Vibro Hydrojet	Harmstorf Corp.	1970	Plow	305m	Sand/Clay/Rocky Soil	Operational

manned submersible Pisces V. The submersible buried repeaters left exposed by the plow. Later improvements in the Sea Plow solved this problem. "To adequately protect the TAT 6 cable and repeaters, a new plow had to be designed. [4]" The new plow was the Sea Plow IV which could handle repeaters. Yet this plow is still not able to work in the surf zone or work in soils harder than sands and soft clays. The depth capability of this plow has been extended to 914 m making it the deepest cable burial system available. (This does not include SCARAB which has a 1830 m capability but is not specifically for burial.) In designing the plow to bury repeaters, the plowshare was redesigned to minimize towing force while digging a deeper trench for the repeaters. A great deal of research has gone into the development of this equipment through land and sea trials and studies of plowshare configurations.

Details of other development work being done by the various manufacturers is not readily available. However, some indication of what is being done can be gained by looking at some of the basic characteristics of the developing systems relative to the systems of the sixties and early seventies. During the early period, most systems were towed plows for cable burial. Then jetting systems were introduced for pipe burial and that technology spread to cables. These systems were all towed. A review of the premier systems of today shows the propulsion systems are divided between bottom crawling systems with six and towed systems with eleven. (The SCARAB uses thrusters but part of its mission requires that it operate off the bottom in a flying mode). The actual trenching device leans toward mechanical cutters found on eight vehicles. Three systems use water jets, five

use a plow, and one uses a jet plow. The last system, Clem II, is lay only vehicle.

These two areas, the propulsion and cutting techniques, have seen the greatest advancement in the newly developing hardware. A general upgrading of the system hardware has been taking place as each piece of equipment is built or modified for a new job. In general this upgrading provides for better monitoring, better line handling and more reliable operation. One other development in progress is greater depth capability. A Sea Plow V is being developed for greater than 914 m and RTM III is being designed for 1600 meters water depth.

6 ALTERNATE METHODS OF PROTECTION

A number of alternate methods have been developed for subsea cable and pipe protection. For the most part these are expensive stopgap measures. Some such as the split pipe, sandbagging, and rock dumping techniques, were initially developed for surf zone areas over hard bottom where deep trenching to avoid movement in the surf was not practical. Sandbagging and rock dumping have been used in a few instances in deeper water to protect pipelines from movement and trawl damage. Sandbagging which requires divers for installation has been generally limited to shallow water application. Other subsea techniques associated with transmission line protection include anchoring, blasting, concretre pouring and horizontal drilling. These should not be considered substitutes for trenching but rather installation alternatives to be applied where they provide a more feasible approach to a problem.

In one highly publicized operation rock dumping (and sandbagging) was used to cover 30 Km of line for Norpipe/Phillips Petroleum Co. This is the longest line to be covered by this technique. Unlike most lines that are allowed to backfill with normal current moved soil, this line was required by Danish authorities to be backfilled. A portion of the line was covered by sandbags. A year later the rock dumping through a fall pipe system was developed and used for covering the rest of the line. The procedure was an expensive alternative to satisfy Danish regulations and not a method to be applied for all buried lines.

There is development in progress in anchoring techniques. Anchoring has been used for pipelines particulary in surf zone areas. This is a normal part of the split pipe technique used for protecting submarine cables. The anchors may vary but the objective is to hold the line on the bottom against current and wave forces. Anchor Systems Inc. and Comex are both developing bottom crawling anchoring systems to be used on lines in shallow water. These systems do not appear to have application to submarine cables.

Blasting has been used for removing obstructions from the bottom for many reasons. In transmission line installation, the use of blasting is avoided by routing when possible. When it is used, a method is generally required for removing the broken rock from the trench prior to installing the line. Questions by environmentalists about the impact of blasting on the environment limits use of this technique. The charges are normally set by divers which limits the practical depth. For the Trans-Med pipelines, charges were placed by submersible to remove large obstructions. Some submersible operators have reservations about using explosives with manned submarines so this technique has seen limited application.

Some areas of pipeline have been covered with preformed concrete covers. These are used over mechanical connectors and valves where future maintenance is anticipated and could have application to repeaters on communications cables. The installation procedure is time consuming and expensive relative to trenching. Along the same line, a study performed in Norway has evaluated extension of the fallpipe technique to pour concrete over a pipe resting on the bottom. This has not yet been applied.

Horizontal drilling; which is an extension of directional drilling used in producing large fields from a single platform; has been used for some river crossings by pipelines. The use of this technique is generally limited to cases where normal pipelaying and trenching techniques would cause unacceptable slowdowns in traffic on major waterways. Although no application to cables has been found during the study, it appears that directional drilling techniques might provide a feasible method for protecting cables over a steep embankment.

One protection technique that was used off the coast of Italy was specifically designed to protect an existing cable from trawlers. In this application concern about handling an old cable with a cable burying machine led to the installation of steel cables parallel to the transmission lines to intercept any trawl boards. These steel cables running parallel to two power transmission cables were secured and suspended off the bottom to purposely snag any fishing gear moving through this restricted corridor.

The most common approach to transmission line protection involves the use of various methods on the same line. Each technique will be used where it provides the most feasible approach. The laying of two cables for power and communication between an oil refinery and oil storage yard by Idemitsu Kosan Co., Ltd, for

example, used several techniques after considering the results of the sea bed surveys:

- The cable was protected inside a specially processed steel pipe stake driven in the landing point of the Tokuyama oil refinery.
- A concrete duct was used at the Oura oil storage yard landing point.
- Cast iron guard pipes cover the cables for 80 m at the cobblestone sea bed at the depth of 0.4 m with concrete bags placed on top of them for protection.
- The remaining parts of the cables were buried at a depth of 1 m, the same as existing pipelines.

The same approach is taken with transoceanic communications cables where various types of cable armour are used and various methods employed for burial. One of the Sea Plows designed by Bell Laboratories will be utilized by AT&T to bury lines to a depth determined necessary for protection. The plow will be used only into shallow water but not to shore. Areas of hard bottom will be avoided by routing and the shore approach will be protected by a subcontractor using alternate methods.

Although research is being conducted to design better anchoring systems, new pads for supporting suspended sections of pipe, and methods for pouring concrete from surface vessels, none of these techniques appears to provide a viable alternative to trenching except in special cases. "It is generally conceded that burial provides the best protection against most of the hazards that threaten pipelines and cables both on land and under the sea. With favorable soil conditions, burial may also be the most economical potection, but with hard bed conditions, burial can be prohibitively expensive using existing technology. [5]" Thus, the research in these areas will not provide a complete solution to cable protection any more than research in trencher design will provide the all purpose transmission line burial system. It will be a combination of these techniques, trencher technology, and route planning that will protect future OTEC cables.

7. SUMMARY AND CONCLUSION

The survey identified a total of 37 cable burial systems and 31 pipe burial systems. The pipe burial systems were presented because of the related technology and not because they are suitable for cable burial. Out of the 37 cable burial systems, 17 built and tested systems were selected and identified as suitable for burial of the OTEC cables. These were selected based on past performance and an assessment of their trenching capability.

In order to adequately compare the individual trenching systems, cost information should be evaluated. This information is hard to obtain and harder to compare. However, it is possible to make some relative conclusions concerning costs. In general, for cable trenching systems, the plow is the least expensive to operate. The requirement of a cable ship for support will result in significant support costs. The alternate methods for protection are considered the highest, but in many applications they may be the only solution. The jet systems and mechanical trenchers appear to cost approximately the same and rate between plows and the alternate methods. The range of costs for jet and mechanical trencher systems is from $12 thousand to $47 thousand per day. Additional support costs were not determined. Support requirements may vary significantly from a supply boat to a barge with cranes, pumps, compressors, dive systems, tugs, and 80 support personnel. Frequent experience with offshore operations provides general understanding of the impact of support and mobilization costs. Such costs can easily be many times higher than the costs of the operating hardware.

A review of the techniques used for pipe burial and cable burial, when compared, suggest that trenching systems usually are not suitable for both pipes and cables. This is due to basic differences in the line configurations, mainly size and flexibility. Significant variations in the operational environment of one site over another, and even variations along one route, create further limitations on the capabilities of existing hardware. This is reflected in detailed planning performed prior to the installation of a new line. The planning often results in new equipment, modified equipment, and changes in routes.

Despite the limitations of pipe burial machines to bury cable and vice versa, the technology being developed is finding application in both fields. Recent development has been primarily with plow technology, rock trenching (soft) capabilities, and bottom crawling systems. General system upgrading is occurring, riding a trend of advanced subsea equipment occurring over the last decade. Alternate protection systems have been developed with application to special situations. These include rock dumping, anchoring, and horizontal drilling.

The present state of the art is at a turning point. The new plows and mechanical trenchers that are just coming on the scene have been developed over the last few years. The mechanical trencher experience is limited mostly to tests at this time but within two years considerable operational time will be logged. They will undoubtedly undergo modification and improvement. Two areas that may well see

increased trencher capabilities are water depth and soil shear strength.

A single cable trenching machine does not presently exist that has proven its cabilities to trench all potential OTEC cables. However, the developing systems or extensions of those systems (particularly for depth and soil strength) can provide protection for future OTEC cables. Evaluations of the individual sites with reference to the capabilities of existing trenching systems will be necessary to specify protection methods. The final approach will most probably use at least two cable protection techniques.

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OTEC AND ISLAND INDUSTRY SYNERGY - THE ST. CROIX CASE

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ABSTRACT

The U.S. Virgin Islands has developed a plan to use OTEC to generate electricity and fresh water, and to supply nutrient rich deep seawater for land based mariculture and aquaculture facilities. Projects of this nature have the potential to ameliorate shortages of food, fresh water and energy which limit the possibilities of improving life for inhabitants in many of the world's tropical islands.

The project has been sized to produce 12.5 MW of electricity, up to 5 million gallons per day (MGD) of fresh water and 50MGD of deep seawater. Its output would offset between 250,000 and 275,000 Bbl of petroleum products derived from imported oil currently used to generate electricity and desalination.

Introduction

The proposed site for the OTEC demonstration plant is on the island of St. Croix, U.S.V.I. The plant will be owned and operated by the Virgin Islands Water and Power Authority (VIWAPA), a Virgin Islands government owned corporation established in 1964 to produce and distribute electricity and water for the Virgin Islands. The diffuse nature of the population on St. Croix and the very hilly terrain lead to high distribution costs for both water and electricity.

VIWAPA has about 87 MW of hydrocarbon-fueled generating capacity on St. Croix. This capacity is made up of a mix of high heat, rate oil-fired steam plants of ancient vintage; gas turbines on both industrial and aircraft frames; and diesel engines.

VIWAPA produces about five million gallons of fresh water per day on the island which is distributed by the Virgin Islands Public Works Department to industrial, commercial, and residential customers. This water is normally produced by multistage flash desalination using petroleum fuel oil as the heat source. When the requirements exceed the capacity of the desalination equipment, or when the equipment is down for frequent repairs, additional water is transported by barge from Puerto Rico.

Desalination is an energy intensive operation, which results in abnormally high water production energy costs in comparison with the continental United States. High fuel costs and the extended electrical distribution system dictate an electrical power cost for residential customers of about 17¢ per kWh, which is two to three times the U.S. national average. Much of the water is distributed to residential customers by tank trucks which use additonal petroleum products. Because of the high energy costs associated with desalination, the present cost of water production in the Virgin Islands is about ten to twelve dollars per 1,000 gallons. With distribution costs added, the price of water to a remote customer is about thirty-five dollars per 1000 gallons.

St. Croix uses about 800,000 Bbl of imported petroleum products per year for electrical power and water production with the present generation equipment. The proposed OTEC demonstration plant should offset between 150,000 and 225,000 Bbl of petroleum products derived from imported oil used for generating electricity and additionally, would save about 250,000 Bbl used for desalination if all of its water requirements were supplied locally.

Site Characteristics

St. Croix is one of the three major islands constituting the U.S. Virgin Islands, and is located 113 km east-southeast of the island of Puerto Rico as shown in figure 1. Steep bathymetric gradients surround the island particularly on the north coast. Figure 2 outlines the 500 fathom line which surrounds the island. The frequent number of observations of water mass structure here show excellent thermal potential for OTEC development. This data shows a marked similarity to the data for the Punta Tuna, Puerto Rico proposed OTEC site. In as much as these sites are on opposite sides of the same marine trench, the similarity is not unexpected.

There is a long history of oceanographic research on St. Croix. Perhaps the best documented is the work by Roels, et al[1-2] at the "Rust-Op-Twist" marine research station on the north shore of the island (Figure 2). A 1000m isobath was obtained approximately 1.6km offshore. The bathymetric profile of the shore indicated a reef extending 410 m from shore, gently sloping to a depth of 18 meters. At the end of this reef, the drop-off begins with the sea floor sloping downwards at an angle of 31°. Extensive oceanographic data from a site 15 km north of St. Croix

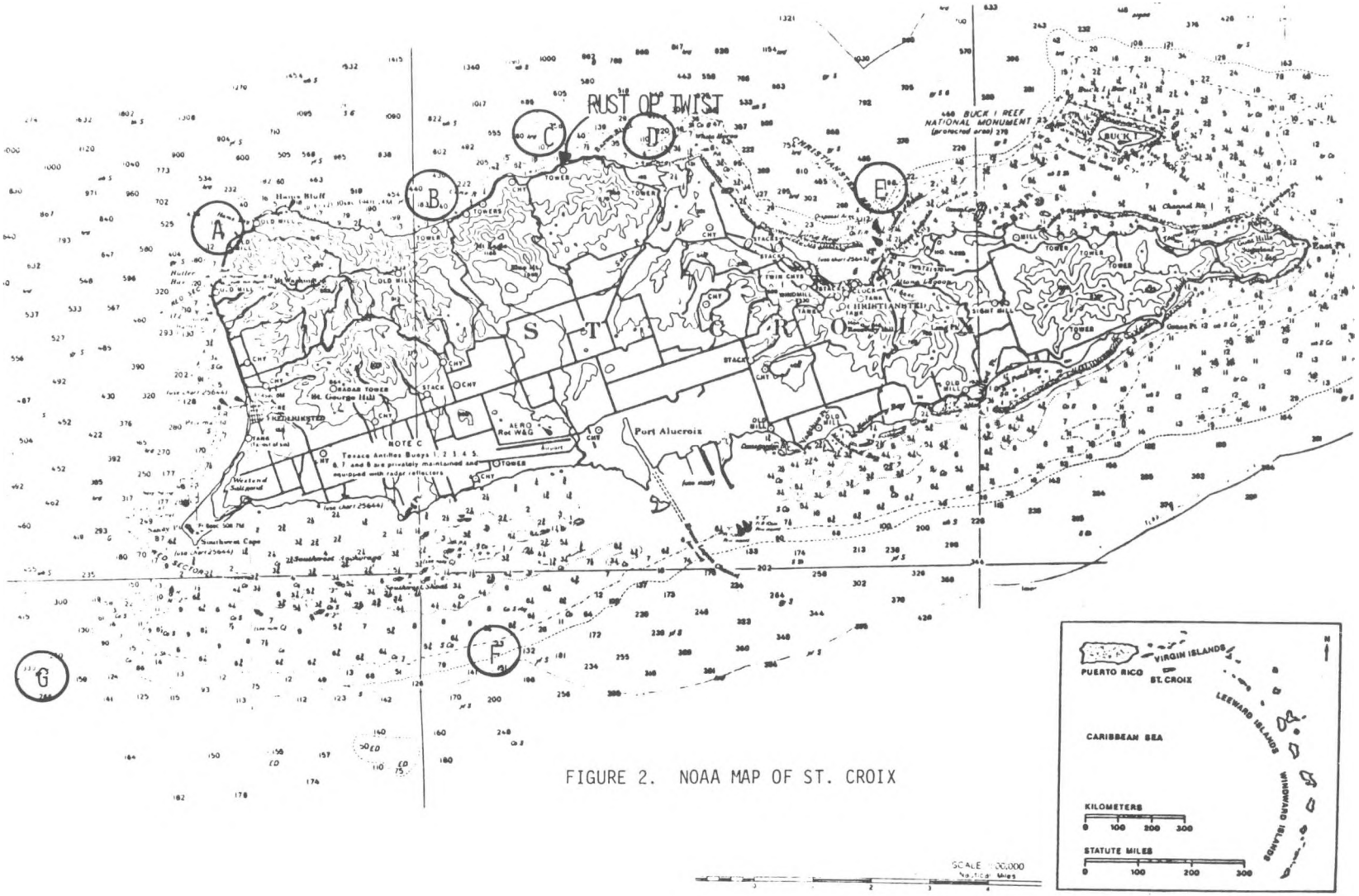


FIGURE 2. NOAA MAP OF ST. CROIX

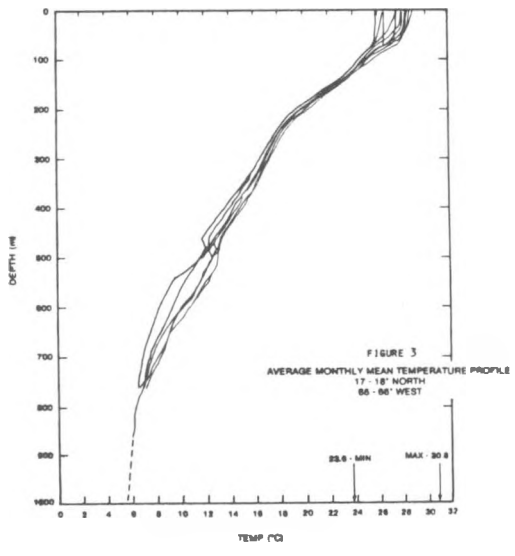
FIGURE 1. THE CARIBBEAN SEA

is given by Munier, et al [3]. From salinity, temperature, and density measurements at that site, they identify an underwater stratum of Antarctic water at depths below 800 m, flowing past St. Croix.

To evaluate the thermal resource around the island, information on the temperature structure in the vicinity of the Virgin Islands has been acquired from the National Oceanograpic Data Center, NOAA, and examined. Temperature data were separated into four 1° squares:

SQUARE	NO. RECORDS
17-18°N 64-65°W	799
17-18°N 65-66°W	1099
18-19°N 64-65°W	266
18-19°N 65-66°W	1483

Within each 1° square, obtained data indicates the average monthly mean value versus depth, and the min-max values at each depth. The values show a consistent pattern which is shown in Figure 3 for the square 17-18°N, 65-66°W, the region around St. Croix. Above 450 meters the number of data sets is large (20), but below 450 m it drops to fewer than 6. The data have been extrapolated to 1000 meters, and in all cases a minimum T of 20°C was obtained. The region around St. Croix, shown in the data presented in Figure 3, appears to provide the best resource.



From the hydrographic chart, Figure 2 it appears that any site along the northern coast of St. Croix between Hams Bluff and the western edge of Christiansted Harbor would be an extremely attractive OTEC site from the standpoint of thermal resource evaluation and underwater topography. Any plant constructed in this area would need a cold water pipe less than 2 km in length. These north coast sites appear to be well suited for a shallow water tower mounted plant. One area which was investigated for the pilot plant is about 10 km west of "Rust-Op-Twist" in the vicinity of Hams Bluff. In this area, the edge of the reef is about 230 m from shore, and the bottom slopes downward at an average angle of about 39°. This region is attractive because the seacoast is uninhabited, and output from the plant could easily be integrated into the electrical and water distribution systems on the west end of the island, where more capacity is needed. Figure 4 shows a profile of the surface and the gross underwater topography for a site in this area.

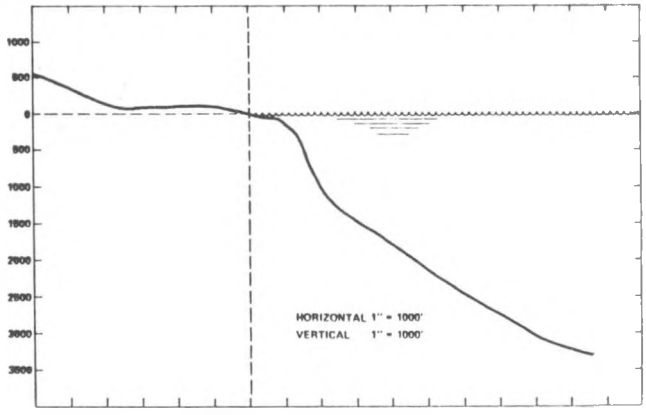


FIGURE 4. BATHYMETRIC PROFILE FOR SITE B

If the OTEC power system were to be a shelf-mounted unit in water 100 m deep, the length of the bridge or trestle required to reach from the shoreline to the OTEC platform would be only about 150 m. For this site, the length of the cold water pipe is about 1.28 km to reach 5°C deep seawater at 1000 m depth. It is noted that the data given in Figure 4 are based on a hydrographic office chart, which does not give the detailed information required for the design of an OTEC plant. Much more bathymetric data are needed to properly evaluate this site.

The proposed OTEC plant will produce not only electricity, but fresh water, and deep sea water for mariculture and aquaculture facilities. The costs of distributing these three products to their point of consumption, or to existing distribution systems, must be considered as part of the overall project. Therefore, the costs associated with the transmission lines, pipelines, and the losses incurred with product distribution; i.e. pumping power, head losses, etc., become part of the economic equation to determine the optimum location for the plant. For this reason the eight sites shown in Figure 2 will be evaluated in the conceptual design phase. For those sites on the southern shore of the island, the platform would be further from the shore, and the underwater slopes to 1000 m depths are less, so the cold water pipes would be longer. However, these sites are closer to potential sites for the mariculture and aquaculture projects; therefore, the costs of the deep sea water systems should be less. It is within the context of overall project costs and environmental considerations that the plant siting decision must be made.

OTEC System Characteristics

A simplified flow chart (Figure 5) for the various systems in the project is included under the assumption that the fresh water would be produced by reverse osmosis (alternate water production alternatives are discussed later). In the closed-cycle OTEC concept, warm seawater from near the surface is used to evaporate the ammonia working fluid, which flows through a demister to produce high quality vapor. The ammonia then drives a turbine, and is condensed by a heat exchanger with cold water drawn from a depth of about 1000 m. The generator, which is turned by the turbine, provides electrical power which is used to drive the various pumps and auxiliary systems. Any remaining power is distributed to the grid, or used for desalination and/or for pumping the deep seawater to the mariculture and aquaculture facilities.

OTEC Power System

The Department of Energy (DOE) has sponsored several power system development (PSD) studies which have resulted in preliminary designs of 10 MWe and 12.5 MWe power modules (PSD-I and PSD-II). These designs (by Westinghouse[4], Lockheed[5], G.E.[6], and TRW[7,8]) differ primarily by the type of heat exchanger selected, materials of construction, and the plant arrangements. For the proposed St. Croix pilot plant it is planned to use the equivalent of a 12.5 MWe module which was examined in PSD-II. While the peak load on the VIWAPA system on St. Croix is now 32 MWe, for system reliability purposes it is generally not desirable to have more than 25 percent of the system load carried by one generating unit. For this reason, the 12.5 MWe module was selected. Since about 2.5 MWe will be used by the desalination plant and for pumping water to the mariculture and aquaculture project, the net output will be 10 MW (which falls near the 25 percent criteria for the load expected when the OTEC plant is operational). By curtailing water production for short periods, the 1.67 MW used for that purpose can be made available for meeting peak power needs on an occasional basis, i.e., to cover outages, etc. Conversely, power can be fed back from the grid to power the desalination equipment, if the OTEC plant is shut down for repairs or maintenance. Since excess generating capacity is already available on the island, the only major economic penalty is the fuel charge.

The TRW PSD-I design configuration was the basis for our preliminary evaluation. For this project, the PSD-I design was increased in size from the 10 MW used in the PSD-I study to 12.5 MW which was used in the PSD-II study. Table I gives the pertinent dimensions, flow rates pressures, and other physical parameters for the proposed OTEC power system.

The 12.5 MW power module for a shipboard type installation includes externally mounted heat exchangers, the tube cleaning machine on top of the heat exchangers, a turbine/generator and ammonia piping and pumps. This arrangement is compact, yet provides space and access for maintenance and repair. As is discussed later for the shelf mounted platform, a different power system configuration may be preferred.

The heat exchangers incorporate a vertical fluted tube, falling film, evaporator concept, and a vertical fluted tube condenser concept.

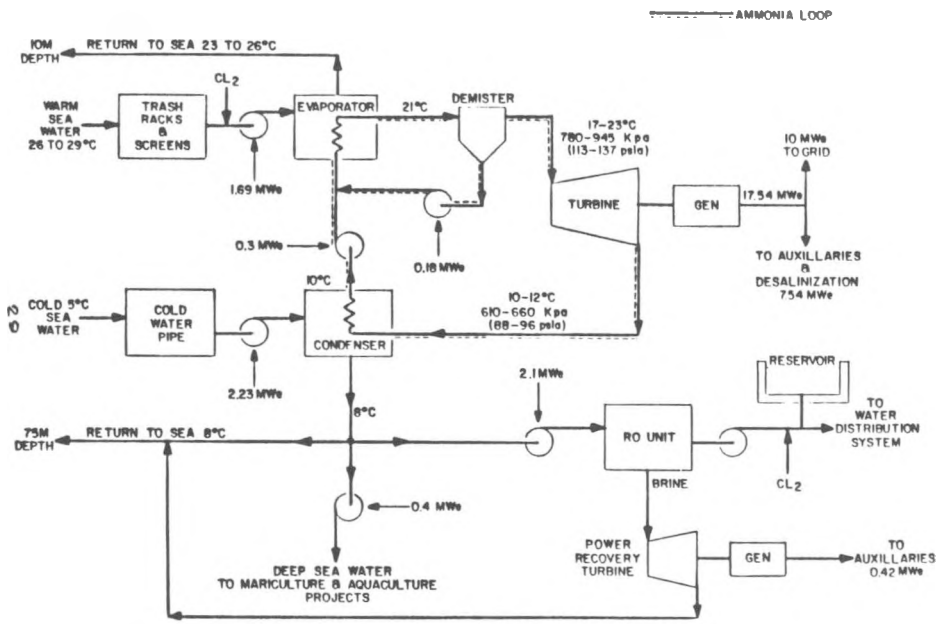


FIGURE 5. FLOW CHART FOR VIWAPA OTEC PILOT PLANT

Ammonia is the selected working fluid since it is conducive to more compact and less expensive equipment than other fluids. The overall dimensions of these heat exchangers, if they were to be in one unit, are approximately 10.2 m O.D. by 9.2 m long (tubesheet-to-tubesheet).

Titanium is the selected material for the tubes based on its expected long life in a seawater environment. This is a minimum risk approach. However, it is noted that the falling film heat exchanger concept, with extended surfaces, has only been tested at Argonne National Laboratory, using aluminum heat transfer surfaces and not titanium. If the use of extended surface titanium heat transfer surfaces is deemed necessary, further development would be required.

The thermal efficiency of an OTEC plant is low, typically between 2 and 2.5 percent, versus conventional power plants with thermal efficiencies in the range of 30 to 40 percent. However, since the "fuel" is free (except for parasitic pumping power), the thermal efficiency is not a good measure of plant performance. A better measure is what may be called "power efficiency," defined as the ratio of net power to gross power. This ratio is approximately 70 percent for the TRW PSD-I design at the design T of 40°F. As the available$\triangle$T decreases, the power efficiency decreases. At a $\triangle$T of approximately 25°F (13.9°C) the plant yields no net power, i.e., the gross power equals parasitic pumping power.

For the PSD-I design, the net power is essentially linear for the overall available $\triangle$T. For a nominal 10 MWe net module (at design $\triangle$T = 40°F) a detailed analysis shows that to a very good approximation the net power is closely approximated by the equation:

$$P_{net}(MWe) = 10.00 + 0.694(T(^{\circ}F) - 40)$$

This is discussed in TRW's preliminary design report. An approximate analysis, assuming that efficiencies of rotating machinery (pumps and turbines) and heat exchangers are constant and independent of the T, leads to the following model:

$$P_{net} = \left[P_{Gross\ Design}\right] \cdot \left[\frac{\triangle T}{\triangle T_{Design}}\right]^2 - \left[P_{Parasitic\ Losses\ Design}\right]$$

Tower Configuration

The northern shore of the Island of St. Croix is ideally suited for a shelf-mounted, tower-based, closed-cycle OTEC system. Figure 6 shows a configuration for the shelf-mounted 12.5 MWe OTEC system which is being studied for the VIWAPA installation. The tower concept shown roughly follows the design developed by McDermott, Inc. under NOAA sponsorship[9,10]. Such a platform represents a logical extension in the development of offshore structural technology, which began almost fifty years ago. The platform is fixed to the sloping seabed by steel pilings, a concept with proven stationkeeping reliability in the North Sea and Gulf of Mexico. Installation of the platform utilizes conventional offshore installation procedures and practices. The power cable and water product pipes are completely stationary after installation.

An important design constraint on any offshore structure is the effect of waveloading on the sizing of the platform members. Typical offshore platforms are designed for all equipment and deck supporting structures to clear the most extreme waves that could occur during the most severe of storms, generally a 100-year frequency of occurrence storm. By clearing the most severe wave ever expected, the maximum loads on the structure and the foundation are kept within safe limits.

One configuration is to locate the OTEC heat exchangers above the water for access purposes. However, the height above the water level is constrained by the necessity of maintaining a syphoning effect in the heat-exchanger discharge lines, such that the tops of the exchangers can be a maximum of only 9 m above the water. This constraint places the heat exchangers at the elevation of the highest wave pressures on a fixed type platform. It subjects both the equipment and supporting platform to extremely high wave forces. This results in prohibitively large loads and vibrations in the structure, OTEC components and sea bottom foundations, caused by exposure to the high energy portion of the waves; wave slamming effects, and differential buoyancy effects.

While a monolithic OTEC installation with a large water plane area could, possibly, be designed to accommodate the forces in the wave zone, it would not be cost effective. Two approaches allow an effective design through reduction of global wave forces on the structure. Each approach is contingent on the installation site conditions and the allowable configuration of the OTEC equipment.

One approach divides the single body (monolithic) OTEC equipment containment into several relatively large, discrete, vertical-cylindrical containment bodies, connected together with a deck above the wave zone, and interfacing tubular braces below the wave zone. The second approach submerges all large bodies below the high energy wave zone. Each approach allows a manageable marine structure which takes advantage of wave transparency principles.

Both approaches are influenced by the water depth at the platform site and the height of the wave expected at that water depth. If the platform is in shallow water, wave heights and resulting wave pressure forces (except for breaking waves), will be limited. In deeper water, the wave heights will be greater, and the subsequent wave forces more difficult to withstand.

Since, depending on heat exchanger location, the weight of the power generating equipment may be extremely large (much larger than typical oil field equipment), it is anticipated that the support structure could be larger than most oil field structures.

In the concept shown in Figure 6, the physical configuration of the OTEC power system is somewhat different from those shown in much of the previous OTEC literature. In this case, the plant is designed to have the evaporators and condensers at some convenient depth under the water, in a position such that the wave action on the submerged structures is minimized. The design provides for a warm water inlet leading from the mixed surface layer to the evaporators, which are mounted on the side of the tower. In this configuration, the total amount of evaporator heat exchanger surface is provided by four units, which are approximately 4.5 m in diameter, rather than by one unit 9 m in diameter. This is to reduce wave-loading on the tower. Another reason for breaking down the heat exchanger and circulating pumps into multiple units or modules, (rather than in one large unit) is to facilitate repair of an evaporator, or the other element in the module, while maintaining the output of the plant at an operating level; i.e. 75 percent of rated power. High performance heat exchangers such as those proposed by Trane[11] or Alpha Laval, which would reduce the projected area for wave loading, could be preferred for this type of application.

The ammonia from the evaporators is directed above the surface of the water through the tower legs to the platform, which supports the turbine and electrical generator, and the ammonia loop support equipment. Then the ammonia exhaust from the turbine is lead back down the legs of the tower to the condensers, which are mounted at approximately the same elevation as the evaporators. The dimensions of the tower legs are appropriate for the ammonia transfer piping.

Hot and Cold Water Pipe Systems

The proposed CWP system uses an extension of current offshore practices and equipment to install a cold water intake pipe, approximately 5 m in diameter, on the sloping seabed from the OTEC platform to a water depth of about 1000 m. The proposed pipe is to be constructed of fiberglass reinforced plastic (FRP) with a foam core. Fiberglass has been tentatively selected because it can be made neutrally buoyant by varying the core thickness during design. However, either a concrete or steel cold water pipe could be used.

The pipe is to be installed using a marine railway system. The railway is used to guide the pipe segments into position and align them on the sloping seabed while sealing is affected. Use of this installation technique avoids deep water control problems inherent in other methods. Both intake and discharge pipes would be installed in a similar manner.

The hot water intake pipes (HWP) are installed in the platform during fabrication. These intake

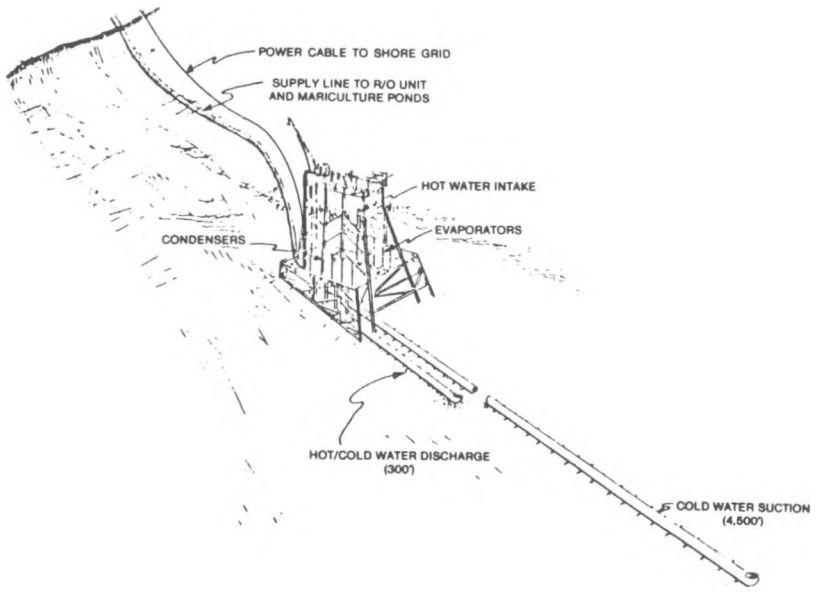


FIGURE 6

PERSPECTIVE — 12.5 MW SHELF-MOUNTED OTEC POWER PLANT

pipes are short flow passages that extend upward, inside the platform, from the evaporator containment vessels that are shown submerged, and on the side of the platform structure in Figure 6.

Because of the surface currents which are present along both shores of St. Croix, there will be minimal mixing of the warm water discharge with the warm surface water under most meteorological conditions. The used surface water will be discharged immediately after exiting from the evaporator at a depth of about 60 m. Because of its higher density it will remain at that level or sink to a depth of between 75 m to 125 m, where it will be in equilibrium with the surrounding water.

In the case of the cold water discharge, the water density is high enough for discharge at depths greater than 75 meters (the start of the thermocline for the region as is shown in Figure 3) to occur. Because of the higher density of the cold water, it is expected that it will flow back down the slope as a fairly homogeneous mass until it reaches a depth appropriate for its temperature, and spread out from this point with minimum mixing from the surrounding water.

Figure 6 shows how the condenser and evaporator discharges would be connected to the hot/cold water pipe outfall, necessary if the depth of the discharge from the tower were above the desired 75 meter discharge depth. The design objective is to prevent the nutrient-rich cold water from forming an algae bloom similar to a natural upwelling. However, for socioeconomic reasons it may be desired to discharge part of the used cold water at the surface and mix it with the surface water, which is deficient in nutrients, as a form of controlled artificial upwelling for open ocean aquaculture and mariculture. Such a controlled upwelling could boost the Territory's protein supply and its attractiveness to sport fishermen.

An advantage of this concept for the shallow water tower mounted system is it allows the entire OTEC power system to be preassembled as part of the tower, at a shipyard site in the United States. It also allows the entire platform, plus the OTEC power system, to be moved by barge to the site where it may be possible to have the connections to the shore and shore support facilities constructed by a local labor force. The construction would require a minimum of skilled personnel at the site. In terms of other island applications, this approach could be an important factor in potential commercialization of OTEC.

Integration with the VIWAPA System

The net output of the proposed OTEC demonstration plant is planned to be up to 12.5 MW of electricity, between 5,000 and 19,000 m^3/d of fresh water, and 190,000 m^3/d of deep seawater for mariculture and aquaculture. For example, if the plant were to be built in the vicinity of Hams Bluff, site A in Figure 2 the electricity and fresh water would be delivered to the distribution system on St. Croix by means of a pipeline and overhead transmission line, which would be built along the road which follows the coast on the west side of the island. The electricity would be delivered to the existing substation on the outskirts of the city of Frederiksted, and would be tied to the VIWAPA central electrical distribution system. The fresh water would be delivered to a new 10-million gallon storage reservoir to be located on the side of St. George Hill just east of Frederiksted, and would be connected to the V.I. Public Works distribution system at Frederiksted. From the Hams Bluff site, the deep seawater would be delivered via large diameter pipelines to locations on the north shore, or the west shore of St. Croix where, tentatively, mariculture and aquaculture plants are planned. Because of the steep terrain which slopes down to the seashore in certain sections and the desirability of keeping the pipeline at or near sea level to avoid excessive pumping costs, the construction of the pipelines for deep seawater may be expensive. It may, therefore, be appropriate to move the OTEC Plant site to a region where the cold water pipe might be slightly longer (sites B through H), but the overall construction costs less. During the conceptual design phase of the project the site selection for the mariculture and aquaculture projects will have been finalized and can be considered as part of an overall economic optimization study.

Electricity

All the electrical energy generated from the proposed OTEC pilot plant will be used by the Virgin Islands Water and Power Authority electric grid, supplementing energy which is provided by present generating plants using fossil fuels. VIWAPA does not produce all of the electricity that is consumed on the island. The Martin Marietta plant, which uses the Bayer process to produce alumina from bauxite, has the capacity for generating roughly 50 MW of electricity using cogeneration. The high pressure steam output is used in their digestors. The Amerada Hess refinery also generates about 100 MW of electricity, using gas turbines which burn flare gas. Both of these plants have room for future expansion and could be potential customers for OTEC generated electricity at some later date if the OTEC plant capacity were to be increased.

At the present time, the proposed OTEC generated electricity would be used only in the VIWAPA grid on St. Croix, but there is potential for industrial development, which could also require additional power.

Fresh Water Utilization

The fresh water produced by this project will be delivered by VIWAPA to the Virgin Island Public Works Department (VIPWD) for distribution through their water main system to industrial, commercial, and residential customers. Most of the fresh water which is introduced into the Public

Works distribution system is produced by multi-stage flash desalination using hydrocarbon fuels; this water is supplemented by limited groundwater supplies. There is a total of 8 million gallons per day capacity of desalination equipment installed in the VIWAPA system. The daily demand on St. Croix from the VIPWD distribution system is approximately 3.5 MGD. There are also many small, privately owned and operated desalination units on the island for regions not served by the water distribution system. If these private water systems were connected to the VIPWD system total demand could exceed 5 MGD.

The proposed OTEC project will generate between 1.4 and 5 MGD of fresh water depending upon the technology which is chosen and its level of development. There are two basic options which will be examined, reverse osmosis and open-cycle OTEC flash distillation.

Currently, reverse osmosis is an available technology. It is known from work on St. Croix by the Fairleigh Dickinson University Desalination Laboratory that by using deep seawater as the feed for the reverse osmosis unit, the necessity for pretreatment of the water can be eliminated. This reduces the capital and operating costs of the plant. At present levels of development, 2.1 MW of electric power, would produce about 1.4 MGD. It is projected that in the next few years, through the commercial development of advanced reverse osmosis membranes, and the use of power recovery systems, the quantity of water produced for the same electrical input can be increased by a factor of about two.

Another attractive option for this application is to use something akin to an OTEC open-cycle system where the warm seawater is pumped up to a level such that a barometric leg can maintain a vacuum sufficient to cause the warm surface water to flash at its temperature of 25 to 28°C. This corresponds to a vacuum of about 2 cm of mercury. The low-pressure steam is then condensed using the cold deep seawater as a heat sink.

The warm surface water passes through a two stage deaerator before entering a three stage evaporator. Cold deep seawater is used in the condenser and then passed through a water injector to pull a vacuum on the dearator. It is also used in the spray condenser to remove non-condensible gases. Experimental work by the Nord Aqua group in Finland has shown that by using this technique, it is possible to produce about 3800 m^3/d of fresh water for each 500 kW of OTEC electricity. This electricity is used to pump the warm water up to the flash evaporator and for other pumping requirements. On the basis of the requirement for 19,000 m^3/d of fresh water, it is projected that roughly 2.5 MW of electrical power would be required. Preliminary calculations suggest that the open-cycle OTEC concept would require about 27.5 m^3/ sec of warm water and about the same amount of deep seawater to produce the desired m^3/sec of fresh water.

Deep Seawater Utilization

The deep seawater from the OTEC plant is viewed by some authorities[12] as having a value equivalent to the electrical power that is generated. For the proposed project on St. Croix, two corporations have expressed interest in receiving a total of about 4 m^3/sec of deep seawater from the proposed demonstration plant for a mariculture project, and an aquaculture project. The total of these two flows is equivalent to about 10 percent of the projected deep seawater used by the OTEC power system. One important economic consideration is that pumping deep seawater to the mariculture and aquaculture projects reduces the size of the discharge pipe returning the deep seawater to the 75 meter depth. This will reduce the amount of horsepower required to circulate the water for the power system. However, additional energy will be required to distribute the water to the commercial projects.

Use of the deep seawater for mariculture places some limitations on the project in terms of materials which can be used for heat exchangers, piping, etc. For example, it is known that the use of copper-bearing materials has an adverse effect on marine organisms.

A second application of the deep seawater, which has not been addressed, is the possibility that, if the plant is built near the urban centers such as Christiansted or Fredericksted or if it is built near the other major commercial facilities such as the Hess Refinery or Martin Marietta plant, then the cold water would have other economic uses such as in the chillers of air-conditioning systems.

Socioeconomic Impacts

The expansion of tourist trade on St. Croix as a result of OTEC generated electricity and water would have a dramatic effect on the high unemployment rates which prevail in the western part of the island. There are large federal-social program subsidies to the islands, and revival of the tourist industry on St. Croix could have a large immediate impact, reducing these payments.

The second major impact is through the mariculture and the aquaculture projects, which could provide new jobs also increase the Territory's economic base.

If the OTEC generated electricity can be viewed as reliable, which is not the case with the present VIWAPA power generation system, it may influence, positively, potential manufacturers to locate light industry in this region as has happened in Puerto Rico. Having 10 MW or more of electricity available could result in as many as 1,000 new jobs if these industries are not energy intensive. For an island with a population of about 35,000 people, (roughly 8000 potential job holders) 1000 new primary industry jobs would have a large impact.

One of the most significant impacts of OTEC would be the reduction in fuel oil payments for power plants and desalination facilities. The requirement to buy imported petroleum supplies imposes a very severe drain on the Virgin Islands economy. Relief from some of these costs will result in a much better standard of living for all the people within the Virgin Islands.

Project Economic Evaluation

The estimated cost for the 12.5 MW closed-cycle tower mounted OTEC system and the systems required to distribute the three products is about $141 million, in constant 1981 dollars. It is expected that about six years will be required to design and construct the plant and the distribution systems. This estimate is based on using "conventional" titanium heat exchangers and reverse osmosis for fresh water production. The use of high performance aluminum heat exchangers could reduce the estimated cost, both for the heat exchangers and the tower.

The revenue derived from the electricity produced by the OTEC plant and delivered to the VIWAPA distribution system is about $13 million per year based on a sales price of 17¢/kWh. The value of the fresh water to be produced is roughly $16.5 million per year at a $10/1,000 gal sales price. It is estimated that the total value of the deep seawater could be about 25¢/1,000 gal with a total annual revenue of about $4.1 million. This results in a revenue of about $93,500 a day for the project, or about $34,000,000 a year (in 1981 dollars).

A preliminary capital budgeting analysis was performed based on the above revenues. A 30 year plant life, 90% capacity factor, 2% O&M cost, 46% U.S.V.I. tax rate, 22 year Straight Line Asset Depreciation Range, and a 95% tax forgiveness (over the first 15 years of operation) were also assumed. The after tax Internal Rate of Return (IRR) was about 15%. With 30% government cost sharing, this rate increased to about 20%. This equates to before tax rates of return in the 30-40% range, a profitable investment by most standards.

Conclusion

Because of the small size of the island of St. Croix, and, in fact, the whole Virgin Islands territory, the proposed 12.5 MW pilot plant and its supported industries will have a far greater economic impact on the local area than the impact a 40 MW pilot plant would have on any region in the continental United States. St. Croix appears to be an ideal microcosm for testing the economic viability of OTEC coupled with non-electric supported industries.

Tourism is the primary industry of the territory. High local energy costs threaten to reduce the current Virgin Island tourist trade and its resulting economic growth and development. For this reason it is difficult to project future demands for electricity and water above the historical trends, unless some new technology such as OTEC can provide reliable and reasonably priced electricity and water. Once such reliable sources are available, it is projected that the island's economy will experience a period of sustained growth in both tourism and light industry. Such industrialization, particularly in the chronically unemployed western part of St. Croix, would have a profound impact on the amount of income supplemental payments, i.e., welfare, food stamps, etc. (about $300 million per year), which are provided to the Virgin Islands economy each year by the United States Federal Government. The proposed OTEC plant would have a large but as yet unquantified impact reducing these income supplemental payments by stimulating the territory's economy. The amount of this reduction could equal or exceed the value of the revenues received from the sale of products, produced by the project.

The concept outlined here, whereby the OTEC power plant produces not only electricity but also fresh water and deep seawater for mariculture, could have a profound effect on many developing countries in the world. These countries have requirements for limited amounts of electricity. Generally, they are not industrialized and their per capita use of electricity is low. They do have requirements for fresh water (for both domestic consumption and for agriculture) and these countries, generally, have a very great need for the protein developed as part of such a project. This implies that there could be a large, widespread market for OTEC plants of this size, together with the various supporting systems.

One element of commercial impact is the concept of prefabricating the major plant components in a U.S. shipyard; then delivering them at a competitive price to the foreign site. There, only conventional construction trades would be required for installation.

The proposed OTEC pilot plant, in addition to offsetting substantial purchases of imported energy, will have fundamental social benefits and will be of direct economic benefit to the U.S. Virgin Islands. Indirectly it will benefit the United States Government. The successful demonstration of OTEC in the U.S. Virgin Islands will advance the application of this technology world-wide.

Acknowledgements

We would like to acknowledge the assitance of Dr. Edward Snyder of TRW Inc., who provided the analysis of the NOAA bathymographic data, and the TRW power system design.

TABLE 1

12.5 MWe POWER MODULE CHARACTERISTICS (NOMINAL)

WATER (HYDRAULIC) SUBSYSTEM	WARM	COLD
TEMPERATURE, °C	26.7	4.5
VOLUMETRIC FLOW RATE, m^3/sec	42.2	39.0
MASS FLOW RATE, Kg/SEC	43,074	39,973
PIPE SIZE (ID-BASED ON 1.83 m/sec), m	5.42	5.21
TOTAL PRESSURE DROP, m	3.23	4.57
PUMPING POWER MWe	1.69	2.23
SHAFT HORSEPOWER, BHP	1680	2210
ASSUMPTIONS: MOTOR/GEAR EFF. 92.4% PUMP EFF. 87%		

HEAT EXCHANGER SUBSYSTEM	EVAPORATOR	CONDENSER
TUBE LENGTH - TOTAL, m	9.1	9.1
TUBE OUTER DIAMETER, m	0.025	0.025
TUBE WALL THICKNESS, mm	0.79	0.66
ENHANCEMENT RATIO, GEOMETRIC - I/D	1.46/1.50	1.46/1.50
NUMBER OF TUBES	42,667	43,883
SHELL DIAMETER (ID), m	8.95	9.23
TUBESIDE WATER VELOCITY, m/sec	2.0	1.77
TUBESIDE PRESSURE DROP, ATM	0.28	0.25
WATER INLET TEMPERATURE °C	26.7	4.4
WATER OUTLET TEMPERATURE °C	23.4	7.9
AMMONIA TEMPERATURE, °C	21.1	10.0
LMTD, °C	3.7	3.6
THERMAL DUTY, MBTU/HR	1543	1495
OVERALL HEAT TRANSFER COEFF., BTU/HR	896	796

AMMONIA CYCLE	
AMMONIA VAPOR FLOW RATE, Kg/SEC	366
AMMONIA VOLUMETRIC FLOW RATES	
TURBINE INLET, am^3/sec	52.9
TURBINE OUTLET, am^3/sec	73.5
AMMONIA RECIRCULATION FLOW RATE (EVAPORATOR INLET FLOW) Kg/SEC	601
FEED PUMP HEAD, ATM	1.76
RECIRC. PUMP HEAD, ATM	1.03
AMMONIA QUALITY, TURBINE INLET, %	100
AMMONIA QUALITY, TURBINE OUTLET, %	97.5
EVAPORATOR TEMPERATURE, °C	21.1
CONDENSER TEMPERATURE, °C	10.0
ENTHALPY DROP ACROSS TURBINE, KCAL/Kg (AT ASSUMED EFF. OF 85%)	16.8

POWER BUDGET	
GROSS POWER, MWe	17.54
NET POWER, MWe	12.50
GROSS POWER/NET POWER	1.40
WARM WATER PUMPING POWER, MWe	1.69
COLD WATER PUMPING POWER, MWe	2.23
AMMONIA FEED PUMPING POWER, MWe	0.30
AMMONIA RECIRCULATION PUMPING POWER, MWe	0.18
CHLORINATION POWER, MWe	0.06
MECHANICAL CLEANING POWER, MWe	0.01
CONTROL, AMMONIA SUPPORT, MISC., MWe	0.58

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OTEC ALUMINUM INTERGRATION STUDIES*

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Abstract

The feasibility of using OTEC power to produce aluminum was studied under different geographic, commercial and production scenarios. Projection of returns on investment from such projects was made using the method of discounted cash flow analysis.

Three different ways of producing aluminum were considered. The conventional Hall reduction process was considered for shore based applications where the OTEC power was delivered by cable. The Hall process with drained cathode cells and the aluminum chloride reduction process were considered for OTEC plantship applications. Cases were considered where the reduction plant was located on shore at various geographic locations or on the OTEC platform. These were compared with a baseline case of conventional Hall process reduction plant situated on the U.S. Gulf coast.

Geographic locations, other than the U.S. Gulf coast, offer many advantages. The ΔT near the tropical islands such as the U.S. Virgin Islands, Puerto Rico, and Mindanao in the Phillipines Islands etc., ranges up to 24°C which reduces the cost of the OTEC power units. The high ΔTs are available close to shore (ranging from 1.5 to 20 nautical miles) which reduces the cost of power transmission. The effects of location, labor rates and tax policies were also investigated.

The capital and operating costs were estimated for the different scenarios considered and the rates of return were computed by discounted cash flow analysis. The base case of a Hall plant on the Gulf coast projected a rate of return of only 7.8% under the most favorable tax and investment assumptions. The maximum rates of return projected (≈18.4%) are for a chloride process plant situated on the U.S. Gulf Coast, powered by OTEC through a 100 mile cable. For a similar plant in the U.S. Virgin Islands, with a 3 mile cable, the rate of return is projected as 18.3%.

1. INTRODUCTION

1.1 Background

We have previously reported [1,2] on a number of the technical issues which must be resolved before OTEC could be considered for widespread use by the aluminum industry. These studies have shown that the conventional Hall process for converting alumina, Al_2O_3, to aluminum metal (the processing step which is energy intensive) is not suitable for being conducted aboard a floating plantship using on-board generated OTEC electrical energy. The primary reasons are, (1), that the Hall cells are susceptible to electrical shorting which would place restrictions on production through motion of the platform, (2), the physical size of the reduction plant, and hence the size of the OTEC/ Aluminum plantship hull, at the anode current

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TABLE I

ESTIMATED PRODUCTION COST FOR A BAYER-HALL PLANT ON U.S. GULF COAST
POWERED BY OTEC PLATFORMS THROUGH A 100 MILE UNDER WATER CABLE

	Units	$/Unit	# of Units Per Short Ton of Aluminum	$ Per Short Ton of Aluminum Bayer	Hall + OTEC	Total
Raw Materials and Other						
Bauxite	Short Ton	33.80	4.56	154.13		
Limestone	Short Ton	7.35	0.253	1.86		
Soda Ash	Short Ton	105.00	0.143	15.02		
Starch	Short Ton	260.00	0.011	2.86		
Cryolite	Short Ton	493.90	0.035		17.29	
Aluminum Fluoride	Short Ton	514.50	0.02		10.29	
Water				1.68		
Maintenance Materials (Bayer)	1.5% of C.I.			12.79		
Maintenance Materials (Hall)	2.5% of C.I.				58.62	
Maintenance Materials (OTEC)	2.5% of C.I.				105.74	
				188.34	191.94	380.28
Purchased Fuel	10^6 BTU	4.00	22.12	88.48		
Purchased Fuel	10^6 BTU	4.00	6.60		26.40	
Calcined Coke	Short Ton	120.00	0.52		62.40	
Pitch	Short Ton	103.00	0.15		15.45	
				88.48	104.25	192.73
Labor, Bayer	MH	14.50	3.19	46.26		
Labor, Hall	MH	14.50	8.00		116.00	
Labor, OTEC	MH	24.75	2.79		69.08	
Plant Overhead (45% of wages)				20.82	83.29	
Local Taxes & Insurance	2% of C.I.			17.06	131.49	
				84.14	399.86	484.00
Subtotal						1057.01
Energy						
Electric Power (10% of Total Requirement)	Kwhr	0.03	53.1	1.59		
Electric Power (10% of Total Requirement)	Kwhr	0.03	1378.0		41.34	
				1.59	41.34	42.93

densities which are used in commercial practices are so large that the capital costs per unit of capacity were non-competitive, and (3), the temporal variability of the thermal resource did not match with the physical requirements of the Hall process which must be operated at essentially constant power input for periods of up to 20 or 30 years.

The drained cathode Hall cell reduction plant was then examined for suitability in the OTEC plantship environment and it was concluded that the reduction cells could be designed so as to be less motion sensitive. However, the anode current densities are practically the same as for the conventional Hall cell, so a very large plantship hull would still be required and the process would still be vulnerable to temporal variations in the resource.

An alternative process, the electrolytic reduction of aluminum trichloride, $AlCl_3$, was examined in the OTEC/Aluminum plantship context and it was established that the chloride reduction process is best suited. The chloride process reduction cell uses bipolar, nonconsumable, graphite plates in a horizontal stack. This allows for the aluminum produced to drain off into a storage well. Thus, the chloride reduction process can be made very motion tolerant. Because of the fact that the bipolar plates can be stacked vertically in a common pressure vessel, say twelve to a container, the amount of deck space required on the plantship per unit of capacity is correspondingly reduced. The chloride process reduction plant can be designed to conveniently fit on the deck of an OTEC power plantship. For example a 100 MWe OTEC power system would require a hull with a deck of about 80m X 80m, whereas the aluminum chloride reduction cells which would use the 100MWe output require an area only 47m by 58m. This leaves adequate deck area for a facility to convert the molten aluminum to millimeter sized particles which can be easily passed by dense phase fluidized flow from the plantship to a support ship by means of a flexible hose. This technique would allow resupply and product removal from the platform in almost any weather. There is room on the deck of the chloride process plantship to allow for the chlorination processing steps to be placed aboard the plantship, if desired. However this option was not examined in as much detail as those where the chlorination of bauxite or aluminum rich clays was conducted on the shore.

The aluminum chloride reduction process has another advantage in that it is more efficient in the use of electrical energy. It requires only about 11 kwhr/kg Al, whereas the drained cathode hall when operated at high current densities appropriate to an OTEC plantship would require about 15 kwhr/kg Al.

It was concluded that the chloride reduction process was the best suited technically for operation in the OTEC/Aluminum plantship environment. Having developed technically feasible solutions to the production of aluminum on an OTEC plantship, the purpose of our continuing studies was to investigate the economic attractiveness of the various ways that OTEC power systems could be used within the aluminum industry.

1.2 Economic Analyses

As an economic baseline we adopted a conventional Bayer process and Hall process complex on the U.S. Gulf coast which would be capable of converting bauxite to 362,700 MT/yr of aluminum ingot.

This size was selected on the basis that a new Bayer process plant to convert 1.4 million MT/yr of bauxite to 700,000 MT/yr of alumina and a Hall process plant to reduce the alumina to aluminum metal are the essential capacity increase decision making unit for the industry. This complex requires about 650MWe of electrical power. For the baseline it was assumed that the complex would purchase its electricity from the local utility grid. For the OTEC power cases, it was assumed that the plant would receive 90% of its power from OTEC platforms in the Gulf of Mexico. This power would be delivered to shore through underwater cables 100 miles in length. The projected cost of the alumina and aluminum production facilities in 1980 U.S. dollars is $1,278.13 million. These costs were obtained using the data from reference 3 updated to mid 1980 using the Chemical Engineering magazine Construction Cost Index. The OTEC plant capital costs were assumed to be $2655/kw, based on the OTEC decision tree data given in reference 4 and updated to mid 1980. The total capital investment required is $1.69 billion.

Table I gives the estimated production costs (in 1980 dollars) for

the complex, including the estimated costs for operating the OTEC power system. These production costs are based on the data given in reference 3 updated to mid 1980 using current unit proces for materials and the mid 1980 prevailing labor rates under the various union agreements for the production facilities. The labor rates for the OTEC plants are based on offshore oil industry data.

In all of the economic analyses it has been assumed that any aluminum produced would be sold at the world price, which was $0.72/lbm ($1612.80/MT) in mid 1980. It was assumed that the sale price of aluminum and all other costs, with the exception of electricity, would escalate at an annual rate of 7%. A model which allowed the cost of electricity to escalate faster than the GNP deflator was used for studies which examined the sensitivity to electricity costs.

2. METHODOLGY

The primary tool used in evaluating the various options which were developed was a discounted cash flow to arrive at an internal rate of return after taxes, for the various projects, with various tax policies and investment strategies considered. The procedure is to find a discount rate which gives a zero net present value for the cash flows over the 33 year life of the project (3 years construction, 30 years of operation).

The traditional "S" curve for disbursement of funds during construction was used and it was assumed that output during the initial year of operation production would be only 70% of name plate capacity.

For the baseline case the U.S. corporate income tax was assumed with a 10% investment tax credit. It was assumed that all OTEC facilities would be eligible for the additional 15% solar energy investment tax credit specified in PL 96-223. For those non-U.S. Gulf Coast cases examined, i.e., Puerto Rico, the U.S. Virgin Islands, and the Phillipine Islands, the appropriate tax structure was assumed. Details of the tax treatment, depreciation, and examples of the cash flow calculation are presented in reference 5.

In addition to the Bayer Hall complex, production configurations for the chloride reduction process were examined which placed the Toth process aluminum chloride production facilities at a shore base and the reduction facilities either on OTEC plantships, or on the shore with power delivered by cable from the OTEC platforms. The return on investment which might be realized by operating these production complexes on the U.S. Gulf Cost, the U.S. Virgin Islands, Puerto Rico, and on Mindanao in the Phillipine Islands, was estimated. The capital and operating costs for each location were adjusted using construction cost includes, local labor rates, etc.

3. RESULTS OF CALCULATIONS

For a conventional production complex on the Gulf Coast, powered by OTEC platforms through a 100 mile cable, a rate of return on investment calculation was performed using the production cost data given in Table I, and the assumed sales price of $1612.80/MT. It was determined that a rate of return of 1.2% could be achieved if the project was totally financed internally, and if the parent corporation had sufficient income tax liability to use the entire investment tax credit in the first year of profitability. This rate of return is far below traditional industry thresholds for investment.

Rates of return were calculated for Bayer-Hall complexes located on Mindanao, Puerto Rico and the U.S. Virgin Islands. These are given in Table II.

Our conclusion is that conventional aluminum production complexes, i.e. Bayer-Hall technology, powered by floating OTEC platforms with the power delivered by a cable would provide marginal rates of return on investment for investors.

TABLE II

RATES OF RETURN FROM BAYER-HALL PLANTS POWERED BY OTEC PLATFORMS WITH UNDERSEA CABLES SALES PRICE = $1612.80/MT

Location	Rate of Return %
U.S. Gulf Coast	7.8
Mindanao	12.4
Puerto Rico	5.6
U.S. Virgin Islands	8.2

The rates of return for those cases where the Toth Process was used to produce the $AlCl_3$ on the shore, with the chloride reduction plant located on the OTEC platform are given in Table III. For the Gulf Coast location we examined two plantship and five plantship configurations. The highest rates of return, under the assumption of a unlimited income tax liability for the parent corporation, were for the cases where 30% of the shore-plant was financed and 87 1/2% of the floating plant was financed under a MARAD loan guarantee. For Mindanao, the U.S. Virgin Islands and Puerto Rico the five plantship configuration was assumed. The projected rates of return for all locations fall in the range of 12 to almost 18%.

For the configuration where we have assumed that the chloride reduction plant would be on the shore, powered by OTEC platforms through an underwater cable, the rates of return shown in Table IV are the highest calculated, in the range of 18%. Again financing 30% of the shore facilities and 87 1/2% of the floating power plants under a MARAD guaranteed load provides the highest rate of return for that location.

TABLE III

RATES OF RETURN FOR ALUMINUM CHLORIDE REDUCTION PLANT ON THE OTEC PLATFORM WITH THE TOTH PROCESS PLANT ON SHORE

Location	Financing %	Rate of Return %
U.S. Gulf ($461.2\ MW_e$ 5 Plantship, 362,700 MT/yr)	72.8	17.0
	0	11.3
U.S. Gulf ($744.6\ MW_e$ 2 Plantships, 580,320 MT/yr)	74.2	17.9
	0	12.0
Mindanao ($461.2\ MW_e$, 362,700 MT/yr)	0	13.7
U.S. Virgin Islands ($461.2\ MW_e$, 362,700 MT/yr)	0	13.7
Puerto Rico ($461.2\ MW_e$, 362,700 MT/yr)	0	13.1

TABLE IV

RATES OF RETURN FOR ALUMINUM CHLORIDE REDUCTION PLANTS ON SHORE POWERED BY A FLOATING OTEC PLATFORM WITH AN UNDERWATER CABLE

Location	Financing %	Rate of Return %
U.S. Gulf	64.8	18.4
	0	13.0
Mindanao	0	17.6
Puerto Rico	0	17.12
U.S. Virgin Islands	0	18.3

For the overseas locations comparable rates of return are projected. The primary reason for the higher projected rates of return for these cases is the lower capital cost of the chloride process facilities and their more efficient utilization of energy which requires less investment in the OTEC power systems.

4. CONCLUSIONS

It is concluded that:

- Powering of conventional Bayer-Hall complexes for the production of aluminum with electrical energy from floating OTEC plants, where the power is delivered by cable, provides marginal rates of return on investment.

- Floating OTEC/Aluminum plantships based on the reduction of aluminum chloride produced at a shore base result in reasonable rates of return for investors.

  The option of placing the chlorination facilities on the plantship, while not examined in detail, may improve the projected rate of return for this option.

- Aluminum chloride plants located on the shore and powered by floating OTEC platforms with the power delivered to shore by an underwater cable give the highest projected rates of return.

The thermal resource available to the OTEC/Aluminum plantship is much greater than for the shore mounted units. If the chlorination step could be carried out on the platform the total system cost could be reduced with higher potential rates of return. Further studies of this concept are suggested.

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A REVIEW OF OTEC ENERGY COST CALCULATIONS

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ABSTRACT

A review of a simplified revenue requirements model for a synthetic utility application is presented, illustrating the three components of energy cost. An example illustrating the use of the revenue requirements technique in arriving at a single value for the cost of energy from an Ocean Thermal Energy Conversion (OTEC) plant is then illustrated.

A cash flow interpretation of the cost of energy resulting from the investment in the OTEC technology is then presented. It is based on the unit cost of energy as calculated by the revenue requirements method and the original assumptions. From the annual revenues generated by the sale of energy at the rate calculated by the revenue requirements model, costs of amortizing capital, payment of taxes, operating, maintenance and fuel costs are deducted on a yearly basis. At the end of the system life, all capital expenses (including return on equity), fuel expenses, and operating expenses are seen to equal to revenues generated from sale of the product.

INTRODUCTION

There are many ways an investment in an energy technology can be evaluated by a potential investor. Generally, the project is considered in light of the corporation's existing business. Projects are viewed favorably if they enhance the corporate position in existing markets or help establish inroads in a new or related area.

But once a firm has decided on the types of products it wants to produce and has identified the markets for which they are aimed, the firm is faced with choosing its funding priorities. Such choices are sometimes based on criteria such as simple payback period, total initial cost or first year cost. More sophisticated analyses are often made by evaluating the likely return on the corporate investment weighed against the perceived level of risk inherent in the investment.

Alternatively, a minimum required rate of return on equity funds can be postulated, minimum product costs calculated on that basis, and risk estimated in terms of the likelihood of achieving that product cost in the marketplace. The general method of estimating product costs in this way is termed "Revenue Requirements". The concept, in essence, calls for the costs of producing a product, in each year of an investment's life time to be exactly equal to the revenues generated from the sale of the product in each year.

The revenue requirements method requires that the discounted present worth of the three component revenue streams (operating and maintenance, fuel, capital related) be summed to arrive at a value of the discounted present worth of all required revenues over the life cycle. Such a value is a perfectly acceptable basis for comparison. But, to lend it more meaning, the discounted present value of required revenues is typically converted into an equivalent (in a discounted cash flow sense) revenue stream of annually recurring costs. When this value of annually required revenues (equivalent to costs) is divided by annual plant outputs, the result is a representation of annualized product cost on a unit basis. This result is usually expressed as: $/MMBtu, mills/kWh, or $/bbl.

Generally, production costs vary over time, but for the sake of comparison, these costs are often represented by a levelized stream, and product costs are calculated by dividing the annual levelized costs by the annual output of the plant. Among alternative investments designed to produce the same product, the one with the lowest unit product cost is the best, all other attributes being more or less equal.

The single parameter of energy cost, reported in its various ways, is simply a surrogate for a cash flow estimate resulting from a particular investment, made under the initial assumptions of the analysis. Many investigators have proposed techniques and methods that, when properly applied, provide values of the energy cost surrogate. While some amount of uniformity in these analyses is actually ocurring, in general, energy costs supplied from different analysts should be compared carefully. Depending on the method used, such energy costs have been reported as levelized life-cycle costs per unit output in both nominal and real dollars and referenced to various base years. Caution must always be used in comparing results from various investigators due to the myriad opportunities available for inconsistency in assumptions and in reporting format.

This paper will review the formulation of the revenue requirements equations and the assumptions and method used to arrive at a levelized revenue

stream. Then, cash flows, resulting from the levelized stream of revenues, will be compared with the projected annual expenses associated with the plant investment. It will be seen that the levelized revenue stream will pay off all operating and capital costs including taxes and equity returns over the life of the plant. The method will be illustrated for ocean thermal energy conversion (OTEC) technology deployed by a synthetic utility.

THE REVENUE REQUIREMENTS METHOD

To be economically viable, an enterprise must generate sufficient revenues from the sale of its products to meet the expenses it incurs in a given year. Revenues must cover the costs of operating and maintaining a plant, of acquiring the fuel or feedstocks used in manufacturing the product, tax charges and capital-related expenses including a return on investors equity. This requirement is illustrated schematically in Figure 1. A general expression indicating the relationship between revenues and costs can be given by Equation 1 of Table 1. This table contains all the development leading to the levelized revenue requirements equations.

FIGURE 1

REVENUE REQUIREMENTS REPRESENTATION OF ENERGY COSTS

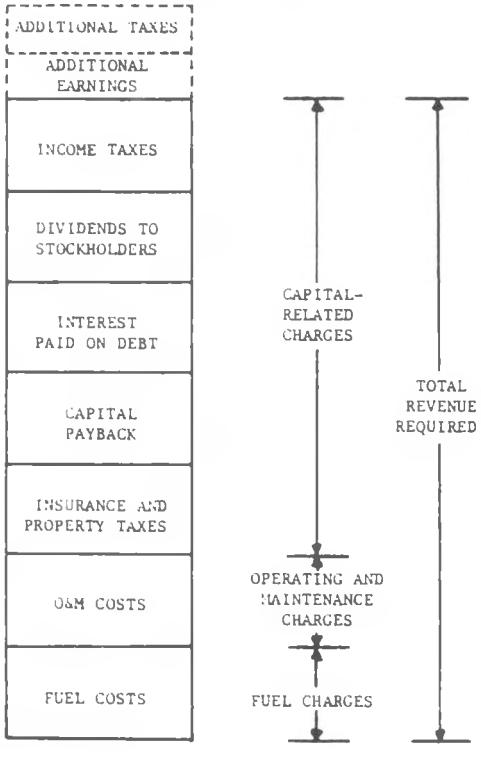


TABLE 1-A

DEVELOPMENT OF REVENUE REQUIREMENTS

$$R(t) = O(t)+F(t)+T(t)+C(t) \quad (1)$$

$$T(t) = \tau\,[R(t)-O(t)-F(t)-ITC(t)-DEP(t)] - ITC(1) \quad (2)$$

$$R(t) = O(t) + F(t) + \frac{1}{(1-\tau)}\left\{C(t)-ITC(1) - \tau[IC(t)+DEP(t)]\right\} \quad (3)$$

$$C(t) = i_d d\ Bal(t-1)+i_e(1-d)\ Bal(t-1)+PD(t) \quad (4)$$

$$R(t) = O(t)+F(t) + \frac{1}{(1-\tau)}\,[Bal(t-1)i_D+PD(t) - \tau(DEP(t)-ITC(1)] \quad (5)$$

$$i_D = i_e(1-d) + i_d d(1-\tau) \quad (6)$$

$$Bal(t-1)i_d + PD(t) = \text{constant} \quad (7)$$

$$CCC = Bal(\emptyset)\ CRF_{i_D,N} \quad (8)$$

$$CRF_{i_D,N} = \frac{i_D}{1-(1+i_D)^{-N}} \quad (9)$$

$$\text{Cash Flow}(i) = ONC\,[CF(i)(1+esc_c)^i] \quad (10)$$

$$Bal(\emptyset) = \sum_{i=1}^{K}[\text{Cash Flow}(i)](1+i_D)^{K-i+1} \quad (11)$$

$$Bal(\emptyset) = ONC\ (\text{Cost Basis Factor}) \quad (12)$$

$$\tau DEP(t) = \tau Bal(\emptyset)\, f_D\left[\frac{t-M+1}{.5t(t+1)}\right] \quad (13)$$

$$ITC = Bal(\emptyset)itc \quad (14)$$

$$\tau = \tau_f + \tau_s - \tau_f\tau_s \quad (15)$$

$$O(\emptyset) = O_{(present)}(1+esc_O)^{(\emptyset-present)} \quad (16)$$

$$O(t) = O(\emptyset)(1+esc_O)^t \quad (17)$$

$$R(t) = O(\emptyset)(1+esc_O)^t + F(\emptyset)(1+esc_F)^t + \frac{1}{(1-\tau)}\left\{Bal(\emptyset)CRF_{i_D,N}\tau_D\ Bal(\emptyset)\left[\frac{t-M+1}{.5t(t+1)}\right] - Bal(\emptyset)itc\right\} + Bal(\emptyset)(ipt) \quad (18)$$

PRESENT VALUE OF REVENUE REQUIREMENTS

$$PV[O\&M(t)] = O(\emptyset)\sum_{t=1}^{N}\frac{(1+esc_O)^t}{(1+i_D)^t} \quad (19)$$

$$PV[O\&M(t)] = \frac{O(\emptyset)}{CRF_{x_O,N}} \quad ; \quad x_O = \left(\frac{1+i_D}{1+esc_O}-1\right) \quad (20)$$

$$PV[F(t)] = \frac{F(\emptyset)}{CRF_{x_F,N}} \quad ; \quad x_F = \left(\frac{1+i_D}{1+esc_F}-1\right) \quad (21)$$

$$PV(capital) = \frac{1}{(1-\tau)}\left[Bal(\emptyset)-\tau_D PVDEPS\ Bal(\emptyset) - \frac{Bal(\emptyset)itc}{(1+i_D)}\right] + \frac{Bal(\emptyset)ipt}{CRF_{i_D,N}} \quad (22)$$

$$PVDEPS = \left[\frac{1-\frac{1}{CRF_{i_D,N}}}{.5M(M+1)i_D}\right] \quad (23)$$

$$PV[R(t)] = \frac{O(\emptyset)}{CRF_{x_O,N}} + \frac{F(\emptyset)}{CRF_{x_F,N}} + Bal(\emptyset)\left\{\frac{1}{(1-\tau)}(1-\tau\, f_D\, PVDEPS) - \left[\frac{itc}{(1+i_D)}\right] + \frac{ipt}{CRF_{i_D,N}}\right\} \quad (24)$$

LEVELIZING REVENUE REQUIREMENTS

$$\bar{R}(t)_{\emptyset} = PV[R(t)]\ CRF_{i_D,N} \tag{25}$$

$$\bar{R}(o)_{\emptyset} = PV[R(t)]\ CRF_{z,N} \qquad z = \frac{1+i_D}{1+inf} - 1 \tag{26}$$

$$\bar{R}(o)_{\emptyset} = \bar{R}(t)_{\emptyset} \frac{CRF_{z,N}}{CRF_{i_D,N}} \tag{27}$$

$$LFAC(A) = \frac{CRF_{i_D,N}}{CRF_{x_A,N}} \tag{28}$$

$$FCR = \left\{ \frac{CRF_{i_D,N}}{(1-t)} \left[1 - t\, f_D PVDEPS - \frac{itc}{(1+i_D)} \right] + ipt \right\} \tag{29}$$

$$R(t)_{\emptyset} = O(\emptyset)[LFAC(O)] + F(\emptyset)[LFAC(F)] + Bal(\emptyset)(FCR) \tag{30}$$

$$Output = Cap(CF)8760 \tag{31}$$

$$\bar{EC}(t)_{\emptyset} = \frac{\bar{R}(t)_{\emptyset}}{Output} \tag{32}$$

$$\bar{EC}(o)_{\emptyset} = \frac{\bar{R}(o)_{\emptyset}}{Output} \tag{33}$$

$$\bar{R}(t)_{1980} = \bar{R}(t)_{\emptyset} \left[\frac{1}{(1+inf)^{(\emptyset-1980)}} \right] \tag{34}$$

TABLE 1-B

VARIABLES DEFINITIONS

- $R(t)$ = revenues required as a function of time
- $O(t)$ = operating revenues
- $F(t)$ = fuel/feedstock revenues
- $T(t)$ = tax revenues
- $C(t)$ = capital-related revenues
- τ = tax rate
- $IC(t)$ = interest on debt
- $DEP(t)$ = depreciation for tax purposes
- ITC = investment tax credit
- i_d = debt rate
- d = debt fraction
- $Bal(t)$ = outstanding capital balance
- i_e = dividend rate
- i_D = effective after tax cost of capital
- $PD(t)$ = amount of capital investment paid down in year t
- CCC = cost annual capital charge
- $Bal(\emptyset)$ = total initial investment
- $CRF_{i_D,N}$ = capital recovery factor at i_d for N periods
- $\emptyset$ = on-line year
- Cash Flow (i) = construction funds expended in year i
- ONC = overnight construction cost
- $CF(i)$ = fraction of overnight construction cost expended in year i
- j = number of years from present to construction year
- esc_c = escalation in capital costs
- K = construction period
- f_D = depreciable fraction of $Bal(\emptyset)$
- M = tax life
- itc = investment tax credit rate
- f = federal tax rate
- s = state tax rate
- esc_O = O&M escalation
- esc_F = fuel escalation
- ipt = insurance and property tax rate
- $PV[A]$ = present value of annual cost stream, A
- $PVDEPS$ = present value factor of sum of years digit depreciation
- $\bar{R}(t)_{\emptyset}$ = levelized revenue requirements, nominal on-line year dollars
- $\bar{R}_{\emptyset}$ = levelized revenue requirements, constant on-line year dollars
- $LFAC(A)$ = levelizing factor for annual cost, A
- FCR = fixed charge rate
- $output$ = annual plant production
- cap = plant capacity
- CF = plant capacity factor
- $\overline{EC}(t)$ = levelized energy cost, nominal
- $\overline{EC}_{\emptyset}$ = levelized energy cost, real
- $\bar{R}(t)_{1980}$ = levelized revenue requirements, nominal 1980 dollars

All the terms on the right side of Equation 1 can be defined explicitly, but taxes are a function of both the revenues and the other components as shown by Equation 2. Equation 2 simply says that taxes paid in year 1 are simply the tax rate times the revenues generated in that year less deductible expenses and credits. The term IC(t) refers to interest paid on outstanding capital debt, and DEP(t) to depreciation for tax purposes. Combining Equations 1 and 2 yields Equation 3 as an expression for revenues required in a given year.

The term C(t) is the amount of the original capital investment paid back to both bond and equity holder in year t plus the interest and dividend payments made for the use of the money during the year.

C(t) can be given by the sum of interest, dividends and, capital returned as shown by Equation 4, where i_d is the interest rate on debt capital, d is the fraction of total decapitalization that is debt, i_e is the required rate of return on investors equity, PD(t) is the amount of original capital actually paid back in a given year and Bal(t-1) is the amount of capital not yet paid back, or the balance.

The term $i_d d\ Bal(t-1)$ represents the interest paid on outstanding debt obligations and can be substituted for IC(t) in Equation 3. R(t) can now be rewritten as Equation 5. Where the new variable $i_D = i_e e + i_d d(1-t)$ and represents the after-tax cost of capital, and the sum $[Bal(t-1)i_D + PD(t)]$ represents the after-tax cost of amortizing the original capital.

Equation 5 represents the revenues required in any given year t as a function of operating and fuel costs in that year and of the amortization schedule for capital, the tax rate and credits and basic financial parameters.

The revenues required to cover operating and fuel charges are equal to those direct charges themselves since these items are expensible on taxes. The third term represents the revenues required to meet capital amortization, tax credits, and liabilities.

The revenues required to amortize the capital, $[Bal(t-1)i_D + PD(t)]$, can be determined by many different schedules depending on the capital financing arrangements in force or the character of regulations that apply in a given situation and industry.

In a utility, for example, the original capital returned to investors is returned on a straight-line basis. That is, an amount equal to the total capital cost of the facility divided by the number of years of investment life is paid back annually, plus interest on the balance. Additionally, the rate of return on the outstanding capital investment is set by regulation; thus, the funds earned on the investment are dependent on the cumulative value of the payback in a given year which in turn is determined by the payback schedule.

In an unregulated industry, capital can be amortized in a manner similar to a conventional mortgage. The annual dollar value of amortization remains constant, while the fractions of that value assigned to returning the investment and the interest and dividend payments vary over time.

For the sake of simplicity in describing annual cash flows, it will be assumed that capital is amortized in the more familiar manner of the conventional mortgage. A development of the more correct form for capital-related cash flow of a typical utility is given by Clark et al. (1).

CAPITAL-RELATED EXPENSES WITH TIME

In a conventional mortgage, the dollar amount paid annually to amortize a sum is constant over the life of the mortgage. With this concept, then, the sum of interest and principal payments is unchanging annually as shown by Equation 7. The constant payment can be represented by the Cost Annual Capital Charge (CCC) calculated like a conventional mortgage by Equation 8. The Balance at the time the plant begins operation, Bal(Ø), is equal to the capital cost of the plant plus Allowance for Funds Used During Construction (AFUDC). The treatment of AFUDC can vary among utilities due to the regulatory requirements of various state Public utility Commissions. In this treatment, interest costs on funds dispersed during the construction period are assumed to be borne by the utility at the after tax-cost of capital until the plant begins operation and becomes part of the utility rate base at time t=Ø.

Generally, when comparing energy investment alternatives, one must translate a present engineering cost estimate effectively, an Overnight Construction Cost (ONC), into the capital cost of a plant that is to go on-line at some date in the future and requires some number of years to construct prior to starting operation at time Ø. The present cost estimate must be adjusted for the effects of inflation and to reflect the interest paid on funds expended during the period of construction.

There are many ways to handle these effects. Phung (2) presents one, and a simplified, yet quite accurate treatment is given by Clark et al. (1). In all cases, the approach is to escalate a present day cost estimate to the start of the construction period at the appropriate inflation rate. Then, to include the interest paid on dispersed funds during the construction period while costs continue to escalate to the date of initial operation. In this analysis, the ONC is dispersed during the construction period at various percentages each year, represented by CF(i).

The cash flow required in year i of the construction period is given by Equation 10, where CF(i) is the fraction of the ONC cost expended in year i, esc_c is the inflation rate in capital cost, j is the period in years from the date of the overnight construction cost estimate to the year in which the funds are spent.

The total capital cost of the plant, Bal(Ø), also must include the interest charges accumulating on the spent funds up to the time of plant start-up. Bal(Ø) is given by Equation 11, where K is the construction period, i is the i^{th} year of that period in which the cash flow is occurring and i_D is the effective after-tax cost of capital.

The relationship between Bal(Ø) and the overnight construction cost can be related by the Cost Basis Factor, CBF, where CBF embodies all the calculations of the previous two relationships into a single convenient value.

The other components of the third term of Equation 5 can be defined as a function of time as well. The term DEP(t) represents the contribution of depreciation for tax purposes to the cash flow of the enterprise and is given, if a sum of Years Digits Method is used, by Equation 13, where f_D is the fraction of Bal(Ø) that is depreciable, and M the tax life of the asset. The value of ITC(1) can be given by Equation 14 where itc is the investment tax credit rate.

The tax rate τ represents the combined federal (τ_f) and state (τ_s) tax rates and can be given by Equation 15. The term $\tau_f\tau_s$ indicates that state taxes are deductible from federal taxes.

OPERATING AND MAINTENANCE COSTS AND FUEL COST WITH TIME

Operating and maintenance costs and fuel costs in a given year of plant operation are often projected by defining those costs in the present and then applying a reasonable rate of inflation at which these costs will change annually. For example, operating and maintenance costs in any year t can be estimated by Equations 16 and 17 by escalating present costs to the on-line year and defining costs beyond that point as a function of time.

A more complete expression can now be written for the revenues required in year t as a function of specified basic parameters as given by Equation 18. A term for insurance and property taxes, ipt, that is generally assumed to be proportional to the initial cost of the plant is added here.

It is clear from Equation 18 that revenues required can vary substantially depending on time. But plant output is generally assumed to be constant on an annual basis. One way to compare competing investments of equal life times is to calculate a single value that represents the life-cycle costs (or revenues required) to produce a unit of energy output. This can be done by simply calculating the present value of revenue requirements R(t), and representing that value as a constant annual payment in either real or nominal terms per unit of plant output.

PRESENT VALUE OF THE REQUIRED REVENUE STREAM

One single parameter that represents the Revenue Stream, R(t), is the discounted present value of that stream. While there is some controversy over the discount rates that should be used for such a calculation, (Tebbets (3), for instance, uses different rates for capital-related charges and operating costs) the usual practice is to use the after-tax cost of capital, i_D as suggested by Clark et al. (1), Phung (4), and Oso (5).

The present value of operating costs; as of the on-line year, t=Ø is given by Equation 19 and, similarly, the present value of fuel charges by Equation 20. Both annual cost streams are assumed to escalate at a constant rate esc_A over the life time and are discounted to the present by the after-tax cost of capital, i_D. The present value of the time-dependent revenue stream PV[R(t)] is the sum of the present values of the three components as given by Equation 24.

THE LEVELIZED REPRESENTATION OF REVENUE REQUIREMENTS

While the present value of annual Revenue Requirements is an acceptable basis for comparison of alternatives, a more intuitively satisfying concept is the annualized cost equivalent of that value. This is represented by the annuity that possesses the same present value as that of the revenue requirement stream, as illustrated in Figure 2. Like a common mortgage, the equivalent nominal dollar value to be expended annually can be given by:

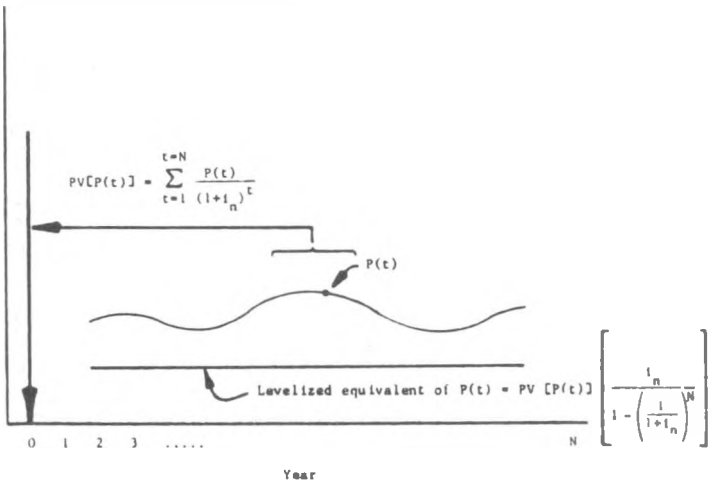
$$\bar{R}(t)_{\emptyset} = PV[R(t)]\ CRF_{i_D,N}$$

Where $\bar{R}(t)_{\emptyset}$ is the levelized annual revenue requirement that, when paid for N years and discounted at i_D, is equal to PV[R(t)]. $\bar{R}(t)_{\emptyset}$ is often termed a nominal annuity since the discount rate with which it is calculated includes an expectation of future inflation over the period of plant operation, t.

Another way to represent annuitized revenue requirements is to set the present value of the required revenue stream, PV[R(t)], equal to a series of annual payments that stay constant in the dollars of the on-line year. That is to say, the stream escalates at the inflation rate in the dollars of year t.

FIGURE 2

ILLUSTRATION OF LEVELIZING PROCEDURE



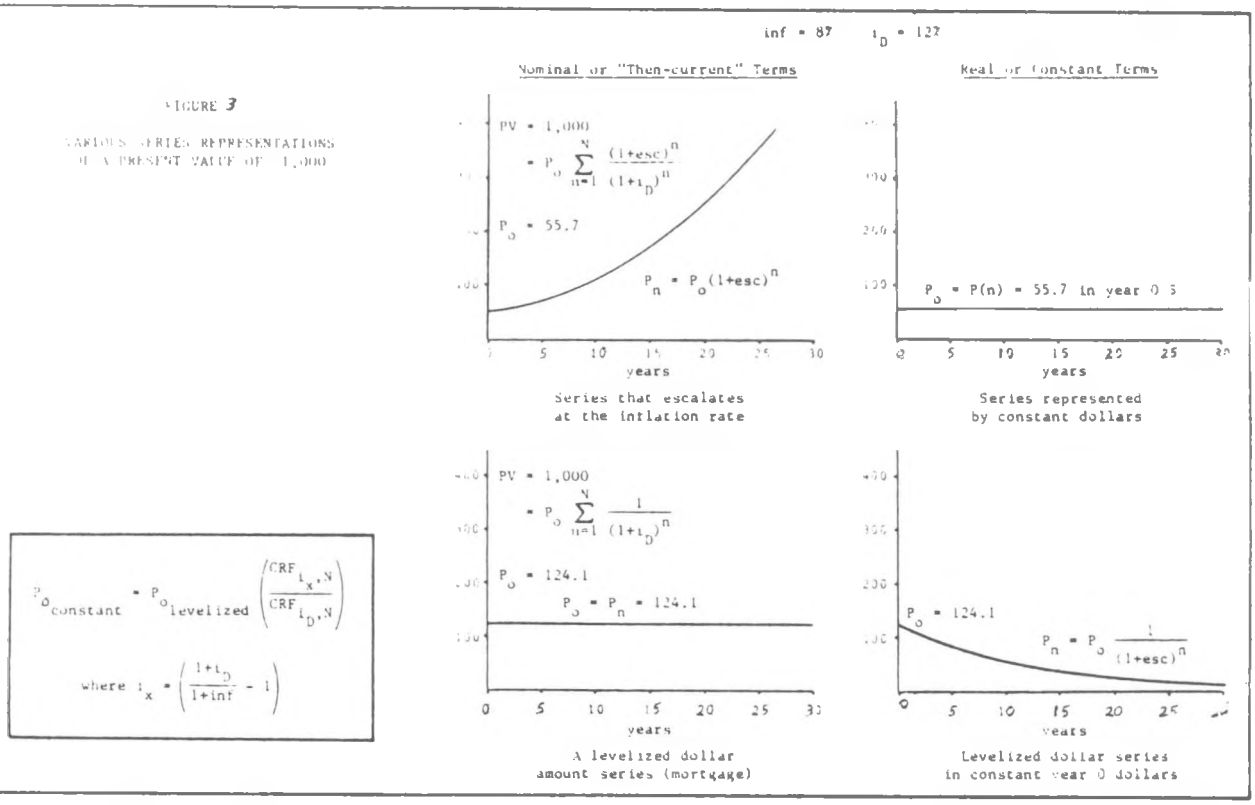
This can be written as:

$$PV[R(t)] = \bar{R}(o)_{\emptyset} \sum_{t=1}^{N} \left(\frac{1 + inf}{1+i_D} \right)^t$$

The value of $\bar{R}(o)_{\emptyset}$ is the constant or a real dollar equivalent of R(t). If dollars are discounted annually for the assumed rate of inflation, revenues defined by $\bar{R}(o)_{\emptyset}$ would be constant over the life time. The annuitized value of revenue requirements in real or constant terms is related to the levelized value of revenue requirements in nominal terms as given by Equation 27. Figure 3, after Tebbets (3), illustrates the nominal and real dollar representations of a cash flow stream that has a present value of $1,000.

FIGURE 3

VARIOUS SERIES REPRESENTATIONS OF A PRESENT VALUE OF 1,000



$$P_{o_{constant}} = P_{o_{levelized}} \left(\frac{CRF_{i_x,N}}{CRF_{i_D,N}} \right)$$

where $i_x = \left(\frac{1+i_D}{1+inf} - 1 \right)$

The complete formulation for levelized revenue requirements can be given by Equation 30. The first year annual costs are multiplied by levelizing factors that convert the escalating series that represents them into a levelized series. The capital investment in the plant, Bal(Ø), is multiplied by a factor commonly referred to as the Fixed Charge Rate, FCR. The FCR embodies capital return, interest, dividends, taxes, and tax credits into a single value of annual costs that is proportional to the original capital investment.

PLANT OUTPUT

The production output from the plant investment is generally considered to be constant over the life time, even though actual output will vary with dispatching strategies and probably decline in later years. Annual output is generally given as a function of hourly plant capacity and the percentage of the year that the plant operates at that capacity (capacity factor) and is given by Equation 31.

ENERGY COST

Levelized life-cycle energy cost $\overline{EC}(t)_{\emptyset}$ is calculated as the levelized revenues required annually per unit of plant energy output in levelized on-line year dollars. This is given by:

$$\overline{EC}(t)_{\emptyset} = \frac{\overline{R(t)}_{\emptyset}}{\text{output}}$$

in constant, on-line year dollars:

$$\overline{EC}_{\emptyset} = \frac{\overline{R}(o)_{\emptyset}}{\text{output}}$$

Both $\overline{R}(t)_{\emptyset}$ and $\overline{R}(o)_{\emptyset}$ are computed using the on-line year of the plant as the base for dollar values. The calculated values can be related to present dollars by discounting them by the appropriate inflation indicator (CPI, GNP deflator, electric power price index, etc.) for the number of years from the on-line date to the present.

For example,

$$\overline{R}(t)_{1980} = \overline{R}(t)_{\emptyset}\left[\frac{1}{(1 - inf)^{(\emptyset-1980)}}\right]$$

and both $\overline{EC}(t)_{\emptyset}$ and $\overline{EC}(o)_{\emptyset}$ relate to the present by the same procedure.

Thus, Revenue Requirements over the plant life time can be represented as the sum of levelized operating and maintenance cost, levelized fuel cost, and levelized capital-related charges. In terms of either nominal or constant dollar annuities, these values can be expressed in the dollars of the on-line year or the present or any other base year that may be convenient.

In summary, the revenue requirements method allows calculation of a single value of energy cost that represents the cash-flow stream required to just meet costs over the plant life time. The levelized value of energy cost can be presented in nominal or real terms and expressed in the dollars of any convenient year.

REVENUE REQUIREMENTS AND CASH FLOW

The revenue requirements method should yield a value of energy costs and associated annual revenues from the sale of the produced energy to amortize all capital, pay all taxes, and cover all annually occurring costs. James (6) presented a cash flow table that illustrates the levelized capital portion of the calculation. But it is useful, and perhaps adds some insight into the meaning of the calculations and derived values to consider the entire surrogate revenue stream over the life cycle. Both the levelized nominal and real representations of annual revenue requirements will be seen to effectively pay all the costs of the energy system investment over the predetermined life of the plant from a discounted cash flow sense. But it can be seen that caution in using the method is required because the cash flows resulting from the levelizing calculations may be unlikely in the real world or may simply be inconsistent with the financial operating plan of the overall corporation.

Example

As an example, consider a 400 MWe OTEC plant to be deployed in 1989 under the assumptions presented in Table 2-A. The revenue requirements

TABLE 2-A

EXAMPLE INPUT DATA AND FINANCIAL ASSUMPTIONS (1980 $)

INPUT DATA FOR: OTEC I LOW		
1980	IPRYR	PRESENT YEAR
1989	IOLYR	ON-LINE YEAR
.400000E+06	PSIZE	PLANT SIZE (kWe,MMBtu/hr)
3	K	CONSTRUCTION PERIOD
0.79	CF	CAPACITY FACTOR
2130.	CCAP	CAPITAL COST ($/kW,$/MMBtu/hr)
0.0082	COM	O&M COST ($/kWh,$/MMBtu)
0.0	CFUEL	FUEL COST ($/kWh,$/MMBtu)
0.0	ESCC	REAL CAPITAL ESCALATION
0.0	ESCO	REAL O&M ESCALATION
0.0600	GINF	GENERAL INFLATION
0.8750	D	DEBT FRACTION
0.0800	DI	INTEREST ON DEBT
0.1200	EI	INTEREST ON EQUITY
30	N	INVESTMENT LIFE
20	M	TAX LIFE
0.0200	TXIP	INSURANCE & PROPERTY TAX
0.5000	TXFED	FEDERAL TAX RATE
0.0	TXST	STATE TAX RATE
0.1000	TITC	INVESTMENT TAX CREDIT
0.0	TXGR	GROSS RECEPTS TAX

and associated levelized energy cost can be calculated as shown in Table 2-B. From Table 2-B, $\overline{EC}(t)_{1980}$ is \$0.46/kWh in a levelized nominal stream of 1980 dollars. The system is expected to produce 2.77×10^9 kWh/yr which would generate \$127.8 x 10^6 1980 dollars [$\overline{R}(t)_{1980}$] per each year of the plant life.

TABLE 2-B

LEVELIZED REVENUES REQUIRED
AND ENERGY COST CALCULATION

$O(\emptyset) = .0082(2.77\times10^9)(1.06)^9 = \$38.3\times10^6/yr$

$LFAC = \frac{.0651}{.0287} = 2.27$

$FCR = .0910$

$Bal(\emptyset) = \$1.42\times10^9$

$\overline{R}(t)_{\emptyset} = O(\emptyset)\ LFAC(O) + Bal(\emptyset)\ FCR = \$216\times10^6/yr$

$\overline{EC}(t)_{\emptyset} = \frac{\overline{R}(t)_{\emptyset}}{output} = \frac{\$216\times10^6/yr}{2.77\times10^9\ kWh/yr} = \$.078/kWh$

in 1980 \$:

$\overline{R}(t)_{1980} = \overline{R}(t)_{\emptyset}\left[\frac{1}{(1+inf)^{(\emptyset-1980)}}\right] = \$216\times10^6\left[\frac{1}{1.69}\right]$

$= 127.8\times10^9/yr$

$\overline{EC}(t)_{1980} = \frac{\overline{R}(t)_{1980}}{2.77\times10^9} = \$.046/kWh$

For stream in constant on-line year dollars:

$\overline{R}_{\emptyset} = \overline{R}(t)_{\emptyset}\left(\frac{CRF_{Z,N}}{CRF_{i_D,N}}\right) = \$216\times10^6\left(\frac{.0287}{.0651}\right) = \$95.2\times10^6/yr$

$\overline{EC}_{\emptyset} = \frac{\overline{R}_{\emptyset}}{output} = \frac{\$95.2\times10^6/yr}{2.77\times10^9\ kWh/yr} = \$.034/kWh$

in 1980 \$:

$\overline{R}_{1980} = \overline{R}_{\emptyset}\left[\frac{1}{(1+inf)^{(\emptyset-1980)}}\right] = 95.2\times10^6\left[\frac{1}{1.69}\right]$

$= \$56.1\times10^6/yr$

$\overline{EC}_{1980} = \frac{\overline{R}_{1980}}{output} = \frac{\$56.1\times10^6/yr}{2.77\times10^9\ kWh/yr} = \$.020/kWh$

CALCULATION SUMMARY

PARAMETER / BASE YEAR	$\overline{R}(t)$	$\overline{R}_{\emptyset}$	$\overline{EC}(t)$	$\overline{EC}_{\emptyset}$
1989 \$	216×10^6	95.2×10^6	.078	.034
1980 \$	127.8×10^6	56.1×10^6	.046	.020

Figure 4-A shows the levelized values of O&M and capital-related charges stretching over the life cycle of the plant. Each year, revenues of \$127.8 x 10^6 are required to assure payment of all the bills by the end of the investment life. Taxes in the first year are seen to be substantially negative. This is due to the investment tax credit that occurs at that time and an operating loss in that year. Taxes continue to be negative through year 12 when an operating surplus is finally gained. The balance on outstanding capital is paid down by the net cash flow each year (including the substantial tax credits) after all other expenses are met, including interest on outstanding debt and dividends on outstanding equity and insurance and property taxes (a constant amount, not shown). In Figure 4-B, the outstanding capital is seen to be finally paid off at the end of the 30-year investment life. Levelized O&M costs are seen to be substantially greater than the projected O&M values in the early years. The cash flow interpretation requires that this difference accumulate in a "fund" that gains interest at the after-tax cost of capital rate. This O&M "sinking fund" accumulates over the life of the investment and, by the later years, is drawn upon to pay the O&M costs that are by then greater than the levelized value. At the last year the fund is empty and all O&M and other costs have been paid.

If revenue requirements are represented by a real 1980 dollars annuity, energy cost, $\overline{EC}(o)_{\emptyset}$ is \$0.20/kWh in the first year as shown in Table 2-B. This translates into generated revenues of \$55.4 million dollars in year $\emptyset$ or \$59 million in year 1 dollars. This value escalates at the inflation rate over the life of the plant and the cash flow is shown in Figure 5-A. Again taxes resulting from this cash flow are seen to be substantially negative in the early years. The outstanding balance of capital is paid down by the annual net cash flow after taxes (including credits), dividends and interest, and other ex-

FIGURE 4-A

DISPOSITION OF ANNUAL LEVELIZED NOMINAL DOLLAR REVENUES, $\bar{R}(c)_{1980}$

(Expressed in dollars of the day)

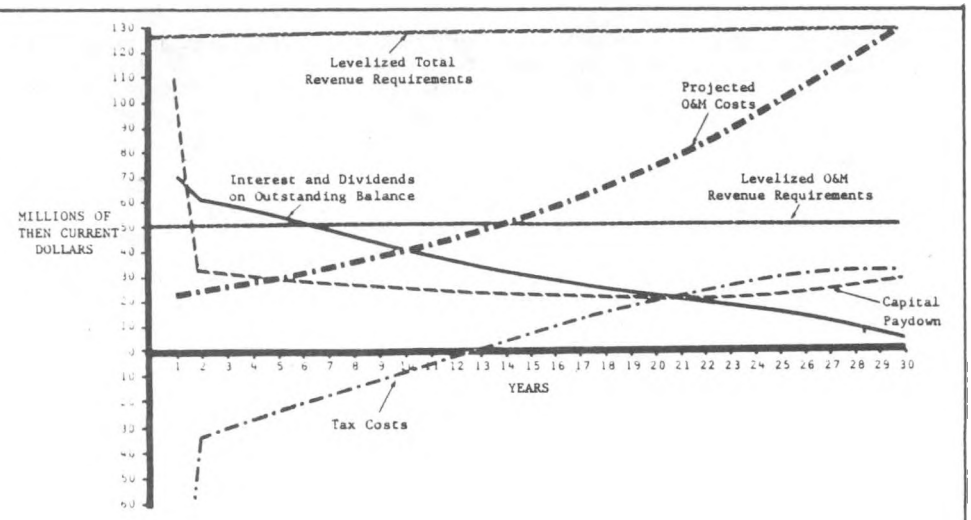


FIGURE 4-B

O&M FUND AND OUTSTANDING CAPITAL

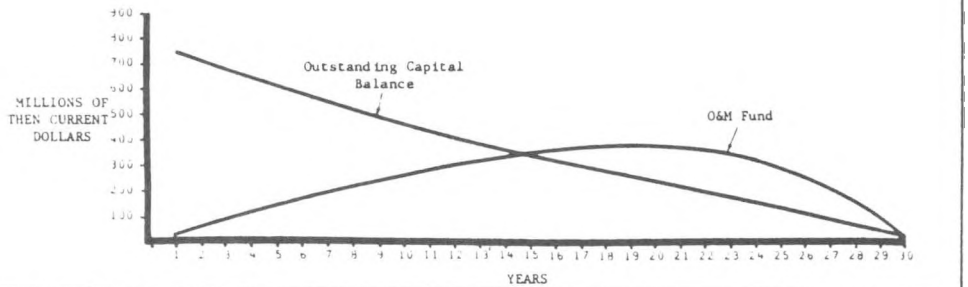
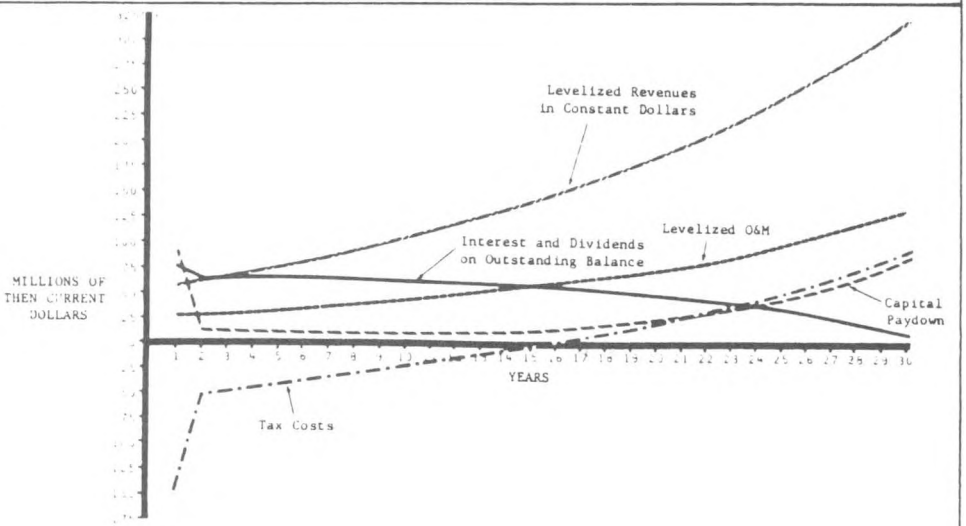


FIGURE 5-A

DISPOSITION OF ANNUAL ANNUITIZED CONSTANT* DOLLAR REVENUES, $\bar{R}(o)_{1980}$



*Escalates at the inflation rate in nominal dollars.

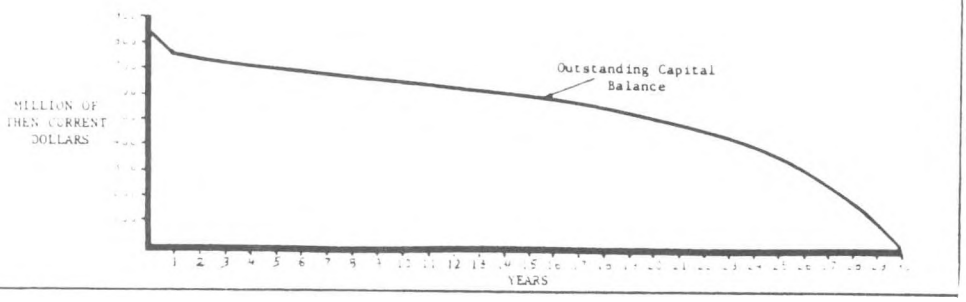


FIGURE 2-B

OUTSTANDING CAPITAL

penses are paid. The capital investment is the same value as earlier, but the pattern of its paydown is quite different from the levelized representation. Here, most of the capital is paid back in the last third of plant life, as shown in Figure 5-B.

Again, this surrogate cash-flow stream is seen to completely payback the capital investment over the life cycle. The O&M portion of revenue requirements is represented by a stream that escalates at the inflation rate. This mirrors the projected actual stream of O&M revenue required and thus all funds acquired each year for O&M are dispersed that year and no "fund" for O&M is needed.

CONCLUSIONS

In both manners of representing revenue requirements it is seen that the necessary conditions of paying back all the capital invested, the specified interest and dividends, and paying operating costs are met. In both cases, the return on outstanding equity investment was specific and the dividends and return of capital completely amortize the equity at the specified rate over the life cycle. Both representations are equivalent in a discounted cash flow sense since the present value of the revenue streams are equal.

Revenue requirements is a useful tool to compare investment alternatives. The calculations result in a single value of energy cost, and thus generated revenues, that represent an actual cash-flow stream projected for an enterprise. But the type of dollars and the base year must be carefully specified to avoid confusion.

It is also seen that the surrogate cash-flow stream established from the annuitized cash flow representation of required revenues, pays back all investments at the specified rates of return and satisfies all operating costs over the plants life. But this stream and the energy cost values upon which it is based should be interpreted with care. The projected revenue stream, R(t), is dependent on market conditions and not the requirements of an enterprise, and presumes that the investors have substantial tax bills to fully take advantage of the tax credits and losses in the early years.

A projected balance sheet could reveal cash flow problems over the life cycle of the enterprise based on projections of market behavior and a specific firm's financial condition with time. However, the method discussed here is very useful by offering an economic comparison of investment alternatives under consistent assumptions in a way that results in a single figure of merit for evaluation.

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OTEC: Estimating Total Systems Benefits and Costs

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Abstract

Mini OTEC has clearly demonstrated the technology for this energy supply option to be reliable, safe and sound. However, the very low priority accorded OTEC in the Reagan energy budget is seen to jeopardize its chances of early market penetration and successful commercialization. This paper attempts to develop guidelines for a reappraisal of the OTEC program viewed in a national perspective. First, it identifies all relevant costs and benefits associated with OTEC power systems. Second, it clarifies the treatment of certain items of cost in the analysis. Third, it discusses certain externalities and linkage effects of the program and fourth, explores the "ripple effect" in the domestic economy and cautions against erroneous double counting. A successful determination of social profits in the OTEC program is seen to emerge from a careful adherence to various economic concepts discussed in the paper.

Introduction

The technology for utilizing OTEC clearly exists at the present time. There have been some changes in the configurations of alternate systems in the recent past, together with general improvements in design conceptualizations of OTEC plants. Future development of the OTEC program, however, appears to have snagged under induced "inertia" of the Reagan government. While the government has decided to phase out the Department of Energy in its effort to balance the budget, a more direct threat to the sustainability of the OTEC program stems from zero funds being allotted to it in the proposed Fiscal '82 budget. This extremely conservative stance of the government may be a reflection of the attitude that a government directed OTEC development program is a departure from the norms of a free enterprise system. It may also result from an assessment that the greatest potential for ocean thermal energy conversion, to date, is seen to occur in tropical locations remote from major industrial and population centers where energy is most needed. It may also be part of the government's drive to promote and hasten private sector involvement in all phases of OTEC development activities, should there be opportunities for profit in that business.

Lavi and Lavi (1979), on the other hand, have stressed government involvement at least into the early commercial stages of the OTEC development program. They point out that frequent budgetary battles over federal outlays have deterred long term planning by the private sector and served to dissuade large investors from committing capital on the scale needed to accelerate OTEC penetration in the U.S. market. Many benefits have been claimed for the OTEC program, by its proponents, in order to justify continued investments in the industry. However, whether OTEC would ever become a "commercial reality," at this stage, appears at limbo given the concern in the private sector over the high capital risks associated with it and the governmental apathy experienced at the hands of an administration in its infancy, much too preoccupied in sorting out its current military and social priorities. What is needed at this juncture therefore is a reappraisal of the OTEC development program. As a first step, this paper, then, attempts to identify some relevant costs and benefits pertaining to the deployment of OTEC technology on a sufficiently large scale to serve the power generation industry using some of the concepts discussed by Squire and vanderTak (1976).

Identifying Relevant Costs and Benefits

At the very outset it must be recognized that an accelerated OTEC development program is likely to impact on several categories of inputs so as to curtail their supplies to the rest of the economy. Materials commonly used for constructing OTEC plants include concrete, structural steel, aluminum, copper and other alloying agents. The breakdown for OTEC materials is provided in Table 1.

Current schemes for large floating OTEC plants also entail the production of other resources through mariculture (such as shellfish and kelp), production of fresh water and hydrogen, and other ocean minerals besides generating electricity. The high demand, high growth rate products that could be derived from recovering marketable chemicals from sea water and producing energy intensive products in conjunction with floating OTEC are listed in Table 2. Thus OTEC technology deployment also increases the supply of certain outputs to the economy. The supply pattern of the various inputs and outputs mentioned above in the discussion would in all likelihood be different if the OTEC program

Table 1

OTEC Materials Breakdown

Material	Bulk Weight (short tons)	Normalized Weight (ST/MW)
Concrete	333,000	900
Rebar	165,000	450
Structural steel	28,000	76
Aluminum Sheet/tube	8,000	22
Copper*	7,600	21
Alloying Agents (Mg., Mn., Cr., Zn.)	800	2
Total	540,000 ST	1470 ST/MW

*Includes transmission lines

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Source:

Cohen, Robert, "An Overview of the US OTEC Development Program," in Griffin, Owen M., ed., Ocean Thermal Energy Conversion (OED, Vol. 5) 1978, p. 21.

is never initiated. Thus a basic method of identifying the program's costs and benefits would be to examine availabilities of inputs and outputs under these two alternate scenarios. It is quite conceivable that if the OTEC program were to be scrapped, the situation resulting may not be a continuation of the status quo, rather it may reflect a situation that would result from a failure to develop or be indicative of a continued negligence of this alternate energy resource. Inasmuch as the objective of developing OTEC may be in part to prevent future fuel cost escalations and to minimize dependency on foreign sources, the situation of not developing OTEC must then include the cost increases for conventional fuels and other outputs as well as benefit decreases due to suspected vulnerabilities in the economic, political and military spheres to more fully reflect the gains engendered by the OTEC development program. Thus in reality an accurate description of the two alternate scenarios could involve difficult determinations and judgements since they may not simply correspond to the "before" and "after" situation of OTEC development.

Transfer Payments

The Federal Government, major industrial corporations, and a handful of electric utilities are expected to be potential sponsors for the OTEC development program (General Electric Company-Tempo, 1978). Their sound financial standing is expected to help induce reluctant lenders to release the needed capital from the debt market. Thus some items of cost that are listed in the projected financial statements of the sponsors may not represent direct claims on resources as in the case of fixed charges related to the cost of capital. These merely involve a transfer of the control over resource allocation to lenders in the debt market. Whereas the above interest payment transaction transfers actual purchasing power and thus effectiveness in control over resources, it does not involve real resource costs and to that extent is not an economic cost. Similarly, loans secured in capital markets and their repayments constitute basic financial transactions. However, loan financed expenditures on plant components (e.g., heat exchangers, evaporators, condensers, generators, tubes and pumps), materials (e.g., steel, concrete) and labor (direct and indirect) do involve real economic costs. It is clear then that financial and economic costs are not joint in their occurrence. The financial cost of a loan is met when it is repaid, and the economic costs encountered when the loan is spent. It is therefore not necessary for an economic analysis of the OTEC program to concern itself with the sources of funding nor its repayment. Depreciation allowances (especially accelerated depreciation schedules currently proposed) may not correspond to the actual use of resources, and therefore should not be a part of the cost stream. The economic cost of using aluminum heat exchangers, for example, would be reflected in the initial investment cost for the heat exchangers less present value of the aluminum scrap after fifteen years or as in the case of Titanium tubed evaporator and condenser, the initial capital cost less present value salvage after 30 years (TRW, 1978).

The government could also promote non conventional energy technology through a wide variety of tax and expenditure incentives. The tax incentives may be designed to cover compensation to the tax payer for expenses and losses incurred, deductions for R & D, net operating losses, interest paid and depreciation. Expenditure incentives may result from grants, interest and insurance subsidies and price support payments. These taxes and subsidies are also to be eliminated from the economic cost analysis as they are transfer payments and do not reflect true resource costs.

The transfer payments mentioned above do impact on the distribution of incomes in society. The improving income distribution or resulting inequities, therefrom, should however be taken note of in determining costs and benefits of the OTEC program.

Contingencies

Contingency allowances normally claimed for OTEC facilities range between 10-15% (Hornburg et al., 1976 and Lockheed, 1977). These allowances may arise out of engineering or financial considerations. Physical contingency allowances that would be part of the expected costs of the OTEC facilities and price contingencies to cover expected increases in prices of items or inputs needed by the OTEC program should be included in the economic analysis. Price contingencies for general price level

Table 2

High Demand or High Growth Rate Products

Product	US demand 1975 ('000 tons/yr)	Growth rate (percent/yr)	Market price (price/ton)
Potash	4,999	5.0	40
Chlorine	11,753	6.0	120
Caustic	11,821	6.5	140
Magnesium	144	8.0	1,640
Ethylene	12,678	7.0	--
Vinyl Chloride	2,000	4.0	200
Polyethylene (LD)	3,324	9.0	480
Polyethylene (HD)	1,471	9.0	--
Ethylene Oxide	1,900	6.0	600
Ammonia	16,218	5.0	200
Ammonium Nitrate	8,750	7.0	100
Aluminum	6,400	6.0	800
Steel	113,000	2.4	260

Reference:
Hornburg, C.D., Lindal, B., and N. El-Ramly. Preliminary Research on Ocean Energy Industrial Complexes. In proceedings of joint Conference on Sharing the Sun, Solar Technology in the Seventies (August 15-20, 1976) as cited in

Source:
Congressional Report, U.S. House of Representatives, Energy from the Ocean, April 1978, p. 60.

adjustments should however be excluded. It is expected that as a result of OTEC technology maturation, engineering costs could be substantially reduced due to the learning effect.

Sunk Costs

Within this category of costs could be included all the costs included by the Federal Government in promoting R & D of OTEC technology throughout the decade of the seventies. It includes the portion of costs shared by the private sector under various cost sharing programs with the government. It involves all moneys invested in the program by the private sector to improve the efficiency, design and deployment of OTEC plants. These colossal amounts of money (in hundred millions of dollars) nevertheless have to be excluded in any reappraisal to determine the costs of achieving OTEC commercialization, since benefits from a program designed to complete work started earlier do not depend on costs incurred earlier, but rather on costs that affect its completion. It may, however, be useful to calculate the rate of return on the total investments in the program from inception in order to check, in hindsight, if the OTEC development program has been a conceptually sound idea.

Externalities and Linkages

Certain externalities attach to the development and deployment of OTEC technology. These are effects which may bear positively or negatively on the economy and would therefore be included in the analysis.

The National Research Council (1979) has projected a range of 6.1-12.9 quads per year of synthetic liquids produced from coal by the year 2010. Craven (1980) estimates that in the unlikely event of the imbalance in the hydrogen/carbon ratio being rectified by carbon elimination this would imply a requirement of 19-30 quads of coal per year. Under an alternate scenario where hydrogen may be obtained from the water molecule either by the interaction of steam and hotwater or by the generation of electricity in coal-fired plants followed by electrolytic dissociation of the water molecule, the annual coal requirements to produce the required synfuel may be in the range of 12-25 quads.

However, if the hydrogen is obtained from OTEC, energy resource requirements may be 4.7 to 9.9 quads for coal-produced fuel and 1.4 to 3.0 quads for OTEC produced hydrogen. Thus OTEC produced hydrogen in the synfuel would result in a resource saving of 5 to 15 quads every year. The impact of this saving would be dramatic in the national

energy picture, greatly boost the country's efforts to minimize energy dependence and shift the ever improving logistics for oil away from domination.

Another use for hydrogen produced at OTEC installations is to produce methanol, a motor fuel (Avery, 1981). Coke could be reacted with hydrogen in a chamber to produce carbon monoxide and then be passed through another chamber with a catalyst, and hydrogen added to that causing the two to combine to form methanol or methyl alcohol. OTEC produced methanol thus could be an attractive commercial operation in the late 1980's, competitive with methanol produced from other sources.

Negative externalities could occur from environmental effects of the OTEC program. Lavi and Lavi (1979) have identified four potential problem areas. The first could result due to ocean water mixing. Because of the draw on huge volumes of water, the resulting reduced surface temperature could alter local and global weather patterns. Leakages of certain working fluids as that of a halocarbon (Freon) or a hydrocarbon (propane, butane) could be potentially hazardous to the marine ecosystem as would be the discharge of biocides that may be used to control macro fouling in water passages. Deployment of numerous OTEC hulls could result in significant cumulative effects of substantial CO_2 release into the atmosphere, and finally the presence of a number of moored plants connected by transmission lines may interfere with shipping and increase the risk to OTEC installations from submarines and other surface vessels.

The externalities discussed above may not readily lend to economic quantification and analysis. These then should be addressed at least in qualitative terms.

Price effects caused by the OTEC program are to be included in the scope of externalities. An accelerated OTEC deployment program could lead to higher prices for aluminum, titanium, steel, concrete, etc. It could also result in lower prices for some of the high energy products, listed in Table 2, which it produces. It could, in the future, lower demand for electrical output from oil or nuclear sources, and increase demand for synfuels that use OTEC produced hydrogen. Thus "forward linkage effects" may be felt in the market for maricultural procucts, fresh water supply, fertilizers, and industrial chemicals. The "backward linkage effects" would occur in factor markets supplying inputs for the OTEC program. Thus OTEC penetration of the market could involve some sweeping changes in the demand for inputs and outputs and cause gains and losses for producers and consumers in other industries.

These external costs and benefits may or may not have to be added to the more direct and indirect costs of the OTEC program. The direct social profit from the program would be an enumeration of all economic gains and losses associated with it, provided two conditions are met. As a first condition, it is required that the government be indifferent as to who gains or loses as a result of the OTEC program. The greatest potential for OTEC currently exists in areas off Florida and the Gulf, Puerto Rico, and Hawaii. If the value judgements of the administration reflect that different weights are being attached to regions affected by the OTEC program, then the direct social profit discussed above may not be a reliable measure. When the price changes have been minor and income distribution weights among affected groups are approximately uniform, exclusion of the role of externalities from the economic analysis of the program could result in a fair approximation.

Secondly, the direct costs and benefits from the OTEC program arising from its own output and inputs may not provide a complete measure of the social profit in certain cases where oil producers, for example, whose output may be affected, do not sell in perfectly competitive markets where price is equated with social marginal cost. In this case, the direct social profit measure could understate the gains and losses from the program. Even though it may be difficult to trace externalities in all affected markets due to existing market imperfections, it is important to investigate some of the grosser ones.

Multiplier Effects

The U.S. currently has general excess capacity in the metal and ship building industries (Lavi and Lavi, 1979). OTEC development spending could impact on these two industries in the early stages. As OTEC develops into a major energy resource, future investments are likely to be made in OTEC dedicated manufacturing facilities, which would improve the capability of U.S. shipyards to construct platforms and cold water pipes for large OTEC based electricity generating systems. Investments in new OTEC plants would encourage production growth for certain metals such as titanium. Secondary expenditure effects of the OTEC program could be measured by examining the consumption patterns induced by it. These expenditures are likely to be different among different economic classes and different regions of the country.

International Effects

The external effects of the OTEC program may be realized gradually since OTEC in the opinion of many is a long term option. To the extent OTEC substitutes for energy imports, it would contribute to a relative decline in the real world price for conventional fuel, thereby benefiting some oil importing countries in the western world having limited energy supply options and harming other oil producing nations of OPEC. These international effects may also exist for other outputs of OTEC industry. The increase in demand and, possibly, prices for certain input factors used by the industry may affect other countries that export the raw materials. For example, aluminum exports from Jamaica and Brazil and titanium exports from Australia and India may contribute to increased foreign exchange earnings for these countries.

Large OTEC systems could adversely effect the climate of a neighboring country such as in the Caribbean, the Pacific basin or Mexico. It may cause navigation problems in international shipping lanes. These external effects on other countries are similar to externalities discussed earlier both

in nature of occurrence and their subsequent treatment. It may be necessary to take note of the physical externalities and make appropriate compensation for any untoward effects. These should then be included in the economic appraisal. The external price effects may however be excluded from the analysis.

There are a number of countries in Asia, Africa, latin America and the Pacific that could benefit from OTEC technology. Gains from transfer of technology and improving trade may also be a part of the discussion under this category.

Double Counting

The analysis of the OTEC program should take into consideration all relevant costs and benefits, but prevent any from being recorded twice. Double counting in an appraisal of the OTEC development program may arise in two ways. First, external benefits and costs may be included even if they already have been accounted in the social profit measure evaluated for the program. For example, increases in synfuel production may be claimed erroneously for the OTEC program, when it may already be evident in the social surplus gained from the OTEC industry's by-product utilization. Second, since OTEC is a labor intensive industry (100 MW OTEC plants generate 3000 man-years demand of direct labor and an even larger demand for ancillary services), employment benefits may be claimed in addition to estimated social profits of the program. Provided the labor inputs for the OTEC program have been evaluated in relation to their shadow prices i.e., value of their contribution to the country's goal of reducing unemployment resulting from marginal changes in the availability of labor, the employment effects of the industry have been previously noted and should not be included as additional benefits of the OTEC program.

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OTEC PRODUCED AMMONIA - AN ALTERNATIVE FUEL

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ABSTRACT

A survey of prior work on the use of ammonia as a fuel and results of preliminary investigations of its use in ship and land vehicle propulsion systems are presented. Ammonia is a synthetic fuel which can be made at sea on cruising Ocean Thermal Energy Conversion (OTEC) plantships using only hydrogen from seawater (via distillation and electrolysis) and nitrogen obtained from the air by a liquefaction process. The projected f.o.b. price of OTEC ammonia delivered to U.S. ports from commercial plantships in 1990 is ~$260/short ton (in 1980 $'s). Systems and technology for distributing ammonia by pipeline, barge, rail and truck for fertilizer and chemical markets in the U.S. already exist. Additional distribution systems for fuel markets can be developed, and OTEC ammonia may well become an economical fuel in the near future, particularly in economies or distribution areas dependent on foreign oil. Ammonia fuel, although toxic and presenting different hazard/safety considerations, is easily handled, transported, and stored and has a lesser fire-explosion risk than most liquid fuels.

INTRODUCTION

OTEC Ammonia Plantships

The potential OTEC resource is vast comprising all the worlds oceans within or near ± 20° of the equator which have water depths of 1000 meters or more. While there are many areas where OTEC plants can be located, as fixed or moored structures, with electric cables transmitting power to shore, by far the greatest utilization of the resource will be via free-floating "grazing" plantships producing energy intensive products or fuels. Of the many products or uses to which OTEC energy can be applied, the first and apparently most economic application (requiring the least development) is the synthesis of ammonia (1)*.

Following the original 1976 study by APL of a conceptual 100 MW plantship designed to produce ammonia (2) and other products, detailed baseline OTEC pilot plant designs were undertaken incorporating OTEC heat exchanger design test data, heat exchanger biofouling-removal and materials tests and evaluations, and the results of extensive analyses of platform and cold water pipe designs to meet the requirements for both operational and survival sea states. This work culminated in the design of a 40 MW OTEC pilot plant (3) including a nominal 125 ton/day ammonia synthesis plant (Fig. 1), for which detailed fabrication-construction analyses, equipment requirements and arrangements, and cost estimates were made. A 1/30th-scale model of the pilot plant was tested in a wave basin (4) and demonstrated more than adequate stability, generally confirming motion and "green-water" predictions for both operational and survival sea states.

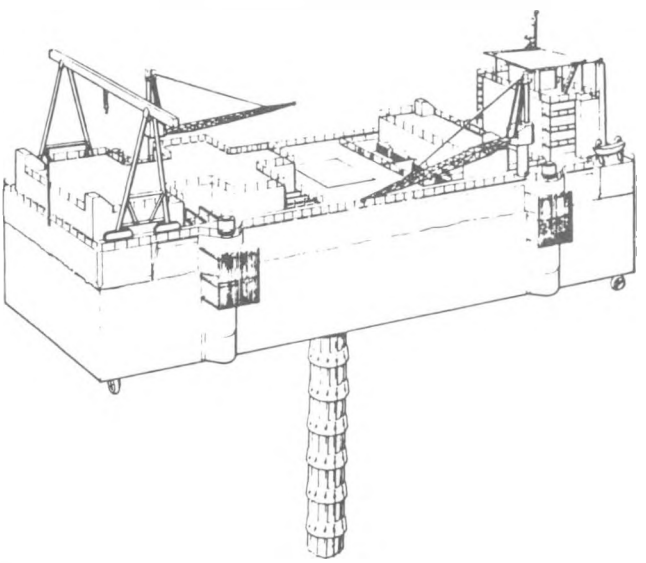


Fig. 1 40 MW_e (nominal) OTEC pilot plantship ~125 ton/day ammonia synthesis plant.

Extrapolations to conceptual commercial plant sizes (5) based on the pilot plant design, shown in Fig. 2, maintain the same basic modular OTEC power equipment layouts with increasing turbine-generator sizes. In the larger plants the areas and volumes available are more than adequate for any anticipated ammonia synthesis plant requirement including product storage for

* Numbers in parenthesis refer to References listed at the end of the paper.

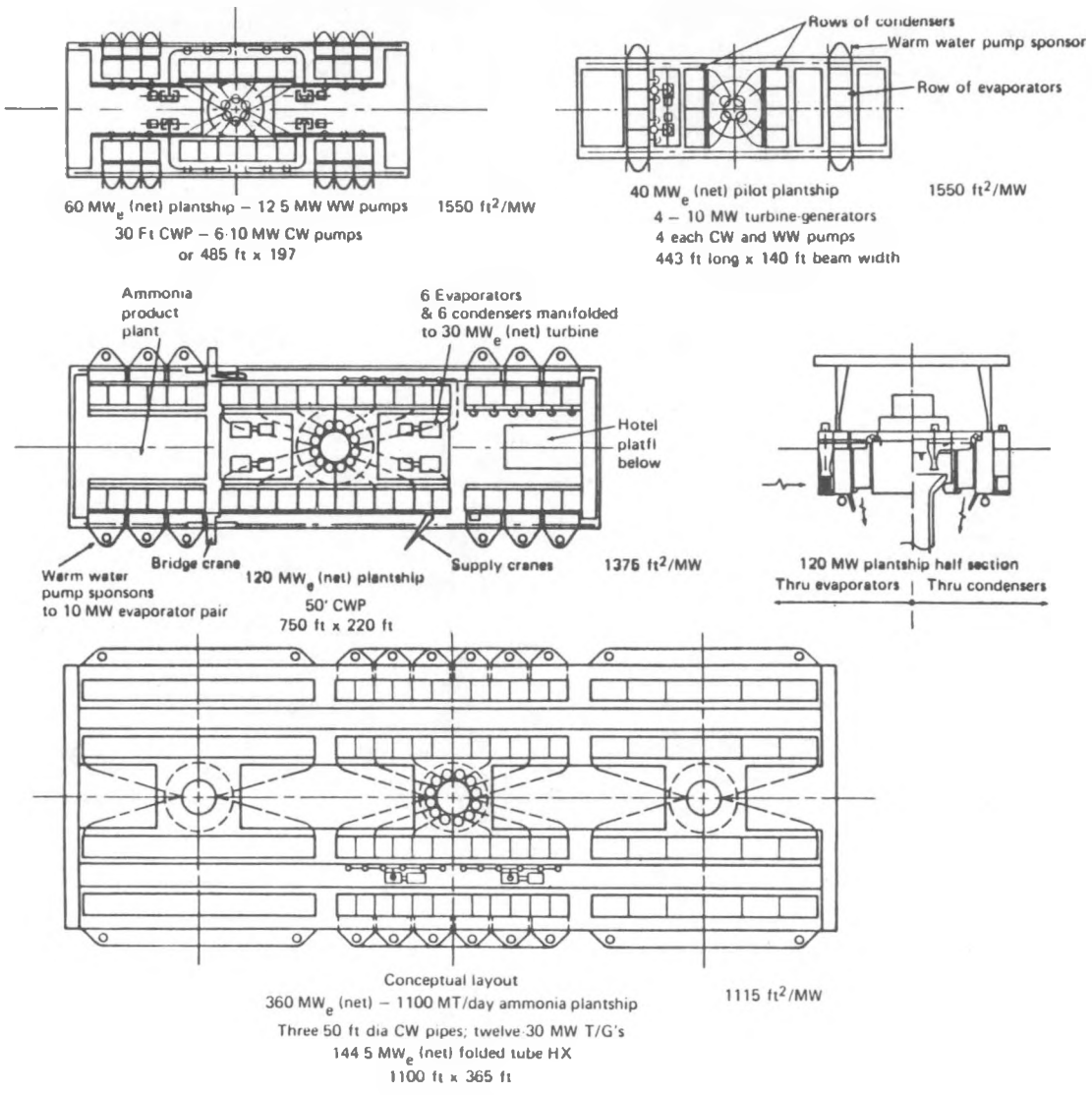


Fig. 2 Conceptual plantship layouts.

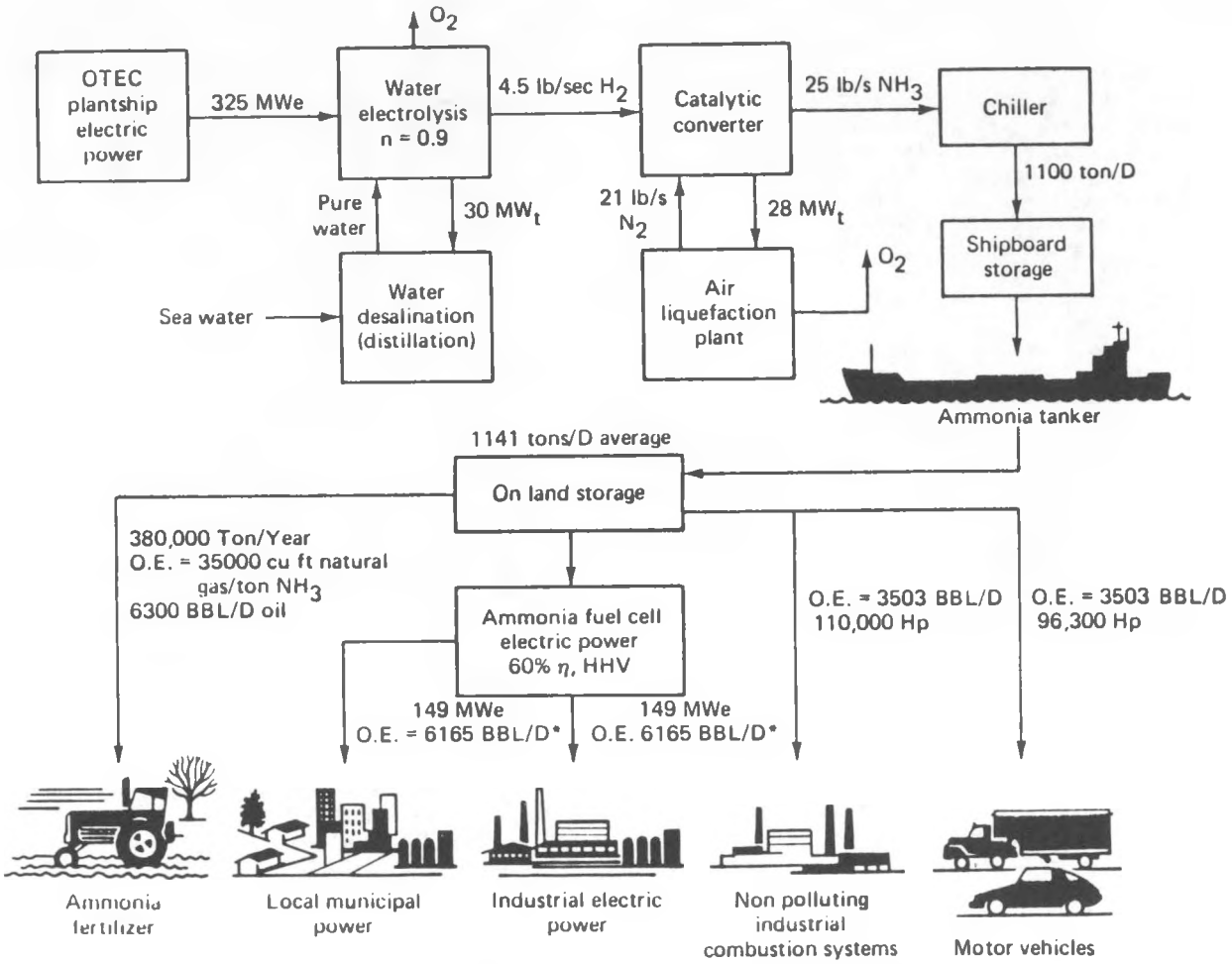
30 days or more. While product transfer (to a shuttle tanker-supply vessel) has not been investigated, an astern towed moor-hard line product transfer appears most practical, based on current open sea LNG loading designs.

Construction, deployment, and O&M costs reported in Ref. 1, and the resulting product ammonia costs are based on the eighth commercial (325 MW) plantship and learning curves associated with modular repetitive construction as indicated in Fig. 2, estimated to be commercially competitive in the 1990's. Later estimates show OTEC ammonia from the first commercial plant may be competitive in the domestic U.S. market depending on natural gas pricing; however, the purpose of this paper is to show that OTEC ammonia can be a competitive and possibly more economic fuel than imported LNG or fuel oil, and that commercial OTEC ammonia plantships can be the "oil wells" for specific areas now.

Ammonia as a Fuel

Ammonia from natural gas today (U.S. ~ 20 x 10^6 T/yr) is mainly used for fertilizer and chemical feedstocks, but as shown in Fig. 3, OTEC ammonia could not only supplant this usage but provide for power requirements, with the fuel cell-electric power resulting in the greatest resource application.

Ammonia may be used directly or dissociated (with dissociation reaction loss ~12-14%) to regenerate hydrogen as the energy source for fuel cells, engines, and direct or catalytic combustion systems. Work on both direct and dissociated ammonia fuel cells has been reported, from which the technology to attain conversion efficiencies of the order of 50 percent of the HHV of ammonia appears to be within the current state-of-the-art and efficiencies $\geq$ 60 percent possible.



O.E. = Oil equivalent, *Based on present average of 10,000 btu/kwh
Subscripts e = electrical
t = thermal
D = day

Fig. 3 OTEC ammonia plantship fuel utilization.

A considerable body of work on ammonia fueled reciprocating and gas turbine engines has been reported. Many studies stem from applications related to the mobile nuclear reactor energy depot concept of the 1960's where, of the possible fuels that could be synthesized, ammonia was considered to have the most potential. It is possible to modify existing engines to operate with ammonia fuel and attain equal or even higher performance than with conventional fuels.

Fuel Cells

Both fuel cells that use ammonia directly (6-11) and those that use dissociated ammonia (12-17) have been investigated. In either case, the maximum amount of energy obtainable is the high heat of combustion (H.H.C.) of ammonia; i.e., 9665 Btu/lb NH_3 or 2.833 kWhrs/lb NH_3. The maximum conversion to electricity for a fuel cell in which the ammonia is oxidized directly at the anode is theoretically 2.511 kWhrs/lb NH_3 (88.6% of the H.H.C.). Where the ammonia is first dissociated and hydrogen oxidized at the anode the maximum conversion to electricity is theoretically 2.350 kWhrs/lb NH_3 (83.0% of the H.H.C.). Based on this, a direct ammonia fuel cell should out perform an indirect ammonia fuel cell; however, the current and voltage efficiencies of the two types of cells effect their actual performance. The current efficiency of the direct ammonia cell is high (> 99%). That of the hydrogen oxidizing cell is also high, so current efficiency for the indirect cell depends in effect on the efficiency of the dissociator. Both types of fuel cells have high anode over-potentials at ambient temperatures which reduce voltage efficiency, but more so in the case of the ammonia oxidizing cell than in the case of the hydrogen oxidizing cell. Increasing the temperature at which the cells operate and the use of catalysts reduce over potential and increases voltage efficiency. Because of internal resistance, cell voltage also decreases with

current density, with power density being optimum at some particular current density. Use of oxygen rather than air at the cathode increases cell voltage slightly and has a greater effect at higher current densities. Although it has still to be demonstrated, conversion on the order of 50% of the H.H.C. of ammonia at current densities of 100 amperes per sq. ft. should be within the present state-of-the-art for either direct or indirect ammonia/air fuel cell systems.

With two exceptions, the referenced work on ammonia fuel cells was done over eight years ago. The most recent (1980) report (11) deals with a direct type cell for cogeneration of electricity along with the manufacture of nitric acid and is unique since the object is to obtain nitric oxide at the anode rather than nitrogen. The other recent (1978) report (17) deals with the development of a simple indirect ammonia/air fuel cell at Wu-han University in China. The authors of this report state that the system was chosen, "....because liquid ammonia is cheap, easily available everywhere, and can be stored in not very heavy containers." For similar reasons, both direct and indirect ammonia fuel cells were investigated in this country during the 1960's and early 1970's. The work at the General Electric Research Center, Schenectady, NY, (9, 10) is representative of the state-of-the-art for direct type and that done at Englehard Minerals and Chemicals Corp., Newark, NJ, (14-16) is representative of the state-of-the-art for the indirect type. In general, these fuel cells are capable of delivering between 30 to 35% of the H.H.C. of ammonia as electricity at current densities of about 100 amps/ft^2.

The General Electric, direct ammonia/air fuel cell of Ref. 10 has a voltage efficiency of about 42% at 100 amps/ft^2. In terms of the H.H.C. of ammonia, this corresponds to a conversion efficiency of 37% and, allowing for parasitic load, an overall efficiency of 35%. The Englehard, indirect ammonia/air fuel cell of Ref. 16 has a voltage efficiency of about 53% at 100 amps/ft^2. This corresponds to a fuel cell conversion efficiency of 49%, but the dissociator or "cracker" efficiency is only about 70%, and the parasitic load about 10% of the gross electrical output, so that the overall efficiency is about 30% of the H.H.C. of ammonia. Significantly higher efficiencies are possible if a more active catalyst is used at the anode of the direct cell or in the "cracker" of the indirect cell (18). The voltage efficiency of the direct ammonia/air fuel cell can be increased probably to 56% and "cracker" efficiency to 85% by means of an iridium catalyst. It would appear that the basic technology for constructing indirect and direct ammonia/air fuel cells capable respectively of converting 37 to 47% of the H.H.C. of ammonia to electricity at current densities of 100 amps/ft^2 has existed for more than 8 years.

It is not evident that much has been done since 1969 on developing direct ammonia fuel cells. On the other hand, development of hydrogen fuel cells has continued. Voltage efficiencies as high as 73% at 100 amps/ft^2 have been obtained with hydrogen/air fuel cells (19); and, indirect ammonia air fuel cell systems with overall order of 50% of the H.H.C. ao ammonia would appear to be within the current state-of-the-art for both direct (47%) and indirect (52%) ammonia/air fuel cells; although this remains to be demonstrated. Research and development on both types of cells should yield further improvements in performance and the ability to produce reliable and durable systems at reasonable cost.

Gas Turbines

For industrial power and transport usage, ammonia can be burned directly in gas turbine engines, and for similar engine sizes can deliver 10 to 20 percent increased power over hydrocarbon fuels at equivalent turbine inlet temperatures. This possible gain is not without modification, to varying degree dependent on engine design and usage and for practical applications would require specific design for ammonia fuel. References 20 to 23 report both analytical and experimental work on ammonia fueled gas turbines and while much work has also been reported by others, the discussion here is limited to the cited references which extensively cover the subject area.

Newhall (20) compared the theoretical performance of both regenerative and non-regenerative Brayton cycles treating the combustion products as a chemical equilibrium system for both ammonia and cetane ($C_{16}H_{32}$, pure hydrocarbon) fuels. The cycles and the processes were programmed for analysis on an IBM 7094 digital computer where, following the determination of working fluid properties at each point of the theoretical cycle, the corresponding cycle performance was calculated. Newhall points out that: "Specification of a chemical equilibrium system of combustion products implies the major assumption that ammonia can be made to burn successfully following direct injection as a liquid or vapor. While one of the major problems to be encountered in the practical development of ammonia as a turbine fuel is that of successful ignition and combustion of ammonia, the purpose of this report is the prediction of maximum potential performance to be realized."

Gas turbine performance and efficiency, as a continuously fired combustion system, is generally limited by the allowable turbine inlet temperature due to materials considerations, which is the peak cycle temperature for performance analysis. Materials research to raise allowable gas turbine inlet temperatures has been a continuing effort. The fuel to air ratio, determining maximum turbine power, is limited by the allowable inlet temperature, and for gas turbines is comparatively lean (typically 0.4-0.6) in contrast to reciprocating engines where maximum power is usually attained at fuel-air equivalent ratios greater than 1 (at lower efficiencies). Ammonia fuel, having a much lower heat content than hydrocarbon fuels products a significantly greater number of product moles at a slightly higher energy

INFLUENCE OF CYCLE PRESSURE RATIO ON THERMAL EFFICIENCY OF THEORETICAL REGENERATIVE BRAYTON CYCLE

COMPRESSOR EFFICIENCY = 0.85
TURBINE EFFICIENCY = 0.85
REGENERATOR EFFECTIVENESS = 0.9
T = TURBINE INLET TEMPERATURE – R = °F + 460

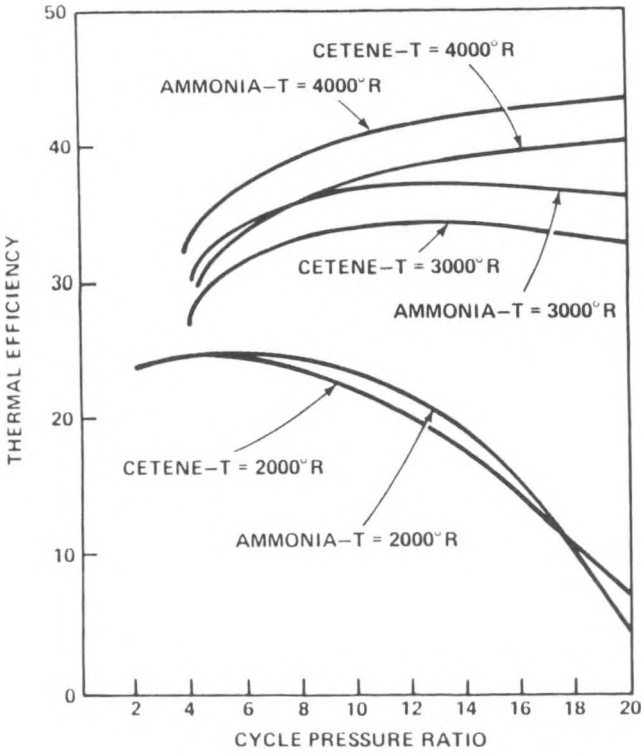


Fig. 4 Gas turbine efficiencies.

INFLUENCE OF CYCLE PRESSURE RATIO UPON SPECIFIC FUEL CONSUMPTION FOR THEORETICAL REGENERATIVE BRAYTON CYCLE

T = TURBINE INLET TEMPERATURE – °R = °F+460
COMPRESSOR EFFICIENCY = 0.85
TURBINE EFFICIENCY = 0.85
REGENERATOR EFFECTIVENESS = 0.9

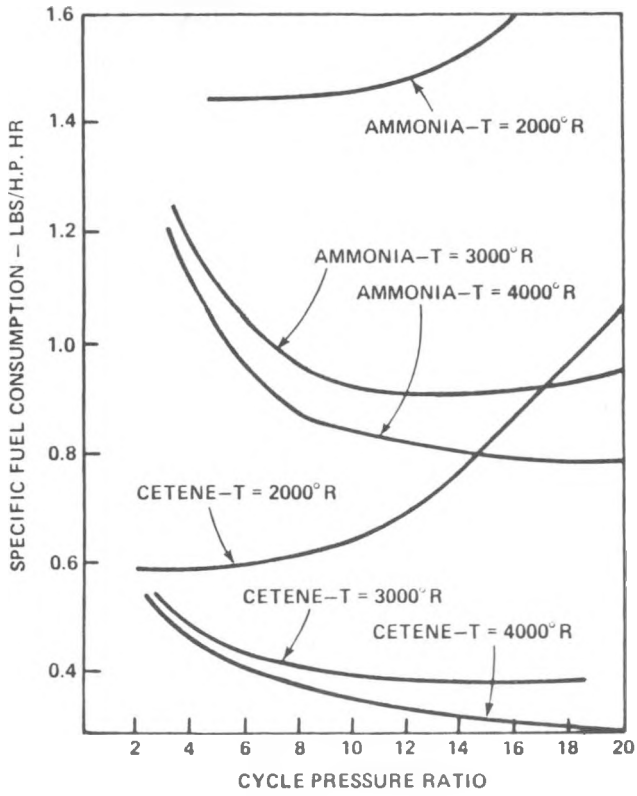


Fig. 5 Gas turbine fuel consumption.

content per lb of air at equivalent combustion temperatures. At equal fuel-air ratios the combustion temperature is also lower leading to theoretical performances typical of those in Figs. 4, 5 and 6 taken from (20). A near ten percent better thermal efficiency is indicated in Fig. 4, decreasing at lower combustion temperatures as fuel-air ratios decrease. Specific fuel consumption (SFC)-lbs/HPhr, shown in Fig. 5, generally a more practical measurement of engine performance, is shown to conform to Fig. 4 in that SFC for ammonia is 2.3-2.5 times that for hydrocarbon relating to the higher thermal efficiencies and relative fuel heat contents. Figure 6 showing work output per pound of air at various fuel air equivalence ratios (Ø) is illustrative, in that for a given inlet temperature Ø will always be greater for ammonia than hydrocarbons, leading to possible power gains of 20 percent.

D. T. Pratt (21) and F. J. VerKamp et al (22) both conducted studies of ammonia combustion properties and combustion performance tests in gas turbine "can" combustors. Results of these studies indicate that direct gaseous ammonia ignition energy, low flame speed, and mixing problems were such that to attain adequate flame stability and combustion efficiencies would require extensive tests and specific design. It was not possible to directly inject liquid ammonia. VerKamp found that pre-cracking up to 28 percent of the ammonia (equivalent to 5 percent H_2), the flame stability limits were approximately equal to hydrocarbon fuels.

A specific program to develop an ammonia burning gas turbine was conducted by the Solar Division of International Harvester Company in 1965-66 (23), again using a single can burner configuration on a gas turbine engine in the 250 HP size range. Two different combustor systems were successfully developed and tested, one essentially similar to conventional hydrocarbon but of increased size and one incorporating an oxidizing catalyst bed. The larger combustor increased combustion time and flame stability but would introduce limitations for applications requiring fast response. Two integral catalyst bed designs in the smaller combustor were tested, designed to attain better combustion control and response. The report quotes: "There is still reason to believe the catalyst combustion system can.....provide performance comparable with the best hydrocarbon systems."

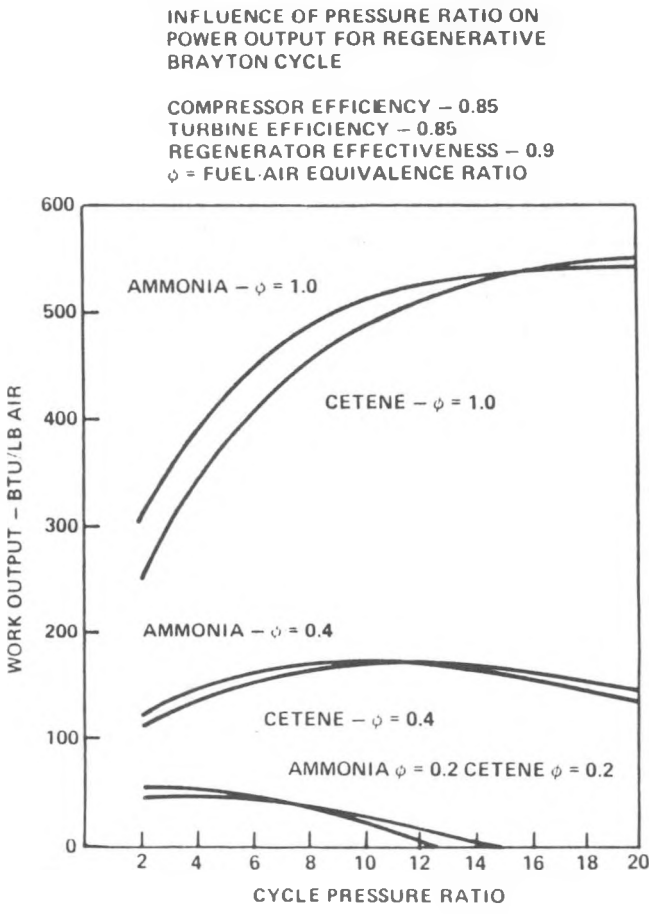


Fig. 6 Theoretical gas turbine power comparison.

The Solar program abandoned direct liquid injection early, and all tests were conducted with vaporized ammonia without cracking or hydrogen addition. It is feasible that exhaust heat vaporizing and precracking could provide the desired response capability with ammonia fuel with the simpler combustor. It is noteworthy that these engine tests confirmed Newhall's theoretical work both for turbine inlet temperatures and gain in horsepower, and based on diesel equivalent fuel flow an apparent thermal efficiency gain of 2.5 percent. With regard to combustion efficiency, the vapor combustor gave almost constant combustion efficiency (~94 percent) over the complete load range, but at lower load ranges the catalytic combustor efficiency exceeded 100 percent. It is theorized that larger HNO_2 and HNO_4 molecules are created, implying increased calorific values of the product.

It was concluded from the tests that "ammonia is a satisfactory substitute for hydrocarbon fuels in a simple cycle gas turbine engine. Conversion of a single can combustor engine to ammonia fuel operation can be accomplished without major redesign or development." It is also noted that it is probable that engines with annular combustion systems could be operated on ammonia fuel without any increase in combustor size.

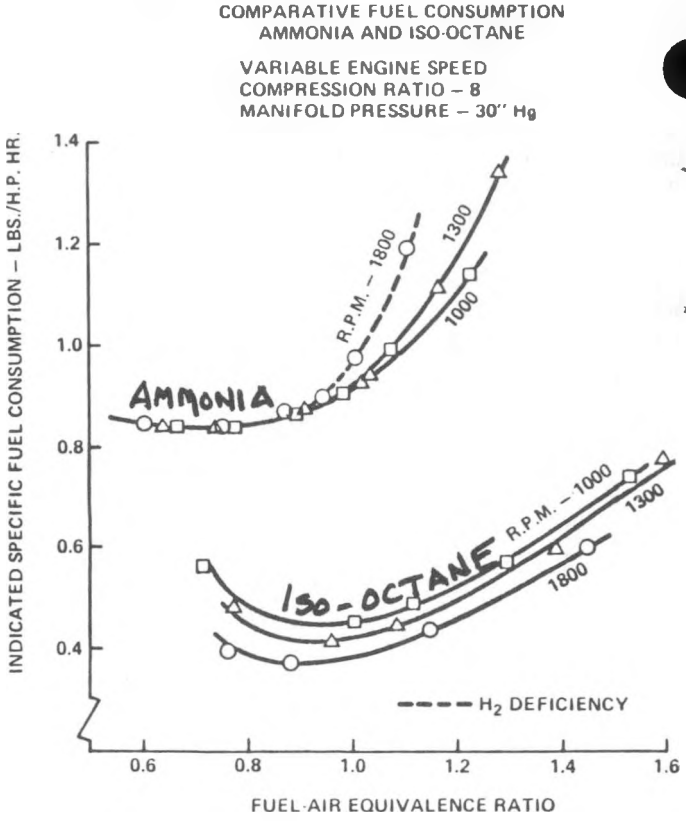


Fig. 7 Spark ignition single cylinder engine tests.

Reciprocating Engines

Many evaluations and tests of ammonia fueled reciprocating engines have been reported in the literature including actual service usage. References 24, 25, 26, and 27 have been selected as probably representing the most comprehensive discussion and evaluation of this use of ammonia fuel for the purpose of this paper. All report successful use of ammonia fuel, to varying degree, in progressive tests where the requirements for optimum operation with ammonia were determined.

Smith and Starkman (24) ran comparative hydrocarbon-ammonia fuel tests on a single cylinder engine and found little engine modification necessary other than spark timing and ammonia flow control, providing the ammonia was introduced as a vapor and partly dissociated to ~5 percent hydrogen (~28% NH_3). Figure 7 presents an indicated fuel consumption comparison from these tests, showing that at optimum fuel-air ratios the thermal efficiency of ammonia betters that of hydrocarbon. Maximum power for this engine with ammonia was reported as 72 percent that of hydrocarbon, compared with a theoretically predicted output of 75 percent. Optimum ammonia performance was attained at higher compression ratios (max 10) and fuel-air equivalence ratio ~0.9. No adverse effects were reported from 36 hours of ammonia operation except copper-lead bearing corrosion products in engine oil analysis.

Gray, et al (25) ran compression-ignition tests and materials compatibly studies with ammonia fuel, finding no simple method to attain satisfactory performance except with pilot fuel injection or blended additives (diesel, amyl nitrate, dimethyl hydrazine), but reported that"compatibly of ammonia and its combustion products with engineering materials and lubricants presents no substantial problem." Deleterious effects on copper-lead bearings were observed and swelling and loss of shape of both rubber and neoprene was noticeable, but materials most commonly used in engine systems "will be adequate for ammonia service."

Pearsall and Garabedian (26) also ran compression ignition investigations on a Continental air cooled diesel combat tank engine, with pilot diesel fuel injection. At 18.6:1 compression ratio a 13 percent improvement in thermal efficiency and 32 percent improvement in power was attained over diesel fuel alone. While this work was successful and included detail modifications to pilot injectors and pistons, it was concluded that better performance would be attained from engines specifically designed for ammonia fuel utilizing high energy spark ignition, high compression ratio, supercharged, and with (near) spherical combustion chambers.

W. Cornelius, et al (27) at General Motors Research Laboratories investigated ammonia fueled spark ignition engine performance, with similar conclusions to those above, specifically: "An ammonia.....engine can be developed with performance equivalent to that obtained in current automotive gasoline engines." Development of ammonia evaporation, dissociation, and fuel metering systems are described as feasible. Figure 8 shows the improved thermal efficiency obtained by partial ammonia dissociation, and Fig. 9 the power output improvement with supercharge and increasing compression ratios.

Exhaust pollutants from ammonia combustion will not include hydrocarbon products or carbon oxides, but direct ammonia emissions (~2 1/2 percent unburned) and oxides of nitrogen will occur. Cornelius, et al (27) found NO_x concentrations similar to gasoline ~1200 ppm at 30 percent efficiency decreasing at lower engine efficiencies. Sutton and Starkman (28) found: "At maximum output more oxides of nitrogen (4.8 vs 3.3 x 10^3 ppm) are produced by combustion of ammonia than with hydrocarbon fuels," (but less at equivalence ratio > 0.9), and "disproportionate quantities of nitrogen oxides.....a probable result of direct production of NO in the ammonia pyrolysis scheme." While these ammonia combustion effects are of concern, they may conceivably be considerably reduced via catalytic exhaust equipment, with the slipped (unburned) ammonia reacting with the NO_x. In current utility power plant developments 80 to 90 percent NO_x removal has been

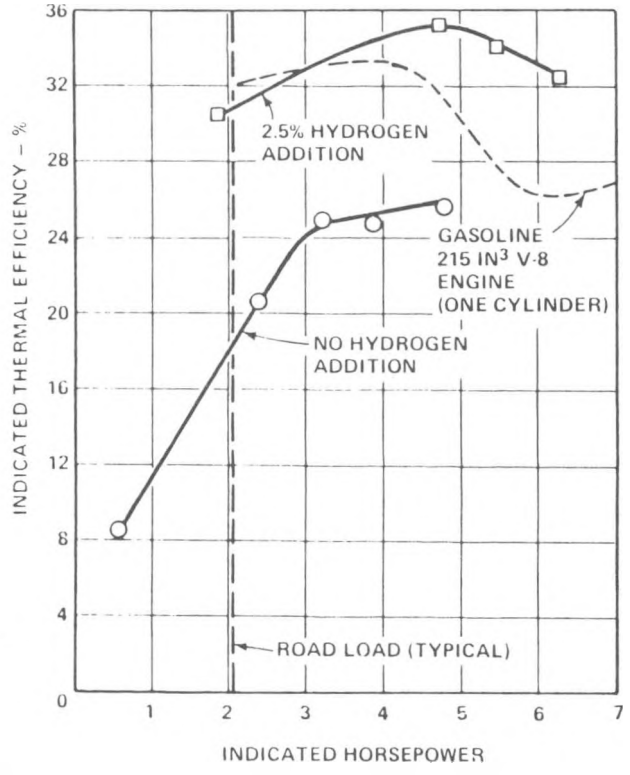


Fig. 8 Spark ignition engine tests ammonia fuel efficiencies 9.4:1 compression ratio.

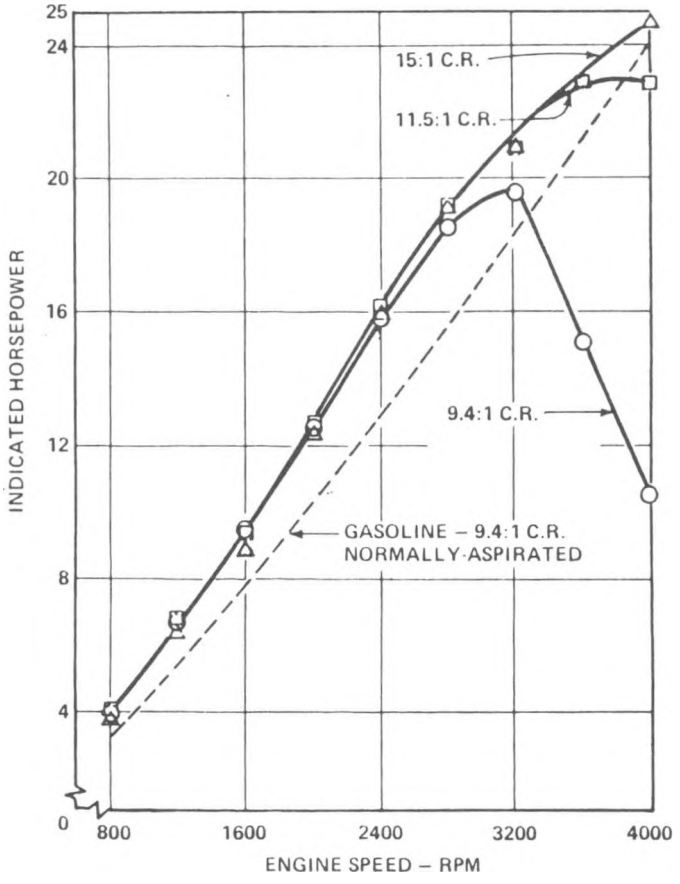


Fig. 9 Spark ignition single cylinder engine tests performance with ammonia fuel 18" Hg supercharge.

Table 1

Comparison of vehicle storage requirements for various fuels

Fuel Grade	Density, lb/ft^3 (60°F)	Energy Density Btu/lb	Energy Density Btu/ft^3	Amount Equivalent to 20 gal Gasoline gal	lb (fuel)	lb (tank and fuel)
Typical gasoline	43.8	19,080	835,700	20.0	117	150
Methane gas (CH_4, 2000 psia)	7.09	21,500	152,400	110	104	1100
Methanol (anhyd CH_3OH)	49.7	8,640	429,400	38.9	258	310
Ethanol (anhyd C_2H_5OH)	49.6	11,550	572,900	29.2	194	235
Liquid hydrogen (at NBP)	4.43	51,980	230,300	72.6	43.0	300
Metal hydride (MG_2Ni-H_x)	110	4,350	479,900	34.8	513	625
Liquid ammonia (108-285 psia)	38.5	8,000	308,000	54.2	279	380

attained via injection of ammonia in the flue gas ahead of a vanadium oxide on titanium oxide catalyst grid (29). The high NO_x emissions noted above are for reciprocating engines where the rapid expansion stroke results in larger than predicted quantities, and NO_x emissions could be considerably less for steady state-continuous combustion systems for ammonia, e.g., direct heating, stirling engines, etc., than hydrocarbon combustion products.

Requirements for Ammonia Fuel

Ammonia is a storable fuel and has been used as a rocket fuel in addition to uses described here. Although not classed as a systemic poison, the liquid and vapor are both caustic and can be toxic. The odor threshold, for most people, is well below the 100 ppm maximum allowable 8 hour exposure limit. Although ammonia is commonly handled in specialized industrial and fertilizer production, usage as a fuel, particularly vehicular use, will require specific safety considerations and vehicular equipment development for practical use. For most bulk storage and transport, e.g., ships, barges, road vehicles, codes and regulations exist which would require extension or additions for the uses considered here.

For vehicular applications, Table 1 compares the tankage required for comparable range (20 gallons gasoline equivalent) for possible OTEC produced fuels. The added weight and volume for ammonia may be offset by possible improvements in overall efficiencies of ammonia engines, and could be of considerably less consequence for larger vehicles, e.g., trucks. For industrial power, e.g., gas turbines, and particularly if ammonia fuel cells are developed, the possible fuel efficiencies could well outweigh minor cost differentials in specific area economies. Ammonia fuel usage for ships would appear improbable except for specific service such as OTEC-ammonia fuel depot transport. Comparable ships requirements are shown in Table 2.

Table 2

30,000 DWT tanker 20,000 HP 700 hrs (12,000 NM)

	Fuel Weight	Fuel Storage Volume
Hydrocarbon Fuel Gas Turbine	3,000 tons	120,000 ft^3
Ammonia Gas Turbine	6,000 tons (-28F)	360,000 ft^3
Ammonia Fuel Cell	3,000 tons (-28F)	180,000 ft^3

ACKNOWLEDGMENTS

This study utilizes previous work in the DOE-OTEC program, and the cited excellent and extensive work of many others to whom the authors extend their appreciation, and which may now have new relevance.

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8th Ocean Energy Conference
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June 1981

OTEC POWER APPLICATIONS TO DEEP OCEAN MINING

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1.0 Introduction

Deep Ocean Mining (DOM) and OTEC are two areas of developing ocean technology which exhibit interesting parallels. Commercial development problems include a developing and untried legal-regulatory regime, and the need to show technical economic feasibility at large scales. The best resources for both OTEC and deep ocean mining occur in the equatorial regions of the world generally between 20°N and 20°S.

There are a number of potential advantages for a combined OTEC-DOM system that warrant its consideration. As already mentioned, the best OTEC and DOM resources known occur in the same areas, Figure 1. There are other valuable nodule resources in the Central and South Pacific and in the Indian Ocean which also represent favorable OTEC sites. Both floating and island shelf-mounted OTEC's could potentially be used to process nodules. Processing in the region of mining can reduce transportation and waste disposal costs. OTEC plants in islands settings are projected to achieve an early competitiveness with power plants powered by imported oil, hence, the cost of power does not necessarily disadvantage this approach. Island communities in the area also acquire an exportable commodity, the nodule-derived metals, which can pay for the OTEC power and other imported goods. The island economies could expand further in the direction of producing fabricated items from the metals. Adding value to the metals in this manner, further expands the economic potential of the OTEC processing of nodule-derived metals.

2.0 Discussion

There are many potential processing routes for manganese nodules. These can be divided into two categories: (1) hydrometallurgy, and; (2) pyrometallurgy. These major alternatives can be summarized as follows:

Hydrometallurgy

- Reduction ammoniacal leach
- Cuprion/ammoniacal leach
- High temperature sulphuric acid
- Reduction/hydrochloric acid

Pyrometallurgy

- Smelting/electrowinning

The hydrometallurgical processing approaches generally require large quantities of fresh water-on the order of $3m^3$/ton of nodules. A plant designed to produce three metals, nickle, copper, and cobalt, are generally found to be most economic at a 3 million tons of nodules per year capacity, while the economic size for a four metal plant, nickle, copper, cobalt, and manganese, is about 1 million tons of nodules per year. Hence, it is clear that potentially large quantities of process water are required. Many of the island sites which are most favorably located with respect to the nodules are low in elevation and have low rainfalls. There are exceptions to this, Tahiti for example. However, to maximize the potential locational advantages, in this paper we will consider the pyrometallurgical approach which requires no process water and can use sea water for cooling.

Pyrometallurgy Process

The simple block diagram of the pyrometallurgy process, Figure 2, shows that the process can be logically divided into two major steps: (1) smelting at the OTEC island site; (2) processing/utilization of the plant outputs at major industrial sites. Manganese in the form of ferromanganese, copper, nickle, and cobalt can be recovered from nodules by a smelting process. The smelting process produces a slag from which ferromanganese and a separate value metal alloy matte consisting of copper, nickle, cobalt and sulphur are recovered. This alloy matte can be shipped in granular form to existing industrial facilities for electro-winning to produce cathode quality metals. The ferromanganese can be shipped to different industrial facilities for use in steel making or further processing. The smelting approach is high in energy consumption, and hence, is generally high in operating cost. However, it involves low technical risk in that it is insensitive to the peculiarieties of nodule chemistry. Electric furnace technology is well established. Subsequent to smelting, the processing steps are compatible with existing processing plants. The smelting phase uses cooling water but insignificant fresh process water. The cooling water can be obtained from the OTEC plant warm water inlet and subsequently cycled through the heat exchangers for partial recovery of waste heat.

The processing approach allows significant flexibility for the organization of the mining effort, Figure 3. The products of the island site, ferromanganese and high-value metal matte, can be shipped to separate industrial facilities for further use. One of the difficulties in conventional processes for producing four metals is that there are no large steel mills on the West Coast of the U.S. The approach considered here would allow shipment of the ferromanganese to Japan for use in steel making and the high-value metal matte to the U.S., or Peru, Chile, or other Latin American countries.

The island processing approach offers opportunities for reduction in system costs and other advantages. These may be summarized as follows:

- Transport requirements to the plant will be associated with transport of coal and consumables.
- Island OTECs must be located in areas with steep bottom topographies. Thus, it will also provide a convenient site for disposal of processing tailings by outfall.
- One, possibly two, specialized transport capable of transferring ore at sea from the mine ship to the transport, is required between the mine ship and the island site (rather than three for a west coast located plant).
- At least partial logistic support can be provided for the mine ship at the island site.
- A 56 MWe OTEC plant is required. This is a reasonable size for an early OTEC plant.
- New plant requirements can be restricted to the smelting/reduction phase only, and existing plants can be used for the subsequent processing steps. This reduces initial capital costs.
- Plant outputs can be marketed from the island site. Thus, the costs of transport of plant outputs can be assumed by the customer(s).

3.0 Conclusions

This paper has briefly reviewed the possibilities for processing manganese nodules using OTEC power. The key aspects of a pyrometallurgical processing approach have been identified, however, an economic analysis remains to be done. Some major preliminary conclusions resulting from this study can be stated as follows:

- OTEC sites are highly compatible with DOM processing requirements
- The OTEC approach to nodule processing should be considered after at least one of the two technologies has been proved.
- Transport fleet requirements are greatly reduced - common bulk carrier for onshore-island, transport with de-watering equipment for mine ship to island are required.
- Ferromanganese can be transported to steel plants and sulfide concentrate to existing facilities (in U.S., Japan, and South America) which may not be located at the same place.
- Island to shore concentrate and ferromanganese transport functions and costs can be assumed by metals buyers.
- Pyrometallurgy provides a practically inert waste product for at sea disposal.

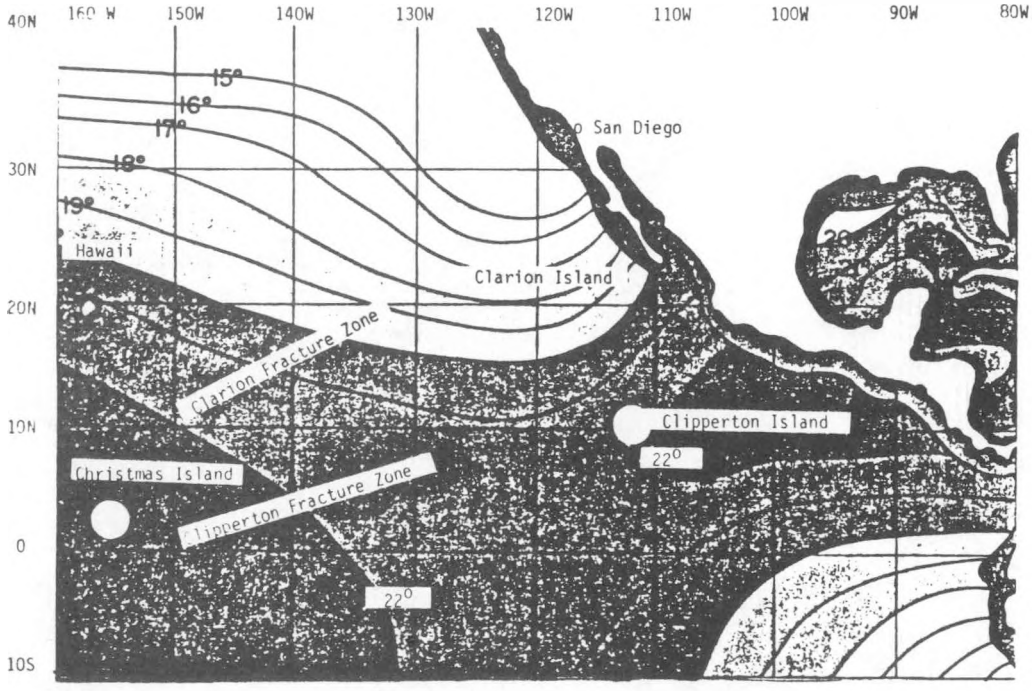


Figure 1. Some Possible Sites for OTEC Processing of Nodules

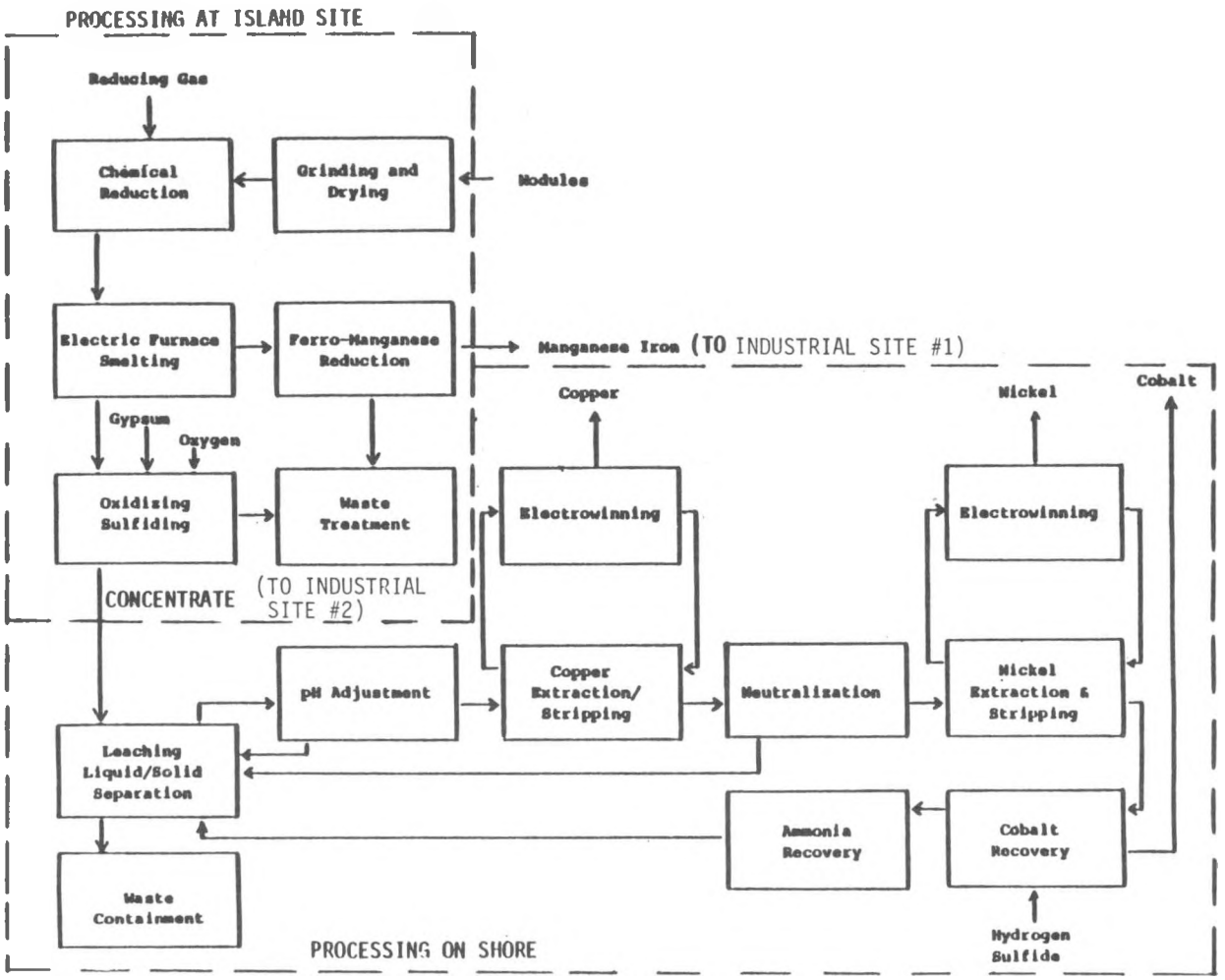


Figure 2. Pyrometallurgical Process - Simplified Block Diagram

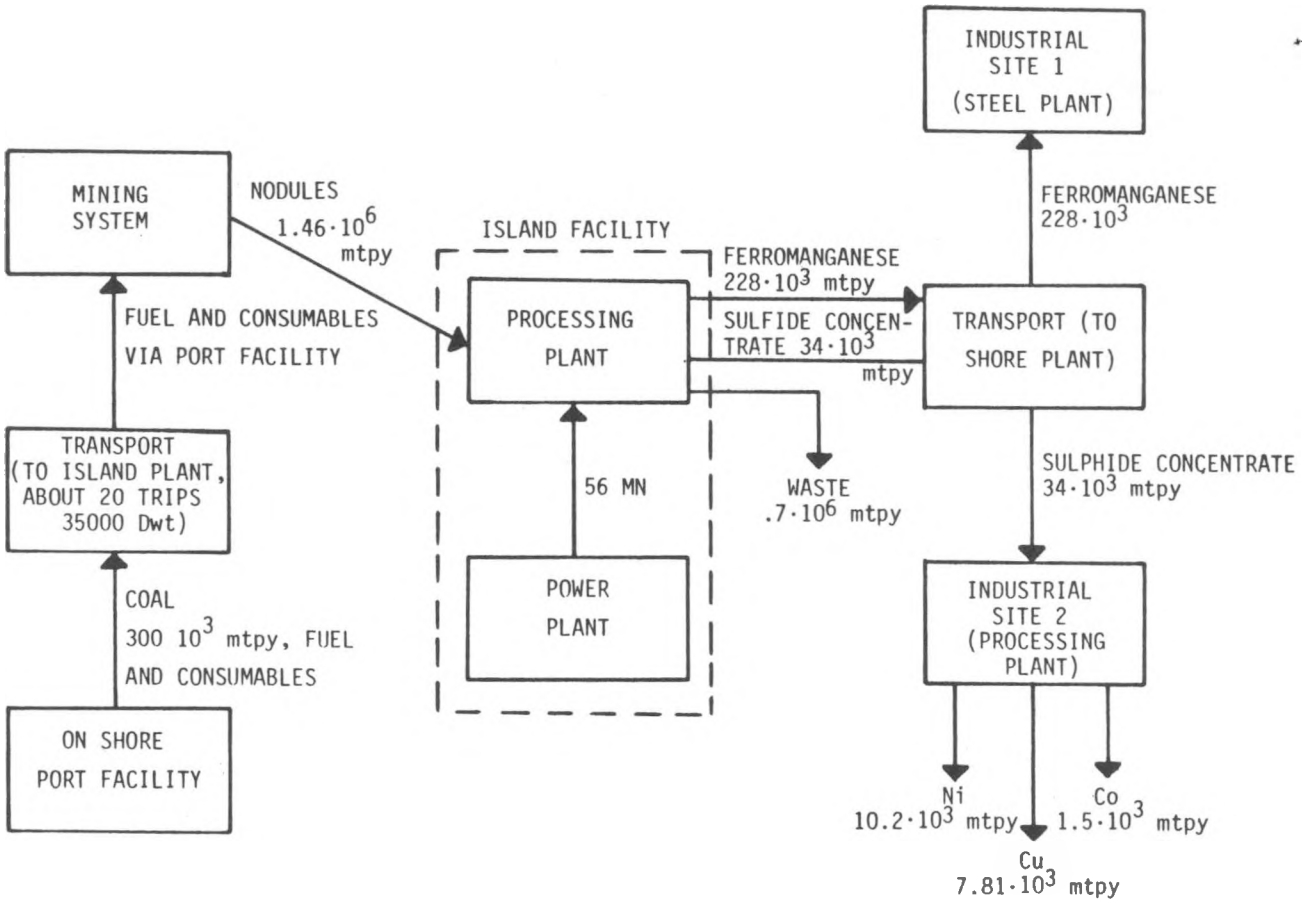


Figure 3. Overall Material Balance

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ADVANCED WATER ELECTROLYSIS TECHNOLOGY FOR EFFICIENT UTILIZATION OF OCEAN THERMAL ENERGY

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ABSTRACT

One of the major concerns with ocean thermal energy is how the resultant power can best be utilized in view of the remote location of the source from power demand centers. Hydrogen in the form of ammonia represents one promising solution to this problem since it can be produced on board an OTEC plantship and transported to any point on the globe.

Under a program sponsored by the Department of Energy and several electric and gas utilities, the General Electric Company is developing the solid polymer electrolyte water electrolysis technology which offers high efficiency and low cost in a compact system suitable for installation in an OTEC plantship.

This paper describes the solid polymer electrolyte development program which has the potential for demonstrating a 20 MCFH module by 1984.

A conceptual 40 MW system configuration, utilizing multiple 20 MCFH modules, is described for application to a pilot OTEC plantship. The potential of further scale-up to full scale (i.e., ≥350 MW) OTEC plantships is also discussed.

INTRODUCTION AND BACKGROUND

The major portion of the ocean surface which has suitable conditions for practical ocean thermal energy recovery is sufficiently remote from land areas to make it impossible to use direct cable to transmit the energy to a load center. Therefore, for most effective utilization of the ocean thermal resource, it will be necessary to convert the electrical energy into some form of transportable synthetic fuel, or to use it for production of some energy intensive product which can be accomplished at sea. Ammonia appears to be one of the most attractive products since it can be produced from the raw materials available at sea, and can be used either as a synthetic fuel or as chemical feedstock for the fertilizer industry.

Whatever type of synthetic fuel is produced, however, the first step beyond the generation of electrical power in the OTEC system itself would be the use of that power to produce hydrogen by the electrolysis of water. Because of the capital intensive nature of the OTEC plant, the efficiency of the electrolysis process is critical to the overall economics of this energy concept. The solid polymer electrolyte technology being developed by the General Electric Company not only offers one of the highest efficiency water electrolyzers available as shown on Figure 1, but will also provide a compact system which will require a minimum amount of deck space on board the plantship.

This technology was originally developed for use as a fuel cell to provide electrical power on board spacecraft. The initial development for water electrolysis was also as a potential spacecraft system to generate oxygen in a regenerative life support system for the crew's metabolic consumption. The development of a larger system to perform the same function for the crew on board nuclear submarines was subsequently contracted for by the U.S. Navy in 1975 and is expected to begin sea trials in 1983.

Because of the higher efficiency and potential cost savings which the solid polymer electrolyte technology offers over conventional electrolyzers, a Department of Energy contract was awarded in 1975, supplemented by General Electric's in-house development effort, for the adaptation and further development of this technology for use

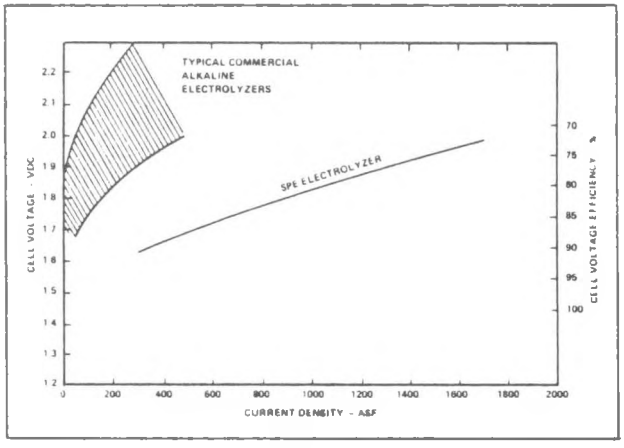


Figure 1. SPE Electrolysis Cell Performance

in large scale hydrogen production applications associated with energy storage and advanced energy systems. This program was subsequently augmented by additional funding support from the Niagara Mohawk Power Co. and the Empire State Electric Energy Research Corporation for complementary technology development tasks.

An initial task under this program was a preliminary design study of a 58 MW system. On the basis of that study the general goals for the development program were established as follows:

- overall system efficiency: 85-90%
- system capital cost: (battery limits) $\leq$\$170/kW (1981 dollars)
- system life: 20 years
- scale-up: 2.5 ft^2, 10 ft^2
- demonstration: multi-MW demonstration system

The milestone schedule for the program and an indication of the status as of March, 1981 is shown in Figure 2.

Systems up to 2000 SCFH have been tested to date, and the program was to result in a 20,000 SCFH capacity demonstration system in 1984. However, recent funding cut-backs by DOE have left the schedule for completion of the larger system undefined at the present time.

The 20,000 SCFH module would form the basis for a 320,000 SCFH system to be proposed for the OTEC pilot plantship.

SPE electrolyzer cell/module design

The solid polymer electrolyte is a thin sheet (5 to 10 mil thickness) of a sulfonated fluoropolymer (NAFION ®). It is a high strength plastic material which, in the SPE cell, serves as the sole elec-



Figure 3. 2 1/2 Ft^2 Solid Polymer Electrolyte Membrane Electrode Assembly

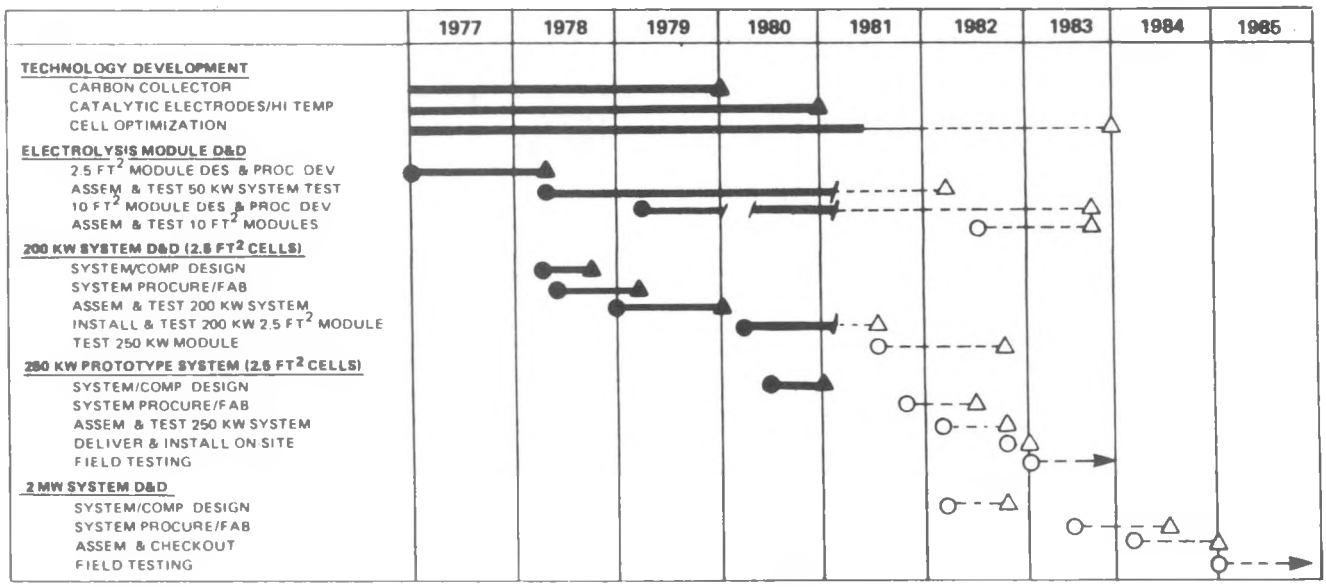


Figure 2. Large-Scale SPE Electrolysis Development Program - Major Milestones

trolyte (there are no acid or caustic liquids in the system), and also forms a rugged barrier between the hydrogen and oxygen chambers. The electrodes consist of a thin catalyst layer bonded to the surfaces of the plastic sheet as shown in Figure 3, the completed cell being referred to as a membrane-electrode (M&E) assembly.

This assembly is supported between two current collector/separators as shown in Figure 4. These collector/separators are solid structural members molded from a mixture of a fluoropolymer plastic and graphite such that they combine the physical properties of the plastic with the electrical conductivity of the graphite. Thus they serve as a bi-polar plate to electrically interconnect the anode of one cell with the cathode of the next cell while also serving as a separator between the product hydrogen and oxygen gases. Flow passages for the process water and the product gases are molded directly into the separator plates, as well as internal manifold ports to provide inter-cell fluid distribution.

In order to prevent the flexible membrane from deflecting into the flow passages, a rigid sheet of porous material is used as a support between the membrane and the collector/separator.

The cells are stacked up in a bi-polar arrangement and clamped between endplates. Compressive loading to maintain good electrical contact between the various cell and stack components and to assure integrity of the seals around the cell edges and manifold ports is provided by a pneumatically-loaded, flexible diaphragm in each endplate. All fluid connections to the stack are made through fluid-feed plates in the center of the stack.

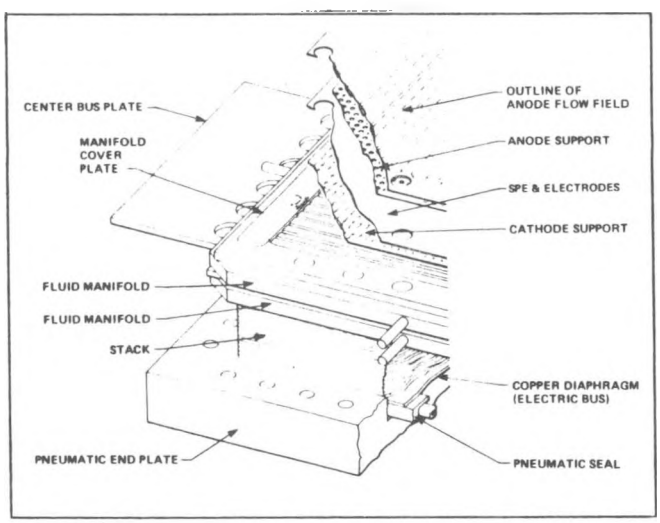


Figure 4. SPE Electrolysis Cell/Module Design Detail

A grounded bus is connected to the center fluid feed plates, which maintains all of the fluid connections at ground potential. The positive bus connection is made to the top endplates and the negative bus connection to the bottom endplate thus placing the two half-stacks electrically in series.

200 SCFH system

The initial scale up of the SPE electrolysis cells has been completed to a cell area of 2 1/2 ft^2 as noted on the milestone chart. Modules comprised of various numbers of cells, from single cells up to as many as 60 cells, have been tested to date under this development effort. The 60-cell module, operating at the normal design point of 1000 amps per square foot, generates more than 2000 standard cubic feet per hour of hydrogen at a pressure of approximately 100 psig. It is shown in Figure 5 prior to being installed in the overall system. Figure 6 shows the completed system installation.

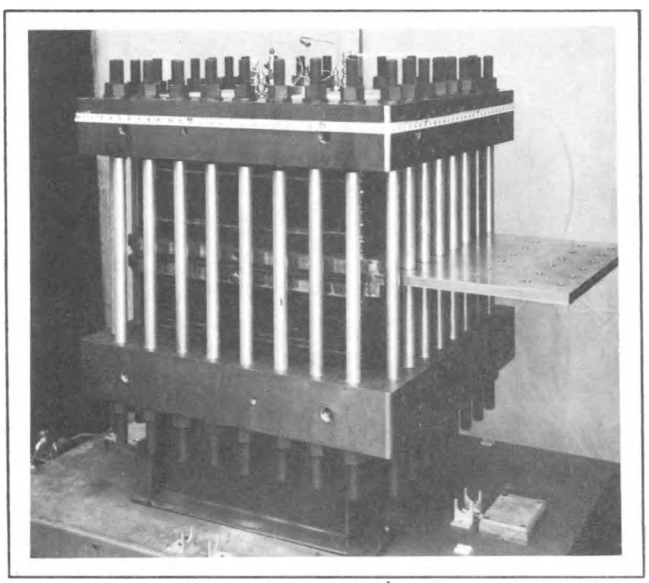


Figure 5. 60-Cell, 2000 SCFH SPE Electrolysis Module

The 60-cell module was operated for more than 700 hours at an average temperature of 205°F before the system shut down due to a spurious instrumentation signal. As overall system performance and current collector manufacturing optimization were both under active study through concurrent program tasks it was decided to postpone further testing on this particular system until the results of this parallel work could also be incorporated.

Analysis of cells removed from the 60-cell module indicated that a major contributor to the higher-than-anticipated

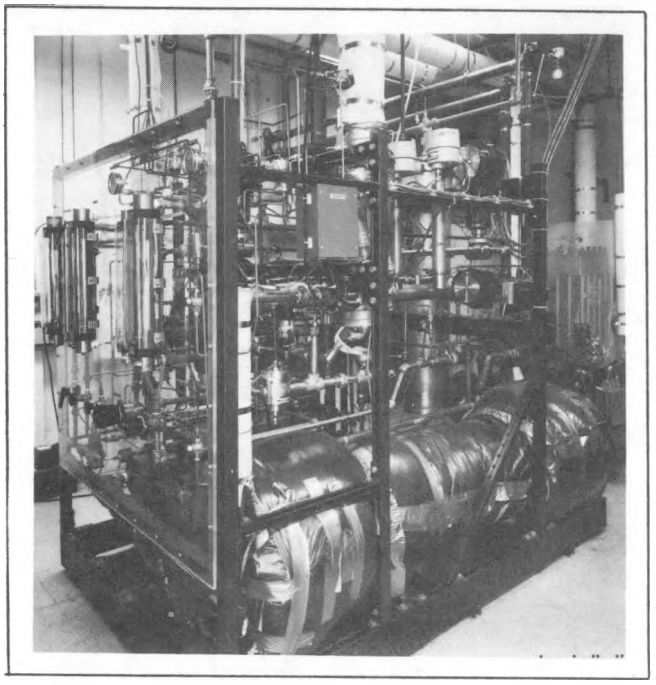


Figure 6. 2000 SCFH SPE Electrolysis Development System

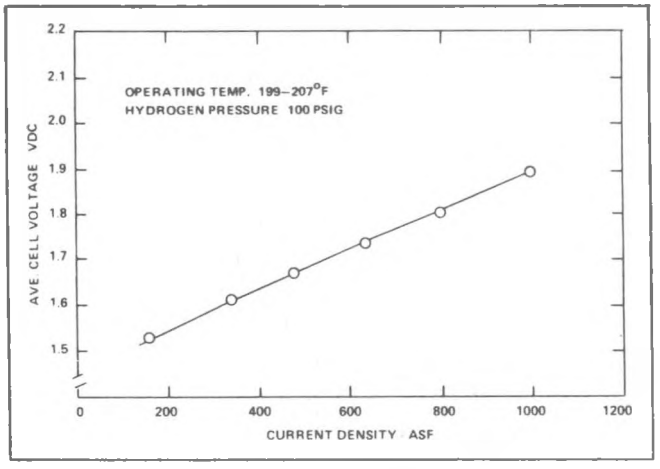


Figure 7. 2000 SCFH Module - Average Cell Performance

voltage was the contamination of the cathode by amines emanating from the anion water purification beads in the polishing deionizer. To confirm this analysis, a section was cut out from one of the M&E's and tested in laboratory cell hardware on amine-free water. The initial voltage at 1000 ASF, 180°F was 1.95V. Over a short period of operating time, the performance improved markedly to a voltage of 1.81 V at the conclusion of the test.

Another contributor to the higher-than-projected voltage in the 2 1/2 ft^2 cells is somewhat high ohmic resistance in the current collector/separators as compared with the calculated values from 3" x 3" cell testing. The corrective action for this difference will be adjustment to material composition and processing techniques. Some changes in the manufacturing processes used in making the separator have already been implemented as a result of the investigation and has already resulted in some improvement in the resistances.

10 ft^2 cell scale-up

The design of the 10 ft^2 cell was completed during 1979. A rectangular cell configuration was selected in order to maintain the same oxygen side flow configuration as the 2 1/2 ft^2 cell and to conform to material availability and manufacturing process considerations. The release of tooling and fixtures for fabrication of the 10 ft^2 collectors and M&E's however, has been held up due to the questionable availability of Department of Energy support for this phase of the scale-up. 140 of the 10 ft^2 cells will comprise the 20 MCFH module.

Although the 10 ft^2 cells have not yet been fabricated, initial M&E's for even larger cells ($\sim$37 ft^2) have been fabricated under a parallel program in which SPE cells are being developed for electrolyzing brine for production of chlorine and caustic. One of these M&E's is shown in Figure 8. The success of this project has demonstrated the capability of using SPE cells for systems of very large capacity.

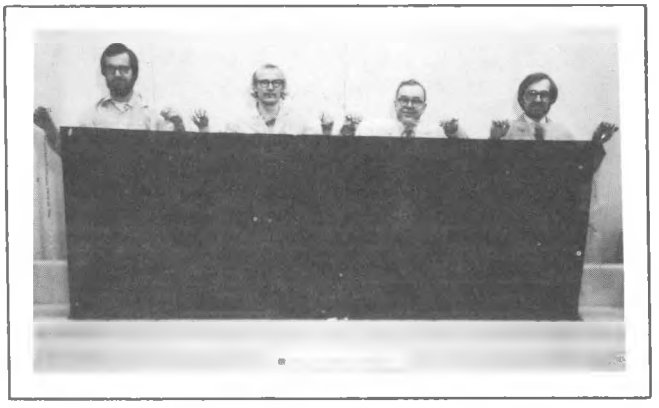


Figure 8. 37 Ft^2 Membrane-Electrode Assembly for Brine Electrolysis

320 MCFH system for pilot plantship

Since the 20 MCFH module is the largest one planned to date under the Department of Energy development program, it would be proposed as the basic modular building block for the 320 MCFH system required for the pilot plantship program. More than one module can be used to form a modular subsystem if desired, and a trade study should be made to determine the most suitable number and size of subsystems.

Figure 9 shows one possible subsystem configuration, incorporating two of the 20 MCFH modules which occupies a floor space of approximately 450 square feet. The total equipment weight for this subsystem would be in the order of 62,000 pounds. Eight of these subsystems would be used for the pilot plantship installation.

A fluid schematic for the 2-module subsystem is shown on Figure 10.

Electrolyzer module for commercial size OTEC plantship

The full scale commercial OTEC plantship will probably require something in the order of 2 to 3 million SCFH of hydrogen generation capacity. It is proposed that the 37 ft^2 cell size shown in Figure 8 would be used for such an installation with a modular building block having a rating of perhaps 100 MCFH.

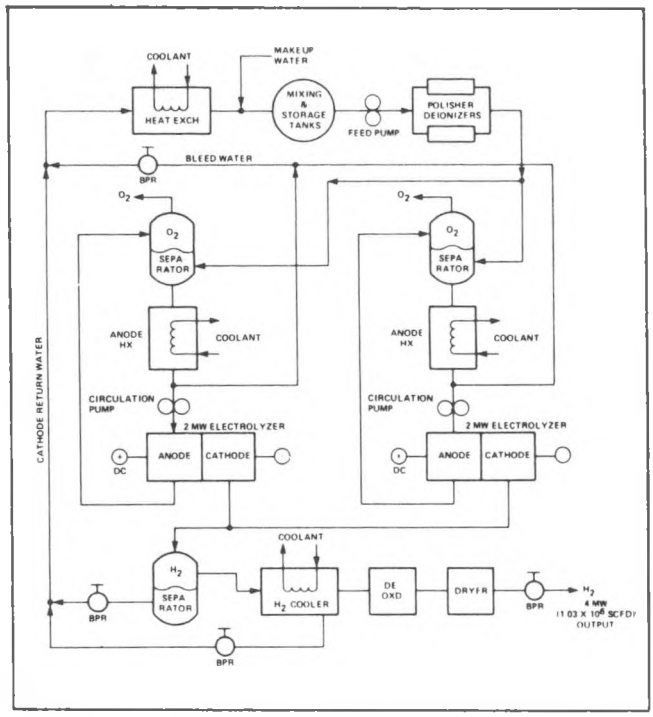


Figure 10. Fluid Schematic Diagram for Two-Module SPE Electrolyzer System

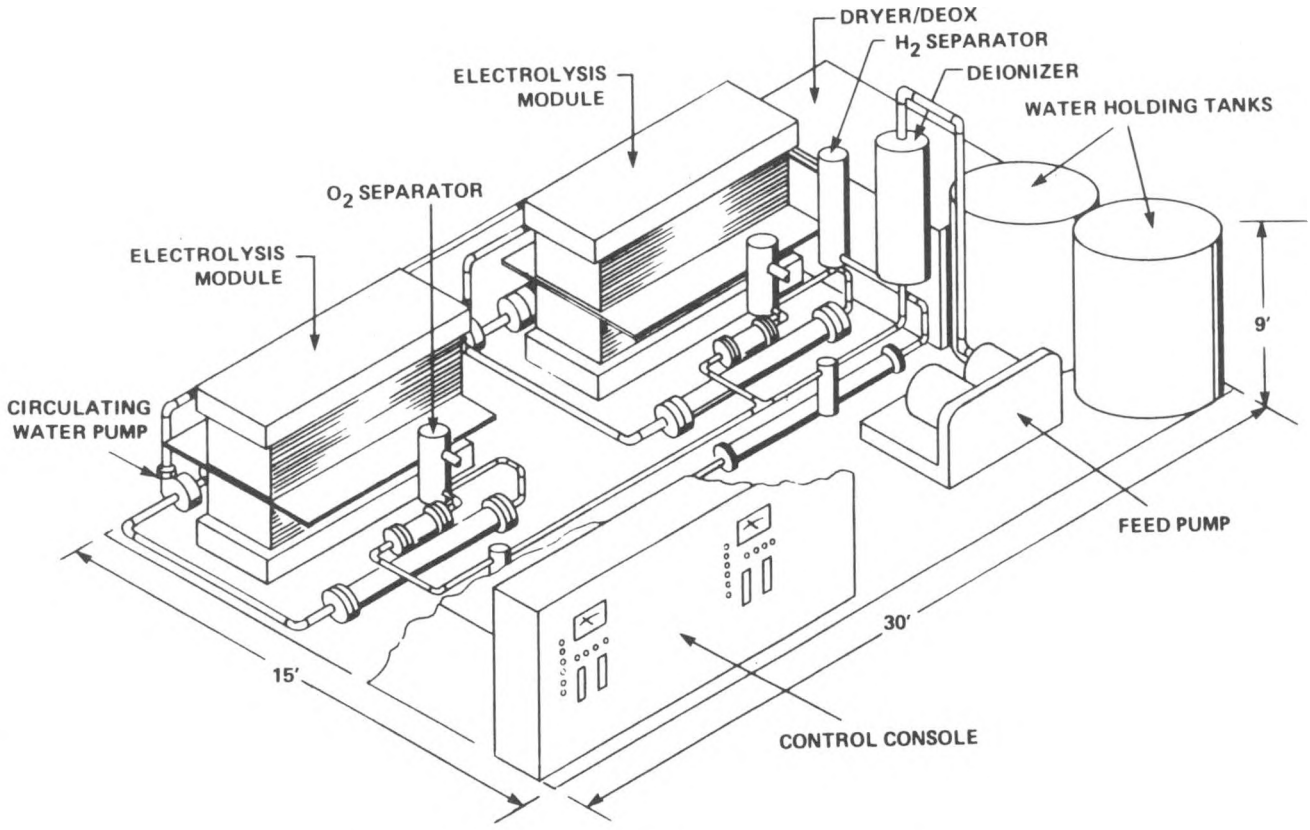


Figure 9. 40 MCFH SPE Electrolyzer System

8th Ocean Energy Conference
Washington, DC
June 1981

ADVANCED ALKALINE ELECTROLYSIS SYSTEMS FOR OTEC

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ABSTRACT

Several of the more attractive options for physically transporting OTEC energy to the market place involve electrolytic hydrogen as a key process element. The status of water electrolysis technology at Teledyne Energy Systems as pertained to OTEC application was discussed in a paper presented at the 6th Ocean Energy Conference in 1979. This paper updates the status of the technology at Teledyne Energy Systems and re-examines the economics and design tradeoffs for OTEC in light of the situation today.

Over the ensuing years, the majority of the research at TES has gone directly into improving the basic process efficiencies. Systems work has been oriented towards the development of a new hydrogen generator product line with capacities of up to 1500 SCFH (150 KW_e). Although this new line of industrial generators is much smaller than that required for OTEC, the basic process loop is representative of large equipment and is directly scalable.

More recently, Teledyne Energy Systems developed a comprehensive economics computer model for the Department of Energy to allow a true benefit evaluation of research products. As has been noted by several investigators, given an electrolysis module design and fixed financial constraints such as operating cost rates and capital expense consideration, there is a minimum hydrogen cost when this value is calculated as a function of the module current density. The value of this hydrogen cost as well as the optimum module design current density is a function of many factors, and the Model for Alkaline Water Electrolysis Systems (MAWES) attempts to consider all.

The MAWES Program was restricted to system sizes less than 1 MW power input. Work is now underway to modify the program so that systems up to several hundred MW can be evaluated.

In any energy application the end cost of the product is of paramount importance whether it be for an industrial application or energy conversion scheme such as OTEC. The cost must consider the initial investment, cost of capital, and operating costs, and each of these factors influences the design of the equipment.

This paper discusses an alkaline electrolysis system for a 40 MW_e OTEC. Basic systems design considerations are discussed along with the relative economic impacts. Scale-up beyond 40 MW is also addressed.

INTRODUCTION

The conversion of ocean thermal energy to a hydrogen-based product is one of the more attractive options for investors in this resource, particularly where the plant ship location is more than a hundred miles from shore. In this scenario, the conversion step to hydrogen is most effectively accomplished by the electrolysis of water, and the economics of the situation demand that this be accomplished for the lowest cost in terms of dollars per unit product. The status of large alkaline electrolysis systems in the United States with regard to ocean energy conversion was discussed in a paper[1]* presented at the 6th OTEC Conference in June 1979. It is the objective of this paper to update that information in light of the ensuing years and discuss some of the program requirements that would be required to put a large, high-performance alkaline electrolyzer on a 40 MW demonstration ship before 1990.

TECHNOLOGY SCALE-UP STATUS

Teledyne Energy Systems has been manufacturing alkaline electrolysis equipment for the specialty gas market since the early 1970's. The largest single unit currently offered is the HS-200 shown in Figure 1. This unit will deliver up to 400 SCFH of hydrogen continuously on demand and has been used in multiples to satisfy individual applications up to 2000 SCFH. The HS generators are automatic systems, designed to deliver high purity gas to the customer's process manifold at pressures up to 100 psig, on demand. They are strictly industrial machines and in this size range efficiency is not usually as important to the customer as low initial cost and operating convenience. The overall system efficiency of the machines is about 55 percent, not good enough for an energy conversion or storage application.

Between 1974 and 1979, Teledyne Energy Systems conducted an in-house program to design and develop a large alkaline electrolysis system product line called

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* Numbers in parenthesis refer to References listed at the end of the paper.

the HP-series (Hydrogen Plant). Figure 2 shows an artist's concept of the type and size of plant under consideration. Driven at that time by a combination of the "natural gas shortage" and the whoopla of a hydrogen economy, Teledyne developed a first generation computer analysis program to evaluate the economics of large equipment[2] and built and tested the prototype HP system shown in Figure 3. This new large cell represented a ten-fold jump in active area, i.e., from three quarters of a square foot (HS technology) to eight square feet. The prototype, with four of these cells, was successfully tested in the 1977-1978 time frame. Shortly after this test period, as the gas crisis eased, the effort was mothballed in favor of the expansion of smaller industrial electrolyzer equipment. In-house research and development efforts were re-ordered to augment and support a Department of Energy program to improve operating efficiency of alkaline cells.



Figure 1. HS-200 Units Acceptance Testing

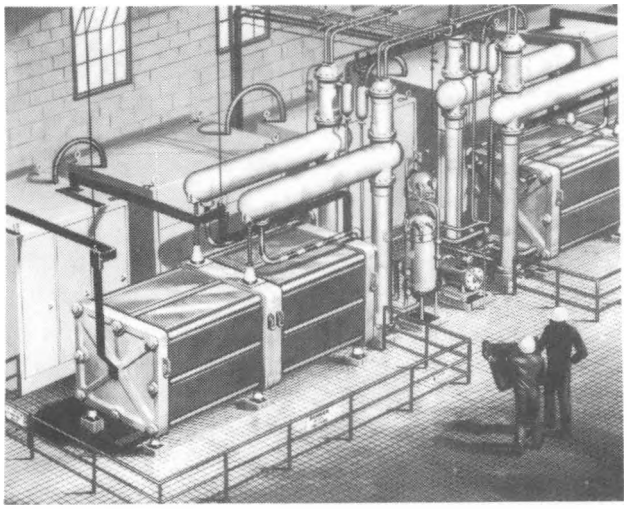


Figure 2. Hydrogen Plant Concept

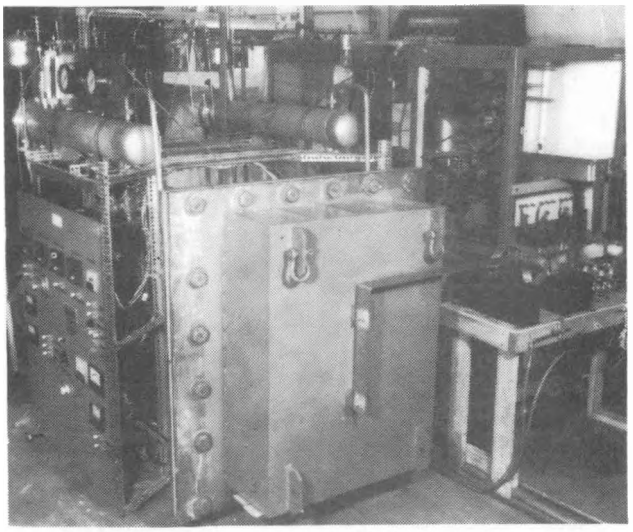


Figure 3. Four-Cell HP Prototype

At the present time, there is essentially no program in the United States to develop large, cost-effective electrolytic hydrogen generators of the size required for a commercial ocean thermal energy plant. The original work begun in the 1970's has been re-ordered toward smaller unit sizes, i.e., < 1MW, and, aside from some work in the SPE area, there is no significant government support for capital cost reduction or scale-up design.

For the past two years, Teledyne Energy Systems has been working with the Electric Power Research Institute (EPRI) to develop an electrolytic Hydrogen Generator System (HGS) specifically for electric utility use. Like the HS-series equipment, the HGS is designed to deliver high purity hydrogen directly to the user's manifold automatically on demand at pressures up to 100 psig. The HGS will be more efficient than the HS, will require less routine maintenance, will be easier to service, and will have significantly more growth potential.

The HGS is a three-cabinet system as shown in Figure 4. The main cabinet houses all of the gas and liquid handling loops and, of course, the electrolysis module. The HGS is designed to operate on three-phase electrical power, and the second largest cabinet houses the AC-to-DC rectification equipment. The smaller console is the instrumentation and control cabinet. The mechanical schematic for this new system is shown in Figure 5. Unlike the HS equipment where electrolyte is only circulated through the oxygen cavities of the module, the HGS is a dual-circulation system and is representative of that required for large multimegawatt applications such as an Ocean Thermal Energy Conversion plant.

The production prototype HGS (Figure 6) is now in a checkout phase. In-house testing is scheduled to begin in the middle of June and will continue until the fall at which time it will be shipped to a host utility for extended field testing. The initial prototype electrolysis module is sized to deliver up to 500 SCFH (98 cells) which will satisfy most utility installations, however, the basic

process loops and frame have been designed to accommodate a module with a capacity of up to 1500 SCFH. And, although the HGS is tailored to electric utility requirements, it will be perfectly satisfactory for most other industrial application. The HGS should satisfy applications requiring up to 6000 SCFH using multiple units. Assuming that the prototype tests are successful, the HGS series should be ready for the general market in early 1982.

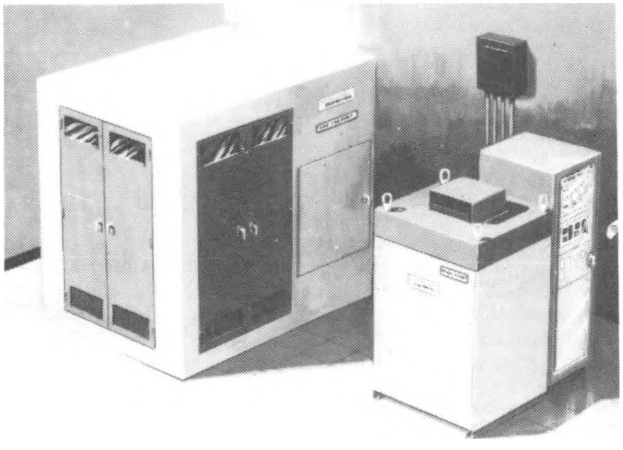


Figure 4. HGS Generator Concept

EFFICIENCY IMPROVEMENT STATUS

Teledyne Energy Systems has been working with the DOE/BNL since 1976 to improve the operating efficiency of alkaline solution water electrolysis cells. The program has been oriented toward the identification of materials that can withstand the alkaline environment at 125 C or above and electrodes that exhibit greater catalytic activity and yet are cost-effective. To date, the program has been successful in identifying a cathode technology that is both more efficient and cost effective.[3] Figure 7 shows a comparison of three of the cathodes that have been studied over the past several years. The first is pure nickel screen which represents the baseline state of the art. The TES-C-110 cathode is a very lightly platinized cathode structure developed by Teledyne Energy Systems, while the C-AN technology was developed by the British Petroleum Research Corporation and employs no noble metals. The C-AN cathode is obviously superior, performance-wise, and testing to date shows that it is stable in hot alkaline solutions. In fact, TES has elected to introduce the C-AN technology in the HGS product series, discussed earlier.

Comparable improvements in anode structures have not been demonstrated, although the latest candidate, identified only as the A-380 catalyst, is showing considerable promise in initial screening tests. Figure 8 shows a comparison of some of the anode technologies tested over the past few years. The A-380 is obviously better than anything tested to date, however, much remains to be done before it can be judged commercially acceptable, particularly with regard to stability and life.

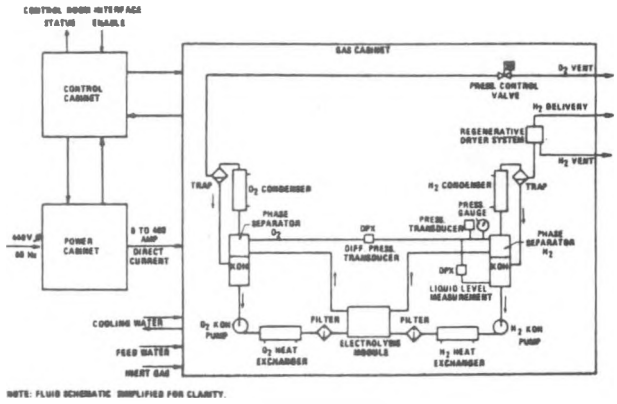


Figure 5. HGS System Schematic

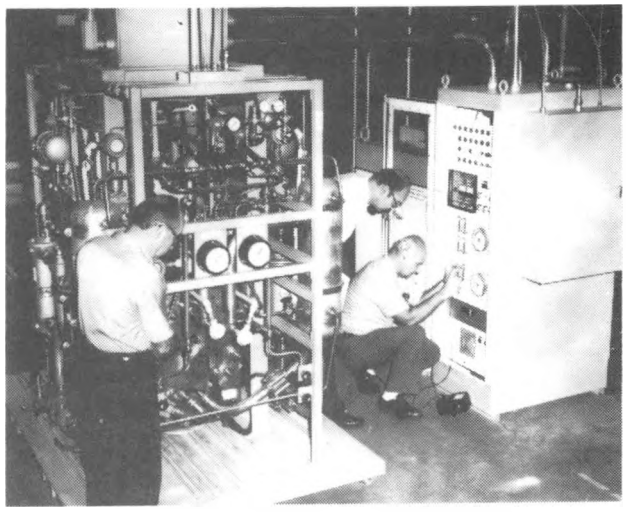


Figure 6. HGS Prototype Checkout

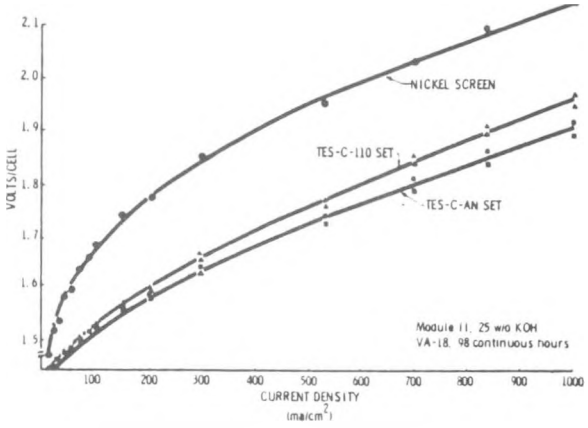


Figure 7. Comparison of Improved Cathode Technology, 100°C

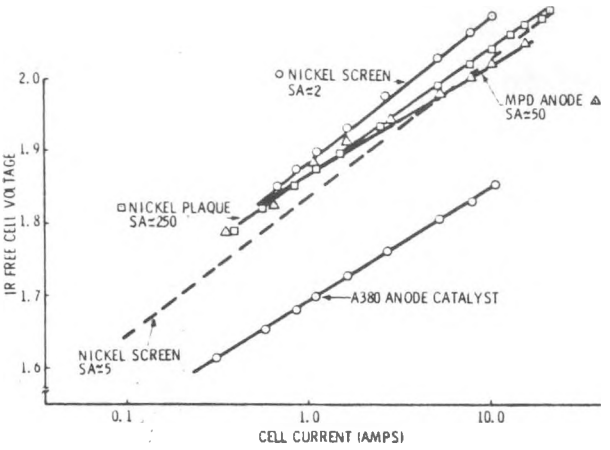


Figure 8. Comparison of 50 cm^2 Experimental Anodes, 57°C, Single Irriguous Test Cell & Fixtures, 25 w/o KOH, 4 Hours on Test

The use of these advanced electrocatalysts at process temperatures significantly higher than the 60 to 80°C operating range of commercial electrolysis hardware will probably require an alternate to the conventional chrysotile asbestos separator material. Although several previous studies have suggested that the conventional chrysotile asbestos separator may survive at temperatures above 100°C by controlling the silicate ion concentration of the alkaline electrolyte, there is no conclusive long-term proof and alternate materials are being tested. Candidate materials currently being considered include potassium titanate, polybenzimidazole (PBI), polysulfone, polyantimonic acid (PAM), and various combinations of these materials. The only separator found acceptable to date is one prepared from PBI fibrids, a special particle form of PBI that allows very small-sized pore diameter porous boards to be fabricated. However, the long-term stability and life characteristics of PBI are yet to be demonstrated.

Figure 9 summarizes the progress made to date in the joint Teledyne/Brookhaven program to improve the performance of alkaline electrolysis cells. The

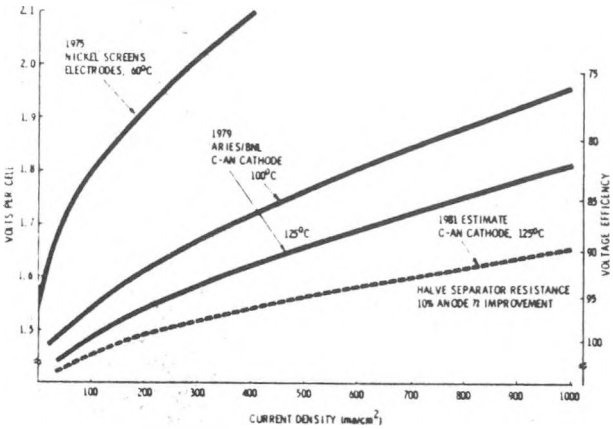


Figure 9. Progress of TES/BNL Alkaline Electrolysis Technology.

dashed curve represents the program goal. At this time, it is estimated that the goal will be achieved with the C-AN cathode, an anode yet to be defined that is roughly 10% better than standard nickel wire mesh, a 50% reduction in separator resistance, and operating at 125°C.

PROJECTIONS FOR OTEC SIZED PLANTS

As mentioned in the 1979 OTEC paper[1], Teledyne Energy Systems was funded to update and expand the simple economic model developed earlier to allow one to optimize an electrolytic hydrogen system to any given set of requirements, in terms of minimum cost of product. This was accomplished and a model dubbed the MAWES program, for Model Alkaline Water Electrolysis System, was created and checked out. The program was limited to system sizes of less than one megawatt by BNL direction because the renewable resource applications of interest to the DOE Advanced Conservation Technologies Group, such as low head hydro, solar, and wind, did not justify large hydrogen plant sizes. This discussion presents techniques for extrapolating the MAWES result to large plants and shows several comparisons with previous prognostications that suggest the technique is relatively accurate.

Prior to any discussion of hydrogen value, Table 1 is provided to allow the various numbers within the text to be interchanged into units for which each reader may be more familiar.

The general factors and components comprising the cost of hydrogen are given in Table 2 as a reference. Although the list is not complete, it does include the major items that contribute to product cost. The total of all others is probably less than 1% of the cost. This list is further subdivided into variable (operating) and fixed (capital) cost factors, each of which is discussed in separate sections.

VARIABLE COST FACTORS

The variable costs are essentially the "operating costs" and for water electrolysis they include:

- Electric Power
- Cooling Water
- Feed Water
- Electrolyte
- Maintenance and Repair Parts
- Labor, including supervision and overhead expenses
- Other (differs from technology to technology)

By far, the single largest operating expense is the cost of electricity, amounting to between 40 and 85% of the total cost depending upon plant size, operation efficiency, and, of course, the cost of electricity. Figure 10 shows the influence of electricity price on the cost of hydrogen as a function of plant operating efficiency.

Table 1. Basic H_2 Conversion Values

$/nM^3[1]	$/100 SCF	$/LB	$/KG	$/GJ	$/MBTU[2]		¢/KWH[3]
1.000	2.831	5.4130	11.936	84.146	88.774	≡	31.96
0.353	1.000	1.9119	4.215	29.715	31.343	≡	10.70
0.185	0.523	1.0000	2.205	15.545	16.397	≡	5.60
0.084	0.237	0.4536	1.000	7.050	7.436	≡	2.54
0.033	0.093	0.1778	0.392	2.774	2.926	≡	1.00
0.012	0.034	0.0641	0.141	1.000	1.055	≡	0.36
0.011	0.032	0.0608	0.134	0.948	1.000	≡	0.34

(1) Gas at 1 std. atm., 68 F ≡ 20 C; 100 SCF ≡ 0.5231 lb H_2.

(2) For $H_2(g.) + 1/2\ O_2(g.) \rightleftarrows H_2O(l)$; $\Delta H^\circ_{25\ C} = -68.312$ Kcal/mole H_2.

(3) 100 % conversion, 1 KWH = 3413 BTU.

Table 2. General Hydrogen Cost Factors

Variable Costs	=	Electricity	=	Module D. C. Auxiliaries (AC) AC→DC Losses Electricity Rate
		+		
		Other Materials	=	Cooling Water Feed Water Electrolyte Inert Gas Maintenance Items
		+		
		Operating Labor	=	Labor Supervision Overhead
+				
Fixed Costs	=	Capital Charges	=	Plant Price Installation Costs Buildings and Facilities Startup Costs
		+		
		Interest(s)	=	Debt Rate, % Debt Financed Equity Rate, % Equity Financed - Tax Depreciations, etc.
+				
Time Trend Costs	=	Inflation	=	Labor Materials Electricity
		+		
		Repairs	=	Components Modules Downtime Costs

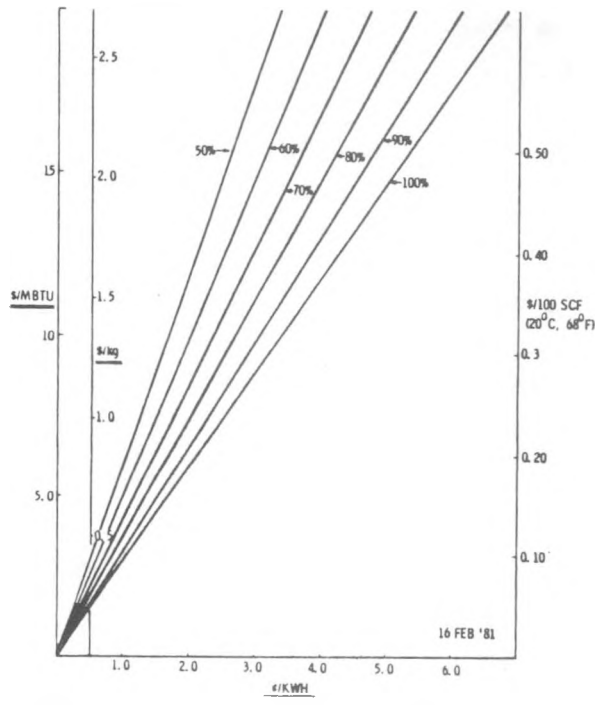


Figure 10. Influence of Electricity Price and Process Efficiency on Segment of Hydrogen Cost

FIXED COST FACTORS

The MAWES hydrogen plant economics program is a comprehensive model wherein the plant requirements are fed in along with the known costs and an alkaline electrolysis system is sized and costed at the conditions that result in the minimum life cycle or levelized product cost. The analysis of levelized cost is taken from the financial analysis technique developed by the Electric Power Research Institute (EPRI).[4]

One of the primary reasons for developing the MAWES Program was to allow the government and industry to assess the true value of advanced electrolysis cell components in terms of investment dollars and "sense." For example, it is a well-documented fact that an electrolyzer with high percentage platinum electrodes can operate at efficiencies approaching 100%, however, the cost of these electrodes would be unbearable. Anything that goes beyond plain nickel or iron electrodes adds cost and the MAWES Program is intended to provide an overall value evaluation.

Typical general interpolative results are given in Figure 11 for nickel wire screen electrodes operating at 60° C. A comparison of this technology with the new C-AN cathode is shown in Figure 12. As can be seen, although the C-AN cathode catalyst will add expense to the module ($6.50/ft^2 versus $8.50/ft^2), the resulting lower operating voltage, i.e., 265 MV saved at 600 ma/cm^2 and 60° C, predominates and the use of the C-AN catalyst can be justified, even at low plant utilization and low electricity costs.

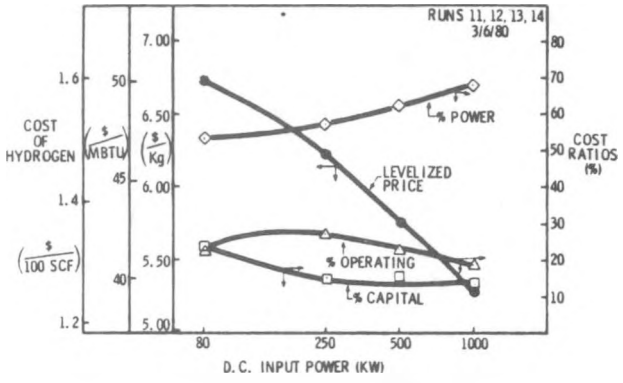


Figure 11. Levelized Gas Price Vs. Size: Baseline Technology

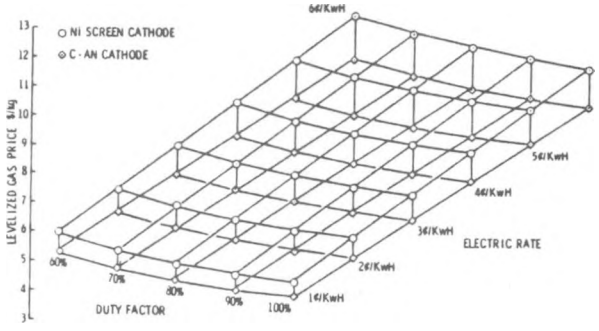


Figure 12. Levelized Gas Price Vs. Electricity Cost and Duty Factor, Two Technologies

SCALE-UP CONSIDERATIONS

As noted earlier, the MAWES input data file is limited to the evaluation of plant sizes of 1MW and smaller because of the BNL interest in smaller renewable energy applications such as low-head hydroelectric power plants. The basic program is capable of accommodating larger plant analyses, however, the data file has not been expanded and "other" techniques must be employed to estimate the costs associated with large plants.

Interpolative plant cost estimations, by the very nature of having two or more plant cost data points, i.e., large and small, are considerably less risky than an extrapolation technique. However, since no one in the United States has built anything like a multi-megawatt-sized plant, extrapolation is about the only means available, using the general equation:[5]

$$\$\,L = \$\,S\left(\frac{S_e}{S_s}\right)^k \quad , \qquad \text{Equation 1.}$$

where $ L and $ S are the cost of the plant sized at S_e and S_s, respectively, and k has exponent value of between 0.5 and 1.0. Figure 13 gives general results for the $500/KW plant cost value at 1MW size, extrapolating out to a H_2 plant size of 1000MW as might be associated with a dedicated nuclear power plant.

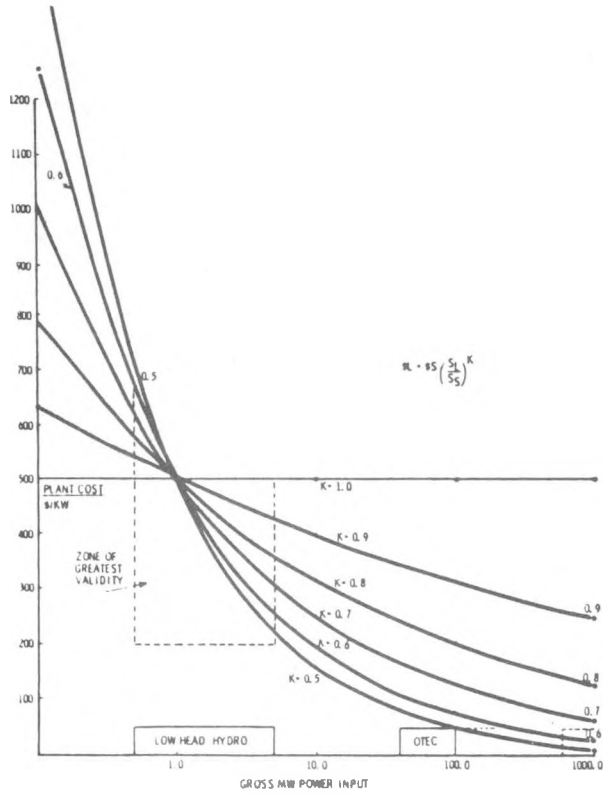


Figure 13. Extrapolative Cost Calculations

If one plots the values for a 1 MW TES-designed plant and a corresponding 58 MW SPE plant, the two values have reasonable agreement to Equation 1, utilizing k values of 0.75, as can be seen in Figure 14. On this high risk basis, both parties would appear justified in projecting capital costs in the range of less than $100/KW.

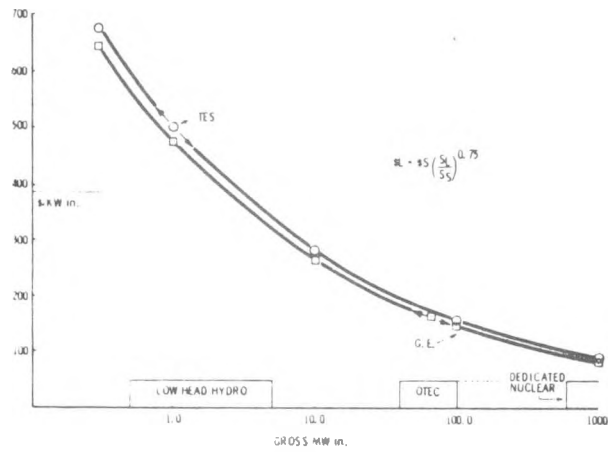


Figure 14. Extrapolative Unit Cost Fit

This approach is reasonably valid for technologies that are fully scalable. There are two alternate scenarios to the fully scalable approach. The first is that at some size limit -- perhaps a cell area of 10 M^2 (100 ft^2) -- one must go to parallel systems because of some "natural" barrier. This effect is presented as part of Figure 15, as "Chilton's Risk." A second corollary authored by one of our colleagues and shown in Figure 15 as "Laskin's Risk." This latter concept is that above some plant size most of the components become custom, one-of-kind devices compared to off-the-shelf components; thus, higher per-unit price results.

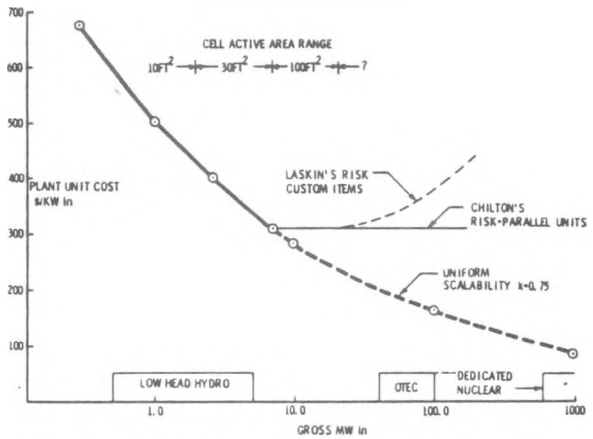


Figure 15. The Plant Cost Scalability Caveat

Normally, Chilton's Rule (Equation 1.) utilizes a 0.6 k term and the approach was shown valid[5] for a variety of chemical plants. Several electrolysis plant cost data points have been accumulated over the last three years from various technical publications, potential and actual customers. These are shown in Figure 16. Although the data are from five separate companies, it is interesting to note the k value lies between 0.45 and 0.65. Therefore, for general cost estimating at this stage, perhaps the plant cost curve shown in Figure 14 is not too bad an estimate.

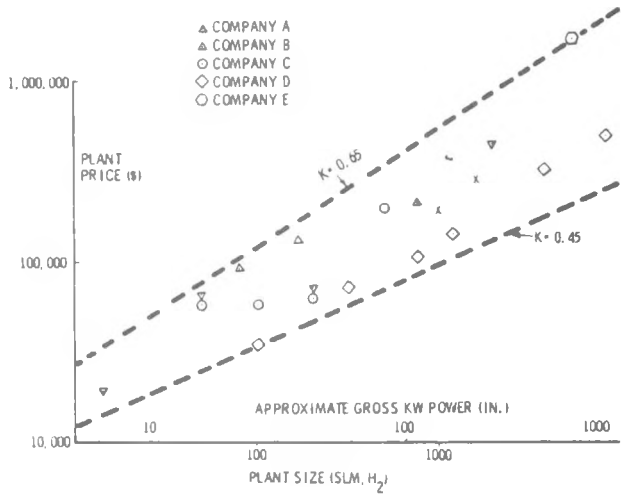


Figure 16. Electrolysis Plant Prices Vs. Plant Size

In summary, it is not practical to estimate the program and production costs for large electrolysis plants beyond that discussed earlier without a better definition of the requirements and a tool such as MAWES at one's disposal. It is probably safe to assume that operating efficiency will be more important in the long run than initial plant cost. This being the case, it can be expected that the analysis should quickly show that it is desirable to (1) select the largest cell area possible to get the current densities down, (2) operate at the highest temperature practical, and (3) use advanced electrode catalysts. All of this must, of course, be strongly tempered by the fact that the first prototype must operate satisfactorily, certainly beyond the first hour of the test.

With this in mind, then, and assuming that development dollars could be made available, Table 3 updates our assessment of what technologies might be available for a 1986 40 MW OTEC alkaline electrolysis plant. The risk term used here is synonymous with development dollars and success. The consideration ranges shown are not firm by any means and could change dramatically once a serious development program was initiated. For example, it may turn out that availability of construction materials is not a constraint and it is just as easy to build a 4 x 8 foot cell as a 4 x 4 foot cell. Likewise, it may not be possible or practical to assemble single modules with more than 200 cells due to hydraulic press opening limitations.

Table 4 presents a 40 MW_{gross}/35 MW_{net} hydrogen plant configuration based upon a middle of the road nominal risk design. Figure 17 shows a representative plant layout.

Again, this information is provided so the reader can get an appreciation for the technology situation. Obviously, an optimization study is very much in order, however, based on the generalities presented, the hydrogen production option for OTEC is viable within the time frames under consideration. Teledyne Energy Systems is confident that an advanced alkaline technology will more than satisfy user needs for efficient, reliable, and economic utilization of Ocean Thermal Energy.

Table 3. 1986 Multimegawatt Alkaline Electrolysis Plant

Cell/Module Level Considerations	Low Risk	Nominal Risk	High Risk
Cell Active Area, Ft^2	<10	10 to 20	20 to 30
Number of Cells/Module	<150	150 to 250	250 to 500
Operating Temperature, C	80 to 100	100 to 125	>125
Current Density, $Amps/Ft^2$	<500	500 to 1000	>1000
Single Module Capacity Range:			
SCFH	10,000	10,000 to 79,000	79,000 to 240,000
Lb/Hr	52	52 to 413	413 to 1255
MW_e	1.0	1.0 to 7.9	7.9 to 24.0
Module Efficiency, %	<80 (78)	>80 (82)	<85 (85)
Input Power Requirement, MW_{in}	1.3	1.2 to 9.6	9.3 to 28.2
System Considerations			
Number of Modules per Aux. Set(1)	1	2	>2
Electrolyte Pumps	2	1	⩽1

(1) Auxiliaries include power supplies, process controls, gas and liquid controls, water treatment, gas purification.

Table 4. 40MW OTEC Pilot Plant Electrolysis System Concept

Single Module	
Cell Active Area	15 Ft^2
Number of Cells	200
Operating Temperature	100°C
Current Density	750 Amperes per Ft^2
Cell Voltage	1.75 V/Cell
Module Dimensions	4' x 4' x 10'
Capacity	35,000 SCFH, or 183 Lb/Hr, or 3.5 MW_e
System Package[1]	
Modules per Aux. Set	2
Number of Electrolyte Pumps	1
Operating Pressure	100 psig
Package Efficiency[1]	80%
Input Power Requirement	8.8 MW
Capacity	70,000 SCFH, or 366 Lb/Hr, or 7 MW_e
Single Package System Size Envelope	4' x 8' x 28'
Pilot Plant[1]	
Number of Packages Required	4
Total Input Power Requirement	35.2 MW
Plan Area Required	~1,600 Ft^2
Volume	~12,800 Ft^3

[1] Does not include power supplies, water conditioning, or gas drying equipment, if required.

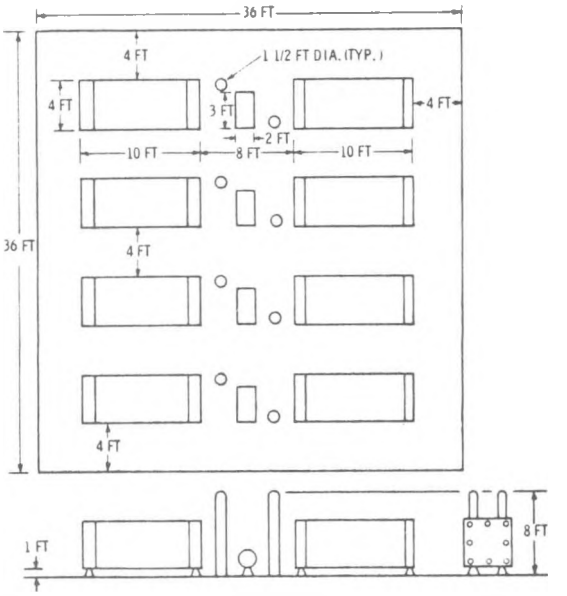


Figure 17. Representative 40 MW OTEC Alkaline Electrolysis Plant Layout

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OTEC ENERGY TRANSFERENCE VIA BIOMASS: THE PROS AND CONS

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ABSTRACT

Biomass may be produced from OTEC effluents through aquaculture, or OTEC energy may be used to convert terrestrial biomass to liquid fuels and chemical feedstocks. The added value of biomass used for energy probably does not justify the cost to produce it, but food production appears promising. The value of food production may exceed that of electricity production if various difficulties can be overcome. Some systems might lead to a significant savings in fossil fuel used to produce animal protein.

INTRODUCTION

Biomass produced by a combined OTEC-aquaculture system may be considered an energy transfer medium. Some of the electricity produced by the OTEC facility can be used to operate the aquaculture system and to process the products. If the generating capacity of the OTEC plant is reduced by the presence of the aquaculture system, the loss can be considered an energy "input" to the products. Cultivated marine algae add another energy input: solar energy captured by photosynthesis. The output, or "energy product equivalent", is biomass for energy conversion, chemical feedstocks, or food.

The biomass used as an energy transfer medium need not be grown at the OTEC facility. Energy generated by the OTEC plant might be used to convert terrestrial biomass into liquid fuels or chemical feedstocks. This type of conversion system is still in the concept stage, however (1)*.

OTEC BIOMASS PRODUCTION: ADVANTAGES AND DISADVANTAGES

The use of OTEC effluents for aquaculture offers the possibility of large-scale environmental control at a relatively low energy expenditure. The large volumes of water pumped by the OTEC plant can reduce or eliminate pumping costs to the aquaculture system. Deep ocean water contains little organic matter and few microorganisms (2), so elaborate filters or purification mechanisms are probably unnecessary. The rapidly flowing, high quality seawater should permit high densities of the cultured organisms. Deep water contains a higher concentration of inorganic nutrients than oceanic surface water, reducing the need for chemical fertilizers.

Another major advantage of an OTEC-aquaculture combination is the potential for large-scale temperature control by mixing the warm and cold effluents in different proportions. Optimal temperatures for the growth of a wide variety of organisms could be maintained on a year-round basis. In addition, temperature changes may help control disease outbreaks (3). Year-round temperature control on such a scale is energetically and economically infeasible for conventional aquaculture systems.

Merging OTEC and aquaculture presents difficulties as well as advantages. The low oxygen concentration of deep water (1 mg O_2/l below 600 m off Hawaii) (2) may be insufficient for the cultured organisms. Chlorine or other biocides used to control biofouling in OTEC heat exchangers might kill or severely stress the organisms. If the culture system relies on a continuous flow of water, unscheduled plant shutdowns could destroy an entire crop. The latter two problems might be avoided by a modular OTEC system in which the effluent from one component could be shut off or diverted while the others continued to support the aquaculture system.

A poorly designed aquaculture system can reduce the effectiveness of the OTEC plant. Any backpressure will increase pumping costs. The release of biomass or cold effluent near the warm-water intake could clog the intake

*Numbers in parenthesis refer to References listed at end of the paper.

screens or destroy the thermal gradient necessary for electricity production. Clearly, the two systems must be well integrated. Of course, if the aquaculture component is sufficiently profitable, some reduction in generating capacity will be tolerated.

A floating or "grazing" OTEC plant poses severe technological problems. The cold deep water is denser than surface water; it will probably need to be contained and supported. Wave action may loosen farm structures, which in turn might damage the OTEC plant. The technology for such large open-ocean containment structures has yet to be developed.

The following sections examine the potential of OTEC-aquaculture biomass production. The estimates presented are based on a variety of assumptions and are probably optimistic; they are meant to indicate potential rather than proven yield or profit. For comparison, an OTEC plant could produce 8.76 x 10^6 kw-hr/yr per megawatt of generating capacity (MWe) if operation were continuous. At 3.5-7 cents/kw-hr (4) this electricity is worth $300,000 to $600,000.

BIOMASS FOR ENERGY CONVERSION

A prime candidate for marine biomass production is the giant kelp, Macrocystis pyrifera; it has been proposed that Macrocystis be grown in vast open-ocean energy farms for conversion to methane gas (5). Estimates of the potential biomass production of an OTEC-supported kelp farm, based on a preliminary analysis of the potential for large-scale Macrocystis culture (7), indicate a yield of some 1100 dry tons/yr-MWe. Gross methane production would be approximately 6 x 10^6 ft^3, equivalent to 0.2 MW (6); if the gas is valued at about $5.00/1000 ft^3 (7), the gross value is $30,000/MWe.

Presumably, the kelp farm must be isolated in some way from the OTEC plant to prevent cold effluent and kelp fronds from reaching the warm-water intake. In addition, the deep water from a single upwelling source (in contrast to the multiple sources planned for a non-OTEC-based kelp facility) may need an elaborate distribution system to spread nutrients adequately throughout the farm area (11 ha/MWe) (6). Finally, farm operations, harvesting, and processing would consume some 20% of gross kelp energy production even with extensive use of environmental energy (7). The net value of methane produced most likely would not justify the cost of the modifications to OTEC facilities. Using the kelp process residues as animal feed and fertilizer, and culturing food organisms in addition to Macrocystis, may provide additional revenue, but OTEC and large open-ocean algae energy farms will probably be more successful separately than together.

Phytoplankton may also be used as biomass for energy conversion. Phaeodactylum tricornutum, a marine diatom with a substantial lipid content, has given unusually high yields when grown in shallow raceways under controlled conditions (8). Further experiments on a somewhat larger scale are being carried out in Hawaii. However, Phaeodactylum production is envisioned as a recirculating system because of harvesting considerations, with little makeup water added. It is probably not well suited to an OTEC-biomass combination (9).

BIOMASS FOR FOOD

The major study of potential OTEC food production has been that of Roels (10) at St. Croix, U.S. Virgin Islands. In this study, the deep water was used to grow phytoplankton in ponds. Shellfish were fed on the algae-bearing water. Pilot-scale experiments were done with the diatom Chaetoceros curvisetus and the clam Tapes japonica. The maximum potential yield was extrapolated to be 711 tons/MWe of clam meat worth over $1.5 million, substantially more than the electricity produced by the OTEC plant. Penaeid shrimp and brine shrimp (Artemia) have also been grown successfully in this system (11).

An alternative OTEC-aquaculture system will be tested at the Seacoast Test Facility, Keahole Point, Hawaii starting in Fall 1981. This system will mix deep and surface waters in approximately equal proportions to achieve temperatures suitable for rapid growth of such valuable organisms as silver salmon (Oncorhynchus kisutch) and Porphyra tenera (an edible seaweed highly prized among persons of Oriental ancestry). Gelidium robustum, a seaweed that produces high-quality agar, will also be tried. It is hoped that the rapidly flowing water will permit high-density, disease-free cultures. Fast (3) has estimated that 7 lbs/yr of salmon can be raised per ft^3 of pen volume (approximately 110 kg/m^3-yr) at 6 water exchanges per hour in an OTEC growout facility. A combined deep and surface water flow of 8 m^3/s, equivalent to about 1 MWe capacity, could support 4,800 m^3 of salmon pens producing 528,000 kg/yr. At $3.85/kg ($1.75/lb), the gross value of salmon production would be approximately $2,000,000. The actual yield must of course be determined experimentally. A major advantage of this system is the relatively low volume of enclosures required. Since the fish do not need much light, the pens could be placed beneath the ocean surface to avoid wave action. Such a system might be easier to

integrate with an open-ocean OTEC plant than would a system requiring the surface area and light intensity necessary for primary producers.

At present, it is assumed that the salmon will be fed commercial fish feed. this requirement involves a major cost in both energy and dollars. Land-based hatchery facilities may also be necessary. Nevertheless, if sufficient feed can be obtained at a reasonable price, the farm amy be profitable.

Porphyra, is grown in Japan (12) on nets horizontally suspended in bays. It has also been grown in high-density suspended culture in tanks (13). It is sold as dry sheets; these sheets may command up to $40/kg (14). Potential Porphyra yield may be calculated from the amount of available nitrogen in the water. Below 800 m off Hawaii, the deep water contains approximately 40 ug-at N/l (15). At 4 m^3/s deep water flow, about 7 x 10^4 kg of nitrogen are brought up each year. High-quality Porphyra may contain 7% N by dry weight (16); assuming 50% of the available N is actually used by the plants, and a yearly production period of 330 days, about 5 x 10^5 kg of dry Porphyra can be produced. At $20/kg, this crop would be worth $10,000,000. Again, the real potential must be demonstrated experimentally. It should be noted that total Japanese Porphyra production in 1975 was approximately 1.8 x 10^7 dry kg (12); presumably market forces would come into play to reduce prices or restrict supplies if very large additional quantities are produced. Also, the reproductive cycle of Porphyra is strongly responsive to photoperiod; this factor might have to be controlled artificially if Porphyra is grown in tropical regions where OTEC systems will be placed. A variety of other algae could be raised, including those that produce useful colloids like agar and carrageenan, but at a substantially lower price ($250-$1,200/dry ton) (17).

CONCLUSIONS

Although OTEC-supported biomass for energy conversion is of questionable value, OTEC food production shows strong economic potential if a variety of assumptions are correct. Gross revenues from food production may exceed those from electricity generation. This analysis is supported by Japanese studies which propose small OTEC plants to provide electricity for Pacific islands (18). Atoll lagoons would be used to contain the water for aquaculture. The water might actually be sold to the aquaculture facility, significantly reducing the unit power cost.

The energy contained in OTEC-grown biomass is rather small relative to OTEC electricity production. However, in U.S. agriculture a substantial input of fossil fuel is needed to produce food, especially animal protein. For example, broiler chickens require 8.8 x 10^4 kcal of fossil fuel energy to produce 1 kg of protein; pond-raised catfish require 1.39 x 10^5 kcal/kg (19). If OTEC-based aquaculture can produce seafood protein with a minimal external energy input (including that for materials and construction), it may be a valuable addition to the energy contribution of the OTEC system.

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APPLICATION OF MOLTEN CARBONATE FUEL CELLS TO OTEC-GENERATED FUELS

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Ocean thermal energy conversion is recognized as a valuable source of supplementary, renewable energy. This energy can be transported as electricity or a chemical energy (methanol, ammonia), depending on the distance between the OTEC plant and shore. Molten carbonate fuel cells (MCFC) can efficiently reconvert OTEC generated fuels to electric power, also producing high-temperature thermal energy that is available with no generation efficiency penalty.

In this paper, we review the status of MCFC technology and discuss its potential application to generation of onshore power from OTEC-generated fuels. We also discuss MCFC power generation in cogeneration modes.

INTRODUCTION

The general acceptance of the permanent rise in energy costs and the realization that energy has been greatly underpriced have created a revitalized interest in new and varied means of supplying our energy needs. Since many of these are known or are suspected to have deleterious environmental effects, there has also been an emphasis on renewable energy sources. Such sources are derived either directly from the sun, as photovoltaic or solar thermal energy, or indirectly through vegetative growth or from solar-driven systems, wind, and oceanic currents or temperatures (OTEC). This paper will discuss the integration of OTEC-generated chemical energy into power-producing systems.

OCEAN THERMAL ENERGY CONVERSION

These systems are based on thermal engines driven by the temperature difference between the warm water at the ocean surface and the colder subsurface water at a depth of, say, 1000 meters. The thermodynamic cycle may be closed and use a working fluid, such as ammonia or a freon, or it may be open, using the evaporation and condensation of the sea water. The critical feature is that the temperature differences are not large (20° to 25° C); therefore, the potential efficiencies are low, and net efficiencies after pumping losses and parasitic needs are lower still. Land-based and near-shore, tower-mounted plants make use of a much lower temperature difference than that available in the open ocean. These will produce electricity and transport it directly to the point of use by an underwater cable. Floating tethered plants can be built much farther from shore, with the potential for larger thermal differences, but the technical problems of coupling to a cable increase considerably. The floating plants that function in the open ocean, where the thermal gradient is at its maximum, can no longer rely on the direct transmission of electricity. They must transport the energy produced in another form for either direct use or for reconversion to electricity. Prior studies (1)* have indicated that ammonia is the least expensive form of energy storage and transportation (Figure 1). However, this energy form requires an electrolysis plant for hydrogen, an air separation plant for nitrogen, and finally the ammonia synthesis step. These increase the capital investment and result in increased efficiency losses, thus a reduction in the effective efficiency.

However, this energy in the form of ammonia may be supplied to a widespread market and geographic area. A more expensive form, methanol, requires that a carbon source, such as carbon dioxide, be provided to the OTEC plant. An advantage of methanol is its more ready integration into the present energy transportation and utilization systems and its potentially higher conversion efficiency in use. When the final methods of utilization and their efficiencies are fully considered, methanol may actually be the most cost-effective form.

During the mid-60's, the Army looked at various concepts of generating a useful form of energy from a mobile nuclear reactor (2). The two optimal energy forms were liquid hydrogen and ammonia, with the latter being most useful in military scenario. However, combustion of ammonia in various heat engines was shown to be inefficient, resulted in reduced power, and gener-

*Numbers in parenthesis refer to references listed at the end of the paper.

ated high nitrogen oxide (NO_x) emissions. One means of energy conversion that showed more promise is electrochemical power generation via fuel cells.

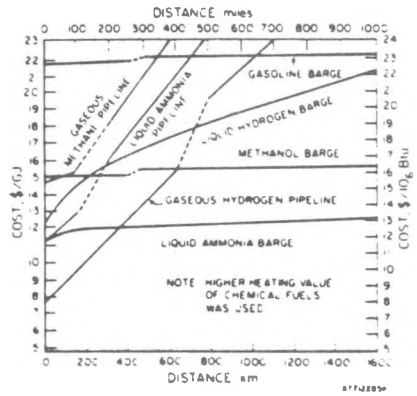


Figure 1
Delivered Energy Transportation Cost Comparison With OTEC Shaftpower Cost of 20 Mills/kWhr (100-MW Plant)

FUEL CELL SYSTEMS

A fuel cell is a direct energy conversion device that converts chemical energy to electrical energy without a thermo-mechanical intermediate — that is, a heat engine driving a generator. However, since hydrogen is the electroactive fuel and fuel cells produce direct current, they require an appropriate fuel processor to convert the primary fuel to hydrogen and an inverter to produce alternating current, as shown in Figure 2. The major fuel cell systems for present or near-term application are alkaline, phosphoric acid, and molten carbonate, based on their electrolyte. The first was used in the space program with pure hydrogen and oxygen as reactants. Phosphoric acid fuel cells are the most highly developed systems for terrestrial applications that utilize air and hydrogen derived from carbonaceous fuels (methanol) or other sources, such as ammonia. Such systems operate at a temperature of 200°C (390°F).

Phosphoric acid fuel cells have been designed to use thermally decomposed ammonia fuel (3). However, residual ammonia in the fuel stream will partially neutralize the electrolyte by forming ammonia dihydrogen phosphate, and consequently, these systems require scrubbing to reduce the ammonia concentration to less than 1 ppm. This effect on cell performance is not permanent if the source of ammonia is reduced or eliminated. The ammonium ion will be oxidized and performance restored (7) (Figure 3). High concentrations for long periods may cause irreversible losses; however, the appropriate testing has not been documented in the literature.

Methanol is easily converted to a hydrogen-rich fuel stream at low steam-reforming temperatures, 250°C. Carbon monoxide, which is a poison to the platinum catalyst on the phosphoric acid fuel cell eletrodes, must be reduced to below 1% to 2% by the shift reaction with water.

Molten carbonate systems do not have the same problems as the previous systems and have numerous advantages over them.

Molten Carbonate Fuel Cell Systems

These use a mixture of $(Li, K)_2 CO_3$ as electrolyte held by surface tension in a matrix configuration with very fine particles of $LiAlO_2$. These cells use nickel and nickel oxide electrodes and operate at about 650°C (1200°F). At this temperature, reaction rates and thus performance are very high. Performance goals for a commercially viable system, i.e., adequate market penetration, are given in Table 1. The elevated temperature of operation provides high-quality reject heat that can be utilized in a bottoming cycle for increased production of electricity. The net electrical efficiencies of a molten carbonate fuel cell power plant integrated with coal gasifiers and bottoming cycles are projected to be 50%. In many industrial applications, there is also a need for high-quality process heat. This can be provided by the reject heat from the fuel cells (reducing or eliminating the bottoming cycle). In those cases in which the heat available matches the quality of that needed, overall energy utilization may exceed 80% (4). These industrial

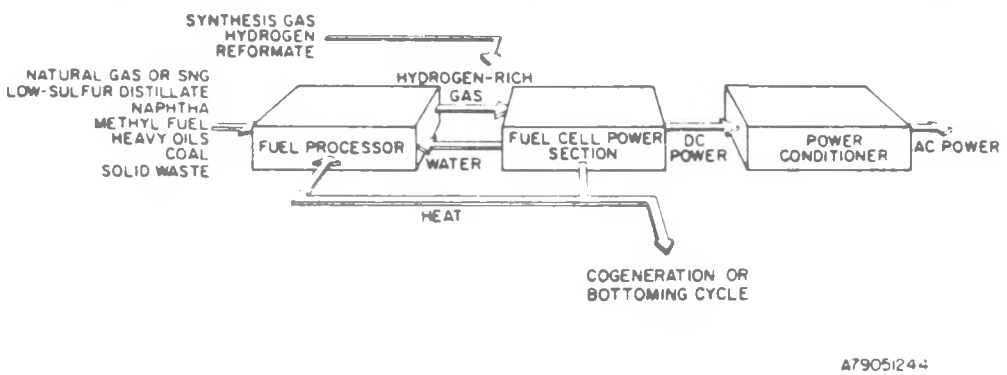


Figure 2. Complete Fuel Cell Power Plant

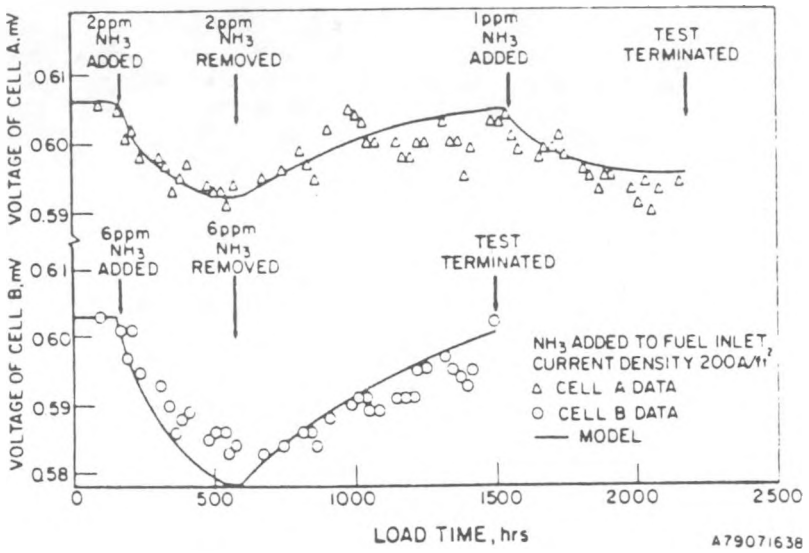


Figure 3 Cell Endurance in the Presence of Ammonia

cogeneration systems obtain benefits not only from heat utilization, but also from the molten carbonate fuel cell efficiency in power generation. Net energy saving yields of 35% to 50% for some major energy-consuming industries have been estimated (Table 2).

Table 1 Technology Categories and Goals

Performance	650 mV (End of Life) 160 mA/cm² 650°C 10 atm 75% Fuel Utilization 50% Oxid. Utilization
Cost	$100/Stack kW (1978 $)
Life	40,000 hours (< 4mV/1000 hr) 20 plus thermal cycles
Scale-up	700 Cell Stack 2 ft by 2 ft or larger

Table 2 Effect of Cogeneration On Energy Savings With Molten Carbonate Fuel Cell

Process	Total Energy Savings	Energy Savings Due to High Fuel Cell Efficiency	Energy Savings Due to Cogeneration
	%		
Caustic	49.0	19.0	30.0
Newsprint	50.0	18.5	31.5
Magnesium	46.0	18.0	28.0
LDPE	36.0	16.5	19.5

Table 2. Continued

Process	Total Energy Savings	Energy Savings Due to High Fuel Cell Efficiency	Energy Savings Due to Cogeneration
	%		
Carbon-Steel Castings	34.0	14.0	20.0
Copper	45.5	12.0	33.5
Cement	8.0	3.0	5.0
Aluminum Fabrication	37.7	8.5	29.2

Besides the advantages of higher quality reject heat, molten carbonate fuel cells are not poisoned by carbon monoxide as the phosphoric acid type is. On the contrary, CO serves as a fuel and is consumed, not directly but by supplying hydrogen through the shift reaction with product water. Carbonate systems are more sensitive to sulfur-containing species than are phosphoric acid systems. Hot gas cleanup systems, used with coal gasifiers, reduce almost all sulfur-bearing compounds, H_2S and COS, to negligible levels; however, neither ammonia nor methanol contains sulfur compounds, so cleanup is not required. There is no published data to indicate that any deleterious effects occur or can be expected in molten carbonate systems as a result of residual ammonia in the fuel stream.

The major failure mechanisms for molten carbonate systems are migration of electrolyte into the electrodes, causing flooding, loss of electrolyte as a result of a finite vapor pressure, and cracking of the electrolyte tile as a result of stresses created during thermal cycling. The last two result in eventual cross-leakage of reactants and thus performance and efficiency losses. A fine and stable $LiAlO_2$ powder can be produced

that would appear to maintain a satisfactory surface area for a sufficient time (Figure 4). These high surface powders also yield a strong tile whose ability to withstand thermal stresses is enhanced. Figure 5 shows the result of 12 cycles through the freezing point of the electrolyte; notice that the nitrogen crossover, a sign of leakage from the cathode to the anode, has not reached a significant level. Electrolyte is lost by evaporation and by reaction with and migration into the cell components. The initial reaction losses versus longer term vapor pressure losses during operation at one atmosphere are clearly shown in Figure 6. Preloading the cell components with electrolyte, changing the electrolyte to a composition with a reduced vapor pressure, and increasing the operating pressure seem to cause sufficient electrolyte to be retained for a satisfactory lifetime. The status of the present technology is summarized in Table 3. Molten carbonate technology is about ten years behind phosphoric acid in comparable prototype demonstrations; however, it is progressing in about the same time frame as OTEC plants with planning for megawatt sizes in the late 80's and multimegawatt scale in the early 90's (5).

System Design for OTEC-Generated Fuels

The electrochemical reaction between hydrogen and the carbonate ion results in water and carbon dioxide. To maintain the electrolyte composition, carbon dioxide must be mixed with the oxidant to form the carbonate ion electrochemically at the cathode. This is normally accomplished by recycling the spent anode reactants to the cathode with fresh oxidants. Since the fresh fuel stream contains carbon dioxide when derived from coal, oil, or natural gas, the overall balance is maintained without appreciable system complication.

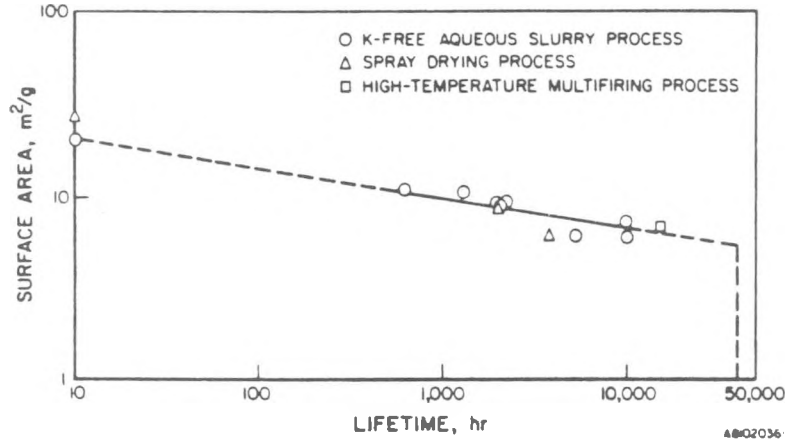


Figure 4 $LiAlO_2$ Surface Area Loss in 94-cm^3 Cells

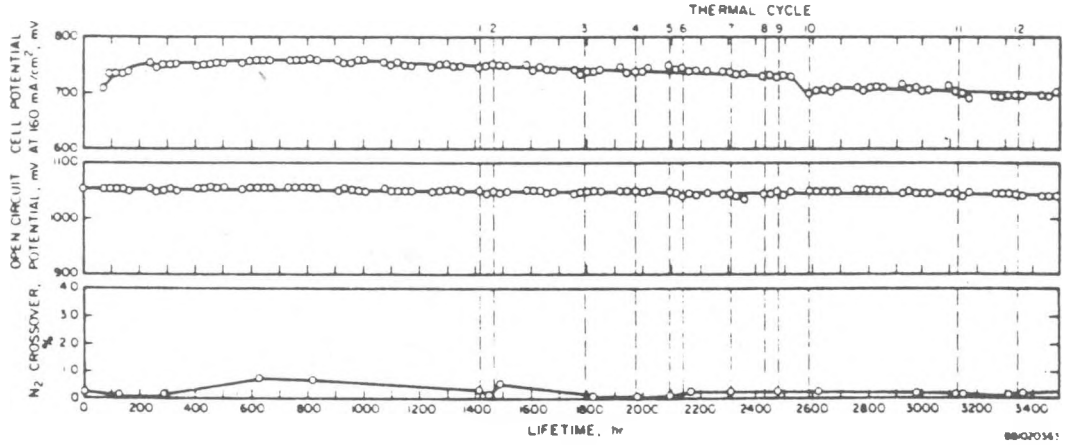


Figure 5 Thermal Cycle of Cell IGT-BS-2 With Tile From Spray-Dried Powder (AD60-4A)

Table 3 Technology Status Summary 1959 to 1980, Life Limitations

Item	Fix	10,000 to 15,000 hr Demonstration	40,000 hr
Anode Sintering	Chromium Stabilization	Yes	Good
Carbonate Loss	Component Mod. Pressure	No	TBD
Wet Seal Corrosion	Aluminization	Yes	Excellent
Separator Plate Corrosion	Nickel or Nickel/SS	Yes	Excellent
Performance Decay	Carb Mgt. Stable Comp.	10 mV/1000	2.5 mV/1000 Desired
$LiAlO_2$ Stability	Doping and Pretreat	Yes	Good
Electrolyte Tile Cracking	Crack Arrestors Microstructural Improvements Bubble Barriers	No	TBD
Cathode Strength	Reinforcement, Tape Casting, Modified Thickness	No	TBD

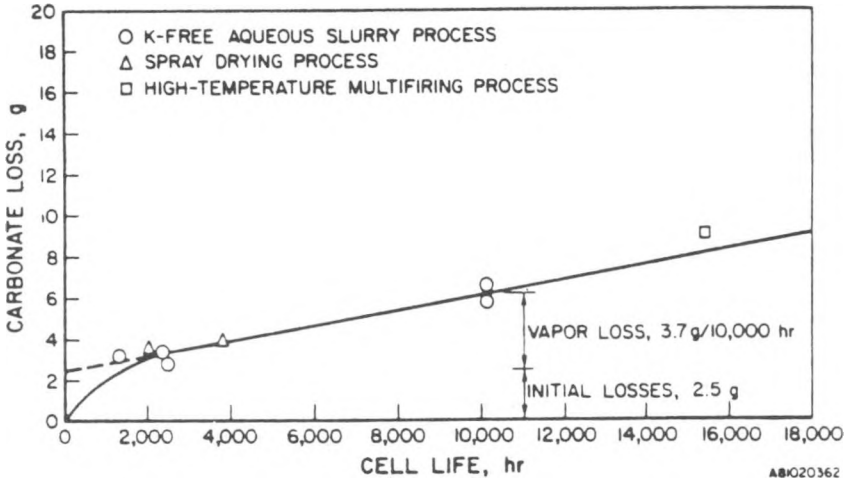


Figure 6 Carbonate Loss Curve From Standard 94-cm^2 Boiler Plate Fuel Cells

This is not the case with cracked ammonia, which contains no carbon dioxide and appreciable nitrogen as an inert. This will affect the recycle loop and may require some adjustment in composition through a CO_2 purification system as well as CO_2 makeup as a result of less than complete quantitative transfer in the cathode. This makeup could be most easily accomplished by introducing methanol into the feed stream along with cracked ammonia. Though the cell operates at about 200°C below the ammonia cracking temperatures, it may be possible to feed ammonia directly to the cell, since nickel is a typical decomposition catalyst. The kinetics of this reaction and the performance of either anode and cathode with realistic conditions and compositions have not been measured. A typical diagram of such a system for central power generation is shown in Figure 7. Efficiencies of about 50% to 55% (ammonia to ac power) could be attained.

Utilization of methanol is much more straightforward because it is an eventual source of carbon dioxide and its reformation occurs many hundreds of degrees below the cell operating temperature. Methanol or methanol-steam could be fed directly to the cell. Pure methanol would probably result in deleterious carbon deposition within the cell; this might be avoided by some anode recycle in which the water and carbon dioxide concentration would inhibit the deposition reaction.

The use of methanol would result in a very simple and efficient system (~60%, from methanol to ac power). This reduction in system complexity and probable increase in net efficiency might off-

set the initially higher cost of methanol. These facts, as well as the ready integration of methanol into other uses — for example, turbine peaking and transportation — may make this fuel preferable to ammonia.

RECOMMENDATIONS

Complete system designs based on experimental cell performance should be made to establish net system efficiencies. This information, in conjunction with efficiencies determined for other prime movers, will provide for a life-cycle comparison of the two fuels.

This complete life-cycle comparison, which includes end use, should be made more thoroughly and in more detail to establish the relative cost-effectiveness of the two fuels.

Should methanol be the optimal fuel, it might not result in any increase in OTEC plant complexity, since methanol synthesis would be added versus air separation and ammonia synthesis. Some plans being considered for transport of nature gas from offshore wells have made a strong case for production of methanol on barge-mounted plants (6).

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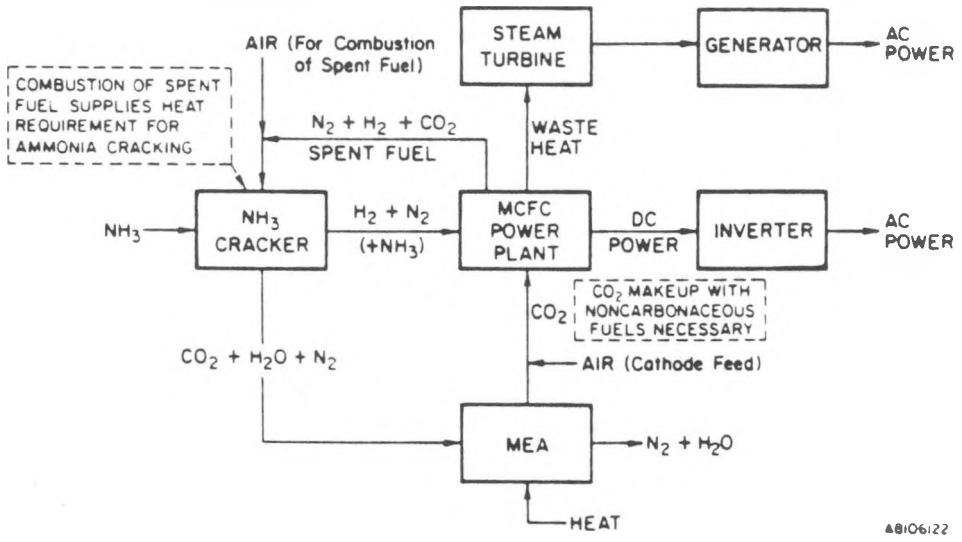


Figure 7. OTEC-Fueled Power Plant

Session Group V

CONSTRUCTION AND TEST CAPABILITIES

8th Ocean Energy Conference
Washington, DC
June 1981

THE ART OF OTEC CONSTRUCTION

Reg Clare

Sir Robert McAlpine & Sons, London, U.K.

ABSTRACT

The paper describes recent British experience and research into offshore structures and shows how it could be applicable to OTEC construction and maintenance. The Author's colleague, John Derrington, had the privilege of addressing this conference two years ago (1) and referred to the U.K. work. Much has been achieved since then, not only in connection with North Sea oil and gas production but in R & D programs on wind, wave and tidal energy.

1. GENERAL REQUIREMENTS

A permanently floating facility, capable of staying on station, riding out all storms and remaining at sea for the whole of its servicable life, without dry-docking for inspection or maintenance, calls for a structure outside the normal specification for ship building. Materials are required of proven durability, resistant to corrosion, chemical or biological attack and with an adequate fatigue strength to resist 4×10^6 cycles of loading per annum (based on an average wave period taken as 8 secs).

The total value of the OTEC plant is huge and loss cannot be contemplated. Hence the design and construction must be such as to give a high degree of security against all conceivable natural events and accidents. The hull design must be such that any sustained damage does not result in sinking, lack of seaworthiness or an unacceptable list. Repairs must be possible on station at sea.

2. MATERIALS FOR THE HULL

North Sea oil and gas production platforms have been built of steel or concrete (2, 3) and successfully installed. The time scale is too short to be able to claim durability advantage for one or the other though it is significant that some steel platforms have had to undergo repair in port for major cracks and others have been lost. In one case at least, fatigue failure early in the life of the structure has been established. In the U.K. and Europe, research is being undertaken by the Safety and Reliability Directorate, Atomic Energy Authority and in the "Concrete in the Oceans" program (4, 5), into fatigue and corrosion fatigue.

The construction of the North Sea concrete platforms led to a recognition that more detailed knowledge of material properties was needed if the advantages of concrete in this particularly aggressive marine environment were to be maximised. A research program entitled "Concrete - in - the Oceans" (CIO) was initiated in 1976 by Construction Industry Research and Information Association (5,6). Phase I of CIO, which was largely completed in 1980, had seven projects, four of which were concerned specifically with marine exposure effects on steel and concrete, two projects considered design aspects peculiar to concrete storage and caisson structures and one project considered modes of failure.

In the four projects related to exposure, particular attention was given to deterioration of reinforcement associated directly or indirectly with corrosion. One project consisted of a review of previous work, including some reanalysis and discussion of design implications (7,8). This was coupled with a continuing series of durability tests at two natural exposure sites whilst another project examined corrosion processes under laboratory conditions. A third project surveyed an existing offshore concrete structure and the fourth investigated fatigue loading of reinforced concrete beams in a sea water environment. Though concerned with fundamental processes in a field in which research data is not lacking, the CIO projects were conceived so that the results have direct relevance to engineering design of a wide range of offshore structures, including OTEC design.

A finding which was common to both natural exposure and laboratory tests, also to the structural survey, was that, under conditions of permanent submergence, there is no significant corrosion of steel bars in cracked concrete for crack widths up to 0.3 mm or more. This situation has been observed notwithstanding full chloride penetration in the region of the cracks. It appears, therefore, that the protective coating provided by the cement hydration products remains effective even where some bond slip occurs.

In the splash zone, the only protection to reinforcement may be the resistance offered by the cover to the passage of oxygen. This situation is well known qualitatively and has led to the use of large concrete cover, frequently supplemented by resin coating, in the splash zone of existing structures. However, the variety of requirements in existing specifications indicate a lack of precise knowledge in this area and further work is being undertaken in Phase II of CIO.

Phase II is largely an extension of Phase I and has six projects. The main objective is to examine areas of concrete technology which continue to cause problems. Three projects are relevant to OTEC structures. The first is a continuous study of crack and corrosion criteria. It aims to build on results from the Phase I program and to include special investigations of the behaviour of p.f.a. concrete, the effect of localised patches of porous concrete and the possibility of justifying relaxed design criteria for cracking.

A second project, "Fatigue and Corrosion Fatigue", extends the Phase I study and examines inter alia the effects on reinforcement fatigue strength of low grade concrete, p.f.a. addition and reduced cover. The third project, "Survey of Existing Structures", has the task of collecting information on the long term behaviour of existing structures in the sea. It is intended also to investigate the resistance of existing structures to impact from ships or dropped objects.

The one certain conclusion that can be drawn from this research is that properly constructed reinforced or prestressed concrete has far superior corrosion fatigue properties than any steel.

3. DURABILITY

The durability of marine concrete structures is well established and is demonstrated by certain well known examples, amongst which is Tongue Sand Tower in the Thames Estuary, which has been recently examined in detail (8) with very satisfactory results.

4. CONSTRUCTION OF THE HULL

Both the overall size and the draft, when ready for final tow away from the construction facility, can dictate construction procedures. The overall size of hull required for a large OTEC plant will almost certainly preclude any schemes to build on shore and launch into the water. The probable complexity of the structure, together with the size of elements, is likely to minimise opportunity for precast work with a concrete design. Hull sizes could be of the same order of magnitude as caissons constructed for the North Sea or those which have been recently studied in England to carry the turbines for the Severn Tidal Power scheme.

For example, the base caisson for the Cormorant A North Sea Platform (Fig. 1) has dimensions 100m x 100m x 57m. and a tow away draft of 38m. The proposed caissons for the Severn Tidal Barrage (Fig. 2) have dimensions of 69.5 x 60m and a tow away draft of 23m.

The methods of construction used or proposed for these caissons therefore have relevance to the OTEC construction. It is worth outlining the methods particularly as they have been devised for different requirements, the one off and the multiple production.

The Cormorant platform was built at the McAlpine Ardyne facility in Argyll, Scotland as were platforms for Elf and Shell's Brent C. As has been reported before (1,2,3), the essential features of the Ardyne construction method were :-

1. Building a base tray of the caisson with walls about 15m high in a dry shoreside basin. (Fig.3),
2. Breaching the bund wall and flooding the basin with the tray section water ballasted to keep it in position during the flooding.
3. Deballasting the tray to bring it to the floating mode.
4. Tow out to a close inshore mooring in sufficiently deep water.
5. Completion of caisson, superstructure construction and components of mechanical and electrical installations whilst in the floating mode at the inshore mooring.

The completed caissons were then towed to very deep water in either a Scottish loch or a Norwegian fjord for mating with their decks and topside facilities.

One difficult with this method of construction is that activity 5, above, represents a very considerable volume of work that has to be done with the structure rising and falling with the tide. Access for labor was by floating Bailey bridge (Fig.1) which also carried the concrete pump line, all other supplies and components being brought to the structure by barge. These constraints are acceptable when construction is on a one-off basis but should be avoided if possible where multiple production is anticipated.

For the Severn Tidal Power project, about 100 concrete caissons will be required to house the turbine generators and the sluice gates, the turbine caissons each comprising some 38,000m^3 of reinforced concrete. In addition, up to eighty plain caissons could be required, to act as abutments to the powerhouse and sluice blocks and to form the embankment in deep water. With these large numbers of major structures, it is clearly necessary to develop a production line basis as far as possible. It is proposed to build a construction facility (Fig.4), combining dry and wet basins. The dry basins will be closed by caisson type gates and several bottom tray sections of the caissons will be constructed simultaneously in each dry dock. The dock will then be flooded and the trays towed out to the first set of wet basins where they will be water ballasted down onto prepared beds, thus permitting construction to be continued from a quay unaffected by the rise and fall of the tide. Dependent on the draft of the completed caisson and the tidal range, it may be necessary to move the partly completed caisson to a deeper basin where again it would be ballasted down onto a prepared bed for completion of construction. Such a method, it is believed, will reduce construction time and costs. It could possibly be adapted for OTEC hull construction. Lessons learned in North Sea construction, of minimising offshore work, must be followed.

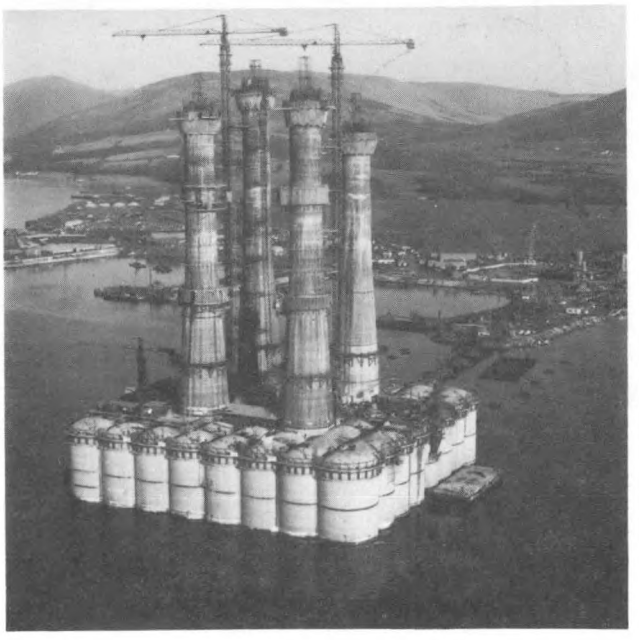


Figure 1

Cormorant "A" North Sea Platform

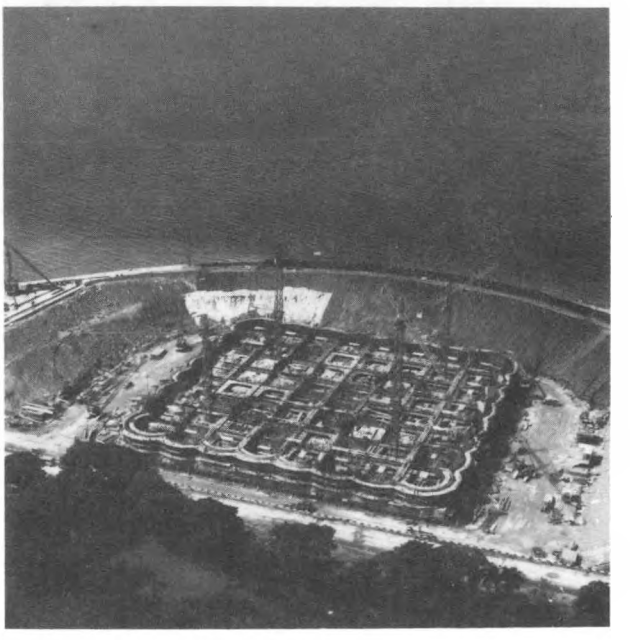
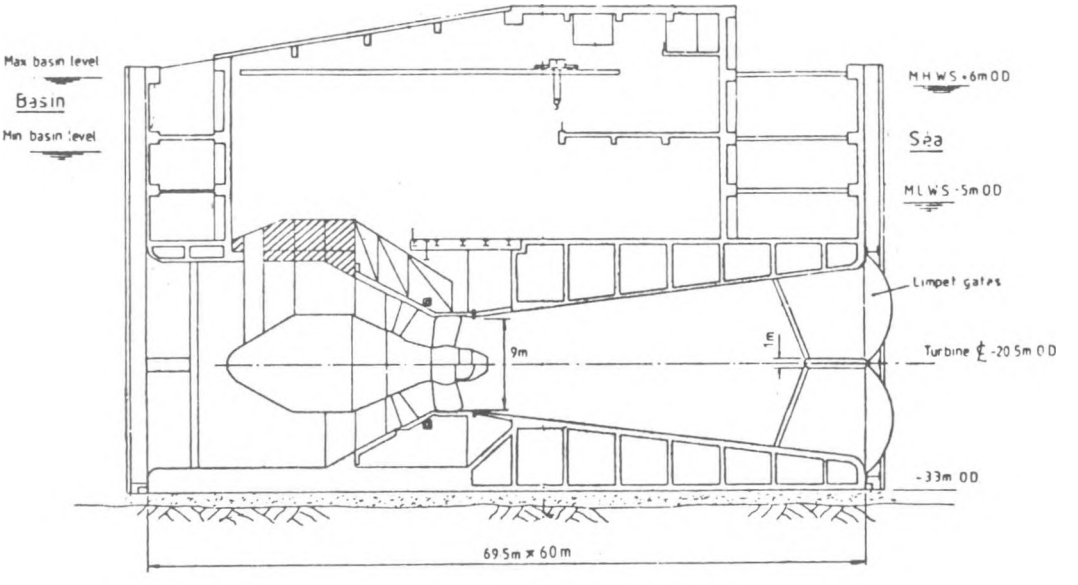


Figure 3

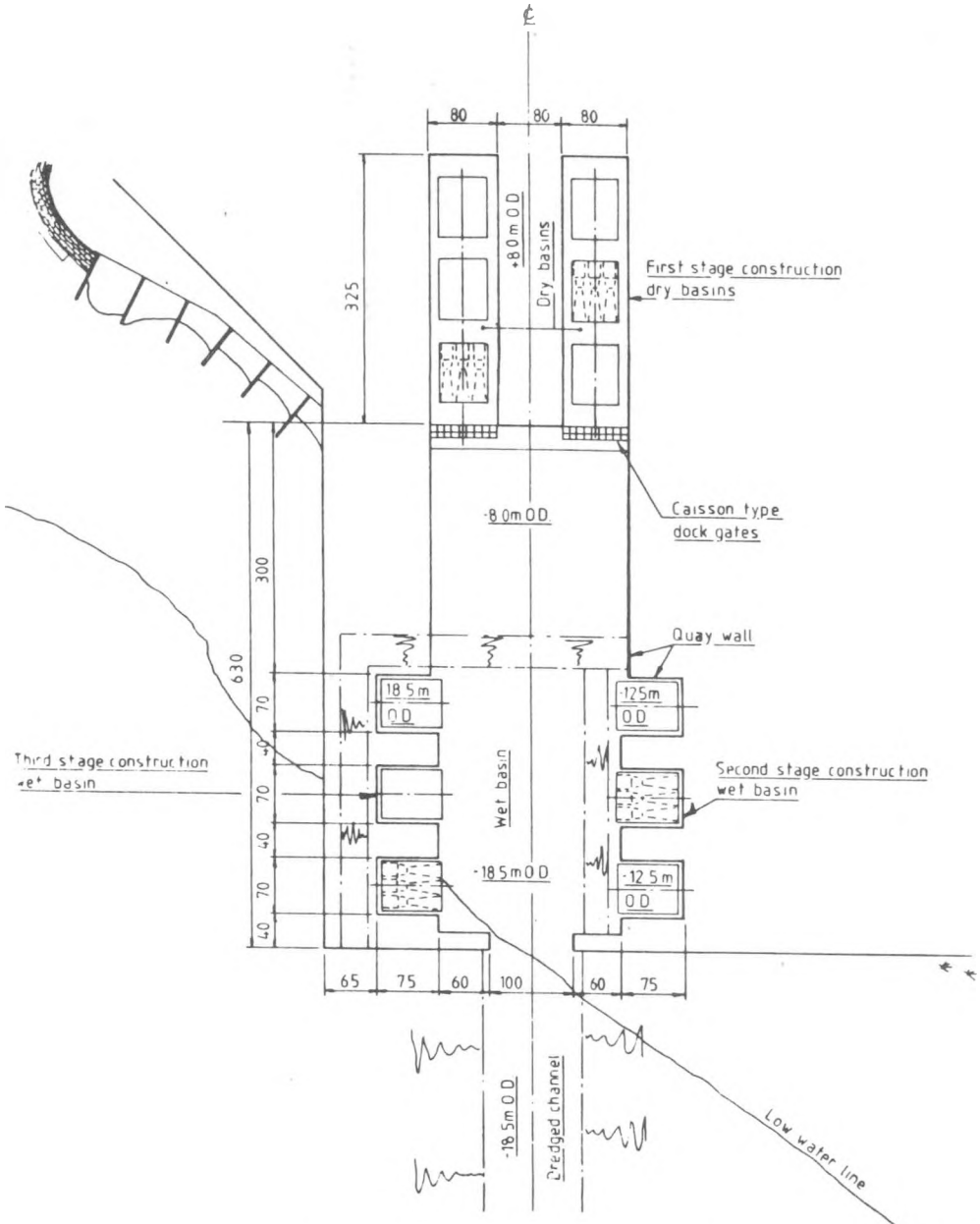
Base of North Sea Platform in Dry Basin



SEVERN TIDAL POWER - SECTION THROUGH CAISSON FOR 9M DIA. BULB TURBINES

Figure 2

Severn Tidal Power - Section through caisson



LAYOUT OF SITE FOR CONSTRUCTION OF
3 × 9.0m DIA TURBINES CAISSONS

Figure 4

Layout of Site for construction of
3 x 9m dia Turbines caissons

5. CONSTRUCTION SITE

Great care is necessary in selecting suitable construction sites with the dominant criterion being ready access to sufficiently deep water close inshore. Other important criteria relate largely to the logistics of labor and materials. It is cheaper to take the construction site to the centres of labor and materials and accept a longer tow than to transport the labor and material. Therefore many regions may be economically suitable for the construction facilities.

6. QUALITY CONTROL

Earlier in the paper, the high quality of concrete construction necessary for an OTEC has been stressed and the standards that have been obtained for the North Sea platforms demonstrate that this is achievable. The Contractor must accept the need for a high level of quality assurance at site. Careful preplanning of the works can bring benefits in both quality and cost control. This preplanning must start at the design stage, when careful appreciation of construction problems and methods will yield substantial bonuses. The study reported by Woolley and Tricklebank (10), in connection with the mass production of the Cockerell raft wave energy device, is a good example of this. Not only can this preplanning permit a high degree of mechanisation at the construction facility but the reduction of the work to relatively few repetitive tasks aids quality. Management as well as labor become highly skilled at their jobs.

7. RELEVANT UNITED KINGDOM R & D PROGRAMS

Much R & D work is proceeding in the United Kingdom on marine structures, some relating to other energy projects. The most relevant to the subject matter of this Conference may be listed as:-

Severn tidal power scheme (to which reference has already been made).
Wave energy program.
Wind energy program.
Offshore structure development for oilfields at ocean depths in excess of 300m.
Underwater inspection and repair of concrete.

7.1 Wave Energy

Britain is playing a leading role in the technically difficult and challenging attempt to devise means by which wave energy may be economically harnessed. Considerable progress has been made during the last two years. Of the four best known first generation devices referred to by Derrington at your 1979 Conference (1) only one, a modified version of the oscillating water column, remains a front runner. The Russell rectifier and the Cockerell rafts (10) have reached the end of their development possibilities during which they have made most useful contributions to the program and to the art of offshore structures. The Salter ducks, with the sophisticated gyroscope controlled power takeoff system, are considered too complex to develop for a first full scale device. From the numerous second generation devices, two have emerged as a leading contenders, the Bristol Submerged Cylinder (Fig. 5) and the Flexible Airbag developed by Prof. Michael French at Lancaster University (Fig. 6).

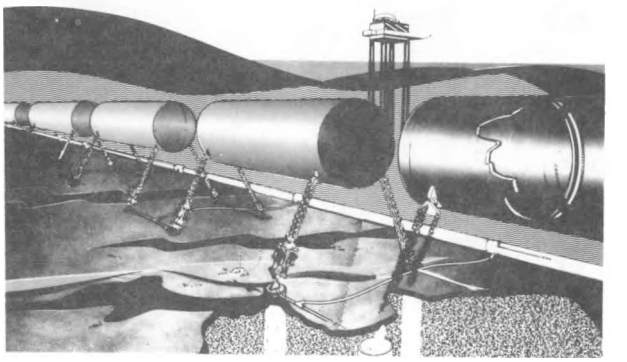


Figure 5

Array of Bristol Cylinder Wave Energy devices

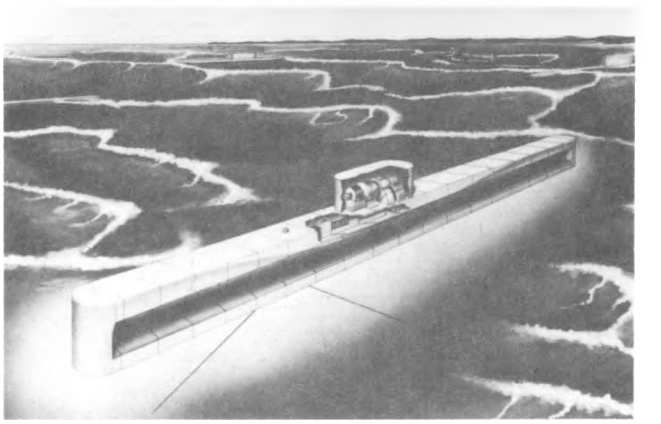


Figure 6

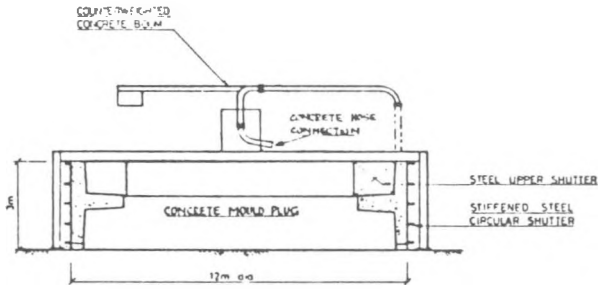
Lancaster Flexible Bag Wave Energy device

In the Bristol device, the cylinder is of hollow concrete construction with a specific gravity of 0.6 and is 12m in diameter by 51m long. It is held down below mean sea level by four moorings or rodes which are thus pretensioned to about 750 tonnes each. Reacting to the water motion within waves, the cylinder describes an approximately circular orbit thus varying the tension in the moorings. Within the moorings, just above the seabed anchorages, are the power takeoff units. Compliance in the moorings is concentrated in these units, any compliance or stretch in the remaining part of the rodes results in less power in the system. Thus the movement of the cylinder

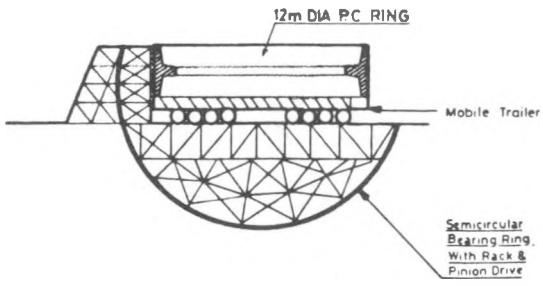
varies the tension in the rodes and activates a double acting reciprocating pump in the power takeoff. This delivers high pressure water, by means of a large diameter seabed main to a power station either on a marine platform or on shore. The power takeoff units include oil/nitrogen accumulators and pumps which act as powerful springs to drive the return stroke of the main pump and to tune the system by providing the desired damping to the cylinder. The device is being designed for deployment off the West Coast of the Outer Hebrides in approximately 45m depth of water where the sea has a high level of energy averaging 48 kW per m. Each cylinder device will have a rated capacity of about 4.0 MW and thus a string of about 500 would be required for a 2000 MW power station occupying a coastal length of about 30 miles.

Though the cylinder is designed for shallow water depths the moorings will be subject to the same cyclical variations of stress as those for the OTEC. In a 25 year design life some 10^8 cycles of stress must be accommodated and designs are being prepared accordingly.

The concrete cylinders are not insignificant structures and should afford good opportunity for mass production. It is planned that they will be precast in circular segments in special moulds (Fig. 7), then placed on a horizontal cradle and prestressed together using epoxy joints. The completed cylinder will then be launched into the sea and towed into position. The development of installation and maintenance methods is underway with the assistance of experts in underwater technology.



CASTING ARRANGEMENT FOR CYLINDER RINGS



TILTING TABLE

Figure 7

Construction details of Bristol Cylinder

The Lancaster flexible bag (LFB) wave energy converter (Fig 6) is moored bow into the waves in contrast to the Bristol cylinder which is moored parallel to the oncoming wave crest.As the waves pass down its length the many air compartments within the bag are alternately compressed and released. They are connected by non return valves to high and low pressure air ducts which lead to a Wells air turbine which in turn drives a generator. This wave energy converter uses less materials than many other devices and requires relatively simple and conventional moorings. Much research and testing is required, however, to develop the material for the flexible bag. This development is being carried out by Wavepower Ltd. in Southampton.

The British R & D program on wave power is aimed to reach a conclusion at the end of 1981. A full scale demonstration unit of the preferred device will then be made if the anticipated cost of energy is sufficiently encouraging. The detailed studies of mooring problems will be of direct interest to the OTEC program and initial work has served to underline the high costs of materials, installation and maintenance.

7.2 Wind Energy

Reference must also be made to the U.K. wind power program. The U.S.A. is, of course, well in advance of Britain in the design of the aerogenerator, particularly the horizontal axis version but more attention is being paid in the U.K. to offshore wind power due to the shortage of land in Britain (11). It is suggested that concrete substructures and towers be constructed in shoreline facilities, towed out and ballasted down onto the seabed. Thus yet another renewable energy project utilizes the same technology.

7.3 Offshore Structure Development

Other research on offshore structures has been related to oil and gas production from the more inaccessible fields lying under great depths of water. This work is split into programs dealing with tethered buoyant platforms and subsea completions.

Tethered buoyant platforms (12) have now been designed for water depths of 500m and their advocates claim the technology is there to go even deeper. Figure 8 shows a platform developed by BP using tubes for the tension legs. Dynamic motions set up by wave action and drift forces are major considerations in the design of such structures. Theoretical and experimental research is being carried out in the U.K. on piled anchorages for buoyant platforms, including cyclic loading, and has been reported recently by Gallagher and St. John. (13).

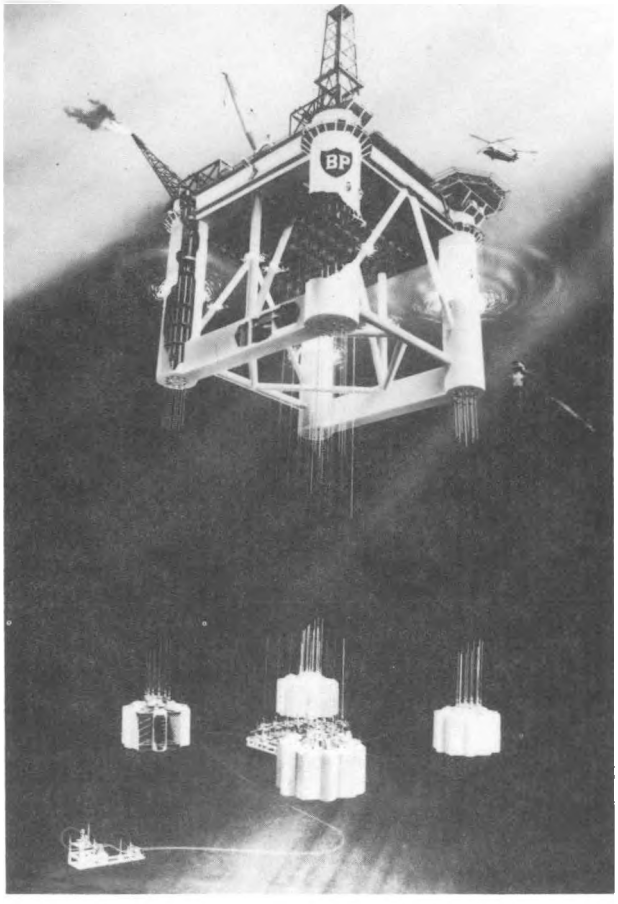


Figure 8

Model of B.P. Tension Leg Platform

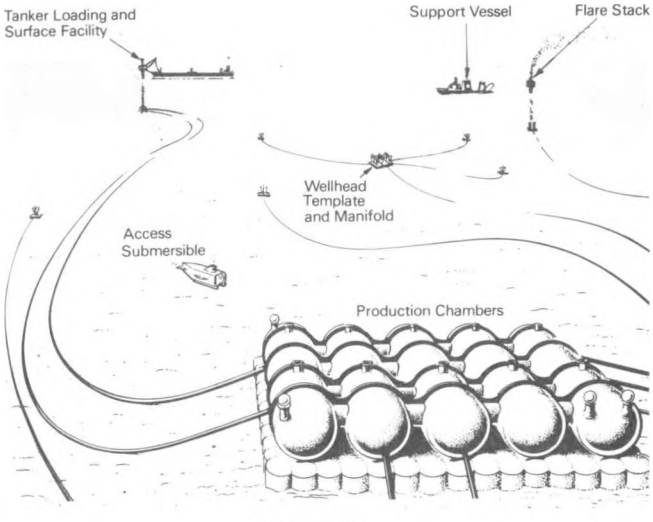


Figure 9

Deep Sea Production System for Oil & Gas

A total deep sea production system for oil and gas (Fig.9)is being developed by an industrial consortium led by McAlpine as reported by Collard (14) and others. One atmosphere containment supported on a submersible caisson will be constructed in a shoreline facility, then towed out to station and lowered to the seabed. Some modules, containing plant needing infrequent maintenance, will have a nitrogen atmosphere whilst the remainder, including habitats, will have a breathable atmosphere. These units are designed for sea water depths down to 1000 m. Those in water shallower than 500 m will be in prestressed concrete whilst the modules for the greater depths may be of sandwich construction of high grade concrete and steel. In all cases, the supporting caisson will be in reinforced and prestressed concrete. Current work involves model experimentation of implosion and permeability under great pressure, methods of lowering through the water/air plane and accurately positioning on the seabed at depth. Again this work could have relevance to OTEC design.

8. MAINTENANCE OF HULLS

Maintenance costs with concrete hulls should be small compared with steel. Designs must be prepared with the aim of facilitating inspection and maintenance.

Three organizations in the U.K. have been carrying out R & D studies, supported by the Department of Energy, into underwater concrete repair (15) and this work has a direct relevance to the OTEC program. Divers involved in inspection and repair must be trained in the methods of construction so that they can readily comprehend locations of possible weakness such as construction joints and around built in items. They should also have a basic understanding of the mode of operation of reinforcement and prestressing tendons as the ill informed diver cannot be adequately instructed from the surface.

Causes of deterioration or damage to concrete that may require remedial measures can be summarised as follows,

1. Chemical action.

   (a) Salts in the seawater attacking the cement.
   (b) Alkali aggregate reaction.

Both these can be avoided by the proper selection of materials and good concrete design.

2. Physical action on concrete.

   (a) Abrasion reducing thickness of reinforcement cover.
   (b) Accidental damage reducing or removing concrete cover.
   (c) Cavitation caused by high velocity of water (more than 12 m/sec).
   (d) Cracking caused by overloading.

3. Corrosion of embedded steel.

inspection procedures and methods will have to be agreed with the U.S. Coastguard or relevant certifying authority. The records that can be obtained for the engineer on the surface include:-

(a) T.V. pictures of varying quality which should show up any damage before it reaches a critical stage.

(b) Color photographs, which can usually be of good quality, of any areas where damage is observed or suspected.

The maximum information however comes from the reports of the divers.

8.1 Underwater Concrete Repair

When the underwater survey reveals the necessity to carry out repairs to concrete, this can be satisfactorily carried out at considerable depths by specialists. The depth is only limited by diving technology. The U.K. research has included laboratory testing, tank and open sea trials, which have determined satisfactory methods and materials.

Repair materials fall into two categories, cementitious and epoxy resins. They have different characteristics and the following points must be considered in making a selection.

(a) Cementitious grouts are very similar to concrete in all respects in their hardened state. These would have to be used where the repair is required to replace concrete and reinstate the full strength of the structure.

(b) Resin materials are as strong as concrete and even stronger in tension but much more elastic. They are consequently more resistant to impact but not suitable to replace concrete for reinstating full structural strength.

(c) Cementitious materials cannot be mixed under water at the work site therefore the period between mixing and placing is critical.

(d) Resins can be mixed as part of the placing operation.

(e) Resins are less permeable and more inert in sea water than cementitious materials

(f) The bond of cementitious grouts is generally stronger than resins and less affected by microbial surface contamination.

(g) Resins have lower viscosity than cementitious grouts and therefore are more suitable for injection into narrow cracks.

(h) The high exothermic reaction of epoxy resin materials restricts the volume/surface area ratio that is acceptable for a satisfactory repair; the higher the ambient temperature the smaller the ratio must be. In water at 5° to 7°C the maximum depth of repair with resin is about 100mm. The introduction of a filler, such as very coarse agregate, into a void before injection of resin will reduce the heat generated and permit its satisfactory use in larger volumes of damage repair.

The research has identified the most suitable epoxy resins and grouts. The grouts are based on ordinary portland cement but with careful grading and inclusion of additives to:-

(a) improve the adhesion to the concrete substrate under seawater,

(b) maintain the stability of the grout as a liquid and prevent segregation and bleeding,

(c) increase the impermeability and resistance to chemical attack of the hardened grout,

(d) maintain a satisfactory flow characteristic during transportation and placing.

The design of these additives is critical, to avoid chemical interference and to match the appropriate seawater conditions.

The U.K. work has included the design and testing of hydraulically operated applicator pots for both grouts and resins.

Good preparation of the damaged area is essential prior to repair. High pressure water jetting (10-15,000p.s.i.) is most effective for preparation of concrete. A fine "pencil" jet will cut out concrete to a satisfactory texture and remove loose material. Final cleaning with a fan jet, immediately prior to application of the repair material, will minimise microbial contamination which could adversely affect the bond of the repair material, particularly resin.

Where the nature of the damage requires the repair material to be placed behind a shutter it is essential that this is sealed against the concrete surface and special gaskets have been designed for use under seawater. It is also helpful if the shutter is transparent, to permit visual check that filling is complete. Total filling of cracks is also essential but should be achieved using resins of sufficiently low viscosity rather than high pressure which can create further damage.

The techniques developed for the underwater repair of concrete structures, were first used in July 1979 on a column of a concrete drilling and production platform in the North Sea. The damage at a depth of 36m was caused by abrasion forming a horizontal gouge 2.6m long, 150mm wide with a maximum depth of 80mm; two rebars were exposed flush with the face of the concrete. The repair was successfully carried out by enclosing the damaged area with a shutter and injecting the void with epoxy resin.

In April 1980 the technique was used successfully again to seal 3 leaks with epoxy resin on the forward half of the oil tanker, "M.V. Tanio", which had sunk off the coast of Brittany after the vessel had broken in half. The work was carried out at a depth of 90m with divers locked out from a submersible.

At the time of writing, preparations have been completed to carry out repairs, as soon as weather conditions permit, to the damaged caisson roof of a concrete North Sea platform. Other repairs are also scheduled.

9. CONCLUSIONS

1. U.K. work in the North Sea and in research programs is relevant to the design, construction and mooring of OTEC plants.

2. The design of construction facilities can vary substantially dependent on numbers of hulls to be produced and the float out draft.

3. Technologies have been developed to ensure that underwater damage to an OTEC hull may be satisfactorily inspected and repaired insitu at all depths where such damage is likely to occur.

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CONSTRUCTABILITY OF EXTENDED SURFACE HEAT EXCHANGERS FOR OTEC

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ABSTRACT

The time has arrived when OTEC system selections must be made on the basis of current technology and current manufacturing capability for the various key components in order to meet cost and schedule goals. Many heat exchanger surfaces have been studied through the auspices of the DOE OTEC program. Some of these show promise worthy of continued research and development. Very few of the many surfaces investigated have undergone the rigors of meeting competition in the marketplace. The brazed aluminum plate-fin heat exchanger concept suggested herein is a technically feasible adaptation of an existing product that has undergone many years of industrial experience.

Brazed aluminum plate-fin heat exchangers were introduced to the OTEC program through a cooperative effort by the U.S. Department of Energy, the Argonne National Laboratory, and The Trane Company. This initial effort consisted of an evaporator performance demonstration of a test unit expediently fabricated from available components in a design considered not suitable for seawater exposure. The highly satisfactory results of this test led to additional tests, analytical investigations, and efforts to qualify for OTEC operations. The additional tests consisted of falling-film evaporation, falling-film condensation, and effects of ammonia contaminated by water. Analytical investigations were carried out by ANL, jointly by Westinghouse and Trane, and independently by Trane to establish power system costs based on the use of the brazed aluminum plate-fin heat exchangers. Encouraged by the favorable test results and analytical conclusions, extensive work was initiated to design, fabricate and qualify these extended surface heat exchangers for OTEC.

This paper deals with the issues of manufacturability, performance, compactness, serviceability, modularization, seawater worthiness, and cost effectiveness. Several active test programs will be discussed that are intended to address the issue of sea-water worthiness of this compact brazed aluminum OTEC heat exchanger concept. In addition, the paper challenges the generally accepted notion that the very success of the OTEC program depends on innovative heat transfer surfaces to reduce required surface area and hence unit cost.

INTRODUCTION

At the Fourth Annual Conference on Ocean Thermal Energy Conversion, the Andersons of Sea Solar Power Inc. stressed their thoughts that compact plate-fin heat exchangers made of aluminum offered significant advantages to the OTEC program. (1) Figure 11 of the Anderson paper related Area/Cu Ft and Cost/Sq Ft for various shell and tube designs with that of the plate-fin aluminum heat exchangers commonly used in the cryogenic industry. Although these surface area, volume, and cost parameters offered significant advantages, there was no practical approach known at that time to allow seawater exposure into the configurated matrix surface of these heat exchangers. Crevice corrosion would have been tantamount to early failure. Cleanability would be impossible due to the inaccessibility of the extended surface area.

During the last several years, a considerable amount of work was undertaken by The Trane Company to modify the well established brazed aluminum technology to adapt to the challenges of seawater corrosion and cleanability without seriously impacting on the desirable surface area, volume, and cost parameters. The Argonne National Laboratory has played a significant role in determining the thermal/hydraulic characteristics of two versions of this hybrid brazed aluminum configuration. The first design was fabricated in 1979 and consisted of flat water passages sandwiched between the working fluid passages. This

test core was expediently fabricated from existing material and, therefore, did not contain the preferred hollow extrusion. The Argonne National Laboratory introduced the data from this initial design at the Sixth Ocean Energy Conference. (2) The test results clearly exhibited the highly desirable performance and volume characteristics and provided ammonia boiling and condensing coefficients previously unavailable for this type of heat exchanger. The major task remained to develop an adaptation to the basic brazed aluminum configuration that would qualify for seawater exposure.

The alternatives available at that time were to pursue the alclad protective system with the flat plate design or to pursue the hollow extrusion concept and depend on finding an alloy that would extrude, braze, and resist seawater corrosion.

The flat plate design of the above core could be fabricated with ALCLAD 3003 sheets with the 7072 zinc-containing surface exposed to the seawater side. McNamara and Singleton of Reynolds Aluminum described the redistribution of the zinc as a result of the time-temperature of a brazing cycle. (3) A first and optimistic consideration predicted that a sufficient amount of zinc remained to protect the substrate from deep pitting by the galvanic protection principle. It was thought that thicker layers of the clad and/or higher zinc concentrations could be used to compensate for the removal of zinc in the outer surface. Continued analysis of the "wash-out" effect of the zinc at the outer surface indicated an adverse and undesirable condition existed.

This adverse condition that is now considered unacceptable for exposure to a corrosive atmosphere was described by McNamara. The outer surface had little or no zinc with increasing amounts of zinc (toward one percent) at depths of three to four thousandths. In that the galvanic sacrificial driving potential is a direct function of the zinc concentrations, it can be shown that the outer surface would be protected by the deeper portions. Or, the pitting corrosion action would be accelerated, not inhibited. Through investigations to either protect or restore the alclad layer to its desirable portion of zinc in aluminum, we learned of a process that could provide an "alclad-effect" subsequent to manufacturing procedures.

A considerable effort was undertaken by Trane to develop this subsequent plating/diffusion concept for application to the seawater passages of a heat exchanger. In fact, it was found practical to make this metallurgical treatment inside the preferred hollow extrusions for additional seawater qualification benefits.

A second test core was fabricated and tested at the Argonne National Laboratory that utilized the preferred hollow extrusion for the seawater passage. The most significant advantages offered by this hollow extrusion configuration are:

1. Complete elimination of crevice corrosion sites. Crevice corrosion is the most adverse form of seawater corrosion.

2. The seawater passages provided by hollow extrusions are fully accessible by various cleaning methods.

3. The technology of extruding aluminum requires wall thicknesses in excess of that required for structural purposes. This excess wall thickness will provide for extended life in the seawater atmosphere.

Test results of this hollow extrusion heat exchanger were as favorable as those of the simpler flat-plate design previously described. A full report on the performance test was presented by ANL at the Eighth Ocean Energy Conference. (4)

To date, we are fortunate to have an ongoing seawater test program offshore Puerto Rico sponsored by NASA and DOE with technical and evaluating support provided by Trane, Kaiser Aluminum, and the Center for Energy and Environmental Research of the University of Puerto Rico. This program will investigate the corrosion control concept described above under conditions of required cleaning to assure good heat transfer conditions. Actual testing started in May, 1981, and will be reported after six months of observation. The initial results are encouraging and already suggest that the removal of the zinc-aluminum surface may occur in a stratifying or layering manner as a result of the decreasing zinc concentration gradient vs. depth. Mr. Frank LaQue (5) has suggested that a nominal rate for removal of an alclad layer would be 0.001 inch per year. The current test program is following that suggested by LaQue.

CONSTRUCTIBILITY

Although the main object of this paper is to present a heat exchanger concept for OTEC that can be fabricated with existing technology and production facilities, it was apparent that these desirable attributes were of little consequence if the issue of seawater worthiness was not addressed. We now have good reason to believe that the

seawater worthiness issue is progressing very well and can soon be shown to qualify this innovative design.

Trane has brazed-aluminum facilities in La Crosse, Wisconsin and in Epinal, France. The technology of brazing aluminum dates back to World War II when aircraft heat exchangers were fabricated. The first major use of brazed aluminum occurred in the cryogenic application mainly because aluminum exhibited highly desirable mechanical and thermal properties at these low temperature levels, was inexpensive and readily available. The demand for reliability under adverse conditions has led to a very sophisticated technology steming from the nearly forty years of experience. Thus, when one compares brazed aluminum with shell and tube heat exchangers, it is not a matter of new vs. old. The La Crosse facility has an annual production capacity of $30 million, or, when related to OTEC capacity, 60 megawatts. A variety of extended surfaces are available to the designer to allow optimization for many thermal/hydraulic conditions. A detailed production sequence is provided in Reference (6).

The extended surfaces provide the structural support of adjacent flat surfaces and provide for heat transfer augmentation through boundary layer disturbance and utilization of inexpensive surface area. Meticulously made piece parts of exacting tolerances are stacked between flat sheets (or hollow extrusions) to provide for cohesive bonding throughout. Single piece cores are available now in 4 ft x 4 ft cross section by 20 ft long. Each single core would have an OTEC equivalency of 0.5 megawatts. Headers are welded to the completed brazed core to meet stringent ASME (or other) code requirements. Leakages are essentially non-existent in the completed and qualified heat exchanger as evidenced by very low level mass spectrometer verification. Each rectangular cubed heat exchanger core is a self contained pressure vessel capable of being stacked into rectangular compartments with very little waste volume. The cryogenic application requires complex headering and manifolding to accommodate the heat transfer relationship between many different streams. These are frequently preassembled in the La Crosse facility to provide for minimum field erection and assembly labor. Although the test cores fabricated for testing at Argonne included headers on both the working fluid and seawater streams, it is anticipated that only the working fluid headers and manifolds would be required on a plantship installation. Based on previous transportation experience, an assembly of heat exchanger cores and associated manifolds equivalent to two or three megawatts could be pre-assembled in La Crosse.

There are a number of subtle features of this fully modularized configuration worthy of comment. The two or three megawatt assembly described above could be isolated and removed from an operating power module for service or replacement without disrupting power generation. After the large assembly was removed from its compartment, any separate core could be removed by cutting two pipe weld joints. Even without removing the individual core, a premature localized leak could be weld sealed by closing off each end of the faulty water passage. If it would be found desirable to perform periodic extensive cleaning or service of the seawater passages, an extra heat exchanger/manifold assembly could be rotationally exchanged with those in service and reduce (not terminate) power generation only during the exchange procedure.

COST CONSIDERATIONS

One of the most confusing and often misleading parameters associated with the various OTEC power system components is that of heat exchanger costs. It is extremely difficult to relate various heat exchanger concepts without first reducing the many performance, volume, maintenance, and life expectancy considerations to a common denominator. Since the OTEC system does not require fuel, it is logical that amortized capital cost per generated power is a realistic divisor. Even then, a system analyst could influence a decision by adjusting certain parameters. It will be the object within this paper to identify several of common misnomers associated with comparing heat exchanger costs and to recap some of the previously published cost projections for the Trane brazed aluminum OTEC heat exchanger. The identifiable misnomers are as follows:

1. Comparison of Overall Coefficient of Heat Transfer.

   Much of the early work in the OTEC program was directed toward soliciting innovative heat transfer surfaces because of the expectation of reducing overall heat exchanger costs proportional to the working fluid coefficient of heat transfer. The practicality of a design or the constructability of the proposed equipment were considered of lower importance to that of heat transfer coefficient. Also neglected in this scenario was the fact that the cost of the heat transfer surface area could vary substantially from one proposed surface to another. It was thus possible to overlook a good potential if it exhibited a low test value of coefficient of heat transfer even though it had offsetting attributes. The futility of this pursuit

should have been apparent when one observes that the seawater heat exchanger coefficient is not only controlling but also constrained to smooth surfaces for cleanability and corrosion concerns.

2. Comparison of Heat Exchanger Cost Per KW of Installed Equipment.

   Each integrated system will have a unique thermal/hydraulic balance based on the relative cost of the various components. It would be unrealistic to compare a second choice heat exchanger without seeking the new thermal/hydraulic balance. This thought can be illustrated best by observing the trend in the thermal/hydraulic selection process when the unit cost of a given heat exchanger is incrementally changed. The system selection process will choose more of the given heat exchanger merely because its unit cost decreased. This concept is greatly expanded as other variables associated with other heat exchanger designs are introduced.

3. Constructability

   A very important requirement of any proposed heat exchanger is that it can be produced with existing technology and, if at all possible, in existing production facilities. The OTEC program carries many risks and uncertainities. It cannot be further burdened with learning how to fabricate a new heat exchanger concept however intriguing the potentials of that concept.

4. Free Enterprise

   A review of our free enterprise system should alert system designers to the fact that a heat exchanger, or any other component, will be priced incrementally lower than the nearest competitor. Only through a fair competitive market can the best possible costs be attained.

COST PROJECTIONS

At the Seventh Ocean Energy Conference, Ashworth and Slebodnick (7) presented the findings of a privately funded study between Trane and Westinghouse which amounted to being a "first-cut" on design, system matching, and cost determination. Since the time of that study, a number of performance tests have been carried out at the Argonne National Laboratory. The overall significance of the test program was to not only confirm the performance data used in the Westinghouse/Trane study but also to show that a considerable amount of conservatism was used in that study.

The second heat exchanger tested at ANL consisted of the hollow extrusion concept which is much favored for seawater exposure over the design used in the Westinghouse/Trane study and the first ANL test core. A summation of the significant factors of the Trane OTEC heat exchanger concept relating to cost are as follows:

1. First-cut analysis by Westinghouse and Trane previously cited. Heat exchanger costs provided as follows:

Year	First Unit	Future Units**
1980	925	583
1979	841	530
1978	765	482
1977*	695	438

   * year of study
   ** based on 100 MW/year

2. Sufficient work carried out by Trane to show that the hollow extrusion design is as cost-effective as the initial flat-plate design.

3. A number of separate tests have been carried out at ANL and cited in the Reference as (2) and (4).

4. The costs provided in 1 above include "accessories" beyond that basically required for or provided with heat exchanger such as: phase separator, wells for both condensor and evaporator, associated manifolding, and working fluid connections above water line.

5. The ground work now exists to make a final design that would include the latest performance information, the results of developmental production efforts, the preferred hollow extrusion concepts, and the zinc plating/diffusing corrosion control concept.

REPLACEMENT COSTS

Until such time when aluminum can be qualified for a thirty-year service life in seawater to directly compete with titanium, it is necessary to include replacements in the cost analysis. In addition to the abundant wall thicknesses of the hollow extrusion design and the related increase in life expectancy, the use of hollow extrusions offers a highly desirable replacement cost consideration. The predominant weight component in this design is the hollow extrusion. The raw material sequence for the extrusions is as follows:

1. Ingots provided by major aluminum producer.
2. Melt ingots and place in much smaller billet form for insertion into extruding press.
3. Extrude to desired shape with

approximately 25% of billet winding up as scrap for immediate recycling.

4. Once a unitized production facility is available to accept ingots and convert these to OTEC heat exchangers, approximately 45% of the final product cost will be that of ingot from raw material.

5. In the case of the Trane OTEC concept, the entire heat exchanger will consist of certified 3003 with trace amounts of silicon added for brazing and trace amounts of zinc added for the seawater corrosion control concept.

6. At such time when a given heat exchanger can no longer be economically repaired and is declared scrap, it still retains its original certification of 3003 aluminum. The zinc would have been dissipated by means of the corrosion control sequence and would not appreciably change the normal small silicon content of 3003.

7. The above scrap heat exchanger can reenter the above production sequence where it would have the same assessed value as the ingot or 45% of the new heat exchanger cost.

8. The above recycling sequence is particularly impressive when one considers that scrap aluminum price varies between 25% and 50% of ingot price based on the purity and condition of the scrap.

CONCLUDING REMARKS

The brazed aluminum heat exchangers concept suggested herein (and References) for OTEC is supported by many years of production experience and process equipment operating experience. Although production facilities do not now exist for the projected mature OTEC market, there are now adequate facilities for the first several hundred megawatts of OTEC power. The hollow extrusion concept combined with the zinc plating/diffusion corrosion control concept offers the best possible configuration to qualify aluminum for OTEC. Crevice corrosion sites are entirely eliminated, wall thicknesses offer good potential for success, and the plating/diffusion procedure should be the added assurance necessary to risk the use of aluminum for OTEC use. Brazed aluminum has long exhibited the characteristics that place it in a highly desirable economic picture as observed by the Anderson's.

The current test program on the CEER facilities of the University of Puerto Rico will be the last major verification for this unique OTEC heat exchanger concept.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the OTEC staff at the Argonne National Laboratory for their continued support throughout the introductory period for this sometimes controversial OTEC heat exchanger concept. In addition, the author wishes to thank ANL and NASA for funding the test program currently underway in Puerto Rico. Of all the monies spent on OTEC, this test at Puerto Rico may prove to be the most significant toward the continuation and advancement of OTEC.

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TRANE OTEC HEAT EXCHANGER CONCEPT

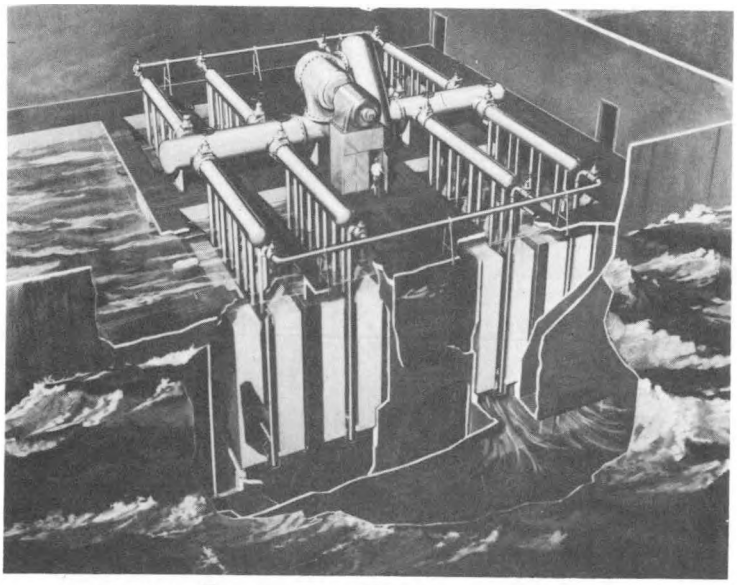


FIGURE 1, 10 MEGAWATT OTEC CONCEPT

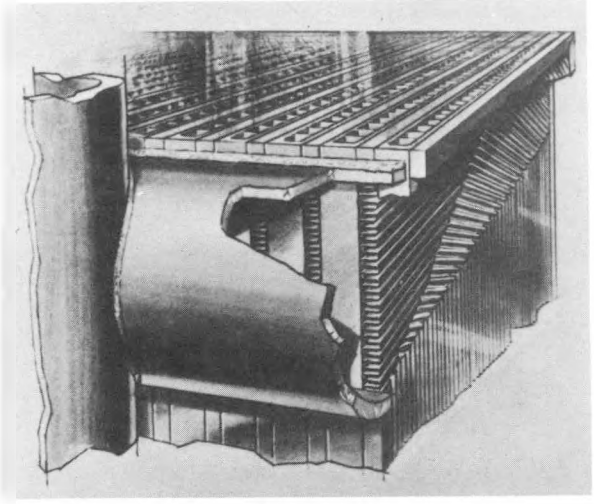


FIGURE 2, CUT-AWAY VIEW AT END OF CORE

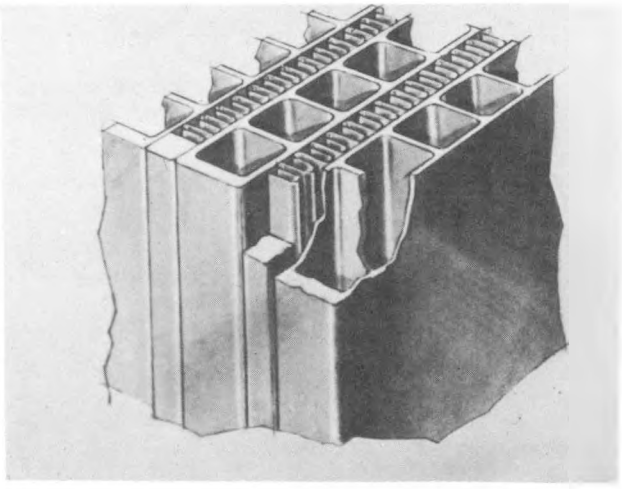


FIGURE 3, CROSS-SECTION AT MID CORE

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APPLICATION OF OTEC-1 PERFORMANCE AND FABRICATION COST DATA TO ESTIMATION OF OTEC POWER SYSTEM COST

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ABSTRACT

Recent experiments conducted onboard OTEC-1 off Hawaii have resulted in considerable data on the thermal/hydraulic performance of a 1 MWe scale heat exchanger test loop. These data can be readily scaled up to heat exchangers and power system components at the 5 MWe scale. The design and fabrication of the 1 MWe test articles, instrumentation, and auxiliary equipment were specific to the experimental test objectives of the OTEC-1 program. Thus, equipment costs are specific to the test articles and are not typical of those for production designs.

The purpose of this paper is to develop an OTEC power module cost estimate based on the extensive itemized fabrication cost data for the 1 MWe test articles, their measured performance onboard OTEC-1 and changes in the test article designs to exclude test specific features. The result is an OTEC power system module cost estimate based on off-the-shelf hardware cost and performance data. These data can serve as a benchmark for future improvements in OTEC technology and expected reductions in capital cost.

1. INTRODUCTION

Ocean Thermal Energy Conversion (OTEC) utilizes the temperature difference between warmer water at the ocean's surface and colder water at depths of 2000 ft. or more to drive a heat engine and generate useful energy. Systems studies performed by TRW (1)*, Lockheed (2) and others investigated the cost and performance aspects of closed cycle OTEC plants capable of producing 100 MW of electrical power. These studies indicated that a significant percentage of the total plant cost was due to the heat exchangers and that overall performance is critically dependent on successful heat exchanger operation.

Recognizing the heat exchangers as a critical component, the U. S. Department of Energy initiated the OTEC-1 program to design, fabricate and test on an ocean platform, large scale heat exchanger test articles.

These shell and tube heat exchangers with a thermal duty of 40 MW (an equivalent electrical output of 1 MW) were completed in late 1979 (3). Designated the 1 MWe Heat Exchangers for OTEC, they were installed on-board a former U. S. Navy tanker renamed the S.S. Energy Converter and deployed off Hawaii in late 1980 for ocean testing. Experimental results obtained during this test program are reported in Reference (4).

The purpose of this paper is to relate the experience gained in designing, building and testing the 1 MWe heat exchangers to design and cost estimating of heat exchangers for future OTEC pilot and commercial power plants.

The 1 MWe units were designed and built to achieve the goals of the OTEC-1 experimental program. The configuration, materials selection and fabrication methods would therefore change if similar units were to be designed and built specifically for a pilot or commercial OTEC plant. Recognizing the experimental objective for the 1 MWe heat exchangers, the following method will be used to derive design and cost data for pilot and commercial OTEC heat exchangers:

1. Revise the heat exchanger design to reflect removal of the test-specific features and use data obtained from the OTEC-1 experiments in predicting performance.
2. Recognize the learning curve in fabricating these first large-scale OTEC heat exchangers and revise the designs and fabrication procedures accordingly.
3. Scale-up the revised designs to the expected output of a pilot or commercial scale plant.

2. REVISION OF 1 MWe HEAT EXCHANGER DESIGNS

2.1 Exclude Test Specific Features

As previously stated, the 1 MWe heat exchangers and their associated auxiliary equipment include a large number of features which are not necessary for achieving measured heat transfer performance but were included to make measurements useful for future designs.

Figure 1 is a schematic of the 1 MWe test loop. Figure 2 shows a cross-section of the evaporator

*Numbers in parenthesis refer to References listed at the end of the paper.

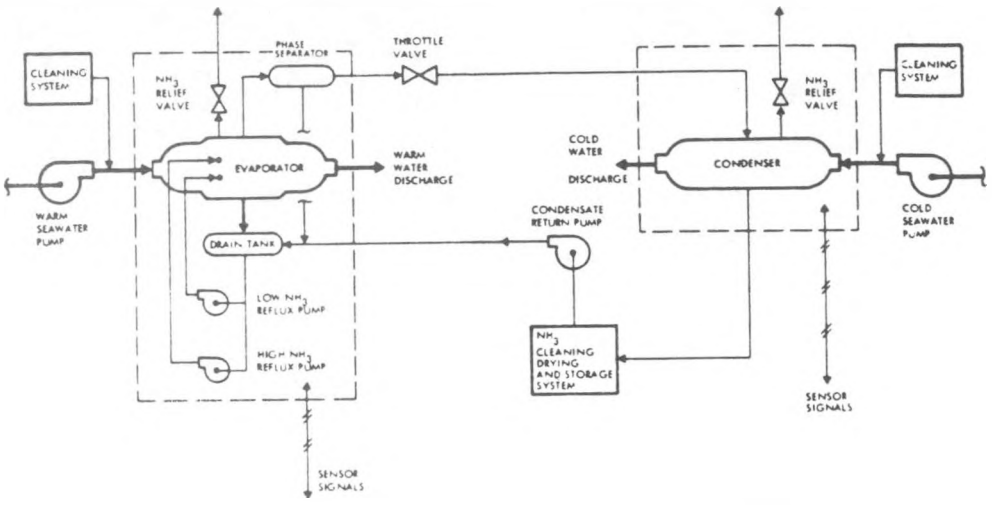


Figure 1. 1 MWe Test Loop Schematic

during fabrication. The test specific features of both units are enumerated in Table 1.

Table 1. Major Test Specific Hardware Changes

Feature	Change
Evaporator shrouds	Delete
Ammonia feed system	Single feed plane
Phase separation	Delete external
Enhanced tubing	Revise performance
Evaporator feed/drain tank	Single reflux system with surge tank
Condenser drain pots	Delete
Waterboxes	Not removable
Miscellaneous	Delete: manways, nozzles, observation ports, test instrumentation

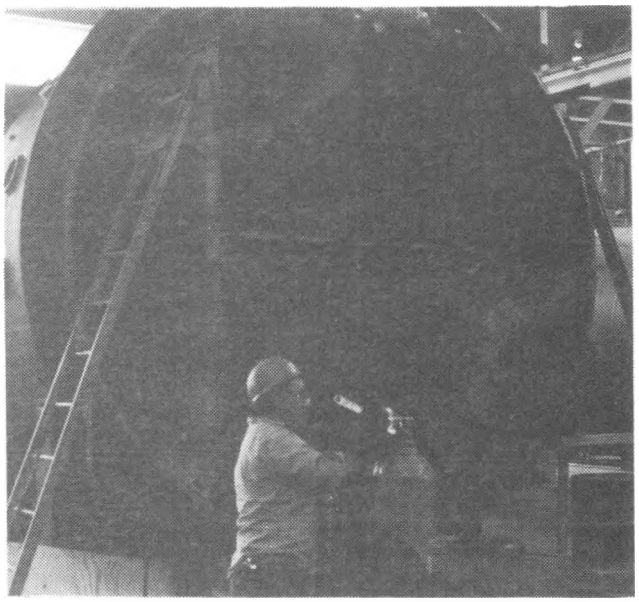


Figure 2. End View of Evaporator

Evaporator Test-Specific Features

From Figure 2, the evaporator is seen to have a square heat transfer tube bundle cross-section. The larger pipes at the top and center of the tube field are the liquid ammonia supply headers which wet the tubes with liquid ammonia to enable ammonia evaporation. The multiple feed headers and two levels of liquid ammonia supply were included in order to assure complete wetting of the evaporator tube bundle. The bundle itself is square as can be seen in Figure 2 in order to be representative of a section from a larger bundle. Although the basic design causes vapor to exit at both sides of the bundle, removable shrouds were included to evaluate a variety of configurations. A detailed description is provided in Reference (3).

Evaporator performance was relatively insensitive to liquid ammonia feed rate and use of the mid-plane feed supply: a single high flow rate supply at the top of the bundle will result in satisfactory performance and deletion of the mid-plane and low flow rate supply systems will reduce both the pressure loss in the reflux system and complexity of the feed system.

The 1 MWe unit included the Union Carbide Corporation - Linde "high-flux" enhancement on the outside of the tubes in the lower half bundle.

Because test results on the heat transfer performance of this enhancement were inconclusive, the remainder of this paper assumes a smooth tubed evaporator.

A vapor separator was included external to the evaporator with capacity sufficient to trap and measure a liquid ammonia carry-over of up to 3 percent of the total mass flow in the evaporator vapor exit. Data from the OTEC-1 experiments do not provide a quantitative measure of liquid ammonia carry-over. However, since the data do indicate that the separator capacity was adequate (no liquid ammonia exited the separator) the external separator can be replaced with an internal separation capacity equal to that provided by the external unit.

The evaporator was also provided with an external drain tank sized to accommodate liquid hold up in the tube bundle during start up of the liquid ammonia feed system at maximum reflux. This tank can be reduced in capacity to reflect operation at the nominal reflux of 2:1 which proved satisfactory during the OTEC-1 tests.

Condenser Test-Specific Features

Test specific features unique to the condenser are limited to the condensate drain measurement system which permits condensate flow rate and temperature measurement in five zones uniformly spaced along the length of the condenser. These measurements were intended to compare the condenser design predictions with performance to determine whether the effective length of the condenser heat transfer tubes could be reduced without significantly reducing the thermal duty. These data were not obtained. However the overall condenser performance was within design predictions. The drain measurement system would be deleted in a commercial OTEC condenser.

Miscellaneous features common to both heat exchangers and unique to the OTEC-1 can also be deleted for a pilot/commercial OTEC plant design. These features would include all test instrumentation not necessary for control, observation ports and nozzles designed specifically to assess heat transfer performance and numerous manways for access to the test hardware.

2.2 Reflect Results of OTEC-1 Experiments

The 1 MWe heat exchanger test articles have an equivalent electrical output of 1 MW based on assumptions made during the design phase which were necessarily conservative. A more realistic equivalent output is described here.

The 1 MW electrical equivalent for the heat exchanger test articles is based on an assumed overall efficiency η of 2.5%:

where

$$\eta = \frac{w}{Q_H} = 0.025$$

w = useful power from turbine
Q_H = heat duty of evaporator

Thus,

$$w = \eta Q_H = (0.025)(40\ MW) = 1\ MW$$

The units were designed using conservative assumptions for the ammonia, water and fouling resistance as discussed in Reference (3).

The operating conditions for the 1 MWe output are stated in Table 1 of Reference (3). The overall evaporator heat transfer coefficient used for predicting the 40 MW thermal duty with an effective heat transfer surface of 61,890 ft^2 was U_o = 364 Btu/hr-ft^2-^oF. Using an average value of U_o = 480 Btu/hr-ft^2-^oF based on the measured data in Reference (4), an average equivalent electrical output of approximately 1.25 MWe is predicted.

In discussions of cost per unit output this higher value of approximately 1.25 MWe should be used rather than the 1 MWe associated with the title for the heat exchanger test articles.

3. INCORPORATE EXPERIENCE GAINED IN FABRICATION OF THE 1 MWe UNITS

3.1 The Fabrication Experience

Fabrication experience with the units in the several phases from shop planning to shipment preparation has demonstrated at least two significant points: First, no fabrication operations differed significantly from normal production common to a pressure vessel fabricating shop. Second, observed performance on the job was close to predictions made during job preplanning in both spent time and assembly sequence. The most significant variable in shop fabrication cost of these heat exchangers was probably labor.

In reviewing fabrication periods where labor loading was intensive, it can be seen that such labor intensive operations were associated with three requirements:

1. The titanium tube welding process developed was unproven and was necessarily conservative and time consuming.

2. Because the exact configuration of the units was not fixed, the designer was forced to provide additional flexibility including margins and trims.

3. The proportion of design changes during fabrication to accommodate the above requirements was excessive as compared to conventional jobs.

Once the above requirements are eliminated, an adjusted basis can be established for estimating the costs of comparible commercial units. Table 2 illustrates the projected variances between the OTEC-1 test unit and a comparible commercial unit. The table provides a cost comparison between the actual 1 MWe unit costs and its commercial equivalent if such is ordered in 1979 dollars. The cost reduction is possible only if the final design configuration reflects deletion of the test specific features and the fabrication improvements described in the following sections are implemented.

The construction of the heat exchangers largely involved conventional steel shop practices augmented with available technologies from such highly specialized sources as explosive cladding and automated tube welding. Problem areas associated with the construction were normal and common to very large pressure vessel fabrication, such as Code compliance, tolerance maintenance, cleanliness, and detection of material and welding defects. A summary of some of the major fabrication activities in their scheduled sequence is given below, including an adequacy assessment of such activity for future construction of similar hardware.

Table 2. Cost Comparisons Between OTEC-1 Test Article Heat Exchangers and Commercial Equivalent

Activity/Component/Feature (A) (C) (F)	ACF	OTEC-1 Function/Purpose	OTEC-1 Cost $	Commercial Equivalent Compared to OTEC-1	Commercial Equivalent Cost $
1. Conceptual Design	A	Define form & functions	86,000	Delete	--
2. Final Design	A	Producible Design	108,000	Reduce	50,000
3. Titanium Tech. Devel.	A	Welding Techniques	18,000	Delete	--
4. Sea State Stress Analysis	A	Structural Worthiness	22,000	Reduce	6,000
5. 4 to 1 Reflux	F	Testing Range	18,000	2 to 1 Reflux	12,000
6. 3 Spray Plenums	C	Operational Modes	60,000	Single Spray Plenum	25,000
7. 8 Manways	C	Access for Modifications	28,000	2 Manways	7,000
8. Waterbox Neoprene Coat	F	Anti-corrosion	30,000	Waterbox Epoxy Coat	8,000
9. Flanged Bolted Waterboxes	F	Accessibility to replace tubes	35,000	Delete	--
10. Flow Directional Shrouds	C	Operational Modes	36,000	Delete	--
11. Observation Ports	C	Inspect Test Conditions	8,000	Delete	--
12. Pool Boiling Conversion	F	Operational Modes	41,000	Delete	--
13. External Mist Eliminator	C	Excessive Design	38,000	Delete	--
14. Condenser Drain Pots	C	Test Measurements	27,000	Delete	--
15. 10 Drain Nozzles		Gravity Drain	6,000	Reduce number to 4	2,000
16. Test Instrument Provisions	C	Testing	10,000	Delete	—
17. Sectional Mock-up Fit-up Testing	A	Producibility Check	5,000	Delete	—
18. Evaporator Drain Tank	C	Mixing Sump for High Reflux	35,000	Reduce	15,000
19. Rolled Tube Joint	A	Backup Joint	15,000	Welded Only	--
20. Enhanced Evaporator Tubes (sintered)	F		300,000	Delete	--
21. Shipping	A		150,000	Reduce	110,000
TOTAL COST OF ITEMS			Actual: 1,076,000		Projected: 235,000
COST OF UNCHANGED HARDWARE			Actual: 1,924,000		Actual: 1,924,000
TOTAL COST OF HARDWARE			Actual: 3,000,000		Projected: 2,159,000

Detailed Job Planning

The successful fabrication of both units in the relatively short period of eight months from completion of detailed design was due, in part, to detailed job planning during both the design and fabrication phases. A principal planning approach was the subassembly of many components outside the shells such as the evaporator ammonia spray and condenser condensate collection systems. Also, for critical fit-up of support plates, the planning called for welding lapping bars to the shell to allow easy fit-up for final attachment of the large support plates to such intermediate bars rather than the shell itself. This confirmed the principal of the "longer path is the shortest way" in avoiding fit-up manipulation of large, tightly fitted, support plates.

Shell Fabrication

Plate layout and burning produced plate configurations which, when rolled, resulted in convenient to handle, 10 foot shell courses to be welded together into two approximately 50 foot cylindrical shells. The large diameter courses with relatively thin walls did not present any difficulties in matching edges for seam welding. Temporary "spider" bars were used to maintain roundness during fit-up and welding. Automatic submerged arc welding was employed throughout in ajoining the courses into final cylindrical shells, ready for tubesheet installation to complete the ammonia pressure boundary.

Drilling

The components drilled for the OTEC-1 vessels were the titanium cladded steel tubesheets and the large number of tube support plates. The tubesheets were drilled individually by a single spindle numerically controlled machine which provided highly accurate tube pattern as well as high quality surface finish as shown in Figure 3.

The plates were drilled from the softer shell side to provide an axially uniform hole through the hard titanium cladding. To save time the cladded tubesheets were not finally machined for true flatness on the titanium surface since the "as is" flatness of the plates was adequate for both drilling and tube joint welding. Prior to cladding, the steel tubesheet plates were ultrasonically inspected for hard spots and intergranular defects to prevent drilling difficulties.

The tube support plates were drilled by a 43 spindle tape controlled machine in stacks of 4 plates per drilling set-up. The hole quality and pattern were adequate in providing hole alignment and easy tube movement during insertion. Accuracy in this drilling operation is critical to any shell and tube heat exchanger fabrication.

Shell Assembly and Tubing

With due concern for cleanliness, the shells were totally assembled, including tube insertion, outdoors. The work plan of two shifts per day progressed without confusion by extending the individual foreman workdays to overlap with one another. Portable mobile cranes were used to move assembled materials and eventually to haul the completed shells back into the shop for tube welding. After the tubesheets were fitted and welded onto the evaporator vessel, one tubesheet, including a short cylindrical course of the shell was benchmarked and cut off to facilitate the insertion of the evaporator enhanced tubes. These tubes had unenhanced ends with smaller O.D.'s than their central sintered lengths. The cut tubesheet and shell course section were then rewelded onto the shell and the recessed tubes back-inserted into the tube holes. The evaporator is shown prior to rewelding in Figure 2.

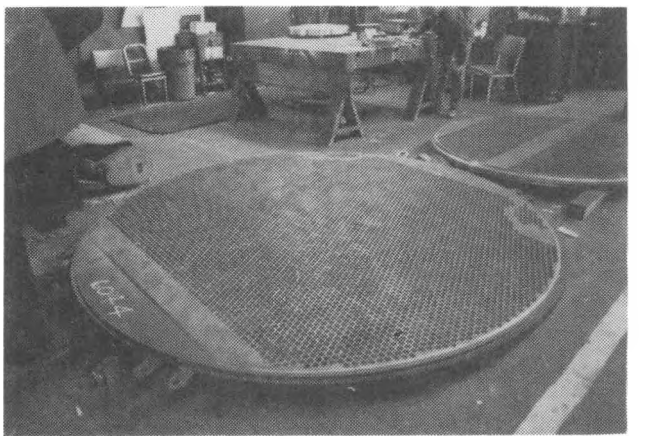


Figure 3. Condenser Tubesheets

Tube Joint Rolling and Welding

To achieve reliable tube-to-tubesheet joints, it was decided to weld the tube ends to the tubesheet cladding and then roll them into the tubesheet. This provided for redundant strength joints, one metallurgical, the other mechanical. The weld procedure was based on the following conditions:

- No tubesheet final resurfacing - as long as cladding flatness criteria is met.
- Automatic welding to accommodate very large number of welds.
- Progressive visual inspection of welds to avoid "batches" of bad welds.
- Minimum acceptable cleanliness for both the environment and the prepared surfaces to achieve successful welds.

- Employment of two or three welders simultaneously on one tubesheet to shorten weld time.
- Minimum cladding thickness required for good metallurgical bond of tube material with clad material
- Flush tube-to-tubesheet holes, tube I.D., and tube O.D. in the weld vicinity with acetone followed by wiping immediately prior to welding.

During tube welding, the vessels were moved indoors, in steel fabrication surroundings. Portable clean rooms were attached to both ends of each vessel to maintain a required clean environment during the welding operation as shown in Figure 4. Although the given tube material, titanium, was never welded in this shop, the welding process itself was similar to other comparable welding operations, with no deviations from the common practices. Some of the approximately 24,000 successful welds are shown in Figure 5.

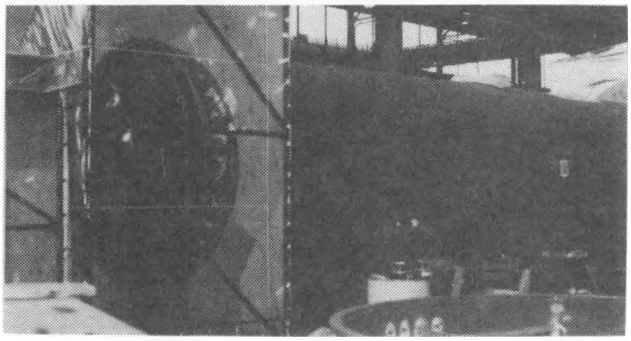


Figure 4. Portable Clean Room on Condenser

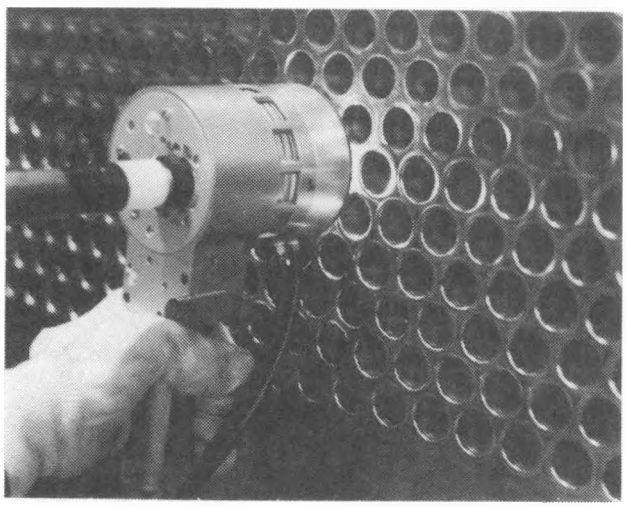


Figure 5. Automatic Weld Gun and Condenser Tube Welds

The fabrication of future units will benefit from the learning curve during tube welding. Cleanliness was maintained at very high levels which might not be required. Lack of time in a short fabrication schedule prevented a proper study of the minimum degree of required cleanliness.

Furthermore, automatic tube welding could be more time efficient by better planning the welding related activities such as tube joint preparation and post-weld examination. This is supported by improvement in welds-per-hour rates demonstrated toward the end of the welding operation. Such improvement is likely to reduce the total cost of a commercial unit by an additional 3 percent as indicated in Table 2.

Assembly of Waterboxes

The large dish-shaped waterboxes shown in Figure 6 were designed to be bolted into the shell ends

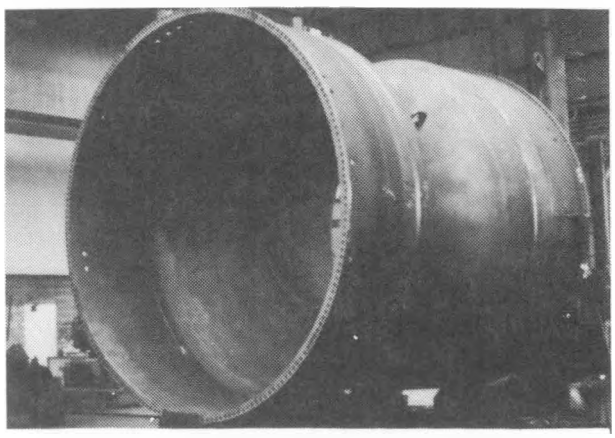


Figure 6. Removable Waterboxes Showing Flange With Bolt Holes

through flanges welded to the two mating circumferential edges. Full faced rubber gaskets were placed between the flange faces to provide a compressed seal. Difficulties arose in getting a watertight seal since the large bolting circle was coupled with a fairly thin dished head and torquing one side would either relax the other or cause local yield and deformation. Since the bolt circle provided adequate structural integrity, it then was decided to apply an internal circumferential seal weld to assure no water leak across the flanges. In retrospect, the best joint would be a welded waterbox rather than bolted.

Shop Testing

Since the vessels were constructed to comply with Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code, all mandatory non-destructive examinations were performed to meet pertinent requirements, primarily radiographical examinations for weld defects and hydro-testing for integrity under pressure. Additional examinations were performed throughout the fabrication to assure early detection rectification of potential problems.

Test procedures differed from those typical of a production unit due to the special OTEC-1 test requirements. These special tests included use of demineralized water during the shell-side hydrotest to avoid potential contamination of the units.

Special tube strength tests were made to check the resistance of both tube welds and rolled joint resistance to pull-out failure. These tests revealed the tube-to-tubesheet joint to be redundant: only a weld or roll is required for strength.

Extensive leak tests were also performed which went well beyond the ASME code requirements including air and soap as well as visual inspection. Elimination of the redundant tube weld and roll construction as well as the additional shop testing will also reduce the cost of a production unit as indicated in Table 2.

Shipping

Several modes of hauling and movement were associated with the transportation of the heat exchangers from the fabrication floor in Los Angeles, California to the final placement below deck in OTEC-1 at the Portland, Oregon shipyard.

The land movement by multi-axle truck was extremely efficient and the units were moved from the shop to the Los Angeles harbor over approximately 20 miles of public roads without incident. One of the multi-axle trailers is shown in Figure 7. The units were lifted from the trucks to a barge using a floating crane.

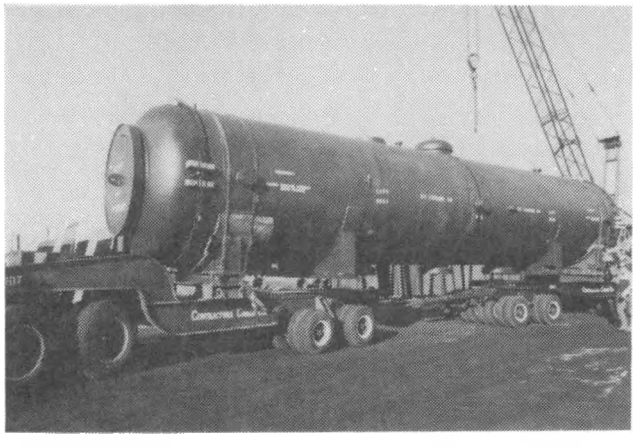


Figure 7. Multi-axle Trailer with Evaporator

Both units were then barged from Los Angeles, California to Portland, Oregon as shown in Figure 8. The 1 MWe evaporator was near the limit in size for truck or rail transportation from the fabrication shop. However, as indicated by Figure 8, barge capacity could have accommodated much larger units. Installation of the evaporator using a shipyard crane is shown in Figure 9.

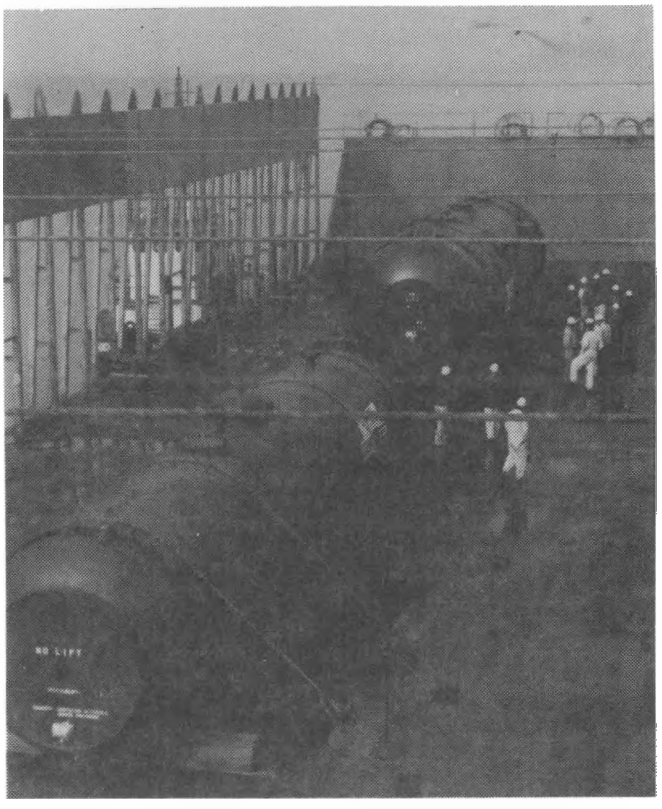


Figure 8. Barge Transport

3.2 An Assessment of Shop Versus Field Fabrication

As indicated earlier, a significant portion of the shell final assembly work was performed outdoors with no particular protection from the elements, except for vapor barrier blankets placed on openings during idle time and nights. This scope of activity - with the exception of shop convenience in providing support services and stock room consumables - is nearly equivalent to field fabrication. OTEC shell and tube heat exchangers of similar construction to the 1 MWe units can therefore be field-fabricated, providing all machining operations, component fabrication and subassemblies are performed in a controlled shop environment.

In evaluating shop versus field assembly, the following additional points learned during fabrication of the OTEC units should be considered:

- The movement of a completed vessel of the 1 MWe size, from land to barge loading point is an operation well executed by commercial heavy haulers, and its cost is very moderate.
- Field construction of pressure vessels is not covered by the ASME Code (this requirement is not mandatory for federally-owned vessels, but will be mandatory for commercial customers).
- Field labor is comprised of hire-for-the-job temporary help, while shop labor includes a significant proportion of permanent employees.

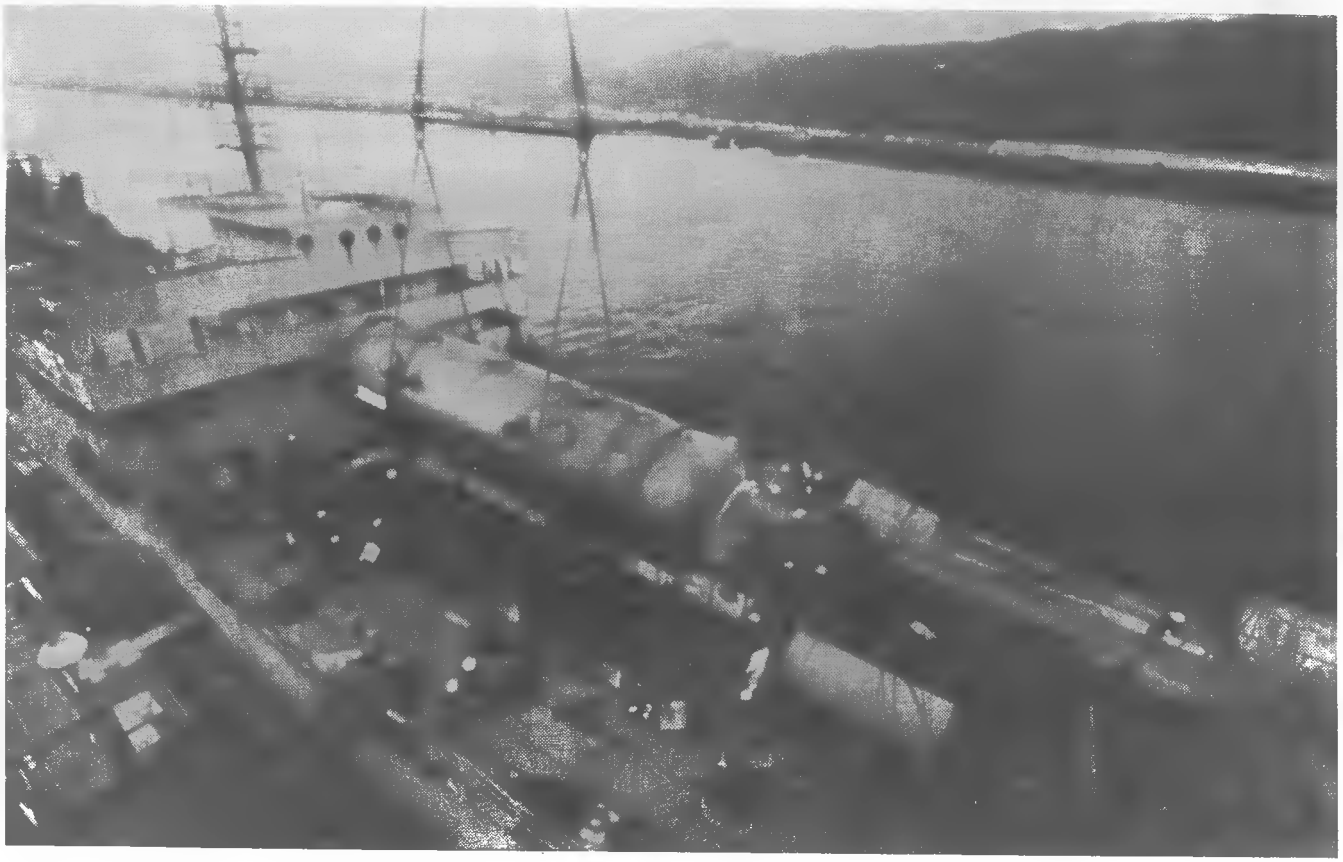


Figure 9. Installation of the Evaporator on OTEC-1

- Misplaced, lost, damaged or unfit items could expeditiously be replaced or fixed in the shop - not in the field.

4. SCALE-UP OF REVISED DESIGNS TO PILOT/ COMMERCIAL PLANT SIZE

4.1 Multiple Module Approach

One design approach to large thermal duty is to use several low capacity exchangers in parallel which is common in many power generating plants. Examples include the dual steam generators for a single nuclear reactor, parallel strings of feed-water heaters and the battery of evaporators used in cogeneration. Considerations which favor such a "module" design approach for OTEC are the following:

- Ease and lower cost of fabrication and installation.
- Incremental load management, by running any desired number of units at design conditions.
- Increased reliability through maintenance, repair or replacement of one module without total plant shutdown.

Considerations unfavorable to "module" design are as follows:

- Requires additional cross around piping, valving and auxiliary equipment.
- Duplicate external preparations and multiple openings of many units for inspection and/or maintenance (such as scaffolding, air, water and power services, etc.).

A conceptual design employing the modular approach with 1 MWe (1.25 MWe output) units is presented in Figure 10. The modularized design of 5 MWe capacity is comprised of 8 vessels; one bank of 4 evaporators and another bank of 4 condensers, where the vessels within each bank are interconnected in parallel to a single process line carrying the total flow of the ammonia vapor. The single liquid line feeding the evaporators is branched symmetrically into separate lines which distribute the liquid ammonia to each vessel. Isolation valves as shown provide for complete isolation of any one unit. Individual sea water pipes are shown for each vessel although such pipes may draw their flow inventory from a common surge tank.

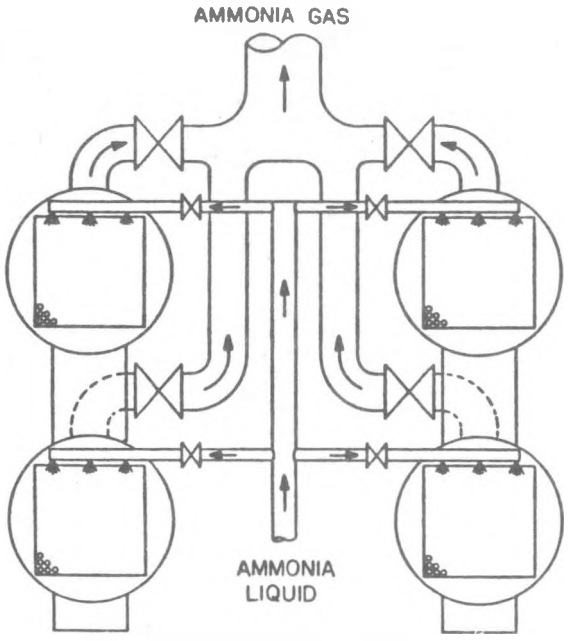


Figure 10. 5 MWe Evaporator Arrangement Using 1.25 MWe Modules

4.2 Increase Unit Size

Tests on OTEC-1 have verified the relatively uniform heat transfer performance of the 1 MWe evaporator utilizing a square tube bundle geometry configured to represent one quarter of a unit capable of a 5 MWe output. The most direct approach to scale-up using a single module would be to incorporate a square bundle with geometry similar to the 1 MWe unit and having four times the tube surface area.

If the tube length is held constant, increased heat transfer surface area is directly proportional to the number of tubes. Pressure vessel diameter is proportional to the square root of the number of tubes. A 5 MWe scale-up of the 1 MWe evaporator is shown in Figure 11. All of the necessary thermal/fluid properties for this scaled-up design have been validated with the OTEC-1 tests.

It is evident that there will be a practical size limit when using this approach to scale-up. As vessel diameter increases, the wall thickness must also increase. Both this wall thickness increase and attendant structural changes drive up the cost of a module. There is also a practical limit to size for shop fabrication. The 5 MWe module size with a shell diameter of 27 foot is probably close to this practical size limit.

5. SUMMARY AND CONCLUSIONS

As a result of the OTEC-1 heat exchanger design, fabrication and test program, the following conclusions can be reached for titanium-tubed, horizontal shell and tube heat exchangers for OTEC application: such units have predictable performance based on verification of design calculations by the OTEC-1 data. Units of 1.25 MW electrical equivalent are available today using proven fabrication techniques.

The unique configurations of the 1 MWe evaporator resulted in test data which is directly applicable to scale-up to pilot/commercial scale using modules of 5 MWe capacity.

Finally, the 1 MWe test articles and experimental data represent an established reference point from which improved OTEC heat exchanger designs can be evaluated.

It is expected that improved OTEC heat exchanger designs will be developed but that a pilot plant with an electrical capacity of 40 MWe can be constructed today with high confidence in both predicted performance and cost.

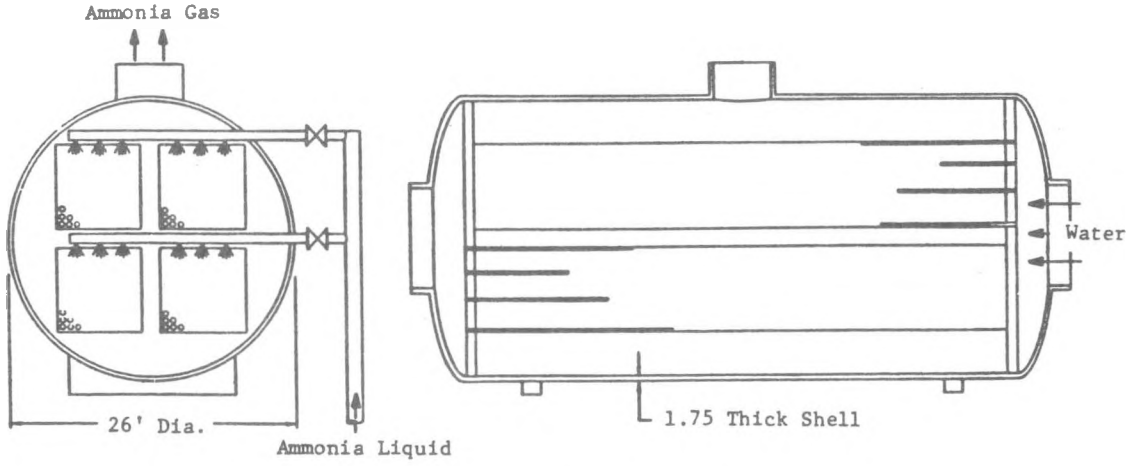


Figure 11. 5 MWe Single Shell Arrangement

ACKNOWLEDGEMENTS

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DEVELOPMENT OF LARGE THRUSTERS FOR DYNAMIC POSITIONING OF OTEC SYSTEMS

H. Bartholly and D. R. Deter

TRW PLEUGER

ABSTRACT

The dynamic positioning of OTEC platforms and other large offshore structures requires propulsion devices of larger performance capabilities than the ones manufactured at present.

Even under moderate environmental conditions, the shape and size of the platform and its appendixes such as the cold water pipe, will cause a high resistance against current.

To counteract the current forces by installing a high number of conventional propulsion thrusters may be less desirable for reasons of installation and control problems.

This paper discusses TRW Pleuger's development of two different designs of propulsion thrusters, which have more than twice the performance capabilities of the thrusters available at present. The first design alternative is a large horsepower (6000 HP) right angle gear type thruster. The second design is a combination of a submersible motor with an integral reduction gear driving a controllable pitch propeller. The result of this design is a relatively low-weight, compact, self-contained propulsion arrangement.

1. INTRODUCTION

The majority of the dynamically positioned vessels have conventional ship-shaped hulls. These hulls have a predominant direction of low resistance. They are also equipped with a conventional main propulsion plant which provides the desired service speed of the vessel. In the positioning mode, only a part of the installed main propulsion power is needed to provide station keeping force in the longitudinal direction of the vessel. A much greater propulsion force is needed in the lateral direction. This lateral force is usually provided by tunnel or retractable thrusters. They have a fixed direction of thrust laterally, and are unable to supplement thrust during cruising.

For a hull configuration without a predominant direction of low resistance, the optimum propulsion arrangement is sized for station keeping. During cruising - should it be required for relocating the structure - only a part of the installed propulsive power can be utilized efficiently.

A propulsion system for this type of offshore structures, utilizing fixed propulsion devices in both longitudinal and lateral direction is feasible. However, the total amount of installed power has to be greater than for a system which provides directional control of thrust by means of azimuthing (steerable) propulsion devices. With an azimuthing thruster, the full magnitude of thrust is available in whatever direction is desired. So, for a structure with equal or nearly equal resistance in the two axes, the azimuthing thruster installation is no greater than 1.4 the requirement of one single axis. This makes the azimuthing thruster the logical choice for the station keeping propulsion for any non-shipshaped structure. Steerability became one of the major design criteria for the design of the large thrusters.

A conventional vessel will be drydocked in regular intervals. The underwater portions of the propulsion systems can then be inspected and serviced. The size, location and intended operation of an offshore structure prohibit mostly any drydocking at all. In order to enable inspection and maintenance of the underwater installed parts of the propulsion devices, they have to be designed for removal from their installed position. The most common way to accomplish this is the watertight encapsulation of the main motor compartment including the auxiliary machinery. The actual thrust unit is installed at the bottom of the capsule. The capsule itself is installed in a well which protrudes the full height of the hull. The bottom of the capsule is flush with the bottom of the structure, the thrust unit operates underneath the hull. For maintenance, the entire assembly can be lifted by a crane and transferred to an area at which service can be performed.

The weight of the encapsulated thrusters (approx. over 110 tons for a 3000 HP unit) is a limiting factor for this installation method. For this reason, other methods are propagated

by the industry. The "detachable" thruster is one of the designs which eliminate the heavy - and expensive - encapsulation. In this design, the drive machinery is permanently installed in the bottom of the platform. The actual thrust unit is remotely installed from the outside and guided with wire ropes. The connection with the power train is made from the inside.

For both described thruster systems, a detachable installation arrangement is available.

In order to be prepared for the demand of propulsion units for the positioning of OTEC and other large offshore structure, TRW Pleuger developed two different designs of thrusters. Both designs comply with the following criterias:

- large (6000+ HP) power
- high efficiency
- high reliability
- high maintainability

2. LARGE HORSEPOWER RIGHT ANGLE GEAR TYPE THRUSTERS

2.1 General

Until 1978, the size of a right angle gear thruster, utilizing a single reduction high spiral angle gear, was limited to 3000 - 3500 HP. The limiting factor was the size of the then available gear generating equipment.

In 1978, newly developed, large size Klingelnberg spiral bevel gear generators were installed at Philadelphia Gear Corporation as well as at Klingelnberg in Germany. With this equipment, it is feasible to cut curved tooth, parallel depth spiral bevel gears up to 80 inches diameter, 30 inches more in diameter than on the previously largest generators. Spiral bevel gears of this new size and shape will be capable of transmitting in the 6000 HP range.

Parallel to the development of these large gear generators, Klingelnberg introduced a new spiral bevel gear finishing technique, called PHC - PRECISION HARD CUT. During manufacturing, a right angle gear passes various steps of machining, heat treatment and hardening. The final hardening, a precision gas carburizing process, is done after the finished cut of the gear. Following carburizing, the gears are quenched. Though the ring gear is quenched in a stabilizing press having controlled, high volume oil flow to ensure optimum case, a certain distortion of the gear cannot be avoided. As a result, large right angle gears were not mathematically true gears after carburizing. The final lapping process could only correct minor inaccuracies. The Precision Hard Cut process is a final finishing method which is applied to the hardened gear. The result is a true right angle spiral bevel gear which was never available before. This process produces gears which are highly accurate, mesh more gradually and operate more smoothly and quietly. They have substantially lower levels of vibration and their improved tooth contact allows a higher load carrying rating. (Figure 1)

2.2 Design Details

Utilizing this new gear technology, TRW Pleuger developed two sizes of right angle gear thrusters for the horsepower range of 4000 HP and 6000 HP. The design complies with the rules and regulations of all major classification societies as well as DIN, ISO and AGMA standards. It is very similar to the design of the smaller 3000 HP thruster which is very successfully utilized for the dynamic positioning and propulsion of three semisubmersibles. The gear pinion is integral with the shaft. It is cantilever mounted keeping the deflection well within tolerances. The design of the housing was optimized by finite element analysis. The ring gear is mounted detachably on the forged propeller shaft.

The seals of the shaft penetrations are designed for the severe and deep draft applications. An automatic pressure compensating provides constantly an internal pressure in the thrust unit of 3 to 5 psi over the ambient seawater pressure, independent of draft or variations of draft. The propeller shaft is sealed by a SIMPLEX type seal consisting of a multiple arrangement of reinforced Viton seal rings acting on a chromium oxide coated liner. The pressurized gear housing is sealed at the pinion shaft against atmospheric pressure by a mechanical seal. The total seal system warrants a trouble and maintenance free operation for a target period of four years.

2.3 Thrust Control

Control of thrust can be accomplished by either

- control of the pitch of the propeller

or

- control of the speed of the fixed pitch propeller.

The selection of the method of thrust control is directly linked into the selection of the electrical power system. Speed control requires a prime mover capable of speed control, i.e., a DC motor. The controllable pitch propeller can be driven by a constant RPM prime mover such as an AC inductive or synchronous motor.

The speed controlled thruster with fixed pitch propeller is the most reliable and simple mechanical drive. It is best suited for a deep submerged installation in which access for maintenance may be difficult. The total number of parts of a fixed pitch propeller thruster, in particular the number of wear parts and sealing devices, is only a fraction of that of a controllable pitch thruster. There are no complicated mechanisms for pitch control. For example, there are no rotating propeller blades with vulnerable seals, no hydraulic sliprings or pressure distributions, no hydraulic connections, no complicated mechanical or electric pitch feedback

systems. In a fixed pitch thruster, the only moving part subject to wear and maintenance is the power train itself.

The downtime for maintenance and routine repairs of a fixed pitch propeller thruster is considerably less than the one of a CP propeller thruster. An exchange of the propeller seal rings, the most vulnerable part in every thruster, requires on a controllable pitch thruster a total disassembly with strip-down of ring gear and bearings. This operation usually cannot be accomplished while leaving the thrust unit in installed position. The thruster has to be taken out after removal of the propeller blades. The disassembly and seal replacement is then conducted under shop conditions with trained personnel. The thruster is then reinstalled.

An exchange of propeller shaft seals on a fixed pitch thruster can be performed from the outside leaving the thrust unit in an installed position provided that access is available.

Only the propeller has to be removed from the shaft, which can be easily accomplished by a hydraulic jacking tool supplied with the thruster. The controlled draw-up of the propeller for reinstallation is easily and quickly accomplished and can be done by shipyard or rig personnel.

Minor repairs on the propeller, due to impact damage, can usually be performed without removing the fixed pitch propeller. No secondary damage to the inside pitch actuating mechanisms can occur as with controllable pitch propellers.

A fixed pitch propeller thruster consumes power only when thrust is required. A controllable pitch propeller absorbs power continuously, approximately 20% of the rated power, when idling with full RPM and propeller blades in neutral position.

During operation of a fixed pitch thruster, power is only consumed as long as thrust is delivered. No other auxiliary systems, such as hydraulic sytems, have to run continuously as long as power is assigned to the thruster. The lubrication system for the fixed pitch thruster is a passive, static system. The circulation pump has to be actuated only in certain time intervals for filtering purposes.

The propeller efficiency in the range between zero and full power of a fixed pitch propeller, is higher than that of a controllable pitch propeller operating at constant RPM. The controlled RPM results in less propeller friction losses.

The response times of a DC thruster system for acceleration maneuvers from zero to full load and reverse maneuvering from full load in one direction to full load to the other direction meet or exceed the response times for hydraulically actuated pitch control maneuvers. Many thrusters, with fixed pitch propeller and DC drives, in continuous service on dynamically positioned drill vessels have response characteristics which cannot be matched by a hydraulic pitch control system. Flow separation problems due to high acceleration with deceleration of thrust development were not observed.

Unlike the AC drive motors for thrusters with controllable pitch propellers, the DC prime movers of fixed pitch propeller thrusters have to be powered by a current with relatively low voltage (industry standard is 750 VDC). The distribution of high magnitudes of power at this low voltage results in very high currents which in turn require cables of a large cross section. On those offshore structures on which the thrusters are installed a far distance from the power plant, the weight (and costs) of the heavy DC cables can be of a noticeable influence into the design. Parameters such as weight distribution and stability of the floating structure may not tolerate the excessive cable weight and may favor a lighter weight, high voltage AC system (4160 to 6000 VAC) driving thrusters with controllable pitch propellers.

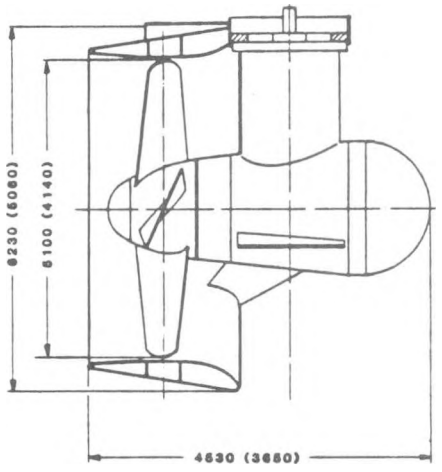


Fig. 1 - Dimensions (in millimeters) of a 6000 HP (4000 HP) right angle gear type thrust unit with fixed pitch propeller.

Input (pinion) speed	207 (255) RPM
Propeller Speed	116 (143) RPM

2.4 Installation Arrangements

For both size thrust units, the input speed at the pinion shaft is too low (255 and 207 RPM) to be economically driven by a direct coupled electric motor. A further top reduction gear is necessary. This provides the opportunity, however, to compound two smaller motors which results in a drive arrangement of lower weight and costs.

The most suitable method of installation of these large thrusters is the encapsulation system as shown in Figure(2). Prime movers and all auxiliary machinery are installed in a watertight capsule. The thrust unit is flange connected to the azimuthing section which protrudes the bottom of the capsule. The capsule is self-contained, auxiliary systems including the cooling water system with sea chests, strainer, pump and heat exchanger, azimuth system, bilge system, ventilation system, motor controllers for auxiliary motors, hydraulic system for pitch control, lubrication system with incorporated pressure compensating system. Further refinements include fire extinguishing systems and dehumidifiers.

As mentioned earlier, these thrusters are also available for remote installation and removal.

3. LARGE HORSEPOWER SUBMERSIBLE MOTOR TYPE THRUSTERS

3.1 General

This type of thruster was developed to offer an alternate system to the right angle gear type thruster. This design offers the following advantages:

- compact dimensions
- low weight
- easy removal for maintenance.

The design of this thruster is backed by over 50 years of experience in design and manufacture of submersible motors. These motors are used as pump drives, dredge drives, propulsion drives for tunnel thrusters, active rudders (a submersible motor type thruster installed in a vessel's rudder blade), and secondary propulsion for submarines, and many other uses in deep submerged applications.

The majority of the submersible propulsion motors were direct drive submersible induction motors in the range up to 1000 HP.

The new design of the large horsepower propulsion units incorporates a high RPM, high voltage submersible AC motor, combined with a planetary gear for the reduction of the motor RPM to a suitable propeller RPM.

This design results in a compact, self-sustained propulsion unit which features a considerably lower weight/horsepower ratio than the right angle gear type thruster driven by a conventional dry-running motor.

Thrusters of this configuration were developed up to a maximum output of 6,800 HP (5000 KW). (Figure 3)

3.2 Submersible Motor

The drive motor is a submersible induction motor. It is completely filled inside with fresh water for cooling and lubrication. The armature wires are insulated and protected by waterproof and pressure resistant plastic material. The inside waterfilling and the seawater surrounding the outside of the housing provide an excellent transfer of waste heat. The bearings are water lubricated rubber bearings.

Internal seals separate the water-filled motor part from the oil-filled reduction gear. A planetary gear was selected to give the total assembly a streamlined, hydrodynamically optimized shape.

3.3 Thrust Control

The AC propulsion motor is characterized by high electrical efficiency and low maintenance cost. The major disadvantage is the inability to continuously vary the speed of the motor from zero to maximum. The speed of the AC submersible induction motor is set by the line frequency. The control of propeller thrust has to be accomplished by controlling the pitch of the propeller.

The controllable pitch propeller, incorporated in the submersible motor, is of identical design as the propellers for the right-angle gear type thrusters.

3.4 Installation Arrangements

The compact design of the submersible motor propulsion systems allow installation locations and methods which are not feasible for the larger and heavier right angle gear type thrusters. The weight of the total assembly of self-contained submersible motor thruster is approximately a third only of that of an encapsulated right angle gear thruster. Though the costs of a submersible motor are higher than those of a dry-running conventional motor, the overall costs of the submersible motor thruster will be competitive. The capsule including all auxiliary systems such as bilge and ventilation system, as well as the elaborate cooling system for the drive motor, can be deleted.

Space requirements for the installation are widely reduced, so is the capacity for handling gear, such as cranes.

The self-contained submersible motor thruster is ideally suited for remote installation. (Figure 4). Unlike the right angle gear thruster,

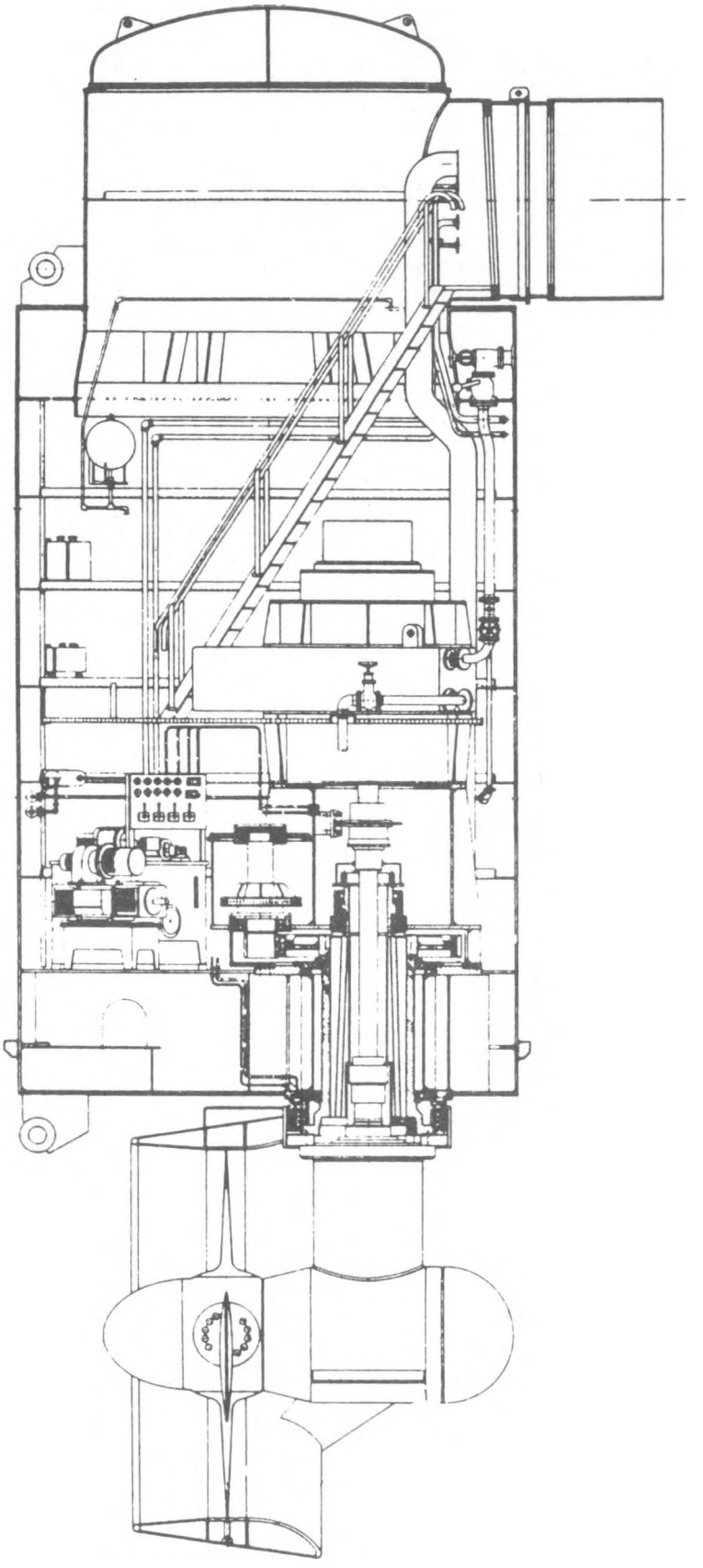


Fig. 2 - Large horsepower (3000 to 6000 HP) right angle gear type thruster with capsule and controllable pitch propeller.

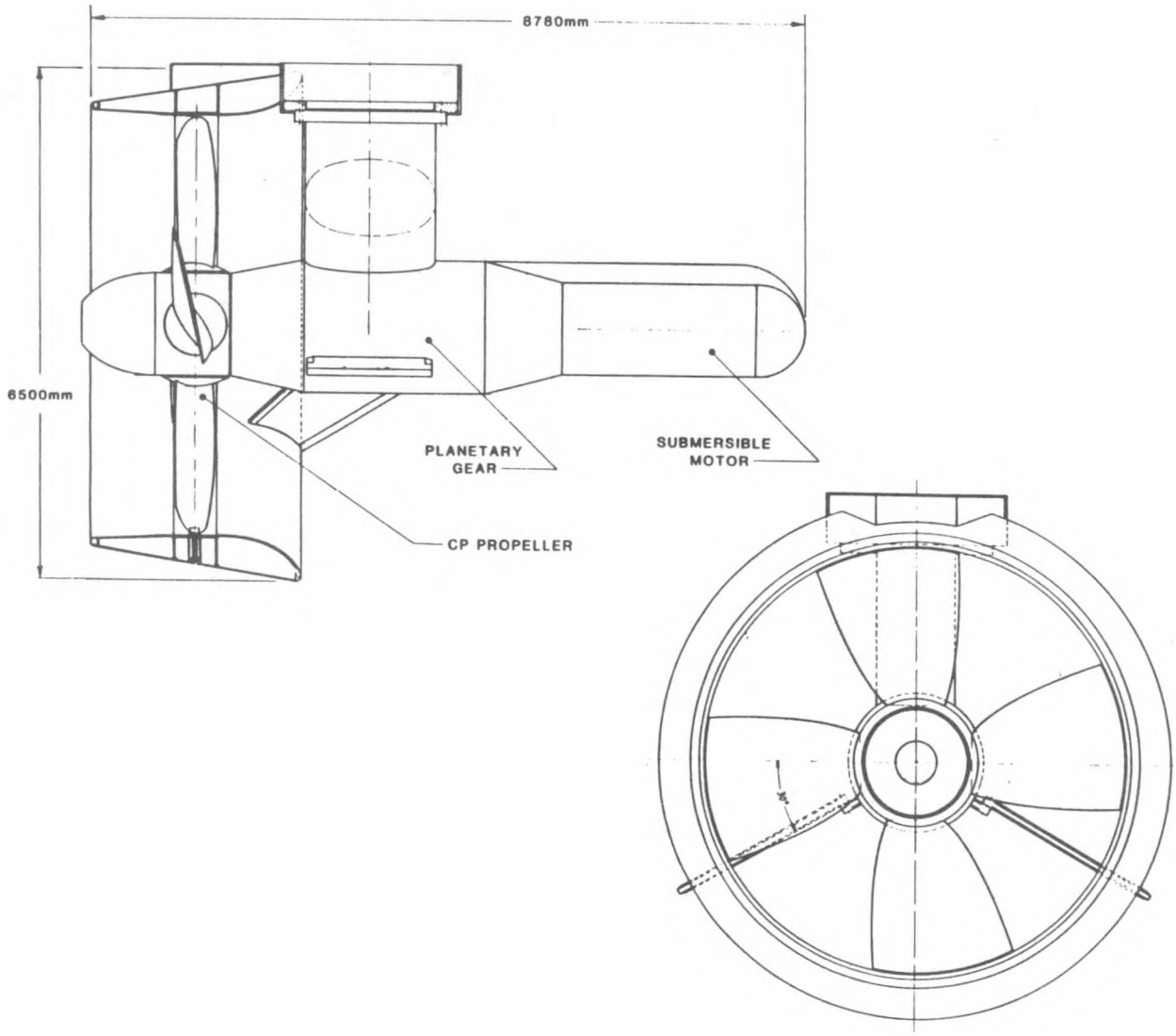


Fig. 3 - 5000 KW (6800 HP) Submersible Motor Type Thruster
Motor Type VZLU 50-150-4
Motor Speed - 1750 RPM at 60 Hz and 6000 VAC
Propeller Diameter - 5100 mm
Propeller Speed - 110 RPM

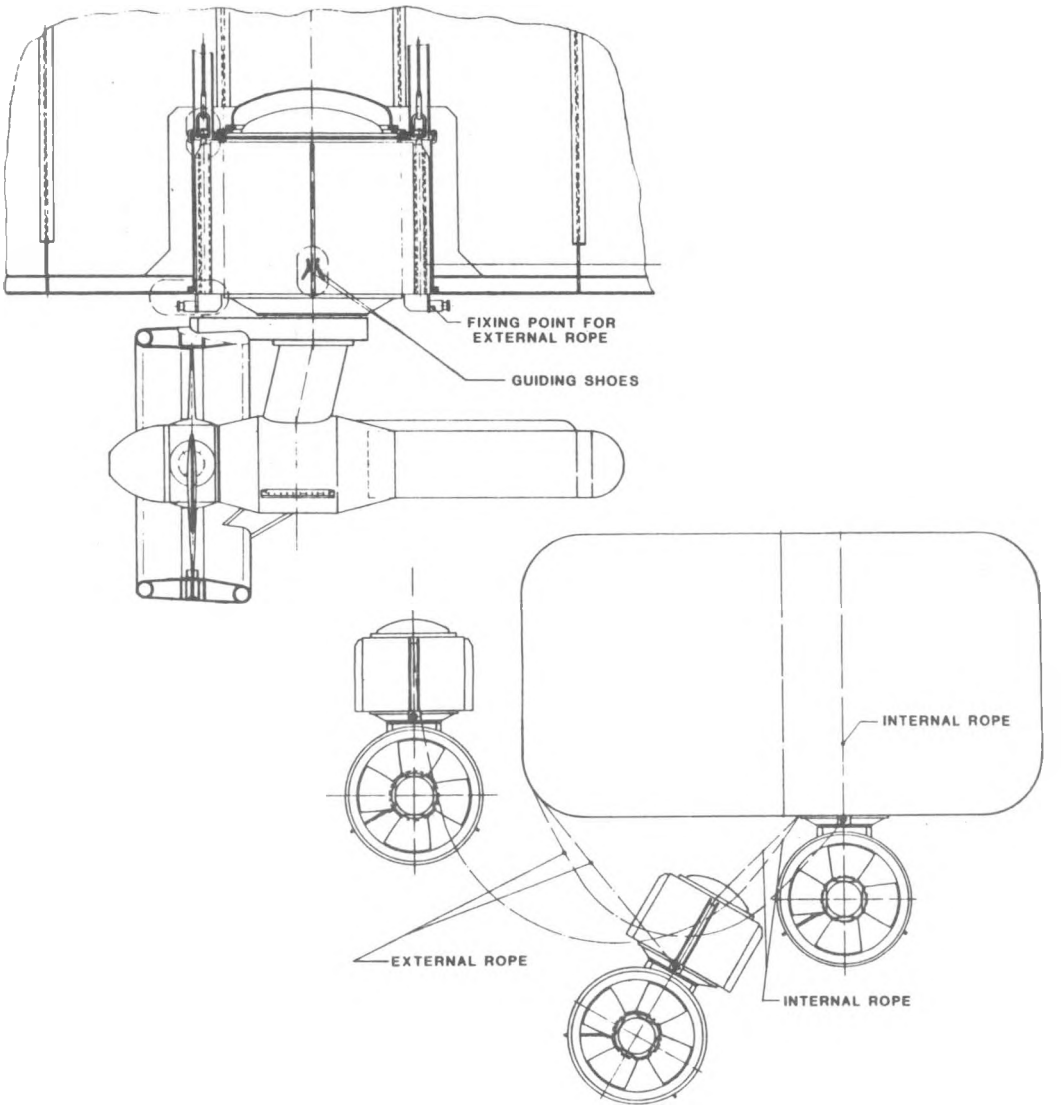


Fig. 4 - Detachable Thruster (with Submersible Motor and Controllable Pitch Propeller) for Remote Installation and Removal

no power train components such as the drive shaft have to be coupled. Only the mechanical support and hoses and cables have to be connected.

The compact design of these propulsion systems allows other types of installations. On floating structures with straight vertical hull sections, a simple vertical guide rail system can be utilized for the installation and removal of the thrusters.

One more outstanding feature of the submersible motor thruster is its ability to be operated in extreme water depths. Though the installation of an encapsulated right angle gear thruster in high water depths is technically feasible, the high costs of the pressure proof capsule could make the installation uneconomical. The submersible motor thruster is, in standard execution, manufactured for an installation in a water depth of up to 6000 feet. Custom designs allow operation up to 20,000 feet.

4. AZIMUTH SYSTEMS

Both thruster systems, the right angle gear type as well as the submersible motor type, are available with azimuth systems for the directional control of thrust. These systems allow a 360 degree endless rotation of the thruster in both directions.

Because of the size and the flow characteristic of the nozzles the azimuth gear has to overcome a high hydrodynamic steering moment. This moment grows with the propeller load and, in particular, with the speed of advance of the system. The quantitative values of azimuth forces can only be determined in model tests. Mathematical approaches are unreliable.

The azimuthing speed is 6 degrees per second for normal propulsion applications, such as cruising and maneuvering. For dynamically positioned systems, a proportional controllable speed of 0 to 12 degrees per second is an optimum selection.

The mechanical arrangement of the azimuth drives for large thrusters consists usually of one bull gear which rotates the thrust unit. Because of limitations of loads and space, the bull gear is driven by two pinions.

The great value of total gear reduction requires further speed reducing components. Worm gears in the azimuth drive train can provide a self-locking feature which is greatly desired. It prevents creeping of the thrust unit while exposed to current forces and to gravity forces caused by the roll and pitch motions of the floating structure. Without a self-locking device in the power train, the installation of a brake is mandatory.

The azimuth gear is powered by either a hydraulic motor or a SCR controlled D.C. motor. Both are suitable for a four quadrant operation of speed and torque and both arrangements can be protected against overload by torque or power limiting devices.

A short response time of the control system is desirable for a proper interphase of the azimuth control system into the DP system.

5. HYDRODYNAMIC CONSIDERATIONS

Both types of thrusters are hydrodynamically designed for optimum performance under low speed of advance conditions. The final propeller design is customized to deliver maximum efficiency under the intended service and installation conditions.

Careful attention has to be given to the selection of the location of a propulsion unit at an offshore structure. The low pressure area in front of the propeller as well as the high velocity wake produced by the propeller can cause interaction effects with the hull. These effects and the resultant thrust deduction can be of such a magnitude that the overall system performance is severely reduced.

Attention has also to be paid to the avoidance of hydrodynamic noise in order to prevent interference with the acoustic position reference system. This noise can be caused by the cavitating propeller as well as by the wake acting on the structure.

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THE COMMERCIAL ASPECTS OF OTEC POWER CABLE MANUFACTURE

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ABSTRACT

This paper discusses the essential capabilities required of a U.S. cable manufacturer to successfully build the submarine power cable required by commercial OTEC power plants. The paper will illustrate that the domestic manufacture of the OTEC power transmission cable is a realistic and attainable goal and a promising business venture. Market demand and the time frame of manufacture for the OTEC power cables outlined in Public Laws 96-310 and 96-320 passed by Congress in 1980 are utilized in development of the paper.

A brief review of existing U.S. power cable technology and cable manufacturing capacity will be presented. A detailed plan will be shown which illustrates the additional factory components necessary to complete the U.S. manufacturing capability to produce the OTEC cables. Essential material suppliers will be defined and financial aspects of this effort will be addressed.

INTRODUCTION

Today's energy problems in the United States will, to a large extent, be reduced by the implementation of several renewable energy sources. Ocean Thermal Energy Conversion, OTEC, can be a viable and vital energy source. The ability of OTEC power to be linked to the U.S. mainland power grid and provide a steady source of energy makes it a promising commercial venture.

Public Laws 96-301 and 96-320 require that 10,000 MW of OTEC generated equivalent power be on line by the year 1999 (total electrical requirements for 5 million families). The U.S. cable industry welcomes this challenge.

This paper explores the potential commercial OTEC power cable market as it is presently envisioned. It describes the type of cable manufacturing ability required to meet tomorrow's power cable requirements. Existing manufacturing ability is outlined with a plan to enhance this capability and increase its output as the demand for OTEC power cable grows. Included in the plan is a plant layout for primary manufacturing facilities with expansion capability, the time frame of construction, and the associated costs. Raw material suppliers are outlined and their ability to service this new cable market affirmed.

POTENTIAL COMMERCIAL OTEC CABLE REQUIREMENTS

Of the many studies performed by both private industry and the Department of Energy, there are six sites which are viable for commercialization of OTEC. These six sites with the number of plants shown in Figure 1 would supply 4800 MW of electrical power to the United States by the year 1999.

If OTEC is to be a significant source of energy, the plants must be able to provide electrical power directly to the United States mainland. The Florida and New Orleans sites are the most probable sites through which OTEC renewable energy can be supplied to the mainland grid. As can be seen from Figure 1, four 400 MW plants supplying electrical power would be placed off both New Orleans and the West Coast of Florida. The most referenced site for New Orleans is 81 nautical miles from

Commercial OTEC Plant Locations

Location	Plants	MW	Total MW
West Coast Florida	4	400	1,600
New Orleans	4	400	1,600
Hawaii	1	400	400
Puerto Rico	1	400	400
Key West	1	400	400
Virgin Islands	1	400	400
			4,800

Figure 1

shore and off the West Coast of Florida the distance is 148 nautical miles. It is both feasible and economical to interconnect two 400 MW plants and transmit power from these two plants to shore using one cable circuit. One 400 MW unit would be installed off the coasts of Hawaii, Puerto Rico, Virgin Islands and Key West, Florida. One plant would be sufficient for each of these areas. In Figure 2 the type and number of circuits and the total number of nautical miles (NM) of submarine cable for each location are shown.

This conservative estimate of the potential OTEC market would supply 50 percent of the OTEC generated power required by Public Law 96-310.

It is generally accepted that both the OTEC riser cable and the OTEC bottom cable will use the expanded and refined state of the art design of two generic cable types: self contained, oil filled (SCOF) and oil impregnated paper insulated cable (solid paper cable). The SCOF cable would be used in a system requiring either 138 kV, 230 kV or 345 kV AC transmission system. The solid paper cable would be used in applications requiring a DC transmission system.

For definition in this paper, an AC transmission system is composed of 3 phase, 60 cycle, alternating current which requires four single phase cables, one of which is a spare. The DC system would use a typical bi-polar scheme which requires three cables, one used as a spare.

Of the six sites considered for OTEC commercialization, four are close enough to shore to use an AC electrical power connection from plant to the mainland. The remaining two sites would require power to be transmitted to shore via a DC power connection.

MANUFACTURING REQUIREMENTS

Presently, there is no manufacturer of long length, high voltage submarine cable in North America. The need to transmit large blocks of power over long distances, greater than twenty miles, has not previously existed. However, the location and type of developing primary energy supplies such as OTEC will refine long length power transmission within the next five years.

The current U.S. manufacturing capability of 3,000 foot lengths of high voltage submarine power cable is a matter of logistics. Although cables of this type can be manufactured in the U.S., only one cable manufacturer presently has access to a deep water port allowing the shipment of submarine cable by means other than large reels. Therefore, the finished product capability has, in the past, been limited to the amount of cable which can be transported on reels.

The only North American submarine cable facility with the capability of armoring and shipping the lengths required for commercial OTEC plants would have to install additional insulating facilities to manufacture the amount of power cable required.

Figure 3 shows one scenario of the amount of cable and manufacturing time necessary to complete the installation schedule shown in Figure 4.

Locations and Cable Quantities

Location	Circuit Type and Number	NM
West Coast Florida	DC–2	920
New Orleans	DC–2	518
Hawaii	AC–1	20
Puerto Rico	AC–1	16
Key West	AC–1	168
Virgin Islands	AC–1	8
		1,650

Figure 2

Cable Production Timetable

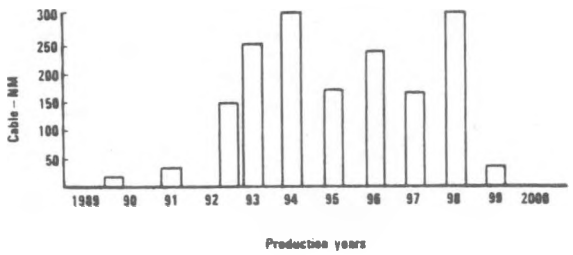


Figure 3

Installation Schedule

Year of Installation	Location	Cable—NM
1990	Hawaii	20
1991	Puerto Rico	16
1992	Key West	160
1993	New Orleans—	243
	Virgin Islands	8
1995	West Coast Florida—	444
	New Orleans, 2nd unit	16
1996	New Orleans, 2nd circuit	243
1997	West Coast Florida, 2nd unit	16
1998	West Coast Florida, 2nd circuit	444
1999	West Coast Florida, 2nd unit	16
2000	New Orleans, 2nd unit	16
		1,650

Figure 4

A primary facility with the capability of manufacturing a maximum of 150 miles per year of OTEC cable must be on line and operational by 1989. In addition, the production capacity of this plant must be increased to 300 miles per year by 1992.

The anticipated increase in production will depend upon the accuracy of the installation schedule, Figure 4, and the economic climate at the time of plant procurement. It is possible to level out the manufacturing curve by ordering cable well in advance of installation and therefore eliminating the need for additional facilities.

Figure 5 shows a typical plant layout of the major manufacturing components required. In brief, the manufacturing process for solid paper cables consists of compacted round strands or of keystone-shaped strands formed in layers around a solid core. Keystone-shaped strands formed in layers with a hollow center to be used as an oil channel would be manufactured in the case of the SCOF AC type cable. The conductor is stranded, wrapped with a sacrificial tape and taken up on a 38 foot turntable.

Application of the conductor shield, dielectric and dielectric shield tapes are then done in a one-pass operation. These tapes are always applied under specified tensions and lay angles with a designed butt spacing. The paper arrives

Cable Plant Layout

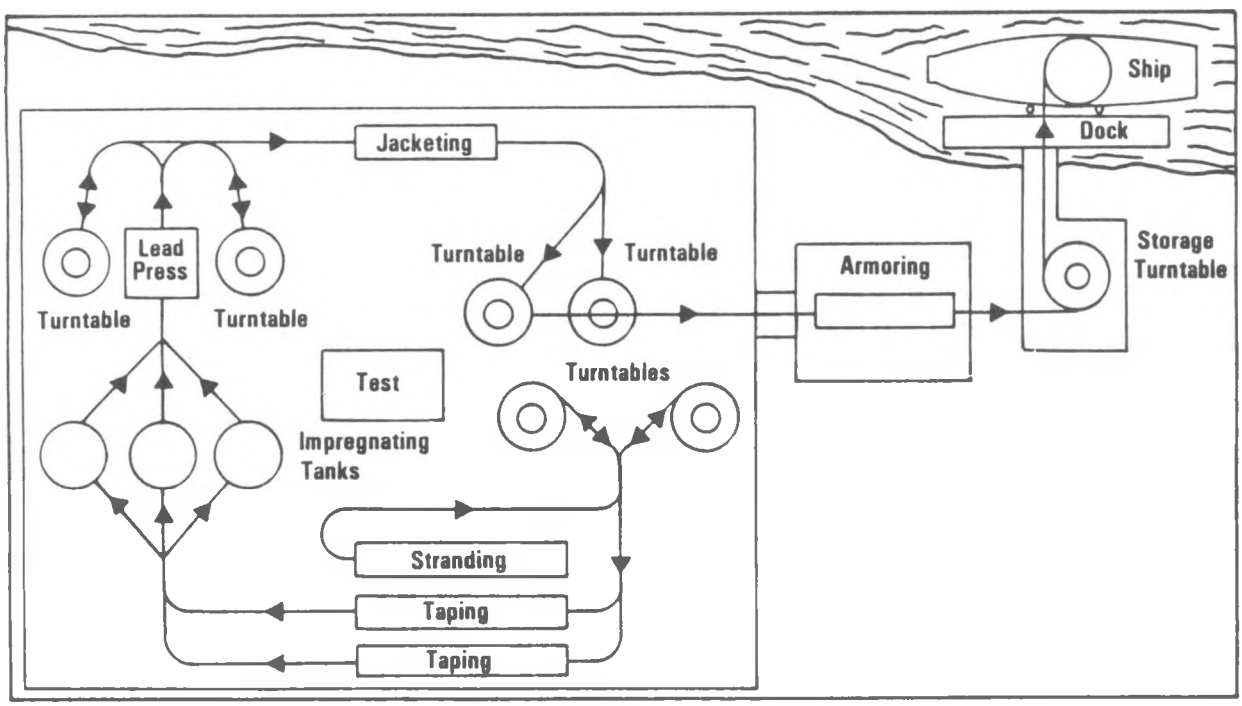


Figure 5

on large 30-inch rolls and is then dried, slit and conditioned. The relative humidity of the hermetic air-conditioned taping room is in the range of 5 - 10 percent. The completed core is conveyed to the impregnating tanks.

The rotating impregnating tanks are loaded from the conveyor system. The control system synchronizes the starting, running and stopping of the impregnating tank and the taping line. When fully loaded, the tank will be covered and sealed. The core is then dried and impregnated with cable oil.

The cable is conveyed to the continuous lead press. The cable is sheathed with a lead alloy using a 3000 ton continuous lead press. The sheathed cable is then taken up on a 1500 ton turntable.

Next, the cable is passed through an extruder which applies a high-density polyethylene jacket. The core is again taken up on a 1500 ton turntable.

After testing, the cable is conveyed to the armoring line. The cable would be armored by the existing extensive armoring facilities. Bedding tapes followed by metallic reinforcing tapes are applied to prevent bend fatigue and distortion. Jute or yarn bedding and two layers of torque-balanced steel armor will be applied. Finally, two layers of high strength nylon overserve are applied and the material is protected with asphaltic cable mix.

The cable is conveyed to a 7000 ton turntable for storage until loaded aboard ship.

MATERIAL SUPPLIERS

The raw materials required for the manufacture of 150 nautical miles of OTEC power cable, the annual production output, are readily available in North America. Figure 6 shows the material amounts required for an annual manufacturing cycle of 150 miles.

As previously described, the cable manufacturing process subjects these materials to several in-plant processes which rework and refine these materials for application in the final cable product.

Suppliers for each of these materials are aware of the potential demands. Since no new technology is required to develop these materials, suppliers could readily increase their output to meet the 300 NM per year OTEC cable requirements commencing in 1992.

Material Quantities

Material	Quantity—Tons
Copper	2150
Paper Tapes	1044
Bronze Tapes	85
Electrical Oil	250
Lead Alloy	2660
Polyethylene	214
Cotton-Rubber Tapes	33
Galvanized Steel Tapes	291
Jute	116
Galvanized Steel Wires	6300
Nylon Overserve	174
Tar Mix	87

Figure 6

CAPITAL INVESTMENT

The additional facilities required to manufacture 150 miles of OTEC type cable must be operational by 1989. At the existing North American submarine cable facility an investment of $50 million would be required. If a completely new cable facility with the same capacity were constructed, the figure could easily exceed $100 million. The incremental capital outlay to increase this existing facility from 150 to 300 NM production per year would be approximately $20 million.

It should be noted that to design, manufacture and install the necessary equipment to manufacture the commercial OTEC cables in an existing North American facility, a minimum lead time of three years is required. However, a different location demanding a completely new power cable facility would substantially increase the lead time required for cable production.

CONCLUSION

The scenario of potential OTEC plants described above is a very conservative one, if OTEC is to be used as a vital renewable energy resource. The estimated market value of the OTEC cables required is $750 million to $850 million; $75 to $85 per foot.

Another commercial aspect of Ocean Thermal Energy Conversion is the export of OTEC plants in various sizes ranging from 100 MW to 400 MW. This technology would be sold to Third World nations with rich ocean thermal resources.

The technology and manufacturing capability of these cables is, for the most part, available in this country. The United States cable industry is willing to make the investment necessary to manufacture these cables. At least one U.S. cable manufacturer with existing submarine cable capability has completed a detailed study and plant design for the additional facilities required for the manufacture of these power cables.

In addition to OTEC, these same facilities could be used to manufacture deep-water power cables required for other major power interties in North America. Major submarine cable intertie requirements have been identified in Hawaii, Alaska, Florida and several areas of Canada including British Columbia and the Canadian East Coast.

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CONSTRUCTABILITY OF SUBMARINE BOTTOM CABLES FOR OTEC POWER TRANSMISSION

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ABSTRACT

The most promising submarine bottom cables for OTEC purposes are solid paper impregnated cables and self-contained oil-filled cables. These cables do not offer electrical problems. Instead, important difficulties arise from the exceptional laying depths. Important preliminary research and development work is necessary to correctly define the detailed cable construction for each actual case. A short description is given of the manufacturing facilities to be installed in a factory intended to produce the mentioned cable types in very long lengths and suitable to great depths.

1. INTRODUCTION

In connection with the theoretical work carried out in 1977/1978 to investigate the technical and economical feasibility of bottom cables for submarine links of OTEC plants to mainland (1), it was made clear that the most promising cable types are: conventional paper impregnated (PI) cables at ± 250 kV d.c. to transmit 400 MW on 80-150 N.M. distances; self-contained oil-filled cables (OF) at 345 kV a.c. to transmit the same power on distances of a few N.M. only. In the second case also the transmission of 100 MW only was considered, for which OF cables result again to be the more reliable solution.

In principle, with the mentioned cable types no electrical problems arise: in fact, submarine PI cables up to ± 300 kV d.c. and submarine OF cables up to ± 400 kV a.c. are in regular service since a number of years. All problems of OTEC bottom cables are related to the exceptional water depths, which are 4000-6000 ft in place of the already experienced 1500 ft. Said problems are not present in OTEC installations only, but in all submarine cable links involving very high water depths: industry is therefore working in order to improve the state of art independently of OTEC.

The cable constructional characteristics heavily affect the relevant manufacturing facilities. First of all, it is essential to reduce the number of joints, which always must be considered critical points of the link, even when designed and manufactured according to the most advanced technique. Therefore the cable must be manufactured in very long lengths. When high voltage cables must be manufactured in elementary lengths many kilometers long each, use can not be made of reels (which are always and anywhere present in conventional cable factories). Instead, large rotating platforms must be used at each manufacturing stage as well as for the complete cable. The insulated conductor must be impregnated in huge tanks which rotate during winding and unwinding operations, thus preventing dangerous torsion phenomena. The lead alloy sheath must be extruded in a continuous operation during days and nights. The same applies to the protecting polyethylene jacket. The armouring machine must allow the application of complex cable armour types.

Another constructional problem arises from joints, which must be flexible and free from longitudinal components of the external forces. They must be experimentally defined case by case, because they practically consist of a careful reconstruction of all cable components in order to avoid any discontinuity in size and flexibility.

2. PRELIMINARY RESEARCH AND DEVELOPMENT WORK

Laying and recovery operations of large high voltage cables at 6000 ft water depths

involve pulling tensions up to 70 tons, which are 2 - 3 times the present ones. These tensions are transversally distributed according to the geometrical and mechanical characteristics of the "resisting components" (conductor, lead sheath, polyethylene jacket, armour layers), as well as of the "transmitting components" (insulation, bedding layers). In addition, during bending of the cable on the laying machine the insulation undergoes a radial pressure which must be minimized. The best solution is usually obtained by applying a contrahelical double armour having size suitably larger than the conductor, by carefully defining the laying pitch of conductor and armours, by properly choosing the material and thickness of the bedding layers.

Submarine power cables laid at 6000 ft depth must also withstand the external water pressure, which is approx. 190 kg/cm^2 (2700 p.s.i.). In case of PI cables, the key to the correct constructional design lies in the shape of the conductor. In case of OF cables, the solution lies in developing high density insulating oils: as a matter of fact, the use of conventional oils would require prohibitive compensatory pressures, intended to maintain an internal oil pressure greater than the external water pressure, thus preventing water ingress in the event of mechanical damage to the lead sheath.

An European manufacturer, having more than 30 years experience in this particular field, faces the mechanical problems involved in submarine cables for deep waters according to the following three stages: a) theoretical calculations, which take advantage of previous experimental data; b) synthetic laboratory tests on full scale samples, representative of the cable construction and size; c) sea trials, in which the actual cable dimensions and laying conditions are reproduced for any real submarine crossing.

The theoretical calculations and the synthetic laboratory tests provide results in satisfactory agreement with the results of the sea trials (which are carried out in limited number) as well as with the actual laying practice. It is therefore possible relaying on theoretical and laboratory work to extrapolate to actual practice and give reliable feasibility judgements. Theoretical and laboratory work according to this approach has already been completed for cables up to 3000 ft water depths; similar work is at present in progress for cables up to 6000 ft depth. The following sections provide some hints on said work, as well on the sea trials which can be envisaged for OTEC bottom cables.

2.1 Pulling tensions during laying and recovery operations

The mathematical and physical theory of the distribution of the cable-laying pulling tension was theoretically developed and experimentally checked. The distribution depends on the geometrical and mechanical characteristics of the already mentioned "resisting" and "transmitting" components. The relevant calculating method has been computerized, so that new cable designs can easily be theoretically checked.

Similarly, the mathematical and physical theory of the relative movements between the cable components during laying was developed and the conditions at which said movements can be prevented (proper choice of the materials with reference to their friction coefficients) were established.

Again, the theory of paper lapping was developed which allows stating the paper lapping parameters preventing formation of wrinkles during cable bending under mechanical tension.

In parallel with the theoretical approach, over the years suitable laboratory experiments were carried out simulating the actual conditions and giving the necessary support to the theoretical evaluations. The test equipment essentially consists of: a piston machine applying pulling tensions up to 150 tons; a 6 m (19.7 ft) pulley equipped with fleeting rings, to carry out bending tests of the cable including flexible joints under mechanical tension (Fig. 1); various sets of pulling heads to be applied to the cable for the tensile tests and bending tests under tension; etc. It is intended that suitable electrical tests, both at industrial and impulse frequencies, are carried out before and after the mechanical tests; and that, after completing the tests, the cable samples are dismantled and carefully examined.

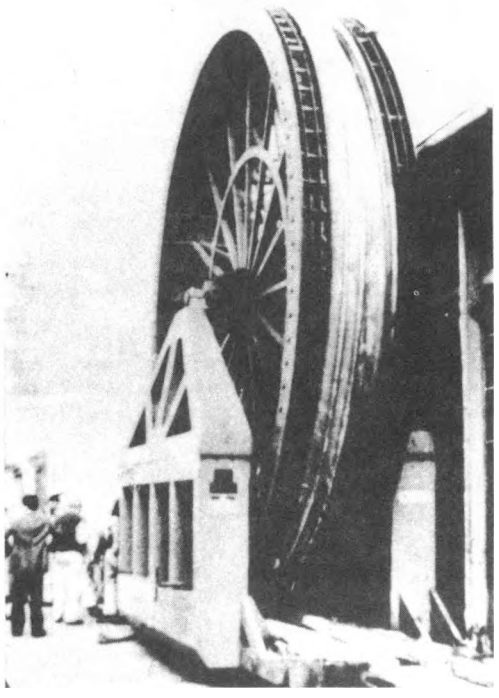


Fig. 1: Pulley with 6 m (19.7 ft) diameter, for bending tests

2.2 Behaviour of cables under high external water pressure

The mathematical and physical theory of the behaviour of PI cables under high external water pressure was theoretically developed and experimentally checked. The problem essentially consists of evaluating the critical external pressure above which the cable fails due to mechanical instability, moving from the original core shape to a deformed shape involving a bulk deformation of the insulation and a strong reduction of its electrical performance. It was possible to state that a great increase of the critical external pressure is obtained by giving the conductor an oval instead of a round shape, as well as by properly choosing and applying the insulating papers and the impregnating compound.

The equipment shown in Fig.2 is able to apply external pressures up to 250 kg/cm^2 (3600 p.s.i.). It is designed in such a way as to evaluate not only the cable behaviour with respect to mechanical instability, but also the squeezing effect of the external pressure on the impregnating compound.

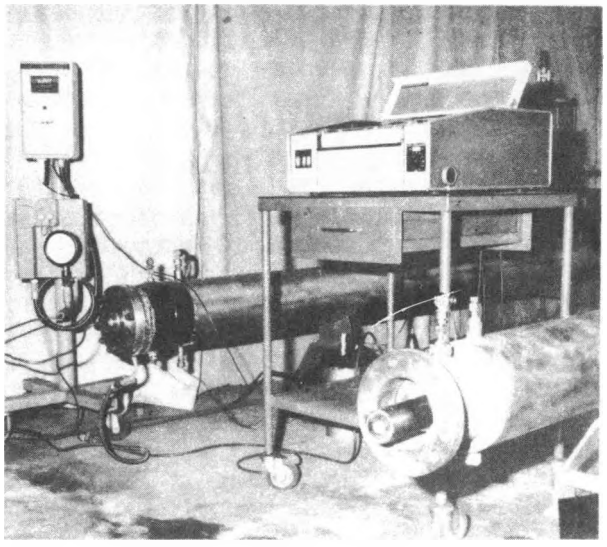


Fig. 2: Equipment for tests under high external pressure

In case of OF cables, the problem is to counteract the external water pressure with the internal oil pressure. Since conventional oils have a density more than 10% lower than sea water, laying depths of 6000 ft would give rise to a water overpressure of approx.28 kg/cm^2 (400 p.s.i.). A pressure of this amount would have to be applied to the cable oil at both ends of the link in order to maintain an internal oil pressure not lower than the external water pressure; the actual pressure of the oil would then be suitably increased to compensate for the hydraulic transients during cable operation or due to possible (though unlikely) cable severance close to a shore (2). By so doing the cable oil working pressure would result practically unacceptable from the point of view of the mechanical characteristics of the sealing ends and of the cable itself. The correct practical solution is to use a heavier oil: this has been accomplished with approved patents and promising electrical tests are at present in progress.

2.3 Sea trials

Sea trials concerning bottom cables for OTEC purposes, i.e. for laying at 4000-6000 ft depth, are in principle to be carried out when the decision concerning actual sites for OTEC plants has been taken. Then the project parameters (power, route, length, depth) are exactly known and the detailed cable dimensions can be

stated. Purpose of any sea trial is not only to obtain a final check of the actual cable design (based on what was mentioned in 2.1 and 2.2), but also to check the behaviour of the relevant flexible joint and laying equipment by reproducing in real scale all laying and recovering operations. In particular, bottom cables for OTEC plants will always require antitwist construction involving contrahelical double armour. It follows that the laying equipment will always include: rotating platform for cable storage; speed controlling device; capstan of suitable size with fleeting rings; pulley of suitable size. According to the particular characteristics of the cable and to the laying conditions, a tensioning linear machine close to the capstan can also result necessary.

3. MANUFACTURE OF ACTUAL CABLES

As shown in (1), the main constructional data of bottom cables transmitting 400 MW from the OTEC representative sites to mainland are those given in Table 1.

Table 1: Main characteristics of OTEC bottom cables

	Short links (OF cables at 345 kV a.c.)	Long links (PI cables at 250 kV d.c.)
- Copper conductor: cross section mm^2 (MCM)	700 (1400)	700 (1400)
diameter mm (in.)	32.8 (1.29)	34.3/28.4 (1.35/1.08)
- Insulation thickness mm (mils)	21 (825)	15.5 (610)
- Lead sheath thickness mm (mils)	3 (0.118)	2.75 (0.108)
- Antitwist armour (2 layers of flat steel wires)		
- Overall diameter mm (in.)	115 (4.52)	107/101 (4.22/3.99)
- Weight of the cable kg/m (lbs/ft)	36.7 (24.8)	35.2 (23.7)

The length of each bottom cable is in the range of a few miles if reference is made to the case of short links, whereas it is in the range 80-150 N.M. in case of long links. As already mentioned, manufacturing equipment allowing cable lengths many kilometers long is essential in order to reduce as much as possible the number of joints. With said equipment, no joints are in principle necessary to the OF cables anticipated for short links; in case of long links, the relevant PI cables only require a very limited number of joints, to be laid in relatively shallow waters. The sea bottom profiles of the OTEC long links are such that the distance from the deepest end to relatively shallow waters is never longer than 13 N.M. It follows that flexible joints in deep waters can be avoided if a spare cable 13 N.M. long is available; it is however advisable that flexible repair joints for the (unlikely) case of cable damage in deep waters are developed.

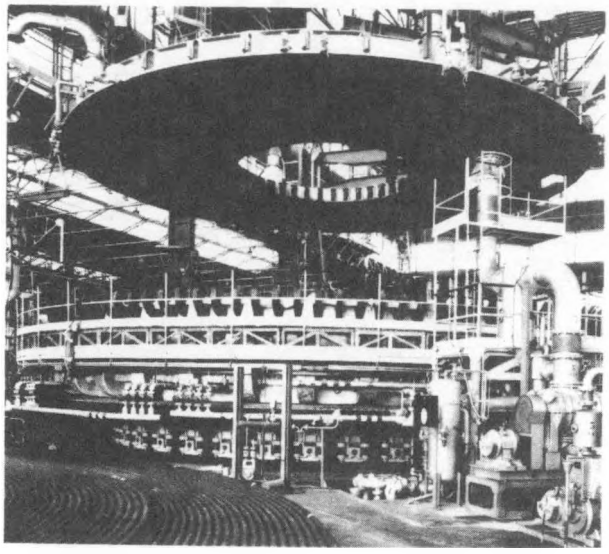


Fig. 3: Large impregnating rotating tank

The basic equipment necessary to manufacture paper impregnated cables in very long lengths comes easily out from what was said in the introduction and in previous sections. Fig.3 gives an idea about the large rotating impregnating tanks; the one here shown is characterized by

14.5 m (48 ft) internal diameter and 200 m^3 (7047 ft^3) internal volume. Fig. 4 and 5 show two rotating platforms : the

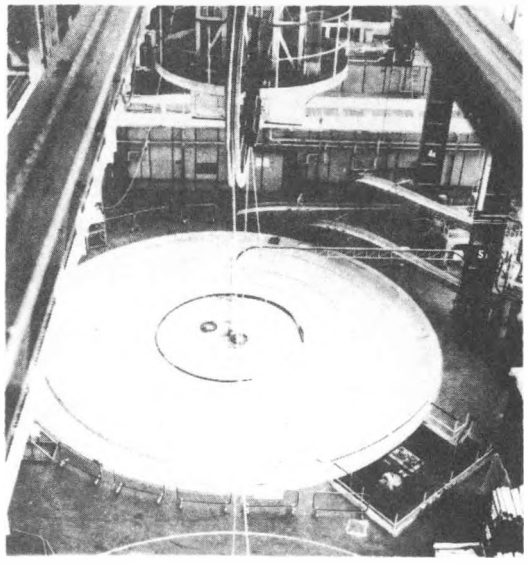


Fig. 4: Rotating platform accomodating the cable between two manufacturing stages



Fig.5: Rotating platform accomodating the completed cable (during assembling)

first one accomodates the cable between two intermediate manufacturing stages, the second one after the application of the armouring. This second platform has a diameter of 30m (98.3 ft) and can accomodate cable lengths weighting up to 5500 tons.

From this platform the cable is transferred, in due time, to the ship or barge for transportation to the site of laying.

The detailed layout of all necessary equipment must, of course, be defined by specialists of the field. The know-how available from previous similar manufacturing equipment will obviously provide important help. Even for cable makers having the largest experience in the submarine power cable field, however, the design of all necessary facilities and the realization of a factory of suitable size will require a time span covering several years.

4. CONCLUSIONS

After showing how the mechanical problems occurring to OTEC bottom cables during and after laying operations can be in principle solved, some general information were provided about the necessary manufacturing equipment as well as about the time required to build an "ad hoc" factory.

The feasibility study was completed in October 1978 and the relevant final report is being printed by D.O.E. The decision on when and how the necessary experimental phase has to start and a suitable factory has to be built is now in the hands of the U.S.A. bodies responsible for the advancement of the OTEC project.

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TURBOEXPANDERS FOR OTEC POWER PLANTS (VA 8)

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ABSTRACT

Substantial energy can be recovered from low grade waste heat, process gas, or waste gas pressure letdown.

Centripetal (radial inflow) turboexpanders are well adapted to such energy conservation schemes. With recent developments, which have increased their reliability, they are quite capable of unattended service in rankine cycles on a 24 hours, 7 days-per-week operational basis. One such application is Ocean Energy.

A "Mini OTEC" demonstration program, completed in 1979, utilized a closed Ammonia cycle to drive a 50 kw Turboexpander generator unit.

The Mini OTEC Barge was installed off the coast of Hawaii and used the warm ocean surface waters as a heat source and the cold waters from the depths as a heat sink.

Detailed process description will be presented together with Expander design, instrumentation and control systems used for Mini OTEC Program.

Special Expander features such as variable inlet guide vanes, special Ammonia Seal system, and speed control will be discussed.

Turboexpanders for future Demonstration (OTEC-1) and full scale power plants are available without any new development being required.

INTRODUCTION

Forty years of development in turboexpander technology has resulted in highly-efficient machines which can be applied in the profitable recovery of energy from waste heat sources, and gas pressure letdown.

With increased demands and with energy sources being depleted at an ever increasing rate, the need for conservation and for the recovery of energy from sources once thought unprofitable, is emphasized.

In the past, the use of the turboexpander as an energy recovery device was limited because of the following:

A. The return on capital investment did not justify a power recovery system unless more than several thousand horsepower was recovered.

B. Finding a market for recovered power, when there is no immediate use for it within the plant was difficult.

C. Continuity and reliability of this energy source was required if it were used as 'base load', which required standby equipment, spares, and constant operator attendance.

D. Lack of confidence in new power recovery schemes which were not yet proven made both government and private industry reluctant to invest in these systems.

At present, these conditions, limiting the use of turboexpanders for power recovery have improved, as follows:

A. With increasing cost of power, the return on capital investment has vastly improved.

B. A more favorable attitude by the utility companies toward returning electricity to their grid has made a number of power producing schemes practical.

C. The high efficiency of expanders and their relatively short payback period make smaller units economically attractive.

D. The present high degree of reliability of expanders, proven by hundreds of units which have been in continuous uninterrupted service for many years, has removed the concern for back-up equipment and has demonstrated that unattended operation is feasible. Several demonstration projects are now operating successfully.

This paper briefly describes turboexpanders for OTEC power plants, the present state-of-the-art, and the features incorporated

in the turboexpander design which enables it to meet most power recovery requirements.

Power Recovery Turboexpanders

The number of applications where the recovery of power is important is growing, and they are being explored and developed to an increasing degree.

Several small demonstration plants are operating, or are about to begin operation, to minimize potential problem areas for new, large power plants, utilizing such sources as ocean-thermal energy conversion (solar heat), geothermal, waste heat, etc. Power recovery from such heat sources utilize the Rankine cycle, that is, using a secondary fluid in a closed loop. Such a system is in the geothermal field also referred to as the binary cycle and it's shown in figure 1 [1].* Working fluids such as fluorcarbons, hydrocarbons and ammonia are used and the final selection fluid depends on the heat source and condensing temperature.

The OTEC power plant principle uses the solar heat of ocean surface water to vaporize ammonia as a working fluid in a Rankine cycle. After the fluid is expanded in a turbine it is condensed by the 22 deg. C colder water pumped from the ocean depths. The Mini-OTEC platform was designed and constructed with funding from several private companies, and has a 50 kw turbine/gear/generator unit [2] which expands the ammonia from 6 Bar and 21 deg. C to 6.5 Bar at 10 deg. C (figure 2). Both the boiler and the condenser were designed for 5.5 deg. C water pumped from 663 meters below the surface. The platform has operated since August 1979, in a location 2.5 Km off the west coast of the Big Island of Hawaii (figure 3).

The Mini-OTEC power generator unit is an expander with integral speed reducing gear, in which the pinion gear is on the turboexpander shaft. The pinion gear directly engages the low-speed master gear and reduces the speed of the available power to 3,600 rpm (figure 4). This arrangement has several advantages. It permits easy application of a mechanical seal on the low-speed shaft that hermetically seals the expander gearbox. These integral gear boxes are designed to be pressurized up to 10 Bar. Effective sealing is especially important in the expansion of poisonous or explosive gases like carbon monoxide or hydrogen, or the expansion of expensive gases like helium or freon. The system also includes a float drainer system. This method uses the front bearing (bearing closest to the expander) as a gas seal.

The small amount of oil in leaving the bearing at the end close to the labyrinth shaft seal and a small amount of ammonia leaking through the shaft seal pressurizes the space between the shaft seal and the bearing and is passed to the float drainer where oil and gas is separated.

The oil is drained to the oil reservoir through the float and the ammonia seal gas is returned to the discharge at the expander through a series of oil mist filters. This provides for a closed system and no loss of ammonia working fluid.

The integral gear also eliminates the power losses in the high-speed pinion gear bearings of an external reduction gear and the windage of the high-speed coupling, as well as eliminating the alignment and noise problems of the latter.

Turboexpander Qualities

From past applications it is apparent that a turboexpander is a special turbine which should be designed with quality features to meet the following requirements:

* Maintain high efficiency with varying flow;
* Toleration of dust or condensation of gas stream;
* Bearing strength to avoid damage if the rotor should be unbalanced by ice deposits, or damaged by erosion;
* High efficiency (usually requiring high speed);
* Proven reliability;
* Positive shaft seals or other special seals;
* Wide range or sizes.

Variable Flow Control

A high quality turboexpander has variable flow control nozzles capable of withstanding the total pressure and acting as the flow control for the main gas stream through the plant (figure 5). The variable nozzle should be matched with a rotor to give high efficiency over a wide range of flows (usually from 50% to 120% of design or wider)[3] [6](figure 6). They should be designed for negligible blow-by and for durable performance.

The Mini OTEC machine was controlled to maintain synchronous speed by means of adjusting the variable inlet guide vanes from a signal received from the high speed expander tachometer system.

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* Numbers in brackets refer to References listed at the end of the paper.

Expansion of Condensing Streams

[redacted] to the utilization of turboexpanders for condensing streams, this is solved by a very interesting development in which the blades in the expander rotor are so shaped that their walls are at every point parallel to the vector resultant of the forces acting upon suspended fog droplets (or dust particles.[5] [6] Then the suspended fog particles do not drift toward the walls, collect and interfere with performance and erode the blades. Over 100 turboexpanders are in successful operation involving condensing liquids.

Dust-laden streams can also cause operational problems. A turboexpander that can efficiently process condensing streams (gas with fog droplets suspended) can usually handle a stream with suspended solid particles, as long as the particle size does not exceed 2 to 3 microns. A new design has been developed for reducing erosion of an expander back rotor seal by disposing of the dust that accumulates at the seal and discharging it through the balancing holes in the expander rotor (figure 7). [7] We believe large expanders can be designed to handle dust or particles up to 10 microns.

Thrust Bearing Force Meters (figure 8)

Machines with an expander inlet pressure of the order of 10 Bars carry thrust loads usually within the capabilities of the thrust bearings. At higher pressures it is essential to carefully balance the thrust loads against each other. Thrust loads, even though originally correctly balanced, may change greatly, and exceed the thrust bearing load-carrying capacity. This imbalance of thrust loads may be caused by either erosion of a seal, icing or off-design operating conditions. This problem has been solved by a force measuring meter on each thrust bearing, and in some cases, such as the one illustrated, a thrust control valve which controls the thrust by control of pressure behind the thrust-balancing drum. [8]

Because of features such as these, the reliability of turboexpanders is exceptionally good. Operation for several years without repair is most common.

Shaft Seals

Virtually all turboexpanders seals are of the close-fitting labyrinth-type, because the high velocities prohibit the use of rubbing-face seals. With close-clearance seals it is important that the shaft be closely maintained in its rotating position, thus flexible shaft design (operation above the first lateral critical) is usually not acceptable. Bearings which maintain the closest alignment of the shaft are obviously the best for such applications, and for this purpose, a close-clearance journal-type bearing is used.

Available Sizes of Turboexpanders

Turboexpanders, currently in operation, range in size from about 1 hp to above 10,000 hp.

We recently delivered five cryogenic expander-compressors, rated at 15,000 hp to the U.S. Air Force (figure 9).

In this enormous scale-up, it is interesting to observe the size ranges where various problems are dominant. In the small sizes, the problems are miniaturization, Reynolds Number effects, heat transfer, seals and mechanical problems, such as bearings and critical speed.

In intermediate sizes, these problems become less significant, but bearing rubbing speeds and vibration become increasingly important. Vibration becomes critical in the intermediate ranges because structural members are relatively less massive and the speeds are high enough to match the resulting natural frequencies in some cases. Thorough testing of rotors is essential, and extensive work has been done in this area. [9]

In intermediate and larger sizes the thrust bearing problem requires more attention, but it has been effectively solved recently by the introduction of the thrust force meter and thrust force adjustment valve, described earlier.

Presently, designs for radial inflow turboexpanders in sizes up to 70 MWe are available for use in OTEC and other power plants.

CONCLUSION

Turboexpander processes have evolved as a result of available turboexpanders with the required high performance capabilities and reliability; and conversely, the development of these processes has pointed the way toward further improvements in turboexpanders.

In summary, the state-of-the-art of modern turboexpanders has reached a very high level of reliability and efficiency.

Mechanical designs of low-temperature, high speed machinery are routine.

Stiff shaft designs have eliminated shaft and bearing criticals in the entire operating range.

Rotor resonance problems are well known to the designers and are, in most cases, totally eliminated.

Thrust bearing problems (weakest area in high-speed machinery) can be accurately monitored and controlled.

Condensing streams and some dust in gas can be handled without erosion.

These are the most important features that make the use of turboexpanders ideal for recovery of power from low grade heat and other formerly wasted energy sources.

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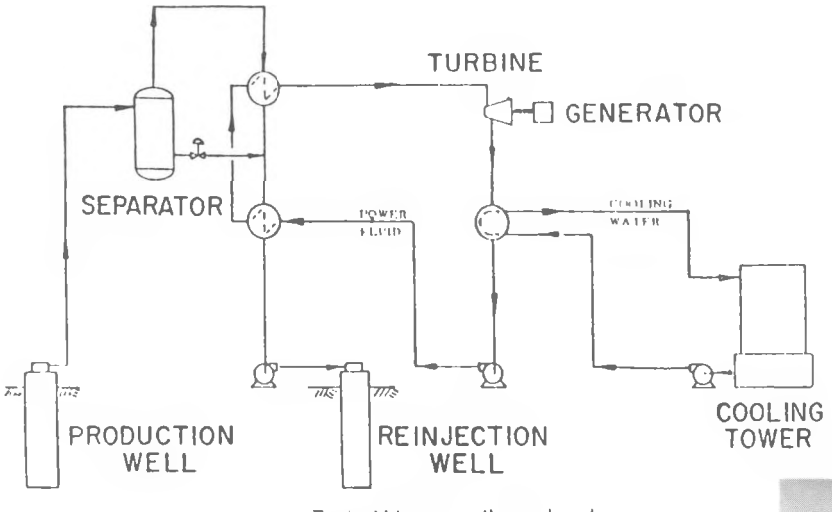
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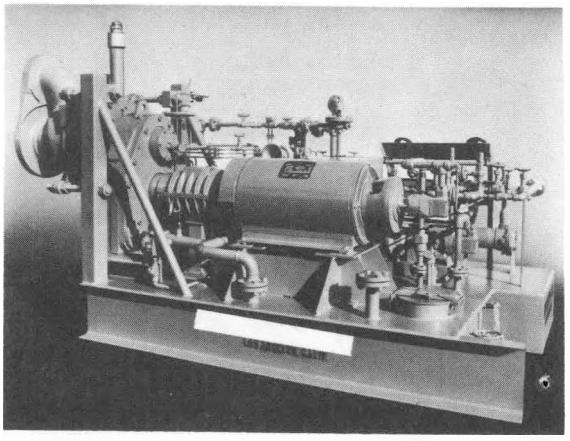
[8] Swearingen U.S. Patent 3,828,610 (February 1974).

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Typical binary geothermal cycle

Figure 1



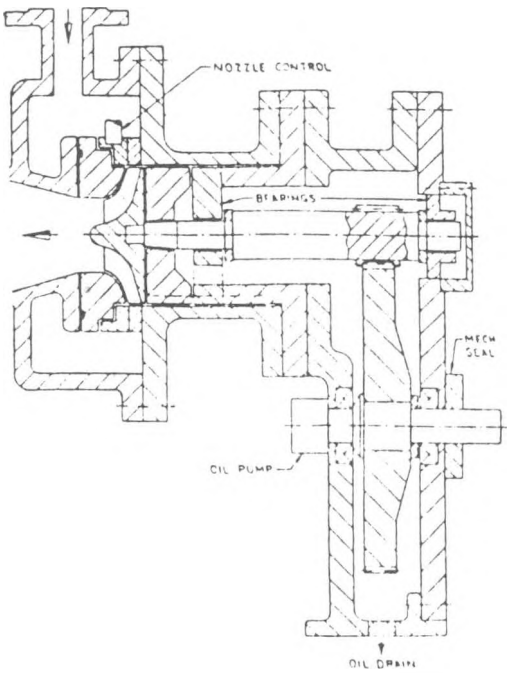
MIni-OTEC ammonia expander/gear with 50 kW synchronous generator

Figure 2



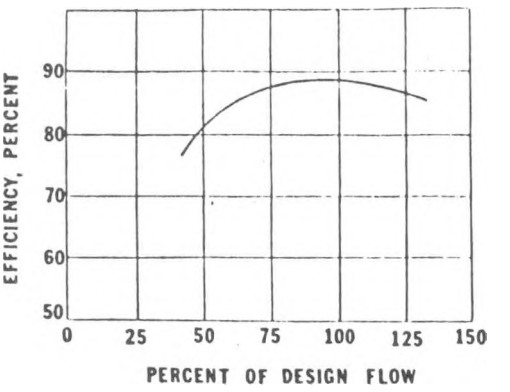
Mini-OTEC platform anchored off Hawaii

Figure 3



Cross-section of an expander with integral gear for power recovery

Figure 4



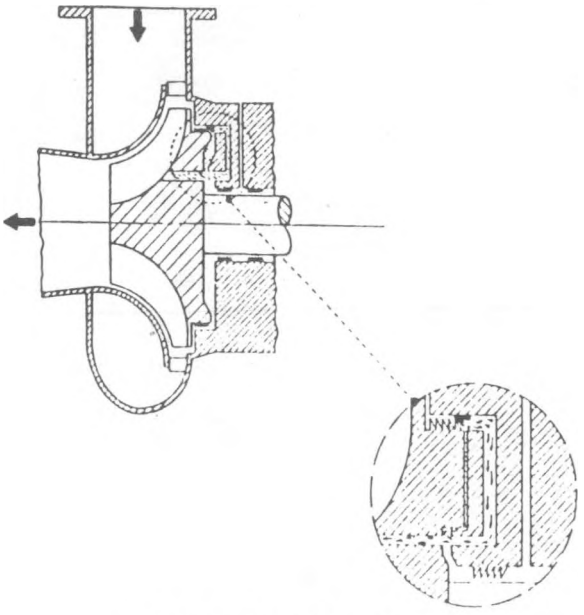
Turboexpander efficiency *vs* flow

Figure 5



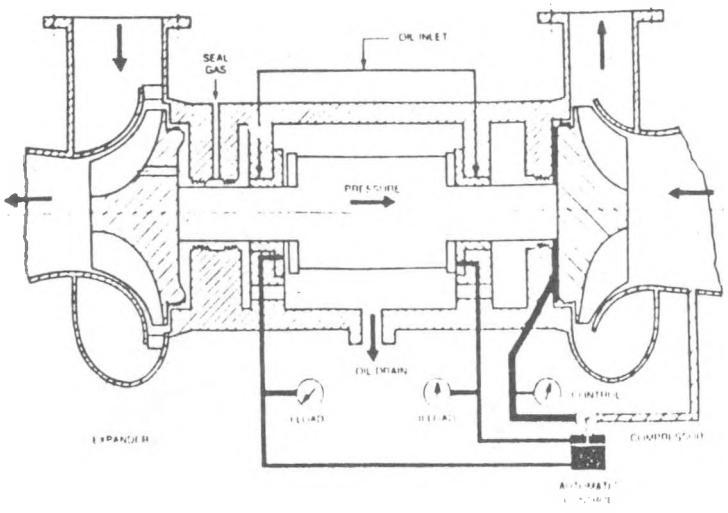
Variable inlet guide nozzles for turbo expanders

Figure 6



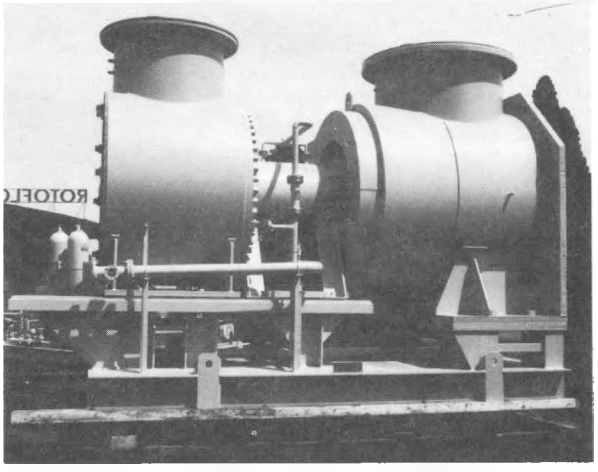
Rotoflow's dust-free expander seal design

Figure 7



Rotoflow's thrust meters and thrust control

Figure 8



11 000 h.p. expander-compressor for US Air Force test facility

Figure 9

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AVAILABILITY OF OFFSHORE INDUSTRY TECHNOLOGY FOR CONSTRUCTION OF OCEAN ENERGY FACILITIES

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ABSTRACT

The offshore petroleum industry has developed a wealth of specialized technology that is directly applicable to construction of ocean energy facilities. This technology makes the offshore industry a primary source of methods, equipment and personnel for building such facilities.

In planning for construction of ocean energy facilities, it is advisable to maximize reliance on existing technologies, such as offshore industry technology, because of the time and costs associated with development of new construction technology.

On the other hand, there are definite limits to what can be done with existing construction technologies. Consequently, in view of the unprecedented nature and scale of many of the proposed ocean energy facilities, it is essential to exploit existing technologies to their limits in order to maximize feasibility of construction of the facilities.

INTRODUCTION

During the recent, on-going program for development of the ocean thermal energy conversion (OTEC) concept in the U.S., the many firms participating in planning, design and testing activities have included a number of firms who are actively involved in the offshore petroleum industry (the "offshore industry"). For instance, the author's firm, Tokola Offshore, Inc., has worked for the past few years as a consultant on OTEC facility design projects headed by Gibbs & Cox and by the Applied Physics Laboratory at Johns Hopkins University.

In the author's opinion, it is not only useful but essential for offshore industry firms to be thus involved in the development of OTEC, and of other ocean energy concepts, because of the great depth and breadth of technical capability and experience that the industry has developed for various types of work in the ocean environment. The primary purpose of this paper is to explain and justify the foregoing statement for the benefit of persons involved in ocean energy who are not fully aware of the relevance of offshore industry technology to construction of ocean energy facilities. A secondary purpose of the paper is to further stimulate the current active interaction between offshore industry firms and those organizations and individuals in the ocean energy field who already appreciate the need for utilization of offshore technology.

RELIANCE ON EXISTING OCEAN TECHNOLOGIES

A wide variety of human activities are carried out in the ocean environment including boating, shipping, fishing, marine works construction (e.g., sewer outfall lines), deep-sea mining (still in its infancy), scientific investigations, defense operations, and the exploration for and production of petroleum (oil, gas and associated products). These activities generally share a basic technology, developed over thousands of years, that is associated with typical marine operations such as vessel design, vessel handling, environmental forecasting, navigation, mooring, diving, etc. In addition, most of these fields of activity have developed their own specialized technologies to meet each field's own particular needs.

With the possible exception of defense technology, all existing general and specialized technologies for ocean activities are available for use by the ocean energy field. Any engineer involved in design or construction of ocean energy facilities would be well advised to maximize his knowledge and use of applicable existing technologies. An alternate approach would be to devise new technology to meet the specific needs for construction of a particular ocean energy concept or facility. However, this approach is fraught with risks. The ocean is a complex, demanding and often unpredictable environment; development of a reliable bit of construction technology, whether "hardware" (equipment, materials) or "software" (techniques, procedures) typically requires not only a sound basic idea but also an extended period of iterative proof-testing and revision.

To restate the point just made, utilization of existing ocean technologies is the easiest and surest way to develop dependable methods for building ocean energy facilities. On the other hand, a corollary to this point must be recognized. There are definite limits to what can be done with existing technologies; such limits on capability typically apply to all the major parameters involved in ocean activities such as the weight and size of objects that can be handled, the depth of water in which activities can be carried out and the environmental conditions in which it is safe to work. While a certain amount of extrapolation of construction technology beyond existing limits may be

feasible in particular instances, designs and construction plans for ocean energy facilities must recognize these limits in order to assure that construction can proceed within reasonable time and costs.

GENERAL COMMENTS ON OFFSHORE INDUSTRY TECHNOLOGY

As noted above, various fields of human activity offer proven technologies for use in development of ocean energy. Of these fields, the offshore petroleum industry stands out as one of the most valuable, if not the most valuable, sources of methods, equipment and personnel capable of building many of the ocean energy facilities currently proposed.

As the terms are used in this paper, "offshore industry" and "offshore petroleum industry" both refer to the broad scope of activities involved in exploring for, recovering/producing, treating and transporting petroleum products (oil, gas and associated products such as natural gas liquids) at offshore ocean locations. This scope of activities includes all the following:

Design and construction/manufacture of facilities and equipment:

- Exploratory drilling vessels and rigs (ships, semi-submersibles, submersibles, jack-up rigs)
- Drilling/production structures and facilities (fixed platforms, tension-leg platforms, guyed towers, floating production facilities)
- Pipelines
- Tanker loading facilities (single buoy moorings, single anchor leg moorings, articulated towers)
- Drilling and production equipment
- Support facilities and equipment (personnel accommodations, supply vessels, crew boats)

Operations:

- Transport of components, materials and personnel
- Sea floor surveying
- Positioning
- Mooring
- Installation/deployment
- String-running (drill string, conductors, casing)
- Drilling
- Cementing/grouting
- Processing
- Maintenance
- Logistics

There are several reasons why the offshore industry is a particularly valuable source of technology for construction of ocean energy facilities:

I. Types and Configurations of Facilities

The offshore industry has developed a variety of types and configurations of structures and vessels that are more or less directly applicable to use for ocean energy plants. These include fixed tower platforms (piled or gravity), tension-leg platforms, articulated bottom-moored towers, guyed towers, spar buoys, semi-submersibles and jack-up platforms.

2. Sizes and Weights of Structures, Vessels and Components

With the exception of conventional ships, most of the world's largest ocean structures and vessels are built for the offshore industry. Examples are:

- Concrete gravity structures weighing up to 900,000 tons complete
- Steel structures weighing up to 80,000 tons complete
- Semi-submersible vessels displacing up to 40,000 tons
- Cargo barges (used as launch barges for platform jackets) up to 650 feet long by 170 feet wide by 40 feet deep

The offshore industry has also developed the capability to handle and assemble very large individual components during installation of structures at ocean sites. Examples are:

- Self-floating, tilt-up steel towers weighing up to 44,000 tons
- Barge-launched steel platform jackets weighing up to 27,000 tons
- Steel piling up to 84 inches in diameter
- Equipment modules weighing up to 1,900 tons
- Single-piece deck units weighing up to 40,000 tons

3. Water Depth Capability

Since the beginning of the offshore industry around thirty years ago, the industry has steadily extended its activities into deeper and deeper water. Following are examples indicating the present water depth capabilities of the industry:

- Installation of fixed towers in water over 1,000 feet deep
- Drilling of wells (including placement of casing) in water close to 5,000 feet deep
- Mooring of vessels in water up to 1,500 feet deep
- Accurate location determination for objects in water up to 6,000 feet deep
- Installation of pipelines in water up to 2,000 feet deep
- Diving work in water up to 1,500 feet deep
- Operation of manned and unmanned submersible vehicles in water up to 3,000-6,000 feet deep

4. Severe-Environment Capability

Through the 1950's and 60's, most of the offshore industry's work was limited to areas with relatively moderate weather and sea conditions, such as the Gulf of Mexico, Cook Inlet, Alaska and the coasts of Southern California, West Africa and Southern Australia. In the 1970's and now in the 80's, however, the industry has moved to ocean areas with much more severe environmental conditions. Most notable of these more hostile areas has been the North Sea, but also included are the Gulf of Alaska, the North Atlantic, the Tasman Sea and the Beaufort Sea. In response to the demands placed on offshore operations by the weather and sea conditions faced in these areas, the industry has developed capabilities such as the following:

- Fixed platforms designed for waves over 100 feet high
- Semi-submersible drilling vessels designed to survive in waves up to 100 feet high with 100-knot winds
- Semi-submersible crane vessels designed to work in waves up to 15-20 feet
- Anchor-handling tugs and supply boats capable of working in extreme conditions
- A variety of structure types (still largely in the conceptual stage) designed to resist Arctic ice up to and over 100 feet thick

5. Operational Capability

A list of typical offshore industry operations was presented above. The industry has developed the capability to carry out these operations efficiently and productively in many areas of the world, some of them very remote from shore-based support. Construction, operation and servicing of ocean energy facilities will involve quite similar sets of operations.

CAPABILITIES OF OFFSHORE INDUSTRY TECHNOLOGY FOR CONSTRUCTION OF OCEAN ENERGY FACILITIES

The comments presented in the preceding sections can be summarized in three points:

a. There is a wealth of existing, proven technology available from the offshore industry, and other sources, for use in construction of ocean energy facilities.

b. Designers and builders of ocean energy facilities should maximize the use of existing construction technologies and minimize the need to devise new technology.

c. There are definite limits to what can be done with existing construction technologies; users of the technologies must recognize the constraints imposed by these limits as well as the opportunities offered by the proven technologies.

A fourth point will now be added to complete the general argument of this paper:

d. In view of the sizes, configurations and locations of many of the proposed ocean energy facilities, it will be necessary to exploit existing construction technologies to the limits of their state-of-the-art in order to maximize the feasibility of actual construction of the proposed facilities.

(It should be noted that this argument concerns the technology used for actual field construction of energy facilities, and not the basic energy-production technology involved in the concepts.)

It is assumed that the audience for this paper is generally familiar with the various types of proposed ocean energy facilities and with the unprecedented nature and scale of many of their features. Nonetheless, it is instructive to list several proposed facility concepts, with some of their dimensions, in order to illustrate the size of the challenges facing their builders:

- Floating OTEC plantships with 3,000-foot long cold water pipes (CWP's) having diameters of 30 feet to 100 feet
- Spar-type OTEC plants tied to the sea bottom in several thousand feet of water with tension-anchors having thousands of tons of uplift capacity
- Fixed-tower OTEC plants with 30-foot diameter bottom-mounted CWP's in water up to 3,000 feet deep
- Wave energy facility installations consisting of many (perhaps hundreds of) large fixed concrete caisson-type structures containing power generating elements
- Wave energy facility installations consisting of extensive arrays of individual moving elements such as oscillating cylinders or floating rafts
- An ocean-current energy facility installation consisting of perhaps 250 turbine generators, each 500 feet in diameter, moored underwater in the Gulf Stream

With ocean energy facility concepts such as these in mind, the remainder of this section is devoted to discussing some particular aspects of potential use of offshore industry technology for construction of such facilities. The discussion is organized in terms of the typical construction work phases of fabrication, transport and installation/deployment. The intent of the discussion is to indicate: (a) the considerable magnitude of the industry's capabilities for a wide variety of particular activities, and (b) the nature and degree of the limits of the state-of-the-art of offshore technology.

It may be noted that this paper does not explicitly identify financial cost as a limiting factor inherent in use of existing offshore technology for construction of ocean energy facilities. The author's attitude on this subject can be summarized in two points:

1. While the costs of using existing offshore technology can be considerable, these costs are reasonably predictable; estimation and consideration of them should become an integral part of the overall project planning and evaluation process. The magnitude of the estimated costs based on existing technology may indicate during the planning stage that a project will be uneconomic; however, if realistically estimated and accepted during planning, these costs should not be the cause of a project's economics changing from favorable to unfavorable during the actual construction phase.
2. Ocean energy projects that require development and use of construction technology beyond the proven state-of-the-art are very likely to become unfavorable economically due to unexpectedly high consumption of both money and time.

In other words, rather than being limiting factors themselves, actual project construction costs can be indicators of how well the real construction capability limits - - limits of technology - - are recognized and respected.

Fabrication

"Fabrication" is used broadly here to include all onshore or near-shore construction of components or units that are later transported to permanent facility sites. Fabrication thus includes off-site construction of steel or concrete plant units or subassemblies, equipment modules, cold water pipe sections, etc.

Some offshore industry structures, vessels or components are built in shipyards or other conventional facilities. Most, however, are built in the offshore industry's own yards, which are set up specially for construction of the industry's particular units, such as platform jackets, platform topside modules and semi-submersible rigs. Special features of these yards may include: graving docks for large self-floating structures; large-capacity, high-reach cranes for assembly of high, wide structures; and/or skidways for loading structures onto transport barges.

Two key parameters defining the limits of the offshore industry's fabrication capabilities are the weight and size of the fabricated units. Another is the draft of the transport vessels or of the units themselves, if self-floating. Other limiting parameters can be associated with the kinds of materials and components involved, as they relate to the equipment and skills available at the fabrication facility.

Table 1 on the following page summarizes the major capabilities and limits of the offshore industry's fabrication capabilities. In the upper portion of the figure, data and comments are presented regarding typical types of completed units fabricated by the offshore industry. As indicated, the industry's yards are capable of building very large units of various types. As far as the actual fabrication/assembly work itself is concerned, there are no obvious limits to the industry's capacities. This is basically due to the fact that offshore yards tend to be flexible, with a minimum of fixed facilities that can limit unit size; the approach is to develop large, open yards and to utilize mobile equipment. The limits that do exist typcially are set by the ability to move the units out of the yards. As noted in the table, for instance, the capacities of existing launch barges place the only size limit on barge-launched platform jackets. Similarly, the depth of water available at the yards can influence unit size capability, as for self-floating steel towers. This depth-limit factor has resulted in the standard method for constructing deepwater concrete structures being a two-step process: a base section is built in a graving dock, then floated out to a water site having sufficient depth to permit completion of construction.

The lower portion of Table 1 presents comments on the personnel-oriented aspects of the offshore industry's fabrication capabiltiies. As noted, there are no obvious limits on management and specialty-craft personnel; both of these groups have had extensive experience on projects similar or greater in size, complexity and skill requirements than proposed ocean energy projects. Also as noted, the experience of structural craft personnel in the offshore industry is limited primarily to moderate-strength structural steel. Ocean energy project work involving high-strength (100 ksi, for instance) steels, or non-steel structural materials such as aluminum or fiber-reinforced plastic, would be outside their present proven capabilities.

Transport

In the offshore industry, transport of units, components, materials and personnel to offshore work sites is generally handled in one of the following modes: tow of self-floating units; tow on cargo barges; supply boats; crew boats; helicopters. The types of vessels and aircraft used are quite conventional; however, the special demands of the offshore industry have produced a supply of transport equipment that, in many instances, is unprecedented in size and capability.

Table 2 presents a summary of the transport capabilities of the offshore industry. In the upper portion of the table, the sizes and capacities of the largest existing vessels and aircraft used in the industry are listed. In the lower portion, notes are presented on some of the industry's record-sized tows of self-floating units.

In the upper portion of the table, separate columns are included for U.S.-built and foreign-built vessels. This is in recognition of the fact that U.S. law (the "Jones Act") can severely limit the use of foreign-built vessels to deliver components or materials from U.S. ports to energy facility sites in U.S. Federal waters (particularly in "Outer Continental Shelf" areas). As recently revised, U.S. Customs regulations prohibit the use of foreign-built vessels in such circumstances once any permanent or temporary "device" has been connected to the sea floor at the site.

When looked at from a worldwide, non-political point of view, the transport capability of the offshore industry is impressively large. On the other hand, in

applicable situations, the U.S. Customs regulations can have a major limiting impact on the transport capability of the domestic U.S. offshore industry. As Table 2 indicates, the sizes of the largest existing U.S.-built tugs and launch barges are considerably below those of foreign-built vessels. This must be given consideration by designers and builders of ocean energy facilities sited in U.S. coastal waters. Effects could be serious, for instance, on: (a) self-floating tows of very large and/or deep-draft concrete structures, or (b) transport-and-launch of large steel components using launch barges.

Installation/Deployment

Over the past 30 years, the offshore industry has developed an extensive technology for installation and deployment operations involving large units, deep water, severe environmental conditions and broad operational requirements. In developing this capability, the industry has primarily drawn on, adapted and extended the technologies of two

Table I

Magnitude and Limits of the Offshore Industry's Fabrication Capabilities

COMPLETED UNITS	PROVEN INDUSTRY CAPABILITY		LIMITS OF TECHNICAL CAPABILITY
	United States	Other Areas	
Steel Structures			
Tubular:			
Barge-Launched Jackets	18,000 tons; 950 feet tall	27,000 tons; 600 feet tall	36,000 tons±; 1,200 ft. tall ±. Limited by capacity of existing launch barges
Self-Floating Towers	3,000 tons; 190 feet tall	44,000 tons; 690 feet tall	No obvious limits except draft at yards. 50,000-ton x 1,300-foot tall tower now under study
Deck Trusses		7,000 tons	No obvious limits
Plate:			
Semi-Submersible Rigs	14,000 tons (light-ship)	18,000 tons (light-ship)	No obvious limits
Concrete Structures			
Platform Substructures		850,000 tons	No obvious limits, assuming construction at a typical deepwater site
Facility Modules and Units			
(Including complex mechanical and electrical systems plus support facilities)	6,000 tons	40,000 tons	No obvious limits

PERSONNEL	CAPABILITIES AND LIMITS
Management	Experienced on management of complex, multi-discipline, multi-contractor projects worth hundreds of millions of dollars; no obvious capability limits
Craftsmen:	
Structural	Primary experience on assembly and welding of moderate-strength (50 ksi), high-ductility structural steels; little experience with high-strength steels or structural materials other than steel
Specialty Crafts (Piping, Mechanical, Electrical, Instrumentation, Etc.)	Experienced on installation and testing of many types of systems requiring high level of skill and workmanship; no obvious capability limits

established industries, the on-land oil and gas industry and the conventional marine construction industry.

As would be expected, the offshore industry has drawn upon the on-land oil and gas industry for methods, practices, procedures and equipment adaptable to offshore use on finding, drilling for, producing and transporting oil, gas and associated products. Offshore operations adapated from on-land petroleum operations include subsurface seismic surveying, well drilling, well completion, well control, product treatment, pipelining and support activities.

Also as would be expected, the offshore industry has drawn upon the conventional marine construction industry for methods, practices, procedures and equipment adaptable to offshore use on installation and deployment of offshore structures, pipelines and vessels. Offshore operations adapted from conventional marine construction include seafloor surveying, vessel mooring, heavy lifting with floating cranes, pile driving, rigging, other structural work, underwater pipelaying and diving.

While technological precedents from the on-land petroleum industry and the marine construction industry have typically been adapted for similar uses offshore (where "construction" operations normally are managed and executed quite separately from "exploration/production" operations), there has also been a certain amount of cross-over and mixing. For instance, oil well completion techniques such as perforating and cementing have been adapted for use in grouting piles for offshore platforms.

In addition to these two primary sources of technology, the offshore industry has drawn on other fields such as subsea science (for subsea vehicles,

Table 2

Magnitude and Limits of the Offshore Industry's Transport Capabilities

VESSELS AND AIRCRAFT	SIZE AND CAPACITY OF LARGEST EXISTING EQUIPMENT			
	U.S.-Built		Foreign-Built	
	Size	Approx. Capacity	Size	Approx. Capacity
Tugs	11,600 H.P.	100-ton pull	26,200 H.P.	200-ton pull
Cargo Barges				
Launch	380' x 100' x 25'	7,000-ton load	650' x 170' x 40'	36,000-ton load
Conventional	400' x 100' x 25'	18,300-ton load	400' x 100' x 25'	18,300-ton laod
Supply Boats	9,000 H.P.	800-ton load	10,800 H.P.	
Helicopters		44 passengers		19 passengers

SELF-FLOATING UNITS	PROVEN INDUSTRY CAPABILITY (Sea-tow weights and dimensions are shown)		LIMITS OF TECHNICAL CAPABILITY
	U.S. Waters	Other Areas	
Steel Platform Towers	3,000 tons 190 ft. tall 10 ft. draft (on-side tow)	35,000 tons 600 ft. tall 15 ft. draft (on-side tow)	No obvious limits except draft at yards; 50,000-ton x 1,300-foot tall tower now under study
Concrete Platforms		900,000 tons 700 ft. tall 270 ft. draft (vertical tow)	No obvious limits except as affected by water depths along tow routes
Articulated Structures (Single anchor leg moorings, flare structures, loading towers)	1,400 tons 510 ft. tall 12 ft. draft (on-side tow)	20,000 tons 560 ft. tall 500 ft. draft (vertical tow)	No obvious limits

diving technology, acoustic positioning, subsea communications), the marine industry (for location determination at sea and for specialized vessels such as survey and safety boats) and the nuclear industry (for monitoring placement of grout around platform piling).

For potential designers and builders of ocean energy facilities, it is worthwhile to note some of the implications of the eclectic approach that the offshore industry has taken in developing its technology. Two of these implications are:

1. The offshore industry's use of existing technologies has been selective and specific; only the particular methods, techniques or equipment with direct applicability offshore have been borrowed. Thus, reflecting the fact that the offshore industry is a narrowly focused one, its technology is quite specialized in its detail. While the industry's activities cover a fairly wide range, its technical capabiltiies in any particular area of activity tend to be sharply defined. For instance, some of the industry's equipment that has been developed over time to perform certain specific operations with accuracy and reliability cannot be relied upon for use on operations that are similar but different in key details. Consequently, users of the industry's technology must proceed with some core, assuring themselves of its adaptability to other uses before assuming that it can be used.

2. While based on existing technologies, development of offshore industry technology has been expensive and time-consuming. A process of 20 to 30 years of evolution has been required to develop some of today's offshore techniques from precedents that were adequate for other uses but not suitable for offshore use. A similar expenditure of time and money could be required to adapt other technical concepts for use on installation/deployment of ocean energy facilities.

Table 3 on the following page presents a summary of the offshore industry's capabilities regarding a number of typical offshore installation/deployment activities. Data presented for the various activities illustrates that capabilities for specific work tasks are extensive, but that there are definite physical limits to what can be done. These limits apply variously:

(a) to the nature of the work that can be done (as, for instance, to what specific functions the manipulator arms on submersible vehicles can perform);

(b) to the magnitude of the work (as for the maximum size pipeline that vessels can lay, or the maximum size piles that drill ships can install);

or

(c) to the conditions under which work can be done (as for the maximum depth at which divers can work or the maximum wave sizes in which crane ships can operate).

CONCLUSION

In summary, the basic argument of this paper is that the use of offshore industry technology, and other existing technologies, should be maximized during construction of ocean energy facilities. A question not addressed in the paper is whether, even with maximum use of existing construction technology, it is feasible to build the sorts of ocean energy facilities that are currently being proposed; i.e., whether these facilities can be built at costs and within times that are both reasonable and predictable.

Based on close familiarity with some ocean energy facility concepts and brief acquaintance with others, the author's answer to this question of construction feasibility is two-fold. On one hand, a number of proposed facility concepts appear to be quite feasible; in terms of this paper, these concepts can be characterized as fully buildable with existing technology. On the other hand, some proposed concepts appear to be infeasible, since they apparently require construction technology beyond the present state-of-the-art. For the sake of discussion, the author suggests that the "apparently infeasible" category may include, for instance, OTEC facility concepts involving large bottom-mounted cold water pipes in deep water.

Table 3

Magnitude and Limits of the Offshore Industry's Installation/Deployment Capabilities

ACTIVITY	PROVEN INDUSTRY CAPABILITY	LIMITS OF TECHNICAL CAPABILITY
Location Determination:		
Long Distance	Remote locations at sea are determined electronically from land or satellite to accuracies of 20 feet or better.	Positional accuracies of: 10-20 feet anywhere on earth; 10 feet at 50 miles; 5 feet at 3 miles
Local (incl. Subsea)	Acoustic systems are used in water up to 6,000 feet deep with accuracies to 1/2% of distance.	No obvious limits, given optimum combination of equipment
Mooring/Position Control	Fixed moorings are used up to about 1,500 foot water depth; dynamic positioning is used in deeper water. Structures up to 900,000 tons have been moored with fixed moorings.	Long-term mooring in water over 1,500 feet deep is not standard; construction vessels are not normally equipped with dynamic positioning. No obvious limits on size of fixed moorings
Handling of Large Units in Water	Self-floating structures up to 650,000 tons have been successfully maneuvered with tugs during placement at sea; structures up to 35,000 tons have been tipped 90° by ballasting.	No obvious limits; could be limited by extreme environmental conditions in particular circumstances.
Placement of Large Bottom-Connected Units (Placed on Bottom or Tied to Bottom)	Self-floating structures up to 650,000 tons have been landed on bottom by ballasting within 30 feet of theoretical location.	No general limits; could be limited by environmental conditions in particular circumstances.
Placement of Smaller Objects on Sea Bottom	Drilling vessels can use drilling/casing string to set objects up to a few hundred tons on bottom in water up to 5,000 feet deep.	700 ton $\pm$ maximum object weights. Few vessels are equipped for work in water over 1,200 feet deep.
Lifting Work With Floating Cranes	The industry has ship-shape and semi-submersible crane vessels with cranes having nominal capacities up to 3,000 tons; loads up to 1,900 tons have been placed on platforms in the open sea.	Maximum wave sizes for safe crane work are approximately 6-8 feet for ship-shape vessels and 15-20 feet for semi-submersibles. Winds over 30-35 knots can make crane work unsafe.
Motion-Compensation Techniques	Drilling vessel drill string (up to 700-tons capacity) compensated with pneumatic/hydraulic "springs". This equipment can be adapted for other uses.	Few existing crane vessels have motion-compensation devices on cranes. Also, large-capacity "constant tension winches" are not common.
Piling Installation: Driven	Hammers with up to 1,800,000 ft. lbs. of energy have driven piles up to 84-inch diameter. Underwater hammers have worked in water depths to 900 feet.	Practical hammer size is limited by crane capacities and pile bending.
Drilled and Grouted	Drilling vessels can use drilling equipment to drill holes, place piles and grout piles	Pile size limited by vessel equipment to 30-42 inch maximum diameter; working depth limited by vessel.
Piling-to-Structure Connections	Standard methods are welding (for above-water connections) and grouting (for subsea connections).	No obvious limits

(Table continued on following page)

Table 3 (Contd)

Magnitude and Limits of the Offshore Industry's Installation/Deployment Capabilities

ACTIVITY	PROVEN INDUSTRY CAPABILITY	LIMITS OF TECHNICAL CAPABILITY
Subsea Operations: Diving	Saturation diving capability exists to 1,500 foot water depth. There is a variety of proven diver task capabilities including welding, mechanical work and structural inspection.	Little on-site diving experience to-date beyond 1,000 foot depth; maximum practical diving limit appears to be about 1,600 feet.
Submersible Vehicles	Numerous manned and unmanned submersible vehicles are available with a variety of work capabilities and with design depth capabilities to 6,000 feet. One manned vehicle has worked frequently at 4,500-foot depth.	Each vehicle has specific abilities and limits; therefore, vehicles must be carefully matched to job requirements. Performance can be highly dependent on operator experience.
Remote Control from Surface	Hydraulic controls currently are standard for offshore drilling and production operations. Electronic multiplex controls are being developed for deeper water. Electronic controls are standard for unmanned vehicles to 6,000 feet.	
Pipeline Installation	Offshore pipelines up to 48-inch diameter (plus concrete coating) have been successfully installed; deepest pipelines to date are 20-inch lines in 2,000 feet of water.	Maximum theoretical capabilities of existing equipment are 60-inch diameter and 4,500-foot depth.
Systems Hook-Up and Commissioning	Offshore platform construction typically involves large craft labor forces (up to 1,000 people) working on-site to complete and commission a wide variety of mechanical and electrical systems.	No obvious limits.

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BUILDING OCEAN THERMAL ENERGY CONVERSION FACILITIES AND PLANTSHIPS--REQUIREMENTS FOR UNIQUE CONSTRUCTION FACILITIES

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ABSTRACT

The construction of OTEC facilities and plantships (Fig. 1) is a major undertaking which will require a full range of specialized skills and resources. Near-site cold water pipe construction and deployment and the placement of deep water moorings and subsea electric cables will require specially designed equipment with large capacity. Vessels with barge-type hulls, bottom-mounted off-shore platforms, and land-based OTEC facilities will all differ in their requirements for construction facilities. While the construction sites themselves will also differ in the additions needed for OTEC construction, the similarity of needed facilities is expected to be greater than the differences. This paper examines a specific case for OTEC construction which may be instructive.

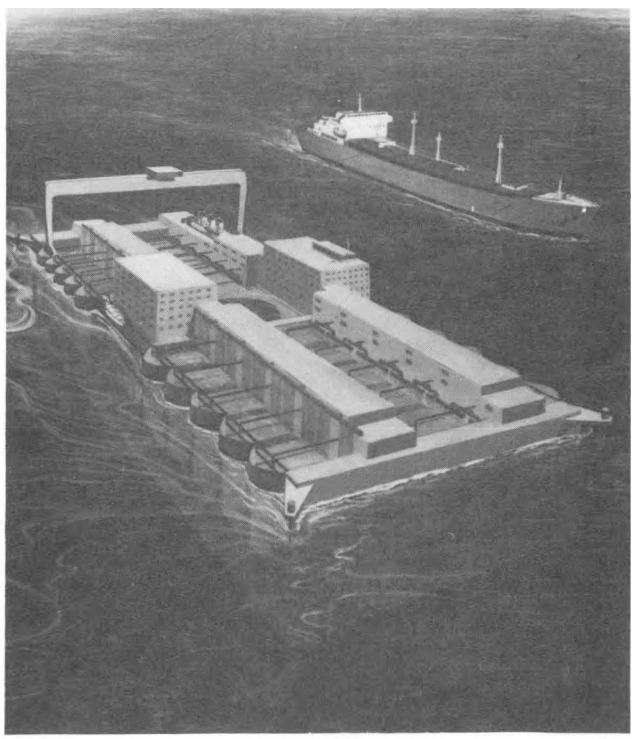


Fig. 1 Artist's conception of an APL designed OTEC ammonia plantship.

INTRODUCTION

In June 1980, an Ad Hoc Committee on OTEC Construction was formed to investigate the feasibility of building OTEC ships in the Greater Baltimore area. The Applied Physics Laboratory supplied copies of its report on the baseline design of 40-megawatt (nominal) OTEC facility for electric power delivery to Puerto Rico and OTEC plantship for ammonia manufacture in Atlantic ocean equatorial waters (1)*. The Committee looked at the construction requirements for four sizes of ship shown in Fig. 2 (2). All have a launch draft of 35-39 feet, concrete hulls, folded-tube design aluminum heat exchangers and lightweight concrete cold water pipes. The planforms are:

40 MW	443 ft long, 140 ft wide
60 MW	485 ft long, 195 ft wide
120 MW	750 ft long, 220 ft wide
360 MW	1,110 ft long, 365 ft wide

For each hull, the construction scenario called for building the bottom of the ship and first 16 feet of the ship's sides in a graving dock with a 12 foot sill, then floating the hull alongside an outfitting pier for completion.

OTEC CONSTRUCTION REQUIREMENTS

Table 1 presents the unique construction facilities which would be needed in the Baltimore area. Six new facilities or modifications needed to build a 40-megawatt baseline OTEC facility and 40-megawatt baseline OTEC plantships are shown, with the total costs in both 1980 dollars and needed year dollars. Delivery of the demonstration-size ships was postulated for December 1985 and delivery of the first commercial-scale ships for December 1989.

The graving dock for Baltimore would be a new facility with a concrete slab and dike which would be excavated to flood the dock and float out the ship. The construction cost was estimated by the Whiting Turner Contracting Company (3).

* Numbers in parenthesis refer to References listed at the end of the paper.

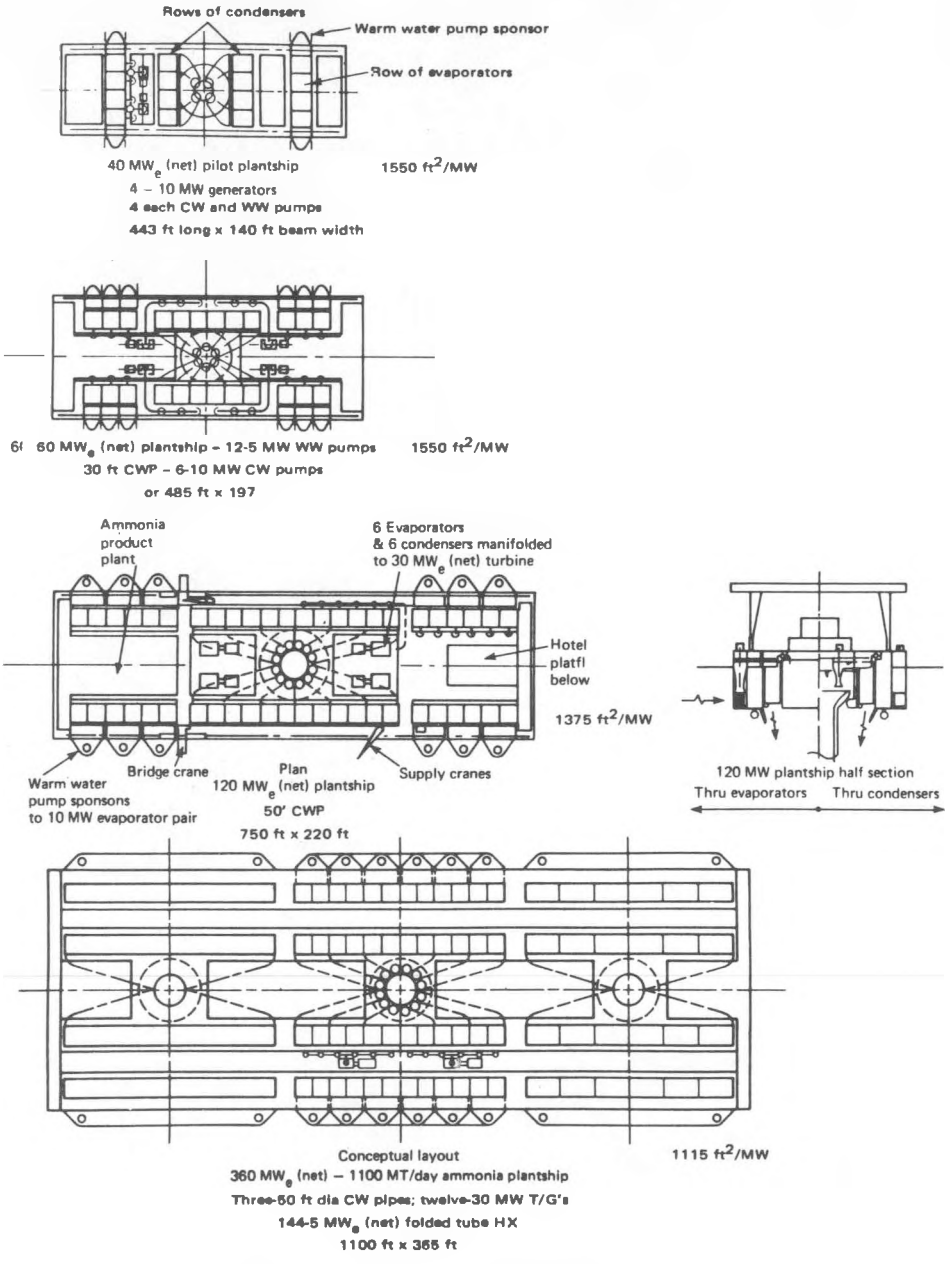


Fig. 2 Conceptual plantship layouts.

For the folded-tube heat exchanger, a new construction facility would also be required. It would consist of two interconnecting buildings, 80 feet wide by 500 feet long with 20 feet of head room. In the final 200 feet of the second building where final assembly would take place, the head room is 40 feet. An existing tube mill would be relocated from Tacoma, Washington, and the 3-inch aluminum tubing for the heat exchanger would be fabricated from coils of Alclad aluminum and the precut tube sheets would be bought pre-drilled. Rolling, welding, bending, assembly, and testing would be completed in the facility and the large modules moved directly to the outfitting pier for installation in the hull. The facility design and costs were done by the Martin Marietta Company (3).

Dredging to accommodate up to a 42 foot launch draft would be required alongside the outfitting pier and for approximately 1,000 yards to the 42 foot deep main Baltimore channel which provides access to the open sea. Dredging costs were estimated by the Bethlehem Steel Corporation (3).

A new outfitting pier is needed to accommodate up to 42 feet of draft. The

Table 1

Unique OTEC construction facilities

	Construction Facilities					
	Baseline OTEC Facility			Baseline OTEC Plantship		
	1980 $'s	Date Needed	Needed Yr. $'s	1980 $'s	Date Needed	Needed Yr. $'s
Graving Dock*	$2.5-3.0M	4/83	$3.2-3.9M	$2.5-3.0M	4/83	$3.2-3.9M
Heat Exchanger Fabrication Plant	$14.3	10/82	$17.0	$14.3	10/82	$17.0
Dredging	0.9	8/83	1.2	0.9	8/83	1.2
Outfitting Pier**	3.0-5.0	10/83	4.0-6.6	3.0-5.0	10/83	4.0-6.6
Cold Water Pipe Fabrication Yard	1.0-1.5	10/84	1.4-2.1	1.0-1.5	10/84	1.4-2.1
Cable Plant***	20.0	1/84	27.0	---		---
TOTAL****	$41.7-44.7M		$53.8-57.8M	$21.7-24.7M		$26.8-30.8M

* For 60 MW add $1.5M and $1.9M (1980 & needed yr. $'s); for 120 MW add $6.0M and $7.5M; and for 325 MW add $14.0M, 4/87 and $25.0M.
** For 325 MW, add $5.0M, 10/87 and $9.4M (1980, date needed and needed yr. $'s).
*** For 120 or 325 MW, add $30.0M, 1/88 and $57.3 (1980, date needed and needed yr. $'s).
**** For 325 MW, add $25.0M, 10/88 and $50.9M for a cold water pipe deployment vessel and $25.0M, 10/88 and $50.9M for a cable deployment ship.

water alongside existing piers could not be deepened sufficiently without overexposing their pilings. The cost estimates for the pier were developed by one of the authors.

The graving dock, heat exchanger fabrication plant and outfitting pier would be co-located on a new waterfront site of 30 to 90 acres now owned by the City of Baltimore. City officials have identified at least three sites which would be suitable.

The cold water pipe fabrication yard would be located in Puerto Rico for the OTEC facility and on the coast near Recife or Salvador in Brazil for the OTEC plantship. The cost estimates for the yard were developed by Whiting Turner Contracting Company (3).

For the OTEC facility, a review was made by the Western Electric Company for the Ad Hoc Committee on OTEC (3). Their conclusion was that the subsurface cable plant should be an add-on to the existing cable facility at the Simplex Wire and Cable Company, Portsmouth, New Hampshire. The cost estimates were developed by Simplex (4).

In total 1980 dollars, the needed unique construction facilities to build a 40-megawatt OTEC facility in the Greater Baltimore area would be $41.7 to $44.7 million, and for a 40-megawatt OTEC plantship $21.7 to $24.7 million. The footnotes to the table provide estimates of the additional costs for facilities to build the larger size ships.

One of the interesting charts, which was developed as part of the Ad Hoc Committee effort, estimates the number of jobs which would be created in the Greater Baltimore area and at the suppliers' plants by construction of a single 40-megawatt OTEC demonstration plant (Fig. 3). Assuming an OTEC contract on July 1, 1981, the new jobs to build the construction facilities and the OTEC ship would reach approximately 2,000 by mid-1982 and 3,500 by 1983. (This chart assumed a $49 million power system test facility to test the power system components at a 5-megawatt scale with fresh water. The benefits of this test did not appear to justify its cost.)

Using the estimated costs from the APL work and the construction facilities analysis, projections were made of the return on equity under a number of assumptions using a computer program available at APL. Figure 4 shows after tax returns of 10% and 11% for a 40-megawatt OTEC facility located off-shore Puerto Rico with 25 year straight life depreciation and 6 year straight life depreciation (approximates the effect of 10-5-3 year depreciation which the Reagan Administration is reportedly considering). The dotted lines show, for comparison purposes, returns on equity if equity had been invested in tax free bonds paying 10% and 18% per year compounded. The following were included in the assumptions:

34.3 megawatts delivered ashore.
$205.2 million OTEC facility cost (1980 $'s), 87 1/2% financed Title XI bonds at 13% interest.
Construction facilities cost, 100% privately financed, 80% by tax exempt bonds at 10% interest, no bond retirement charged.
76.7 mills per kilowatt hour (1985 $'s) paid by PREPA for the power delivered ashore.
330 days operations after shakedown. 65% of plant factor first year to complete shakedown.
9% inflation rate 1980-2010.
15% interest in working capital and other short term debt.
30 in crew.
10% investment tax credit plus 15% business

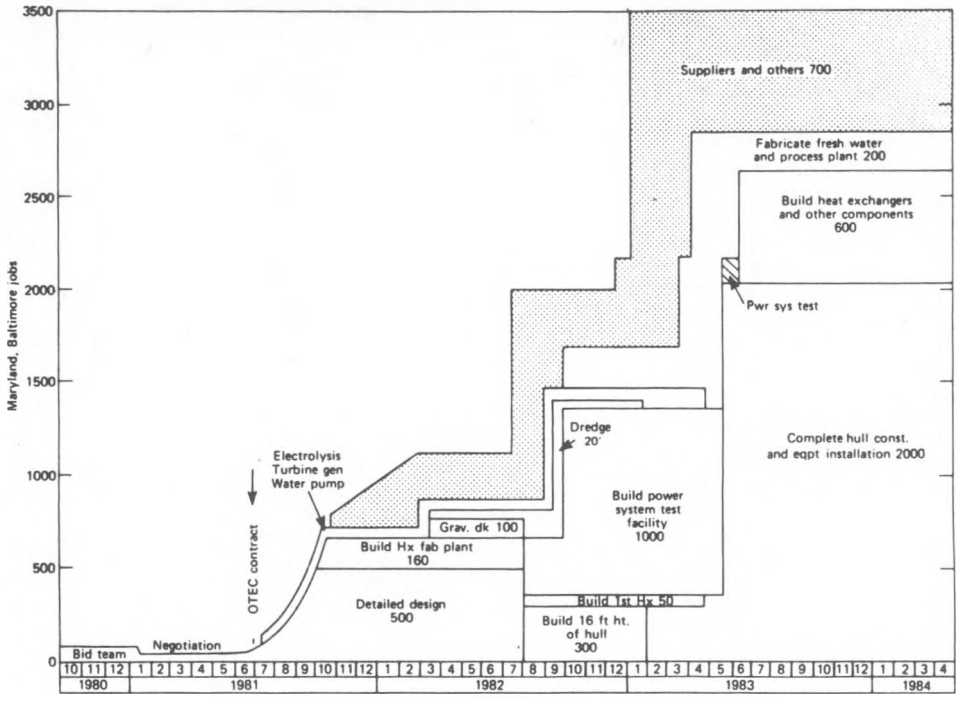
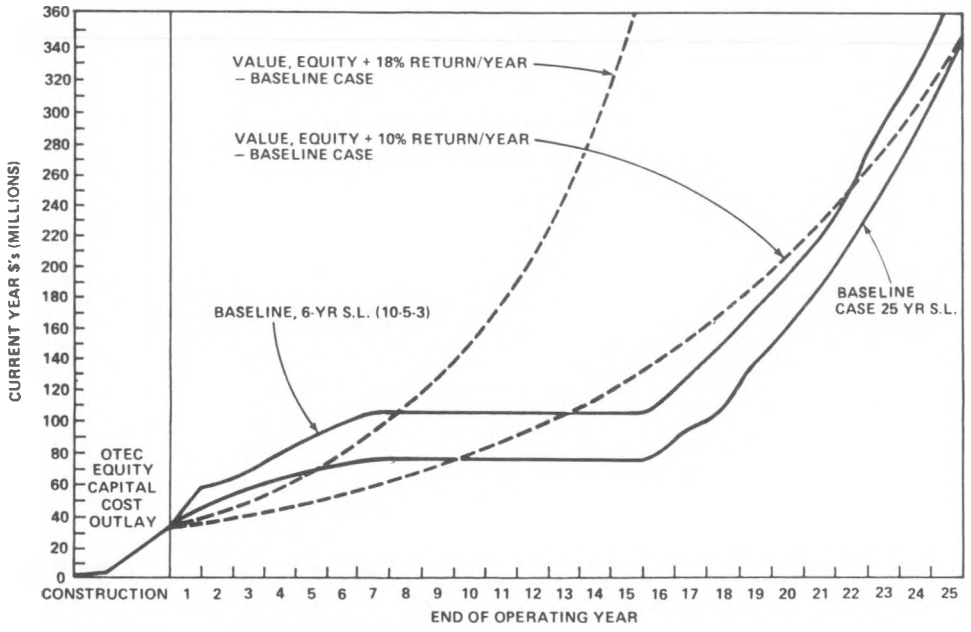


Fig. 3 Estimated number of jobs created in Baltimore and Maryland by construction of a single OTEC demonstration plant.



40-MW_e case: 34.3 MW_e delivered to substation ashore. $205.2 million OTEC facility cost (1980 $'s). $84.7 million construction facilities cost (1980 $'s). 76.7 mills/kWh (1985 $'s) price for power delivered. 9/13/15/10 inflation and interest rates used. 30 in crew. 87-1/2% of OTEC capital Title XI debt. 10% Investment Tax Credit plus 15% Energy Tax Credit. Cost-sharing: 75% Government and 25% private financing of OTEC facility construction costs. 100% private financing of construction facilities and operating costs.

Fig. 4 OTEC: effect of depreciation rate change on return on equity.

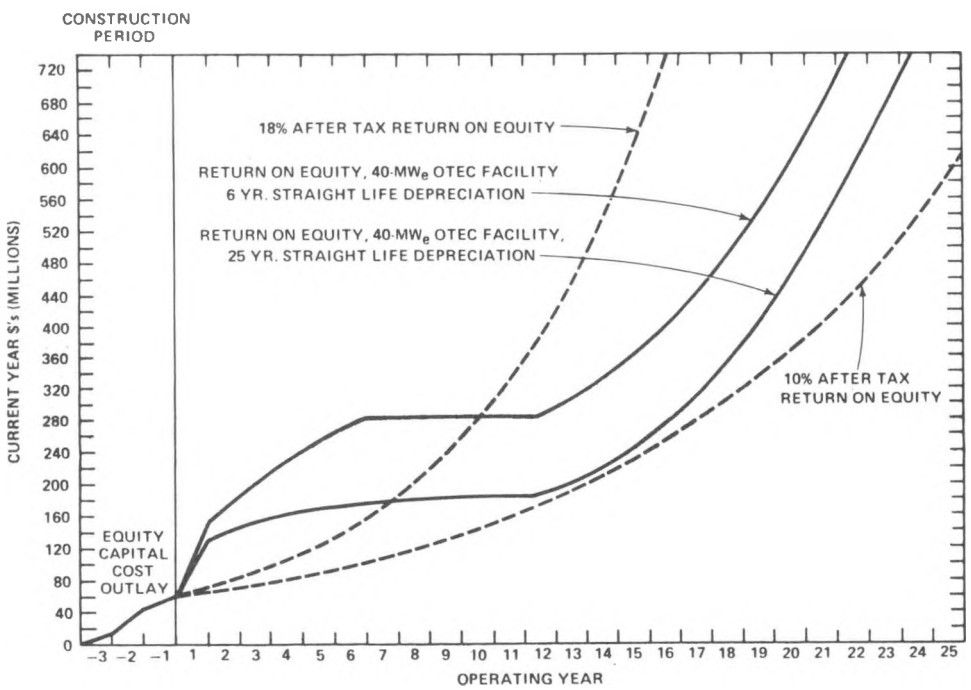
energy investment credit on entire private capital investment in the OTEC facility.
75% of capital investment provided by the Government in 1983-1985 as a grant.
100% private financing of construction facilities and OTEC operating costs, including estimates of proven transmission and customer billing costs.

Figure 5 shows similar cases for a 40-megawatt OTEC facility located off-shore Puerto Rico under different assumptions including 100% financing of the construction costs of the OTEC facility and construction facilities and with the Government providing operating subsidy of $10 million per year for 6 years (inflated by 9% per year to current dollars) from 1986 through 1991. The return on the combined OTEC and construction equity is about 12% and 14% per year compounded under the two depreciation rate assumptions. One key assumption is that PREPA would pay 150 mills per kilowatt hour (1985 $'s) for the power delivered.

Figure 6 presents similar data for a case with a 325-megawatt (nominal) commercial-scale OTEC facility which would deliver 266-megawatts of power to shore with the 40.3°F temperature differential off Puerto Rico. The estimated capital cost of $80.83 million is taken from earlier Ad Hoc Committee work, but is not supported by any specific engineering design effort. The cost estimate was prepared by extrapolation from the 40-megawatt design. An additional $34.4 million for construction facilities is estimated on the assumption that the facilities to build a demonstration-scale OTEC ship would already be available. Delivery is assumed to be 1989 and the power sales price to be inflated by 9% per year from 100 mills per kilowatt hour (1985 $'s). Title XI debt financing at 11 5/8% was assumed for 87 1/2% of the cost. A crew of 60 would man the ship. 330-day operations degraded to 65% of rated capacity the first year was the operating factor used. Financing would be 100% private with a 10% investment tax credit the only Government contribution. The after tax return on the OTEC and construction facilities equity would be 16% and 19% per year compounded for the 25 year and 6 year straight life depreciation assumptions. Thus, even the first commercial-scale OTEC facility would appear to be an attractive commercial venture under the assumptions used.

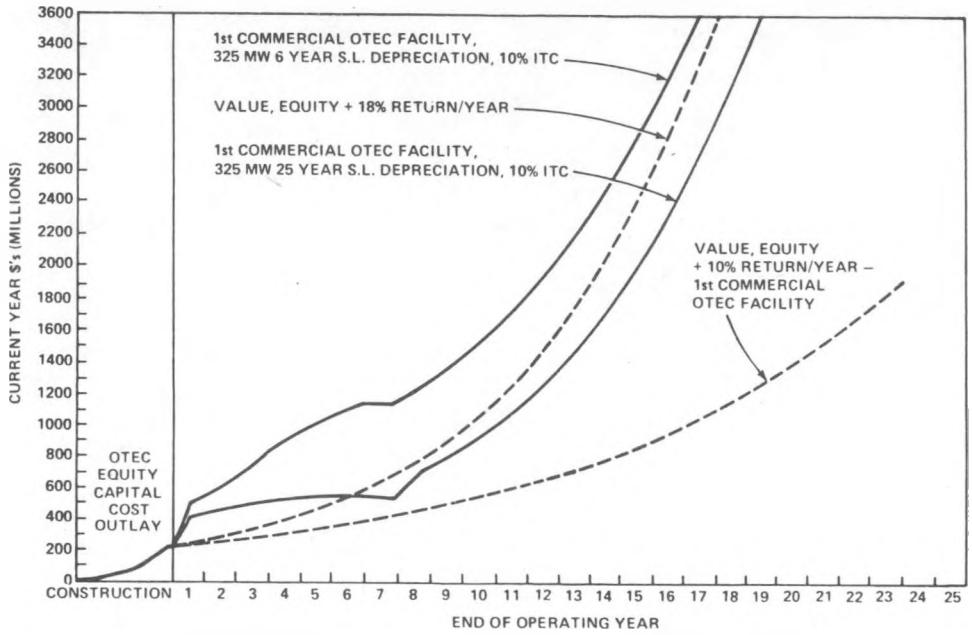
CONCLUSION

In summary, we have presented selected material on the fairly extensive construction facilities which would be needed in one site to build one specific type of OTEC plant - the baseline barge-type hull concrete ship. This material has been based on a specific point design for which extensive engineering detail



40-MW_e case: 34.3 MW_e delivered to substation ashore. $205.2 million OTEC facility cost (1980 $'s). $84.7 million construction facilities cost (1980 $'s). 150 mills/kWh (1985 $'s) price for power delivered. 9/13/15/10 inflation and interest rates used. 30 in crew, 87-1/2% of OTEC capital Title XI debt. 10% Investment Tax Credit plus 15% Energy Tax Credit. Cost-sharing: 100% private financing of capital costs, Federal Government provides operating subsidy of $10 million/yr (1980 $'s) for 1st 6 years of operation.

Fig. 5 Ocean thermal energy conversion effect of depreciation rate change on return on equity.



325-MW_e commercial-scale case: 266-MW_e delivered to substation ashore. $808.3 million OTEC facility cost (1980 $'s). $34.4 million construction facilities cost (1980 $'s). 100 mills/kWh (1985 $'s) price for power delivered. 9/11.625/15/10 inflation and interest rates used. 60 in crew. 87-1/2% of OTEC capital Title XI debt. 10% Investment Tax Credit. Cost-sharing: 100% private financing of all capital and operating costs.

Fig. 6 OTEC: effect of depreciation rate change on return on equity.

and costs are available. Similar information from others on bottom-mounted and island-mounted OTEC plants has been requested, but not yet received. We believe that, with a modest program of Government support, demonstration OTEC plants can be built in such a fashion that private industry can participate and still live with their shareholders. Information is also presented, albeit without supporting engineering design and detailed cost data, which show that even the first commercial-scale OTEC plants can be built in U.S. shipyards and can be profitable ventures.

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8th Ocean Energy Conference
Washington, DC
June 1981

MINI-OTEC 2 PROGRAM PLAN FOR ELECTROCHEMICAL AND SYNTHETIC FUELS DEMONSTRATION

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ABSTRACT

A plan has been presented for a Mini-OTEC second deployment which will be directed toward an OTEC mission to demonstrate the manufacture of synthetic fuels and electrochemical products, and to perform OTEC research to substantiate and expand on the data base acquired from the first deployment. At the time of the 8th OTEC conference, Lockheed is in the process of soliciting participants to share the research costs of the project and the probability is high that we will be successful; however, the zeroing of the federal OTEC budget has had a detrimental impact on the organizational plans. In light of the uncertain plans within the federal government, an operational OTEC plant will play an important role within private industry in their efforts to commercialize the OTEC industry.

The original Mini-OTEC facility successfully operated for approximately 3 months and generated a maximum net power of 18.2 kw, which was higher than the original design estimate of 10 kws. The electrical power was dissipated into demonstration lights and heaters; however, for the next research project, the electrical power will not be wasted, but will be used for useful work.

The project is scheduled to be deployed in the late summer of 1981 and is to remain on station for approximately one year with participation from State of Hawaii, Department of Energy, private industry and international organizations.

1. INTRODUCTION

In 1979 the Mini-OTEC facility, while deployed off the coast of Hawaii, demonstrated for the first time the feasibility of Ocean Thermal Energy Conversion. The plant was designed to generate 50 kw of electrical power, 40 kw of which was required to sustain the parasitic loads and the remaining 10 kw was available as net power. The OTEC plant operated better than the design specifications with a maximum net power of 18.2 kw being achieved and OTEC research was performed for approximately three months until the platform was demobilized as planned and placed into wet storage.

It is now proposed to use the existing equipment, with certain modifications, to continue the Mini-OTEC research project, using the net electricity to provide a demonstration of the electrochemical applications of OTEC power and to conduct OTEC technology development. The project will be directed by Lockheed Corporation with participation from the State of Hawaii, the Dept. of Energy, private industry and international organizations.

The planning that has occurred to establish the baseline program for participating organizations is described herein. Although the detailed planning is not completed, enough preliminary work has been accomplished to establish confidence that the project can be performed within cost and schedule. When the invited organizations have finalized the agreements of participation and have had a chance to coordinate their program suggestions with Lockheed, this plan will be revised to reflect those suggestions and to finalize the details as necessary.

2. PROGRAM OBJECTIVES

The original Mini-OTEC project proved that the OTEC concept was viable and established OTEC as a potential commercial alternate energy source. However, to aid commercialization, an operating OTEC plant is needed to continue the conceptual demonstration for potential domestic and international decision makers. The major objective of this program is to provide an at-sea demonstration project which will not only provide an operating OTEC system but will provide a platform on which additional OTEC research can be performed. The operating OTEC plant will:

- Increase OTEC operational experience.
- Expand the cooperative working relationship between private industry, state, federal and international organizations.
- Provide an at-sea platform on which to expand the OTEC data base.
- Utilize OTEC electricity to perform the OTEC research including production of electrochemicals.

3. MISSION OBJECTIVE

The net power generated on the original Mini-OTEC project was dissipated in test loads on board the platform. Rather than again dissipate the net power, missions have been identified to use the

OTEC generated electricity to perform OTEC research. These missions can be divided into the general categories of Product Mission and Technology Development.

3.1 Product Mission

The primary mission of the program is to demonstrate the electrochemical applications of OTEC generated electricity. The primary product will be hydrogen electrolyzed from deionized seawater. The hydrogen is then to be used in available processes to manufacture three end products; synthetic crude oil, ammonia, and methanol.

Hydrogen Generation: An on-board hydrogen generator, similar to a Teledyne Model HS-50, will be used to electrolyze deionized seawater which will produce, depending upon the available net power, up to 100 standard cubic feet per hour (SCFH) of dry hydrogen. The hydrogen will be compressed to 2300 psi by a compressor (similar to a Pressure Products Industry Model Q-071038) and stored for use in the synthesis of syncrude, ammonia or methanol.

Syncrude: A process has been identified to demonstrate the feasibility of enriching Alaskan coal with OTEC hydrogen to form a clean burning synthetic crude oil. The OTEC hydrogen and coal from the Beluga fields of Alaska will be transported to a laboratory on the mainland United States to perform the synthesis.

Ammonia: A process has been identified whereby the OTEC hydrogen will be synthesized with bottled nitrogen to form ammonia. This process will be performed on the Mini-OTEC platform.

Methanol: A process has been identified whereby the OTEC hydrogen will be synthesized with bottled carbon monoxide to form methanol. This process will be performed on the Mini-OTEC platform.

3.2 Technology Development

The Mini-OTEC platform presents an opportunity to further OTEC research in the at-sea environment. The OTEC research projects to be performed are:

- o Evaluation of aluminum heat exchangers.
- o Low cost cold water pipe development.
- o Control system responses evaluation.
- o Establish reliability.
- o Biofouling/corrosion evaluation of heat exchangers and heat transfer monitors.

Other research projects will be accepted on a funding/space/time/power availability.

4. PROJECT DESCRIPTION

It is planned that the existing Mini-OTEC platform be redeployed using the same design as previously used, modified only to include the following:

- o Incorporate the Trane Company aluminum heat exchangers
- o Improve operating reliability
- o Add the hydrogen generation/storage system
- o Add the ammonia and methanol processes
- o Add the mariculture system
- o Add new instrumentation
- o Add biofouling/corrosion test hardware

The platform and OTEC plant will be refurbished to make "as new" prior to deployment. The refurbishment work will be performed dockside at the Marine Expeditionary Center, University of Hawaii (Snug Harbor). Redesign and refurbishment are planned to be completed three months after project go-ahead.

The operational location will be in the OTEC research corridor established offshore of the Sea Coast Test Facility on the big island of Hawaii. The original design for the cold water pipe/mooring system (single point moor, 24 inch diameter polyethylene pipe) will again be used. Makai Ocean Engineers will perform the marine engineering for the cold water pipe/mooring system and will supervise the deployment to be performed by Dillingham Corporation.

Test operations will be performed 24 hours per day, seven days per week for a nominal one year period. The operational period may be extended or shortened to match the available project funds. Offshore Hawaii, Inc. will perform the logistics, shuttle service and barge manning as they performed on the original deployment.

Test operations will be directed primarily toward the generation of on-board hydrogen using the OTEC power. However, various tests of the OTEC plant, which may interrupt the primary mission, will be performed during the operational period. These tests will be directed toward increasing the data base established during the first deployment to assure that the OTEC plant design criteria are fully understood and can be safely applied to the design of large scale plants. The OTEC plant will periodically be shut down to perform a corrosion inspection of the aluminum heat exchangers and visually to determine the magnitude of biofouling. Initial operations will be conducted without any biofouling countermeasures; however, if it is determined biofouling control is necessary, chlorination of 2 ppm 2 hours per day or less than 0.1 ppm continuous will be used. The project participants will have free access to the platform at all times and will be encouraged to participate in plant operations and testing. Data taken as a result of the tests will be analyzed and the results delivered to the participants.

The start-up generator or the emergency generator will be used for on-board power when the OTEC plant is shut-down. Every effort will be taken to provide a continuous water supply to the mariculture tanks and the biofouling heat transfer monitors. Heat transfer monitor data will be reported through the Sea Coast Test Facility.

Weekly activity reports will be distributed to all participants describing the activity of the week and plans for the following week. Monthly reports will present a preliminary analysis of testing which was performed and will report the results of any visual inspections.

5. OTEC PLANT SPECIFICATIONS

5.1 Heat Exchanger Design

- The working fluid is anhydrous ammonia with the possibility of up to one percent water in the evaporator section of the ammonia loop. The evaporator uses seawater pumped from the surface while the condenser employs seawater pumped from a depth of approximately 2,200 ft.
- Present biofouling control consists of ≤ 0.1 ppm continuous chlorination of the evaporator and condenser seawater supplies. Countermeasures other than continuous chlorination are desired for testing.
- The evaporator is supplied with liquid ammonia which is subcooled approximately $20^{o}F$ below the evaporation temperature of the evaporator. The subcooling may be removed in a separate liquid-liquid heat exchanger if required. The available seawater flow rate for this purpose is approximately 90 gpm at $80^{o}F$.
- The evaporator must produce a minimum ammonia vapor flow rate of 5.3 lbm/sec. The choice of an evaporator exit quality should be based on an optimization of the overall heat transfer coefficient in the quality range of 50 to 100 percent. The maximum liquid ammonia pumping rate is 10.4 lbm/sec.

Evaporator Operating Conditions

Ammonia

Inlet liquid temperature - $50^{o}F$
Outlet saturation temperature - $70^{o}F$
Outlet saturation pressure - 128.8 psia
Outlet vapor mass rate - 5.3 lbm/sec

Seawater

Inlet temperature - 80^{o} - 81^{o}
Flow rate - 2800 gpm
Maximum frictional pressure drop - 4 psi
Outlet pressure - -8 psig
Biofouling level - $\sim 0.0001(Btu/hr\text{-}ft^{2}\text{-}^{o}F)^{-1}$

Condenser Operating Conditions

Ammonia

Inlet temperature - $52^{o}F$
Inlet pressure - 92.6 psia
Inlet mass rate - 5.3 lbm/sec
Inlet quality - ~97%
Outlet quality - 0%

Seawater

Inlet temperature - $43^{o}F$
Flow rate - 2800 gpm
Maximum frictional pressure drop - 4 psi
Outlet pressure - -8 psig
Biofouling level - $\sim 0.0001(Btu/hr\text{-}ft^{2}\text{-}^{o}F)^{-1}$

In order to ensure the cleanliness of the ammonia heat transfer surfaces, only inert materials are to be used in the heat exchangers where there is contact with the ammonia working fluid.

5.2 Turbine/Generator Design Specifications

Turbine

Working fluid - ammonia
MOL % - 100
MOL WT - 17.03
Inlet pressure - 128.3 psia
Inlet temperature - $70^{o}F$
Discharge pressure - 92.8 psia
Discharge temperature - $52^{o}F$
Ammonia flow rate - design pt. - 5.1 lbs/sec
Range - 4.5 to 5.5 lbs/sec
Ammonia inlet quality -96.7% or higher

Generator

Synchronous
50 kw output (minimum), 0.8 pf
60 Hz, 3 ph, 120/208 V (RMS)
Voltage regulation $\pm$ 10% of set voltage

5.3 Power Summary

First Deployment

Power generated - 53 kw
Cold water pump/motor - 14.3 kw
Warm water pump/motor - 10.3 kw
Ammonia pumps/motor - 6.2 kw
Auxiliaries - 4.0 kw
Net power - 18.2 kw

Second Deployment

With the addition of heat exchangers with a lower differential pressure on the seawater side and with other planned improved changes throughout the seawater and ammonia systems, a net power possibly up to 20 kw can be expected. This net power will be directed toward the biofouling evaluation system, the mariculture pumps and to the hydrogen generation system. A typical loading for the above equipment could be as follows:

Hydrogen generator - 4 to 16 kw (.8 pf)
26 to 106 SCFH
Hydrogen compressor - 1.5 kw
Deionizer pump - negligible
Mariculture/biofouling pumps - 3 kw

6. PROGRAM COSTS

The estimated costs of the planned program are approximately $1.8 million as itemized below:

Refurbishment material	$ 190,000
Refurbishment labor	43,000
Engineering support (including Operations)	474,000
Cold water pipe/mooring system	520,000
Marine services support (12 months operations)	400,000
Contingency (10%)	163,000
	$ 1,790,000

The costs of the program do not include various goods and services which have been identified to be donated or loaned to the project by the participants. Although firm commitments have not been received, confidence is high that the following will be available at no cost to the project:

Heat Exchangers
Hydrogen Mission Hardware
Product Synthesis Hardware
Mariculture Hardware
Data Processor/Instrumentation
Program Administration

The project costs will be funded by the participants in either cash, goods, or services, depending upon the participants' background, experience and reason for participating.

8. PROJECT SCHEDULE

1 July 1981 - All agreements finalized, design and refurbishment start
1 November 1981 - Deploy
1 December 1981 - On site testing complete
1982 - Operational testing - 12 months

The scope of the proposed program and the diversity of participants may impact the proposed schedule. However, the program will be launched as soon as the necessary funding commitments are received.

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CAPABILITIES AND POTENTIAL OF THE SS OCEAN ENERGY CONVERTER AS AN OCEAN TEST FACILITY

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ABSTRACT

The SS Ocean Energy Converter, is a floating test facility designed and fabricated by GMDI and presently being operated by the DOE to evaluate the in situ performance of 1 MW_e heat exchangers and ancillary equipment. With the proper programmatic, technical, and financial funding, this government-owned facility could be used by other interested parties for conduct of piggyback research, experiments, parallel engineering studies or other non-OTEC related developmental test programs.

This paper introduces the reader, and potential user, to the four major elements of the test facility; the platform, the cold water pipe, the OTEC plant, and the single point mooring.

INTRODUCTION

Since 1972 the U.S. Department of Energy (DOE) has been directing the development of one of the most promising alternative energy sources known as Ocean Thermal Energy Conversion (OTEC). Application of theory has resulted in a concept which involves the extraction of energy from the oceans by using the difference in temperature between the solar warmed surface water and the colder deep waters. OTEC is a multiphased program which will ultimately result in the demonstration of commercial power plants having up to 500 MW_e net power output. Present plans call for this demonstration to take place sometime during the 1985-1995 time period. Once operational, commercial plants will produce electricity which can either be transmitted to shore or can be used in situ for the manufacture of such energy intensive products as ammonia, hydrogen and aluminum.

Ocean thermal energy is, in fact, a form of solar energy since the system uses surface water which is warmed by the sun. In tropical regions, the difference between the temperature of surface water and deep water is about 20°C to 26°C. This temperature differential can be used to operate a heat engine and thereby generate electricity.

Figure 1 illustrates the major elements of a typical closed-cycle OTEC plant (1)*. Unlike other solar energy processes, however, OTEC can continue to generate power throughout the night, under cloudy skies and even over a period of several days when the sun doesn't shine. This is due to the fact that the surface water is a large heat storage system, and the diurnal temperature gradient remains fairly constant throughout the day and night.

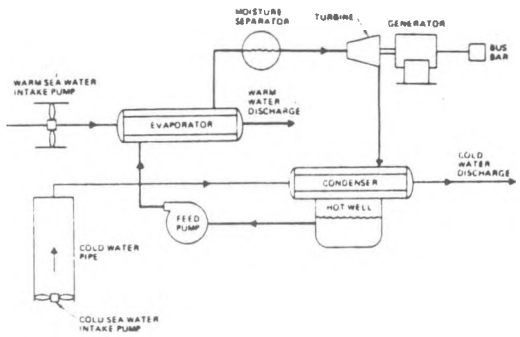


Figure 1
Typical OTEC Rankine Cycle

All studies conducted to date indicate that these ultimate commercial OTEC plants will be installed on one of the following three basic types of platforms:

- o A fixed facility installed on land
- o A floating facility moored on site
- o A "grazing" facility that moves slowly across the surface of the ocean searching out and following the most desirable thermal gradient

One of the major problems with any program of this scope, which requires that very large and costly structures be constructed, deployed and maintained in the open ocean environment, is the accumulation of sufficient and meaningful in situ test data

*Numbers in parenthesis refer to references listed at the end of this paper.

and operating experience. At the present time there are no large facilities of this type which permit controlled research in the open ocean where real time observations can be made, various parametric experiments conducted or test data analyzed. Meaningful exploitation of the extensive, available ocean resource is significantly hindered by this inadequacy. The SS Ocean Energy Converter is an existing facility which could help meet these expanding technological needs if the proper organizational and funding arrangements could be satisfied.

BACKGROUND OF THE OTEC-1 PROGRAM

In October 1978 the Department of Energy (DOE) contracted with Global Marine Development Inc (GMDI) to provide a floating test facility which would be capable of conducting large scale, long term, tests of several prototype OTEC heat exchanger configurations. The basic requirements for the facility were dictated by the primary 1 MW_e experiment, and related equipment. These initial heat exchangers were designed and fabricated by TRW Systems under a separate DOE contract. After an initial design period of six months actual construction of the test facility began in March 1979. The heat exchangers were installed in November 1979 and in July 1980 the completed facility was moored at the operational site approximately 18 miles off Keahole Point on the west coast of the Island of Hawaii. After the 2,200 foot long pipe assembly was mated with the ship and acceptance trials conducted, the SS Ocean Energy Converter was delivered to the DOE in November of 1980 and has been successfully operating under separate contract to Rockwell International's Energy Technology Engineering Center (ETEC) since that time.

The OTEC-1 test platform (2) is comprised of four major hardware elements:

- o Floating Platform
- o Single Point Mooring
- o Plant (including the GFE heat exchanger test articles)
- o Cold Water Pipe

It is hoped that through this paper the reader will be able to comprehend the scale and capability of the overall facility and to envision how it might be used to support other potential scientific programs or engineering experiments.

THE FLOATING PLATFORM

The basic requirement for the overall OTEC-1 program was to provide a safe, reliable test platform which could be moored in 4,500 feet of water and maintain position, on station, for an extended period of time. A nominal 100,000 gallons per minute (gpm) of cold seawater had to be pumped from a depth of 2,200 feet and another 100,000 gpm from the warmer surface layer. These seawater flows were then routed through two large heat exchangers. A closed loop system was used to continuously boil and condense 6,000 gallons of working fluid which, in this case was ammonia. Instrumentation was required to monitor and control biofouling and other heat exchanger related experiments. Other features include a laboratory for onboard analysis, a control and data storage center, personnel accommodations and work spaces, and ancillary support services. Figure 2 illustrates some of the salient features of the converted system as deployed off the Island of Hawaii.

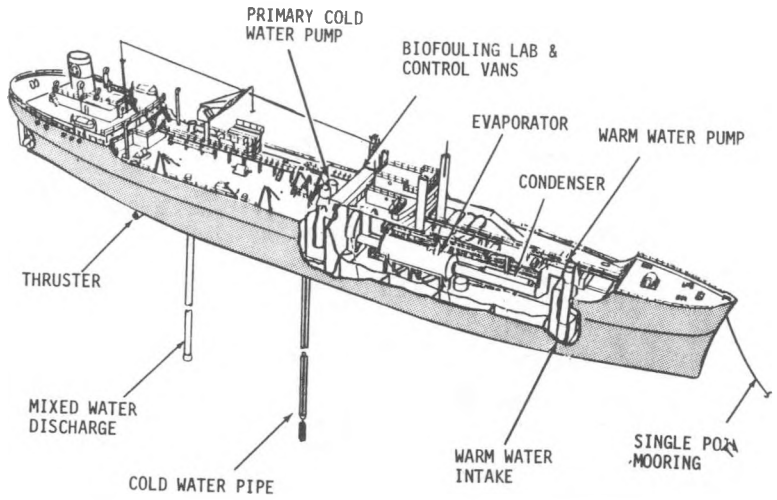


Figure 2
Features of the OTEC-1 SS Ocean Energy Converter

The vessel selected to meet the overall system requirements was a surplus U.S. Navy "T2" tanker, a ship well known for its versatility, seakindliness and durability. Specifically, the ship chosen was the USNS Chepachet, (TAO-78), a T2-SE-A1 turbo-electric driven tanker built in 1943 at the Sparrows Point Shipyard of Baltimore, Maryland. Upon award of the OTEC-1 contract the vessel was withdrawn from the National Defense Reserve Fleet at Suisun Bay, California and was transferred from the U.S. Navy to DOE in early 1979. After conversion, the Chepachet was renamed the SS Ocean Energy Converter, leaving no doubt as to her new mission.

The SS Ocean Energy Converter has the following characteristics:

- Length Overall (LOA) 523'-6"
- Length Between Perpendiculars (LBP) 503'-0"
- Beam - Molded 68'-0"
- Depth
  - Molded at Centerline 39'-3"
  - Operating Waterline 24'-0"
- Navigational Draft
  - Thrusters Down 31'-8"
- Light Ship Draft 10'-4"
- Light Ship Displacement 6,352 LT
- Operating Displacement 16,120 LT
- Propulsion
  - Main Propeller 7,000 SHP @ 93 RPM
  - Thrusters (2) 2,000 SHP (Each)

Motions

The motion characteristics of the test platform are characterized by a gentle roll and reasonable pitch and heave covering a broad range of loading conditions and are typical of a ship shaped hull. The RMS motion characteristics for significant seas of up to 32 feet are shown in Table 1.

TABLE 1 - RMS Motions

SEA HEADING	SIGNIFICANT WAVE HEIGHT (FT)	SURGE (FT)	SWAY (FT)	HEAVE (FT)	ROLL (DEG)	PITCH (DEG)	YAW (DEG)
HEAD	8	0.25	-	0.38	-	0.44	-
HEAD	16	1.31	-	1.75	-	1.56	-
HEAD	32	3.81	-	5.85	-	3.00	-
QUARTERING	8	0.28	0.50	0.44	0.15	0.56	0.25
QUARTERING	16	1.13	1.37	2.31	2.12	1.50	0.63
QUARTERING	32	2.94	4.88	6.50	3.31	2.56	1.13

Arrangements

The general arrangement and compartmentation of the ship is of classic tanker design with cargo tanks forward, engine room aft and a midship house for navigation and quarters for the deck officers. The raised forecastle deck and anchor windlass were left in their original configuration, however, a new large padeye was installed in the bow for attachment of the single point mooring line. Bosuns stores, paint locker, lamp locker and chain locker remained as originally installed.

The hull of a standard T2 tanker contains nine cargo tanks longitudinally and three tanks abreast providing a total of 27 independent tanks. With the exception of the first set of three tanks all tanks are 35 feet long. There are two longitudinal bulkheads dividing the tanks into port and starboard wing tanks and center tanks. The center tank is 35 feet wide and the wing tanks are each 16.5 feet wide. The arrangement of the ship showing these tanks is shown in Figure 3. The No. 1 tank is used as a warm water intake and sump. This tank has a 5 foot hole cut in the bottom which allows it to free flood. A vertically driven propeller pump is mounted in this space and provides warm surface water to the evaporator. The bulkheads between center tank Nos. 2, 3 and 4 were removed to create a space 35 feet wide, 105 feet long and 39 feet high. This newly created space houses the entire OTEC plant,

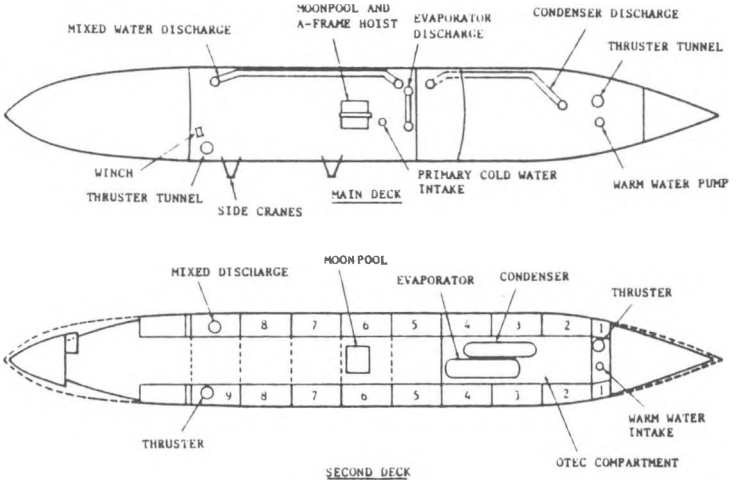


Figure 3
Main Deck & Tank Arrangements

including the GFE condenser and evaporator. Some ancillary equipment is arranged in the forward 30 feet of the OTEC compartment space, however, this area is not crowded and could be used to install additional experimental equipment. Center tank No. 5 is outfitted with access ladders, lights, ventilation, and some instrumentation and, although for reasons of safety is isolated from the OTEC space by air locks it is virtually unused and could house additional experiments without requiring any additional outfitting or modification.

Center tank No. 6 forms a 20 foot square center well which penetrates the hull from the top deck through the bottom shell plate. A double axis gimbal structure, used to support the cold water pipe, is installed in this center well. Since they are not presently outfitted for any specific purpose, center tanks No. 7 and 8 could provide a space measuring some 35 feet wide by 70 feet long for labs or other work areas. Center tank No. 9 houses additional electrical switchgear, transformers and SCRs to support the OTEC-1 program.

All remaining wing tanks are used for ballast with the exception of the No. 5 port tank which is used as a mixing sump for the effluent being discharged from the evaporator and condenser and the No. 9 port tank which is used as a holding tank for oily water waste.

The midship house contains the navigation deck, berthing, offices and a lounge for the scientific personnel. A deck extension was added aft of the midship house on which two pre-outfitted instrumentation and control vans are mounted. One of these vans houses the OTEC control and data acquisition hardware and the other contains a biofouling control laboratory.

The engine room, boiler room, and steering gear room are located in the stern of the ship below the main deck. Crew quarters, galley, mess room, recreation room, and emergency generator room are located above main deck. Raised catwalks connect the aft house to the midship house and the midship house to the forecastle.

Electrical System (3)

The Chepachet was an ideal choice for conversion to an experimental OTEC test platform because her existing main power plant consisted of two steam boilers driving a steam turbine/AC generator with a large 7,000 HP synchronous AC electric motor mounted directly to the single propulsion shaft. Speed control underway is achieved by varying the speed of the turbine and thus the frequency of the generator and motor. Once moored, the propulsion motor is electrically disengaged and the turbogenerator is used to feed 2,300 V, 60 Hz, AC power to the various support equipment associated with both the OTEC plant and the ship systems. The following are the main features of the electrical power generation and distribution system as shown in Figure 4.

- The boilers are Babcock and Wilcox watertube boilers. Each boiler is rated at 32,058 lbs of steam per hour, with a steam pressure of 467 psi at 730°F total temperature.
- The main turbine is a 10-stage General Electric turbine rated at 5,400 kW at 3,600 rpm with steam at 435 psi and exhaust pressure at 1.75 psia. The turbine is coupled directly to a GE main propulsion generator, generating 5,400 kW at 2,300 V AC, 60 Hz 3-phase, separately excited at 110 V.

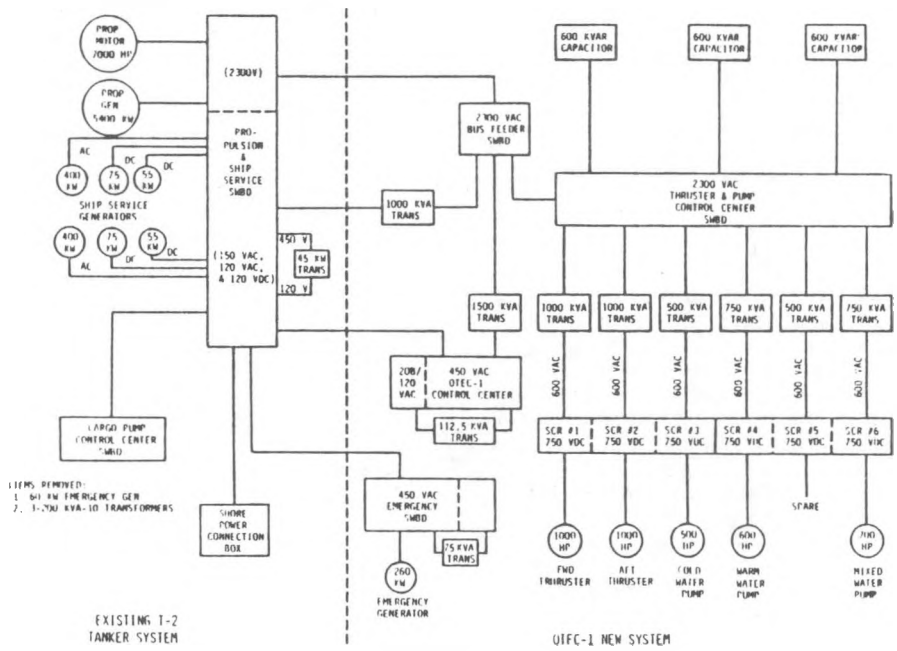


Figure 4
Primary Electrical Distribution

- The 7,000 SHP GE synchronous propulsion motor delivers full power at 93 rpm, and is cooled by an integral air cooler. The motor can be reversed electrically.

The primary power system diagram shown in Figure 4 shows that plenty of reserve power is available for additional electrical loads which might be required by any "piggyback" experiments.

Deck Machinery

Since all of the large 5 foot diameter cold water, warm water and discharge piping is routed along the port side of the main deck this area is relatively inaccessible. The starboard side, however, is relatively free of obstructions and offers sufficient space for installations of other equipment or for conduct of over-the-side operations. Due to the 15 foot freeboard, the main deck of the vessel remains dry under normal operating weather. A Link Belt pedestal crane is mounted on the main deck aft. In order to raise and lower the cold water pipe gimbal and to upend, keelhaul, attach and/or recover the cold water pipe, a large capacity double drum winch, an over-the-side A-Frame and several chocks, bits and fairlead sheaves are provided.

Features of this heavy load handling system are:

- Handling Winch (See Figure 5)
  - Skagit Model No. DTW-150-WP double drum, rated 150,000 maximum each drum
- Centerwell A-Frame
  - Rated at 200 tons
  - Clearance under main beam is 19.5 feet
- Self-Aligning Swivel Fairlead
  - Skagit DWF-24 rated at 75 tons
  - Extends over the side 2 feet and is capable of handling loads applied from any direction
- Over-the-side A-Frame (See Figure 6)
  - Massive pipe structure that can handle 100 tons (62.5 tons rated)
  - Extends 15 feet from the side of the ship
  - A 42 inch diameter sheave, suspended from the boom tip, allows load handling within 30° from vertical cone
- Sheaves - 42 inch (9 available) suitably arranged to fairlead 2.5 inch wire from the double drums of the winch to each of the A-Frames and swivel fairleads, grooved for 2 inch wire
- Electric Winches - 10,000 pound pull (2 available), and 5,000 pound pull (1 available). Each of the electric winches contain between 300 and 600 feet of 5/8 inch diameter wire line
- Release Devices - Reagan Offshore Company remote release for the 2 inch wire. These devices can remotely release a load by sliding a 400 pound line runner ("go-devil") down the wire. One of the devices has a built in swivel which precludes line hockling upon release of load
- Pedestal Crane
  - Link belt
  - Rating (See Table 2 for rating)

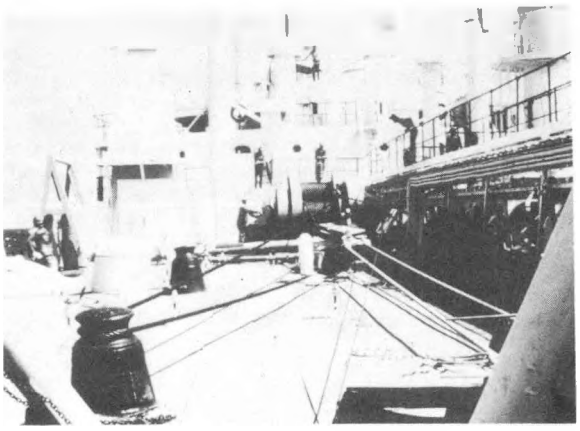


Figure 5
CWP Handling Winch



Figure 6
Over-the-Side A-Frame

TABLE 2 - Pedestal Crane Rating

Boom	Load (lbs)	Boom Radius (Ft)	
		Minimum	Maximum
Whip	10,000	12	-
	4,100	-	53
Main Hook	54,300	12	-
	4,100	-	53

Quarters

Quarters are provided to accommodate a total of 40 persons consisting of 28 marine crew and 12 scientific or engineering personnel. Additional personnel are allowed onboard during daytime hours when the ship is moored on station, as permanent berthing is not available for these temporary personnel. The accommodations are typical of merchant ships of the WW II era, however, they have been refurbished to the point where they are very comfortable, clean and functional. There is a galley, messing facility and a small lounge in the aft house. The boat deck aft is covered by a permanent awning which when coupled with the

Hawaiian climate, provides a pleasant lanai. The navigation bridge, chart room, radio room, captains quarters, ship's office, lounge and quarters for the scientists are located in the midship house. These are more elaborately refurbished.

SINGLE POINT MOORING AND STATIONKEEPING

Ground Tackle

The mooring system for the SS Ocean Energy Converter posed one of the more challenging problems in that the ship had to be permanently moored at a location that allowed the test facility to weathervane around the moor, in a 3 mile watch circle while not allowing the cold water pipe to come in contact with the bottom. This requirement dictated a minimum water depth of 2,900 feet. The maximum water depth was limited to 5,200 feet such that when the cold water pipe was released and vertically stored on the bottom the line from the shipboard winch to the top of the pipe would be long enough for later recovery. When a satisfactory location was identified off the west coast of Hawaii it was determined that the bottom did not contain sufficient sand or mud to allow the use of an embedment type anchor. To complicate the matter, the bottom was actually an old lava flow. A mass anchor or drilled-in pile provided the only logical solution. A pile anchor was quickly eliminated since there were few drillships in the world that could drill such a hole and these were not only expensive, but generally not available when needed. A mass anchor was no small challenge either since it would have to weigh over 120 tons in water. To lower such a large mass in 4,500 feet of water would also require the use of a drillship. The solution was unique and, as it turned out, very cost-effective.

The configuration consisted of 230,000 pounds of scrapped anchor chain bundled together, attached to a 4,200 foot long 2.25 inch wire rope which in turn was secured to a syntactic foam subsurface buoy. This assembly was taken to the mooring site on a barge and launched by merely sliding it overboard. The mass anchor fell to the bottom within 350 feet of the target location which was well within the allowable "drop zone" of 600 feet. The final arrangement of the deployed mooring is shown in Figure 7.

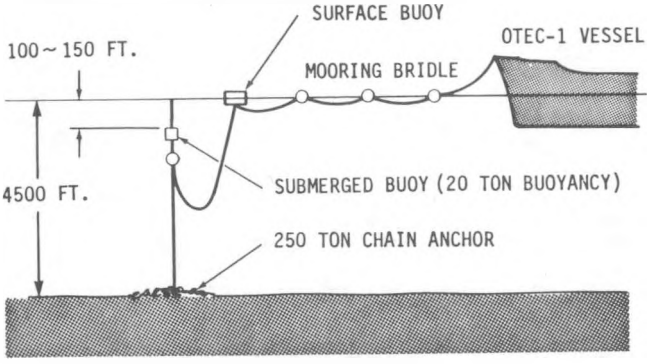


Figure 7
OTEC-1 Mooring System

Thrusters

Two 1,000 HP retractable, variable speed, vertical trunk, azimuthing thrusters, fabricated by Propulsion Systems Inc. of Bellingham, Washington are considered as part of the mooring system. These thrusters are mounted in the No. 1 port and the No. 9 starboard wing tanks. The thrusters deliver a nominal 27,000 pounds of thrust and rotate through 360° such that thrust can be applied in any direction. The thrusters can either be slaved together or operated independently from a control station located on the navigation bridge. In calm weather the thrusters are used to back down on the moor so that the mooring line is always kept under tension.

Tension in the moor is required to insure that the cold water pipe, suspended below the ship, does not become entangled with the mooring line. A load cell in the mooring attachment to the ship provides a continuous real time indication of mooring line tensions. The thrusters can also be used as propulsion units if it becomes necessary to transit from site to site at very low speed.

THE OTEC-1 PLANT

The OTEC-1 plant consists of an evaporator unit and a condenser unit, warm and cold water circulating systems, a biofouling control system, a tube cleaning system, a working fluid (ammonia), and instrumentation and controls. As depicted in Figure 1, warm water is pumped through the evaporator to "boil" the working fluid. This vaporized ammonia is passed through a throttling valve which acts as a mock turbine and thence into the condenser. Cold seawater, is used to condense the ammonia to the liquid state. The ammonia condensate pump, which is comparable to a boiler feed pump, then returns the liquid to the evaporator and the cycle repeats.

Some of the specific features of the heat exchangers are shown in Table 3:

TABLE 3 - OTEC-1 Heat Exchanger Characteristics

Parameter	Evaporator	Condenser
Diameter (ft)	13	10.5
Length (ft)	52	54
Weight-Dry (lbs)		
Tubes-Number	6,300	5,525
-Material	Titanium	Titanium
-Diameter (in.)	1	1
-Surface area (ft^2)	61,050	57,450
Design Pressure (psig)	250	250
Duty Cycle (BTU/Hr)	1.3×10^8	1.3×10^8

Salt Water Circulating Systems

The warm and cold water circulating systems are arranged such that vertically driven propeller pumps draw water from their respective sumps, pass it through the heat exchangers and combine

the discharge flows in a common mixing tank from which the mixed discharge is returned to the sea. The pump intakes are located near the bottom of the sumps with the vertical DC electric motor mounted above the main deck level for ease of maintenance.

All of the cold water and warm water piping is 60 inches in diameter and is made of steel. The pipes are routed up and over bulkheads such that no valves are required and no water tight bulkheads are penetrated. The maximum calculated pressure surges due to the long runs of large diameter pipe are less than 2 percent.

The discharge pump takes suction from the mixing tank and discharges the water back into the sea through a 72 inch diameter discharge hose which is located in port wing tank No. 9. The length of the discharge hose can be varied from a point just under the hull to as much as 240 feet.

Some of the operating features of the water pumps are shown in Table 4:

TABLE 4 - Features of OTEC-1 Circulating Pumps

Parameter	W/W	C/W	Mixed Discharge
Maximum Flow (gpm)	98,000	78,000	176,000
Maximum Head (ft)	15.2	16.5	11.7
Horse Power (HP)	600	500	700
Pump Dimensions			
-Length (ft)	52	53	52
-Diameter (ft)	5.5	5.0	6.75

Biofouling Control

The heat exchangers were designed to accommodate an overall fouling factor of 5 x 10^{-4} ^{o}F-Ft^2-HR/BTU. It was felt that if the overall fouling factor could be reduced to half of this original design allowable, 15 percent less heat exchange surface area would be required. This could result in a potential savings of 5 to 7 percent in overall costs of a commercial plant. Thus the effectiveness of the cleaning system on the water side of the heat exchanger has a significant effect on the overall economic viability of the system. A chlorinate biocide and a mechanical cleaning system were tested on OTEC-1.

The chlorine used in the system is produced on the test platform directly from seawater. The chlorine generator electrolytically produces sodium hypochlorite (NaOCl) and hydrogen gas. As much as a ton of free chlorine can be produced daily. Normal injection rates are on the order of 0.05 to 1.0 ppm. Chlorine is injected every eight hours as required to maintain biofouling within acceptable limits. This amounts to a 15 minute injection about three times per day.

An AMERTAP system, designed to mechanically remove biofouling by circulating small sponge rubber balls through the heat exchanger tubes, can be used separately or in conjunction with the chlorine system. The balls are biodegradable and, on the average, are slightly larger in diameter than the tubes. The balls are injected into the cold water and warm water inlets just upstream of the heat exchangers. After passing through the tubes they are collected, sorted and reinjected into the exchangers. The balls are randomly injected such that at any given time about 10 percent of the tubes are being "scrubbed". It takes an average of 10 minutes for any given ball to pass through the cleaning cycle. If stubborn fouling persists, the sponge rubber balls can be replaced with more abrasive, silicon carbide coated sponge rubber balls.

Ammonia System

The ammonia system is shown schematically in Figure 8. The ammonia liquid enters the evaporator and is sprayed onto the warm water tube bundles from headers located lengthwise above the tubes and in the horizontal midplane between the two tube bundles. The ammonia which does not evaporate, drains into a surge tank below the evaporator shell and is recirculated, or refluxed, back to the top nozzles. The reflux rate can be as much as four times the evaporation mass flow rate. Only the midplane feed level provides make-up fluid to replace the evaporated ammonia.

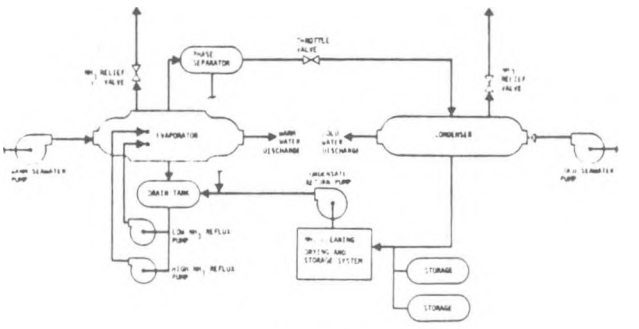


Figure 8
Ammonia System

Approximately 256,000 pounds per hour of ammonia vapor exits the top of the evaporator at 72^{o} and 133.4 psia. The ammonia vapor passes through a phase separator, which removes ammonia droplets and dries the gas, and then passes through a 10 inch throttling valve which simulates an ammonia turbine in terms of pressure and temperature losses, and enters the top of the condenser at approximately 55^{o}F and 85.8 psia. After leaving the throttling valve, the ammonia vapor flows into the top of the condenser and down over the cold water tube bundles. The vapor condenses and drains into five drain pots at 48^{o}F and 88.4 psia. The condensate pumps return the condensed fluid to the evaporator sump at 68^{o}F and 148.4 psia and the cycle is repeated.

There are approximately 6,000 gallons of liquid ammonia in the power loop with 2,000 gallons held in reserve. Two vessels located on the main deck can store the entire required volume of working fluid. In an emergency, or for routine inspection or maintenance of the heat exchanger, the ammonia

is pumped from the power loop to these storage tanks. The power loop can then be vented to atmosphere while purging the system with gaseous nitrogen. The system must be purged several times to insure that a safe entry can be made into the heat exchangers. A total of 48,000 standard cubic feet of nitrogen, maintained at 2,400 psig, is provided in 162 standard ICC bottles located on the aft main deck area.

Monitor and Control System

The function of the test loop monitor and control system is to provide the test environment necessary to test the heat exchangers and to gather data pertaining to the OTEC process.

Local control of the system is provided at certain critical points in the test loop. The controls are independent loops which can be set to hold either the pressure, temperature, or flow at each critical point to a given value regardless of how other test loop parameters vary. The parametric control value can be set, either manually or by computer, through the control console. Critical control parameters are:

- o Evaporator warm seawater inlet temperature
- o Evaporator warm seawater outlet temperature
- o Warm seawater flow rate
- o Condenser cold seawater inlet temperature
- o Condenser cold seawater outlet temperature
- o Cold seawater flow rate
- o Evaporator outlet ammonia temperature
- o Evaporator outlet ammonia pressure
- o Ammonia temperature entering throttle valve
- o Ammonia pressure exiting throttle valve
- o Ammonia temperature in the desuperheater
- o Ammonia quality downstream of the desuperheater
- o Ammonia temperature in condenser
- o Ammonia flow through reflux pumps
- o Evaporator and condenser sump levels

The control console includes a CRT which displays alpha-numeric and graphic information. Through use of a keyboard terminal the operator can cause displays of essential information to be displayed based either upon processed or raw data. An on-line printer can be used to periodically record operational data for diagnosis or to provide permanent test records. Emergency warnings and "out-of-limit" operating conditions which are detected by the control processing unit (CPU) are automatically displayed on the CRT. Thus the test engineer can react immediately using the keyboard controller to correct the situation or to shut down the system. Permanent records are maintained on four magnetic digital tape recorders. Four 8-channel analog strip chart recorders are provided for visual recording and calibration.

THE COLD WATER PIPE (4, 5)

The Cold Water Pipe (CWP) System consists of three major elements: the gimbal/diaphragm assembly, pipe assembly, and special release and recovery equipment.

These three elements are integrated taking into consideration the requirements of fabrication, assembly, deployment, upending, keelhauling, mating, operations, release and recovery. Each of these major elements are discussed in more detail in the following paragraphs. Figure 9 shows the integrated CWP system.

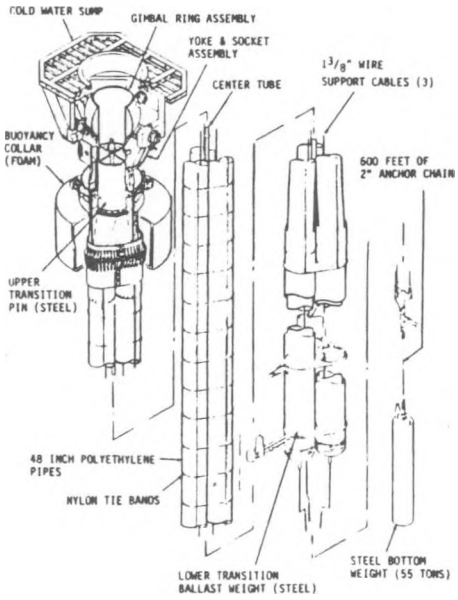


Figure 9
Cold Water Pipe Assembly

Gimbal/Diaphragm Assembly

This assembly provides the structural interface and mechanical attachment between the ship and the cold water pipe assembly and isolates the suspended pipe from the pitch and roll motions of the vessel. A 2 inch thick elastomeric gasket forms a continuous seal between the hull and the periphery of the diaphragm and thus, this diaphragm acts as the bottom of the "moonpool" sump and provides a barrier to the warmer surface seawater. The gimbal roll and pitch axis bearings are designed to support maximum vertical loads of 430,000 pounds and longitudinal and transverse loads of 80,000 pounds. The complete gimbal assembly weighs approximately 50,000 pounds.

The gimbal ring shown in Figure 10 is a large welded structure which surrounds the inner nonload bearing spherical upper socket. The gimbal ring transfers the cold water pipe loads through the diaphragm support into the ship structure. This nonload bearing upper spherical socket provides a sealed path for the cold water flow into the primary sump. The lower cylindrical socket contains a flared end which serves as an entry guide for mating with, and structurally supporting, the top end of the cold water pipe assembly.

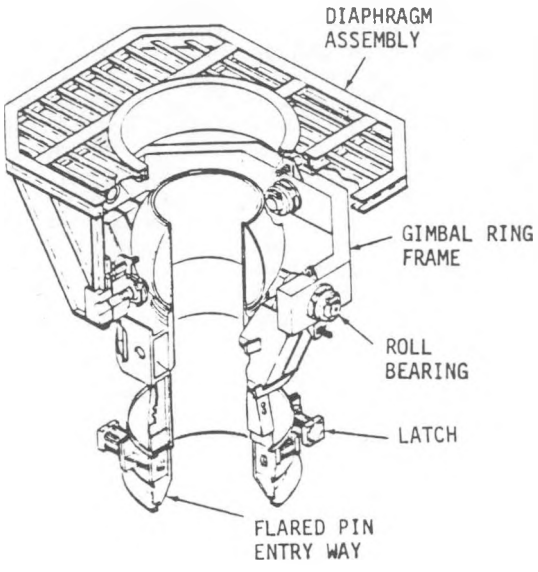


Figure 10
Gimbal Assembly

Pipe Assembly

In order to accommodate the high dynamic loads inherent in suspending a long tubular structure from a floating vessel in the open sea there are three basic design approaches which can be used:

- o Design the structure rigid enough for all possible contingencies
- o Reduce the apparent moment of inertia (I)
- o Reduce the modulus of elasticity (E)

The method used to design the OTEC-1 cold water pipe was a combination of the latter two (i.e., reduce both the E and the I). By designing the pipe with three separate independent elements the overall moment of inertia was reduced, and by utilizing polyethylene (instead of steel) as the basic pipe material the modulus of elasticity was also reduced. Thus, flexibility was the key rather than stiffness and strength. Once this basic design approach was established a purchase order was issued to DuPont of Canada to fabricate 8,500 feet of 48 inch diameter, 2 inch wall thickness, high density, polyethylene pipe. When assembled, with the three pipes bound together as shown in Figure 9, the cold water pipe itself was 2,250 feet long and the entire assembly was 2,800 feet long overall.

The upper section of the assembly is a large weldment of HY-80 steel with a 72 inch diameter cylindrical "pin" section which mates with the gimbal socket. The lower portion consists of three 48 inch diameter steel transition sections which are attached to the polyethylene pipes.

Since polyethylene is buoyant in seawater, steel ballast sleeves weighing about 12 tons each, were attached to the lower end of each pipe thus making the pipe assembly, in effect, neutrally buoyant. To control the verticality of this neutrally buoyant pipe, when exposed to the expected current forces, a large 55 ton steel weight was suspended from the upper steel transition by means of three wire ropes one of which runs inside each of the three polyethylene pipes. The three wires come together at the bottom of the pipe assembly and the bottom weight is suspended from this juncture by means of a 600 foot length of 2 inch anchor chain.

The pipes are loosely banded together by nylon straps placed every 5 feet along the length of the pipe and the three steel ballast sleeves are linked together such that each pipe can move axially relative to each other but are restrained from any significant lateral movement. In this manner the polyethylene pipes, with their low modulus of elasticity, experience bending moments but are not required to carry any axial load. Similarly the steel wires running inside each pipe segment carry the heavy axial loads but have only a small moment of inertia. Due to the surface smoothness of the pipe head losses are very low. Material fatique properties of polyethylene are excellent and evidence to date indicates that there have been no detrimental effects due to long term immersion in seawater (6, 7).

To complete the cold water pipe assembly a smaller, 6 inch diameter polyethylene pipe is located in the central triangular space formed by the three larger pipes. This central tube is provided so that future instrumentation of the pipe string is possible should the need ever arise.

Release and Recovery Equipment

Since the release, recovery and storage procedures call for the abandoned pipe to stand upright while supported on the seafloor, a large syntactic foam buoyancy collar was attached to the top of the pipe assembly. This collar measures 18 feet in diameter by 10 feet high and provides 32.5 tons of positive buoyancy. In order to "store" the pipe it is released and allowed to free fall away from the ship. When the 55 ton bottom weight impacts the seafloor the pipe assembly becomes slightly buoyant and the 600 feet of anchor chain allows sufficient deceleration distance such that the pipes will not impact the bottom. Specially developed guidelines, running tools, buoys, Regan latches, and swivels, when used with the over-the-side A-Frame and double drum winch mentioned earlier, are used to recover and reattach the pipe to the gimbal platform.

Applications and Features

This paper does not attempt to outline all of the possible research that could utilize a test facility such as the one described herein, however, some specific areas that could benefit from real time, in situ, testing are:

- o OTEC open-cycle testing
- o Heat exchanger testing including submerged exchangers
- o Pipe dynamics and vessel motion interaction
- o Establish synergy of biomass and OTEC by providing large volumes of upwelled water
- o Aqua culture research related to massive upwelling
- o Ichthyology research on physiological effects of upwelled water on marine life
- o Electric cable dynamics and fatigue studies in the open sea
- o Environmental and reliability testing of instrumentation and control components and systems

An example of the type of program that could offer significant engineering benefits is the pipe monitoring effort. The conduct of in situ measurements of loads, forces and motions exerted on a large scale CWP has been much more than an exercise in academia. The data gathered on the OTEC-1 program will be used in future designs of similar oceanic structures because the analytical tools presently available are woefully lacking in sophistication and agreement and they are unsatisfactory for optimizing a specific design to obtain both long life and a cost effective solution. This conclusion is based upon a report comparing results from four independent analytical programs, namely: Pauling's ROTEC, TRW's HULPIPE, the NOAA/DOE program and a simplified bounding type program developed by GMDI (8, 9).

The SS Ocean Energy Converter has the following specific features that lend credibility to its use as a unique At-Sea Research and Test Facility:

- o A ship permanently moored in 4,500 feet of water
- o Can withstand a wide range of weather conditions
- o Large enough to support large scale experiments but small enough to maintain realistic sea motions
- o Massive source (100,000 gpm each) of cold and warm water at 40°F and 70°F respectively
- o Plenty of available deck space making parallel experiments possible
- o Two in-the-hull tanks available for additional lab space
- o Additional vans easily accommodated
- o Reasonable life expectancy of 5 to 7 years
- o Research talent onboard
- o Repair facility for instrumentation available
- o Test bed atmosphere and personnel discipline prevalent
- o Data storage and analysis capability onboard

SUMMARY

This paper has presented an overview of the existing OTEC-1 facility. The test objectives of the program were to gather data pertaining to the effects of biofouling and corrosion on the efficiency of the initial 1 MW_e heat exchangers and to conduct a large scale OTEC system demonstration. The gathering of information on pipe string dynamics was added as a secondary objective after initial authorization. Thus the overall program, and the specific facility, were intentionally oriented toward a very specific area of research. However, this type of research can be compared to "watching grass grow" and the equipment and manpower cost inherent in running such a facility could be significantly mitigated by expanding the research base. A rather sophisticated at sea marine test and research facility can be envisioned. Organizationally the facility would be handled in the same manner as other government operated research facilities such as wind tunnels, model basins, various proving grounds and nuclear test facilities. An organizational agreement with the Sea Coast Test Facility located at Keahole Point, Hawaii should be investigated.

Although GMDI has completed its responsibilities to the OTEC-1 program, we feel that the ocean community has a valuable tool in its inventory that, properly structured, could be of benefit to many diverse areas of research and testing.

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8th Ocean Energy Conference
Washington, DC
June 1981

CAPABILITIES AND POTENTIAL OF THE OTEC SEACOAST TEST FACILITY

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ABSTRACT

The Seacoast Test Facility, a joint effort of the State of Hawaii (represented by the Natural Energy Laboratory of Hawaii) and the U.S. Department of Energy (represented by the Argonne National Laboratory) was conceived, designed, and is being built as a shore based research laboratory in which experimental verification and small scale demonstration of OTEC technology developments can be conducted under controlled but realistic conditions. Current capabilities are based on the existing 1000 gpm warm seawater supply system, a 3000 square foot laboratory building, a 6000 square foot test pad, and supporting facilities. The current research effort is focused in biofouling countermeasures and includes 18 heat transfer modules. Future potential includes a 6400 gpm cold and 9600 gpm warm seawater supply system.

INTRODUCTION

From the original presentation of the OTEC concept by D'Arsonval in 1881 until the summer of 1979 OTEC technology remained in the realm of a promising theoretical and laboratory phenomenon. In 1979 Mini-OTEC demonstrated the technical feasibility of the OTEC concept. The challange then became, and remains, the demonstration of economic feasibility. Public Law 96-310, the OTEC Research, Development and Demonstration Act has provided a framework for this demonstration. The process of demonstrating OTEC economics is one with many facets. While no technological breakthroughs are required there are many areas in which engineering advances and adaptations of the existing state-of-the-art are required. Such advances normally begin with theory and paper studies, progress through experimental verification, small and large scale demonstrations and eventually result in a design data base and specifications for commercial OTEC plants.

The Seacoast Test Facility (STF), a joint effort of the State of Hawaii (represented by the Natural Energy Laboratory of Hawaii) and the U.S. Department of Energy (represented by the Argonne National Laboratory), was conceived, designed, and is being built as a shore based research laboratory in which the critical experimental verifications and small scale demonstrations of OTEC technology can be conducted under controlled but realistic conditions. The original facility design was based on a set of criteria developed in 1978, which included:

System Design Life to be ten years minimum.

Intake Depths: Warm Water 50 feet
Cold Water 2100 feet

Minimum Intake Flows:
Warm Water 9600 gpm
Cold Water 6400 gpm

Uninterrupted flow for both warm and cold water (up to 50 percent reduction from full rated flow is permissible).

Cold water temperature rise (from 2100 ft. depth to shore) not to exceed 1°C.

Provision shall be made for degassing the cold water intake ahead of the pumps.

Screening to permit uninterrupted flow at both intakes.

Pipeline materials to be biologically inert and not introduce corrosion product contamination.

The design was completed and presented to the U.S. Department of Energy in July 1979. Due to funding limitations on the federal side construction was divided into Stage 1, which includes the laboratory building, test pad, shops, warehouse, limited office space, power center with emergency diesel electric generators, and the basic site preparation and utilities, and Stage 2 which is to include the main seawater supply system and an administration building. Figure 1 shows the Seacoast Test Facility as it was laid out in the design completed in July 1979.

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*Numbers in parenthesis refer to References listed at the end of the paper.

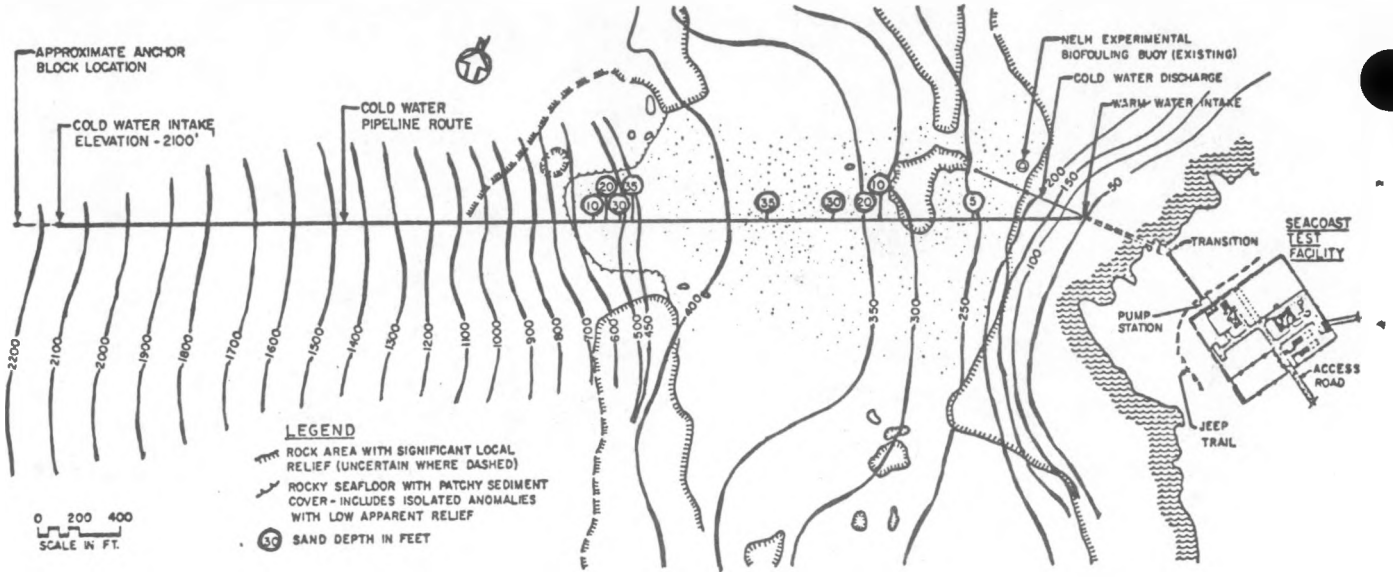


Figure 1
General Plan of Seacoast Test Facility at Ke-ahole Point

CAPABILITIES

The existing capabilities of the Seacoast Test Facility are based around the Natural Energy Laboratory of Hawaii (NELH) owned seawater supply system which at this point in time is capable of supplying 1000 gpm of nearshore oceanic seawater, with an expansion to 2000 gpm capacity in process. Water quality approximates the open ocean quite closely, even though the intake is only 30 feet offshore in 20 feet of water, because Ke-ahole Point is located on the westernmost tip of the island of Hawaii where it is swept by oceanic currents that impinge on this rocky mountaintop rising out of the oceanic abyssal plain. A variety of studies (Reference 1 through 8)* have documented the ocean characteristics of this site.

Current capabilities of the Natural Energy Laboratory of Hawaii/Seacoast Test Facility (NELH/STF) are most easily defined in terms of the existing physical plant and the experimental work now in progress. The physical plant is essentially the STF Stage 1 with the exception that the industrial building (offices, shops, warehouse) is not scheduled for completion for another two months. The balance of the Stage 1 construction effort is complete and includes the basic site preparation, utilities, power center, test pad, and laboratory building. Seawater is furnished by the existing NELH seawater system. The laboratory building and test pad constitute the focal point for the research work now in progress. This effort funded by Argonne National Laboratory (ANL), is concentrated in the area of OTEC heat exchanger biofouling, corrosion, and biofouling countermeasures. The lab building provides 3000 square feet of air conditioned work space for setup and operation of experiments such as the 18 Heat Transfer Modules (HTMs) shown in Figure 2. In addition separate areas have been set aside within the building for data acquisition and water quality analysis. Data acquisition and analysis for the existing, HTM loops is based on the DEC PDP 11, Figure 3, with allowance for future system expansion to accomodate additional experiments. Existing in-house water quality analysis capabilities include the parameters shown in

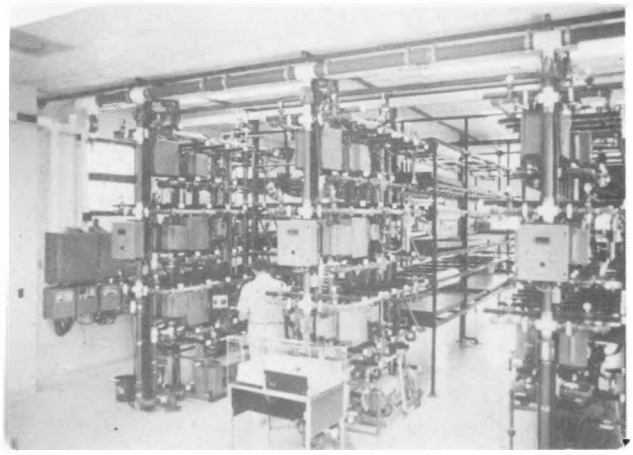


Figure 2
HTM experiments

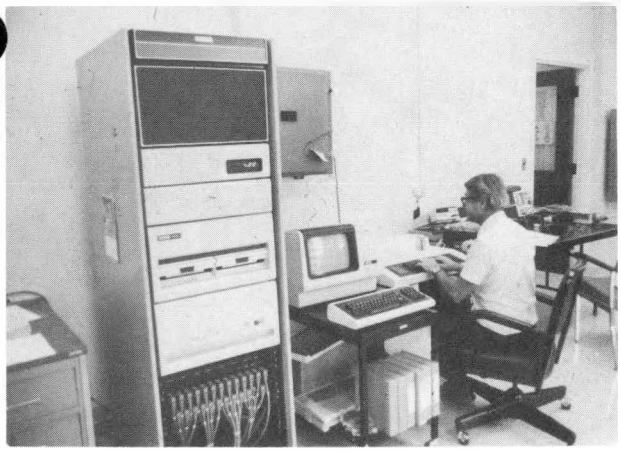


Figure 3
STF Data Acquisition System

Figure 4 with additional capabilities in water quality, biology, and corrosion analysis available through various organizations within the University of Hawaii and the surrounding technical community.

Flow
Temperature
Salinity
Suspended solids of (Particulate Matter)
pH
Alkalinity
Nutrients (nitrates, nitrites, phosphates, silicates, ammonia).
Dissolved oxygen
Chlorine demand
Biochemical Oxygen Demand (B.O.D.)

Figure 4
Water Quality Analysis Parameters

Adjacent to the laboratory building is a 6000 square foot test pad with running seawater, electrical power, fresh water, compressed air, and instrumentation conduits leading back to the data acquisition space within the lab building. This pad was originally conceived of as a place to put large test articles, such as 1 MW_t heat exchanger modules, and as a place for all those activities that do not require a controlled, enclosed, atmosphere. This is exactly how the area is being used, as can be seen in Figure 5 .

Seawater supply for the current operation isbased on a State owned system originally built in 1977 to support an Applied Physics Laboratory heat exchanger test project. With the recent refurbishment and addition of two 1000 gallon header tanks the system is currently capable of pumping up to 1000 gpm of seawater taken from a point about 30 feet offshore at a 20 foot depth. Expansion of the system by adding in the

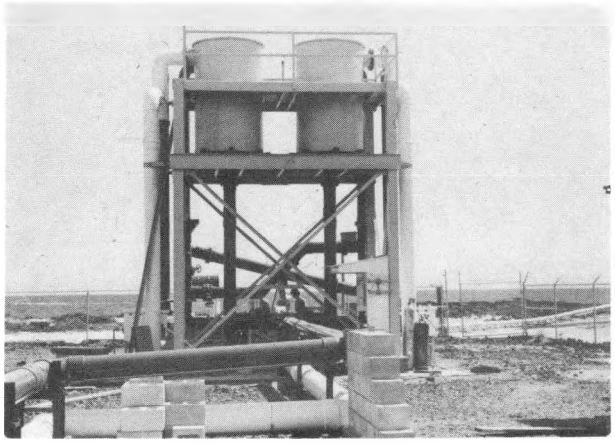


Figure 5
Test Pad and Laboratory Building

planned second intake pipe is in progress and will result in a system capacity of 2000 gpm. Multiple pumps are provided for reliability, and the entire supply system is totally non-metallic to avoid any potential for metallic ion contamination. Discharge is on the rocks about 100 yards from the shoreline, and an NPDES Permit is in place allowing chlorination within the experimental loops.

Electrical power is provided by the local utility, with distribution to the site being from the Ke-ahole Airport substation. Emergency power is provided by three 125 KW diesel electric generators, Figure 6, located in the Power Center and set to start up automatically in case of utility power loss. An uninterruptable power supply (UPS) has been provided for the computer facility. Support facilities in the form of office space, electronics shop, a limited machine shop, and a warehouse area are under construction, Figure 7, and due for completion this August.

POTENTIAL

The future potential of the NELH/STF is limited only by man's imagination and by the funding made available to implement the projects that are envisioned. The near term NELH/STF potential is most readily defined by refering to the existing plans for what was earlier in this paper referred to as the STF Stage 2 construction. Basically, Stage 2 adds a major warm and cold seawater supply system, plus additional administrative and office facilities, to the Stage 1 effort. Also under consideration is additional laboratory and test pad space. Of these additions the most important is the seawater supply system. The current design, based the on criteria established in 1978, is sized to provide a nominal 6400 gpm of cold ocean water from an intake depth of 2100 feet, and a nominal 9600 gpm of warm surface water from a depth of 50 to 75 feet at a location a

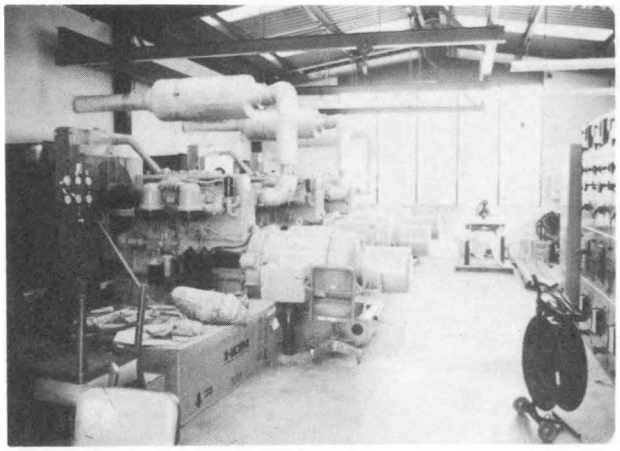


Figure 6
Emergency Power System



Figure 7
NELH Industrial Building

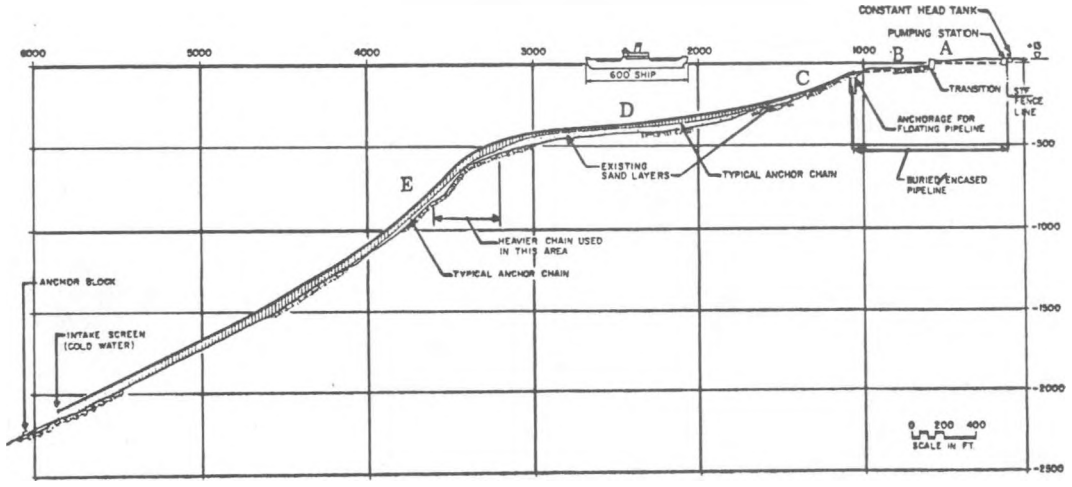
few hundred feet offshore. Maximum allowable temperature rise of the cold water during its transit of the cold water pipe is 1°C. Design calculations indicate that the actual temperature rise will be significantly less than this. All materials in contact with the seawater on the supply side have been carefully selected to insure that metallic ion contamination of the water will not occur.

Multiple pumps, and conservative system design, have been used to insure long term uninterrupted operation of the water supply system. The pipeline design itself is the most unusual and innovative portion of the system. While it has been discussed before (refs 9 - 12) it is appropriate to include a brief description here for completeness. The pipeline material chosen is polyethylene. Onshore and in the nearshore

A COASTLINE LOW CLIFF FROM +10 TO -20.

B 300 FT. WIDE NEARSHORE SHELF LARGELY EXPOSED BEDROCK.

C NEARSHORE SLOPE -- QUITE STEEP 30° - 45° BETWEEN 300 FT. AND 600 FT. AND DOWN TO A DEPTH OF 200 FT. CORAL AND CORAL DEBRIS BASALT NEAR SURFACE.



D LONG RELATIVELY FLAT SLOPE WITH STABLE SAND COVER ABOUT 1,800 FT. WIDE.

E STEEP SLOPE 30° - 40° DOWN TO PROJECT DEPTH, MOSTLY EXPOSED BEDROCK WITH PILLOW LAVA PROMONTORIES AND COVERED LIGHTLY WITH UNSTABLE CORALLINE SAND.

TOPOGRAPHY

Figure 8

Profile of Offshore Facilities

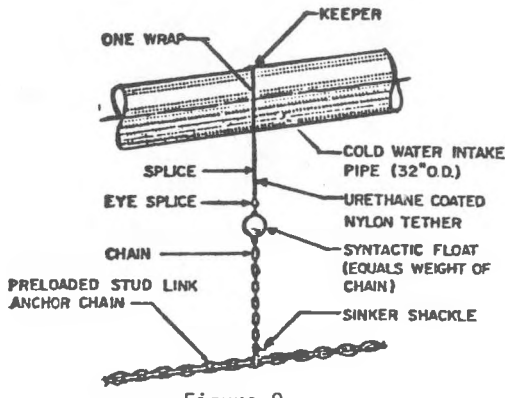


Figure 9
Tether Detail

(surf zone) region the pipes are buried in trenches and armored with concrete and rock in a conventional manner. In the offshore region the buoyant polyethylene pipe is floated up off the bottom while tethered to an anchor chain, as shown in Figures 8, 9. The bottom line for this design is that it provides a minimum cost system that meets all of the design criteria with an acceptable risk.

Additional areas of future potential include OTEC aquaculture, a closely related area which has a significant potential for both food and energy production which fits in directly with the OTEC work and facilities of the NELH/STF. The inclusion of a mariculture component in PL 96-310, the OTEC Research, Development and Demonstration Act, has helped to focus interest in this area. Also, given the existing and planned facilites, capabilities exist for open cycle OTEC research in addition to the currently funded closed cycle work. The NELH is also pursuing potential projects in other related areas such as direct solar utilization and solar desalination. In summary, the NELH/STF potential is limited only by our imaginations.

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UTILIZATION OF THE OCEANS FOR SUB-SCALE TESTING OF OTEC COMPONENTS

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ABSTRACT

An experimental investigation was conducted at sea near Catalina Island, California to determine the effect of ocean waves and currents on the motion of an Ocean Thermal Energy Conversion (OTEC) Cold Water Pipe (CWP). An 8.625 inch diameter 70 ft long polyvinylchloride model pipe was suspended from a 1/30 scale OTEC barge platform and tested in a moored and grazing configuration. Measurements of strain were made at five axial stations along the pipe length.

The results of the grazing tests indicated that lock-on of vortex shedding could occur in several pipe models. The power spectra of the stress for towing tests at 2.40 ft/sec and 2.45 ft/sec showed large peaks at 0.53 Hz and 0.88 Hz, respectively. These frequencies correspond to second and third pipe bending modes.

Pipe dynamics were predicted using TRW's time domain response program HULPIPE. The predicted pipe stress was close to the experimentally measured values.

INTRODUCTION

CWP/platform dynamics and structural design continues to be one of the most important technological areas in the design of the OTEC system. Analytical models have been developed to represent the material, geometric, kinematic, and dynamic characteristics of the OTEC CWP/platform configuration. However, uncertainties inherent in characterizing the ocean environment, the hydrodynamic loads on the platform and pipe, and pipe material and geometry may result in overly conservative OTEC CWP/platform designs.

Test programs have been focused on measuring CWP/platform response data and loads due to waves and currents to improve the understanding of the hydrodynamic forces and added mass coefficients in wave current flow fields. Most of the test programs have been and are being carried out in the laboratory. Unfortunately, laboratory facilities of sufficient depth to avoid all scale effects do not exist, and large scale at sea tests are needed to validate laboratory and analytical methods.

To provide a data base of pipe motions and stresses for validation of analytical models and to determine the relationship between vortex shedding and CWP structural response, an investigation was conducted to measure the stresses on a 70 ft long polyvinylchloride (PVC) model of an OTEC CWP. The tests were conducted at sea near Big Fisherman's Cove, Catalina Island, California. The CWP was suspended from a 1/30 scale model of the APL OTEC barge platform, and was tested in a moored and grazing configuration. In the grazing mode the platform was towed at speeds up to 2 knots.

Measurements of strain were made at five axial stations along the pipe. The strain gage data was recorded in analogue form and later reduced to provide the time history, average, RMS, and power spectra of pipe bending stress in directions parallel and transverse to the current direction.

The towing tests provided data for the case of an OTEC CWP subjected to a high velocity uniform current flow with negligible wave action. Analysis of the towing test data showed vortex shedding lock-on in both the second and third pipe bending modes. Also it was observed that small changes in the free stream conditions could change lock-on in one mode to lock-on in another at a higher or lower frequency.

Pipe response and stresses were predicted using the TRW time domain pipe response program, HULPIPE (1). Good comparisons between the measured and experimental stresses were obtained.

TEST DESCRIPTION

Catalina Test Site

As part of a TRW funded research project a test range was set up at sea near Big Fisherman's Cove at Catalina Island. The site was selected to model the environmental conditions at the Punta Tuna, Puerto Rico site to a 1/30 scale. The objective of the TRW tests was to investigate the performance of several OTEC platform/stationkeeping models. Under contract to NOAA, a CWP was instrumented with strain gages and tested in conjunction with the APL barge platform model. The nearby University of Southern California Institute for Marine and Coastal Studies provided an excellent assembly and check out area, and a platform from which the CWP could be conveniently launched.

The APL model barge was moored a few hundred yards from an underwater reef in about 85 ft of water over a sandy bottom. The platform was subjected to essentially wind driven waves; the reef effectively damped out the longer wave length ocean waves. Preliminary site surveys indicated that north westerly and easterly winds would provide waves with periods of 2 to 6 seconds and heights of 1-1/2 to 3 feet. During the tests average periods of 4 seconds and wave heights greater than 1 ft were measured. Pretest current surveys indicated that currents in excess of a knot were not uncommon and were believed to be tidal driven. On the day the model CWP was deployed a current in excess of 1 knot was observed and persisted for about an hour. During the next 3 weeks of testing, the measured currents at the moored site did not exceed 15 cm/sec.

The recording instrumentation was installed on a 65 ft boat positioned about 60 feet from the platform. The final phase of the test program involved towing the platform behind the instrumentation boat to achieve a strong uniform current flow past the pipe. Wave action was negligible during the grazing tests.

OTEC CWP Test Model and Instrumentation

The OTEC CWP test model is shown in Figure 1. The model CWP was constructed using PVC ducting which is commercially available in 10 ft lengths. The pipe was designed to respond at its second natural frequency at current conditions of about 1 knot. The wall thickness was 0.1875 inch and the outside diameter measured 8.625 inches. Five axial stations of strain gages were placed along the pipe with four gages placed circumferentially 90 degrees apart at each station. A 1000 lb weight was attached to the bottom of the pipe to minimize pipe deflection under high current loading conditions.

The pipe was instrumented at TRW's Advanced Technology Laboratory which has complete facilities for installing and testing strain gage instrumentation. Lead wires from strain gages were brought inside the pipe to minimize external flow disturbances. A waterproofing compound was faired over the strain gages and the exposed portion of the lead wires. Several waterproofing techniques had been previously applied to a test specimen which was placed under 3 atm pressure in a water test chamber. The resistance of the test specimen strain gages were monitored for about a week. Only one of the waterproofing techniques failed. The final waterproofing technique was selected because of considerations of reliability, ease of application, and minimal disturbance to the external flow field.

Test strips of the PVC material were cut from a section of the pipe. Strain gages were cemented to the strips which were placed in a loading device. Stress/strain curves were generated and were found to be nearly linear to stresses of about 2000 psi. Pretest predictions using analytical pipe response codes indicated that the maximum stress expected during the tests would be about 800 psi. The measured modulus of elasticity was 4.6×10^5 psi.

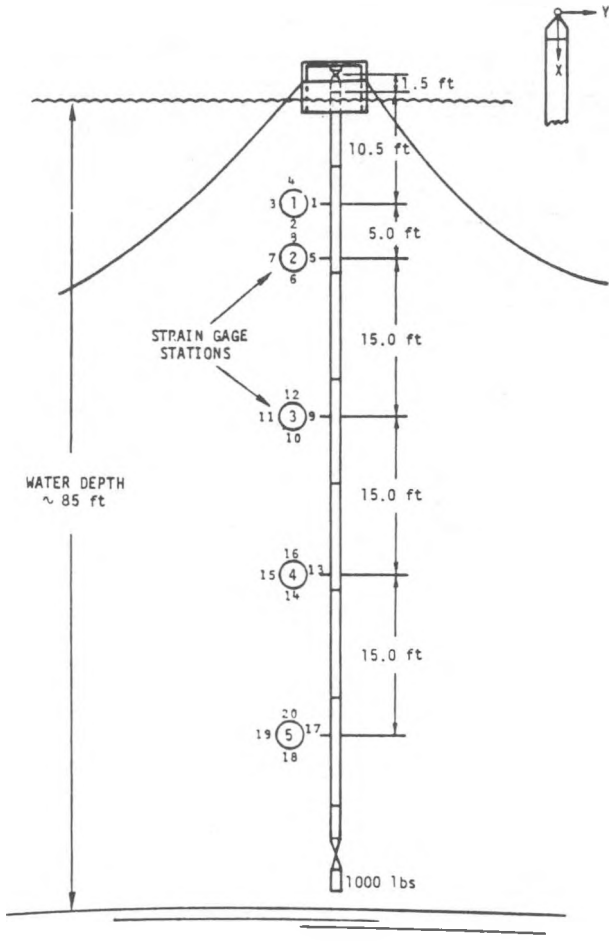


Figure 1
70 ft CWP Test Configuration

The pipe was shipped to the test site in segments of 10 feet or less, and was assembled on site. The procedure for joining the segments had been developed and tested in the lab. Standard couplings were machined to a minimum diameter and length in the lab to minimize flow perturbations and stiffness changes. Test sections were bonded together in the lab and pulled to rate the joint strength against the strength of the pipe.

The pipe was attached to a support structure on the platform using an automobile U-joint, Figure 2. A gear box arrangement allowed the pipe to be rotated to any desired direction prior to a run. A 5000 lb load cell was placed between the U-joint and the top of the pipe support structure to measure axial loads. A ball bearing joint and torque meter allowed the torque to be measured between the pipe support frame and the load cell, see Figure 2.

The design of the support system allowed for the top of the pipe to remain about 1 ft out of the water to allow connection of the instrumentation cables. Strain gage stations were measured from the pivot point.

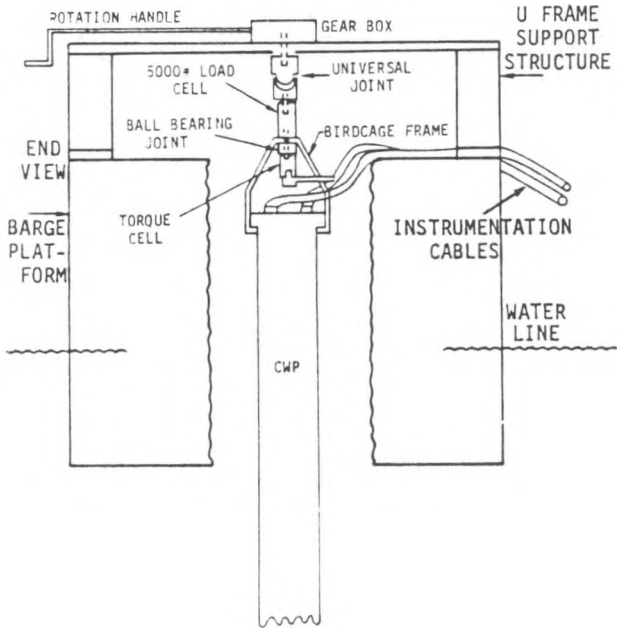


Figure 2

Pipe/Platform Interface

Data Acquisition System

The data acquisition system was built into an environmental enclosure which was mounted on the stern of a 65 ft work boat.

Twenty strain gage signals, torque or load cell, wave pressure, wave follower, IRIG B time code, and two components of current velocity were simultaneously recorded on two 14 track AMPEX AR-200 FM Flight Recorders. Signals from the strain gages were individually amplified and filtered using twenty ENDEVCO Model 4470 signal Conditioner/Power Supplies and ENDEVCO Model 4476.2A Amplified Resistance Bridge Signal Conditioning units. Each unit allowed for a calibration resistor to be switched in to provide an 800 micro strain calibration signal. Processed signals were fed into a patch panel terminated into the two 14 channel FM tape recorders. Most of the recorded data was simultaneously recorded on three 8-track Gould strip chart recorders. A dual beam oscilloscope and digital voltmeter were also used to monitor the signals and balance the amplifier output before each run.

Tests

After assembly of the pipe at the test site, a final check of the instrumentation and data acquisition system was completed. The pipe was then towed to the test site. The pipe was sealed at both ends and remained filled with air during the tow. The pipe was towed to the platform where winch and instrumentation cables were attached to the top of the pipe. Pipe bending stress was recorded as the pipe was keelhauled into position beneath the platform moonpool. The pipe was then winched up and connected to the platform universal joint/load cell structure. The next 14 tests performed over a period of two weeks were conducted with the CWP in this deployed configuration with the platform on a 4 point moor.

The next series of tests were performed in the grazing mode. The platform was released from its mooring and towed behind the instrumentation boat on a 75 ft bridle. The ship speed was measured with an electromagnetic current meter deployed from the instrumentation boat at a depth of 20 ft.

Data Reduction and Analysis

The FM tapes were converted to analogue signals digitized and recorded on digital magnetic tape at TRW's data Conversion Facility. The digital tapes were calibrated into engineering units using programs on the CDC 6600 and were written to digital tapes which could then be conveniently read and analyzed by user defined programs.

The first step in the data analysis consisted of converting the measured strain to stress and separating the bending and tensile components. Because this study was primarily concerned with investigating the forces caused by organized vortex shedding, it was desirable to separate the bending stress into streamwise and transverse components for comparison with analytical results.

During the grazing test runs, the pipe was rotated so that the 0 degree line of strain gages (from the pipe fixed axis) would be along the forward stagnation point. However, the data revealed that some angle of attack existed during the test. If σ_y and σ_z are the measured orthogonal bending stresses, and Θ is the instantaneous angle measured from the pipe fixed y-axis to the plane containing the external load, then the transverse and streamwise components of stress are

$$\sigma_s = \sigma_b \cos(\Theta-\alpha)$$

$$\sigma_t = \sigma_b \sin(\Theta-\alpha)$$

where

$$\sigma_b = (\sigma_y^2 + \sigma_z^2)^{1/2}$$

$$\Theta = \tan^{-1}(\sigma_z/\sigma_y)$$

and the time averaged angle $\bar{\Theta}$ is assumed to be the angle of attack, the angle between the velocity vector and the y-axis.

RESULTS AND DISCUSSION

Time histories, average, RMS, and power spectra of pipe bending stress were computed for the grazing tests. Corresponding plots of the power spectra of the stress for the two tests show sharp peaks at f = .53 Hz and f = .88 Hz. These frequencies correspond to n=2 and n=3 pipe bending modes. Smooth curves were fitted to the experimental data at successive instants in time and plotted to obtain the stress histories shown in Figure 3 and 4. The results presented in Figure 3 and 4 represent typical time histories of the measured stress for two of the grazing tests.

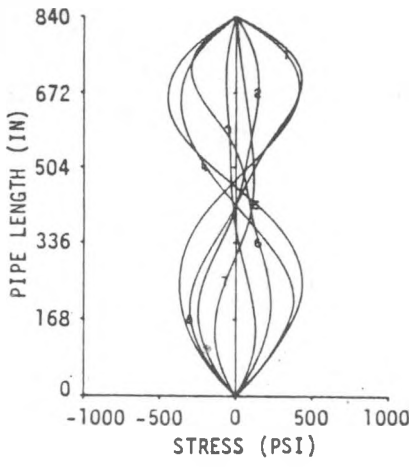


Figure 3

Experimental Transverse Stress History, Grazing Test 1

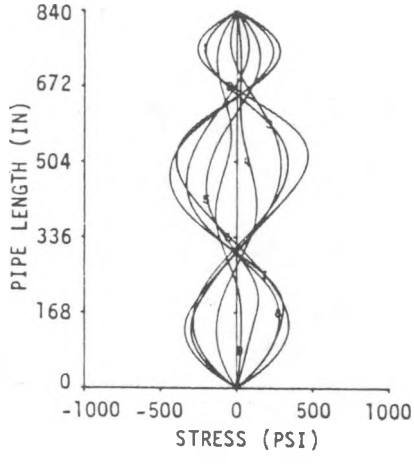


Figure 4

Experimental Transverse Stress History, Grazing Test 2

The average ship speed measured with an ENDCO Model 720 electromagnetic current meter was 2.40 ft/sec and 2.45 ft/sec for the two runs.

The results presented in Figures 5 and 6 were obtained using TRW's time domain finite difference pipe response code HULPIPE. Pipe displacement is shown on the right side of the figure, the corresponding stress history is plotted on the left.

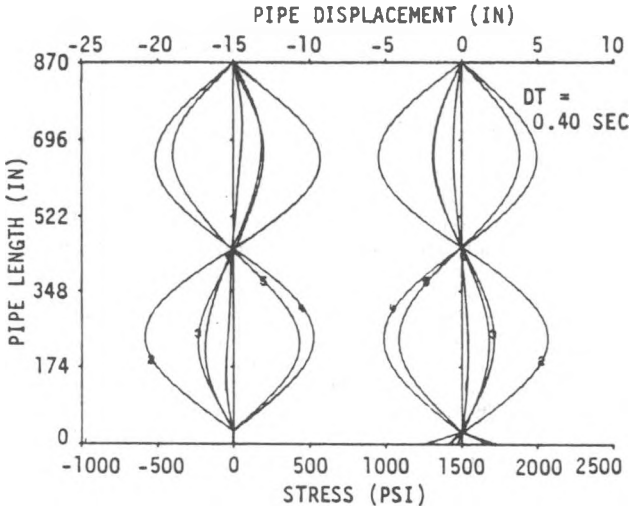


Figure 5

Predicted Transverse Pipe Response, 2 Cell Vortex Model, S = .159

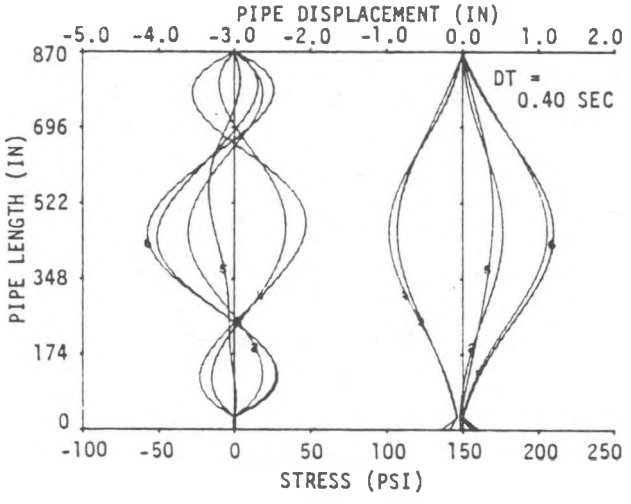


Figure 6

Predicted Transverse Pipe Response, Single Cell Constant Phase Vortex Model, S = .159

Dynamic analysis of the CWP requires not only some knowledge of the magnitude and frequency of the cross sectional lift and drag on the pipe, but also an estimate of the correlation and phase of the vortex shedding along the length of the pipe. To obtain the second mode response shown in Figure 5 a two cell vortex shedding model was used. The first cell covered the bottom 475 inches of pipe, the second cell covered the top 395 inches. The phase of vortex shedding was 180° out of phase in the two cells. The frequency was constant in both cells and corresponded to a Strouhal number,

$$S = \frac{fd}{V} = 0.16,$$ where f is the shedding frequency = measured frequency of pipe oscillation in grazing test 1

d = pipe diameter, and

V = ship speed.

A single cell model with phase constant along the pipe length was also used in an attempt to match the experimental results of grazing test 1. The stress and displacement time history are presented in Figure 6. The constant phase shedding model almost forces a first mode response and the stress is very small. These results tend to support the conclusion that the shedding was locked-on to and in phase with the pipe motion in test 1.

To match the experimental results of grazing test 2 both a three cell vortex shedding model and a single cell model were tried. In either case shedding was assumed to be locked-on to the measured pipe frequency, f_2 = .88 Hz. Both shedding models gave the correct modal response. The third mode response shown in Figure 7 was obtained with the single cell model. The three cell model produced a similar mode shape but with larger displacement.

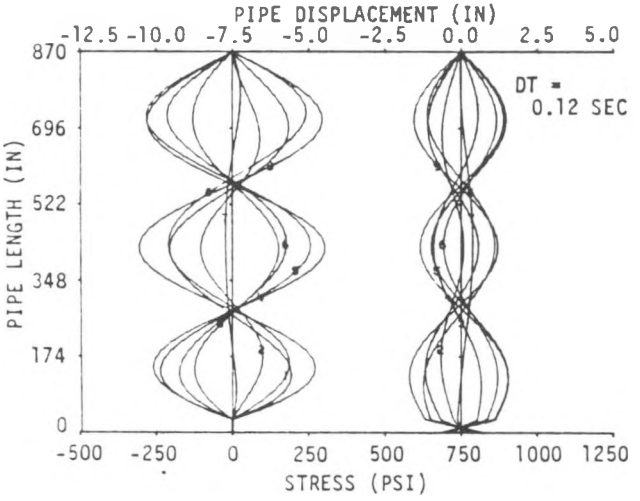


Figure 7

Predicted Transverse Pipe Response, Single Cell Constant Phase Vortex Model, S = .259

All of the predicted results were obtained using drag coefficient, CD = 0.40, lift coefficient, CL = 0.30, and added mass coefficient CM_a = 1.0. The current velocity in all of the calculations was taken to be V = 2.40 ft/sec.

Average and RMS values of streamwise and transverse stress corresponding to the predicted stress and displacement histories shown in Figures 5 and 7 are presented in Figures 8 through 10 and are compared with the measured stresses. The measured streamwise stress in Figure 8 is somewhat higher than the predicted value over the top 20 ft of the pipe for one of the grazing tests. Otherwise the agreement between theory and experiment is close over the length of the pipe. The predicted transverse stress for grazing test 1, Figure 9, agrees well with the experimental data. The RMS stress for grazing test 2 is presented in Figure 10 along with the theoretical curves predicted using the 3-cell vortex model and a single cell model. The measured stress seems to lie between the two predictions, with perhaps the single cell results being slightly better.

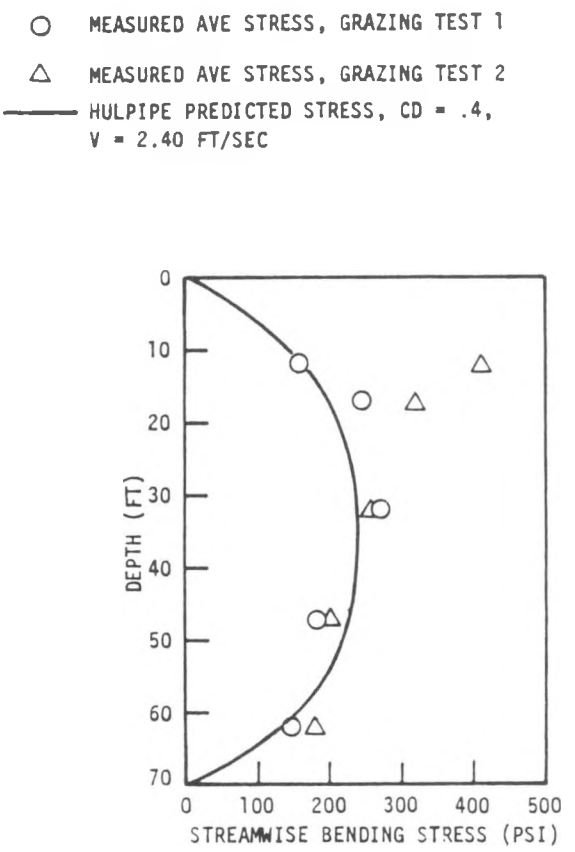


Figure 8

Streamwise Bending Stress

△ MEASURED RMS STRESS, GRAZING TEST 1

——— HULPIPE PREDICTED STRESS,
2 CELL VORTEX MODEL

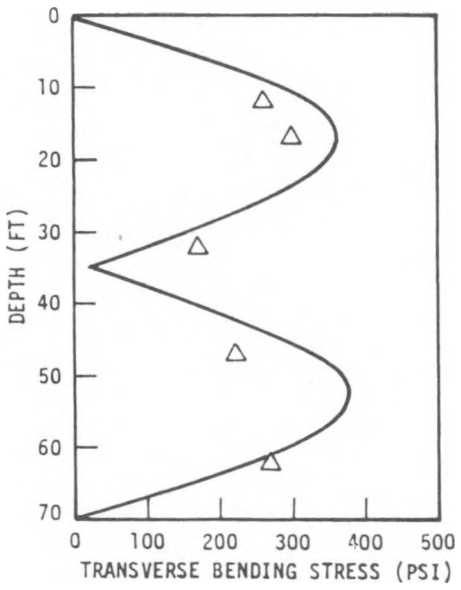


Figure 9

Transverse Bending Stress, Grazing Test 1

Switching of vortex excited motion in one pipe response mode to vortex excited motion at another frequency with little apparent change in current velocity was observed experimentally. Theoretically two different pipe response modes were forced at the same flow velocity by changing only the shedding frequency. The Reynolds number for the tests was approximately Re = 160,000 and is somewhat below the critical Reynolds number range of Re = 300,000 to 500,000. The drag coefficient in the subcritical regions unamplified by pipe motion is about CD = 1.2, three times the value used in the present calculations. However, it is possible that the critical Reynolds number for these tests was lowered due to effects of ocean turbulence and pipe roughness. A drag coefficient of CD = 0.4 would be appropriate for critical flow. If the flow were critical as indicated by the low value of drag coefficient used in the present calculations, then a definite natural frequency would not be apparent and motion of the pipe in one mode or another could cause lock-on to that mode.

△ MEASURED RMS STRESS, GRAZING TEST 2

HULPIPE PREDICTED STRESS

——— SINGLE CELL VORTEX MODEL

– – – – THREE CELL VORTEX MODEL

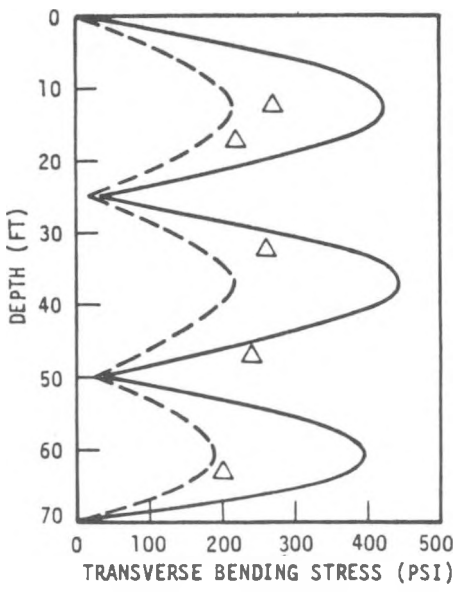


Figure 10

Transverse Bending Stress, Grazing Test 2

CONCLUSIONS

A 70 ft long model of the OTEC CWP was tested at sea in both a moored and grazing configuration. Pipe strains were measured at 5 axial stations along the pipe and reduced to provide time histories, average, RMS, and power spectra of the stress. Results were presented for two of the tests in the grazing mode where pipe motion was primarily caused by vortex excitation. The results of the tests demonstrated that small changes in free stream conditions could change lock-on in one pipe mode to lock-on in a different mode at a higher or lower frequency.

A theoretical model of vortex shedding was developed and used in a time domain response computer program to predict the pipe stress. The model assumed that vortices were shed in cells of constant phase along the pipe length. The phase of the vortex shedding varied by 180 degrees from cell to cell. The frequency of vortex shedding

was constant in all of the cells and equal to a particular pipe natural frequency. The extent of a cell was either the entire length of the pipe, or approximately the distance between nodes of a particular pipe response mode.

Single cell and multi cell shedding models were used to predict the second and third mode pipe responses. The predicted results were in generally good agreement with the experimental data. Using a multi-cell in phase locked-on shedding model yielded a conservative estimate of the stresses with a safety factor of 20 to 50 percent. Better agreement with the data could have been obtained by adjusting the hydrodynamic coefficients. However, the important aspect of the present work is that all of the results of the present test could be reasonably well matched using a single set of lift, drag, and added mass coefficients.

Current OTEC CWP designs are based largely on information obtained from computer codes that numerically solve the equations of pipe bending. That these codes are capable of accurately predicting vortex excited pipe response under high current conditions has been demonstrated. However, the hydrodynamic coefficients for the full scale pipe have only been estimated based on sub scale experiments. The correlation length and phase of the vortex shedding is unknown.

Small scale laboratory experiments will continue to be useful in further characterizing the hydrodynamic models to be used in predicting OTEC CWP pipe response. However, large scale at sea tests will be required to verify the small scale results, and the hydrodynamic models. The present at sea tests were large by laboratory standards but are still only 1/35 of full scale. At sea tests of a scale large enough to achieve high transcritical Reynolds numbers and eliminate questions of scale effects are required. That such tests are feasible has been demonstrated by evidence of the results obtained in the present program.

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THE TEST OF OTEC PLANT IN IMARI BAY

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ABSTRACT

The OTEC Research team of Saga University constructed a 50 kw class OTEC power plant (Imari 2) and settled it in Imari Bay, Imari city, Saga prefecture. The performance of the OTEC power plant has been tested and its results are reported.

1. INTRODUCTION

The Ocean Thermal Energy Conversion (OTEC) Research team [1-3] of Saga University constructed a 50 kw class OTEC power plant (Imari 2) in 1980 and settled it in Imari Bay, Imari city, Saga prefecture, Japan, where is selected to operate this plant using sea water. The tests have been carried out for the performance of heat exchangers, turbine and generator which the Imari 2 consists of. The present paper describes these results.

2. POWER PLANT

Figure 1 shows the whole plant of Imari 2. Figure 2 schematically shows loops circulating Freon 22 as the working fluid, warm water and cold water. As the Imari 2 is settled on land near Imari Bay, whose depth is from 10 m to 20 m with the variation of the tide, it is not capable of obtaining a large temperature difference between the warm water on surface and the cold water in a depth at the same time. Therefore, the experiment during summer is carried out using the sea water at a temperature above 25°C, which is sucked up from the intake set up at the distance of 50 m from the seashore as the warm water, and the fresh water kept at the temperature of 7°C by a refrigerator as the cold water. On the other hand, the alternative experiment during winter is carried out using the sea water at a temperature below 7°C, which is sucked up from the same intake as for

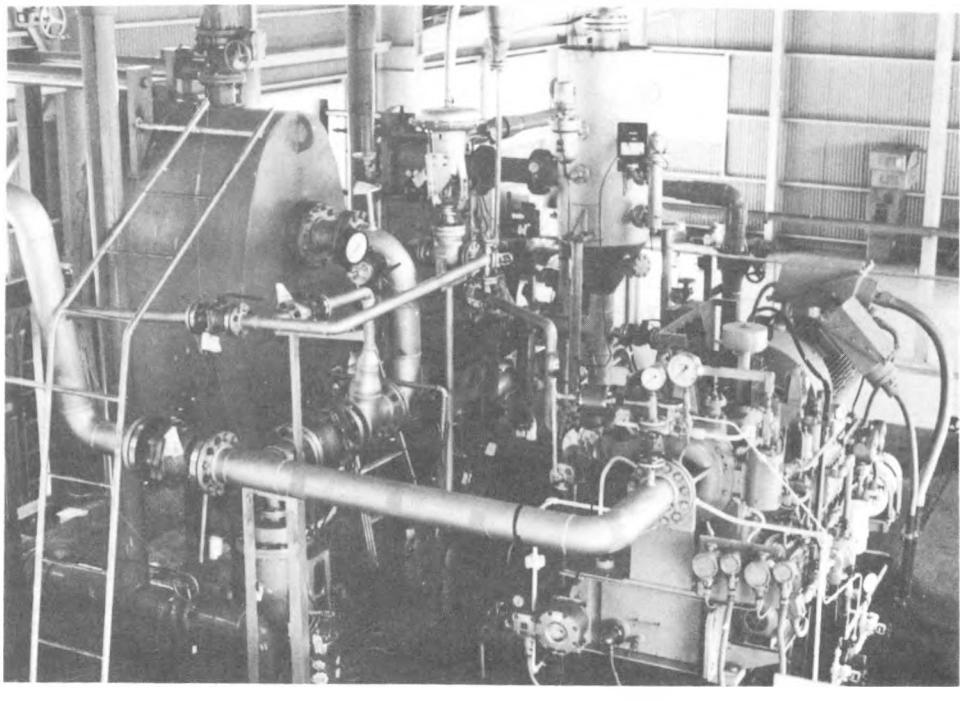


Fig. 1 Whole plant of Imari 2

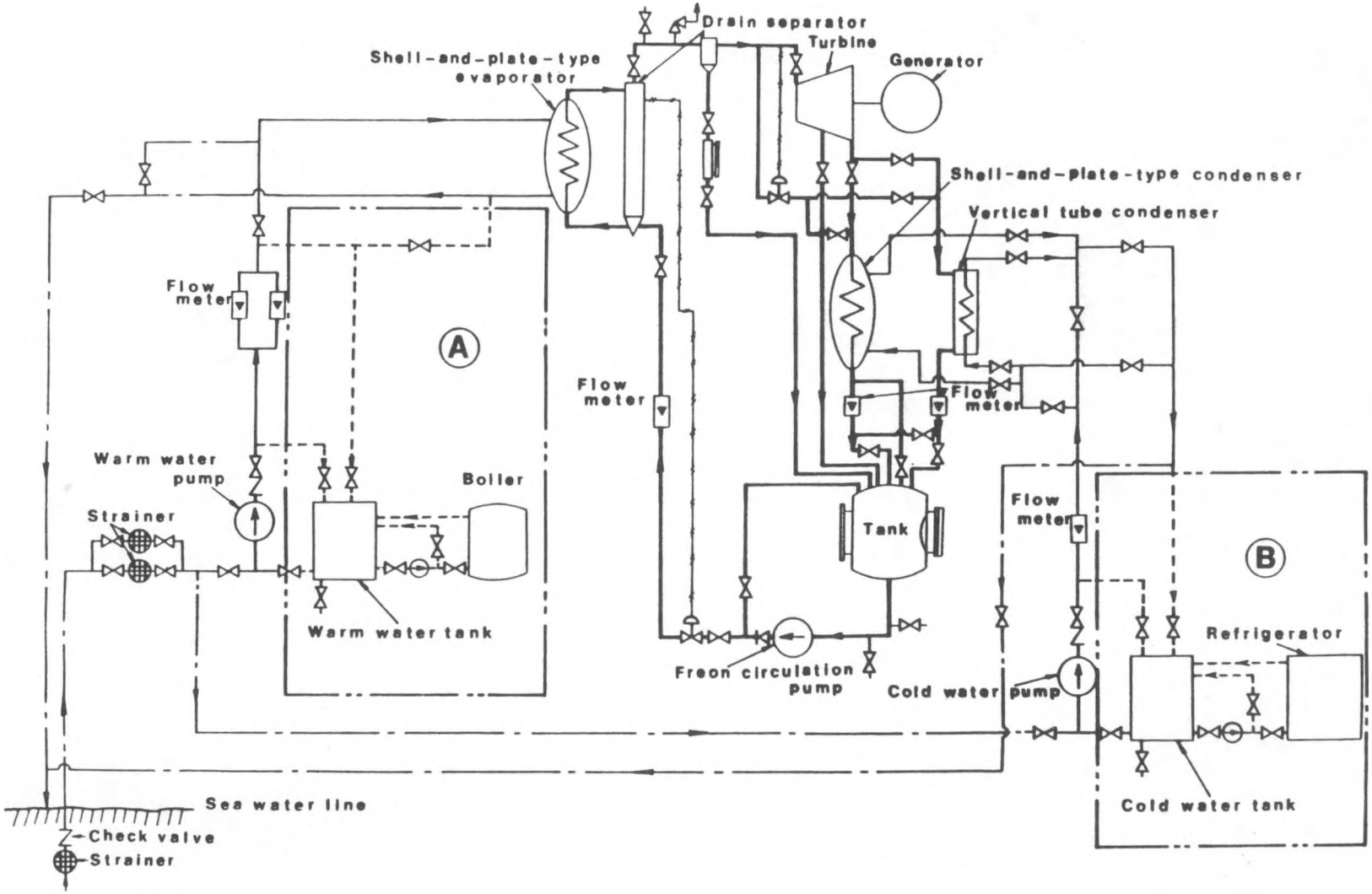


Fig. 2 Flow-chart of Imari 2

warm water in summer. The fresh water kept at the temperature of 28° C by a boiler serves as the warm water. Then, a series of tests employing the sea water has been completed for both the warm water and the cold water by making the experiment during both summer and winter.

The loop circulating the sea water only is shown by a dot-dash line in Fig. 2, on the other hand, the fresh water only, by a broken line. A solid line in Fig. 2 shows the common loop usually used in operating the Imari 2. A heavy solid line shows the loop circulating the working fluid. The part indicated by a mark A is a heat-equipment heating the freshwater and used only in winter, and the part by a mark B is a refrigerating equipment cooling the fresh water and operating only in summer.

2.1 Evaporator

Two different shell-and-plate-type evaporators made by Hisaka Works Co. Ltd. in Japan, are used in Imari 2. Figure 3 shows one of them consisting of three plates made of titanium, and also shows the passage of the warm water and Freon 22. Freon 22 passes through a lot of holes drilled in the left plate and impinges on the mid plate and is evaporated by heat transferred from the warm water through the mid plate. It may be of use to mention that the surface in the mid plate facing the working fluid is coated with the aluminium powder in order to enhance heat transfer. Figure 4 shows both the surfaces of the mid plate and the shell. We gave a name "IPP Evaporator" to this type evaporator. A clearance between the plates is sealed by a rubber packing. The dimensions of this mid plate are 1255 mm in length, 415 mm in width and 0.8 mm in thickness. Figure 5 shows the passage of the warm water and Freon 22 of another evaporator consisting of the same plate without the liquid impingement only. The surface of the plate facing the working fluid is coated with the aluminium powder in order to increase heat transfer rate. The dimensions of this plate are 1450 mm in length, 235 mm in width and 0.8 mm in thickness. The total surface area of this evaporator with 98 plates is 21.95 m^2, and the area of each plate is 0.224 m^2.

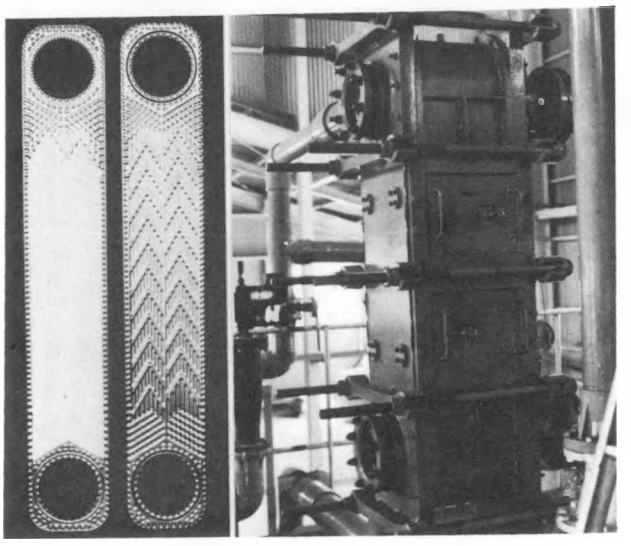


Fig. 4 Both surfaces of the plate and shell of evaporator

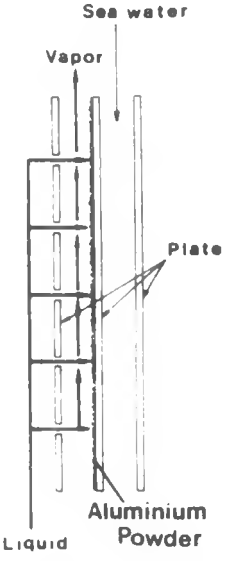


Fig. 3 Passage of the warm water and Freon 22 in IPP type evaporator

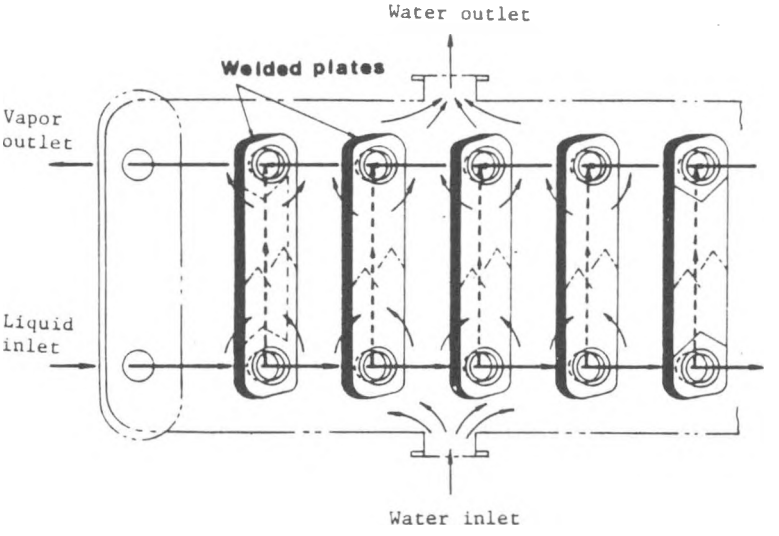


Fig. 5 Passage of the warm water and Freon 22 in PP type evaporator

2.2 Condenser

The shell-and-plate-type condenser made by Hisaka Works Co. Ltd. is used in Imari 2. Figure 6 shows both the surfaces of the plate of which the condenser consists and the shell. The surface of the plate facing Freon 22 has not only a small flute and a large flute but also drainages to enhance the condensation heat transfer. The dimensions of the plate are 1255 mm in length, 415 mm in width and 0.8 mm in thickness. The total surface area of this condenser composed of 54 plates is 21.6 m^2 and is 0.4 m^2 apiece.

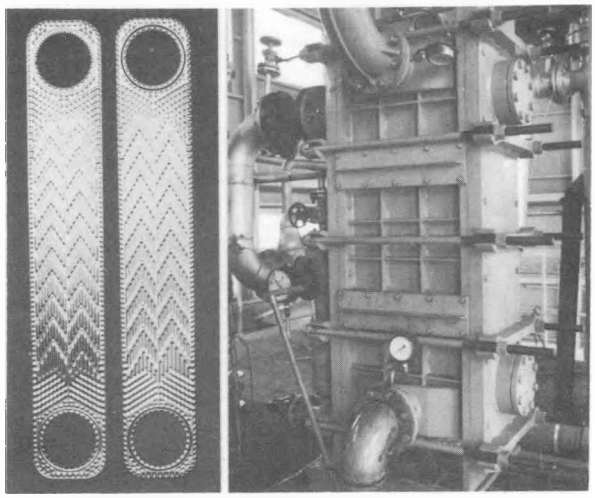


Fig. 6 Both surfaces of the plate and shell of condenser

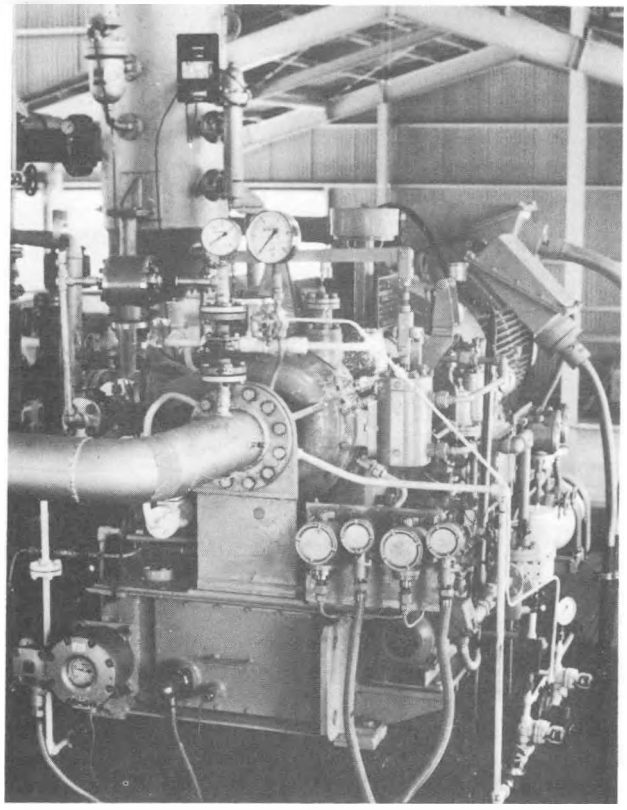


Fig. 7 A 50 kw class turbine and generator

2.3 Turbine and Generator

Figure 7 shows a 50 kw class turbine and generator, made by Mitsubishi Heavy Ind. Co. Ltd. The type of this turbine is radial flow and the rated speed is 28400 rpm. The generator is sheltered from explosion and its rated speed is 3600 rpm.

3. EXPERIMENTAL RESULTS

Figure 8 represents, as an example, the daily change in the temperature of the sea water, its flow rate and overall heat transfer coefficient. From Fig. 8, the temperature of the sea water changes from 25.0°C to 27.0°C, and the average temperature of the sea water appears at about 9:00 a.m. and 10:00 p.m. in a day. This fact is given a guarantee by meteorology. The flow rate of the sea water, which depends on the tide, changes from 46.2 to 49.8 t/h. But it seems that these variations have little effect on overall heat transfer coefficient of about 2000 kcal/m^2h°C.

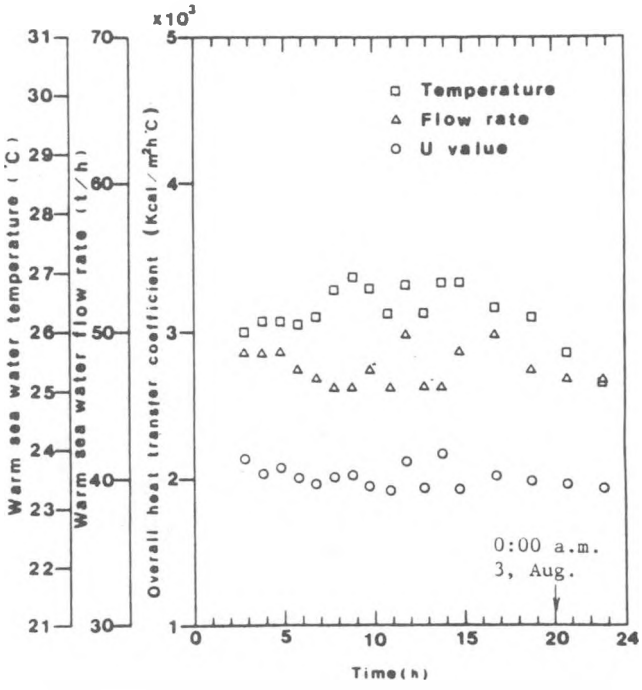


Fig. 8 Daily change in the temperature of the sea water, its flow rate and overall heat transfer coefficient

Figure 9 shows the experimental data for the IPP type evaporator obtained during the continuous running from 29, July, 1980 to 1. Sept., 1980. By the way, the data in Fig. 9 are measured at about 10:00 p.m., a time selected for the reason above-mentioned. From Fig. 9, the temperature of the sea water has been kept at a temperature of 25.6°C to 26.8°C within the whole experimental range, except the first four days of 29, July to 2, August when it had been either rainy or cloudy so that it had been cool summer. It is found from Fig. 9 that the flow rate of the sea water rapidly decreases for the first four days. This reason is that the intake becomes narrow owing to shellfish and seaweeds. After a week, the flow rate is almost kept constant. Fig. 9 shows that in spite of both the temperature and the flow rate of the sea water rapidly decreasing for the first four days, overall heat transfer coefficient decreased little by little. But after a week, it is found from Fig. 9 that overall heat transfer coefficient gradually decreases under the condition that the temperature is kept constant or rises and the flow rate is kept constant or increases. The reason why overall heat transfer coefficient changes as is shown in Fig. 9 is that recovery of the sea water temperature compensates the rapid decrease in overall heat transfer coefficient for the first several days and as time proceeds, the fouling of its surface advances so that the thermal resistance increases. It should be noted that Marks ■, ▲, and● in Fig. 9 are the data obtained when the intake, pipe line and evaporator are rinsed with the sea water recirculated in its loop. These marks ■, ▲, and● show that both overall heat transfer coefficient and the flow rate recover.

Figure 10, for reference, shows that the intake settled in for a month is almost covered with the shellfish and seaweeds. According to observation with the naked eye, the surface of the plate in evaporator is fouled markedly. Table 1, for reference, represents the tpyical data for the PP evaporator. Figure 11 shows the pressure loss for its evaporator. For reference, the pressure loss for the PP evaporator is about one-third to one-fifth as large as that for IPP evaporator.

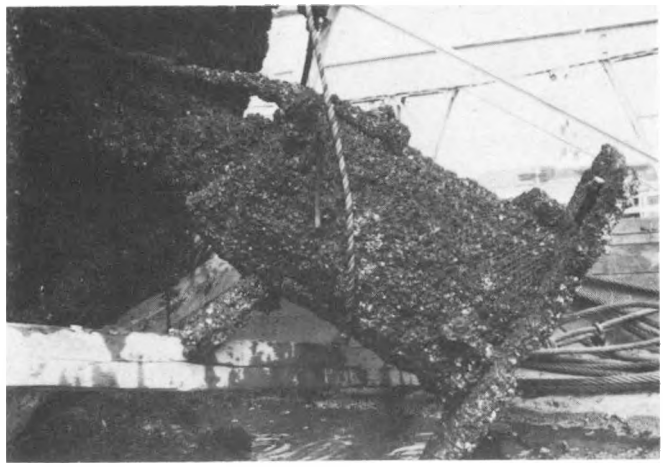


Fig. 10 Intake covered with the shellfish and seaweeds

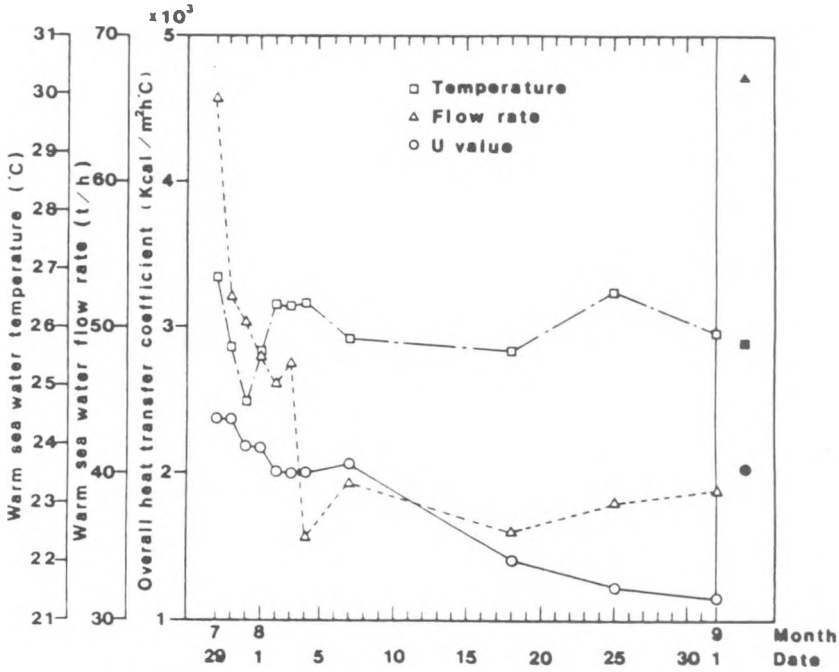


Fig. 9 Change in the temperature of the sea water, flow rate and overall heat r coefficient for a month

Table 1 Performance of PP type evaporator

Item	Unit	
Warm water flow rate	t/h	100.8
Warm water inlet temperature	°C	28.6
Warm water outlet temperature	°C	27.2
Freon flow rate	t/h	1.8
Freon inlet temperature	°C	25.0
Freon outlet temperature	°C	25.9
Warm water velocity	m/s	1.0
Heat transfer area	m^2	21.9
Heat transfer rate	kcal/h	1.4×10^5
Overall heat transfer coefficient	$kcal/m^2h°C$	2600

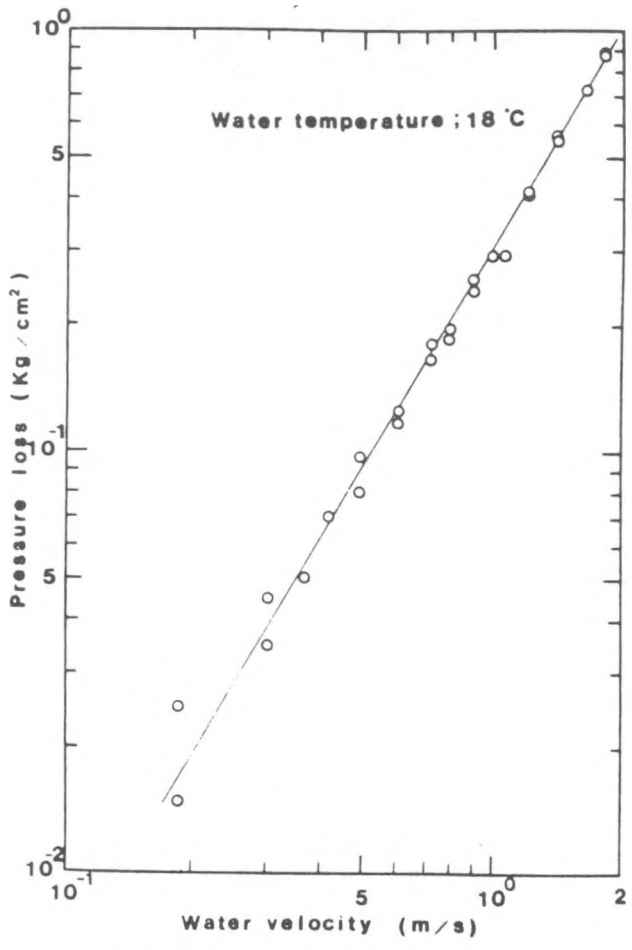


Fig.11 Pressure loss vs. water velocity

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Session Group VI

INDUSTRY DEVELOPMENT FROM HERE TO THE MARKET

8th Ocean Energy Conference
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OTEC: A BUSINESS STRATEGY PERSPECTIVE

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ABSTRACT

The business manager considering an Ocean Thermal Energy Conversion (OTEC) project faces many complex issues. These issues are compounded by a number of uncertainties and a long, often risky payoff period. Moreover, because the federal government will probably take a much less active role in commercialization of alternative energy technologies, top decision makers need more than ever to understand the technical, industrial, market, economic, environmental, and institutional variables affecting any new, energy-related investment decision.

This paper presents an analytical framework and methodology for making a strategic decision, based on an analysis of risks, vulnerabilities, and opportunities facing the decision maker. The RPA approach to strategy development is presented and applied to a hypothetical, commercial-scale OTEC project.

INTRODUCTION

The program for this conference pointed out that OTEC has advanced through the technical feasibility stage. While there are engineering problems that need to be addressed, the technical and environmental risks appear manageable. The great challenge facing OTEC and other alternative energy technologies is to determine and demonstrate economic feasibility. Moreover, the declining role of the federal government in commercialization will force new projects to compete for funds directly in the capital markets. These markets are tough and efficient, and any new energy project will be scrutinized as much from an economic and business perspective as from a technological point of view.

OTEC projects share many of the risk characteristics common to energy and natural resource businesses. These businesses usually involve very large investments in dollars and management attention; often have long payoff periods; are subject to regulation or at least are influenced by federal, state, and local government agencies; and usually must compete in price-sensitive, commodity markets. Consequently, such businesses require a suitable approach for making strategic decisions that can effectively address risks, vulnerabilities, and opportunities.

Unfortunately, traditional approaches to business strategy formulation and project evaluation have a number of shortcomings. First, uncertainty is treated inadequately. Too often, only point estimates of the future are considered. Second, management is presented with a limited set of alternative strategies. Third, traditional approaches do not lend themselves to the development of contingency plans and hedging strategies. Fourth, too little connection is made between judgment and analysis.

This paper presents a specific methodology for conducting a broad-based evaluation of an OTEC project that can be used to overcome these difficulties. To demonstrate the approach, we apply it to a hypothetical, commercial-scale OTEC ammonia plant as viewed by a large, diversified corporation.

THE STRATEGY DEVELOPMENT PROCESS

The development of a business strategy for an individual project or a new business venture is as much an art as it is a science. The strategy development process requires a balance of creativity and analysis founded on a solid knowledge base. Also, risk and uncertainty need to be considered explicitly through the use of multiple scenarios, supported by thoughtful consideration of major controllable and uncontrollable forces underlying strategic alternatives.

Because OTEC is a new alternative energy technology, real world uncertainties are compounded by lack of extensive operating and business experience. In our work with energy and natural resource companies, we have often encountered this kind of situation and have developed an approach to aid the strategy development process in these industries.

The first step in this approach is a situational analysis of the business or project. The output of this analysis should yield an understanding of the strategy elements and scenario variables that affect the project. By strategy element we mean a major decision that shapes specific operational actions, which, in turn, affect the long-term performance of the project. By scenario variable we mean a major uncontrollable force that shapes the future business and operating environment of the project.

A useful tool for communicating insights from the situational analysis is the vulnerability/opportunity grid, shown in Figure 1. We can plot each of the scenario variables and strategy ele-

ments horizontally with regard to the degree of control management has over the element or variable, and vertically with regard to its importance to performance outcomes. Given these axes, we then categorize the quadrants and the variables that fall into each quadrant in terms relevant to strategic planning.

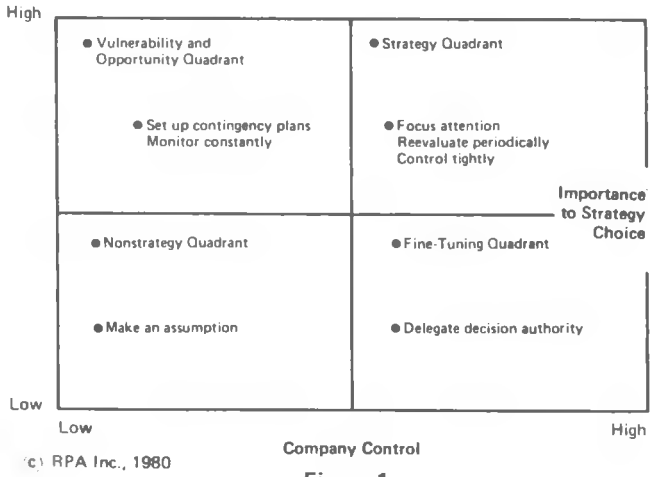


Figure 1

Vulnerability/Opportunity Grid

Starting from the lower left corner and moving counterclockwise, the four quadrants in the vulnerability/opportunity grid are:

- Nonstrategy Quadrant

  Management has little control over the variables in this quadrant, but their values are not important to performance outcomes (and thus to the selection of a business strategy). Consequently, they can often be dismissed with an assumption.

- Fine-Tuning Quadrant

  These variables can be controlled by management, but their values will not affect economic outcome greatly, nor will they have a significant impact on strategy selection. Therefore, decisions on these variables can be delegated.

- Strategy Quadrant

  This quadrant contains the key strategy elements. Their values can be determined by management and a maximum effort must be made to analyze and control them.

- Vulnerability and Opportunity Quadrant

  The key scenario variables in this quadrant have important consequences for the selection of a strategy, but management cannot exercise much control over their values. Therefore, it is vital that these elements be examined carefully to understand their impact. They must be closely monitored and contingency plans must be prepared to deal with any major changes.

The vulnerability/opportunity grid has a number of practical applications. First, the grid enables us to simplify project analysis by dropping strategy elements and scenario variables that fall in the lower quadrants. This saves time and money. Next, the grid is a powerful device for focusing management's attention on items that are strategically important. Finally, a significant use for the grid is in understanding the vulnerability/opportunity quadrant and determining -- through investments, information, or judicious selection of strategy and contingency plans -- how issues in that quadrant can be controlled. The issues are thus moved from left to right or, alternatively, reduced in importance and moved from top to bottom.

APPLICATION TO AN OTEC AMMONIA PROJECT

Having introduced the vulnerability/opportunity grid, we now apply it to a hypothetical OTEC ammonia project and trace the remaining steps of strategy development using this example.

Ammonia is an attractive application for OTEC. Most synthetic ammonia is produced from natural gas, and the variable costs of production have been increasing rapidly. Thus, an OTEC ammonia project could have a relative cost advantage if capital costs can be contained.

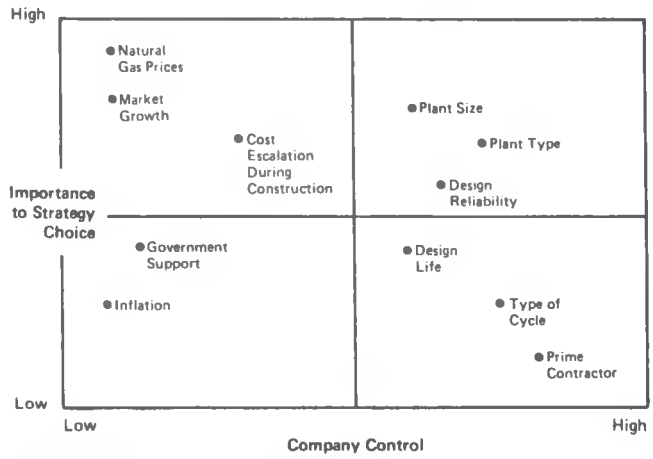


Figure 2

Vulnerability/Opportunity Grid for OTEC Ammonia Project

Figure 2 shows a simplified vulnerability/opportunity grid for an OTEC ammonia project. Clearly, natural gas prices and market growth are important scenario variables over which management has little control. Construction cost escalation is also an important variable, but management may be able to move this variable's position to the right (that is, increasing controllability) through careful selection of construction contract terms and conditions, and design planning. Inflation

shown as being low in importance. Because construction cost escalation and natural gas prices are treated specifically, overall changes in the general price level are not critical to project economics.

Once the variables on the left-hand side of the grid are determined, values can be assigned to them. Using economic forecasts, management judgment, and possibly, Delphi techniques, a range of values is displayed for each scenario variable as shown in Figure 3. Scenarios (that is, possible future states of the world) are constructed by connecting values in the scenario table. For items in the lower left hand quadrant, a single value may be assumed in a "first-cut" analysis. The intent here is not to predict the future; rather, management's attention should be directed to understanding the range of possible futures that can have an impact on the outcome of project strategies.

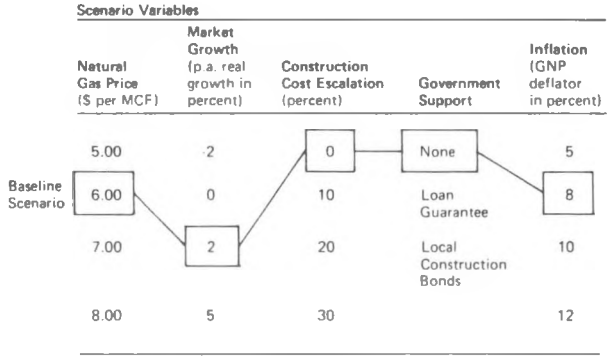


Figure 3

Scenario Table for
OTEC Ammonia Project

The variables on the right-hand side of the vulnerability/opportunity grid are generally within management's control. The most critical variables are those shown in the upper right-hand quadrant. Specific values for these strategy elements fall within a range of decision values, which are viable and attractive to management. Figure 4 shows strategy elements with values that might be considered for alternative project strategies. By connecting values for each strategy element, integrated strategies are constructed. An aggressive investment strategy involving a 1,000 ton-per-day (TPD) ammonia plant is shown in Figure 4. Integrated strategies can be designed to deal with problem scenarios, to gain control over important uncontrollables so as to avoid serious vulnerabilities, or to position the company to capture important opportunities.

Throughout the process of constructing scenarios and strategies, management should work to establish results measures (that is, performance criteria) that reflect the goals of the project and provide a

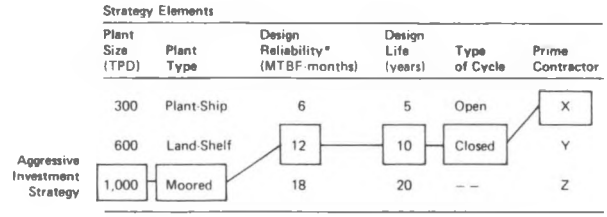


Figure 4

Strategy Table for
OTEC Ammonia Project

means for evaluating strategies against scenarios. Often, net present value and internal rate of return are used as results measures, but other quantitative measures such as earnings per share impact or simple payback period should be considered. Also, qualitative results measures such as company reputation and the benefits of learning and experience in OTEC may be included.

Given a number of alternative strategies selected by management, along with a range of scenarios, Figure 5 provides a simple means of displaying results measures for each pair of scenario and strategy. Usually the strategy comparison table for an actual project is sufficiently complex to justify the use of a computer to aid in the computations.

RESULT MEASURE: NET PRESENT VALUE ($M) -20% DISCOUNT

Strategies \ Scenarios	Pessimistic	Baseline	Optimistic
Demonstration Plant	-2	0	1
Baseline	-5	5	10
Aggressive Investment	-20	-5	20

(c) RPA Inc., 1980

Figure 5

Strategy Comparison Table
for OTEC Project

Once the initial strategy comparison table has been constructed, management begins to develop significant insights as to how strategic alternatives modify the effects of uncontrollable scenario variables. This step usually goes through several iterations where certain strategies turn out to be clearly inferior, while other strategies are created and evaluated. Eventually, a relatively small number of attractive strategies should

remain. Additional analysis coupled with management judgment should lead to consensus, commitment, and implementation of an attractive strategy.

THE ROLE OF DECISION ANALYSIS

For the sake of brevity, this paper has given little attention to the quantitative aspects of this approach to strategy development. However, the essence of the approach is not to develop a complex, all-inclusive mathematical model for decision making. Decision models for even the simplest of real-world projects are usually highly complex. Simulation techniques must often be used because of the vast number of outcomes that can result from a relatively small number of decision variables.

Nevertheless, quantitive methods offer several benefits. First, they bring overall discipline to the strategy development process. Management judgment is supplemented by hard analysis. Second, sensitivity analysis may be used to determine the relative importance of scenario variables and strategy elements. Third, probability distributions are useful for translating uncertainty in management's judgment about uncontrollable forces into a range of values. Finally, decision analysis can help quantify the value of imperfect information, thus putting an upper bound on the value of additional analyses, feasibility studies, and even prototype testing.

SUMMARY

The intent of the methodology presented in this paper is to provide a framework for applying management judgment supplemented by rigorous analysis to complex business issues. Because OTEC projects represent major investments that are subject to a number of uncertainties, they must be evaluated through an approach that considers more than single, point estimates of the future and provides insights into the key risks, vulnerabilities, and opportunities facing management.

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DOMESTIC SOCIAL AND ECONOMIC IMPACTS OF OTEC COMMERCIAL DEVELOPMENT

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ABSTRACT

The widescale domestic development and utilization of OTEC power plants would have a significant impact upon the economy of the United States. This paper describes the detailed economic impact analysis undertaken by Jack Faucettt Associates, Inc., for the U.S. Department of Energy, to identify these economic impacts and to measure them at the national, regional, and industry levels. It focuses on the impacts generated under a likely OTEC development scenario, dividing them into direct, indirect, and induced effects. These impacts include employment and production effects, tax revenue effects, and the effect on the balance of payments.

INTRODUCTION

OTEC power plants can provide the United States with a renewable domestic source of energy. Further, their construction and utilizaton in the United States could increase the nation's economic activity. Consequently, it is important to understand the varieties and magnitudes of the economic impacts associated with OTEC development.

This paper describes the detailed economic impact analysis that Jack Faucett Associates and its subcontractors are conducting for the U.S. Department of Energy. The analysis is designed to identify these economic impacts and to quantify them at the national, regional, and industry levels. It focuses on the effects on the United States' economy of the domestic development and utilization of twenty-five and fifty 400 MWe OTEC power plants by the year 2000.

The methodology employed is characteristic of economic impact analysis (Figure 1). After conducting a literature review, the study team developed a likely future OTEC scenario. This included technological siting, and materials requirements parameters. The technological parameters developed in this phase were then used to identify the industries affected by OTEC development. An economic profile was then constructed for each of these industries. These profiles established an industrial baseline from which subsequent economic impact analysis is being developed, including the measurement of direct, indirect, and induced impacts.

First order output and employment effects are being estimated by consulting studies of materials and manpower requirements at each stage of commercialization. Subsequent output and employment impacts will be estimated at the national and industry levels by employing an existing econometric model. Regional impacts will also be estimated by using an existing model.

Each stage of this analysis is detailed below. Results are presented when they are available. Complete results will be available in the Fall of 1981.

LITERATURE REVIEW

In order to ensure that the study team was fully cognizant of the relevant OTEC technical and economic literature, an extensive literature review was conducted. JFA librarians performed a computer search of appropriate bibliographic data bases so as to locate government, academic and professional papers concerned with OTEC. Consequently, the study team became very familiar with the current state of OTEC development, and was able to apply this knowledge to the design of the OTEC scenario in the next stage of analysis. Furthermore, an extensive bibliography was assembled, with citations from the following bibliographic data bases:

- NTIS
- Smithsonian Scientific Information Exchange
- Energyline
- Congressional Information Service
- GPO
- Oceanic Abstracts

OTEC SCENARIO

The next step in the analysis was to develop a likely OTEC future scenario that would contain technological, offshore siting, and construction siting parameters. This scenario was constrained by DOE requirements that two-thirds of the OTEC facilities were to produce electricity for onshore power needs, and that one-third were to be involved in the production of energy intensive products. This breakdown was to be applied to both the twenty-five plant and fifty plant situation. Furthermore, a preliminary OTEC scenario suggested by DOE (Table 1) was considered while the complete scenario was developed.

Technology

The first issue to be resolved was to determine the most likely technology, open or closed cycle, to be employed in the majority of OTEC plants by the year 2000. Given the government's emphasis on closed cycle systems, plus uncertainties associated with the operation of open cycle systems, the study team concentrated on the closed cycle OTEC. This allowed the team to determine what materials and equipment would be required in the construction and operation of the plant. These included

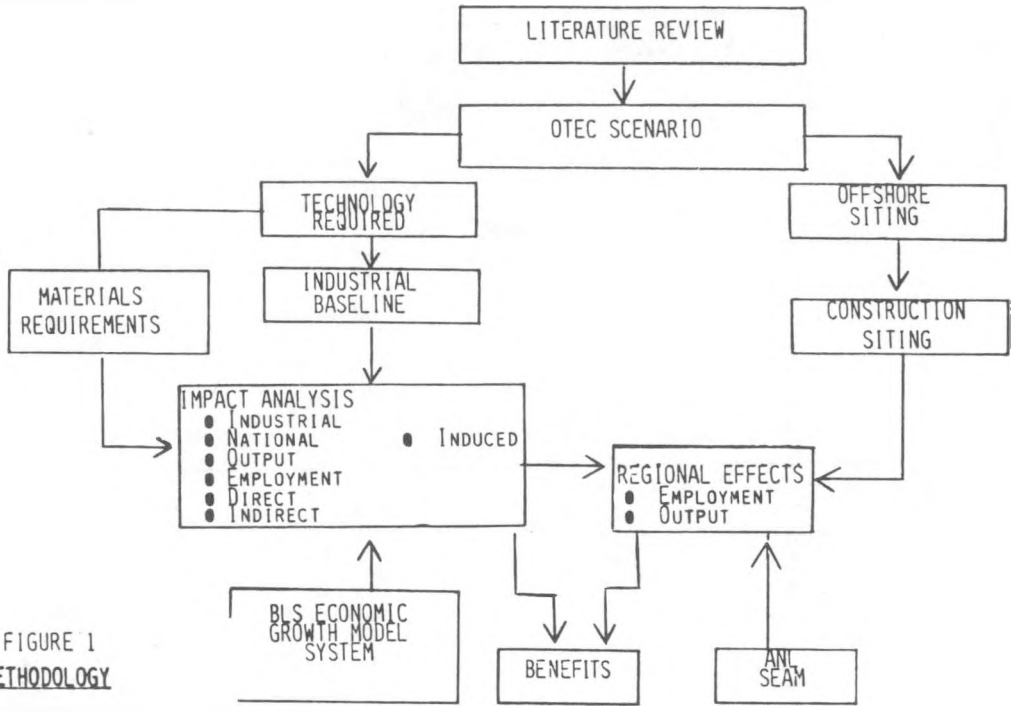


FIGURE 1
METHODOLOGY

steel, concrete, titanium, aluminum, warm and cold water pumps, and heat exchangers. A list of impacted industries was then generated. Finally, the team agreed with DOE's assessment that the most likely energy intensive products to be produced aboard an OTEC plantship would be aluminum and ammonia.

Offshore Siting

OTEC plants are usually designed for a nominal Δ T of 20°C for performance and economic reasons. This requires an ocean depth in excess of approximately three thousand feet. The depth must not be so great, however, that an electricity generating plant cannot be moored. The distance from shore will also have implications for the power cable in the electricity generating mode. Finally, for the OTEC concept to succeed as a commercial power plant system, a market for the power must exist.

Given the constraints cited above, OTEC power is not directly accessible to large portions of the United States. Other than the Virgin Islands and the islands of the Puerto Rico and Hawaii, the only area of the United States that could directly benefit from ocean thermal energy lies along the Gulf of Mexico. This region has both OTEC thermal resources available, and a substantial market growth in demand for electricity. These reasons, and the fact that this coastal area also has a rapidly expanding population as part of the Sun Belt, makes it the most likely U.S. region to consume OTEC generated electricity in large amounts.

The close proximity of Hawaii, Puerto Rico, and the Virgin Islands to a tropical ocean energy source make these U.S. islands potential consumers of OTEC electricity. However, the economies of these islands do not warrant large numbers of 400 MWe OTEC power plants, even if currently existing fossil fuel fired electricity is replaced.

The OTEC power produced offshore can also be used offshore in plantships producing energy intensive commodities. As noted earlier, the two commodities commonly cited in this mode are aluminum and ammonia. Several problems exist, however, in the producton of aluminum at sea. Consequently, the combination of a coastal based aluminum plant with a moored OTEC generating electricity seems more feasible. Ammonia, on the other hand, appears to be better suited to production at sea, where needed raw materials can be obtained from the air and water, and the final product can be easily transported. Furthermore, a strong market for ammonia exists in the United States, particularly for use in fertilizers. Consequently, the South Atlantic off the northeast coast of Brazil may be a good location for grazing OTEC's producing ammonia.

Construction Siting

A shipyard considered for OTEC construction must have both the necessary capabilities and facilities, and be reasonably close to the intended OTEC operating sites in the Atlantic, the Pacific, or the Gulf of Mexico. While there are twenty-eight major shipyards in the United States that have building or graving dock facilities in excess of 475 feet in length, eighteen shipyards are not suitable for OTEC construction. Of those yards, two are closed and four are on the Great Lakes. The remaining twelve were eliminated for a variety of factors, including lack of a suitable access channel to deep water, lack of engineering or skilled labor force, or lack of financial capabilities to undertake a project of this size. The ten shipyards deemed suitable are also forecast to be well below capacity in the 1980's, given current orders. Each also has the graving docks, personnel and support shops required in the construction of an OTEC facility. Furthermore, unemployment data has been developed for each yard's location so as to ascertain those yards that could benefit the most from OTEC construction.

Conclusion

Given the constraints and requirements identified in the offshore siting and construction siting analyses, Table 2 shows the matrix of shipyards, locations, and OTEC plant modes for the twenty-five plant scenario. As can be seen, the majority of OTEC's are involved in the production of electricity along the coast of the Gulf of Mexico.

TABLE 1

OTEC SCENARIO

PRELIMINARY

OTEC SCENARIOS SUGGESTED BY DOE

	1	2	3	4	5
	ISLANDS			GULF	
	FLOATING		SHELF		
	SUBMERSIBLE	SURFACE		SUBMERSIBLE	FLOATING
TECHNOLOGY	CLOSED	CLOSED	1-CLOSED 2-OPEN	CLOSED	CLOSED
HULL	STEEL	STEEL		STEEL	STEEL
PIPE	FIBERGLASS	FIBERGLASS	FIBERGLASS	FIBERGLASS	FIBERGLASS
HEAT EXCHANGER	TITANIUM	TITANIUM	TITANIUM (CU/NI)	TITANIUM	TITANIUM
NO. OF UNITS 25	1	6	3	1	1
NO. OF UNITS 50	2	12	6	2	2

	6	7	8	9	10
	INTERNATIONAL		PLANTSHIP		
	SURFACE	SHELF	NH_3	AL	H
TECHNOLOGY	CLOSED	1-CLOSED 1-OPEN	CLOSED	CLOSED	CLOSED
HULL	STEEL		CEMENT	CEMENT	CEMENT
PIPE	STEEL	CEMENT	FIBERGLASS	FIBERGLASS	FIBERGLASS
HEAT EXCHANGER	TITANIUM	TITANIUM (CU/NI)	AL	AL	AL
NO. OF UNITS 25	1	2	3	2	5
NO. OF UNITS 50	2	4	6	4	10

INDUSTRIAL BASELINE

After the OTEC scenario was determined, economic profiles of the OTEC impacted industries were developed. These profiles detail an impacted industry's history, its financial and economic characteristics, its technological and production traits, and any resource constraints that might impede its operation. Some of the historical data collected includes output, value of shipments, number of firms, employment, prices, exports, and imports. This data establishes a baseline from which subsequent economic impact analysis is developed, including the measurement of direct, indirect, and induced impacts.

Profiles were developed for the following industries: steel, concrete, cement, titanium, aluminum, fiberglass reinforced plastic, underwater electrical cable, metal fabrication, offshore service, shipbuilding, and ammonia.

In the course of developing these profiles, several problems were identified. For example, the underwater electrical transmission cable industry is non-existent in the United States, and may be difficult to create. Secondly, there is a concrete aggregate and cement shortage on the Gulf coast that could impede the construction of OTEC hulls there. Thirdly, a fiberglass reinforced plastic cold water pipe of the size necessary for an OTEC plant has never been constructed. Fourthly, there is insufficient capacity in the titanium industry to support the construction of a large number of titanium heat exchangers, especially if potential defense demand for titanium is considered. Finally, the offshore service industry, which does not currently exist on the East coast of the United States, is projected to experience a severe manpower shortage that could adversely affect the deployment and operation of OTEC powerplants.

	OTEC's Total	Atlantic OTEC Sites	Facilities A	B	C	Gulf Coast OTEC Sites	Facilities D	E	F	Pacific OTEC Sites	Facilities G	H	I	J
ISLAND														
ELECTRIC	4	2		2						2				2
ALUMINA	2'	1			1					1				1
AMMONIA	2									2	1		1	
COASTAL														
ELECTRIC	11					11	3	4	4					
MID-OCEAN														
AMMONIA	6	6		3	3									

MATRIX OF SHIPYARDS UTILIZED IN CONSTRUCTION OF OTEC FACILITIES
25 OTEC PLANT FACILITIES BY YEAR 2000 AND OFFSHORE SITES

TABLE 2
OTEC SCENARIO

MATERIALS REQUIREMENTS

Estimates of materials required in the construction of a 400 MWe closed cycle OTEC power plant were developed from design studies done by Westinghouse for a 50 MWe CC-OTEC powerplant, under the assumption that the 400 MWe system would be comprised of eight 50 MWe modules. These requirements are listed in Table 3.

IMPACT ANALYSIS

Economic impacts generated by the domestic development of OTEC power plants occur at the national, regional, and industry levels. These impacts can further be divided into direct, indirect, and induced effects. Direct impacts are those attributed to the construction, deployment, and operation of OTEC powerplants. Indirect impacts are due to the interrelationship between the different sectors of the economy, since industries must purchase the necessary inputs for production from each other. This affects nearly all industries. Finally, induced impacts occur as the expansion in output and employment result in increased personal income among workers, leading to increased spending. This increased spending induces the production of more consumption goods and services in the economy; it is often called the multiplier effect.

Direct Impacts

First order output and employment efects have been, and are being, estimated by consulting the materials requirements analysis and analysis of manpower requirements at each stage of development. For example, OTEC manning levels have been calculated under the double crew scenario for electricity, ammonia, and aluminum facilities (Table 4). Further, construction employment has been estimated at specific assembly levels.

Indirect and Induced Impacts

Indirect and induced impacts will be estimated at the national and industry levels by employing the Bureau of Labor Statistics Economic Growth Model Sytem. This model consists of three major parts: a macroeconomic model; an industry activity model; and the BLS labor demand model. In this analysis, the study team has been primarily concerned with the last two components.

The industry activity model is an input-output model that provides the framework for projecting gross industry outputs, or the total of final and intermediate sales required of each industry. It also may be used to estimate changes in an industry's output due to changes in demand for its product. Thus, the model can be used to calculate the change in output at the industry level due to OTEC development. Furthermore, aggregation of individual industry changes permits one to estimate the total change in production resulting from OTEC. The required input to obtain these results is the initial change in demand for the vector of products required to construct an OTEC plant and its components.

The BLS Labor Demand Model projects wage and salary workers, unpaid family workers, and the self employed at the industry and national levels. These are estimates of the number of full- and part-time jobs required to meet the projected sales of each industry to all final demand or intermediate users. The principal input is the projected gross output in each industry, developed with the industry activity model. Thus, changes in production due to OTEC development can be translated into changes in employment with the BLS Labor Demand Model. This is done by dividing projected gross output by an estimated output-per-hour ratio in order to arrive at total projected hours in each industry. Total hours are then divided by projected average annual hours, yielding projected employment requirements for each industry. Comparison of this estimate with the baseline yields the change of employment due to OTEC.

Regional Impacts

Regional impacts may be the most significant in the development of OTEC powerplants. Most of these effects are expected to flow from increased shipyard activity at construction sites and from the support industry at the offshore sites. Other potential regional impacts may occur if certain areas of the country supply the materials necessary to construct an OTEC plant ship. For example, if an OTEC plant is built along the Gulf Coast, does all of the steel required come from one particular steel production center? A commodity flow data base is being consulted to determine if such unequal changes in regional production do occur.

The primary regional impact is that on employment. This impact may be estimated by using Argonne National Laboratory's Social and Economic Assessment Model (SEAM). This model uses economic base theory to derive ratio employment multipliers. This theory holds that the growth of an area is dependent upon the growht of basic industries such as construction or manufacturing. The multiplier is simply a scalar that relates total area employment to employment in these basic industries. Thus, the total expected change in regional employment can be estimated by multiplying a given change in basic employment by the multiplier. This provides an estimate of the changes in secondary and induced employment when the change in base employment is subtracted. We anticipate applying such multipliers at the county level.

NATIONAL BENEFITS

The national benefits arising from domestic OTEC development may occur in several areas. Firstly, the stimulus could result in employment and production effects that would reduce unemployment and increase GNP. Secondly, a net energy study by Westinghouse indicates that a 50 MWe OTEC facility is a highly efficient facility in terms of energy inputs and outputs, with an output/input ratio of 9.37 for a steel hulled facility and 12.25 for a concrete hulled OTEC, per year (Table 5). Furthermore, OTEC power plants producing 10,000 MWe by the year 2000 would produce non-renewable fuel equivalent savings that would not be inconsequential. Finally, the balance of payments impacts of OTEC may be favorable, particularly if one considers the potential export of energy intensive products coupled with reduced oil imports. However, the change in net imports resulting from the increase in industry activity must be included if a complete balance of payments analysis is to be done.

TABLE 3
MATERIALS REQUIREMENTS
(400 MWE)

	SHORT TONS
CONCRETE HULL	507,416
STEEL HULL	107,872
OTHER STEEL	24,696
TITANIUM	10,368
TURBINE/PUMP	7,296
MHE	4,800
MOTOR/GENERATOR	6,360
TRANSFORMER	400
SWITCHGEAR	5,320
STAINLESS STEEL	5,440
WIRING	520
AMMONIA	9,248
NITROGEN	1,184

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Stenehjem, Erik J. and James E. Metzger, A Framework For Projecting Employment And Population Changes Accompanying Energy Development. Volume I. Argonne National Laboratory. ANL/AA-14, Vol. I. Argonne, Illinois, May 1980.

U.S. Department of Labor, Bureau of Labor Statistics, Methodology for Projections of Industry Employment to 1990. Bulletin 2036, Washington, D.C., February 1980.

TABLE 4
IMPACT ANALYSIS

A. DIRECT IMPACTS

OTEC MANNING -- DOUBLE CREW SCENARIO

- ELECTRICITY 90 TO 120 PER PLANT
- AMMONIA 140 TO 180 PER PLANT
- ALUMINUM 180 TO 220 PER PLANT
- 25 PLANTS 2830 TO 3880 TOTAL
- 50 PLANTS 5660 TO 7360 TOTAL
- MEETS CURRENT COAST GUARD REQUIREMENTS

TABLE 5
ENERGY CONTRIBUTIONS

WESTINGHOUSE NET ENERGY STUDY

	10^6 BTU
• INPUT ENERGY	
- STEEL HULL	143,863
- CONCRETE HULL	110,026
• OUTPUT ENERGY	
- GROSS 70.0 MWE	
- LESS 19.9 MWE	
- NET 50.1 MWE	
- PER YEAR (90%)	
395×10^6 KWH OR	1,348,000
• OUTPUT/INPUT RATIO	
STEEL HULL	= 9.37
- CONCRETE HULL	= 12.25

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AN APPROACH TO RISK ASSESSMENT IN OTEC DEVELOPMENT PLANNING

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ABSTRACT

Meridian Corporation has developed an approach to implement an ongoing risk assessment methodology which is applicable to all phases of Pilot Plant design and construction. This methodology will provide a systematic mechanism for consolidating expert opinions into a framework that facilitates the orderly comparison of alternative designs. While traditional approaches to risk assessment for decision-making in an environment of uncertainty involve subjective evaluation of expert opinion, the proposed methodology uses such approaches as a departure point and injects several analytical features designed to make the risk assessment process more deterministic. These features include the use of historical data on cost overruns on major R&D programs; the use of statistical techniques to quantify and display individual and group risk estimates; the introduction of feedback from external sources into a Delphi process to facilitate convergence of estimates; and the classification of design alternatives into categories of risk (as opposed to calculation of preference rankings).

1. INTRODUCTION

The OTEC development effort is at a particularly crucial juncture. The basic technological feasibility of major system components (i.e., cold water pipe, heat exchangers, mooring systems, etc.) has been or will be demonstrated in the near future. The OTEC Research, Development, and Demonstration Act (Public Law 96-310) calls for an ambitious program to provide 10,000 MWe of generating capacity by 1999. Thus, OTEC program management — in both government and industry — faces an enormous challenge to meet these goals within established cost and schedule targets. Meeting this challenge necessitates development of an on-going risk management process to evaluate alternative development choices in terms of uncertainty in technical performance, cost, and schedule. The methodology described in this paper is meant to provide an initial baseline from which to establish this continuing management process.

Historically, a variety of techniques has been used to assess risk, ranging from pure judgment to detailed computer modelling. The work described in this paper represents a departure from historical methods, and outlines an innovative conceptual approach to risk assessment that can be used in the evaluation of alternative OTEC Pilot Plant conceptual design proposals.

"Risk" can be defined in many different ways. In the context of the OTEC Pilot Plant Program, it may be thought of as the uncertainties associated with meeting the OTEC Pilot Plant Top Level Requirements within the established budget and schedule. The assessment of risk is, however, a continuous, iterative process in which uncertainties are progressively reduced (both in number and in degree) as new information becomes available. As a result, while all aspects of risk are of interest to OTEC program evaluators, the lack of available information at the outset of the Pilot Plant Program limits evaluation efforts to an assessment of cost uncertainties. In the phases which follow conceptual design, the analysis of accumulated data will provide additional information. The proposed risk assessment methodology will evolve as this information becomes available, making use of newly evaluated data to narrow the band of uncertainty surrounding the true cost and to permit the evaluation of schedule and design uncertainties.

2. ELEMENTS OF THE APPROACH

A broad spectrum of alternatives exists for assessing risk and facilitating a group decision in response to that perceived risk. The alternative methodologies for assessing risk vary dramatically in terms of their rigor, reproducibility, defensibility, sophistication, and cost, and range from the highly judgmental to the highly analytical.

For example, even lacking an empirical or operational basis for assessing risk, an individual still can make a judgment concerning the riskiness of any proposed venture. Such a judgment would necessarily be based upon that individual's personal experience, perceptions of the environment, and expectations of the future. Although a risk assessment methodology relying strictly on a single individual's judgment is both expedient and inexpensive, it is too subjective for use in large-scale government procurements.

A more appropriate technique for such procurements has historically been group judgment or polling, which is somewhat more analytical than individual judgment. Using group judgment, an assessment of risk can be based upon a broader range of experience and collective knowledge in more fields. The experience and knowledge of all individuals in the group can be shared, thus allowing a more accurate evaluation of the risk than any individual in the group could provide alone.

The introduction of group judgment is an

important step toward increasing the amount of information available on a proposed venture, which is essential to an increased understanding of its riskiness. Increases in the amount of available information eventually yield a precise analytical definition of the costs and risks. Such a precise assessment of risk can theoretically be attained through a variety of means — detailed analytical modelling, 100% sampling, or additional advanced research and development. The common element of each of these approaches is that they require a significant investment of both time and money. In the case of the OTEC Pilot Plant, this highly analytical level of risk assessment could conceivably be reached by constructing a detailed computer model of every component and sub-system of each proposed Pilot Plant design. Such an undertaking would be quite expensive, but at the conclusion of the process the risks would be known exactly.

The risk assessment methodology proposed herein combines the positive aspects of the more analytical methods with the low cost and ease of implementation that characterize the judgmental methodologies. Although this idea is a departure from traditional techniques, it is not without precedent. The development of the Delphi technique, for example, is the result of an effort to bring more order and discipline to the process of group judgment. In effect, the purpose of Delphi is to structure a group communication process to provide for formal feedback of both individual contributions and group judgments, thus achieving a more analytical approach at a relatively modest increment in cost and time.

What is novel about the concept presented in this paper is the use of statistical analytical tools to facilitate the group's understanding of its opinions and the introduction of a framework for individual estimates that facilitates rational, well-documented decisions. In addition, this approach provides for a classification scheme to assist in the selection of proposals that can be applied in each phase of the Pilot Plant program.

The methodology has been structured for use by an OTEC Pilot Plant Source Evaluation Board (SEB) composed of DOE technical, procurement, and legal officials. The package prepared for SEB use, also incorporates an empirical data base consisting of data from similar large scale government projects. This data base will serve to inform and calibrate SEB members' preconceived attitudes regarding risk in large R&D programs like the OTEC Pilot Plant. Finally, the methodology has been tailored to meet the special requirements imposed by the SEB process, which does not permit group interaction to be channeled through a monitor.

The conceptual approach to the methodology is structured around three key elements used for evaluating risk: (1) the use of empirical data, (2) the use of statistical methods to illuminate key differences in opinion and to enhance decision-making, and (3) the modification of the Delphi technique to meet the procedural limitations imposed by the SEB process. Each of these elements is described individually below.

2.1 Empirical Data Analyses

A unique aspect of the proposed risk assessment methodology is the inclusion of empirical data in the risk evaluation process. This empirical data base was developed by Meridian Corporation from an analysis of 135 high, medium, and low technology programs undertaken by DOE and DOD.[1] An analysis of the data will be presented in the pre-evaluation briefing as background to the SEB decision-making process and will serve as a baseline in evaluating the reasonableness of individual estimates.

The members of the SEB will be provided with historical cost overrun curves for each technology level (i.e., the high, medium, and low technology classifications). Figure 1 presents an example.

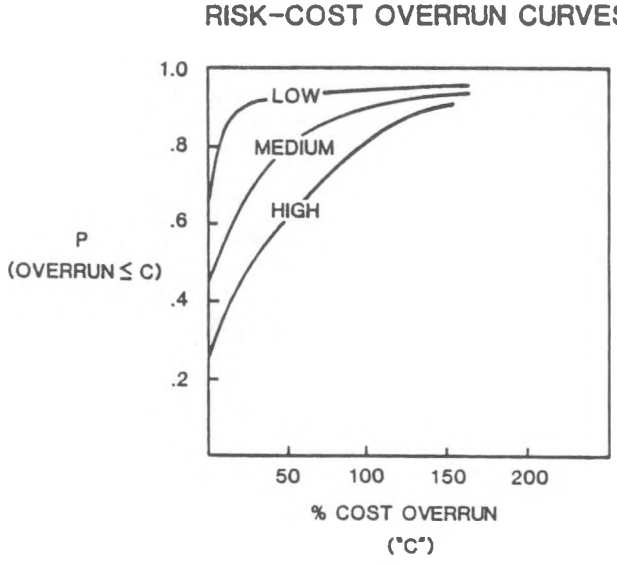


Figure 1

The evaluator can interpret these curves in two basic ways. For any level of technology, the appropriate curve will reveal the risk of an overrun less than or equal to a specified percentage, "C" -- the level of confidence that a manager can have that a reserve of "C" percentage will be adequate. Alternatively, given the minimum level of confidence desired by the evaluator (that is, the probability that the overrun is less than or equal to "C" percent), the curves can be used to determine the amount of contingency funding which might reasonably be set aside to cover potential cost overruns for individual components and subsystems of the OTEC Pilot Plant.

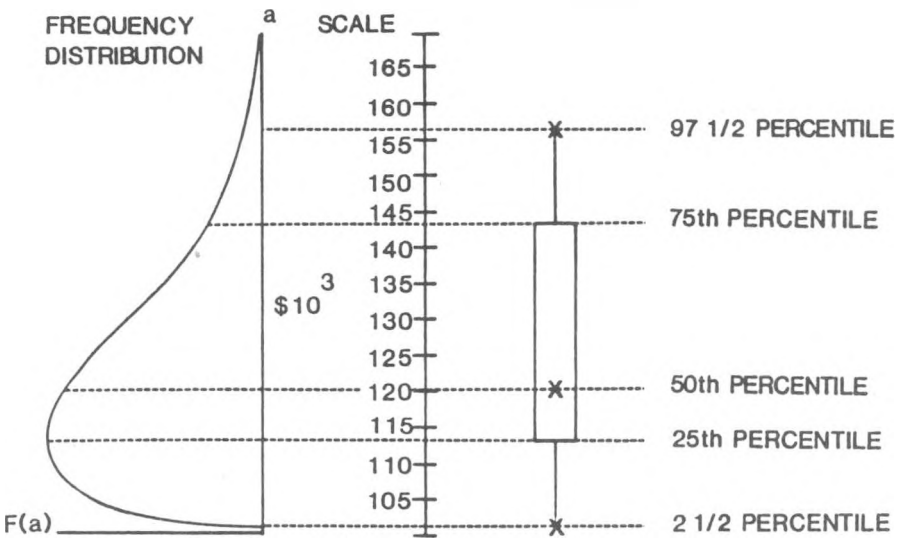
2.2 Statistical Analysis Tools

The methodology also incorporates the use of statistical analysis tools to clarify differences of opinion among SEB members. These tools will graphically display bidder estimates, SEB estimates, and the guidelines established by outside experts, as needed. Comparisons among bidders and among SEB members as a group will be made, allowing feedback to the SEB and creating flexibility in the evaluation of proposals.

The total assessment package includes automated algorithms to compute and display comparative results from individual and group reactions. The graphical techniques facilitate comparison of cost and cost uncertainty data among alternative design proposals and allow a relatively large amount of information to be displayed quickly in a spatially compact manner. Data from proposals and from outside experts are displayed to proposal evaluators, who in turn develop their own estimates. Subsequently, the procedure compares the evaluator's estimates (preserving individual and proposer anonymity) with proposal data. This process is iterated several times in an attempt to resolve differences and produce a consensus. The procedure is flexible enough to produce data comparisons at a very fine level of detail or aggregated at major subsystem level (e.g., cold water pipe). Once the group interaction is terminated, proposals are classified into categories defined by relative ranges of cost and cost uncertainty, which then forms the basis for proposal selection.

The basic tool to be employed is called a "box and whisker" plot.[2] This type of diagram is used to display frequency distributions. The idea is that the key points (fractiles) of a frequency or probability distribution are plotted on a scale and connected to display the probabilistic concepts in a spatially compact manner.

This concept is illustrated in Figure 2.



SAMPLE "BOX AND WHISKER" DIAGRAM

Figure 2

Suppose the distribution in Figure 2 represents the development of a particular component in a large project. Five distinct places on the diagram are important. First there are the two "x's" that appear at the upper and lower points of the diagram (the "whiskers"). Then there are the upper and lower boundaries (lines) of the rectangular region (called the box). Finally, there is an "X" located within the box. Each of these places has a well defined meaning for the probability distribution. The "X" inside the box represents the median of the distribution, i.e., that value about which one-half of the values lie (the 50th percentile). The upper and lower boundaries of the box are the 75th and 25th percentiles of the distribution, respectively. Finally, the upper and lower "x's" represent the 2-1/2 percentile and 97-1/2 percentile, respectively, of the distribution. These percentiles are selected because 95% of the values lie between these two "x" marks. For the purpose of this methodology,

however, the upper and lower "x" marks will be interpreted as the "high" and "low" of the distribution. Using this notation in the example given in Figure 2, the median is about $120,000; the 75th percentile and 25th percentile about $143,000 and $113,000 respectively; and the high and low values are $157,000 and $102,000 respectively.

Box and whisker plots have many advantages. The most important is economy of space and dimension. A simple one dimensional plot provides information regarding the location of the distribution (median), the dispersion (by the percentiles), and the skewness (by the distance from the upper to the lower percentile). Further, because it is one dimensional in nature several such diagrams can be placed side by side to facilitate visual comparison of various distributions on a single page of paper.

2.3 Modified Delphi Technique

The presentation of the data in a spatially compact manner is critical to the structured evaluation of proposals by the SEB, since it will form the basis for making judgments about the relative bidder costs estimated in each proposal and will illuminate areas for further inquiry. Such judgments on the part of the SEB are a natural and essential part of the evaluation process, and are necessary to achieve a balanced consensus for decision-making.

The process of evaluation and choice as structured in this methodology requires several successive iterations of judgment by SEB members as they are presented with graphical displays of information on individual bidder's estimates, aggregate bidders' estimates, outside experts' estimates, and the estimates of other SEB members. After reviewing each graphical display, the SEB members have the opportunity to acquire additional information, alter their opinions, and change their own estimates, if appropriate.

For example, Figure 3 shows one of the exhibits that will be prepared for each SEB member.

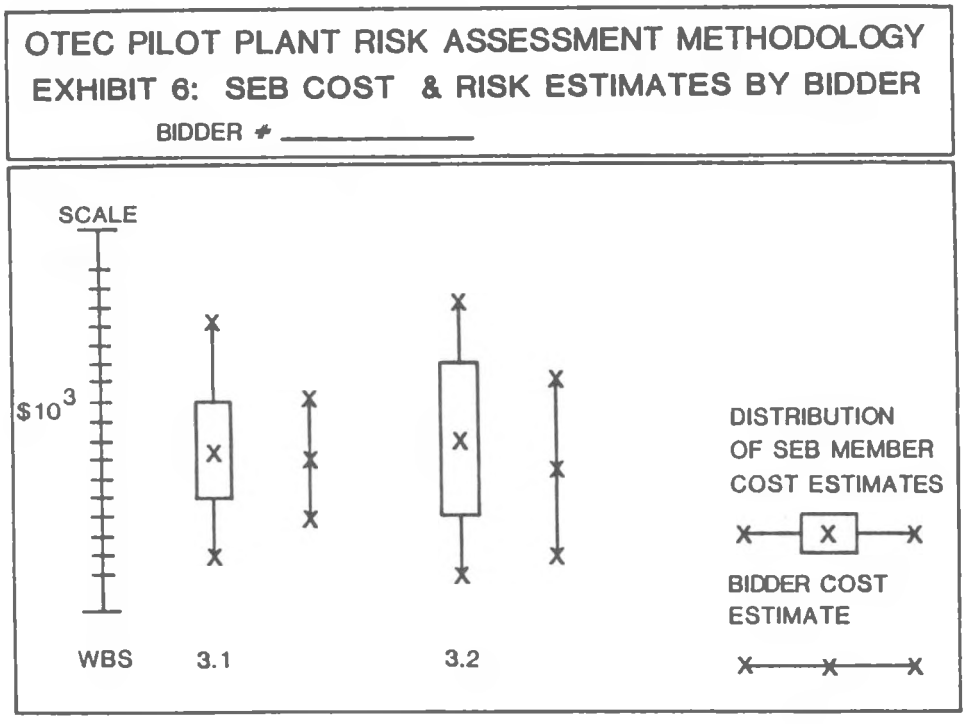


Figure 3

Figure 3 compares a bidder's cost estimate for each OTEC Pilot Plant WBS aggregation level with the aggregated estimates for the SEB as a whole. An individual SEB member may then compare his estimates with those developed by his colleagues to determine the level of disagreement that exists in the group. Technical discussions on specific issues will then occur and opinions can be altered as the individual SEB members deem necessary. In total, the methodology provides for six alternative types of graphical information displays to stimulate discussion and assist in consensus formation. As required, the process can be repeated to update the displays as the group's opinion evolves. However, modifications to the standard Delphi technique are incorporated into this methodology because of the nature of the SEB

evaluation process. The principal modifications include the use of computer printouts to generate topics for discussion in place of a moderator, and the need to allow the SEB members to resolve differences verbally among themselves in the event a consensus cannot be attained through the evaluation process. Further, the need to reach a decision necessitates that a procedure be included to assign a risk measure in the event that agreement cannot be reached any other way.

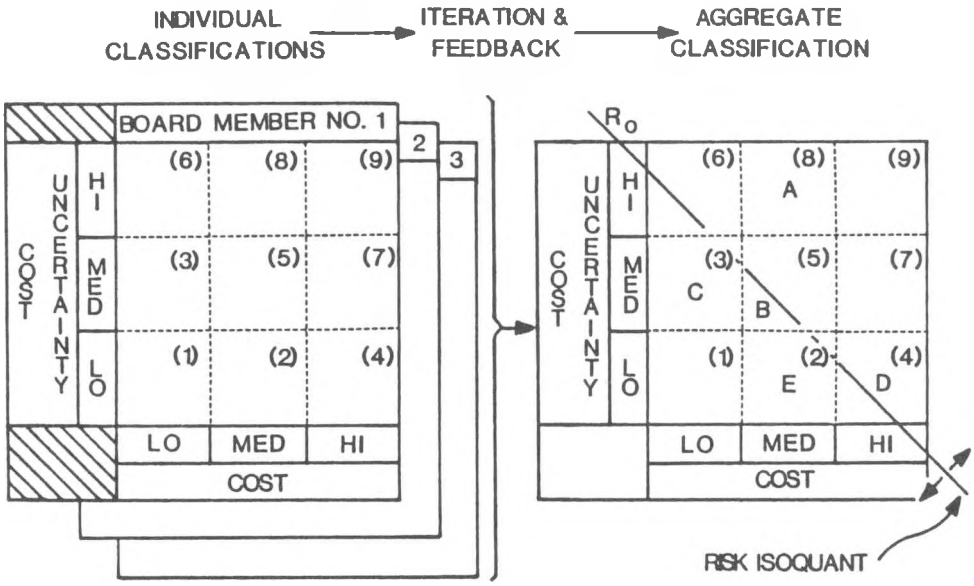
3. EVALUATION AND CHOICE

The information displays discussed above facilitate three types of evaluations by SEB members: 1) comparisons among alternative proposals, 2) comparisons of proposal data with SEB - generated estimates, and 3) comparison of individual and aggregate SEB estimates. These comparisons are repeated at higher levels of aggregation of the Pilot Plant WBS. Completion of this phase of the risk assessment procedure lays the foundation for the final classification of alternatives according to relative degree of risk.

The aim of the risk assessment classification is to discriminate among alternative proposals in terms of their relative cost and degree of cost uncertainty. In devising a classification scheme, it must be recognized that since multiple proposals will be selected for award there is no requirement either to assign specific numerical scores to each proposal or to develop a preference ranking of all proposals. Instead, it is sufficient that the classification scheme provide a means of assigning proposals to various categories for which clear distinctions of the relative degree of risk can be made. Figure 4 shows one such classification scheme.

The classification scheme consists of a three-by-three matrix with each cell representing a category of system costliness and degree of cost uncertainty. In the numbering scheme shown in Figure 4, cell 1 represents the lowest risk region and cell 9 represents the highest risk region. In between these two extremes lie seven other combinations. In this phase of the risk assessment process each SEB member would assign each proposal to one of the cells of the matrix. An "average" classification of proposals is then computed and displayed to all SEB members, who subsequently reclassify. This procedure is iterated several times until the dispersion of the average classification is reduced to a pre-determined level or until the number of iterations reaches a pre-established limit. It is through this modified Delphi procedure that outliers in individual judgment are removed and a consensus is established.

Once a consensus classification is reached, the final step in the risk assessment process is to select from among the proposals. Several alternative approaches exist. One approach would be to devise an ordinal scoring scale and correlate it to the classification structure. Thus, using the numbering scheme shown on Figure 4, proposals in cell 1 might receive nine "points" and those in cell 9 would be scored zero "points". Another method which is especially appropriate for the selection of multiple proposals is to define risk "isoquants" and superimpose them on the classification matrix. Thus, as depicted in Figure 4, proposals below and to the left of the maximum acceptance risk threshold (R_O) would be selected while those above and to the right would be rejected. This selected criteria



RISK CLASSIFICATION SCHEME

Figure 4

could be altered (i.e., moved in both directions along a 45° line extending from the lower left-hand corner of the matrix) to include a greater or lesser number of proposals.

4. SUMMARY

The methodology described in this paper represents an attempt to establish risk assessment as a formal part of the management decision-making process in designing and developing a commercial-scale OTEC Pilot Plant. The procedures described in this effort provide the means to improve the credibility and defensibility of the risk assessment process, which heretofore has remained a largely non-scientific and subjective discipline. In an era of tight budgets and close public scrutiny of government R&D management practices, the refinement of risk assessment approaches for high technology programs like OTEC becomes a necessity.

The preliminary design effort for which this methodology was devised represents the first step toward construction and operation of an OTEC Pilot Plant. As the design effort proceeds, more data of better quality related to OTEC costs, schedule, and technical design parameters will become available. As such, the risk assessment methodology outlined herein can serve as the baseline for more refined risk assessment procedures in the later stages of the development cycle. In this way, as the band of cost uncertainty is narrowed, OTEC program management can be provided with better information on which to make key decisions affecting system cost and performance.

REFERENCES

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2. Tukey, John, Exploratory Data Analysis, Addison-Wesley, 1977.

8th Ocean Energy Conference
Washington, DC
June 1981

THE OTEC UTILITY USERS COUNCIL 2000 A.D. MARKET

Jose Marina, Richard E. Bell, John R. Ridgeway & James Crews

OTEC UTILITY USERS COUNCIL

SUMMARY

The OTEC Utility Users Council representing majority of the potential Electric Power Utility wners or user of OTEC plants or electricity, have concensus forecast that shows their systems could wn some 3,500-5,700 Megawatts of OTEC plants and urchase 10,000 Megawatts of OTEC Electric Power in he year 2000 A.D., for a total of 13,500 to 15,700 egawatts. Critical to realizing this extensive se of OTEC, is an early commercial demonstration of OTEC electric power generation. Creative financing concepts and supportive rate environment are also essential. Three of the council members are participating in the DOE OTEC Pilot Plant Program.

The OTEC Utility Users Council was formed several years ago to provide inputs to the DOE OTEC Program from the Electric Power Utility industry. The membership includes the majority of the princi ›al utility companies who are potential owners or ›uyers of the first commercial OTEC plants and electric power. As OTEC moves toward realization, the utility companies, as the most likely first owners of OTEC plants, have an increasing interest in the OTEC Program. As future owners, they will be setting the criteria for their plants and their system integration.

The Council, while maintaining a conservative view of OTEC in the year 2000, has identified a significant utility market and does believe that OTEC is a viable alternate energy base load electric power source. Our systems, needs, policies, and locations vary and are reflected in our various perceptions of our individual uses of OTEC. The Council does not represent all the suppliers of electric power in our regions nor do we represent the large adjacent tier of states just to the north of our Gulf Coast service areas. While each island utility can speak for the total system for the group of islands, they can also offer an understanding and an interface for other islands in the Caribbean and the Pacific who are potential candidates for OTEC power. Thus, while our forecast is encouraging, it represents part of a much larger market that has yet to be heard from.

It is important to understand that the Council represents the actual utilities who will be involved, not someone studying or surveying the utilities. Our concerns for financing, performance criteria and the size of the market are based on today's reality and our future plans.

COUNCIL MEMBERS

The Council is chartered to include all the United States Power Utilities who will most probably be the owners of OTEC electric power plants, either on land, fixed on offshore platforms, or sited as moored floating plants connected to the shore by a power cable. As you might anticipate, we include the Gulf of Mexico area of southeast United States, the U. S. Atlantic islands and our Pacific Islands. These regions are shown in Figures 1, 2 and 3. Our membership:

HAWAIIAN ELECTRIC COMPANY	Honolulu, Hawaii
PUERTO RICO ELECTRIC POWER AUTHORITY	San Juan, Puerto Rico
KEY WEST CITY ELECTRIC SYSTEM	Key West, Florida
FLORIDA POWER CORPORATION	St. Petersburg, Florida
FLORIDA POWER AND LIGHT	Miami, Florida
SOUTHERN COMPANY SERVICES	Birmingham, Alabama
MIDDLE SOUTH SERVICES	New Orleans, Louisiana
GULF STATES UTILITIES COMPANY	Beaumont, Texas
HOUSTON LIGHTING & POWER COMPANY	Houston, Texas
CENTRAL POWER & LIGHT	Corpus Christi, Texas
ELECTRIC POWER RESEARCH INSTITUTE	Palo Alto, California

FIGURE 4

United Engineers and Constructors Inc. is our support contractor.

It is our hope that several other utilities will join us, perhaps at this conference. They are the Electric Power Companies of the Virgin Islands and Guam.

THE 2000 AD OTEC UTILITY MARKET

The Council has been making an initial survey of what they might be able to forecast twenty years from now (2000 AD) in terms of their use of OTEC electric power. A general concensus on the size and nature of the market has been obtained on a "bottom up" basis. The market is a probable one



FIGURE 1 OTEC UTILITY USERS COUNCIL

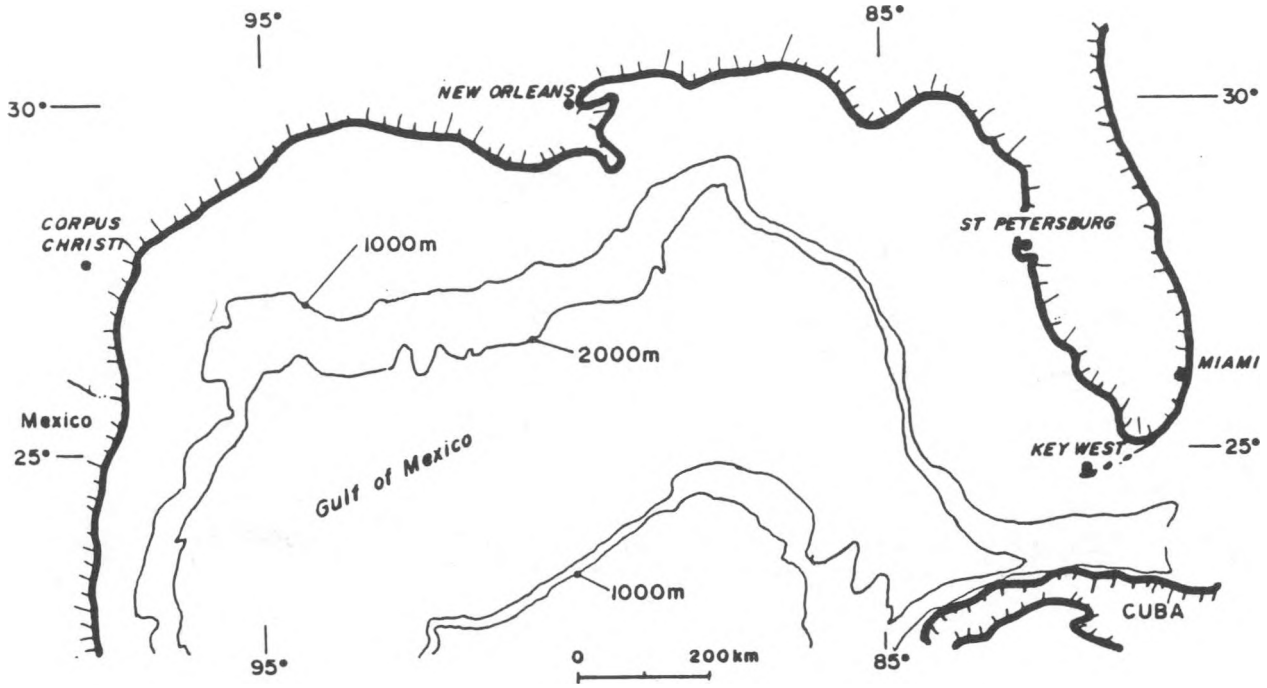


FIGURE 2 GULF OF MEXICO OCEAN THERMAL RESOURCES

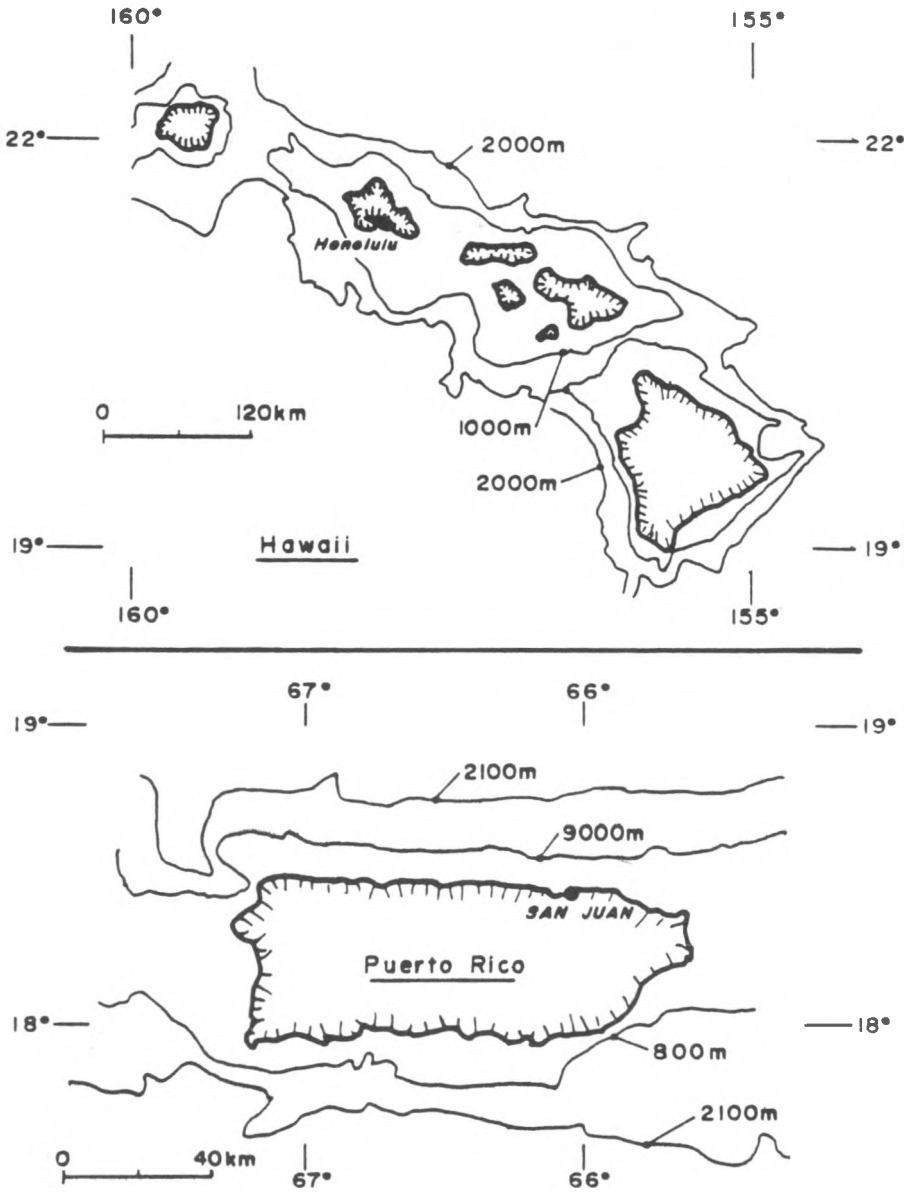


FIGURE 3 HAWAII AND PUERTO RICO OCEAN THERMAL RESOURCES

based on all that is known today. Many factors and circumstances can change or develop in the next twenty years of our planet's energy transition era. Several associated concerns are covered later in my remarks.

The Market is summarized in Figure 5. We should add the United States island territories to our market areas. What is most significant is the OTEC Demand Forecast of some 13,500 to 15,700 megawatts of OTEC generated electricity by the year 2000 A.D. Again, this does not represent all of the electric power utilities adjacent to the Gulf of Mexico, the adjacent inland electric power markets nor the island territories.

THE 2000 AD OTEC UTILITY MARKET

- o THREE MARKETS
  - Hawaii
  - Puerto Rico
  - Southeast U. S.
- o FACTORS
  - Competing Fuels and Policies
  - Market Size and Characteristics
  - Closeness of Ocean Thermal Resource
- o MARKET DEMAND FORECAST
  - Utility Generated OTEC Electric Power 3500 - 5700 Megawatts per year
  - Utility Purchased OTEC Electric Power 10,000 Megawatts per year

Figure 5

The estimate of some 3500 to 5700 megawatts of utility-owned plants includes plants in Puerto Rico, Hawaii and parts of one or more utility systems along the Gulf of Mexico. This market could certainly increase as the demands for electric increase, the cost of OTEC power plants is reduced, more favorable financial conditions develop, commercial OTEC technology is demonstrated,and,buyer confidence generated. This forecast includes consideration of reliance on other fuels than oil as a primary fuel of several utilities. Coal will be increasingly utilized by the utilities of the south east to displace oil. The Puerto Rico Electric Power Authority has just signed a contract to design their first coal fired power plant (300 MW).

PLANT OWNERSHIP

One of the principal challenges facing OTEC is that of a larger than usual capital cost which increases the problems of financing at the beginning of the life of the plant. This is a problem facing owners who are considering purchase of very large conventional electric power plants today. Utility companies have, in general, a tradition of owning their own generating capability and would probably still have that intention twenty years from now. Ownership by utility consortiums or third parties may become a trend for all large facility acquisitions including OTEC plants. This general problem of ownership which is being recognized today has not been studied in sufficient depth to identify with any certainty or detail ownership approaches which might apply in the near and mid-term future. This area is included as one that the DOE OTEC program should develop in greater detail working with the civil sector owners and financiers.

OTEC presents a particular anomaly whose solution could go far towards accellerating the financing of OTEC commercial plants. The total life cycle cost of an OTEC electric power generating plant including fuel or its absence, is much less than the life cycle cost of an oil fired power plant today or in the future. Today, fuel is paid for as it is used and adjustments made (always upward) by fuel adjustment charges. In a sense, the financed cost of an OTEC plant includes a "fuel conservation charge" which is much less than any predictable fuel cost. A guarantee of a very low equivalent fuel cost ten to thirty years ahead of time. "Creative" financing, rate making and regulatory policy supporting the advantages of life cycle costing could be used to encourage the acquisition of OTEC plants. This is another ownership related task for the consideration by the OTEC Program. Figure 6 highlights these points.

OTEC PLANT OWNERSHIP

- o FRONT END COST vs LIFE CYCLE COST
- o UTILITY OWNERSHIP
  - Turnkey Purchase
- o JOINT OWNERSHIP
- o THIRD PARTY OWNERSHIP
  - Sell Power
  - Lease Facility

Figure 6

FUEL TRENDS

The varied nature of our Utility Council reflects a mixed future fuel use which in turn has an effect on OTEC especially if avoided electric power costing is involved. Figure 7 gives a summary of these trends. The smaller utilities and islands may continue using oil at higher prices but eventually should find OTEC plants cost effective. Our future cost of fuels vary considerably due to experience and perception. The varying supply and pricing of oil over the last few years only emphasizes the uncertainty of

predicting the rate of growth of oil prices.

FUEL TRENDS

PUERTO RICO - Oil; Coal Fueled Generation 1987 OTEC Plants as soon as available; Some wind.

HAWAII - Oil; Geothermal; OTEC; with Wind and Biomass Fuel Power as available.

GULF OF MEXICO - Nuclear, Coal, Gas and Oil;
SOUTHEAST U.S. Growing Plans for Coal Fired Plants replacing oil; gas as long as it is available;
OTEC - Both plant purchase and electric power purchases.

FIGURE 7

OTEC COMMERCIAL CRITERIA

The electric power utilities have developed over many years general standards of performance for our conventionally fueled electric power generating plants. Much of this body of experience applies to OTEC power plants primarily from utility system operations' needs and from economic costing of the product. The location of OTEC plants in the ocean environment present anaddditional set of operating factors that have to be considered. A trade-off of cost against changes to current utility plant performance criteria has to be made before the first commercial plants go into their final design phases. A number of commercial criteria considerations have been discussed. Some of them are noted in Figure 8. They are not final nor complete. The Council will be addressing this question in the future and encourages DOE and other concerned organizations to contribute to a set of acceptable criteria as an input to the final design of the first commercial OTEC power plant. It would be very desirable to have such a set of criteria established in time for the final design of the Pilot Plant demonstration.

OTEC COMMERCIAL CRITERIA CONCERNS

Demonstrated 80% Availability or Better

Operated at Least One Year by a Utility
- Utility Operating Staff
- Utility Operating Requirements and Procedures

Demonstrated Acceptable Operating and Maintenance Costs

Demonstrated Environmental Compatibility
-General and Site Specific
-Biofouling System Effective and Environmentally Acceptable

Operated Successfully under a Representative Range of Sea Conditions

FIGURE 8

PILOT PLANT PROGRAM PARTICIPATION

Several of our Council Members are active participants in the current DOE Pilot Plant Program. You are undoubtedly acquainted with the organizations who have proposed in response to the DOE OTEC Pilot Plant Program Opportunity Notice. Figure 9 outlines the type of plant and utility involved in the Pilot Plant Procurement. As potential Council members, we should also recognize both the Virgin Islands Electric Power Company and the Guam Electric Power Company as participants each with one OTEC Pilot Plant. The utility industry is involved with OTEC and cost sharing in the Pilot Plant acquisition. We cannot provide details of our proposed facilities since the procurement is still in competitive evaluation. We hope all the proposals will go forward and that this first commercial size OTEC Project will be followed through and result in a series of successful demonstrations.

OTEC PILOT PLANTS
AND
THE UTILITY USERS COUNCIL

FLORIDA Key West - Floater
Florida OTEC Consortium - Key West City Electric

HAWAII Oahu - Land/Shelf Platform/Grazer
Hawaiian Electric Company

PUERTO RICO Punta Tuna - Shelf Platform/Floater
Puerto Rico Electric Power Authority

FIGURE 9

THE OTEC PROGRAM

As you may have noted in my earlier remarks there are a number of areas that the Council believes should be given more emphasis in the DOE OTEC program. A major concern is the development of innovative financing and regulatory approaches for the first commercial OTEC plants. Inherent in these approaches is the identification of more attractive ownership options. This work should be a part of these early phases of the OTEC Pilot Plant Program so that financial and regulatory obstacles to moving forward with a commercial Pilot Plant are avoided. Such an effort would greatly accelerate the expansion of the OTEC Program beyond the first pilot plant.

Figure 10 gives several of the objectives the Council sees as essential to the OTEC Program. Until there is a demonstration of an acceptable minimum size commercial OTEC Plant, OTEC will not be credible to the financial community nor to the utility managements who are responsible for plant purchases. An early OTEC demonstration must have first priority and support.

THE OTEC PROGRAM

- Demonstration of a Minimum Size Commercial OTEC Electric Power Plant is essential.
- Stronger Development of Commercial Plant Financing and Ownership Options is required.
- U. S. Utilities want to buy American Plants and Equipment - Build on the U. S. OTEC Leadership. DON'T LOSE THE RACE!
- Open Cycle OTEC should be demonstrated.

FIGURE 10

All of the OTEC Program participants have worked to put the United States in a leadership position with regard to OTEC technology. It is important to capitalize on this start and have the United States producing and buying OTEC plants. A strong production capability will also contribute a large export balance. Our support of third world tropical countries with U. S. produced OTEC plants and products is certainly a positive contribution to both our business and our diplomatic interests.

IN SUMMARY

The OTEC Utility Users Council sees a large market within their own utility service areas. We will be buying OTEC power plants in the next twenty years. If our Councils' survey of the OTEC market is to be met, the OTEC Development Program and the first OTEC commercial demonstration must be accelerated. All the benefits ascribed to OTEC are just fiction until the technology is demonstrated. We are supporting OTEC and hope that OTEC will be an important part of our systems' generating capabilities even before 2000 A.D.

8th Ocean Energy Conference
Washington, DC
June 1981

THE OTEC PERSONNEL CONSIDERATION

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ABSTRACT

Operating procedures for Ocean Thermal Energy Conversion (OTEC) plants is one of several entirely new areas that need consideration prior to the development of an OTEC industry. One large aspect of this area is the plant manning requirements. This paper addresses the manning question in terms of personnel training, operator licensing, and labor considerations.

Manning estimates are made based on the engineering requirements for the different prototype concepts under consideration by the consortia involved in OTEC development. The concepts studied include barges, spars, shelf-based towers, and land-based plants. In addition to engineering requirements, the labor mix chosen depends on the education level desired and available. Also, different plant concepts will have different support requirements; support personnel are included in the personnel estimates.

Licensing procedures and education requirements used by state agencies for stationary power plants and by the U.S. Coast Guard for the merchant marine are compared with the guidelines now under consideration by NOAA and USCG. Minimum criteria for personnel currently anticipated by plant operators are examined here.

Training programs for both immediate, plant-specific instruction and for long term secondary education are discussed. Included here is an evaluation of simulators to increase operator proficiency and plant safety. A college program is outlined that would give graduates the requisite abilities to work effectively in the OTEC environment.

A functioning organizational structure and job fulfillment are also essential components to the successful commercialization of the OTEC concept. Having studied the optimum labor mix for plant operation, the paper describes the living environment needed to attract the people necessary to run such a complex floating island. Working shift lengths are evaluated as are the domestic and recreational requirements. Similes are drawn from oil rigs and the merchant marine.

1. THE PROTOTYPE COMPLEMENT

A wide variety of OTEC plant prototype designs were submitted in response to DOE's Program Opportunity Notice (PON) in January 1981. The particular complement for each prototype varies with the plant's design. Those plants engaged in grazing for power generation require a higher personnel complement to fulfill navigation and position-keeping demands. The occupational requirements also vary with plant design. Energy intensive plant operation, for example, requires manufacturing personnel that are well-versed in the processes employed. Finally, support requirements vary widely depending on the OTEC plants' distance from shore. To effectively understand the broad spectrum of personnel requirements, industry estimates for four different prototypes are presented in the following sections. To begin with, though, a brief introduction to manning in conventional land-based power plants is provided.

1.1 Conventional Land-Based Power Plants

Current manning requirements for the four basic power sources used by Virginia Electric Power Company are shown in Table 1.

It should be noted that a large part of the people employed at the nuclear power plant are auxiliaries including security guards and health inspectors. The plant itself is highly automated. The unmanned hydroelectric plant is controlled by telemetry from its downstream sister plant.

1.2 Barge-Based Plants

In a barge-based OTEC plant there are actually two cases to be considered: moored and grazing. The Applied Physics Lab (APL) performed manning studies for both these cases. The moored case considered a barge moored close to shore off Puerto Rico. The grazing version included energy intensive ammonia production. The procedure APL followed in developing their estimates was first to examine Merchant Marine manning requirements. These requirements were modified after considering the power plant requirements and current OTEC-1 employment. This initial estimate was reviewed by a naval architect and, for the grazer, by an ammonia plant operator. The final requirements for the grazer for one shift are shown in Table II. The average salary for this force is $40,600. Notice that this industrial manning takes advantage

of "double hatting," i.e., having people capable of two or more jobs each.

There are several differences in personnel requirements between the moored and grazing versions. The moored version would use 3 shifts of ten people each for a total of 30 people. The grazing version would use two shifts of 12 hours with 23 people per each shift for a total of 46 people. Crews would be changed every 28 days.

Estimates for larger barges were also made. For a single shift, a 325 MW plant would use 39 people. A different estimating technique based on percents of Operation & Maintenance costs which in turn is a percent of Capital Costs gave a manning requirement of 60 people for the same 325 MW plant.

1.3 40MW Spar Type (Moored)

The conceptual design submitted to DOE by Gibbs & Cox, Inc. is to be tensioned-moored at a site several miles northeast of Punta Tuna, Puerto Rico.[2] Because it will remain stationary, the only navigational system requirements are those necessary to warn other craft of the location of the plant. In addition, the plant will utilize surface scanning radar to warn the plant or shift supervisor of possible collision situations. The crew complement, therefore, includes only those people necessary to effectively operate the OTEC generating plant and the various support personnel. A listing of these occupations is presented in Table III.

1.4 Shelf-Based Tower

The shelf-based tower presents an entirely different personnel requirement. Because of its proximity to shore, the shelf-based plant may be manned by markedly fewer personnel. Plant operational assistance will come mainly from the onshore support facility. Conceivably, the plant could be operated remotely by telemetry with personal visits occurring only during control procedures or abnormal situations. The energy systems program department of General Electric Company has submitted a prototype for consideration involving this shelf-based concept. Although extensive occupational planning has not taken place, preliminary estimates reveal that the plant could be operated with 3 men per shift. If this is to be feasible, the industrial practice of "double-hatting" to obtain men with dual-field experience may be necessary.

Abasco Inc. has also been involved with a shelf-based plant prototype to be build off St. Croix. This plant would require five watch-standers with a total support complement of 6 workers. These personnel would work on rotational 8 hour watches, walking to and from the plant via a bridge connecting it to shore.

1.5 Land-Based OTEC Plants

Several land based options are now under consideration for power generation. Those involved

Table I Land-based Manning Requirements

POWER SOURCE	YEAR OF CONSTRUCTION	SIZE(MW)	NO.OF UNITS	NO. OF EMPLOYEES
Coal	1950, 58	236	2	92
	1956, 66, 73	1057	3	257
Hydro	1961	100	4	27
	1963	225	4	Unmanned
Nuclear	1978, 80	1700	2	385
Oil	1969, 70	2044	3	180

Table II Grazing Energy -Intensive Barge Manning Requirements

Ship Crew		OTEC Systems Operation	
Position	# of People	Position	# of People
Master	1*	Proj. Manager	1*
Officers	3	Oceanographer	1
Bridge Watch	3	Eng. Turbine/Pump	1*
Deck Crew	0	Eng. Ammonia	1*
Chief Eng.	1	Control Systems	1*
Engineer	2*		
Cooks & Stewards	4		
Radio	1*		
Total	15	Total	1

* indicates double hatting

Table III Spar Manning Requirements

	Men Per Shift	No. of Shifts	Total	Type of Accommodation
Plant Supervisor	1	1	1	Private
Shift Supervisor	1	2	2	Private
Control Room	2	3	6	2 Man ER
Roving	1	3	3	2 Man ER
Deckhand (AB)	1	3	3	2 Man ER
Clerk	2	1	2	2 Man ER
Mech. Foreman	1	1	1	Semi-Private*
Elec. Foreman	1	1	1	Semi-Private*
Instru. Foreman	1	1	1	Semi-Private*
Mechanic	2	1	2	2 Man ER
Electrician	2	1	2	2 Man ER
Instru. Specialist	4	1	4	2 Man ER
Cook	2	1	2	2 Man ER
Messman	2	1	2	2 Man ER
Repair/Janitor	2	1	2	2 Man ER
Misc. & Transient			17	2 Man ER
Total			51	

* Private stateroom, shared sanitary facilities.

with this prototype at Abasco Inc. say these plants are to be modeled after conventional power plants in many facets, including manning. The organizational structure will most likely reflect the operating company's existing utility hierarchy, with the exception of the support complement. The support personnel will include divers and others concerned with the C.W.P. component function. Due to the similarities existing between conventional utility plants and an OTEC land-based operation, manning this type of plant would present the fewest complexities.

1.6 Conspectus

A comparison of the relative numbers of people needed for the three personnel areas of navigation, power generation, and support is given in Table IV for each of the four prototypes studied. Despite the diverse functions to which the OTEC concept will be applied, the operation of the basic power cycle will require a basic set of workers; this set consists of a plant supervisor, his associated shift supervisors, and a set of staff engineers. This arrangement reflects the structure currently required by the U.S.C.G. for merchant shipping, the amount of automation being considered, and automations' concommitant personnel educational level. A plant supervisor would assume duties similar to that of maritime chief engineer while the shift supervisor would stand watches similar to those of the assistant engineers. Staff engineers would actually run the plant from the control room. Because of the expected broad implementation of this supervisory labor mix, the occupational requirements for these positions shall be examined further.

Table IV Relative Prototype Manning Needs

	40MWe Spar	Shelf-Based	Land-Based	Barge
Support	High	Med.	Low	High
Navigation	Med.	None	None	High
Power	Med.	Med.	Med.	Med.

2. LICENSING

The National Oceanographic and Atmospheric Administration (NOAA) and the United States Coast Guard (USCG) were tasked under public law 96-320 (Ocean Thermal Energy Conversion Act) with developing licensing procedures for OTEC plants and OTEC plant personnel. The OTEC industry appears to fall between two extremes delimited on one hand by offshore oil rigs and conventional power plants which require no operator's licenses and delimited on the other hand by the merchant marine and the nuclear power industry, both of which have strict licensing procedures. The Coast Guard currently anticipates that OTEC plant operators will not be required to obtain any sort of official operator's license. However, the Coast Guard is retaining the right to require approval of the total manning level.

Some type of license internal to the industry is, however, desirable. Insurance companies will most likely require a certification of knowledge and responsibility of the prople operating the OTEC plant before they will insure the OTEC plant. Utilities have, of course, minimum hiring criteria for many jobs; OTEC engineers and operators are no different. In light of these facts we outline below some minimum job requirements for the general categories of senior operator, shift supervisor, control room operator, and staff engineer. These requirements are based on those found in the nuclear power industry as prescribed by the NRC.

Senior Operator: 4 years reponsible power plant operation (maximum of 2 years can be fulfilled by academic or related technical training);
shall have had operator's license for 1 year; at least 2 years experience at an OTEC plant (6 months at same plant for which he seeks license);
100 hours simulator training;
engineering degree;
pass a written examination (9 hours).

Shift Supervisor: 4 years experience power plant operation (maximum of 2 years can be fulfilled by academic or related technical training);
at least 2 years experience at an OTEC plant;
80 hours simulator training;
3 months training as extra man on shift;
engineering degree;
pass a written and oral examination (6 hours)

Control Room Operator: associate degree (technical); 80 hours simulator training;
1 year power plant experience;
pass a written and oral examination (4 hours).

Staff Engineer: associate degree (technical);
40 hours simulator training.

3. TRAINING

3.1 Short Term Plant-Specific Training

The engineers running the OTEC plant will, of course, have to be given appropriate training. The method for providing their training can have important effects on the operating and maintenance (O&M) costs of the OTEC plant. A report by the Rand Corporation developed for the DOE in May 1980[3] shows that the cost of electricity is highly sensitive to plant availability (Figure 1). The more time the plant is actually producing electricity, the cheaper the electricity. Proper training methods use less plant time, reduce plant down time, mitigate damage effects and reduce the time necessary for control procedures, thus increasing plant availability and thereby decreasing the cost of the generated electricity.

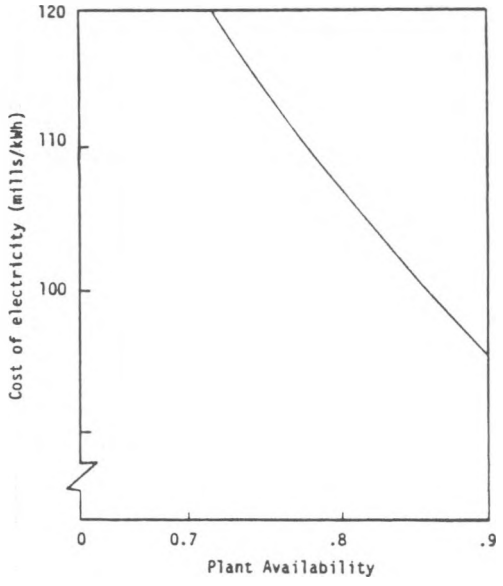


Figure 1 COE vs. Plant Availability

Currently, high-technology capital-intensive industries that require a high level of operator competence to protect their equipment use simulators to train their employees. These industries include shipping and aviation as well as the nuclear power industry where the training problems are more comparable to those faced by OTEC operators. The term, power plant simulator, refers to an exact replica of a power plant control room in which all displays, indicators and alarms are controlled by dynamic computer models of the plant processes. A simulator is interactive and runs in real-time, allowing an operator to take any action available in the repertoire of OTEC plant control procedures and then to observe the plant responses as they would appear on the instrumentation. This realism, combined with the ability to simulate emergency or abnormal conditions, has made simulators a valuable training tool.

Ten years experience in training both conventional and nuclear power plant operators has made apparent the wide range of benefits that accrue from using training simulators. In addition to entry level training, training benefits include extending the operator's capabilities and assisting them in plant operation. For this benefit, the ability to simulate malfunctions is important, and training to handle emergency conditions supplants much of the normal-procedure training of the first phase. Simulator realism provides high stress test situations giving operators experience in handling emergencies. As another benefit, operators can use the OTEC simulators to rehearse procedures covering routine but infrequently or sporadically performed control maneuvers. Moreover, assuming that licensing requirements will mandate periodic upgrading of operators' skills, simulators are the ideal retraining tool.

In addition to initial training and periodic requalification, simulators can provide benefits prior to plant operation. Through the built-in malfunction capabilities, simulators allow operational testing of the plant in ways that are impractical on the demonstration units. More specifically, simulators can be used to verify the integrity of the plant in situations where more than one malfunction occurs simultaneously, such as the deluge system failing during an ammonia leak. Also, simulators can be used as an operating-procedure test and development tool.

The uses enumerated above result in direct cost savings in three specific area. First is the area of replacing on-the-job training with simulator training. Since the simulator can jump from one plant condition to another, training time is shortened and training costs are reduced. A study performed by the U.S. Army Research Institute in May 1979 (#1209) showed training time is cut in half (.48).4 Also training capitalization costs are much less: it costs less to rent (build and operate a simulator) than it does to rent (reduce electric generation) an OTEC power plant. It was discovered from studies involving the airline industry, the Coast Guard, and the Air Force, that simulator costs could be recovered in 0.75-2.0 years even when considering only savings from equipment operation and investment.

Second, regarding plant availability, the plant can be devoted exclusively to power generation instead of going through less than full power manipulations solely for training purposes. Availability is further increased by improving plant operating efficiency. Practice on training simulators reduces the time required to perform plant control maneuvers. Also, operational experience with malfunctions on a simulator allows operators to recognize and correct abnormal conditions before they turn into major problems. Even new operators can run an OTEC plant efficiently because of their simulator experience.

The final area where cost savings occur is through a reduction of plant equipment costs. The familiarity imparted to operators of the various failure modes of the plant tends to mitigate the equipment damage resulting from malfunctions or accidents. Faulty design changes can be corrected before they are installed in the plant. Even during normal operations, the superior training provided by simulators can reduce the amount of wear and tear the equipment suffers. Again, according to the Rand Co., the cost element subject to the greatest degree of uncertainty is plant O&M costs. A reduction in O&M costs would reduce the level of uncertainty faced by an OTEC developer.

All these cost benefits are summed up in a power plant study done in 1979 by D. W. Latham (Tables V & VI).[5] First year savings for a power plant are $7 million. Annually recurring benefits after the initial year are $2.5 million.

Table V Nuclear Plant Simulator Benefits

A	Initial Training	$ 564,000
B	Refresher Training	$ 121,800
C	Training of Hot License Candidates	$ 527,400
D	Licensing Examination on the Simulator	-0-
E	Requalification Training	$ 417,788*
F	Replacement Training	$ 194,259*
G	Checkout of Procedures	$ 60,000
H	Decrease in Time to Full Power (Unit 1 only)	$ 6,400,000
I	Training of Other Plant Staffs	$ 87,750*
J	Increased Operator Reliability	$ 1,788,500*

* ANNUALLY OCCURING BENEFITS

Table VI Annual Benefits Nuclear Plant Simulator

YEAR*1	A, B & C	E	F	G&H	I	J	TOTAL
-2	564**	0	0	0	0	0	564
-1	122	0	0	60	0	0	182
0	527	0	0	6,400	0	0	6,927
1	0	0	97***	0	88	912	1,097
2	0	209***	194	0	88	1,788	2,279
3	0	418	194	0	88	1,788	2,488
4	0	418	194	0	88	1,788	2,488

* Relative to reactor core loading.
** Dollar Values are in thousands of 1979 dollars.
*** Applicable only to Unit I during first year of effect.

3.2 Long Term Post-Secondary Training

As the OTEC industry becomes established a pool of OTEC operators will need to be created. Originally the pool can be filled from land-based power plant operators and marine engineers. Eventually, however, colleges should develop an education program to train engineers in those skills necessary to run an OTEC plant. For instance, the program could be an option at an institution offering degrees in Marine or Ocean Engineering. Alternately it could be part of a program leading to an associate degree at any of the state universities. Conceivably it would consist of a set of five electives in addition to the basic engineering curriculum which would give the engineer more detailed study in thermodynamics, fluid dynamics, and power transmission techniques. Specific topics to be studied should include:

1. Basic Properties of Fluids and Matter. This section should cover a basic introduction to matter and its properties. This section should include such concepts as temperature measurements and effects, density and its effects, specific weight, buoyancy, viscosity and other properties of fluids. A working knowledge of ammonia tables should also be included. Energy movement should be discussed including such fundamentals as heat exchange, specific heat, and latent heat of vaporization.

2. Fluid Statics. This section should cover the pressure, temperature and volume effects on fluids Example of these parametric changes should be illustrated by the instructor and related calculations should be performed by the students and discussed in the training sessions. Causes and effects of pressure and temperature changes in the various components and systems should be discussed as applicable to the facility with particular emphasis on safety significant features. The characteristics of force and pressure, pressure in liquids at rest, principles of hydraulics, saturation pressure and temperature and subcooling should also be included.

3. Fluid Dynamics. This section should cover the flow of fluids and such concepts as Bernoulli's principle, energy in moving fluids, flow measure theory and devices and pressure losses due to friction and orificing. Other concepts and terms to be discussed in this section are kinetic energy, head-loss relationships and two phase flow fundamentals.

4. Heat Transfer by Condition, Convection and Radiation. This section should cover the fundamentals of heat transfer by conduction. The course should include discussions on such concepts and terms as specific heat, heat flux and atomic action.

In addition, the curriculum should cover the fundamentals of heat transfer by convection. Natural and forced circulation should be discussed as applicable to the various systems at the facility. The convection current patterns created by expanding fluids in a confined area should be included in this section. Heat transport and fluid flow reductions or stoppage should be discussed due to vapor and/or noncondensible gas formation during normal and accident conditions.

The fundamentals of heat transfer by thermal radiation in the form of radiant energy should be included. The electromagnetic energy emitted by a body as a result of its temperature should be discussed and illustrated by the use of equations and sample calculations. Comparisons should be

made of a black body absorber and a white body emitter.

5. Change of Phase - Boiling. This section should include descriptions of the state of matter, their inherent characteristics and thermodynamic properties such as enthalpy and entropy. Calculations should be performed involving steam quality and void fraction properties. The types of boiling should be discussed as applicable to the facility during normal evolutions and accident conditions.

4. ENVIRONMENT

The success of OTEC development has been linked to the availability of qualified personnel. The ability to attract a highly trained workforce will be enhanced by the reputation that the OTEC lifestyle develops in its first years of operation. It is imperative, therefore, that industry make the required investments to create an attractive environment from the beginning. This will avert the difficulties encountered by maritime and offshore industries who have had to contend with low morale and a high turnover of reputable personnel.

4.1 Leisure

In the last several years, maritime unions have been successful in their attempts to alter the occupational lifestyles of merchant marine workers. In the tanker area where the quick turn-around time and recent development of offshore loading technologies have precluded any recreational shore activities for crew members, pools, gymnasiums, and even tracks have been provided onboard. In addition, video cassette recorders offering popular movies have made their appearance in the U.S. Maritime Fleet. Computer games may be soon to follow. By providing diversions such as these, environmentally induced depression and subsequent effects such as alcoholism, erratic emotional response and poor job attitude are significantly diminished.

Figure 2 depicts the Gibbs & Cox plan to provide a crew movie theater and recreational area for their 40 MWe spar plant. Additionally, space should be provided for exercise equipment such as a universal gym or nautilus machine.

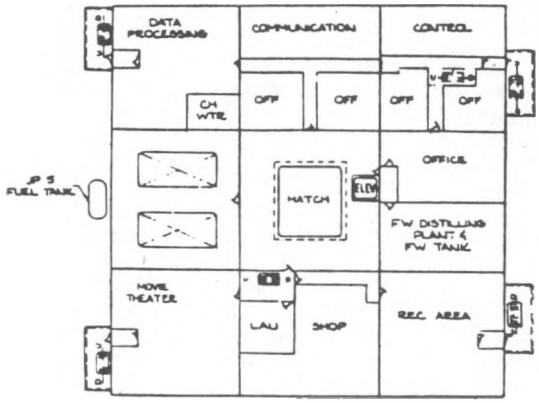


Figure 2 Spar Plant (01 Level)

4.2 Work

4.2.1 Shift Length

Creating the proper working environment will not only increase the retention rate of qualified personnel but will also improve job performance and safety records. One element to be considered in the development of this environment is the length of the working shift. A study done by the Office Of Merchant Marine Safety evaluated accident frequency as a function of the length of time on tour.[6] The results revealed that the number of accidents increased in the first to fourth hour on tour and fell off dramatically from the tenth to twelfth hour. This led the researchers to the conclusion that the length of tour had no bearing on accident frequency. Yet, between the seventh and tenth hour the number of accidents increased by 40% with workmen's compensation figures and 28% with the U.S. Coast Guard figures. In addition the offshore oil industry (which frequently uses the twelve hour work day) displays a fatality rate (55 deaths per 100,000) that is 511% above industry's average.

Although this is due in part to the dangerous nature of the industry, the report states that human factors accounted for 93% of all injuries. The study reports several times that attentiveness to duties could have prevented many of the mishaps. With these figures in mind, the most reasonable option for an OTEC operation would be to incorporate the 8 hour workday into the watchstanding schedule. This will ensure that the watchstander remains attentive to plant conditions; a requirement that is paramount in the monitoring of plant performance. The shift will end before the statistical jump in accident occurrence develops. The shorter shift will also feel less monotonous to the worker and this could be a major factor in personnel retention.

4.2.2 Operating Station

The design of the operating station should be geared towards simplicity and arranged to facilitate watchstander attentiveness. Human engineering research has produced much new thought in this area. For instance, to improve operator proficiency the concept of figural continuity has been applied to gaugeboards. S. G. Dashevsky performed research analyzing the effects of extending the line formed by gauge pointers when system performance is normal.[7] Any abnormal condition would create a break in the figural continuity of the dials. Using the extended displays, gauge reading performance improved by 85%. Figure 3 illustrates this concept.

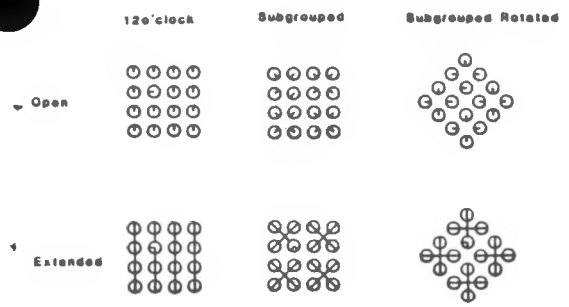


Figure 3 Figural Continuity

The use of cathode ray-tube (CRT) based control rooms in power plants has led to a gradual replacement of old fashioned gaugeboards at operator stations. The major advantage of these computer systems is that two or more plant performance characteristics can be read on the same screen. In a conventional control room these variables may have appeared on widely separated gauge meters. The CRT can also reduce manning requirements. The computer reports an alarm with a bell warning which will not stop until the operator has the correct display screen depicting the operating flow and has acknowledged the problem through various interlocks. Once the condition is corrected the computer will log the entire occurrence. The use of information displays greatly reduces the possibility of human error. The implementation of such a concept in the OTEC environment will set OTEC on a proper course from a safety standpoint.

4.3 Organizational Structure

A functioning organization structure is a key element in any plant operation. The power industry has a diverse occupational ladder, but a general pattern is readily discernable. White collar and professional employees make up approximately 10% of the work force. Plant supervisory foremen account for an additional 10% of the labor mix. The remaining employees follow a somewhat rigid structure of 6 steps from entry level to the foreman's position, which is usually achieved within six years.

Beacuse of the OTEC's heavy emphasis on automation and the nature of the system's operational requirements, the necessary work force will be smaller and encompass a significantly higher percentage of professional workers (as much as 50%). Due to the utilization of highly qualified personnel and the comparatively small work force needed, a rigid hierarchal structure can be replaced with a professional team concept where each worker's abilities are complimentary, generating a self-motivation atmosphere.

Another concept which will need to be implemented in the OTEC organizational framework is the principle of plant independence. This means that the plant supervisor is in charge of all plant operations with shore-side support management operating in an advisory mode. The implementation of this principle will allow the person with the most information available to make the major plant decisions.

5. SUMMARY

Despite the varying personnel requirements for the several OTEC prototypes, the core of plant operators for each OTEC plant will be similar: there will be a plant supervisor, several shift engineers, and the staff engineers. Because of the number of professionals being used in these power plants and because of the level of automation being considered, the OTEC island should substitute a self-motivating team atmosphere for the conventional hierarchal structure existing in the power industry. In order to attract the required talent in the workforce, the OTEC industry must invest in a desirable living environment. Also, a working environment which is conducive to plant and worker safety must be instituted.

The Coast Guard will not require operator licensing but industry will need to develop internal qualification criteria. The use of simulators could aid in standardizing operator skill levels. At the least, simulators will provide proper training and significant training, O&M, and plant availability benefits.

When appraising the manning needs for the OTEC industry it is imperative that past industry experience be explored in the analysis. It is just as important, however, that the OTEC industry develop it own identity in the area and create a synthesis of manning concepts to fulfill its requirements.

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OCEAN THERMAL ENERGY CONVERSION PLANT DYNAMIC SIMULATION MODELS

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ABSTRACT

Dynamic simulation models for Ocean Thermal Energy Conversion (OTEC) plants utilizing a closed Rankine power cycle have been developed. The models represent the conversion of energy from the thermal gradient in the ocean to electrical energy delivered to an electric bus on shore. The models are useful for the evaluation of plant dynamic performance, control and regulation. The dynamic performance of a 50 MW modular prototype plant to disturbances in ocean thermal and seastate disturbances and electric bus disturbances is evaluated.

INTRODUCTION

Ocean Thermal Energy Conversion (OTEC) can be accomplished with a closed Rankine cycle heat engine utilizing the thermal gradient in the ocean (1).* In the prototype plant considered warm (~80°F) surface seawater is used to evaporate and pressurize ammonia in a heat exchanger. The vapor is expanded through a turbine-generator to produce electric power and then condensed in a heat exchanger using cold seawater (~40°F) drawn from a depth of approximately 3000 ft. The low pressure liquid condensate is repressurized by a feedpump and returned to the evaporator to complete the cycle. The principal OTEC plant components are illustrated in Figure 1.

OTEC plants are planned primarily for baseload operation since the cost of fuel is low and the plant capital cost is relatively high. Thus, operating efficiency is an important factor in plant economic viability and a number of detailed studies have been conducted to design and optimize the principal components including the evaporator, condenser and turbine as described in references (2), (3) and (4).

One of the areas which must be addressed in OTEC plant development is plant control and operation when integrated into a utility grid. In the integration of a plant into a grid three control and operating conditions may be identified: (1) plant start-up and shut-down, (2) steady-state operating point optimization and (3) control and regulation at an operating point. In this paper dynamic models are described for determining OTEC plant control and regulation characteristics when subjected to ocean thermal or seastate disturbances and electrical grid disturbances.

The study summarized in this paper complements and extends earlier studies directed to plant dynamic performance as described in references (5), (6), (7) and (8).

OTEC PLANT DYNAMIC PERFORMANCE MODELS

In this study three basic lumped parameter physically based models of an OTEC plant are developed for evaluating dynamic performance. The models are developed for a fixed platform, closed Rankine cycle plant connected to a shore-based electric grid through AC lines and include:

(1) A highly detailed, nonlinear dynamic model which focuses on the turbine-generator, heat exchangers and pumps. The model is useful for the study and optimization of plant components.

(2) A reduced order linear model useful for studying stability and transient performance of the plant connected to a grid. This model is tailored for use in transient stability studies.

(3) An algebraic quasi-steady model useful for determining power availability as a function of seawater thermal changes. This model is useful for electrical load/flow studies and for developing optimized control systems for maximizing efficiency.

The reduced order linear model and the quasi-steady power availability model are derived from the general nonlinear model. A prototype plant with eight nominal 50 MW power modules sharing a single 3000 ft cold water pipe is considered as described in references (1) and (2). The plant consists of horizontal thin film shell and tube heat exchangers, a double-flow single stage axial turbine and seawater pumps driven by synchronous motors.

* Numbers in parenthesis refer to References listed at the end of the paper.

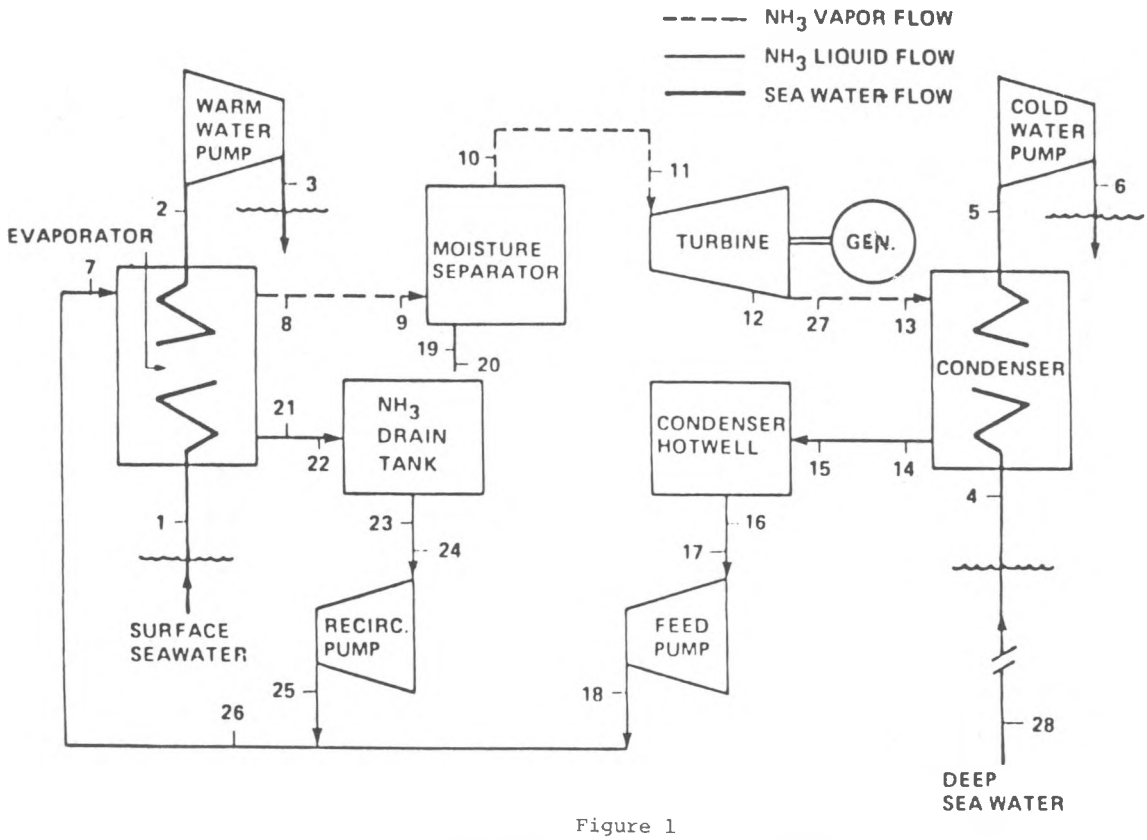


Figure 1

Detailed OTEC Power Cycle Schematic
(adapted from reference (1))

The detailed nonlinear model is described in reference (9). The model represents the major plant components as follows:

(1) The evaporator and condenser heat exchangers are represented in lumped parameter form. To achieve steady-state and dynamic representations with better than 5% accuracy, more than six axial lumps are required for each heat exchanger. In each heat exchanger lump, the vapor capacitance and a combined tube and water capacitance yield thermal state variables. For each lump, the local nonlinear heat transfer coefficient is utilized.

(2) The turbine is represented using the Stodola flow law with an efficiency which decreases at off design point operation. Turbine speed is a state variable.

(3) The main seawater pumps are represented with head/flow characteristics derived from Euler's equation coupled to synchronous motors represented with torque/slip curves. Pump speed and motor power angle are state variables.

(4) The cold water pipe is represented in terms of slug flow with inertance and resistance properties.

(5) The electrical generator is represented using classical power/slip relationships with power angle as a state variable.

(5) A finite length AC line with impedance properties is coupled to an infinite electrical bus on shore.

(7) The principal plant control is effected with a turbine bypass valve which is controlled with a speed governor which compares turbine speed with a set point speed to generate an error signal to modulate the bypass valve.

The nonlinear model has been incorporated into a modular digital computer simulation program which provides the capability to evaluate the influence of seastate and ocean thermal disturbances as well as electrical disturbances on the plant performance.

OTEC PLANT PERFORMANCE

Power Output

The prototype plant performance with baseline parameters summarized in reference (1) has been determined using the nonlinear model. The plant gross power output as a function of warm-cold water temperature difference for three values of cold water temperature has been summarized in Figure 2. For a fixed cold water temperature the power output increases with nearly the square of the temperature difference as shown by the square law correlations in the figure:

$$P = 0.04\Delta T^2 \qquad (1)$$

where: ΔT = difference between cold and warm temperature °F

P = power in MW

These data illustrate that a 5°F decrease in warm water temperature reduces the power output from 65 MW to 45 MW. The square law data correlation given in equation (1) can be used to estimate plant power output for quasi-static analysis. The pumping and auxiliary power requirements of the plant are 15 MW, thus at the design point the plant module yields nominally 50 MW.

Response to Seastate Conditions

The nonlinear dynamic model has been used to determine the plant response to a steady surface wave of 12 ft amplitude and 10 sec period. The primary effect of the surface wave for the fixed platform considered is an alteration of the heads on the warm and cold water pump discharge ports. The influence on warm water flow rate and plant net power output for the case when the warm water discharge is submerged 200 ft and the warm water inlet is at 50 ft is shown in Figure 3. The mass flow deviation in the pump is 8% and results in a net power output change of $\pm$ 0.8%. Data corresponding to non-submerged pump ports indicated power output may vary by 1.6% as described in reference (8) while data for ship plants heaving in seastate 6 have indicated that power may vary by 14% as described in reference (7).

System Time Constants

The reduced order linear analysis which represents each heat exchanger as a single lump has been used to determine the time constants of the thermal-fluid components in the system. The time constants are calculated for open loop control (no governor) and for the case in which the pump AC motor time constants are neglected and the electric load to the turbine is represented as a constant load torque. The system time constants determined by eigenvalue analysis are summarized in Table 1 for 100% and 60% load where the load has been altered by opening the turbine bypass valve. The data in the table show that the cold water system flow time constant is the largest, 26.6 sec. The turbine generator time constant is 14.1 sec. The evaporator and condenser both have thermal time constants on the order of 7 secs. The data show that the system time constants do not vary significantly with load level between 60% and 100% load.

Examination of the system shows that the cold and warm water flow rates are essentially independent of the remainder of the system. Thus, for fixed pump operation, OTEC plant dynamics are essentially controlled by the turbine-generator time constant and the evaporator and condenser thermal time constants.

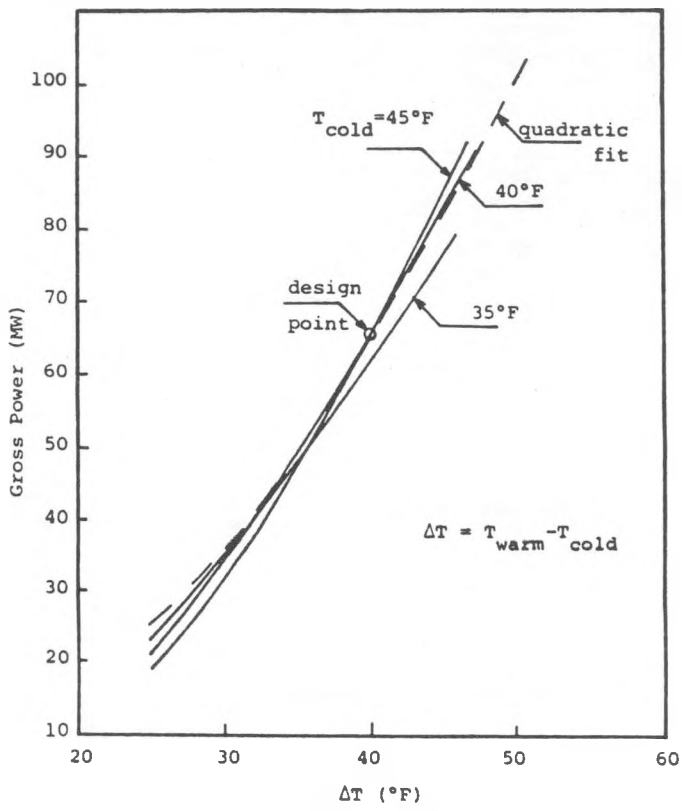


Figure 2

Gross Power Sensitivity to Seawater Temperatures

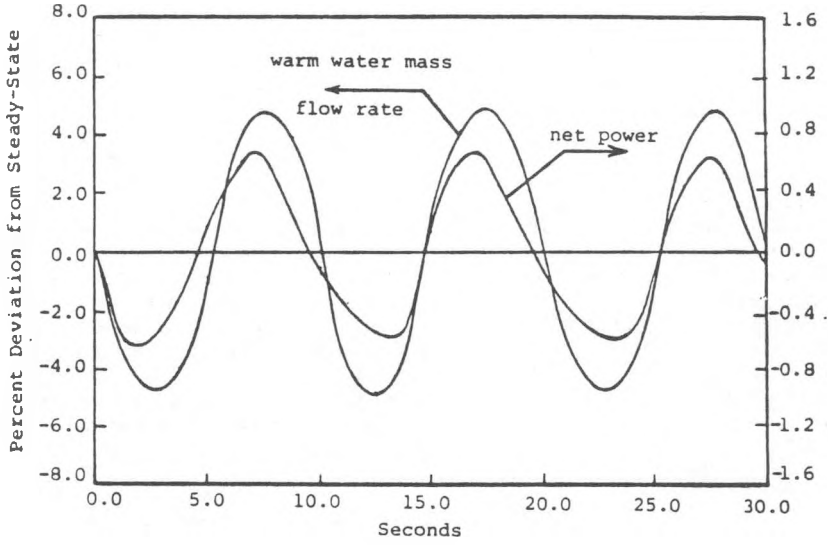


Figure 3

Pump Flow and Net Power Response to Sea Waves

Table 1

OTEC Plant Time Constants (seconds)

COMPONENT	100% LOAD	50% LOAD
Evaporator: Thermal	5.56	5.05
Evaporator: Vapor Flow	0.64	0.55
Condenser: Thermal	7.20	7.14
Condenser: Vapor Flow	0.77	0.77
Turbine-Generator	14.10	15.90
Warm-Water System	0.23	0.23
Cold-Water Pump	0.14	0.14
Cold-Water Flow	26.6	26.6

System Response to Load Demand

The reduced order linear model has been used to determine the response of the turbine to a 5% increase in electrical load with the system initially operating at 90% load. The system response with a 5% governor droop setting is shown in Figure 4. The data show that the turbine speed and turbine power output respond and reach steady-state in about 12 sec. The turbine steady-state speed is reduced by 0.25% with the governor droop set at 5%. As the governor gain is increased the response is less damped and the steady-state turbine speed error reduced as described in reference (8). The data show that the governor speed control through the bypass valve is effective.

System Response to Abrupt Change in Seawater Temperature

The linear model has been used to determine the plant response to an abrupt change in warm water temperature with the plant operating at 90% load. The response of the turbine speed and evaporator vapor flow rate are summarized in Figure 5 for the system operating with 5% governor droop. The data show that with the thermal disturbance the vapor flow rate and turbine-speed reach a new steady-state in 20 secs. The turbine speed steady-state value is reduced by less than 0.001% while the vapor flow is reduced by 1.2%. These data illustrate that the governor-bypass valve control loop maintains nearly constant turbine speed even as the evaporator vapor flow rate decreases.

System Response to Electrical Fault

The response of the plant operating at 90% load to a fault at the electrical bus connected through a 1.4 mile AC cable has been determined using the reduced order linear model. The system response is shown in Figure 6 for the plant operating with a 5% governor droop subjected to a 0.1 sec duration fault (zero voltage) occurring at the shore bus at the time of one second. The data show that at the instant of the fault the system output power falls to zero and the turbine speed suddenly increases. The data show that the turbine speed and power sustain a series of oscillations for about ten seconds and with a period of 1.5 secs. The system stabilizes in ten seconds and returns to steady state. These results indicate the ability of the plant to sustain an 0.1 sec bus fault and remain online.

SUMMARY

A spectrum of performance models for use in OTEC plant studies have been developed. The simplest model is an algebraic model given by equation (1). It is useful for determining plant power output as a function of ocean thermal conditions under quasi-static conditions. Such a model is useful for projecting plant output in utility load-flow studies. A small order linear performance model has also been developed which is useful in identifying the principal dynamic and stability performance characteristics associated with a plant interconnected to a utility grid. The most detailed model is a nonlinear high order model developed for evaluation of component performance.

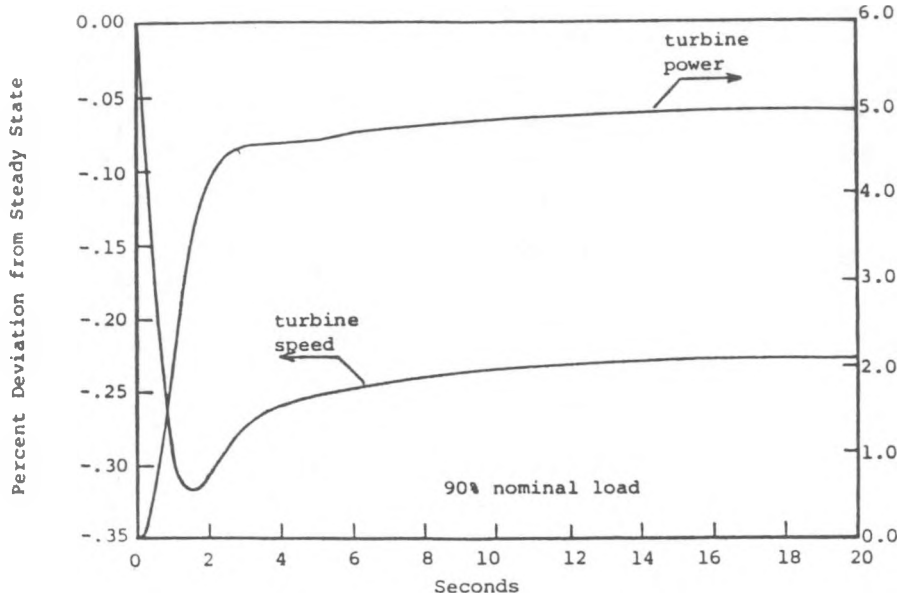


Figure 4

Turbine Speed and Power Response to 5% Increase in Load Demand with 5% Governor Droop

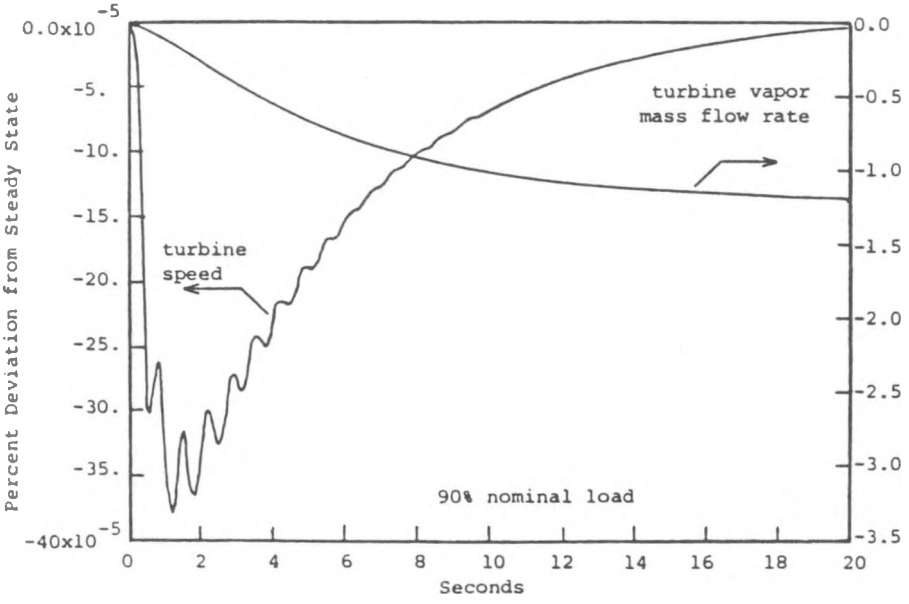


Figure 5

Turbine Flow and Speed Response with 5% Governor Droop to 1°F Decrease in Warm Water Temperature

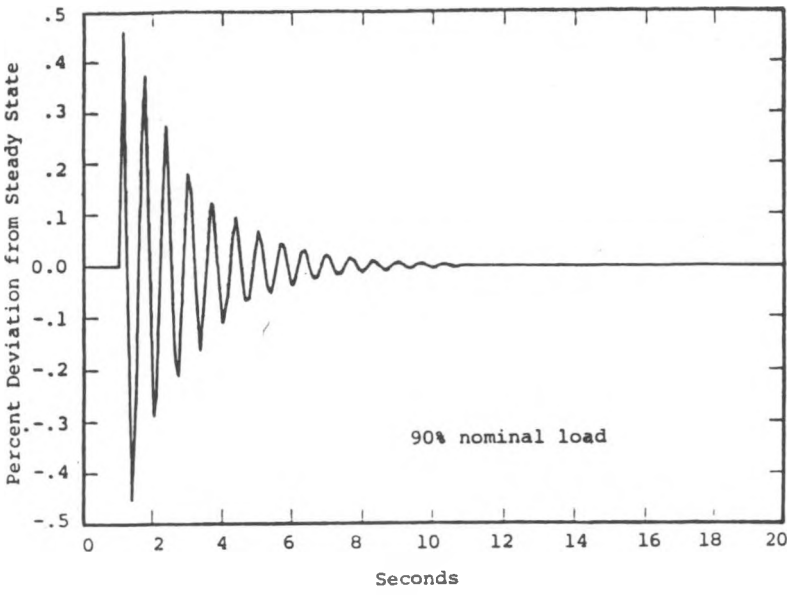


Figure 6a.

Turbine Speed Response to 0.1 Second Fault in Infinite Bus Voltage

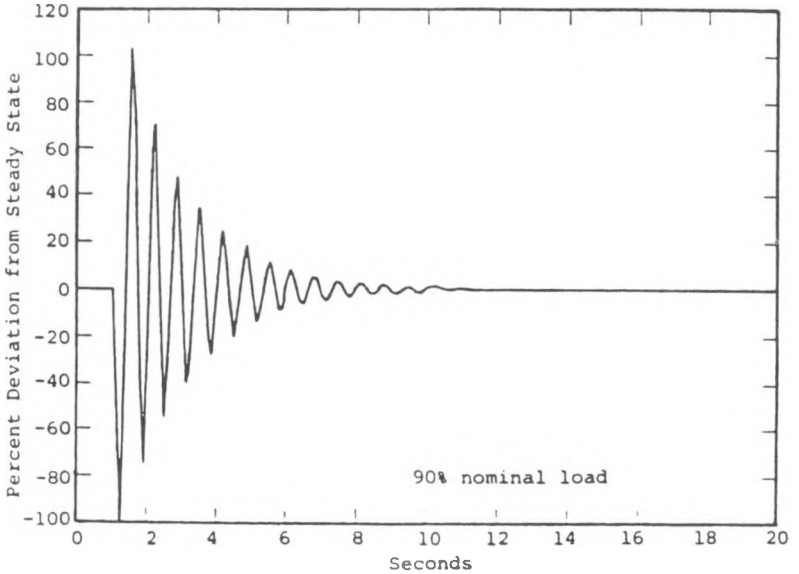


Figure 6b.

Turbine Power Response to 0.1 Second Fault in Infinite Bus Voltage

The models have been used to determine the influence on plant performance of ocean related thermal and seastate disturbances and electric bus faults. The plant under speed governor control acting to modulate a turbine-bypass valve has been shown to be stable and provide good regulation in the presence of these disturbances. To provide control with the turbine bypass valve, the plant has been operated below 100% load. Thus, control has been achieved with some reduction in maximum plant output. Further study of alternate control techniques and of the turbine bypass valve type of control is merited to achieve the necessary control and regulation with a minimum reduction in output.

ACKNOWLEDGEMENT

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OCEAN THERMAL ENERGY CONVERSION: THE EVOLUTION OF AN INDUSTRY THROUGH REGULATION

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This paper reviews the legislative history leading to passage of the Ocean Thermal Energy Conversion Act of 1980, Public Law 96-320 (the Act); briefly analyzes the major provisions of the statute; and documents the efforts of the executive branch to respond to the mandate of the Act. Particular emphasis is placed on examination of the approach taken by the National Oceanic and Atmospheric Administration (NOAA) as lead agency in implementing the "one-stop" licensing provisions of the Act.

Introduction

In many cases Federal intervention in private industry activities through imposition of entry requirements, controls on rates charged consumers for products or services, or through establishment of mandatory industry-wide standards occurs after the particular industry is well established. This intervention tends to happen when public opinion galvanizes the legislature into action to halt perceived abuses of free-market forces or the industry itself requests protection from them. It is much more unusual to find government regulatory intervention occuring during the early, formulative stages of the development of a private industry. Typically the rationale for this type of early intervention is presented by the industrial entrepreneurs themselves as a need to reduce or eliminate institutional barriers which would otherwise impede their efforts to commercialize.

This paper describes and analyzes the legislative and regulatory responses being made to the perceived needs of a new, emerging private industry, that of ocean thermal energy conversion (OTEC. OTEC is a renewable process for using solar energy stored in the warm surface waters of the tropical and subtropical oceans to perform useful work. OTEC may be applied commercially to produce electricity or other energy intensive products such as ammonia or aluminum.[1] The OTEC process is driven by the temperature differential between warm ocean surface waters and cold, deep waters. It can be implemented by means of an OTEC facility, which is moored or fixed to the ocean bottom or located on land with intake and discharge piping running out to appropriate locations at sea. It can also be employed aboard a plantship which moves over the ocean surface while producing energy intensive products such as ammonia or aluminum.[2]

The Need for Federal Intervention

As private industry, potential consumers of OTEC produced power, and the state and Federal legislatures reviewed the state of OTEC technology and the deepening fossil fuel energy crisis, two primary reasons for Federal intervention were perceived. As stated by Senator Daniel K. Inouye from the state of Hawaii, there were:

> The principal barriers to immediate commercialization of OTEC are first, the need for demonstration of large-scale OTEC systems, and second the need for a Federal regulatory and siting framework and financial assistance. Hearings Before the Committee on Commerce, Science, and Transportation, United States Senate on S. 2492, 96th Cong. 2d Sess. 1 (1980) (statement of Hon. Daniel K. Inouye), Serial No. 96-103.

The need for Federal intervention with regard to demonstration of large-scale OTEC systems stems from the fact that OTEC plants are capital intensive, with initial costs estimated to be one and one-half to two times greater than for equivalent nuclear power plants, and that public utilities are, of necessity, extremely conservative regarding investment in new and novel baseload power generating technologies. In short, it was felt that the national energy crisis provided a rationale for Federal intervention to stimulate OTEC technology development at a more rapid pace than normal free competitive marketplace forces would yield. The basic desire was for legislative action to clearly establish a Federal priority on OTEC technology development. The United States Congress responded to these entreaties to foster development of commercial scale OTEC technology with passage of the Ocean Thermal Energy Conversion Research, Development, and Demonstration Act, Public Law No. 96-410, 94 Stat. 941 et seq. That act established a national goal of ten thousand megawatts of electrical capacity or energy product equivalent from OTEC systems by

the year 1999. As a means of achieving that goal, the legislation directed the Secretary of Energy to pursue at least two OTEC demonsration projects with a combined capacity of 100 megawatts by the year 1986.

Having dealt with the problem of technology development, the Congress then turned its attention to the perceived need for a Federal regulatory and siting framework and financial assistance. Environmental groups were encouraging action at the Federal level to ensure that commercial OTEC development would be conducted with due regard for the marine environment. Private industry representatives were actively soliciting a stable streamlined licensing process and Federal investment incentives for commercial OTEC ventures. Public utilities were concerned about financial incentives and a stable legal regime to govern OTEC power generation. While the states involved generally supported the concept of Federal intervention, concerns over potential interference with state jurisdiction over facility siting and other traditional state regulatory activities was expressed.

As these concerns and the underlying enthusiasm for commercial development of OTEC as an alternative to fossil fuel consumption were articulated to the U.S. Senate and House of Representatives, the legislative branch began its response.

The Legislative Process

The first formal response to the above described needs for Federal intervention in commerical OTEC development was the introduction by Congressman Studds of Massachusetts of H.R. 6154 during the second session of the 96th Congress. That legislation was sponsored by Mr. Studds and twelve other representatives from states including New York, Maryland, Louisiana, and Hawaii as well as representatives of Puerto Rico and the U.S. Virgin Islands. The states purpose of the bill was:

> To regulate commerce, promote energy self-sufficiency, and protect the environment, by an establishing procedures for the location, construction, and operation of ocean thermal energy conversion facilities and plantships to produce electricity and energy-intensive products off the coasts of the United States; to amend the Merchant Marine Act, 1936, to make available certain financial assistance for construction and operation of such facilities and plantships; and for other purposes, H.R. 6154, 96th Congress, 2d Sess. (1979).

Senate action was not long in coming and a bill very similar to that introduced by Congressman Studds was introduced in January, 1980 by Senator Inouye of Hawaii as S. 2492. Extensive hearings were held on both the Senate and House of Representatives bills. During the course of these hearings, it became apparent that the only serious opposition to passage of the bills was due to objections by the executive branch. The Carter administration generally opposed the passage of either S. 2492 or H.R. 6154 on the grounds that they were premature given the state of OTEC technology development and the likely timeframe in which financial incentives for commercialization might actually be useful.

In addition to that overall philosophical objection, there was some executive branch controversy over which particular agency should be given lead responsibility for regulation of commercial OTEC activities. These concerns were considered by Federal lawmakers during legislative action on the two bills. Language in the House and Senate bills was adjusted so that the Coast Guard's traditional maritime regulatory authority was preserved and separated from the "one-stop" licensing responsibility assigned to the National Oceanic and Atmospheric Administration within the Department of Commerce, 42 U.S.C. §9112(f). The legislators were, however, unconvinced by various arguments regarding changing to a lead licensing agency other than the National Oceanic and Atmospheric Administration (NOAA) and that designation remained the same in the final version of the bills in both houses of Congress, 42 U.S.C. §9111(b). The bill was thus ready to be presented to the President for his signature or veto. After considering all aspects of the situation, President Carter signed the Ocean Thermal Energy Conversion Act of 1980 into law on August 2, 1980 thus clearing the way for executive branch intervention in the commercialization of OTEC.

The Ocean Thermal Energy Conversion Act of 1980

The Ocean Thermal Energy Conversion Act of 1980, Pub. L. No. 96-320, (the Act) responded to many of the concerns expressed during its development and movement through the legislative process. Its stated purposes were to:

(1) authorize and regulate the construction, location, ownership, and operation of ocean thermal energy conversion facilities connected to the United States by pipeline or cable, or located in the territorial sea of the United States consistent with the Convention on the High Seas, and general principles of international law;
(2) authorize and regulate the construction, location, ownership, and operation of ocean thermal energy conversion plantships documented under the laws of the United States, consistent with the Convention on the High Seas and general principles of international law;
(3) authorize and regulate the construction, location, ownership, and operation of ocean thermal energy conversion plantships by United

States citizens, consistent with the Convention on the High Seas and general principles of international law;

(4) establish a legal regime which will permit and encourage the development of ocean thermal energy conversion as a commercial energy technology;

(5) provide for the protection of the marine and coastal environment, and consideration of the interests of ocean users, to prevent or minimize any adverse impact which might occur as a consequence of the development of such ocean thermal energy conversion facilities or plantships;

(6) make applicable certain provisions of the Merchant Marine Act, 1936 (46 U.S.C. 1177 et seq.) to assist in financing of ocean thermal energy conversion facilities and plantships;

(7) protect the interests of the United States in the location, construction, and operation of ocean thermal energy conversion facilities and plantships; and

(8) protect the rights and responsibilities of adjacent coastal States in ensuring that Federal actions are consistent with approved State coastal zone management programs and other applicable State and local laws.

42 U.S.C.§9101(a)

Title I of the Act provided the framework for regulation of ocean thermal energy conversion facilities and plantships. The Administrator of the National Oceanic and Atmospheric Administration (NOAA) within the U.S. Department of Commerce was given lead responsibility for the required commercial OTEC licensing program. A license application to NOAA was to constitute application for all Federal authorizations required to conduct commerical OTEC operations, except for those administered by the U.S. Coast Guard. To the extent possible, the Administrator of NOAA was to consolidate NOAA's public hearings on a license application with those of other Federal agencies. NOAA was instructed to prepare, for each license application, a single environmental impact statement to fulfill the requirements of all involved Federal agencies under the National Environmental Policy Act of 1969.

Since one of the primary purposes of the Act was to foster commercialization of OTEC technology, a deadline by which the NOAA Administrator had to complete issuance of final licensing regulations was established. The deadline was set at one year after enactment, or August 3, 1981. Title II of the Act provided financial assistance for commercial OTEC activities in the form of access to Federal guarantees for loans used to finance construction of OTEC facilities and plantships. The remaining provisions of the Act dealt with enforcement of its requirements and with other miscellaneous items including the potential effect of a Law of the Sea Treaty and other international negotiations. Thus the stage was set for NOAA to shape the nature and extent of Federal regulatory intervention in the OTEC industry.

The Regulatory Response

NOAA was faced with a mandate to impose a regulatory regime on an emerging industry and also with an equally clear mandate to ensure that any such regime continued to foster development of the commercial OTEC industry. The Act in fact required a periodic review of all Federal regulations impacting commercial OTEC development.

Control over entry by means of licenses was the regulatory method prescribed in the Act. However, the specific mechanism by which the licensing decision was to be made was left open. Thus the possible range of options was broad. Specific OTEC facility and plantship design standards could be developed and issued as regulations. At the other end of the spectrum, licensing regulations could be limited to specifying the types of concerns which would go into the licensing decision. That approach would be accompanied by a statement of the types of information which a license applicant should provide to enable NOAA to make the licensing decision. This would preserve the maximum amount of flexibility and room for innovation to private industry. On the other hand, the predictability of detailed design standards would not be available to OTEC facility and plantship designers.

The range of regulatory options from detailed design standards to a statement of generic concerns with specified information requirements was presented to the public in the form of an Advance Notice of Proposed Rulemaking on OTEC Licensing, 45 Fed. Reg. 77,038 (November 21, 1980). Comments received from private industry, potential OTEC power consumers, interested state governments, and the general public all favored use of the generic approach to licensing. A regulatory impact analysis on the OTEC licensing program had been prepared in response to President Reagan's Executive Order on Regulatory Reform, Executive Order 12291 of February 17, 1981. The analysis is that document concluded that the generic approach to OTEC licensing would most effectively meet the goal of the Act of fostering OTEC commercialization while minimizing costs, both to the Federal government and to the ultimate consumer of OTEC power. Based on public comments received and on the results of the Regulatory Impact Analysis, the NOAA issued proposed OTEC licensing regulations for comment on March 30, 1981, 46 Fed. Reg. 19,418. Those proposed regulations specified the concerns which would go into a decision on an OTEC license application by drawing heavily on the concerns expressed in the Act. Detailed specifications for information to be provided with an OTEC license application were set out. The ultimate decision on regulatory constraints which would be applied to

a specific licensee was to be made in the form of license terms and conditions to be developed during the application review process.

Another concern addressed in the proposed regulations was the desire stated by private industry during legislative hearings for a single consolidated or "one-stop" Federal OTEC licensing procedure. The Act itself specified that the application to NOAA was to consitute application for all necessary Federal authorizations except for those administered by the Coast Guard. Consolidated license application hearings to the extent practicable were mandated. Finally, the Act provided for a consolidated environmental impact statement on all Federal actions associated with an OTEC application. However, the Act also specified that none of its provisions altered in any way the responsibilities and authorities of the United States or the agencies of the Federal government unless the Act explicityly so stated.

Thus NOAA had a mandate for a consolidated application processing method, but one with very little actual statutory authority. Because of this, the process proposed was made voluntary on the part of the applicant, other involved Federal agencies, and affected state and local governments. As set out in the proposed OTEC licensing regulations, the process dubbed Consolidated Application Review or CAR, has the following features.

> (a) The voluntary CAR process, which supplements the preceding mandatory steps in this subpart includes the following procedures:
> (1) Early designation of a representative from each participating Federal, State, and local government entity, as well as the OTEC license applicant, to serve as members of the Consolidated Application Review (CAR) Team.
>
> (2) Development and signing of a Joint Agreement among the participating Federal, State, and local government entities and the applicant. The Joint Agreement identifies the members of the CAR Team, details the regulatory and review responsibilities of each participating government agency having jurisdiction over any aspect of the construction or operation of OTEC facilities or plantships, and outlines the responsibilities of the applicant in the CAR process.
> (3) Conducting an interagency meeting with all members of the CAR team which includes a briefing by the applicant on the details of the proposed OTEC facility or plantship and a briefing by the government members on the procedures to be used in processing all necessary permits, authorizations, and approvals.
> (4) Implementation of the CAR schedule, including completion of required regulatory reviews, conduct of necessary public hearings, preparation of an Environmental Impact Statement, and other CAR Team activities necessary to ensure close coordination of the OTEC license review process, 46 Fed. Reg. 19,435 (1981)(to be codified as 15 C.F.R. §1001.380).

The proposed CAR process would clearly fulfill the spirit intended by the drafters of the OTEC legislation. However, the actual extent to which the other involved Federal agencies will actively work to make it a success remains to be seen.

Conclusions

The technical development of ocean thermal energy conversion and the simultaneous legislative resolve to provide for Federal intervention to foster commercial development have resulted in a unique real world laboratory for regulatory innovation. The challenge of providing a stable legal regime while not impending further innovation and refinement of OTEC technology is a difficult one. The initial steps taken by the National Oceanic and Atmospheric Administration appear to strike an appropriate balance in this area. However, major uncertainties remain. Chief among these is the degree to which other involved Federal government agencies will actively cooperate to expedite the licensing process. Without this active and ongoing cooperation, the potential exists for the licensing process itself to become an impediment to rapid commercialization.

Another overriding concern which was not treated in detail here may prove to be the major barrier to commercial development of OTEC. This is the ability of private industry enterpreneurs to amass the capital necessary for OTEC technology to make a significant impact on U.S. energy supplies. While the Act provides a package of incentives for financing, the degree to which private investors are willing to comment their assets to the OTEC industry will most assuredly be the one factor which determines the rate of growth, and ultimately the success, of a commercial OTEC industry in the United States.

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UNITED STATES COAST GUARD AND OTEC DEVELOPMENT

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ABSTRACT

The Ocean Thermal Energy Conversion Act of 1980 contained an exception to the one - stop licensing scheme it established. That exception was in favor of the Coast Guard's traditional role in the documentation, inspection, certification, construction and manning of U.S. flag vessels and registered structures. To meet the needs of this emerging industry, and to discharge its mandate to insure the safety of lives and property at sea, the Coast Guard will tailor existing regulations to set specific standards for regulated OTEC facilities and plantships.

The OTEC Act specifies that certain regulatory actions must be taken within prescribed periods. Other areas amenable to regulation are left, in the discretion of the agencies concerned, for regulation at some future date. Initially, the philosophy of the Coast Guard has been to implement OTEC - specific regulations only to the extent required by law, holding in abeyance the discretionary authority conveyed by the Act pending a demonstrable need for additional agency action. The absence of a historical data base upon which to found safety regulations demands such a flexible approach to avoid expensive overregulation; expensive for the industry and expensive for the Coast Guard. This approach is the most appropriate of the possible alternatives to assist in the removal of legal and institutional uncertainties which could impede the commercial application of the OTEC concept.

INTRODUCTION

This paper describes the regulatory approach taken by the United States Coast Guard in order to fulfill its responsibilities under the OTEC Act for the preservation of the marine environment and the fostering of safety of lives and property at sea. The philosophy of minimum necessary regulation is apparent throughout the efforts to date, as the Coast Guard attempts to apply well - established regulations of general applicability to OTEC installations. Although not strictly subject to the one-step licensing system, the approach taken by the Coast Guard is consistent with the goal of minimizing the burden on the regulated industry and avoiding the premature development of regulations that may prove unwarranted.

The private sector will have a significant hand in establishing design and safety standards for OTEC installations, as the Coast Guard will likely make extensive use of classification societies to augment agency efforts to determine specific standards for these novel devices. By reviewing pre-existing rules in Titles 33 and 46 of the Code of Federal Regulations, it was possible to identify those regulations appropriate for application to OTEC operations by adaptation and revision of applicabilitiy statements, definitions and authority citations. Coordination with NOAA, required by the OTEC Act, will provide the means to insert requirements of specific applicability in license conditions for individual OTEC facilities.

The target dates for Coast Guard regulations contemplate the publication of final rules no later than July 3, 1981; with the regulations becoming effective on August 3, 1981 - within the period specified by the underlying statute.

The authority of the Coast Guard pursuant to the OTEC Act extends to: promotion of the safety of life and property at sea; prevention of marine environmental pollution; removal of discharged pollutants; minimization of adverse effects from the construction and operation of OTEC facilities and plantships; control of movement of plantships to prevent adverse impingement by a plantship thermal plume on other OTEC facilities or areas of recognized jurisdiction of foreign states; and technical requirements related to documentation, design, construction, alteration, equipment, repair, maintenance, inspection, certification, and manning of facilities and plantships licensed under the Act.

LICENSE APPLICATION REVIEW

In order to meet its supervisory burden under the OTEC Act, certain information will be needed by the Coast Guard at the time of initial license application. To minimize the burden on applicants and avoid submission of redundant information to government agencies, the Coast Guard submitted an outline of the data it would require at the time of application, to conduct an effective license review in the areas assigned primarily or jointly to the Coast Guard, to NOAA. NOAA's proposed rules have taken these requirements into consideration and will serve to elicit information in six distinct areas of interest to the Coast Guard. Information in the following areas will be utilized by the Coast Guard to conduct both its internal license application review and to meet the statutory requirement for consultation with the Administrator concerning license applications: the emergency discharge contingency plan for the facility, including provisions for coping with both operational and accidental discharges; ship routing measures suggested by the applicant as necessary for the protection of the proposed installation; the proposed navigational lights and shapes for an OTEC plantship; the communications facilities aboard a plantship or structure that will be used

to communicate with nearby vessel traffic to promote operational safety; the navigational safety equipment to be used on proposed plantships; and, all aids to navigation to be placed on the OTEC facility.

REGULATION BY REFERENCE

Although the review conducted during the license application process will be guided in functional terms by pre-existing regulations, Title 46, Code of Federal Regulations will be amended to insert a new Part 106. Part 106 will resemble nothing quite so much as a central directory for regulations applicable to OTEC operations; containing few substantive regulations, but steering the reader to specific provisions elsewhere in Title 46 and to portions of Title 33, CFR.

Currently, petroleum transfer operations are governed by 33 CFR, Parts 154 - 156. These regulations prescribe pollution prevention procedures for virtually all marine oil transfer facilities and vessels. To the extent that OTEC facilities engage in such transfers, these regulations will be applicable by cross-reference between the existing regulations and proposed Part 106.

A comprehensive scheme for the promotion of marine safety by proper marking of various hazards to marine commerce already exists in Title 33, CFR. The regulations address sunken vessels and obstructions (33 CFR, Part 64), structures and permanently moored floating obstructions (33 CFR, Part 66), and the comprehensive International Regulations for Prevention of Collisions at Sea, 1972, which will govern mobile OTEC facilities (33 CFR, Part 87, App. A). Part 106 will contain express reference to the foregoing regulations, but the applicant will have the opportunity to suggest his precise manner of compliance in the information included on the NOAA coordinated application. This will allow each unique design and circumstance to be allowed for, while assuring through the review process that the fundamental safety concerns embodied in the regulations are met.

Bridge-to-bridge radiotelephone capability is currently required for all vessels navigating within the navigable waters of the United States. Under the rubric of " safety equipment" these regulations (33 CFR, Part 26) will apply as well to OTEC facilities located within the navigable waters. It is anticipated that any future international communication equipment standard which may be adopted for vessels in waters beyond the limits of national jurisdiction would result in application of the new standards to OTEC facilities in international waters. Although current navigational safety regulations are inapplicable to all OTEC facilities, some portions would be applied, as feasible, to floating OTEC facilities (33 CFR, Part 164).

DOCUMENTATION, DESIGN & MANNING

Section 108(e)(2) of the OTEC Act requires that regulations be promulgated which will insure that all OTEC facilities, as defined by the statute: be documented; meet design, construction, alteration and repair standards; and be crewed by United States citizens or resident aliens.

Thus far, the documentation question has raised the most persistent and vexing problems. The fundamental concern raised has been the proper interpretation of the Act's effect on the Coast Guard's traditional documentation authority. The Act by its express terms requires the Coast Guard to assimilate certain fixed facilities to the status of vessels, and document them accordingly. This approach is readily explicable in light of Congress' desire to make Title XI funding available to OTEC installations within the scope of the statute. Not expressly mentioned in the statute is the treatment to be accorded an OTEC installation which is land-based; and therein lies a certain controversy. The definition of "OTEC facility" contained in the Act would, in this author's view, preclude the regulation of any facility not standing or moored in or beyond the territorial sea of the United States. In the view of the Coast Guard, as stated in a public comment addressed to the NOAA notice of proposed rulemaking (NPR) (46 FR 19418, March 30, 1981), no authority is conveyed by the Act to document or set design standards for devices which are constructed landward of the mean low water mark. This position is founded on the statement of policy in the Act at section 2(a)(1) and the definitions contained in sections 3 (11) and (12). In its NPR, NOAA referenced a single sentence of the legislative history to support its view that the Act would require documentation of land-based devices, or at the least of equipment extending seaward of the high water mark which is appurtenant to such land-based devices. In the view of this writer, customary rules of statutory construction do not countenance the use of a legislative report accompanying a companion bill to render nugatory the effect of the express language adopted by Congress. The impact of this position is, of course, obvious: section 101(b)(7) of the Act precludes the Administrator from issuing a license to an OTEC device which is not documented under the laws of the United States. Since the OTEC Act expands the documentation authority of the Coast Guard only to the extent specified in the statute, it would appear that shore-based devices would not be amenable to documentation or licensing under the present statute.

The existence of appurtenances to land-based devices, which project seaward of the high water mark, would not seem to remedy the problem identified above. This result obtains for several reasons. First, some confusion was introduced into the statutory scheme by the failure of the Act to deal effectively with the concept of the point from which the territorial sea is measured, vis a vis the occasional use of the high water mark as a significant demarcation line of statutory scope. Secondly, the statutory definitions make clear that only appurtenances to "such facilities"[those standing or moored in or beyond the territorial sea] are to be deemed part of the OTEC facility. Finally, nowhere does the Act suggest that an OTEC device should be documented or licensed if it does not qualify by itself; appurtenances do not create coverage where the device itself falls outside the scope of the Act.

It should be apparent from the foregoing that a sizeable gap exists in the statutory scheme. I doubt seriously that anyone would assert that failure to include land-based devices was more than an inadvertent oversight on the part of Congress. The need to avoid multiple-user conflicts and the economic inefficiency that thermal plume degradation could visit on licensed facilities by the construction of unlicensed shore based devices should be obvious. Yet it is not properly the function of administrative agencies to attempt to rectify this problem by, in the case of the Coast Guard, assuming documentation authority not conferred by the OTEC Act. A radical departure from the comprehensive structure of U.S. documentation laws requires more than a brief comment in the legislative history, when such comment would purport to justify the documentation of land-based devices, contrary to the express statutory language. One is even minded of the statement frequently attributed to a Justice of the Supreme Court: every resort to legislative history is an indictment of the Congress.

The fundamental concept that must be recognized is that licensing status under the Act arises by virtue of situs - facilities seaward of the low water line are standing or moored in or beyond the territorial sea, and they and their appurtenances (to the limit of the inter-tidal zone) will be within the scope of the licensing authority.

Minimum standards of design, construction, alteration and repair are essentially a before the fact effort to insure that adequate margins of safety are incorporated into OTEC facilities to assure that the facility and the persons onboard are exposed to a minimum of hazard in the marine environment. The majority of safety concerns related to those facilities have already been the subject of long experience in the off-shore extractive industries. The fundamental concepts and measures developed for vessels and platform operations require little alteration to be equally applicable in the OTEC field.

Proposed Part 106, subpart B, will apply the inspection and certification procedures of 46 CFR, Subchapter I - A, Mobile Offshore Driling Units, to OTEC installations. Some modification is, of course, unavoidable: drydocking for inspection of the underwater body will not always be feasible, thus alternative methods of inspection will be available; since fixed floating facilities may depend to a great degree on their mooring system for safe operation, the mooring system will itself be subject to inspection; plan approval will require some additional information, with these requirements being keyed to the particular type of facility.

Part 106, subpart C, will address construction and arrangement requirements. Generally, compliance with American Bureau of Shipping standards appropriate to the design-type facility will be sufficient. Designs not adequately addressed in those standards will be evaluated on a case by case basis. Equivalent standards, established by other classification societies, may be used to determine acceptable design rules after the recognition of the society by the agency. The industrial systems will be required to meet the standards for analogous equipment and systems described in 46 CFR, Subchapters F and J, as an interim measure. OTEC-specific rules may well be required at some future date as more experience is acquired with the industrial engineering and electrical systems that come into use.

Part 106, subpart D, will address the dangers posed to the crew and industrial personnel aboard OTEC facilities by the potentially hazardous working fluids. In order to allow design flexibility, no single protective program will be imposed by the regulations; rather, the owner or operator of an OTEC facility will develop a plan to assure the safety of his personnel which will be approved on a case by case basis. It is envisioned that a combination of passive protection, achieved through system design and arrangement, coupled with active protection in the form of protective gear and procedures, will attain an acceptable level of crew protection in the event of a hazardous material incident.

Part 106, subpart L, incorporates the manning restrictions in the OTEC Act into the regulations. Manning requirements, other than those limitations derived from the Act, will be determined by reference to Subchapter P of Title 46, CFR (Manning of Vessels).

CONCLUSION

Although the regulations proposed by the Coast Guard address the many areas wherein regulatory action is required by the OTEC Act, they should clearly not be taken as the final word. Problems of considerable complexity remain to be delt with under the discretionary authority conveyed by the Act. A mechanism for controlling plantship movement and a procedure for dealing with foreign complaints founded on impingement of recognized resource zones will likely be required at some point. Additionally, NOAA and the Coast Guard will need to develop a working enforcement relationship which recognizes the competencies of each agency and reflects the actual enforcement climate in the industry.

Areas amenable to future regulation are really of little pressing concern. Priority should be given to technical amendments which will "cure" the drafting problems which have been identified in the underlying statute. If Congress deems it appropriate to extend licensing authority to the Administrator over land-based OTEC devices, it should be done without requiring documentation of the device under a scheme that has never been concerned with shore-side structures. The Act should also be modified to set to rest the view held by some that construction in the tidal zone would suffice to bring an OTEC device within the present regulatory arrangements. None of these alterations may be necessary, strictly speaking, to the formulation and implementation of a regulatory framework capable of overseeing the OTEC industry. However, to develop a legal regime to encourage the development of OTEC off the coasts of the United States, these anomalies should be eradicated.

* The views expressed herein are those of the author and do not necessarily represent the views of the United States Coast Guard, the Department of Transportation, or the U.S. Government.

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OTEC AND THE EPA PERMITTING PROCESS

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ABSTRACT

The statutory responsibilities of the Environmental Protection Agency (EPA) to issue National Pollutant Discharge Elimination System (NPDES) permits under Section 402 of the Clean Water Act (CWA) to ocean thermal energy conversion (OTEC) facilities are presented. The paper contains an overview of the regulations which govern the issuance of NPDES permits including application and information requirements, development of effluent limitations, and ocean discharge criteria considerations.

Section 301 of the CWA prohibits the discharge of any pollutant without an NPDES permit or in violation of the terms and conditions of a NPDES permit. NPDES permits contain technology based effluent limitations or effluent limitations to meet the water quality standards of the receiving waters. Since OTEC facilities represent a new industrial category, EPA will have to identify treatment technology, best management practices, and best engineering judgment for these facilities to establish appropriate permit conditions.

In addition, the final Ocean Discharge Criteria under Section 403(c) of the CWA may require more stringent effluent limitations for discharges to the territorial seas, contiguous zone, and the oceans to prevent the degradation of marine waters. The paper presents some of the concerns contained in this criteria and mentions the ramifications of the determinations of unreasonable degradation and irreparable harm on NPDES permit issuance.

INTRODUCTION

Permitting of OTEC facilities will basically follow the same EPA procedures which govern any applicant proposing discharge into ocean waters. However, the first step - application for permit - will be done through NOAA because of the requirement in the OTEC Act stating that an application filed with NOAA shall constitute an application for all Federal authorizations. It is in this respect, that EPA and NOAA have been consulting with each other to coordinate the application requirements. Much of the EPA's information requirements for the NPDES permit application have been incorporated into NOAA's proposed regulations published in March of this year. NOAA's final regulations will probably contain refinements to EPA's information needs because of new guidance which is currently being developed on the evaluation and determination procedures for ocean discharge criteria.

OCEAN DISCHARGE CRITERIA

Ocean Discharge Criteria (Section 403 of the Clean Water Act) will be the major focus of any evaluation of information supplied on a proposed OTEC facility. EPA will use guidelines published in October of last year to make a determination of whether or not the proposed discharge, with any necessary permit conditions, will cause unreasonable degradation of the marine environment. If it will, no NPDES permit can be issued. If there is insufficient information to make such a finding no NPDES permit shall be issued unless EPA can make a determination that the discharge will not cause irreparable harm to the marine environment during the monitoring period and there are no reasonable alternatives to on-site disposal.

These determinations will be made based on consideration of factors outlined in Section 403(c) of the Clean Water Act and those in the October 3, 1980, guidelines. Unreasonable degradation of the marine environment is defined as: (1) significant adverse changes in ecosystem diversity, productivity, and stability of the biological community within the area of discharge and surrounding biological communities; (2) threat to human health through direct exposure to pollutants or through comsumption of exposed aquatic organisms; or (3) loss of esthetic, recreational, scientific or economic values which is unreasonable in relation to the benefit derived from the discharge. Irreparable harm is defined as significant undesirable effects occurring after the date of permit issuance which will not be reversed after cessation or modification of the discharge.

The actual issuance of an NPDES permit is done by a EPA regional office - the permit being issued to the operator of an OTEC facility or plantship. There is a potential that, at some point in the future, a General Permit might be issued if there are a number of facilities operating within a geographic area, require the same permit conditions, and will be more appropriately controlled by a general permit.

CONCLUSION

As can be seen from all the preceeding, the permitting mechanics for OTEC - from application to issuance - industry would not change the procedures, but more than likely will make it more difficult to make a 403 determination and develop appropriate permit conditions. There are no effluent guidelines published for OTEC facilities, nor are there any new source performance standards. Therefore, any NPDES permit conditions or limitations will be almost totally dependent on the evaluation (and any resulting mitigating measures of ocean discharge criteria; and to a lesser extent, on best engineering judgement and transfer of treatment technology from other industrial categories. [e.g. chlorine minimization techniques from the power plant industry] Ub tge case of OTEC plantships produ̇cing a product - the industrial process involved would be treated, for the pubpose of establishing effluent limitations, similarly to that type of industry category unassociated with OTEC. Also, it should be clear, that if an OTEC facility is located so as to come under the jurisdiction of any State, any more stringent state requirements would have to be incorporated into the NPDES permit.

EPA is ready to evaluate any applications for discharge and, while carrying out the mandates of the Clean Water Act and permitting of OTEC facilities, will strive not to duplicate requirements imposed by other agencies, especially if protection of the environment is achieved.

Any opinions or policy expressed in this paper do not necessarily reflect that of the Environmental Protection Agency.

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REGULATORY AUTHORITIES OF THE U.S. ARMY CORPS OF ENGINEERS OVER OTEC PROJECTS

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ABSTRACT

The U.S. Army Corps of Engineers has regulated work in navigable waters for 91 years, since the passage of the River and Harbor Act of 1890. Originally designed to protect only navigation, the Corps' regulatory program has evolved into an important, full-scale mission that protects the full public interest, balancing both protection and utilization of important resources.

As the program expanded over the last decade--reflecting increased public concern for environmental protection--it also grew more complex. This report aims to lessen that complexity by providing basic, general information on the authorities governing the program, the activities regulated, and Corps program policies.

AUTHORITIES

The statutory authorities of the Corps in navigable waters of the United States, within the territorial seas and on the outer continental shelf are based on three major laws: Section 10 of the River and Harbor Act of 1899 (33 U.S.C. 403), Section 103 of the Marine Protection, Research and Sanctuaries Act of 1972 (33 U.S.C. 1413) and Section 404 of the Clean Water Act (33 U.S.C. 1344).

The River and Harbor Act of 1899 established the government's authority to keep the nation's water commerce routes operable and free from obstructions to navigation. Section 10 addressed structures or work in or affecting navigable waters of the U.S., defining those as coastal waters subject to the ebb and flow of the tide and those inland waters which support interstate or foreign commerce.

It wasn't until the late 1960's that the program underwent significant changes. In 1968, the Corps revised its permit regulation to require a "public interest" review of all applications in lieu of the previous "navigation only" review used up to that time. This self-imposed review reflected the Corps growing concern with environmental problems and issues.

Congress enacted the Federal Water Pollution Control Act Amendments (FWPCA) four years later with one basic objective in mind: "to restore and maintain the chemical, physical and biological integrity of the nation's waters." The 1972 amendments combined most of the then existing environmental legislation into one act and added some new items. One of those was Section 404 which makes it illegal to place fill material or dredged material in navigable waters without a permit from the Corps.

Five days after the passage of the FWPCA, Congress passed the Marine Protection, Research and Sanctuaries Act of 1972. Section 103 of that act gives the Corps authority over the transportation of dredged material for the purpose of ocean dumping.

In December 1977, the FWPCA was amended and became known as the Clean Water Act (CWA). The CWA continued the Corps' Section 404 authority, provided for the transfer of Section 404 to the states, required an agreement between the Secretary of the Army and five other involved agencies to streamline the permit process, and designated specific activities (such as normal farming, silviculture and ranching activities, irrigation ditches and emergency reconstruction of currently servicable structures) as exempt from permit requirements.

In addition to these three laws, the specific requirements of a host of court decisions, executive orders and other Federal and state authorities have been fully incorporated into the Corps' regulations--the National Environmental Policy Act, Section 401 of the CWA (state water quality certification), the Fish and Wildlife Coordination Act, the Endangered Species Act, the Marine Mammal Protection Act, the Historic Preservation Act, the Wild and Scenic Rivers Act, and the Coastal Zone Management Act, to name several.

The program is a dynamic one and will continue to be affected and revised by changes in law, judicial decisions, new initiatives and national priorities.

ACTIVITIES REGULATED

The excavation from or depositing of material in waters of the U.S., structures or work in navigable waters of the U.S., or other work affecting the course, location, condition or capacity of navigable waters of the U.S. is unlawful unless a Department of the Army (DA) permit has been issued for the proposed activity.

In Fiscal Year 1980, about 18,000 applications were received seeking permits for typical activities such as boat ramps, bulkheads, breakwaters, artifical islands and canals, groins, jetties, dams, dikes, road fills, tunnels, piers, mooring buoys, wharves and levees. OTEC projects may include cables, pipelines, marine terminals and other support and operational facilities that would require a DA permit.

Not every activity requires a separate, individual permit. Since 1977, nationwide permits have been issued for discharges of dredged or fill material into certain smaller or minor waters of the U.S. and for certain types of activities in all navigable waters of the U.S. Because qualifying activities are permitted in advance, paperwork and delays are eliminated. The use of regional permits--begun in 1975--is limited to smaller specified regions or states and may require some notification or reporting procedures. The district engineer issues regional permits for categories of activities in specified geographical regions that will cause only minimal adverse environmental impact. More than 300 nationwide and regional permits are now in use.

PROGRAM MANAGEMENT

Each Corps permit strives to mirror the dual national concerns for protection and appropriate development of our national resources. As previously stated, the Corps conducts a full public interest review, weighing all factors relevant to the permit proposal--including conservation, economics, fish and wildlife values, navigation, water quality, historic preservation, wetland values and energy development needs.

The Corps charter calls for reviewing all interests, some of which inevitably come into conflict with others. The development of energy sources is a national priority the Corps is committed to pursuing actively. While we must meet this need in a harmonious manner with the equally-important need for environmental quality, the Corps will cooperate fully with efforts to expedite permits for energy development activities such as OTEC.

To alleviate statutory and licensing barriers and streamline processing, the National Oceanic and Atmospheric Administration (NOAA) has been directed by PL 96-320 to provide one-stop application services for OTEC applicants. NOAA has proposed a consolidated application review process which is voluntary on the part of the applicant. We intend to participate fully in this process when requested by the applicant.

Because the Corps is highly decentralized, it is usually the district engineer who must seek to find the appropriate balance of these diverse concerns. As a former St. Paul District Engineer, I speak from experience when I tell you that it isn't a simple task. A wealth of information is considered in making each decision including: the information provided on the application; a review of data compiled from the review of previous permit applications in the same area or of a similiar nature; responses to public notices issued on the permit application; comments made at public hearings; communications with interested Federal, state and local agencies; an environmental assessment; and, in cases where the district engineer determines that the proposal may cause significant impact to the quality of the human environment, the required environmental impact statement (EIS).

We presently expect that NOAA will be the lead agency for the environmental documentation for OTEC applications. However, the Corps will work with NOAA as necessary to ensure that we would not need to prepare separate environmental documentation for our review.

In the decision-making process for permit applications, heavy weight is given to the views of state, regional and/or local agencies. Decision-makers on state/local levels are more knowledgeable about the unique conditions and objectives of their own area and are better long-range planners for themselves. The Corps' organization is decentralized--with 11 divisions and 36 districts nationwide--for many of the same reasons.

The Corps permit program is based, to a great degree, on the proposition that state and Federal regulatory programs should complement, not duplicate, one another. Unless there are overriding national factors of the public interest, the Corps will generally issue a permit on the basis of a favorable state determination. Furthermore, the Corps actively supports the transfer of the 404 program in non-navigable waters to states meeting 404 guidelines. Regional permits, joint processing procedures and interagency review coordination are also encouraged to reduce duplication.

Normally, noncontroversial permits are issued within 90 days after receipt of a complete application; however, controversial permits and those requiring an EIS--categories most OTEC projects are expected to fall in--take much longer. Processing time for activities requiring an EIS averages 36 months, often due to Corps determinations that public hearings are necessary and objections from other Federal agencies.

The Corps believes that applicants are not necessarily due a favorable response, but they are due a timely one. While we believe NOAA procedures can reduce the processing time of a DA permit, there are other requirements that can extend our final decision beyond NOAA's decision. In accordance with Section 404 (q) of the CWA, the Secretary of the Army entered into Memorandums of Agreement with the Secretaries of Interior, Agriculture, Commerce and Transportation and the Administrator of the Environmental Protection Agency.

The agreements, which were finalized in March 1980, stress early agency involvement, set specific time limits on commenting agencies and the Corps, and end the forced upward movement of permit cases to Washington. Only cases involving an EIS--less than one percent of the total--can be referred to the Secretary of the Army. Policy-setting cases with significant environmental impact (without an EIS) can be referred as high as the Assistant Secretary of the Army (Civil Works). All others can be handled at the Corps district or division level, the best level for timely decisions.

Timely decisions and expedious processing are continuing Corps goals. Within the limits we must prescribe to, OTEC project planners can count on the full cooperation of the Corps of Engineers.

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THE REGULATION OF OTEC ENERGY AND ENERGY PRODUCT EQUIVALENTS

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I. INTRODUCTION

Initially, research on the regulation of ocean thermal energy conversion (OTEC) plants focused on jurisdictional issues.[1] The results of the jurisdictional research have been encouraging. Internationally, OTEC development is not likely to be adversely affected by either current conventions or the United Nations Draft Convention on the Law of the Sea. Nationally, most jurisdictional issues were settled by enactment of the Ocean Thermal Energy Conversion Act of 1980[2] a year ago. The National Oceanic and Atmospheric Administration (NOAA) has issued its proposed regulations pursuant to that Act.[3] While specific regulations may give rise to spirited debate, the emerging regulatory framework is generally favorable.

What other regulatory problems may arise? One area for inquiry is the regulation of the energy and energy product equivalents which will be produced by OTEC plants. An "energy product equivalent" is defined in the Ocean Thermal Energy Conversion Research, Development, and Demonstration Act[4] at §9(2) as "an energy carrier including, but not limited to, ammonia, hydrogen, or molten salts or an energy intensive commodity, including, but not limited to, electrometals, fresh water, or nutrients for aquaculture." This paper will briefly consider the regulation of both OTEC energy and energy product equivalents under existing laws.

II. THE REGULATION OF ELECTRICITY

The Public Utility Regulatory Policies Act (PURPA)[5] is one of the five statutes passed in 1978 as the National Energy Act. PURPA provides favorable regulation of electricity produced by OTEC plants of less than 80 MW. Section 210 of the Act requires the Federal Energy Regulatory Commission to prescribe rules which will encourage cogeneration and small power production. These rules must require electric utilities to offer to sell electric energy to qualifying cogeneration facilities and qualifying small power production facilities, and purchase electric energy from such facilities. When the utility purchases electricity from such facilities, the rate must be just and reasonable and not discriminate against cogeneration or small power production facilities. The rate cannot exceed the incremental cost to the utility of alternative electric energy. This means the utility must pay as much as the "avoided cost"—the cost which it would otherwise pay for its electric generation. If this avoided cost is based on oil, a cogeneration or small power production facility can receive a rate equivalent to oil. Thus, the facility is guaranteed a market and as high a price as the utility now pays.

An OTEC pilot plant or small-scale plant would qualify as a small power production facility for purposes of PURPA. Section 201 of the Act provides the following definitions:

> (17)(A) 'small power production facility' means a facility which—
>
> (i) produces electric energy solely by the use, as a primary energy source, of biomass, waste, renewable resources, or any combination thereof; and
>
> (ii) has a power production capacity which, together with any other facilities located at the same site (as determined by the Commission), is not greater than 80 megawatts;
>
> * * *
>
> (C) 'qualifying small power production facility' means a small power production facility—
>
> (i) which the Commission determines, by rule, meets such requirements (including requirements respecting fuel use, fuel efficiency, and reliability) as the Commission may, by rule, prescribe; and
>
> (ii) which is owned by a person not primarily engaged in the generation or sale of electric power (other than electric power solely from cogeneration facilities or small power production facilities);...

Since an OTEC plant produces electric energy solely by the use of a renewable resource, a plant of less than 80 MW would meet the definition of a small power production facility. To be a "qualifying" small power production facility, it would also have to meet Commission requirements and not be owned by an electric utility. Investors could, of course, sell OTEC plants to utilities, obtaining in

the sales price their return on their investment, and no longer requiring the protection of PURPA to guarantee their market or electricity price.

The purpose of PURPA is to encourage the decentralization of energy sources in the United States.[6] Large-scale commercial OTEC plants will have to compete in price and reliability with other energy sources such as oil, natural gas, nuclear, and especially coal. It is expected that the regulation of OTEC electricity above the 80 MW level will fit into existing practices in the coastal states which regulate their utilities.

Local Public Utilities Commissions (PUC's) typically have significant regulatory power over local utilities. They have the power to investigate, hold hearings, require reports, compel the attendance of witnesses, approve mergers and consolidations, make rules, and perhaps most important, set rates. A local PUC could thus prevent a local utility from buying an OTEC plant or OTEC electricity if the PUC determined that it would result in too high a rate or have any other unjustifiable effect on rate payers. This may simply mean that OTEC will not commercialize on a large-scale basis until it is cost competitive with other fuels. A particular disadvantage for OTEC is its heavy capitalization, which focuses attention on the method of financing the debt. OTEC developers may propose rates which are higher in the first few years than the rates for electricity generated by other means. However, rates could remain fairly level thereafter, when fossil fuels can be expected to catch up in price and the "free fuel" of an OTEC operation will make it, in the long term, a far more favorable alternative. The PUC's will have to consider both the short and long-term picture, plus the reliability of OTEC power and supply as compared with uncertain oil, limited natural gas, and delays or dangers in nuclear energy production.

III. THE REGULATION OF ENERGY PRODUCT EQUIVALENTS

Two of the most promising energy product equivalents are ammonia and nutrients for aquaculture.

1. Ammonia

The nation's ammonia industry relies largely on natural gas as a feedstock for ammonia production. However, ammonia could be produced on board an OTEC plant, using hydrogen from the seawater and nitrogen from the air.[7] This ammonia could be shipped from the OTEC plant for use locally, nationally, or internationally as fertilizer or in fuel cells.

The production of ammonia on an OTEC plant will be regulated under the Federal Water Pollution Control Act (FWPCA).[8] The Environmental Protection Agency (EPA) regulates discharges resulting from the manufacture of ammonia. The EPA has set effluent limitations from a point source; effluent limitation guidelines representing the degree of effluent reduction attainable by the application of the best available technology economically achievable; standards of performance for new sources, such as fertilizer manufacturing on an OTEC plant; and effluent limitation guidelines representing the degree of effluent reduction attainable by the application of the best conventional pollutant control technology.[9] It is not expected that these standards will be any more difficult to meet at sea than for an ammonia manufacturing facility on land.

Once the ammonia is brought to shore for transport, it is expected to be handled through the existing transportation system used by fertilizer manufacturers. U.S. Department of Transportation regulations would apply. These regulations, found at 49 C.F.R. 100-179, include special provisions for carriage of hazardous materials such as ammonia by vessels.[10] Whatever the mode of transport, however, the regulations require that shipments of ammonia be properly classed, described, packaged, marked, and labelled. Shipping papers must indicate that the ammonia is a hazardous material.[11] Portable tanks, cargo tanks, and railroad tank cars must be marked with the name for the hazardous material which DOT has assigned to each kind of ammonia.[12] They must also be placarded by attaching large diamond-shaped posters to the container or vehicle.[13] According to one industry spokesman:

> Approximately twenty million tons of ammonia are produced or imported into this country every year and almost 50 percent of this total is transported and handled in existing distribution facilities through the use of barges, rail tank cars, tank trucks, and pipelines. Literally tens of thousands of U.S. farmers pick up ammonia in trailers from retail distribution points and then transfer the ammonia at the farm to smaller tractor-drawn tanks for direct application of the ammonia into the soil. The entire distribution network is under the control of the Department of Transportation and numerous rules and regulations are presently applicable which are enhanced and strongly endorsed by The Fertilizer Institute and all ammonia producers and marketers. To date, our major problem in the distribution of ammonia has been derailment of tank cars where we have had problems with deterioration of railroad beds. Otherwise, the safety record of the industry is excellent.[14]

The distribution of OTEC ammonia would thus be accomplished through an existing, well-established and well-regulated network.

2. Nutrients for aquaculture

The nutrient-rich cold water which is brought up during ocean thermal energy conversion could be run through "ponds" on board an OTEC plantship, or distributed through a "cage culture" attached to the OTEC operation. The FWPCA would apply.

If the cold water were processed through ponds on the OTEC platform, the discharge of the water after use would require a permit under the National Pollution Discharge Elimination System (NPDES).[15] NPDES permits are required for concentrated aquatic animal production facilities as defined by 40 C.F.R. §122.55. A concentrated aquatic animal production facility "means a hatchery, fish farm, or other facility which meets the criteria in Appendix C, or which the Director designates under paragraph (c) of this section." The criteria in Appendix C for cold water aquaculture are as follows:

> A hatchery, fish farm, or other facility is a concentrated aquatic animal production facility for purposes of §122.55 if it contains, grows, or holds aquatic animals in either of the following categories.

(a) Cold water fish species or other cold water aquatic animals in ponds, raceways, or other similar structures which discharge at least 30 days per year but does not include:

(1) Facilities which produce less than 9,090 harvest weight kilograms (approximately 20,000 pounds) of aquatic animals per year; and

(2) Facilities which feed less than 2,272 kilograms (approximately 5,000 pounds) of food during the calendar month of maximum feeding.

* * *

'Cold water aquatic animals' include but are not limited to, the Salmonidae family of fish; e.g., trout and salmon.

Thus, an NPDES permit would be required for any cold water OTEC aquaculture activity which discharges at least 30 days per year, produces at least 9,090 harvest-weight kilograms of aquatic animals per year, and feeds at least 2,272 kilograms of food during the calendar month of maximum feeding. Commercial-scale OTEC aquaculture is likely to exceed these limits and therefore require a permit. If an OTEC-aquaculture facility does not exceed these limits, it could still fall within NPDES requirements due to designation by the Director.[16]

In addition to the need for an NPDES permit for discharges from concentrated aquatic animal production facilities, an NPDES permit can be required for discharges into aquaculture projects, as defined in 40 C.F.R. §122.56. That section requires an NPDES permit for discharges into aquaculture projects, which "means a defined managed water area which uses discharges of pollutants into that designated area for the maintenance or production of harvestable freshwater, estuarine, or marine plants or animals." A "designated project area" is defined under 40 C.F.R. §122.56(b)(2) to mean:

> The portions of the waters of the United States within which the permittee or permit applicant plans to confine the cultivated species, using a method or plan or operation (including, but not limited to, physical confinement) which, on the basis of reliable scientific evidence, is expected to insure that specific individual organisms comprising an aquaculture crop will enjoy increased growth attributable to the discharge of pollutants, and be harvested within a defined geographic area.

Thus, whether the cold water nutrients are poured into a pond for use on board an OTEC platform and later discharged, or discharged directly into an aquaculture operation around or beneath an OTEC platform at sea, NPDES permits will be required.

IV. CONCLUSION

The regulation of OTEC energy and energy product equivalents presents no obvious obstacles to OTEC development. The production of electricity is greatly encouraged by PURPA, and the regulation of OTEC-related products such as ammonia and aquatic animals is expected to be no more burdensome than the regulation under which those products are currently manufactured and distributed.

NOTES

1 See, e.g., Kent M. Keith, "The International Regulation of Ocean Floating Energy Platforms," Law of the Sea: Neglected Issues, John King Gamble, Jr., ed. (Honolulu: Law of the Sea Institute, 1979) (Proceedings of the Law of the Sea Instititue Twelfth Annual Conference, October 23-26, 1978, The Hague, The Netherlands), pp. 275-296; Kent M. Keith, "State and Federal Regulation of OTEC Plants in Hawaii," Solar Law Reporter, Vol. 2, No. 3, September/October 1980, pp. 490-542; Ved P. Nanda, Selected Legal and Institutional Issues Related to Ocean Thermal Energy Conversion (OTEC) Development (Golden, CO: Solar Energy Research Institute, June 1979) (SERI/TR-62-204); Ved P. Nanda, "Ocean Thermal Energy Conversion (OTEC) Development Under U.S. and International Law and Institutions," Denver Journal of International Law and Policy, Vol. 8: 239 (1979); H. Gary Knight, "International Jurisdictional Issues Involving OTEC Installations," Ocean Thermal Energy Conversion (Lexington, MA: Lexington Books, 1977) pp. 45-73; and James C. Higgins, "Ocean Thermal Energy Converion Plants: Federal and State Regulatory Aspects," Id., pp. 165-194.

2 Ocean Thermal Energy Conversion Act of 1980, Pub. L. No. 96-320, 94 Stat. 974 (1980).

3 Licensing of Ocean Thermal Energy Conversion Facilities and Plantships, Proposed Rulemaking, Federal Register, Vol. 46, No. 60, p. 19418 (March 30, 1981).

4 Ocean Thermal Energy Research, Development, and Demonstration Act, Pub. L. No. 96-310, 94 Stat. 941 (1980).

5 Public Utility Regulatory Policies Act of 1978, Pub. L. No. 95-617, 92 Stat. 3117 (1978).

6 Reinier H. J. H. Lock, "Encouraging Decentralized Generation of Electricity: Implementation of the New Statutory Scheme," Solar Law Reporter, Vol. 2, No. 4, November/December, 1980, pp. 704-752.

7 See. e.g., W. H. Avery, "Ocean Thermal Energy—Status and Prospects," Marine Technology Society Journal, Vol. 12, No. 2, April-May, 1978, pp. 9-16.

8 Federal Water Pollution Control Act Amendments of 1972, Pub. L. No. 92-500, 86 Stat. 816, 33 U.S.C.A. §§1251-378 (1972).

9 40 C.F.R. Sec. 418.

10 49 C.F.R. Sec. 176.

11 49 C.F.R. Sec. 172.200.

12 49 C.F.R. Secs. 172.326, 172.328, 172.330.

13 49 C.F.R. Sec. 172.504.

14 J. F. Babbitt, President, Devco International, letter to Hon. Howard W. Cannon, May 12, 1980, in Hearings before the Committee on Commerce, Science, and Transportation, United States Senate,

Ninety-Sixth Congress, Second Session, on S. 2492, the Ocean Thermal Energy Conversion Act of 1980, April 10 and May 1, 1980, p. 148.

15 33 U.S.C.A. Sec. 1342.

16 40 C.F.R. Sec. 122.55(c).

COST TARGETS FOR OTEC: THE IMPACT OF INNOVATIVE FINANCING

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ABSTRACT

Economic analyses leading to determination of cost targets for Ocean Thermal Energy Conversion (OTEC) systems have generally considered electrical utility or heavy industry financing techniques. This is logical and expected since these industrial sectors represent the long-term and principal market for OTEC technology. However, the passage of a number of recent laws suggests an opportunity for application of a type of financing common in the buildings sector, syndication of limited partnerships, to OTEC in an innovative way. This paper explores the background, process and cost-target implications of such tax-advantaged and tax-sheltered financing to the early stages of OTEC commercialization.

The paper briefly recaps the elements of recently passed legislation (the OTEC Act of 1980, the OTEC RD&D Act, the Public Utility Regulatory Policies Act, and the Crude Oil Windfall Profits Tax Act) and their implications for OTEC financing. The principles behind tax-sheltered and tax-advantaged investment options and financing is examined in light of the technological (e.g., maximum MW ratings) and business (e.g., risk allocation) constraints associated with such techniques. The paper concludes with presentation of pro forma cash flows and capital cost target estimates for OTEC ventures that are financed as Small Power Producers and owned by limited partnerships whose investors can take advantage of financial leverage of MARAD financing and the substantial Energy Tax Credits.

1. INTRODUCTION

The last decade has seen an enormous increase in the level of activity of the federal government in seeking to "commercialize" energy technologies. The classic pattern is one wherein the government supports successive levels of laboratory, bench scale, prototype and demonstration efforts. Especially in the case of large scale, capital intensive technologies such as Ocean Thermal Energy Conversion (OTEC), the last stages of the process becomes particularly difficult. This paper explores how OTEC commercialization may be augmented through the use of innovative financing.

The commercialization dilemma typically revolves around risk and its allocation as energy technologies approach the full scale demonstration and early deployment stages. Since OTEC and related large scale energy options are often seen as utility facilities, system vendors look to this industry to assume major risk elements associated with technology commercialization. Significantly, the utility industry is among the most risk averse. This is a natural consequence of their fixed rate of return. Needed is an entity which can take the risks associated with OTEC introduction in the hopes of making significant financial returns. As this paper will detail, we believe the limited partnership may be just such an entity.

The proper role of government in the commercialization process is one which has been long debated. In the OTEC area, government has supported basic R&D and limited scale field testing. In addition, Congress has enacted substantial and powerful incentives (see next section) which encourage OTEC commercialization. While this paper explores how OTEC might be supported through innovative financing options, it is important to remember that until the technology has been adequately demonstrated and proven, no prudent investor will take the kind of risks associated with such an endeavor. Thus, there continues to be a need for federal RD&D involvement.

2. OTEC INCENTIVES

A variety of legislated programs exist which provide financial incentives for development of OTEC facilities. These include research and development subsidies focusing specifically on OTEC plants, Energy Tax Credits allowed under the Windfall Profits Tax Act, and certain provisions of the Public Utility Regulatory Policies Act.

The Ocean Thermal Energy Conversion Research, Development and Demonstration Act of 1979 established goals for commercialization of OTEC to be met by DOE in the form of total OTEC generation capacity milestones. Although at least two demonstration projects were authorized, future federal spending for OTEC pilot facilities is in doubt. In a second piece of OTEC legislation, The Ocean Thermal Energy Conversion Act of 1980, potentially formidable legal and regulatory barriers have been removed

(Title I) and attractive Maritime Administration (MARAD) financing vehicles and subsidies are made available to privately sponsored OTEC plants (Title II). The eligible MARAD incentives, originally designed to aid in the maintenance of an active commercial shipping fleet and ship building industry, include contruction and operating cost subsidies, defferal of tax on construction funds and ship financing guarantees. Furthermore, a $2 billion OTEC Demonstration Fund was created to provide mortgagee guarantees to five OTEC demonstration facilities. Guarantees would be available on up to 87.5% of the cost of the facility.

The Crude Oil Windfall Profits Tax Act of 1980 provides a 15% Energy Tax Credit for OTEC equipment purchased before December, 1985 for plants at two locations to be specified by the Secretary of the Treasury (in consultation with the Secretary of Energy). This credit is over and above the normal Investment Tax Credit of 10%. To avoid being considered "Public Utility Property" (and hence ineligible for the energy tax credits), OTEC must product non-electrical products or qualify as Small Power Producers under PURPA (see below). The credit may not be used on portions of an OTEC facility which have also been subsidized by federal low interest loans and non-taxable grants, but is not reduced by the MARAD loan guarantees.

Finally, the Public Utility Regulatory Policies Act (PURPA) provides OTEC developers with a guaranteed market for electricity generated if OTEC capacity is 80MW or less. Utilities are required to purchase the output of such Small Power Producers at rates tied to the utilities' cost of fuel. As will be seen, PURPA guarantees provide a critical element in assuring a financially feasible price of OTEC facilities because it lowers the non-technological risk factors associated with OTEC as well as binds the price of its product to expensive non-renewable fuels in certain locations (such as Puerto Rico and Hawaii). Significantly, the 80MW size limitations set to qualify as a Small Power Producer may require OTEC facilities to operate at a relatively inefficient scale of operation.

3. THE LIMITED PARTNERSHIP

A limited partnership is an association of one or more general partners who: manage the project technically and financially, assume most risks, and usually make a number of guarantees to the limited partners; and limited partners who: provide equity finding, may not play an active management role and assume risk usually limited to the amount invested or a pro rata share of the partnership's debt (as determined in the partnership agreement). The limited partnership is a useful vehicle since tax benefits are distributed to those partners who can make the most effective use of them. In this regard, there is often great flexibility with respect to how the tax credits, deductions, cash flow and proceeds of asset sale may be distributed. This distribution, as long as it has some basis in the economics of the venture, can therefore be used to allow each class of partner to achieve its economic objectives (e.g., tax-sheltered income, upside profit, long term capital gain, secure income, etc.).

A partnership is preferable to a corporation in this context in that the tax losses of a partnership are distributed to the partners. In a corporation, tax losses and tax credits in excess of tax liability would have to be "carried forward" until they could be applied against tax liability. Thus, the partnership flows tax benefits through to the investors quickly and efficiently. Similarly, once the venture is profitable, profits are treated as income to the partners and taxed once, rather than that being treated as income to the corporation and dividends to the investors (and, hence, taxed twice).

Establishing the partnership would involve:

- An entity (the developer) assembling all the necessary elements (e.g., an OTEC supplier, installer, customer for the product energy).
- Entity finds (or becomes) the general partner who
  - raises equity through sale of limited partnership interest
  - raises debt via MARAD guaranteed loans from banks, insurance companies, pension funds, etc.
- The partnership enters into all purchase and operating agreements.
- Facility is operated and benefits are distributed as per the partnership agreement.

4. INFLUENCE ON OTEC TARGET COSTS

In this section, we will examine the influence of the use of tax advantaged financing on OTEC target costs. Contemplated as a "base case" is a venture in which a 30MW OTEC facility (costing $5,000/KW or $150 million) is owned by a partnership whose funding consists of 87.5% debt (backed by MARAD guarantees) and 12.5% equity (raised through the sale of limited partnerghip interests to investors in a 50% tax bracket). The energy production of almost 225 million kWh/year (a capacity factor of 85%) is sold to a utility under PURPA auspices at a rate of 6¢/kWh, growing at 14% annually. A complete set of assumptions is included as Figure 1.

Figure 2 provides a year by year cash flow analysis of the "base case" OTEC investment from the investor's point of view. Focusing on the first year, we observe:

- 30 MW MACHINE
- COST = $5,000/kW OR $150 MILLION
- ANNUAL O&M = 2% OF CAPITAL COST
- PROPERTY TAX = 0
- ANNUAL INSURANCE COST = 1.5% OF CAPITAL COST
- ENERGY PRODUCTION = 223,380,000 KWH/YR (= 30,000 kW x 0.85 x 8760 HRS/YR)
- EXPENSE ESCALLATION RATE = 7%
- INVESTMENT TAX CREDIT = 25%
- INVESTORS' TAX BRACKET = 50%
- DEPRECIATION PERIOD = 15 YEARS
- INITIAL ENERGY VALUE = 6¢/kWH
- ENERGY VALUE ESCALATION RULE = 14%
- LENGTH OF LOAN = 25 YEARS
- LOAN INTEREST RATE = 11%
- FRACTION DEBT = 87.5%
- FRACTION EQUITY = 12.5%

Figure 1
OTEC Base Case Assumptions

($ x 1000)

YEAR	ANNUAL REVENUE PRODUCTION	ANNUAL EXPENSES	ANNUAL DEBT SERVICES	ADJUSTED BALANCE	INTEREST PAYMENT	DEPRE-CIATION	TAX CREDIT	CASH FLOW	TAXABLE INCOME	RETURN (AFTER TAX	ANNUAL RETURN ON IN-VESTMENT
1	13,402	5,250	15,584	130,102	14,437	10,000	37,500	30,068	(16,284)	38,210	
2	15,279	5,617	15,584	128,829	14,311	10,000	0	(5,922)	(14,649)	1,401	
3	17,418	6,010	15,584	127,416	14,171	10,000	0	(4,177)	(12,763)	2,204	
4	19,856	6,431	15,584	125,847	14,015	10,000	0	(2,159)	(10,590)	3,135	
5	22,636	6,881	15,584	124,105	13,843	10,000	0	170	(8,088)	4,214	
					CUMULATIVE 1-5 TOTALS			17,979	(62,376)	49,167	29%
6	25,805	7,363	15,584	122,172	13,651	10,000	0	2,857	(5,209)	5,462	
7	29,418	7,878	15,584	120,027	13,440	10,000	0	5,955	(1,899)	6,904	
8	33,537	8,430	15,584	117,645	13,203	10,000	0	9,522	1,904	8,570	
9	38,232	9,020	15,584	115,002	12,941	10,000	0	13,627	6,271	10,491	
10	43,585	9,652	15,584	112,067	12,650	10,000	0	18,349	11,283	12,707	
					CUMULATIVE 1-10 TOTALS			68,290	(50,026)	93,304	20%
11	49,687	10,327	15,584	108,809	12,327	10,000	0	23,774	17,032	15,258	
12	56,643	11,050	15,584	105,194	11,969	10,000	0	30,008	23,623	18,196	
13	64,573	11,824	15,584	101,181	11,571	10,000	0	37,164	31,178	21,575	
14	73,613	12,651	15,584	96,726	11,129	10,000	0	45,377	39,832	25,461	
15	83,919	13,537	15,584	91,781	10,639	10,000	0	54,791	49,742	29,926	
					CUMULATIVE 1-15 TOTALS			259,414	111,382)	203,723	18%
16	95,668	14,484	15,584	86,293	10,095	0	0	65,598	70,087	30,055	
17	109,061	15,498	15,584	80,200	9,492	0	0	77,978	84,070	35,943	
18	124,330	16,583	15,584	73,437	8,822	0	0	92,162	98,925	42,700	
19	141,736	17,745	15,584	65,931	8,078	0	0	108,408	115,914	50,451	
20	161,580	18,986	15,584	57,599	7,252	0	0	127,008	135,341	59,358	
					CUMULATIVE 1-20 TOTALS			730,569	616,720	422,209	17%
21	184,201	20,315	15,584	48,350	6,335	0	0	148,301	157,549	69,526	
22	209,989	21,437	15,584	38,084	5,318	0	0	172,667	182,933	81,200	
23	239,388	23,260	15,584	76,689	4,189	0	0	200,544	211,939	94,574	
24	272,902	24,888	15,584	14,040	2,935	0	0	232,430	245,079	109,890	
25	201,109	26,630	15,584	0	1,544	0	0	268,894	282,934	127,426	
					CUMULATIVE 1-25 TOTALS			1,753,404	1,697,154	904,827	17%

Figure 2
OTEC Base Case Pro Forma Financial Analysis

- Cash flow (revenue - expenses - debt service + tax credits) is positive and in excess of $30 million because of the $37.5 million tax credit.

- Taxable income (revenue - expenses - interest - depreciation) is negative, a tax loss of more than $16 million, largely due to the $10 million/year depreciation and deductability of most annual expenses.

- After tax income to the 50% tax bracket investors is $38,210,000. This represents an after tax return on investment of 204% on the original investment of $18.75 million.

Examining subsequent years, we see that the cash flows quickly become positive (in practice, investors would have to cover the early year deficits), and after seven years, the project starts producing taxable income. After 10 years, the $18.75 million investment has produced a total of $93.3 million in after-tax return and still represents an operating OTEC plant. This is equivalent to a 20% after tax return on investment (ROI). Looked at in another way, the income stream represented by the first 10 years of after tax return is equivalent to an annual after tax internal rate of return of 114%. In the subsequent sensitivity analyses, we will fix 10 year after tax return on investment while varying other key parameters.

The curves shown in Figure 3 provide a analysis of the sensitivity of target OTEC capital cost (in $/kW with respect to key parameters.

- Target Cost vs. ROI. Figure 3a relates the annual after tax ROI to capital costs. ROI's calculated on both five year and ten year bases are shown. In all the following curves, a 10 year ROI of 20% is assumed.

- Target Cost vs. Avoided Costs. The avoided cost or electricity purchase price will have a substantial impact on OTEC economics. At today's prices, the energy component of avoided cost on oil-based utilities are some 6-7¢/kWh. If OTEC capacity is judged reliable enough to offset needed base loaded capacity, avoided costs significantly in excess of the 6¢/kWh base case will be likely.

- Target Cost vs. Capacity Factor. Since energy production and revenue are directly proportional to capacity factor, a strong relationship between the latter and target cost is seen. To the extent that high capacity factors augment allowed avoided costs, this dependence will become even stronger.

- Target Cost vs. % Debt. The impact of leverage upon the investment is well illustrated by figure 3d. As percent debt increases, the amount of investment decreases and the allowed cost grows. It is, of course, unrealistic to believe that long term lenders will provide debt in excess of MARAD guanrantees.

- Target Cost vs. Loan Interest Rate. Interest rates do not have the dramatic impact (Figure 3e) one might expect since interest costs are deductible. With this said, it is important to keep in mind that if rates substantially in excess of the assumed 11% base case prevail long term, the future of this and all other capital intensive energy solutions (solar, nuclear, synfuels, etc.) will be in serious jeopardy.

These financial results must be seen as very preliminary and highly simplified. Nevertheless, they point the way towards use of a tax-advantaged approach to financing of the early OTEC facilities. As avoided costs rise to 8-10¢/kWh, OTEC costs of $6,000-$8,000/kW may still represent the basis of attractive investments.

5. CONCLUSIONS

Any energy technology will be commercialized when the risks associated with investing in the concept are commensurate with the potential returns. Early OTEC commercialization will surely be characterized by significant risks, risks that utilities (whose returns are fixed) cannot accept. Financing early OTEC demonstrations through tax-shelter like structures may offer an early if interim solutions to the problems of risk allocation. A key to the success of such ventures will be the continued availability of the Energy Tax Credits and MARAD loan guarantees.

This financing option makes sense because it makes the most effective use of the tax credits and deductions emanating from such projects. It is applicable to both electrical and non-electrical OTECs but the former must be 80MW or less to be eligible for the Energy Tax Credits. It represents a new and potentially important source of capital to the energy technology development community.

In closing, it is imperative to bear in mind that such financing options are not a substitute for technology R&D. Investors may be willing to share prudent risks with manufacturers, insurance companies and the government. They will not, in general, be willing to underwrite highly speculative or unproven demonstrations. While innovative financing can lower the financial hurdles for OTEC commercialization, they cannot eliminate the need for a carefully structured and adequately funded RD$D process.

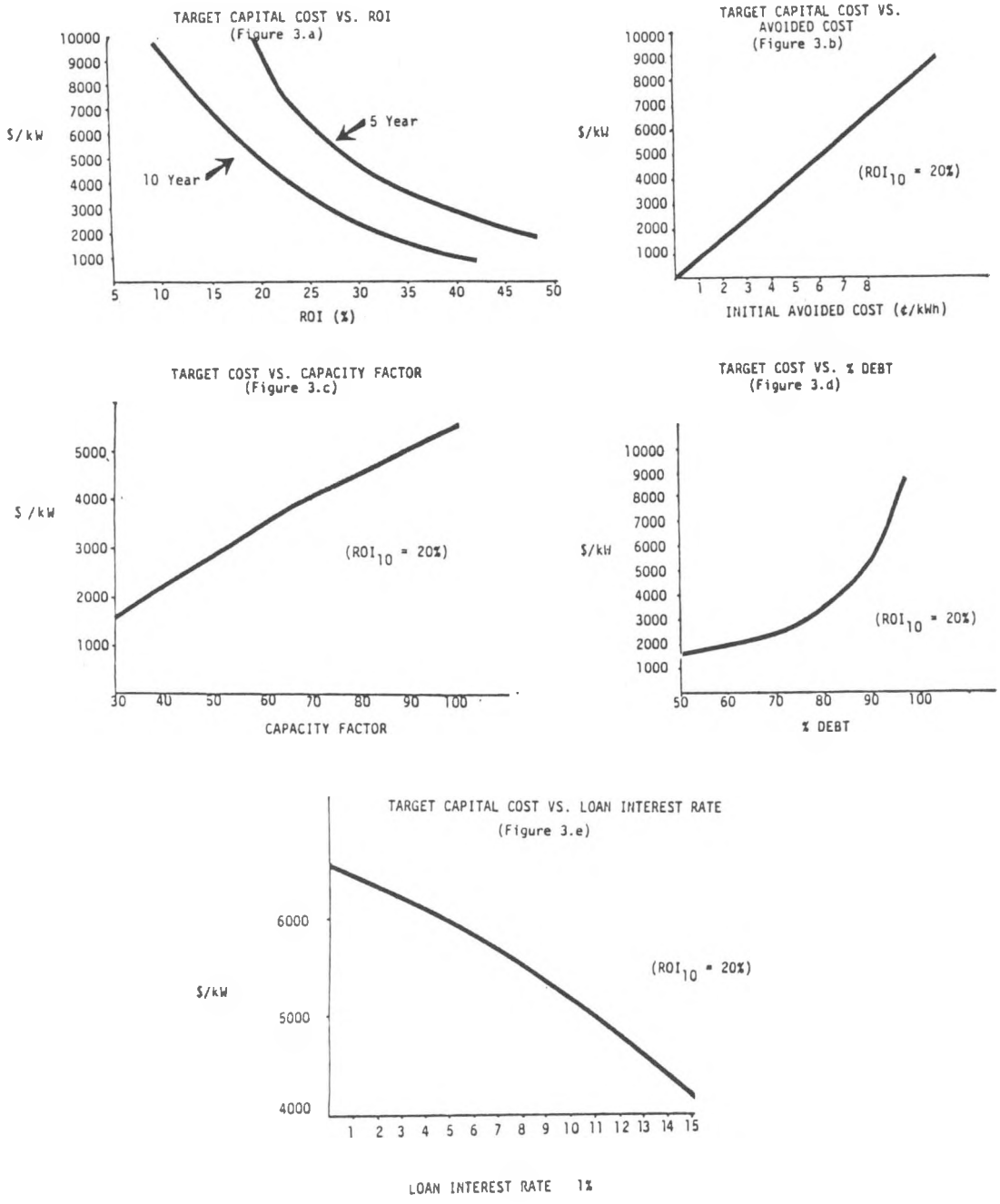


Figure 3
OTEC Cost Targets: Sensitivity Analysis

8th Ocean Energy Conference
Washington, DC
June 1981

PROJECTED ENGINEERING COST ESTIMATES FOR AN OCEAN THERMAL ENERGY CONVERSION (OTEC) CENTRAL STATION

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The Rand Corporation

ABSTRACT

An engineering performance and cost model developed at Rand is used to estimate the potential cost reductions if certain improvements are realized in the engineering, construction, and financing of the OTEC system.

INTRODUCTION

This paper examines the potential for reducing OTEC costs by achieving engineering, construction or financing improvements. A first order comparison of OTEC system costs to coal fired and nuclear power plants is also made.* We found in other Rand studies of advanced energy technology systems that early cost estimates are usually optimistic and that the total integrated systems approach must be used to develop meaningful estimates of both the capital costs and the cost of electricity. We have also found that there are potential areas of technological advances which, if realized, might reduce the total system cost. This paper evaluates the potential cost reductions for several OTEC technology advances.

Previously, we developed an OTEC engineering performance and cost model to estimate total OTEC system costs (Fig. 1). This model was used to develop the projected engineering cost estimates in this paper.

ASSUMPTIONS

In order to provide meaningful comparisons, we first set forth the assumptions used in this study. We then show the results of an analysis of our reference case which is described in more detail in Ref. 1. Our assumptions include:

- Closed cycle OTEC system.
- Central station, commercial scale (240-400 MWe) application.
- Sites: Gulf of Mexico, Puerto Rico, and Hawaii.
- All estimates in consistent 1978 dollars.*
- The EPRI methodology will be followed in computing the cost of electricity.
- The analysis will not address any impact due to proposed tax credits, subsidies, or other financial incentives.

The distribution of capital costs for our reference case is presented in Fig. 2. It is based on a system located off the coast of Tampa, Florida with a capacity of 400 MWe. It has a concrete barge-type platform and a steel coldwater pipe. The heat exchanger is a tube and shell type manufactured of titanium. We assumed a construction period of 5 years and a fixed charge rate of 18 percent.

The reference case also assumes a reliability factor of .9. The effect of system reliability is illustrated in Fig. 3. Down time includes both scheduled and unscheduled maintenance but does not account for any effect due to seasonal variation. Within the range shown, each percentage point increase in down time results in an increase in the cost of electricity on the order of 1 to 2 mills per kwh.

COST REDUCTION ALTERNATIVES

Seven alternatives for cost reduction were considered as shown in Fig. 4. Each of the first six contains one variation from the reference case (or Rand base case) while the last case combines five of the alternatives (an optimistic case). The cost of producing roughened tube surfaces for water-side heat transfer enhancement is estimated on the basis of an analogue to a Linde** process. This plate-type heat exchanger estimate is based on information provided by the Lockheed Missiles and Space Company for the Alpha Laval heat exchanger. The elimination of cable burial may be theoretically possible, but the practicality of establishing a stay-away zone is in question.

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*For a quantitative evaluation, baseline cost estimates and sensitivity analysis, see Ref. 1.

*To obtain a reasonable estimate of costs in 1980 dollars, multiply by 1.2 (the 1978-1980 escalation factor as given by the Chemical Engineering Plant Index).

**See Ref. 1.

Figure 4 presents the projected system costs of these alternative configurations for a Gulf of Mexico application. The plate-type heat exchanger and a shorter construction period appear to have by far the most significant impact on reducing total system cost. A three percentage point reduction in the fixed charge rate will lower the cost of electricity (COE) by 16 percent. Water-side heat transfer enhancement contributes significantly to lower both capital cost and COE.

COMPARISON OF OFFSHORE AND ONSHORE PLANT COSTS

Figures 5 and 6 show the capital costs by subsystem and cost of electricity for two approaches to an island application: (1) an offshore platform similar to the reference case configuration, and (2) an onshore installation with the necessary coldwater pipe and site acquisition. These estimates are compared to the reference case.

The thickness of the coldwater pipe is assumed to be the same for both platform and onshore applications. The increase in power system costs for the onshore application is due to the increased pump power requirement which in turn means larger heat exchangers. System costs for the onshore installation in Puerto Rico are essentially equivalent to offshore platform costs (Fig. 5), while for Hawaii (Fig. 6), the onshore installation is projected to cost approximately 10 percent less than the offshore platform. We find that the effect of coldwater pipe costs (CWP) is not significant. Even with a factor of three variation in the CWP cost, the total system cost differences between onshore and platform applications of OTEC systems are not dramatic. However, there are other considerations:

a. Shore stations do not require advanced underwater transmission cable or deepwater mooring technologies.

b. Shore stations are likely to have higher system availability and lower operating and maintenance costs which are not reflected in the above estimates.

COMPARISON WITH COAL FIRED AND NUCLEAR FUELED PLANTS

The impact of fuel and plant construction cost increases is illustrated in Figures 7 and 8. OTEC is a solar technology with a zero fuel cost. In Fig. 7 we use the potential annual real rate of fuel cost growth for alternative fuel-burning systems as a measure for comparing OTEC with other systems. We assumed a start of operations in the year 2000 and calculated the total cost of producing electricity for the next 30 years. We then calculated what the capital cost of OTEC would have to be in the year 2000 (in 1978 dollars) to produce electricity for the same total cost over the same 30 year time period. This is the breakeven OTEC capital cost. Thus, a 2.5 percent growth rate in fuel cost will make OTEC competitive with a coal-fired plant while in order for OTEC to be competitive with a nuclear power plant, it will take more than a 4 percent growth rate in fuel cost. A detailed description of the methodology used in making these comparisons can be found in Ref. 2. In Fig. 8, we assumed no real growth of fuel costs but instead used the potential annual real rate of growth of alternative plant construction costs as a measure for comparison.

CONCLUSIONS

There are a number of potential engineering and construction improvements which could lead to reductions in OTEC capital costs and cost of electricity. Among the several alternatives considered, savings resulting from changes in heat exchanger design (e.g., plate-type instead of the conventional tube-and-shell) and from enhancing the water-side heat transfer mechanism appear to be most significant. Among the island applications considered, the advantage of onshore installations as compared to offshore platforms appear to lie more in the lessening of technological risks (e.g., the elimination of underwater transmission cable or deepwater mooring technologies) and the lowering of operations and maintenance costs, rather than in any dramatic reduction of system costs. For OTEC to be competitive with conventional fuel-burning and nuclear power plants, there have to be significant real growths in fuel costs and/or construction costs of conventional or nuclear plants.

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2. Gritton Eugene C., Richard Y. Pei, Ronald Hess, Quantitative Evaluation of Ocean Thermal Energy Conversion (OTEC), R-2641, The Rand Corporation, August 1980.

OTEC ENGINEERING PERFORMANCE AND COST MODEL

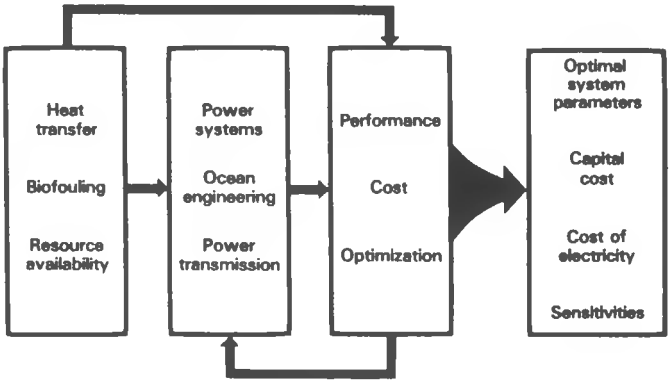


FIGURE 1

DISTRIBUTION OF CAPITAL COST (1978 $)

400 MWe

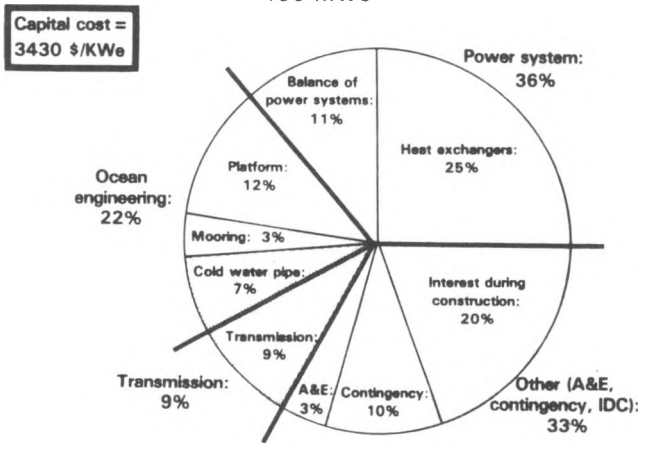


FIGURE 2

EFFECT OF SYSTEM RELIABILITY ON COST OF ELECTRICITY

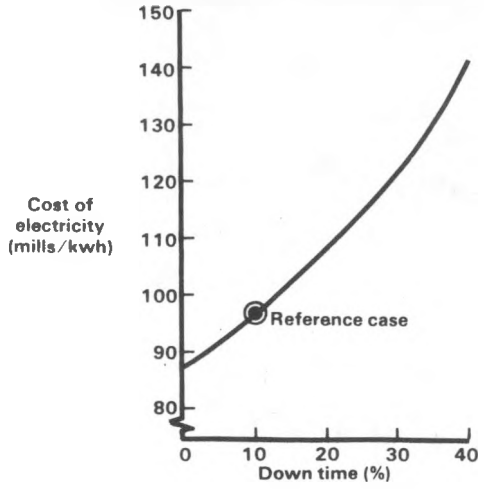


FIGURE 3

ALTERNATIVES

		Capital cost		COE	
		$/kWe	%Δ	Mills/kwh	%Δ
	Reference case	3430	—	96	—
A	Water-side heat transfer enhancement	3140	-8	88	-8
B	Plate HX (from tube and shell)	2930	-15	86	-10
C	FRP cold water pipe (from steel)	3260	-5	92	-4
D	No cable embedment (from 85 nm to 0)	3290	-4	92	-4
E	Construction period (5 years to 2)	3030	-12	86	-10
F	Fixed charge rate (18% to 15%)	3430	0	81	-16
G	Options B, C, D, E, & F combined	2350	-31	60	-38

FIGURE 4

ISLAND SITE: PUERTO RICO

	Reference case Tampa	Platform Puerto Rico	On-shore Puerto Rico
Capital cost by subsystem			
Site acquisition, improvements, buildings	0	0	120
Power system	1235	1235	1332
Ocean engineering			
Platform	408	407	0
Cold water pipe	214	206	628
Mooring	115	47	0
Discharge pipes	(a)	(a)	63
Transmission	328	36	0
Other	1130	939	735
TOTAL	3430	2870	2878
Cost of electricity			
Capital	89	70	70
O&M	7	7	7
TOTAL	96	77	77

[a]Included in platform

FIGURE 5

ISLAND SITE: HAWAII

	Reference case Tampa	Platform Hawaii	On-shore Hawaii
Capital cost by subsystem			
Site acquisition, improvements, buildings	0	0	120
Power system	1235	1235	1285
Ocean engineering			
Platform	408	407	0
Cold water pipe	214	165	314
Mooring	115	37	0
Discharge pipes	(a)	(a)	61
Transmission	328	35	0
Other	1130	911	578
TOTAL	3430	2790	2358
Cost of electricity			
Capital	89	76	64
O&M	7	7	7
TOTAL	96	83	71

[a]Included in platform

FIGURE 6

INCREASING FUEL COSTS MAKE OTEC MORE COMPETITIVE

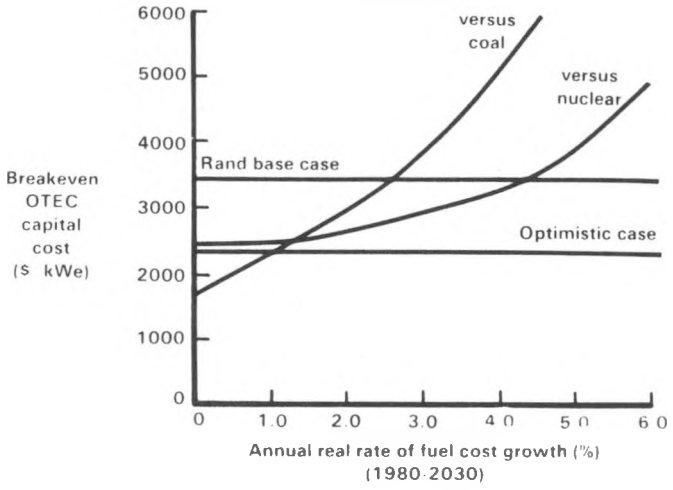


FIGURE 7

INCREASING COAL AND NUCLEAR CAPITAL COSTS MAKE OTEC MORE COMPETITIVE

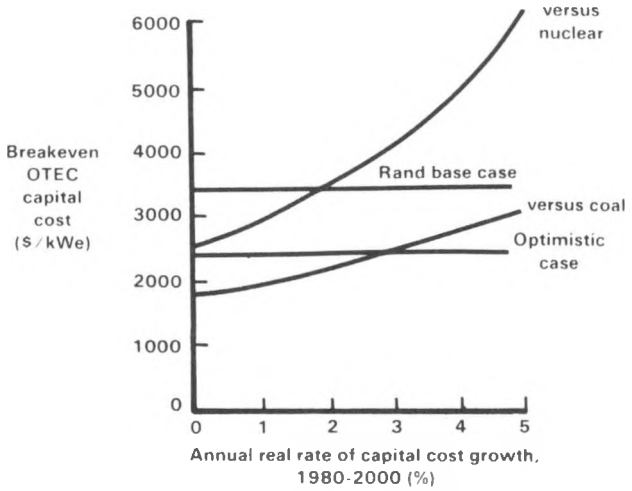


FIGURE 8

8th Ocean Energy Conference
Washington, DC
June 1981

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EFFECT OF PURPA ON OTEC ECONOMICS

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ABSTRACT

Under the National Energy Act of 1978, the electricity surplus of an Ocean Thermal Energy Conversion (OTEC) system must be purchased by the electric utility if the OTEC System is owned by a non-utility entity. In order for an OTEC System to be considered as a qualifying small power production facility, it should meet certain standards which will be addressed in this paper. The Public Utility Regulatory Policies Act (PURPA) of 1978 covers the topics of Cogeneration and small power production under Title II. Under PURPA, the electric utilities must sell and purchase electric power to and from the OTEC systems owner. There are federal and state guidelines for electricity sale and purchase prices that must be considered. The electricity purchase prices are to be based on the utility's avoided capacity and energy costs.

The electric utility is to establish a methodology or a pricing mechanism to purchase the electricity surplus. These rates have to be "just and reasonable" to the electric consumers of the electric utility and in the public interest. These rates must not discriminate against qualifying small power producers. There are general requirements that the electric utility must meet. These obligations include: the requirement to file the cost-of-service data for the electric utility's system, and establish electric rates for selling and purchasing power to and from the OTEC System owners.

Various methodologies of calculating the avoided costs will be discussed in this paper. These different methodologies are based on similar principles which include fuel displacement, fuel cost escalation, fuel use distribution, operation, and maintenance costs and capacity credits.

This paper will also discuss other factors that determine avoided energy and capacity costs. These factors include the utility's system characteristics, such as generation mix, system reliability, load characteristics, fuel mix, planned generation and transmission facilities, geographical location, access to fossil fuels and their availability, etc.

Recommendations on how the avoided energy and capacity costs are calculated will also be made.

INTRODUCTION

The ocean thermal energy conversion (OTEC) is one of the solar electric power applications. The OTEC concept is based on utilization of temperature difference between the surface and deep waters of oceans. In tropical oceans the large amounts of solar radiation is collected and stored as thermal energy in their surface waters and the deep waters temperature remains approximately in the range of 35 to 40°F. The OTEC facilities utilize the temperature differential to generate electric power.

The idea of using temperature differences in ocean water to produce electricity is approximately 100 years old (1). Jacques D'Arsonval proposed building an OTEC facility in 1882, thirty two years later his concept was implemented by George Claude in 1920. This experimental OTEC facility operated in Cuba and unfortunately was destroyed by storms.

In the past seven years the subject of OTEC facilities has gained not only recognition but many organizations have carried out research and experimentations to develop that type of solar electric technology. Two acts were passed on the OTEC subject in 1980.

The OTEC source of energy is an important one and can not be neglected, especially in time of rising fuel costs. The most discussed OTEC facilities (2) are the following:

1. A power producing OTEC facility
2. An ammonia producing OTEC facility
3. An aluminum producing OTEC facility

The economics of OTEC depend primarily on the capital cost of constructing OTEC plants and the cost per kilowatt hour of the produced energy. There are still unknown cost which will determine whether or not OTEC is economically feasible.

NATIONAL ENERGY AND OTEC ACTS

There are primarily five acts that affect the development of the OTEC facilities. The acts are as listed below:

1. Public Utility Regulatory Policies Act (PURPA) of 1978 (3)
2. Ocean Thermal Energy Conversion Act of 1980(4)
3. Ocean Thermal Energy Conversion Research, Development and Demonstration Act of 1980 (5)
4. Energy Tax Act of 1978 (6)
5. Crude Oil Windfall Profit Tax Act of 1980 (7)

The Energy Tax Act of 1978 and the Crude Oil Windfall Profit Act of 1980 will be addressed in another paper.

The Public Utility Regulatory Policies Act of 1978 has under its Title I and II definitions and standards for rate making and guidelines for utilities-rate payers relationships. The main purposes of title I are to encourage the following:

(1) conservation of energy supplied by electric utilities

(2) the optimization of the efficiency of use of facilities and resources by electric utilities, and

(3) the development of equitable rates to electric consumers

One of the six rate standards that will have a positive effect on OTEC systems development is the "Declining Block Rates" standard. This rate standard deals with the energy component of a rate schedule. The amount attributable to the energy component in a rate, charges by any electric utility for providing electric service during any period to any class of electric consumers may not decrease during such period provided that cost of such energy does not decrease when the consumption increases.

Sections 201 and 210 of Title II, provide definitions for cogeneration and small power production facilities and guidelines for utilities to purchase and sell electricity to cogenerations and small power producers. An OTEC facility with less than 80MW is considered a small power production facility. The final rules and regulations on the subject require electric utilities to:

(1) sell electric energy to qualify-cogeneration facilities and qualifying small power production facilities and

(2) purchase electric energy from such facilities

The rates for purchases by electric utilities must be just and reasonable to the electric consumers of the electric utility and in the public interest, and must not discriminate against qualifying cogenerators or qualifying small power producers. The rates for purchasing electricity should be based on the Utility's avoided costs.

The OTEC Act of 1980 establishes procedures for the location, construction and operation of OTEC facilities and plantships to produce electricity and energy-intensive products off the coast of the United States. It also, amends the Merchant Marine Act of 1930, makes available certain financial assistance for construction and operation of OTEC facilities and plantships.

Under the Ocean Thermal Energy Conversion Act of 1980, an OTEC facility is defined as a facility which is standing or moored in or beyond the territorial sea of the United States and which is designed to use temperature differences in ocean water to produce electricity or another form of energy capable of being used directly to perform work, and includes any equipment installed on such facility to use such electricity or other forms of energy to produce, process, refine or manufacture a product, and any cable or pipeline used to deliver such electricity, fresh water, or product to shore, and all other associated equipment and appurtenances of such facility, to the extent they are located seaward of the highwater mark.

The Ocean Thermal Energy Conversion Research, Development and Demonstration Act of 1980 is an act to provide for a research, development and demonstration program to achieve early technology application for the OTEC systems and other associated purposes.

AVOIDED ENERGY AND CAPACITY COSTS ESTIMATIONS

Capacity costs are the fixed costs to generate, purchase, transmit and distribute the electric power. Energy costs are the variable costs to produce (fuel, and O&M), purchase, and deliver the electric energy.

The term avoided cost is self-explanatory but is almost impossible to calculate accurately. Estimates of avoided energy and capacity costs are possible and involve making assumptions and judgments that always can be challenged. The assumptions and judgments stem from the fact that these estimations are based on load, fuel cost, capital costs forcasting, system planning, construction schedules, and future occurrences. All qualified cogenerators and small power producers including OTEC power producers collectively determine a better estimation for the avoided costs for the total capacity and energy available. The aggregate purchased power costs to the electric utility should be equivalent to its true (estimated) avoided costs in order for the rates to be just and fair to all the rate payers. State Public Utility Commissions have the responsibility for assuring that payments to power producers do no exceed the avoided costs as well as not being less than these costs. The quality of the produced power by an OTEC facility and the characteristics of the purchasing utility will determine the value of the electric power. The quality of the OTEC-produced power is influenced by many factors which include, forced and planned outage rates and durations, its availability during the utility's peak periods and emergencies, and OTEC contract duration and expected economic life of an OTEC facility. The utility's system characteristics are of great importance in determining the avoided capacity and energy costs. These characteristics include: present and future fuel costs, fuel mix, purchased energy costs, generation expansion program, construction schedule, estimated installed costs for their generation units, cost of money and the utility's financial picture, capacity factors and the quality of its own generated power.

In general if the power producing facility has a power quality equal with the utility's, then it deserves the full avoided costs otherwise judgement and negotiations will be needed.

METHODOLOGIES OF ESTIMATING THE AVOIDED CAPACITY AND ENERGY COSTS

If an OTEC facility offers non-firm power to an electric utility, then the utility will compensate the OTEC facility with an energy credit only. This energy credit is calculated and based on the cost of energy that would have been consumed by the utility had the OTEC not been in operation. The kilowatt hours delivered by the OTEC facility should be time differentiated related so the actual avoided cost can be determined provided that the benefit/cost ratio is greater than one. The cost of that energy depends on fuel costs, operation and maintenance expenses, cost of purchased power, heat rate, etc. Customer charge which includes administrative billing and metering costs can be relatively high for a small OTEC facility. The utility can offer an alternative pricing scheme based on its average monthly fuel costs. Doing this would eliminate the need for a more sophisticated metering and would reduce the administrative costs.

On the other hand, if the OTEC facility offers firm power, and is reasonably reliable, then the avoided costs would include capacity and energy costs which are estimated by either of the two methods. These two methods are discussed as below:

1. Revenue Requirements Method

This method can be used only if the utility has good generation expansion and financial planning models. Many projected amounts with good accuracies are required for such model to reveal actual avoided costs. Various assumptions are to be made to forecast different quantities including capital costs of planned generation plants in the next 10 to 15 years, construction work in progress (CWIP) inclusion in the rate base, load demand growth rates, capacity factors, allowed return on equity, operation and maintenance expenses, taxes, fuel costs, future penetration levels of power producing facilities including the OTEC facilities and any other factors which affect the annual revenue requirement. Although many utilities are required by law under, PURPA, sections 133 and 210 to file most of such data. It is still quite difficult for many of them to construct the above mentioned models and calculate the avoided energy and capacity costs. Under this method the utility's revenue requirements are calculated in two ways with and without the expected power producing facilities. The difference between the two figures would determine a basis for negotiation for the avoided capacity and energy costs.

2. Average Incremental Capital and Energy Costs Method

This method may produce less precise results but easier to estimate the avoided capacity and energy costs. The basic principle of the average incremental costs method is the same as the revenue requirements method. The avoided costs are based on the long-range estimates of the utility's future costs. The advantages of this method include not needing estimations of power producing facilities penetration levels and sophisticated financial planning model, etc. Instead of estimating the aggregate capacity of power producing

facilities and estimate its impact on the utility's construction plan, the utility's expansion plan is revised each time one or more power producing facilities is (are) integrated with the system. This method uses the data already required by law (PURPA, Section 133 and 210).

A mathematical formulation of this method is shown here. If the power producing facility (PPF) delivers energy on a "when if available" basis, then there will be no avoided capacity cost. The avoided energy cost (AEC) is estimated as the following:

AEC(i) = TFC(i)/TED(i) ¢/kwH

Where

AEC(i) = Avoided energy costs during period (i) in ¢/kwH

TFC(i) = Total fuel cost during period (i) in cents

TED(i) = Total energy delivered to the utility's ultimate customers during period (i) in kwH's

The TFC and TED are estimated by using the following formulas:

TFC(i) = UFC(i) + PFC(i) ¢

TED(i) = UEG(i) + PE(i) kwH

Where

UFC(i) = Utility fuel cost, consumed in all generating units during period (i) in cents

PFC(i) = Purchased energy (fuel) cost during period (i) in cents

UEG(i) = Utility energy generation during period (i) in kwH's

PE(i) = Purchased energy from all other sources in kwH's

The avoided capacity cost (ACC) is estimated by using the following formulas:

ACC = TCC/TC $/kw/yr

Where

TCC = Total Capacity Cost in dollars/year

TC = Total Capacity in kilowatts

And

TCC = UCC + PCC $/yr

TC = UC + PC kw

Where

UCC = Utility Capacity Cost in dollars/year

Where

UCC = Utility Capacity Cost in dollars/year

PCC = Purchased Capacity Cost in dollars/year

UC = Utility Capacity in kilowatts

PC = Purchased Capacity in kilowatts

And

UCC = CC X Acch $/yr

Where

CC = Installed Capacity Cost of all generating units

Acch = Annual Carrying charge rate

It is not necessary for the utility to pay the Power Producing Facility (PPF) 100% of the estimated avoided capacity cost. A judgment will be exercised and the (Acc) will be discounted with a factor in the range of 0 to 1.

OTEC ECONOMICS AND CONCLUSION

The economics of OTEC Systems are highly dependent on many variables including construction cost, available thermal resource, achieved plant capacity factor, financing costs, operation and maintaining the electrical transmission lines underwater. While studies of OTEC completed to date may not indicate overwhelmingly favorable economics, over the long term, with the expected price escalation of fuels, OTEC could prove to be a viable alternative method of electricity generation.

For the ammonia and aluminum producing OTEC facility, there are other variables that influence OTEC's economics. These variables include the availability and price of competing Middle East ammonia production based on low cost gas and the worldwide demand for aluminum.

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THE FINANCING OF OTEC PROJECTS

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ABSTRACT

A key item that will impact the implementation of a commercial OTEC project is the availability of attractive tax incentives. The following is a summary of some of the incentives available under the present fiscal structure and under various public programs. The continuation of some of these programs is uncertain.

It is probable that an OTEC project would benefit from the following:

a. Investment tax credit (ITC) of 25.0 - 30.0% available to solar projects. The credit may be deducted in the first year of operation, but can be spread over several years or carried forward in its entirety and applied against future income.

b. Accelerated depreciation writeoffs, with the specific details depending on the particular types of equipment used.

c. DOE direct funds investment (available under current programs), i.e. cost sharing for production facilities.

d. Leveraged leasing and/or tax-sheltered financing, but contingent on the availability of U.S. government guarantees.

e. Federal loan guarantees for investors.

f. Maritime Administration Title Xl mortgage guarantees. These are essential for the successful financing of the project.

Other incentives that can be pursued include:

- government-furnished equipment for production facilities.
- cost differential subsidies and guaranteed purchases.
- federally guaranteed loans for manufacturers.

Potential ownership options to be reviewed will include both private and public investors as well as combinations of both.

INTRODUCTION

The successful financing of OTEC projects will most likely require the use of project financing, with funds provided from combinations of private and public sources.

The necessity for financial packaging arises from the fact that there is uncertainty about the eventual successful technical (and commercial) outcome of such projects due to lack of precedent experience. As a result investors and lenders may be unwilling to assume the financial risks without the financial participation of public agencies.

Thus, an OTEC project should give consideration to such potential combinations of financing sources and methods as:

a. Maritime Administration (MARAD) Title XI mortgage guarantees.

b. Leveraged leases and tax-sheltered financing.

c. Research and development financing - Federal and tax-sheltered.

d. DOE direct financing and/or guarantees.

e. Federal Loan Guarantees.

f. Government-furnished equipment for production facilities.

g. Cost differential subsidies and guaranteed purchases.

h. Federally guaranteed loans for manufacturers.

In addition an OTEC project would be entitled to utilize:

- Accelerated depreciation writeoffs.
- Investment tax credits.

All of the above are described in the

following sections.

MARITIME ADMINISTRATION (MARAD) TITLE XI MORTGAGE GUARANTEES

MARAD guarantees are applicable to OTEC projects under the amendment (Section 202 of Public Law 96-320 of August 1980) to Section 1101 of the Merchant Marine Act Under Section 1110 the Secretary of Commerce may, on a case by case basis, guarantee or make a commitment to guarantee payment of the principal and interest on an obligation which aids in financing, including reimbursement of an obligor for expenditures previously made for construction, reconstruction, or reconditioning of a commercial OTEC facility or plantship owned by citizens of the U.S.

This is clearly one of the best methods for financing a large percentage of the cost of an OTEC project.

Under Title XI the owner has access to attractive incentives for the construction of U.S. ships, barges, etc. These include:

a. MARAD guaranteed bonds which are easily marketable at the best possible rates available in the U.S. capital markets. Guarantees cover up to 87.5% of the actual cost or depreciated cost of the facility. The maximum coverage of the guarantee depends on whether a construction differential subsidy is applicable to the transaction. These guarantees will not be available before October 1, 1981.

b. A leveraged lease can be arranged that uses Title XI bonds as the long term debt in the package. The availability of MARAD guaranteed bonds provides the project with a ready leveraged lease option.

c. Progress payments during construction can be financed through the use of MARAD guaranteed notes.

MARAD - guaranteed bonds may be issued for periods up to 25 years and in the form of serial or sinking fund bonds. Note(s) to a single lender may be guaranteed and can be used to support construction financing.

MARAD charges annual fees for its guarantees, in the range of 1/8% to 1/2% during the construction period and from 1/2% to 1%.

Other variations of MARAD financing and options available to investors include:

- Short-term notes may be issued against a MARAD guarantee to cover financing needs during construction and replaced by MARAD guaranteed bonds upon delivery of the facility. Equity must be contributed prior to takedown of bonds or notes on a basis acceptable to MARAD.
- The interest cost for MARAD guaranteed bonds will be that prevailing for U.S. government guaranteed debt.
- An investor's loan and lease covenant restrictions can be circumvented by using an unrestricted subsidiary to hold title to the facility.
- The investor may be able to obtain financing for its equity interest in the vessel (12.5 - 25.0% of the capital cost) by entering into a long-term contract with the buyer of the output of the plant (e.g. a major utility) to service MARAD debt, pay operating costs, and service the debt to provide the 100.0% financing. The obligation of the buyer of the electricity must be unconditional.
- The investor can claim the investment tax credit and depreciation.

LEVERAGED LEASING AND/OR TAX-SHELTERED FINANCING

The use of leveraged leases and tax-sheltered financing is a viable way to support the construction and operation of an OTEC project.

Under this arrangement the lessors (investors) provide some of the financing in the form of equity, with the bulk of the funds being debt. The debt could be secured by a "take-or-pay" contract which would ensure that the output of the plant was purchased by a creditworthy party. Thus, the repayment of interest during construction as well as of principal and debt to lenders would be guaranteed by the buyers of the output of the OTEC plant.

At the same time investors can avail themselves of the investment tax credit, accelerated depreciation writeoffs, and interest payment deductions in their individual tax returns.

D.O.E. RESEARCH FUNDS

The exact future role of D.O.E. is difficult to assess at the present time.

However, under existing D.O.E. program

R&D funding is available for OTEC R&D. Large funding commitments may be difficult to obtain until the technology has been proven.

To make an OTEC project viable, DOE could, by showing some flexibility, make available a portion of the funds to be used for R&D. Long-term financing, in 5-15 year maturity ranges, is best suited for OTEC since it would provide the project with sufficient operating time to recoup the initial costs and to repay private investors who are assuming large risks.

FUNDING R&D THROUGH TAX SHELTERS

This method uses tax-sheltered investment partnerships to finance a small portion of the OTEC research and development cost.

The partners who will derive the greatest benefit from this arrangement will need tax writeoffs against their personal income. Tax benefits can be written off almost immediately against the partners' personal income.

The arrangement would provide for the partnership to own some of the rights to the OTEC system, which may have given to a utility or industrial concern an exclusive option to buy back the system if it proves to be successful. If the project sells its output as estimated, then the partners can receive royalties from the sale of the technology which are taxed at the lower capital gains rate. The royalties to the partners can be substantial, depending on the revenues of the project, thereby providing a large return over the life of the project.

The following represent some of the principal advantages and disadvantages to investors in tax-sheltered R&D programs:

1. Tax-sheltered Investments

   Advantages:

   a. Financing does not appear on investors' balance sheets and will not increase leverage.

   b. Financing does not increase R&D or interest expense on the investors' balance sheets.

2. Use of Limited Partnership

   Advantages:

   a. Provides partners with immediate tax benefits since R&D costs can be charged against their personal incomes.

   b. The partnership owns the rights to the R&D developed, for which the project builder may arrange an exclusive option to buy it back if the results are successful.

   c. Partners can receive royalties from the sale of the technology, which are taxed at the lower capital gains rate.

   d. The limited partners bear all the risk of the development effort.

   e. Partners benefit from the profits or the project after a few years of operation.

   Disadvantages:

   a. Royalty payments to limited partners can be high, i.e. the cost of money to the builder is higher than conventional borrowing costs.

   b. There is no guarantee that the IRS will accept the tax treatment of the partnership. This uncertainty may make the organization of the financing difficult to complete.

DOE DIRECT FUNDS INVESTMENT

A direct investment by DOE will help make an OTEC project feasible.

Such direct participation can take the form of a direct equity investment of a temporary nature, whereby DOE purchases and owns shares of the project for a period of time until it proves to be profitable. At that time DOE can give the other investors a first chance to buy some or all of the shares it holds at a price to be agreed on, or to sell the shares to new investors.

The participartion of DOE in the manner described would:

   a. provide funds to the project.

   b. encourage other investors to participate in the projects.

   c. make it possible for the investing group to have funds for working capital and other uses.

   d. ensure that the project is ultimately run as a private enterprise when DOE sells its shares to private sector interests.

FEDERAL LOAN GUARANTEES

Federal loan guarantees, such as those provided by DOE, are an essential ingredient for an OTEC project to be successful in borrowing both short and long-term funds.

The issuance of medium to long-term bonds/debt guaranteed by the Federal government ensures that:

a. the funds can be acquired by the ready sale of debt instruments to private interests or to the public.

b. the cost of funds to the project is obtained at the lowest rates since the credit of the Federal government is involved.

c. repayment of the debt is spread over a sufficiently long period of time to enable the project to generate sufficient funds to repay the loans and interest.

If the commercial facility or plantship is supported with appropriated Federal Funds, such guarantees or commitments to guarantee may not exceed 87½% of the aggregate principal amount.

GOVERNMENT-FURNISHED EQUIPMENT FOR PRODUCTION FACILITIES

The provision of equipment by Federal goverment agencies to an OTEC project offers a number of important advantages. These include:

a. Financing to cover the equipment is sourced by the government.

b. Federal agencies can obtain funds at low interest cost and on favorable terms because of their prime credit ratings.

c. Government purchasing agencies can negotiate low prices for equipment because of their strong negotiating leverage acquired through massive purchasing programs.

d. Government buying generally requires very high standards of performance and quality control. This assures the project of high quality and equipment.

COST DIFFERENTIAL SUBSIDIES AND GUARANTEED PURCHASES

Cost differential subsidies may be a very important element of an OTEC project because the final technical performance and commercial results cannot be verified with certainty without the benefit of prior experience.

The availability of subsidies guarantees that the project can function economically after start-up and make up for any significant cost overruns in both construction and operational costs. Without the subsidies the risks to investors are great and create the possibility that the project will be scrapped because of overruns and/or uneconomic commercial operation.

FEDERALLY GUARANTEED LOANS FOR MANUFACTURERS

Loans arranged on this basis help to ensure the construction of OTEC equipment, which is "one-of-a-kind" and has no alternative purchasers or applications.

In this way manufacturers would be able to build the equipment without sustaining the risk of non-payment or refusal of equipment by OTEC investors because of lack of sufficient funds or large overruns and the non-availability of alternative buyers.

These loans provide manufacturers with:

a. Funds to purchase the materials and cover the labor and manufacturing costs during construction.

b. Provide funds at low interest rates, with principal and interest repayments arranged over convenient schedules.

ACCELERATED DEPRECIATION

The availability of accelerated depreciation to an OTEC project constitutes a strong incentive to build one.

A schedule would have to be worked out, within the existing accounting and tax codes, to the specific economic results of the project. Individual fixed assets may be entitled to different depreciation rates, depending on the types of equipment used.

Accelerated depreciation does not benefit a project in the short-run where income is generated after several years and where deductions cannot be applied against non-existent income. Tax-loss carryovers would benefit the project in the long-run but would not necessarily need accelerated depreciation writeoffs.

The type of ownership form chosen for an OTEC project will determine how accelerated depreciation can best benefit potential investors. The creation of a partnership would enable investors to apply accelerated depreciation (and other deductions) against their personal incomes from all operations. In this way investors would minimize tax liabilities immediately by utilizing accelerated depreciation writeoffs.

INVESTMENT TAX CREDIT (ITC)

An ITC of 30.0% would be available to an OTEC project. This represents a st

incentive to go ahead with such a project.

The ITC may be taken in the first year of operation or may be spread over several years. The key to the method chosen will, in this case, depend on the profit-generating capabilities of the project. Since an OTEC project will not generate sufficient profits in the early stages of operation, it is likely that the ITC will be spread over several years.

The method by which the ITC is taken, i.e. a full credit against net taxable income, means that an OTEC project may not be subject to taxation for several years.

CONCLUSION

As discussed above, funding of an OTEC project could be arranged through a combination of private/public investment, loan guarantees, and other arrangements.

The key to successful financial packaging of the project will be the particular combination chosen and the availability of sufficient funds from each source to cover the total cost.

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AN ESTIMATE OF OTEC COSTS AND ELECTRIC MARKET POTENTIAL

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ABSTRACT

One key economic requirement for the commercialization of ocean thermal energy conversion (OTEC) is that it produce electrical energy at a cost competitive with baseload sources of electricity that use depletable fuels. Those sources include electricity generated using fuels such as oil, natural gas, coal and uranium.

A review of OTEC energy costs in comparison with other technologies is presented and the method by which they are calculated is also discussed. Based on the estimated probability of least energy cost, the technology characteristics presented and the prevailing economic assumptions, OTEC could provide from 6 to 14 GWe of capacity by the year 2000 depending on scenario.

INTRODUCTION

The oceans store vast amounts of solar energy in the form of heat in the warm surface layers of the ocean. OTEC systems will utilize the thermal differences existing in the ocean to generate electrical power via a heat engine and turbine-generator system. OTEC, as an electricity source, is here considered a utility option. OTEC requires no storage or back-up systems as the oceans retain most of their heat even during periods of cloud cover and darkness. OTEC is attractive as a power-generating system since its expected energy costs may be competitive with a mix of nuclear and coal power systems; it is expected to be environmentally sound and it could displace precious fuels used in other alternative power generation systems.

Estimates of the cost of energy of OTEC and its likely competition are made based on financial and performance assumptions using the revenue requirements methodology. Cost comparisons among competing baseload technologies are offered under financial backgrounds of low and high inflation rates. While early commercial plants can best compete against power plants using increasingly expensive oil and natural gas, OTEC cost projections indicate that mature (8th unit) plants will probably be competitve with coal plants in the 1990s, assuming that the cost of coal increases at one or two percent above the inflation rate. OTEC power plants will begin to become economically competitive with nuclear power plants in that time frame if likely escalation of uranium costs occur.

If the other major attributes of generating technologies are more or less equivalent, energy cost can be the major determinant in choosing among technologies. Energy cost is then used as a figure of merit for estimating the projected market capture that OTEC may achieve under a variety of incentive and economic scenarios. On a year-by-year basis, the baseload generating technology which most likely will possess the lowest energy cost is assumed to satisfy the incremental demand in that year. OTEC market penetration is estimated on that basis.

OTEC technology is projected to be cost competitive with other likely baseload technologies in the 1990s time frame. While there are still significant technical and financial difficulties to be resolved and investment risks to be addressed. OTEC has the potential to offer the nation a renewable source of electric power. Before the year 2000, OTEC could help meet the energy growth plans of some utilities and industry and displace existing oil- and gas-fired capacity that is to be converted under the Fuel Use Act and other prohibitions.

BRIEF REVIEW OF THE UTILITY PLANNING PROCESS

The utility planning process provides the utility an estimate of load growth, generating requirements to meet the load, the timing of new capacity, and a construction management plan that will meet customers needs for power and reliability and minimize the revenues required to achieve the system objective. A fairly detailed discussion of the planning process is given by the Florida Power and Light Co. (1). The process, in its details, can be very complicated. Computer modeling of general economic conditions, generating system reliability and load dispatching, projected intertie power purchases and sales, corporate cash flow analysis, and financial evaluation of overall system configurations are all part of the planning process.

The process begins with a series of economic assumptions that yield trends for load growth over the planning period. Several capacity expansion scenarios are then defined that can achieve the expected generating requirements over a long period, generally 20 years. Early in this process, estimates of financial risk to the company associated with each scenario are estimated. The estimates include such factors as expected

regulatory constraints and the availability of fuel and the possibility that emerging technologies may not meet the market entry date proposed or the cost and performance characteristics expected of them.

Each alternative generating system scenario is tested by a computer program that simulates the utilities generating and dispatching characteristics. The program includes stochastic analysis of the reliability of each generating unit on line based on operating data or experimental information if a technology has no commercial history. Each scenario is measured against a basic system reliability criteria. Any scenario that is substantially below that criteria is unacceptable and is not included in further evaluation.

The expansion scenarios remaining are compared using another computer analysis; one that models the company's financial situation over time. The corporate model simulates corporate cash flows, and rate increases over time for each expansion scenario. Each scenario is evaluated to determine if it can be financed through the ability to borrow and issue stock based on the viability of the corporation as determined from the cash flow sequence. Then, the scenarios are evaluated by comparing the revenues required over the planning period to meet all expenses including return on equity.

The scenario that achieves the lowest revenue requirement while still maintaining an acceptable level of reliability is considered to be the most attractive. Further study examines the adequacy of power transmission facilities and addresses siting requirements and interconnection possibilities.

Finally, the planning group will recommend a plan for expansion that reflects minimum revenue requirements and acceptable reliability that can be adequately financed and meets the constraints of schedule as much as possible.

Approximation of Utility Planning Procedure

Planning capacity expansion in detail is a necessity for individual utilities to carry out their business affairs. However, application of detailed utility planning models to a developmental technology in a regional or national context would be a very expensive and cumbersome undertaking. For purposes of national or regional analysis an alternative methodology is used here.

The methodology, employed in the MITRE SPURR model (2), utilizes several basic inputs. The inputs that must be developed are similar to those of the utility planning model but more general:

- potential demand scenario, regionalized
- potential competition
- characteristics of the competition
- financial assumptions.

This approximate method seeks to satisfy the externally specified demand scenario with various types of generating capacity on an annual basis. The choice among competing technologies is made based on the probability that any one among the competition will have the lowest cost of energy. The technology most likely to possess the lowest energy cost in a given year is then assumed to be chosen to satisfy the demand subject to the constraints imposed on its production and use. The primary figure of merit used in the model is a consistently calculated value of the range of energy costs associated with the various technologies in competition.

CALCULATING ENERGY COSTS

The minimum price charged for a product must, in general, be such that the revenue generated from sales of the product over a period of time are sufficient to recover the costs of producing the product, including a fair rate of return on equity. The basic components of product cost can be identified as: capital-related charges, operating and maintenance charges, and feedstock or fuel charges.

Capital-related charges are those associated with amortizing, or paying off, the money borrowed to construct and purchase capital equipment necessary in making a product. These charges include principal and interest on the capital and the appropriate adjustments for taxes, tax credits, and depreciation. Interest and escalation during construction, insurance, and property taxes are also accounted for as part of the capital-related charges.

Operating and maintenance charges generally include employee salaries, spare parts that are used in replacing worn components of machinery, utility charges, and general maintenance of the manufacturing facility.

Feedstock or fuel charges are those associated with the raw materials that are converted by the manufacturing processes to a finished product. Synthetic crude oil, for example, can be produced using coal as a feedstock and electricity can be produced using oil as a fuel. In the revenue requirements method, the sum of the three components of cost must be equal to the revenues generated from product sales. Annual required revenues change from year to year due to such factors as inflation of fuel and O&M costs, the evolving tax position of the enterprise, and the structure of the remaining capitalization.

A firm could be analyzing various technologies to determine which one is the most cost effective to produce the given product. The investments invariably require different patterns of expenditures and yield different patterns of revenues. Investment alternatives with dissimilar cash flows require a common basis upon which to compare their relative merits. One such method of comparison is to convert the varying cash flows of each alternative to an equivalent constant (levelized) cash flow for each year of the investment's life. The equivalent constant yearly cash flow divided by the amount of product manufactured

ach year represents the levelized revenue required from the sale of each unit of product.

Stated slightly differently, the present worth of the time varying revenue requirements is calculated and converted to a uniform annual series of payments that is financially equivalent to the original annual revenue requirements stream. This levelized cost allows a single value to represent the life-cycle unit-cost of energy products.

The levelized stream of payments can be represented either in nominal or real terms. A nominal stream is simply like a conventional mortgage. A constant number of dollars is paid annually regardless of inflation. While the payments stay constant in inflationary times, the value of the payment, in real terms, declines with time. The real dollar stream is based on the assumption that the number of dollars required annually will increase with the inflation rate. In this case, a constant number of "real" dollars is paid annually but they are paid in the dollars of the current year which are related to the real dollars by the inflation rate.

This revenue requirements analysis provides the framework within which OTEC can be compared with other energy technologies under various financial, economic, and performance scenarios. OTEC is a capital-intensive technology and most of the revenue required per unit of output is associated with capital-related charges. Because it is a renewable energy technology its fuel component is zero. Conventional power plants, however, do consume fuel to produce power. Depending on the technology and fuel used, fuel expenses can account for the majority of required revenue for these technologies, while capital charges can be relatively small.

FINANCING AND ECONOMIC ASSUMPTIONS

Values of the financial parameters required for the analysis described above are presented in Table 1. Two cases are considered. One that assumes a rate of inflation of 10 percent (near current levels) and a second with a more moderate rate of 6 percent. The corresponding values of the financial parameters are shown in Table 1 for private and public ownership.

TABLE 1.

FINANCIAL AND ECONOMIC ASSUMPTIONS

PARAMETERS	CASE 1 LOW INFLATION		CASE 2 HIGH INFLATION	
	PUBLIC	PRIVATE	PUBLIC	PRIVATE
General inflation rate (percent)	6	6	10	10
Debt fraction (percent)	100	50 (87.5)*	100	50 (87.5)*
Debt rate (percent)	8	8	13	13
Equity rate (percent)	NA	12	NA	18
Investment tax credit (percent)	0	10	0	10
After-tax cost of capital (percent)	8	8	13	8*
GENERAL				
Financial life (years)	30			
Tax life (years)	20			
State and federal tax (percent)	50		not applicable for public ownership	
Insurance and property tax (percent)	2			
Real capital cost escalation (percent)	0			
Real O&M escalation (percent)	0 - 2			
Real fuel cost escalation (percent)	0 - 2 for coal 2 - 4 for oil and nuclear			

*Federally mandated loan leveraging for OTEC.

Specific legislation (PL 96-320) allows investors in OTEC to qualify for a government guaranteed loan through the Maritime Administration. Up to 87.5 percent of the cost of an OTEC plant may be borrowed in this way at interest rates generally comparable to those paid by credit worthy corporations. The capital structure relating to other technologies is assumed to be 50 percent debt and 50 percent equity financing, which is more typical in the utility industry. Public ownership of power plants is usually financed through bonding authority. This allows the municipality to borrow 100 percent of the money required to build the plant. But the weighted cost of capital or discount rate is almost equal for public and private ownership due to the availability of tax credits for private owners.

The rates at which fuel and operating costs increase over the life of the system are critical in the economic analysis. Price escalation of power plant coal and plant operation and maintenance costs are assumed to range from a rate equal to the inflation rate on the low side to two percent above inflation on the high. Oil and nuclear fuel price escalation are assumed to range from two to four percent above inflation.

TECHNOLOGY CHARACTERIZATIONS

The supply of liquid and gaseous fuels is expected to become critical in the 1980s and 1990s. Most projections show irreversible declines in U.S. oil and gas production, barring development of new and acceptable techniques of recovering oil from the huge western shale deposits. Conventional thinking has it that coal and nuclear power are the only large-scale alternatives to oil and gas that could contribute to U.S. energy supply before 2000. OTEC then must be in competition with coal and nuclear power to satisfy demand for new generating plants. In the islands, the continued use of oil-fired capacity may still be a baseload alternative.

Table 2 presents the technical characteristics of each of the generating technologies that have been chosen for comparison with OTEC. The cost and performance values of OTEC's competition have been taken from EPRI (3) with the exception of capital cost for nuclear power plants. Instead, these costs were based on more recent reported and projected costs by Weinberg (4) which are somewhat higher.

TABLE 2

SUMMARY OF SYSTEM CHARACTERISTICS

SYSTEM CHARACTERISTICS	OTEC* (MAINLAND)	OTEC** (ISLAND)	CONVENTIONAL COAL	COAL AFBC	OIL-COMBINED CYCLE	NUCLEAR LWR
Capacity (MWe)	400	250	50	50	300	1,000
Capacity Factor (percent)	79	84	70	70	70	70
Heat Rate (Btu/kWh)***	N/A	N/A	10,150	10,250	7,520	10,700
1980 Cost of Fuel ($/10^6 Btu)†	N/A	N/A	1.75	1.75	5.75	0.51
1980 Specific Fuel Cost (mills/kWh)	N/A	N/A	18	18	43	5
1980 O&M Costs Range (mills/kWh)	8.20	8.20	6.20	3.36	1.98	2.19
Capital Cost ($/kW)	2,660	3,190	855	750	403	1,500
Capital Cost Range (percent)	-20/+40	-20/+40	-8/+16	-11/+16	-11/+16	-10/+20
Construction Time (yr)	3	3	5	4	1	7

*8th 400 MWe plant.

**2nd 250 MWe plant.

***Average annual load.

†Delivered cost--equivalent to $42/ton coal, $33/bbl oil.

Since commercial-scale OTEC plants are still in the conceptual phases, projected commercial system costs are based on a critical analysis of a composite of available system studies and experimental data. Costs for each OTEC component and subsystem depend upon key assumptions, such as the selection of materials and configurations for heat exchangers. Accordingly, the projected cost of an entire system will vary with the ultimate cost of subsystems. Also, system integration and cost optimization will likely enable certain system economies that are not apparent when simply adding the probable costs for subsystems.

In "OTEC Cost Forecast Trees" (5), cost data derived from the OTEC development program were analyzed and evaluated. This resulted in preparation of OTEC technology cost forecast trees for both island locations, such as Puerto Rico, and for Gulf Coast locations. An example for New Orleans is shown in Figure 1. This illustration pertains to several technological options for heat exchanger, platform, and cold water pipe (CWP) designs, and represents the eighth 400 MWe power plant off New Orleans. A combination of choices for the several technological options leads to the total system costs shown in the right-hand column. The first 400 MWe plant off New Orleans would have probable projected costs as shown in Figure 2. Through learning and system optimization resulting from experience, cost reductions associated with the transition from Figure 2 to Figure 1 can be anticipated.

Note that the capacity factor shown in Table 2 for OTEC plants is higher than for the conventional plants. This is based on the assumption that OTEC plants would be given top priority in dispatching and would be online whenever available. This seems reasonable since, with no fuel input, the OTEC plant costs the same to operate when idle as when at full power. Other technical and cost characteristics for OTEC are shown in Table 2 with the other technologies.

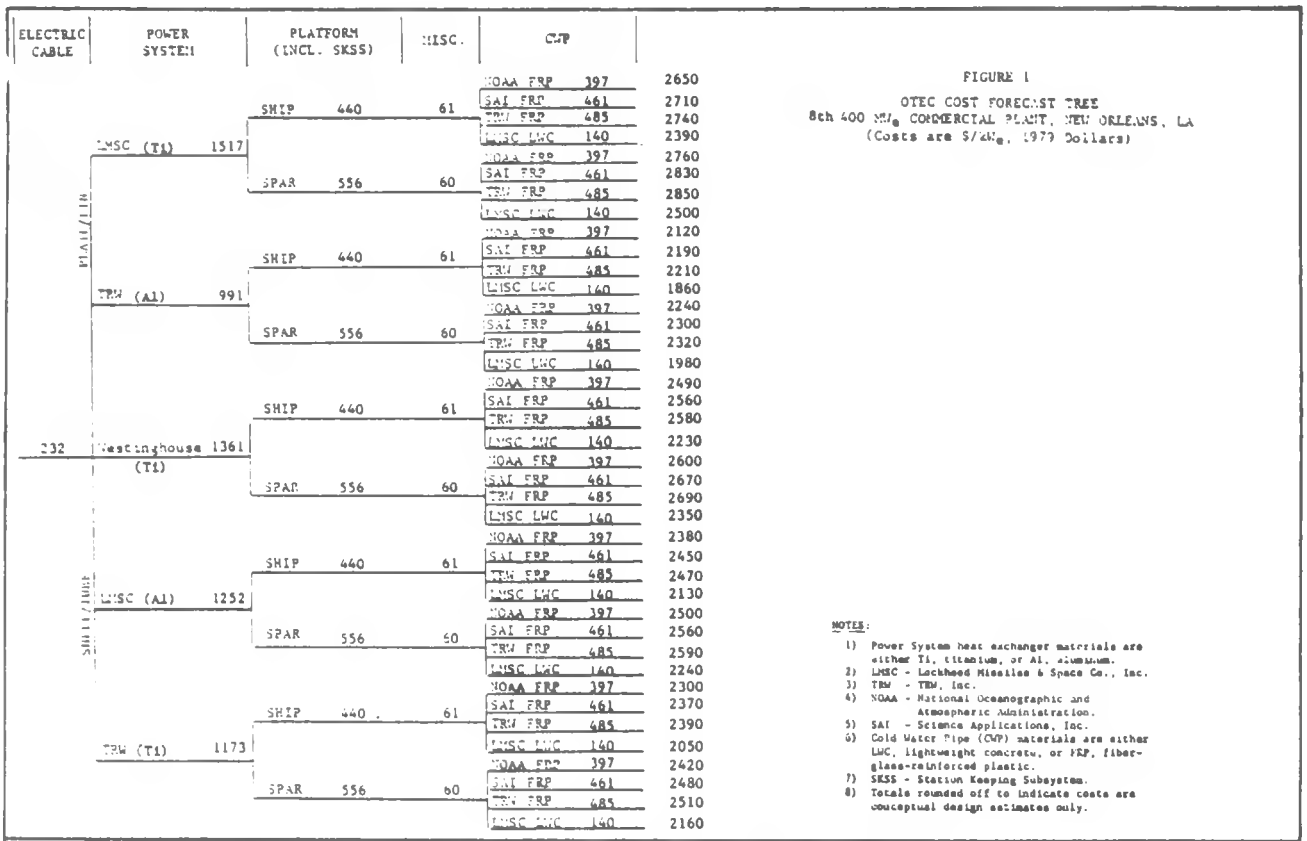


FIGURE 1

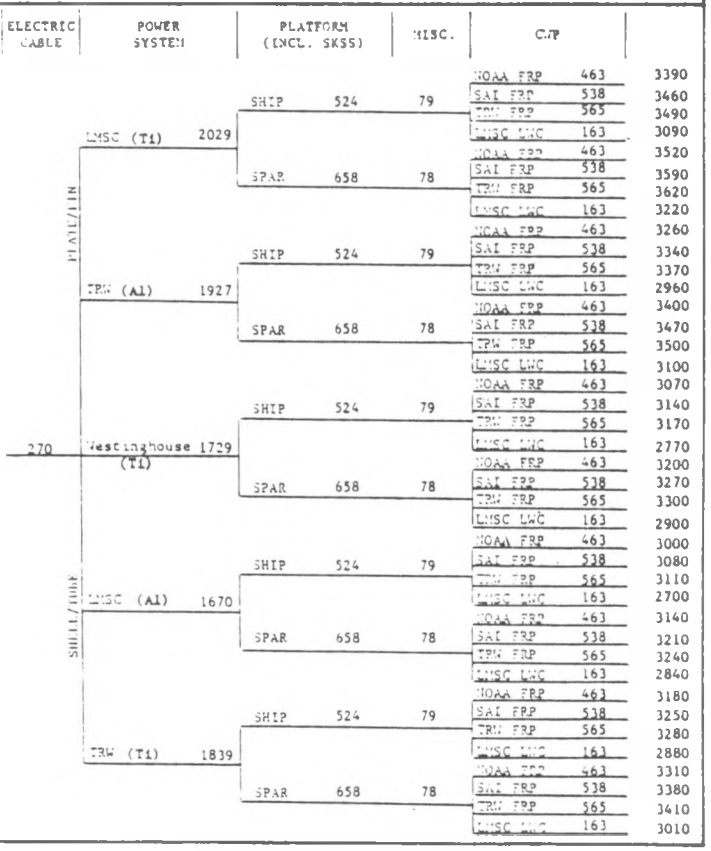
OTEC COST FORECAST TREE
8th 400 MW_e COMMERCIAL PLANT, NEW ORLEANS, LA
(Costs are $/$kW_e$, 1979 Dollars)

NOTES:

1) Power System heat exchanger materials are either Ti, titanium, or Al, aluminum.
2) LMSC - Lockheed Missiles & Space Co., Inc.
3) TRW - TRW, Inc.
4) NOAA - National Oceanographic and Atmospheric Administration.
5) SAI - Science Applications, Inc.
6) Cold Water Pipe (CWP) materials are either LWC, lightweight concrete, or FRP, fiberglass-reinforced plastic.
7) SKSS - Station Keeping Subsystem.
8) Totals rounded off to indicate costs are conceptual design estimates only.

FIGURE 2

OTEC COST FORECAST TREE
1st 400 MW_e COMMERCIAL PLANT, NEW ORLEANS, LA
(Costs are $/$kW_e$, 1979 Dollars)



NOTES:

1) Power System heat exchanger materials are either Ti, titanium, or Al, aluminum.
2) LMSC - Lockheed Missiles & Space Co., Inc.
3) TRW - TRW, Inc.
4) NOAA - National Oceanographic and Atmospheric Administration
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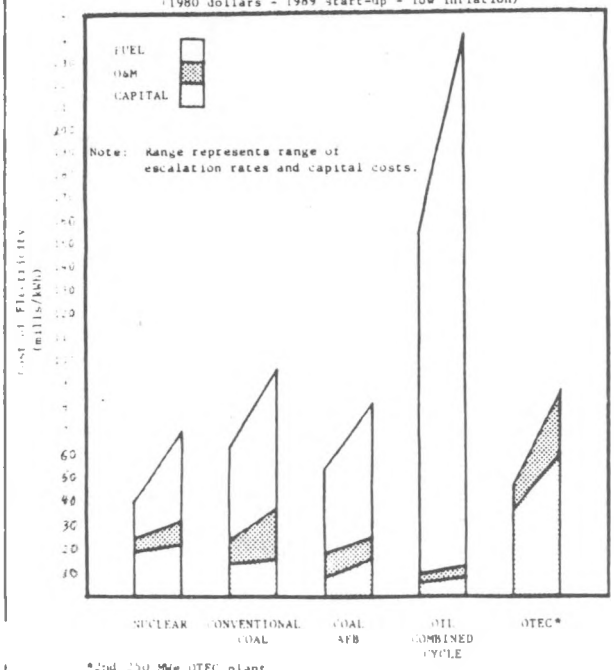
PROJECTED COST OF ELECTRICITY

Based on the assumptions given in Tables 1 and 2 and the methodology described, levelized power costs were calculated for all the cases.

Figures 3 and 4 show a comparison of projected OTEC power costs with those projected for its competition in 1989 in the islands and the mainland for the two inflation cases respectively. It shows the projected cost of OTEC power to be very

FIGURE 3A

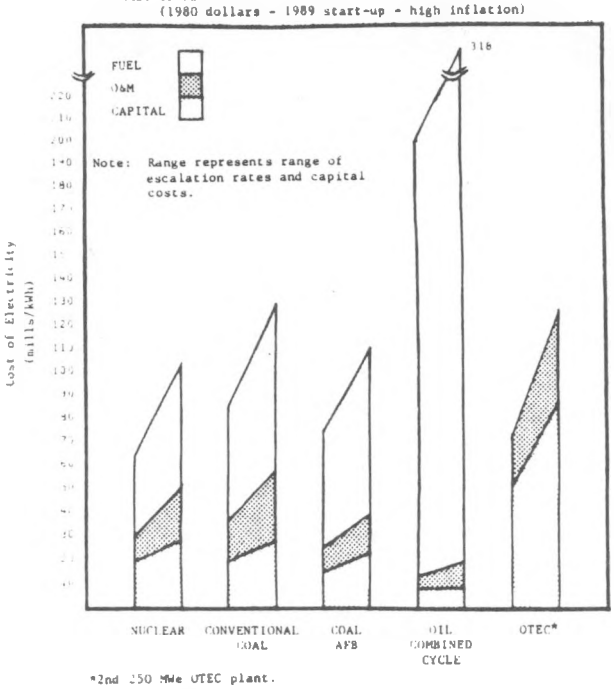
COST OF ELECTRICITY COMPARISON - ISLAND/PUBLIC OWNERSHIP
(1980 dollars - 1989 start-up - low inflation)



*2nd 250 MWe OTEC plant.

FIGURE 3B

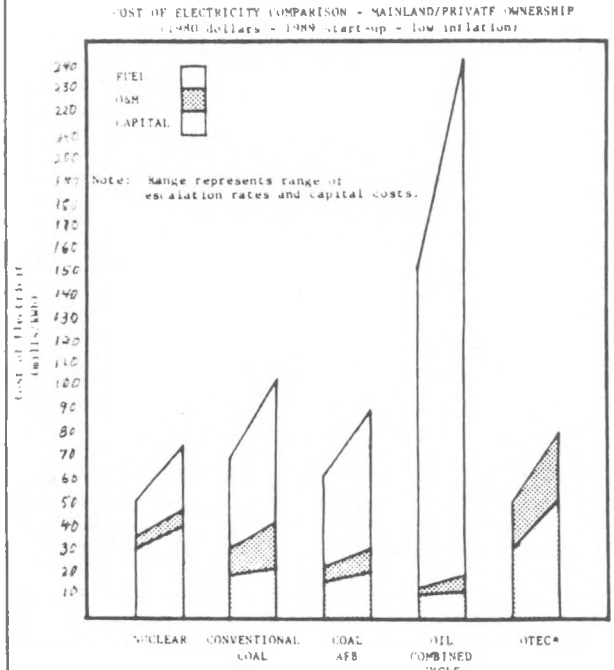
COST OF ELECTRICITY COMPARISON - ISLAND/PUBLIC OWNERSHIP
(1980 dollars - 1989 start-up - high inflation)



*2nd 250 MWe OTEC plant.

FIGURE 4A

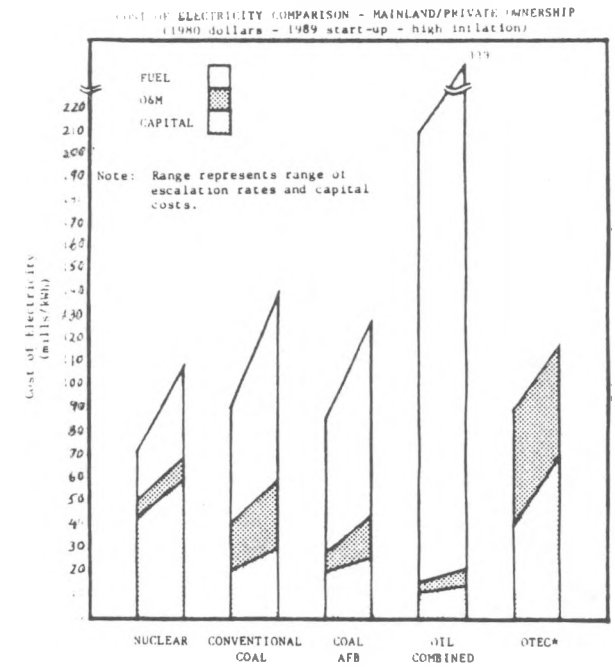
COST OF ELECTRICITY COMPARISON - MAINLAND/PRIVATE OWNERSHIP
(1980 dollars - 1989 start-up - low inflation)



*8th 400 MWe OTEC plant.

FIGURE 4B

COST OF ELECTRICITY COMPARISON - MAINLAND/PRIVATE OWNERSHIP
(1980 dollars - 1989 start-up - high inflation)



*8th 400 MWe OTEC plant.

competitive with that derived from coal and slightly higher than that derived from nuclear LWR technology. Of course, the levelized energy cost of OTEC is several times less than the fuel component alone of oil-fired power. The ranges shown on the bar graphs of Figure 3 show the sensitivity of energy cost to the range of assumptions regarding escalation of fuel and O&M costs and uncertainty in capital cost.

Many conclusions could be drawn from these comparisons. But perhaps the most important is that OTEC-derived power is projected to be competitive with other baseload technologies by the 1990s.

COST DYNAMICS

As fuel costs rise, probably at a rate somewhat higher than the inflation rate, for depletable fuels such as oil, coal, and uranium, and as OTEC technology proceeds from the pilot plant phase to full market readiness, OTEC's competitive position will be enhanced.

Figure 5 is a representation of the levelized energy costs of various types of plants as a function of on-line year. Energy costs associated with coal-based, and OTEC technologies in the islands are illustrated in this case. OTEC energy costs are projected to decline with each successive new plant due to the reuse of existing facilities and OTEC tooling and through the accumulating effects of experience. Table 3

FIGURE 5

COST OF ELECTRICITY AS A FUNCTION OF START-UP YEAR
- ILLUSTRATION -

Island site, low inflation case
2nd through 6th 250 MWe plant
(1980 dollars)

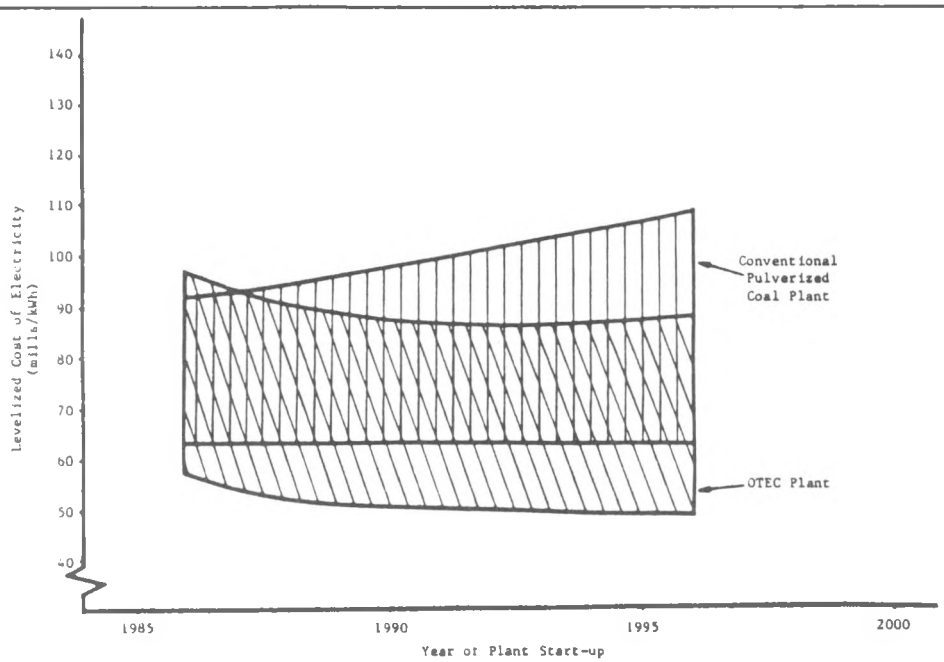


TABLE 3

ILLUSTRATIVE DEPLOYMENT SCENARIO*
250 MWe Plant, Island Siting

CHARACTERISTICS \ YEAR	1986	1989	1992	1996
Cumulative Capacity (MWe)	250	750	1,250	2,000
Plant Number	1	2,3	4,5	6,7,8
Average Modal Construction Cost** ($/kWe)	3,650	3,150	3,000	2,800

*Deployment example simply illustrates the effects of experience on OTEC overnight construction costs. Not be construed as a deployment projection.

**Average construction cost in given year.

presents OTEC overnight construction cost estimates for island sites in the illustrative deployment scenario presented in Figure 5. The costs of fuel-derived energy are seen to increase with time due to real escalation in the price of fuel and the other costs. Further, OTEC's competition are generally mature technologies and little improvement in the unit cost of capacity can be expected.

This is a more or less typical illustration of the expected behavior of OTEC costs relative to those of its competitors in the southeastern part of the U.S. as well.

This "sun belt" region is expanding in industrial activity, and considerable quantities of oil and gas are being used there for the production of electricity for utilities and for aluminum production. OTEC power could contribute to reducing gas and oil usage in meeting the expected Gulf Coast growth in electrical demands.

Market Penetration

OTEC's projected economic position can serve as the basis for estimating OTEC's market capture under various background situations.

In the MITRE SPURR model, generating plant cost estimates and associated energy costs are calculated as a function of time. As shown in Figure 5, both OTEC and the competition can be represented by a range of energy cost with time or, more correctly, a range that depends on the number of plants that have previously been constructed.

Table 4 illustrates the capacity addition requirements that OTEC and the competition are assumed to be vying to satisfy. Between 1990 and the year 2000, it is estimated that about 56 GWe of new baseload capacity will be required in the three continental U.S. OTEC electric regions.

TABLE 4

CAPACITY ADDITION ESTIMATE BY REGION FROM 1990 TO 2000
(GWe)

OTEC REGION	YEAR											TOTAL
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	
South Atlantic												
Baseload	2.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	26.6
Substitution*	0.4	0.4	0.4	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	2.0
East South Central												
Baseload	1.0	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	13.9
Substitution*	0.03	0.03	0.03	0.03	0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.15
West South Central												
Baseload	1.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	15.5
Substitution*	0.9	0.9	0.9	0.9	0.9	0.0	0.0	0.0	0.0	0.0	0.0	4.5
Puerto Rico												
Baseload	0.0	0.0	0.3	0.3	0.0	0.3	0.3	0.0	0.0	0.3	0.0	1.5
Intermediate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.4	0.8

*Substitution for oil- or gas-fired baseload capacity.

TABLE 5

MARKET PENETRATION SCENARIO ASSUMPTIONS

	TECHNOLOGY CHARACTERISTICS PRESENTED IN TABLE 2	FINANCIAL ASSUMPTIONS PRESENTED IN TABLE 1	MARKET OPPORTUNITY AS DEFINED IN TABLE 1	RELIABILITY CHARACTERISTICS EQUIVALENT TO COMPETITORS	NUCLEAR CAPACITY CONSTRAINED TO 200 GWe BY 2000	100 MWe PILOT BY 1986 500 MWe TOTAL DEMO BY 1989	DATA FOR DECISION TO GO OTEC AVAILABLE BY 1987 (1st OP YR 1990) BY 1990 (1st OP YR 1993)	MANUFACTURING CONSTRAINTS (PLANTS/YEAR) 1/YR 1990-94; 1/YR 1996-2000 1/YR 1993-95; 3/YR 1996-2000 UNCONSTRAINED	LOAN GUARANTEE 80 PERCENT DEBT @ 8 PERCENT
SCENARIO 1	X	X	X	X	X	X	X	X	
SCENARIO 2	X	X	X	X	X	X	X	X	X
SCENARIO 3	X	X	X	X	X	X	X		
SCENARIO 4	X	X	X	X	X	X	X	X	
SCENARIO 5	X	X	X	X	X	X	X	X	X
SCENARIO 6	X	X	X	X	X	X	X		

Six scenarios under which market performance of OTEC can be estimated are illustrated in Table 5. All the scenarios assume that the technology characteristics, financial assumptions, and market for new capacity are as presented in Tables 1 and 2, respectively, unless otherwise noted. Further, it is assumed that a 40/100 MWe pilot plant is on line by 1986 and a total of 500 MWe of OTEC demonstration plants are on line by 1989. These demonstrations are assumed to be successful and prove OTEC's reliability characteristics to be equivalent to those of its competitors. Also nuclear power is constrained to a level of 200 GWe by 2000.

The scenarios vary on the assumption of the first on-line year for a commercial OTEC plant in the continental U.S., the rates at which OTEC plants could be constructed, and the level of loan guarantees available.

The resulting levels of projected market penetration, based on the probability of least energy cost are shown for each scenario in Figure 6 as a function of time. Based on the probability of least energy cost criteria, from six to 14 gigawatts of OTEC power could be in place by 1999 depending on scenario.

CONCLUSIONS

This analysis projects that OTEC can be economically competitive in both the U.S. islands and Southeast U.S. utilities during the 1990s as the costs of conventional fuels continue to escalate within the assumptions of this study. The relative attractiveness of OTEC could change if its capital costs were to vary greatly or if fuel escalation rates prove to be substantially different from assumed values.

Nevertheless, projections now show OTEC to have a favorable economic future in the decade of the 1990s. The problems for the government are to assure that OTEC plants are ready to go on line by 1990; that OTEC can achieve the cost, performance, and reliability characteristics that have been projected for it; that potential owners/operators, users, and investors develop sufficient confidence in the technology to begin construction of the first commercial plant by the 1986-87 time frame in order to gain access to the commercial market by 1990.

The federal government can continue to help OTEC realize its potential by recognizing that OTEC not only qualifies as a long-term, high risk technology, but also one that has a large potential. Through continued funding of OTEC research and testing programs to verify and improve existing estimates of technical performance and costs, the government can help establish OTEC as viable contributor to the U.S. energy supply picture. Beyond that, programs aimed at the issues of utility acceptance in the near-term markets, requirements of producers to manufacture the systems for 1990, and financial stimulation of the market through incentives to OTEC owners or investors will aid in establishing an acceptable and market-ready technology in the shortest possible time period. Utility acceptance will probably require demonstration of technical readiness for firm power generation, some means of assuring reliability and projected power production costs, and possibly assistance in capital formation.

Additionally, the financial incentives package already offered to OTEC owners and/or investors in PL 96-320 and the windfall profits tax should be maintained or expanded. This would serve to decrease minimum revenue requirements and enhance OTEC's competitive position and its market potential.

To put programs in place that will help OTEC meet its potential, will require continued legislative support and a near-term national commitment of resources aimed at resolving the outstanding technical and economic issues, the issues of utility acceptance and industrial development.

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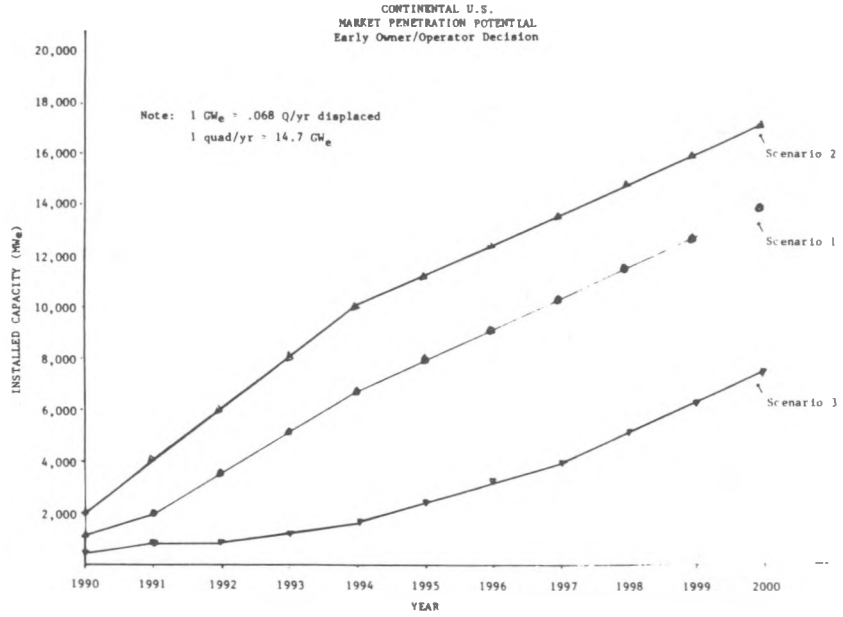
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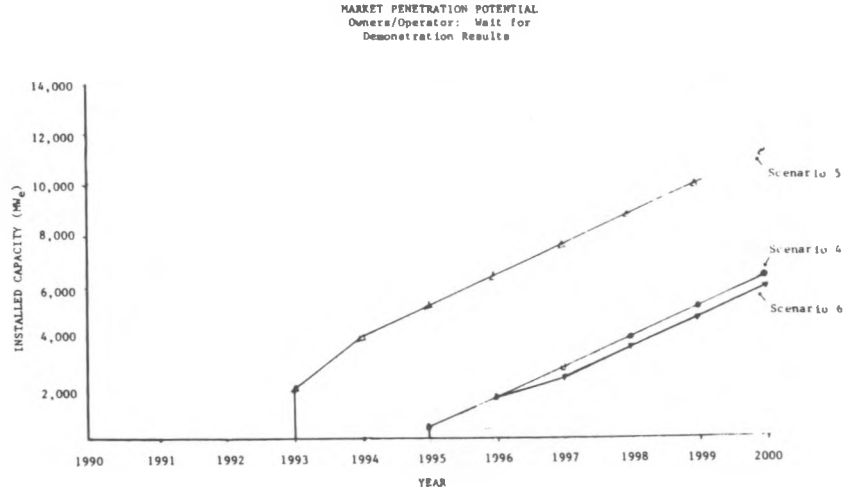
FIGURE 6

MARKET PENETRATION SUMMARY

SCENARIO	U.S. CAPACITY BY 2000 (GWe)	NUMBER OF PLANTS	PRIMARY U.S. ENERGY DISPLACED (quads/year)
1	14.4	36	0.98*
2	17.2	43	1.17*
3	7.6	19	0.52**
4	6.4	16	0.44**
5	11.2	28	0.76**
6	6.0	15	0.41**

*1 GWe and .14 quad/year in Puerto Rico.
**1.6 GWe and .11 quad/year in Puerto Rico.





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SENSITIVITY OF OTEC PRODUCT PRICES TO FINANCIAL PARAMETERS

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ABSTRACT

OTEC is perceived as a baseload power source that may compete regionally with oil-fired and possibly, coal-fired power plants. In this paper, I examine the sensitivity of electricity cost to economic and financial parameters. I first derive a single formula for calculating the price of electricity produced by oil/coal power plants and then derive the maximum capital cost at which investment in an OTEC enterprise produces the same return on investment as may be produced from a fossil fuel power plant. The financial/economic model is based entirely on net annual cash flow discounted at a given after-tax rate. I then compute the present value of the cash stream over the planning horizon of the plant. The parameters included in the model are: capital cost; operation & maintenance; capacity factor; fuel cost (if applicable); interest rate; debt ratio of enterprise; inflation rate; tax rate; investment tax credit; depreciation schedule; plant life; expenses during construction; construction period; fuel price escalation; electricity price escalation and others.

Using the methodology developed for the electric mission, I derive the affordable capital cost of a plantship producing ammonia from OTEC electricity for a given price of ammonia delivered to shore. The ammonia may be sold to a wholesale distributor or it may be desynthesized into hydrogen and nitrogen. The hydrogen can be sold as fuel at a price based on its heat content only. Alternately, the ammonia may be piped to a utility which may then use it as the feedstock for a fuel-cell plant that produces electricity.

It is concluded that in certain markets, OTEC may readily compete with coal-fired plants beginning in 1995 if OTEC's capital cost falls within the $3000-$3500/kw range in (1980$). At an ammonia price of $240 s.t. (in 1980$), an OTEC plantship must cost no more than $2000-2500/s.t. depending on the debt ratio of the enterprise. These capital cost figures are strongly dependent on the financial, tax, and other assumptions used. Thus, it is necessary to exercise extreme care in quoting a bottom line cost figure.

INTRODUCTION

The commercialization of OTEC as a baseload power source or as an energy source for the production of chemicals will depend heavily upon the realizable return on investment in OTEC enterprises. The realizable return depends on numerous factors including market and economic conditions, government incentives, system design and performance. As a baseload power source, OTEC is limited to island markets and possibly the U. S. mainland. As an energy source for the production of chemicals, principally ammonia, because of the ease of its transport and storage, OTEC represents a worldwide resource well suited to international markets. However, in the long run, OTEC must compete with fossil fuels for the generation of electricity or the production of chemicals.

The prevailing economic conditions, such as inflation rate and availability of competitive energy sources, will also influence OTEC commercialization. Government subsidies in the form of low interest rate, high investment tax credit, accelerated depreciation, and others can increase the attractiveness of an OTEC investment. However, the development of a new technology such as OTEC cannot be predicated on long term government subsidies. Early plants may receive considerable government support of one kind or another. But such support is likely to be short lived. If so, it is necessary to evaluate OTEC enterprises conservatively and to assume no long term preferential reatment beyond

what the government makes available to other technologies. In the long run, investors may be induced to risk capital in an OTEC enterprise only if the risk/return ratio is as good or better than in alternate investment. However, return on investors equity depends on many financial and tax parameters. Hence, a simple-minded analysis can be quite misleading.

Assuming that technical and financial risk of OTEC is equal to that of established technologies, I present in this paper a financial analysis from the perspective of an entrepreneur. My emphasis is not on actual parameter values used in the analysis but on the significance of the parameters themselves. Above all, I intend to show that high debt ratios are neither essential nor desirable to the financial success of an OTEC enterprise in order for it to compete with conventional technologies. By compete, I mean the same after-tax rate of return on equity.

ANALYSIS

Let R(n) represent the gross revenue during year (n) expressed in current dollars. Thus,

$$R(n)=p(n)*A \tag{1}$$

where p(n) is the unit price in current-year dollars and A is the annual output. The earnings before tax for year (n) is

$$EBT(n)=R(n)-OM(n)-I(n)-DP(n) \tag{2}$$

where OM, I, and DP are respectively the year's operation and maintenance cost, interest charges, and depreciation expenses. The tax is given by

$$TAX(n)=t*EBT(n) \tag{3}$$

where (t) is the combined tax rate. The net cash remaining on hand at year's end is

$$CASH(n)=[R(n)-OM(n)-I(n)]*(1-t)+t*DP(n)-D(0)/L \tag{4}$$

where D(0)/L is the sum paid to reduce the debt. Should the enterprise show a loss in any particular year, I assume that the owner can use the loss to offset taxable profits from other businesses. Investment tax credit, if any, is realized in the first year. The rate of return on equity (e) is determined by equating the sum of the discounted cash flow to the original investor's equity Q(0). Thus,

$$Q(0)=\sum_{n=1}^{L} CASH(n)/(1+e)^n \tag{5}$$

where L is the useful life of the plant.

ASSUMPTIONS

1. The relevant criterion for comparison is net cash flow discounted at a nominal after-tax rate of return on equity (ROE).

2. All arithmetic is in current dollars. The ROE figure accounts for general inflation.

3. Price of electricity produced from fossil fuel increases at a compounded annual rate which is a weighted average of general inflation and fuel price escalation beyond general inflation.

4. Depreciation expense is based on sum-of-years digits method with zero salvage value. The plant life may exceed the depreciation period.

5. Long-term debt is uniformly retired over the operating life of the plant.

6. Operation and maintenance and shipping (if appliable) costs increase with general inflation.

7. Investment tax credit results in cash disbursement at end of year one.

8. Depreciable assets consist of plant purchase price and all expenses during construction and until plant is on line, less investment tax credit.

9. Working capital is negligible compared to total investment capital.

10. Construction begins in year 1992. The first year of operation is 1995. Construction time is three years.

11. Disbursement to builder during construction is made in equal monthly installments.

12. Interest and other expenses during construction result in an equivalent charge (on borrowed funds only) computed at an "interest rate" which is 25% greater than the annual interest rate on long-term debt.

13. The debt ratio of the enterprise is the quotient of the long term debt to the capital cost (including cost escalation during construction) at the beginning of year one (1995) of operations.

14. No contingency charges are necessary.

ESTABLISHING PRODUCT PRICE

By definition,

$$D(0)=\delta*CC \quad (6)$$

where δ is the debt ratio and CC is the capital cost. The annual debt reduction payment is D(0)/L; the debt at the end of the year (n) and the interest expense are:

$$D(n)=D(0)*(1-n/L) \quad (7)$$

$$I(n)=r*D(n-1) \quad (8)$$

This is a conservative estimate because interest is based on beginning of year and not the midyear or average debt balance. The net effect is a higher cost penalty on enterprises with high capital cost and high debt ratio. The only remaining element to be defined in Eq.4 is the depreciation expense.

Although utilities seldom employ accelerated depreciation in their financial reporting or in cost accounting, I have elected to use sum-of-year digits method for allocating depreciation expenses for both OTEC and competing technologies. Thus, if K is the allowable depreciation period which may be shorter than the useful life of the plant, then

$$DP(n)=CC*(1-ITC)*(K-n+1)/[(K+1)*K/2] \text{ for } n\leq K$$
$$0 \text{ for } n>K \quad (9)$$

where ITC is the investment tax credit available. Again, although investment tax credit is not applicable to utilities, OTEC enterprises not owned by private utilities will want to take full advantage of the tax credit. However, to allow the tax credit in the case of OTEC but not in the case of other technologies will result in gross distortion in favor of OTEC. For a meaningful comparison, the same tax benefits available to an OTEC entrepreneur must be made available to all others.

ECONOMIC MODEL

All cash expenses and revenue are expressed in current year dollars and are escalated by the inflation rate. Thus, if the gross revenue in year (0) when a plant comes on line is R(0), then at year (n), the revenue is

$$R(n)=R(0)*(1-f)^n \quad (10)$$

where f is the inflation rate. It is possible though that revenue may increase at a rate faster than inflation. In such a case, a different escalation rate is used in Eq.(10). For instance, if fuel were to increase by the rate Φ above inflation, the corresponding price of energy may be calculated by separating the cost into three components: capital recovery, O&M, and fuel. Each component escalates at its appropriate rate in order to obtain Φ.

In my analysis, I have escalated O&M cost at the inflation rate. I also assume that the capital recovery (excluding interest expense which remains fixed at a given rate throughout) increases at the assumed inflation rate. This approach differs from the conventional cost computation used by utilities. In effect, I am evaluating energy price based on replacement and not on historic cost. However, for tax purposes, I use historic cost to compute depreciation expenses. I justify my approach because my analysis is made from the perspective of an investor and not a public or private utility.

The present value of the cash stream CASH(n) is discounted by the desired after-tax rate of return on equity (e) as indicated in Eq.5. The value of Q(0) must be equated to the initial investment less any tax credit received subsequently and discounted at the appropriate rate. Hence, assuming that the tax credit is available at the end of the first year, I obtain

$$Q(0)=\sum_{n=1}^{L} CASH(n)/(1+e)^n=(1-\delta)*CC-ITC*CC/(1+e) \quad (11)$$

Normally, the model equations are programmed on a digital computer to obtain annual net cash for different sets of input parameters. However, my model leads to difference equations that can be solved analytically resulting in a simple expression. Solving for unit product price at year (0), I obtain

$$\text{i. } p(0)= CC*[1-\delta-ITC/(1+e)]/[A*(1-t)*S_4] \quad \text{(capital)}$$

$$\text{ii. } +CC*\delta*S_0/[A*(1-t)*L*S_4] \quad \text{(debt amortization)}$$

$$\text{iii. } +CC*r*\delta*S_2/[A*L*S_4] \quad \text{(interest charge)}$$

$$\text{iv. } +OM(0)*S_1/(A*S_4) \quad \text{(OM charges)}$$

$$\text{v. } +FC(0)*S_3/S_4 \quad \text{(fuel charge)}$$

$$\text{vi. } -CC*(1-ITC)*t*T_2/[A*(1-t)*S_4*(k+1)*K/S_2] \quad \text{(depreciation)} \quad (12)$$

where S_0, S_1, S_2, S_3, S_4, and T_2 are levelizers defined in the appendix.

Similarly, I solve for the capital cost, CC, as a function of p(0) and other parameters.

$$CC=[A*p(0)*S_4-OM(0)*S_1-A*S_3*FC(0)]/[C_3+\delta*C_4] \quad (13)$$

where

$$C_3=[1-ITC/(1+e)-t*(1-ITC)*T_2/(K+1)/K/2]$$
$$C_4=\delta*[r*(1-t)*S_2/L+S_0/L-1]$$

Eqs.12 and 13 may be used to investigate the sensitivity of p(0) or CC to changes in financial parameters.

ESTABLISHING THE CAPITAL COST

The plant capital cost as carried on the books and used for allocating depreciation expense and fixed charges consists of components purchase cost, engineering fee, and interest and insurance expenses during construction. There may be cost escalation from the time an order is placed with a supplier until a component is delivered. There may be other contingencies which may contribute to the cost. In the analysis, I assume that the technology is mature and that all component acquisitions are made at fixed price.

If the total debt when the plant becomes operational is D(0) and it takes N years (12*N months) to complete construction, I calculate the interest and insurance expenses assuming uniform monthly disbursement by the lender. The model follows.

The debt increases every month by D(0)/(12*N). Since $D(0)=\delta*CC$,

$$debt(n)=\delta*CC/(12*N)*n$$

where n is the month index counter from the beginning of construction onward. The corresponding charges (paid by the owner) assuming an annual rate (i)% and monthly rate (i/12)% is

$$I(n)=(i/12)*\delta*CC/(12*N)*n$$

The total expense paid over 12*N months is

$$I = i*\delta*CC*(12*N+1)/24$$
$$= \text{capital cost} - \text{purchase price}$$
$$= CC - PP$$

Therefore,

$$CC=[1-i*\delta*(12*N+1)/24]*PP=F1*PP$$

It should be understood that CC is the book value of the plant at the time the plant becomes operational. The investor has a total equity of $(1-\delta)*CC$ and owes the lender then the sum $D(0)=\delta*CC$. The equity represents all cost during construction in addition to contribution towards purchase of hardware. The equity value does not contain any provision for return on funds supplied by the investor during construction. In a more thorough analysis, it is necessary to determine the economic value of the cash stream provided by the investor and to use this economic value to compute a rate of return. I have not pursued this economic aspect in this paper. Hopefully, the effect is minimal if the construction period is short.

In determining F_1, I have assumed uniform disbursement instead of the usual S-shaped curve. In my calculations, I found no significant difference between the two approaches for the case N=3 years. Values of F_1 are given in Table 1.

SAMPLE CALCULATIONS

I consider next the production of electricity using a coal-fired power plant. I determine first the price at which baseload power must be sold in the first year of operation. The data used to calculate p(0) for Eq.12 are given in Table 2. All calculations are based on 1 kw of installed capacity. I have assumed that construction begins in 1992 and the plant becomes operational in 1995. The Roman numbers refer to numbers in Eq.12.

$$CC=PP[1980]*(1+f)^{12}*F_1$$
$$=1000*1.09^{12}*1.131=3181 \text{ \$/kw}$$

$$A=CF*1 \text{ kw}*8760 \text{ hrs/yr.}$$
$$=0.65*1*8760=5694 \text{ kwh/yr.}$$

i. $3181*[1-.5-.1/(1+.18)]/[5694*(1-.5)*10.99]$
$=0.0422$ \$/kwh.

ii. $3181*.5*5.517/[5694*(1-.5)*30*10.99]=0.0093$ \$/kwh.

iii. $3181*.12*.5*136/[5694*30*10.99]=0.0138$ \$/kwh.

iv. $30*(1+.09)^{15}*10.99/(5694*10.99)=0.0192$ \$/kwh.

v. $0.0172*(1+.09)^{15}*10.99/10.99=0.0626$ \$/kwh.

vi. $-3181*(1-.1)*.5*81.37/$
$[5694*(1-.5)*10.99*(20+1)*20/2]=-0.0177$ \$/kwh.

$p(0)=0.0422+.0093+.0138+.0192+.0626-.0177=0.1294$ \$/kwh.
$=0.1294/(1+.09)^{15}*1000=35.53$ mills/kwh in 1980\$

I calculate next the maximum OTEC capital cost at which an OTEC plant produces the same rate of return on equity (e).

$$A=.9*1 \text{ kw}*8760 \text{ hr/yr}=7884 \text{ kwh/yr.}$$

i. $0.0422*CC/3181*5694/7884=9.58\times10^{-6}*CC$

ii. $0.0093*CC/3181*5694/7884=2.11*10^{-6}*CC$

iii. $0.0138*CC/3181*5694/7884*.11625/(.12)=3.04*10^{-3}*CC$

iv. $0.0192*20/30*5694/7884=9.24*10^{-3}$ \$/kwh.

v. 0.

vi. $-0.0177*CC/3181*5694/7884=-4.02*10^{-6}*CC$

Hence, using Eq.12,

$$0.1294=CC*10^{-6}(9.58+2.11+3.04-4.2)+9.24*10^{-3}$$

From which CC=11220 \$/kwh in 1995\$
$=11220/(1+.09)^{12}/F_1=3527$ \$/kw in 1980\$

Table 3 gives the sensitivity coefficients.

The OTEC capital cost as a function of debt ratio δ for different coal plant debt ratio δ is given in Figure 1a. Figure 1b shows the dependence of electricity price on δ. The formulas used in the preceding calculations mask the details of the annual cash flow and the effect of taxes. It is important to note that an OTEC enterprise shows a net loss in the early years of operation. This means that the owner(s) must have a corresponding income from other sources in order to benefit from the tax loss. Another point to consider is the effect of the high debt ratio. For the low inflation high debt ratio case, the enterprise will have negative cash flow for a number of years (slope of curve in Figure 2b is negative from year 14 through 22) even though the total cash remains positive. It is not difficult to envision scenarios in which the total cash may oscillate around zero. This feature of future negative cash flow is a result of fast payback brought about by investment tax credit and accelerated depreciation. It is difficult to attract venture capital to an enterprise that does not generate uniform cash stream. It is probably even more difficult for an entrepreneur to secure long term loans under such circumstances. However, a low debt ratio can produce a positive cash stream throughout the life of the plant. Generally, both the payback period is longer and the number of years the enterprise shows a loss is greater at higher debt ratio.

I have performed a similar analysis for the chemical mission, viz., OTEC plantships producing ammonia. Given a market price in 1980$ for ammonia delivered to a U.S. port, I compute the total capital cost of a plantship and the corresponding OTEC power plant portion of the cost so that an investor may realize a given return. The cash flow for a high debt ratio and low inflation scenario is even more dramatic as shown in Figure 3. Beginning in the 8th year of operation, the cash flow is negative and in fact the total cash becomes negative and remains so from the 13th year onward. Clearly, such a business cannot be considered practical by either an investor or a lender.

CONCLUSION

Investment in OTEC can be attractive only to firms or individuals with a need to shelter taxable profits. OTEC enterprises can be profitable if sound business practices are followed in financing an enterprise. There is neither the need nor the justification for a high debt ratio.

For certain combinations of debt ratio and depreciation schedule, in certain years, the cash flow is negative and the payback period is relatively short (2–3 years). What happens is that the owner–operator benefits from the timing of cash inflow in the early years of the enterprise resulting from investment tax credit, accelerated depreciation, and high debt ratio.

A contribution of the work is the derivation of Eq.12 and 13 and the sensitivity coefficients of Table 3. I have provided program planners with a single formula for establishing cost goals for an OTEC system and consequently, the subsystems. The formula is so simple that a hand calculator is adequate to perform all computations.

It should be noted that design ΔT is not a factor. It is left to an entrepreneur to select a site whose ΔT is high enough so that the required capital cost can be realized.

APPENDIX

COMPUTATION OF LEVELIZERS

The factor $S_0 = \sum_{n=1}^{L} 1/(1+e)^n$

Let

$$g = 1/(1+e)$$

It follows that S_0 is the sum of the series:

$$g^1, g^2, g^3, \ldots, g^L$$

Hence,

$$S_0(g) = g*(1-g^L)/(1-g)$$

The factors S_1, S_3, and S_4 are also sums of similar series except that the value of g is different. The corresponding g values are:

$$g_1 = (1+f)/(1+e)$$
$$g_3 = (1+f+\Phi)/(1+e)$$
$$g_4 = (1+s)/(1+e)$$

The factor $S_2 = \sum_{n=1}^{L} [(L+1)-n]/(1+e)^n$

It can be broken down into two series:

$$(L+1)*[g^1+g^2+\ldots+g^L]$$
$$-[g^1+2*g^2+\ldots+L*g^L]$$

Hence,

$$S_2 = g*(L-S_0)/(1-g)$$

Table 1. Escalation Factor F_1

N = 3 Years

	Linear		S–Curve	
i*	δ=0.5	0.875	δ=0.5	0.875
6.0%	1.0485	1.0881	1.0471	1.0855
7.5%	1.0614	1.1126	1.0596	1.1092
12.0%	1.1019	1.1931	1.0989	1.1869
15.0%	1.1307	1.2537	1.1268	1.2451

* Includes all expenses during construction.

Table 2. Sample Caluclations Data: 1980$

	Electric				Ammonia
	Base Case		Low Inflation		Low Inflation
	Coal	OTEC	Coal	OTEC	OTEC
CC $/kw	1000		1000		
O&M $/yr	30	20	30	20	25
CF %	65	90	65	90	95
Life	30	30	30	30	20
Depreciate	20	20	20	20	12
Tax %	50	50	50	50	50
ITC %	10	10	10	10	10
REQ %	18	18	9	9	9
r %	12	11.6	6	6	6
f %	9	9	3	3	3
Fuel mills	17.2		17.2		
S_0	5.517	5.517	10.27	10.27	9.13
$S_1=S_3=S_4$	10.99	10.99	14.02	14.02	11.63
S_2	136	136	219	219	121
T_2	81	81 121	121	54	

Table 3. Sensitivity Coefficients

Base case: High Inflation

Variable	Coal p(0)	OTEC CC
CC	0.369	1.000
A	−0.371	0.538
δ	−0.213	−5.95
ITC	−0.015	−0.209
Fuel	0.501	

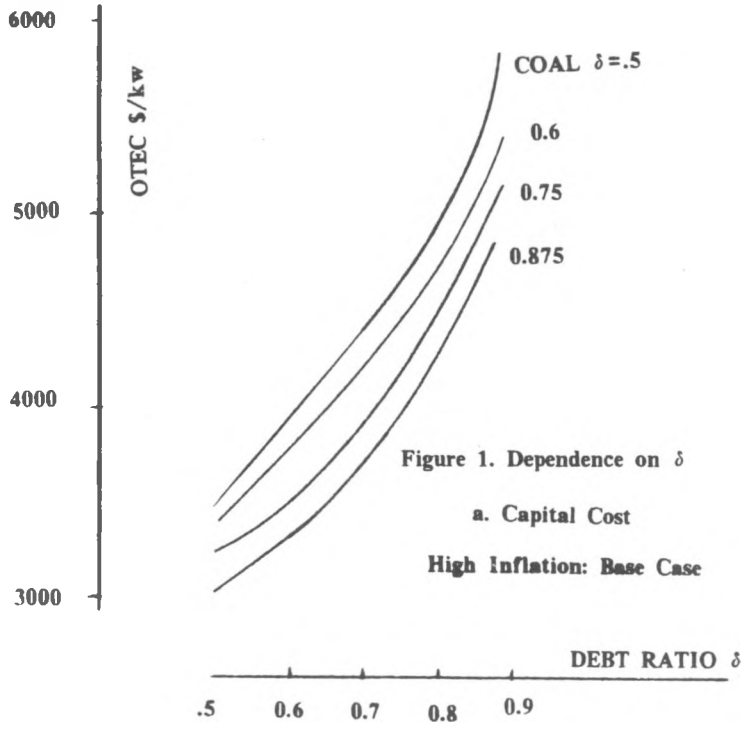


Figure 1. Dependence on δ

a. Capital Cost

High Inflation: Base Case

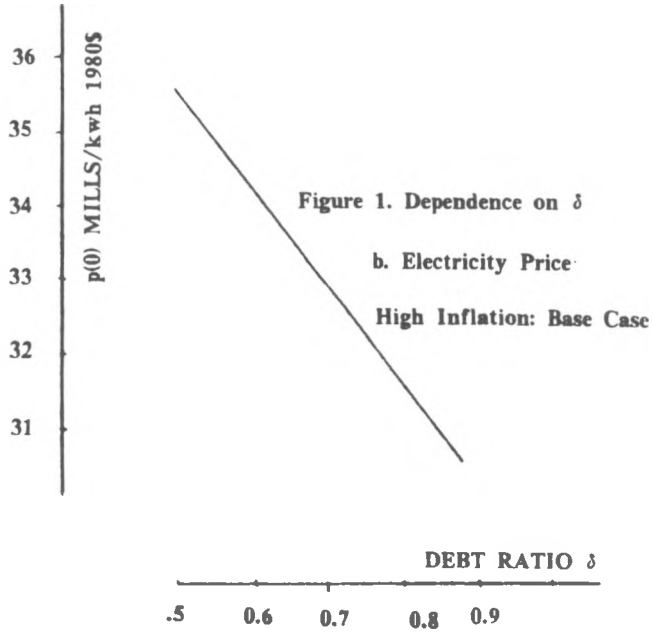


Figure 1. Dependence on δ

b. Electricity Price

High Inflation: Base Case

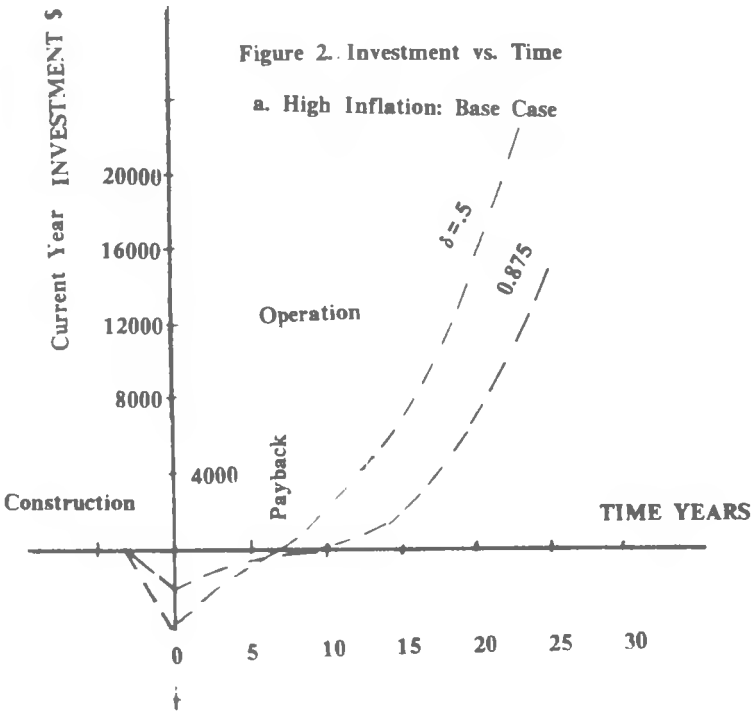


Figure 2. Investment vs. Time

a. High Inflation: Base Case

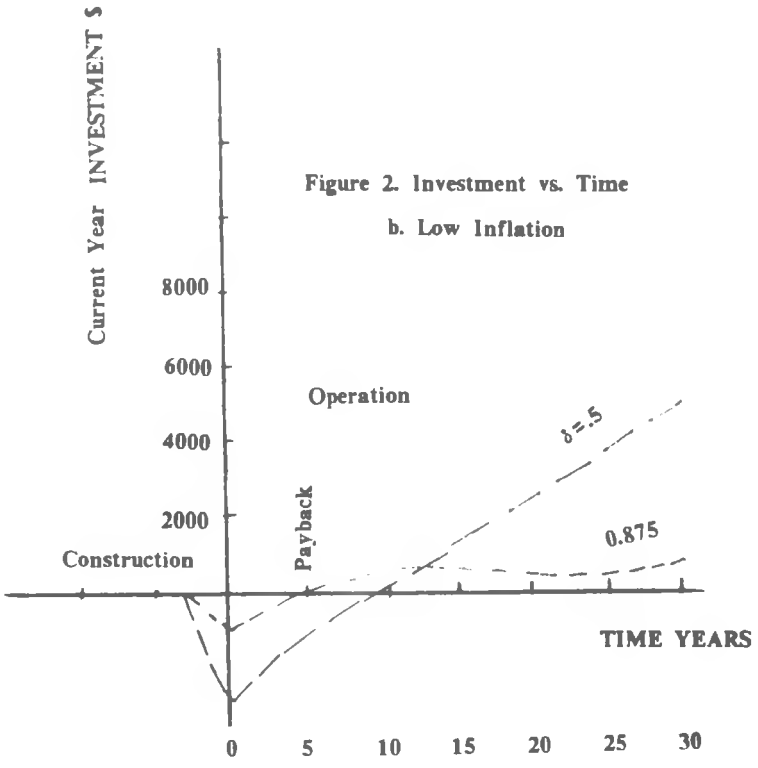


Figure 2. Investment vs. Time

b. Low Inflation

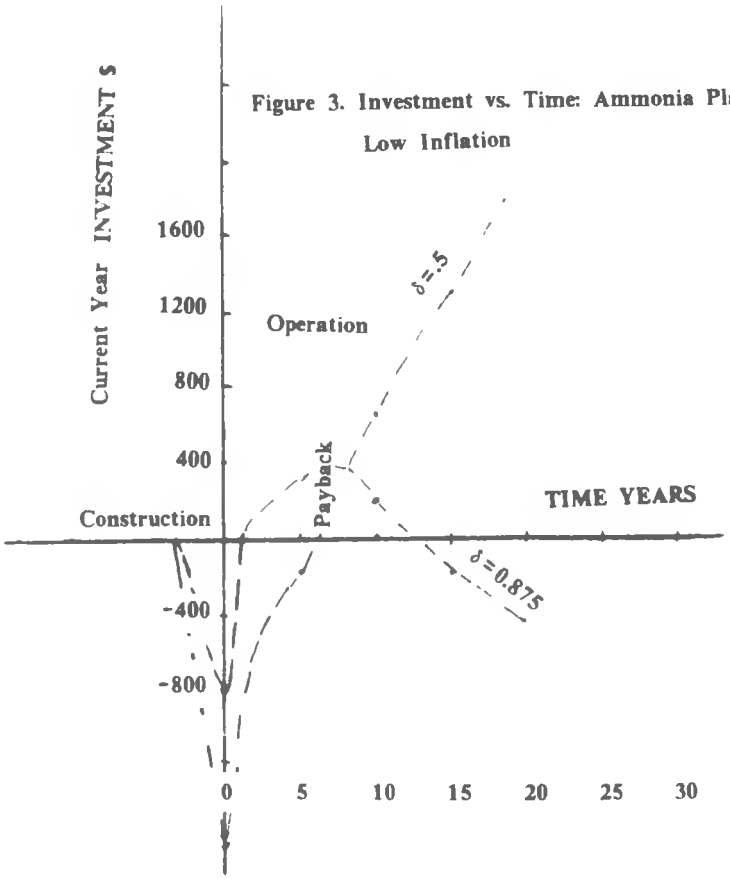


Figure 3. Investment vs. Time: Ammonia Plantship
Low Inflation

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Financing Ocean Thermal Energy Conversion Projects With Existing U.S. Maritime Aids

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INTRODUCTION

Signed into law August 3, 1980, the Ocean Thermal Energy Conversion Act of 1980, Pub. L. No. 96-320 (the "Act"), Title II, makes available to assist industry in financing the construction and operation of ocean thermal energy conversion ("OTEC") projects four types of federal aid that have been successfully administered in support of the United States merchant marine by the Maritime Administration ("MARAD") in the Department of Commerce. The four maritime aids are construction differential subsidies ("CDS"), operating differential subsidies ("ODS"), tax deferral of earnings through use of a capital construction fund ("CCF"), and loan guarantees ("Title XI"), all authorized by the Merchant Marine Act, 1936, as amended (the "Merchant Marine Act"). 1/ The purpose of this paper is to describe the nature of the benefits that are available under these programs and to note the eligibility requirements and restrictions that apply to projects that participate in them.

THE FOUR MARITIME AIDS

Title II of the OTEC Act accomplishes the purpose of providing financial aid to ocean thermal energy conversion projects by making certain determinations under the Merchant Marine Act, by making certain technical amendments to that Act and by adding an entirely new provision to Title XI of that Act.

First, Section 201(a) provides that for the purposes of Section 607 of the Merchant Marine Act, for taxable years beginning after December 31, 1981, any OTEC facility or plantship ("OTEC project") licensed pursuant to the OTEC Act and any vessel providing shipping service to or from such an OTEC project shall be deemed to be a vessel operated in the foreign commerce of the United States. The effect of this provision is to allow owners of OTEC projects and servicing vessels to establish and utilize a capital construction fund under Section 607 of the Merchant Marine Act, providing they satisfy the eligibility requirements of that Act. Section 201(b) sets forth the further determination that for purposes of the Merchant Marine Act (in general), any vessel documented under the laws of the United States and used in providing shipping service to and from a licensed OTEC project shall be deemed to be used in, and used in an essential service in, the foreign commerce or foreign trade of the United States, as defined in Section 905(a) of the Merchant Marine Act. The effect of this provision is to make vessels that provide shipping service to OTEC projects, but not the OTEC projects themselves, eligible to be considered for construction-differential subsidy under Title V and operating-differential subsidy under Title VI of the Merchant Marine Act.

Next, Section 202 makes certain technical amendments to Title XI of the Merchant Marine Act whose effect is to make OTEC projects eligible for consideration for Title XI loan guarantees under the same standards of qualification as other vessels; servicing vessels were (and remain) eligible for such consideration under the statute as it stood prior to amendment. Title XI is designed to be an essentially self-sustaining program funded by fees based on the amounts of guarantees issued, the government being required to pay out of the Ship Financing Fund only in the event of default on a Shipowner's obligation. Title XI guarantees are available only where it is shown that the vessel to be financed will be engaged in an economically sound enterprise; they are not intended to bear the risks inherent in the development stages of a new technology.

For the purpose of providing a similar form of assistance while OTEC is in the early stages of development, therefore, Section 203 of the OTEC Act adds a new Section 1110 to Title XI, creating a subaccount of the Federal Ship Financing Fund to be known as the OTEC Demonstration Fund. The Demonstration Fund, limited in amount to $2,000,000,000, is to be made available for no more than five, or any lesser number that attain a total capacity of 400 megawatts, of "commercial demonstration" OTEC projects that do not qualify for loan guarantees under the other provisions of Title XI.

A summary of each of these maritime aids follows.

CDS And ODS

Under the CDS program, the Secretary of Commerce is authorized to enter into contracts by which the shipowner pays a portion of the contract price to the shipyard and the Secretary pays the shipyard the difference. The Shipowner pays the estimated cost of building a similar vessel in a foreign shipyard, and the Secretary pays the excess of the U.S. shipyard price over the fair and reasonable estimate of cost of constructing, reconstructing or reconditioning the same type vessel if the the work were performed under similar plans and specifications in a foreign shipyard, up to a maximum of 50 per cent of the cost of construction. Merchant Marine Act, 1936, §§501-04, 46 U.S.C. §§1151-54 (1975).

Under the ODS program the Secretary is authorized to enter into a contract with the operator of a vessel or vessels operating in an "essential service in the foreign commerce of the United States" to pay, for a period of as long as 20 years, a subsidy equalling the excess of the cost of wages, insurance, maintenance and repair of a vessel or vessels operating under United States registry over the estimated fair and reasonable cost of the same items of expense were the same vessel(s) operated under the registry of a foreign country whose vessels are substantial competitors of the vessel(s) covered by the contract.

Both CDS and ODS are potentially of importance in bringing within the range of economic feasibility the operation of OTEC projects whose product is to be transported to the mainland by vessel rather than by electric cable or pipeline, because differences between the cost of constructing and operating an American vessel as compared with constructing and operating a foreign vessel are very substantial. In this connection it should be noted that Section 101(b)(8) of the OTEC Act requires that the licensee of an OTEC project agree that only vessels documented in the United States be used to transport to the United States anything produced at the OTEC facility or plantship. However, in view of the federal budget proposals now being considered in Congress, assistance in the form of CDS and ODS is only a legal possibility, and, practically speaking, no such subsidies would appear to be available in the near future for OTEC projects.

Title XI

Title XI authorizes the Secretary of Commerce to guarantee financing of up to 87-1/2 per cent (75 percent for vessels built with the assistance of CDS) of the cost of constructing, reconstructing or reconditioning vessels, including OTEC facilities and plantships as well as the vessels serving them. Merchant Marine Act §§1101-08, 46 U.S.C. §§1271-79B (1975). This permits shipowners to borrow funds from private investors by issuing United States government guaranteed ship financing obligations at lower interest rates and with longer repayment terms than would be possible without the government guarantee. OTEC projects are eligible to be considered for guarantees so long as the aggregate unpaid principal amount of the obligations guaranteed under Title XI do not exceed the present statutory ceiling of $12,000,000,000 (which includes the $2,000,000,000 in the OTEC Demonstration Fund), but, because the $10,000,000,000 maximum amount of guarantees applicable to all categories of eligible vessels has very nearly been reached, it is unlikely that MARAD would allocate to OTEC projects any significant amount in excess of that set aside exclusively for such projects. Moreover, the fiscal year 1982 Maritime Authorization bill (H.R. 2526) now pending before the House of Representatives contains a provision reducing the OTEC Demonstration Fund to $500,000,000, leaving the aggregate ceiling for all Title XI guarantees at $12,000,000,000. Assuming that, if the OTEC Demonstration Fund is so reduced, the amount of guarantee authority that MARAD will exercise for the benefit of OTEC Projects will be limited to the $500,000,000 specifically earmarked for "commercial demonstration" projects, OTEC projects with 87-1/2 per cent government guaranteed financing of a total cost of approximately $571,000,000, that is, probably two OTEC projects, will be funded.

CCF

Section 607 of the Merchant Marine Act, 46 U.S.C. §1177 (1975), authorizes the Secretary of Commerce to enter into an agreement with any United States citizen owning or leasing one or more "eligible vessels" to establish a capital construction fund. Revenues derived from operation of the vessels, proceeds from the sale of the vessels and receipts from investment of amounts held in such fund are deposited into the fund and are excluded from taxable income. Funds withdrawn for the purpose of acquiring, constructing or reconstructing a "qualified vessel" or for payment of the principal or indebtedness incurred in connection with the acquisition, construction or reconstruction of a "qualified vessel," called "qualified withdrawals," are not taxed, but are applied to reduce the basis of the vessel acquired, constructed or reconstructed. 2/ Depending on the amount of income generated by the vessels covered by the agreement and on the shipowner's tax bracket, the effective cost of acquiring vessels can be cut in half.

ELIGIBILITY IN GENERAL

OTEC Act

The OTEC projects and servicing vessels made eligible by the OTEC Act for federal assistance

under the Merchant Marine Act are those projects and vessels servicing such projects that are licensed pursuant to Section 101(c) of the OTEC Act. For purposes of the present discussion the notable qualifications for licensing are that the licensee be a citizen of the United States, as defined in Section 3(18), and that the applicant agree that the OTEC project and any vessel used to transport products manufactured at the OTEC project will be documented under the laws of the United States. The determinations made in Section 201 and the amendments to Title XI contained in Section 202 are designed to establish that licensed OTEC projects and their servicing vessels meet certain of the eligibility requirements of the Merchant Marine Act, but they do not relieve the projects of the necessity of satisfying the other requirements of that Act.

Merchant Marine Act

To be eligible for any of the federal maritime aids a vessel (i) must have been built in the United States, (ii) must be documented under the laws of the United States, and (iii) must be owned by a citizen or citizens of the United States. The definition of corporate citizenship for purposes of the Merchant Marine Act are more stringent than those contained in the OTEC Act and in the law regarding documentation, 46 U.S.C. §11, the latter two statutes containing substantially similar criteria. In addition to being organized under the laws of the United States or of a state, having a president, chief executive officer and chairman of the board who are United States citizens, and having no more of its directors who are not United States citizens than constitute a minority of the number required to constitute a quorum of the board of directors, the recipient of any of the maritime aids must have its controlling interest, that is, in excess of 50% ownership, if operating in the foreign trade, and 75% ownership, if operating in the domestic trade, in citizens of the United States, and the recipient of ODS must have a board of directors comprised entirely of United States citizens. 3/

FURTHER QUALIFICATIONS AND RESTRICTIONS

Vessels constructed with CDS are subject to the restrictions set forth in Sections 503 and 506 of the Merchant Marine Act, 46 U.S.C. §§1153, 1156 (1975). Such vessels must remain documented under the laws of the United States for not less than 25 years. Further, the owner must agree that the vessel will be operated exclusively in the foreign trade, with allowance for conduct of incidental domestic trade for which a prorated portion of CDS must be repaid annually, and with the possibility of a transfer of service to the domestic trade for periods of up to six months in any year with the consent of the Secretary upon similar repayment of CDS. 4/

A shipowner receiving ODS with respect to any vessel is subject to the operating restrictions stated in Sections 804 and 805 of the Merchant Marine Act, 46 U.S.C. §§1222-23 (1975). Under the former provision it is unlawful for any subsidized shipowner or holding company, subsidiary, affiliate, associate, officer, director or agent thereof to operate any foreign-flag vessel that competes with any U.S.flag vessel operating in an essential service; under "special circumstances" and for good cause the Secretary of Commerce has discretion to waive this limitation "for a specific period of time." Under the latter provision it is unlawful for any recipient of ODS or related entity to engage in the domestic intercoastal or coastwise service without the permission of the Secretary; such permission will be refused if it is found, after hearing, that granting it would result in unfair competition to those operating exclusively in such service.

Because Title XI assistance is intended to amount only to the giving of a guarantee of payment of obligations incurred in the first instance by the shipowner, and is granted in the expectation that the shipowner will be able to meet its obligations, will not default and will not thereby require federal monies to be expended, applicants must meet several qualifications beyond the threshold eligibility requirements of citizenship, documentation and vessel construction in the United States. Section 1104(d) of the Merchant Marine Act, 46 U.S.C. § 1274(d) (1975), requires the Secretary of Commerce to make a specific finding that the project with respect to which the obligations to be guaranteed will be executed will be "economically sound." In order to assure that projects that receive Title XI assistance are and remain economically sound, regulations at 46 CFR Part 298 impose requirements respecting management and disposition of covered vessels and of the shipowner itself, including maintenance of minimum levels of working capital, net worth and ratio of long-term debt to net worth. The Secretary also requires a security interest in the vessel construction contract during construction and a first preferred ship mortgage on the vessel at delivery under the Ship Mortgage Act, 1920, §30, 46 U.S.C. §§ 984 et seq.

In the case of "commercial demonstration" projects that do not qualify under normal Title XI standards, Section 203 of the OTEC Act provides for loan guarantee assistance to projects for which the Secretary of Energy certifies to the Secretary of Commerce there is "sufficient guarantee of performance and payment to lower the risk to the Federal Government to a level which is reasonable."

The Secretary of Energy is to base his considerations on "the successful demonstration of the technology to be used in such facility at a scale sufficient to establish the likelihood of technical and economic viability in the proposed market" and on the need of the United States to develop new and renewable sources of energy. In addition, the OTEC Demonstration Fund dedicated to such projects is to be isolated from the remainder of the Ship Financing Fund so that the larger fund will not be subjected to the higher risks borne by the Demonstration Fund. Section 203 does not state that applications for assistance to "commercial demonstration" OTEC projects shall qualify for loan guarantees on the basis of the Secretary of Energy's certification without further scrutiny by MARAD. To the contrary, Section 203(a) states that guarantees or commitments to guarantee under Section 203 "shall be subject to all the provisos, requirements, regulations, and procedures which apply to guarantees or commitments to guarantee made pursuant to Section 1104(a)(1) of this title, except that — ... (2) the provisions of subsection (d) of Section 1104 of this title [requiring the Secretary of Commerce to make a finding of economic soundness] shall apply to guarantees or commitments to guarantee for that portion of a commercial demonstration ocean thermal energy conversion facility or plantship not to be supported with appropriated Federal funds . . ." This provision may be construed as meaning that MARAD is to scrutinize a proposed commercial demonstration OTEC project under its usual standards, assaying its economic soundness as though the cost did not include any sums to be contributed by the Department of Energy or other federal agency. If this is the correct interpretation, however, the necessity of insulating the bulk of the Ship Financing Fund from the OTEC Demonstration Fund is not apparent; it can further be argued that there is no valid way of assessing the viability of a project without looking at the enterprise as a whole. At least with respect to projects that have the backing of the Department of Energy, the thrust of Section 203 is that they should be subjected to more lenient standards. Given the clear signal from the Department of Commerce that OTEC projects would be considered too risky under normal Title XI standards, 5/ the result is that only projects that receive substantial financial support from government programs other than Title XI will be able to qualify under Section 203 of the OTEC Act.

A restriction on the use of vessels covered by a CCF agreement is found in the definitions section, §607(k) of the Merchant Marine Act. "Eligible vessels" are those the revenues from which may be deposited into the fund; "qualified vessels" are those that may be funded by "qualified withdrawals" from the fund which receive favorable tax treatment. Both "eligible vessels" and "qualified vessels" must be constructed and, if reconstructed, reconstructed in the United States, and both must be documented under the laws of the United States. "Eligible vessels" may be operated in the foreign or domestic commerce of the United States or in the fisheries of the United States, but a person who maintains a CCF must agree that any "qualified vessel" will be operated only in the United States foreign, Great Lakes, or noncontiguous domestic trade or in the fisheries of the United States. The important distinction is that the noncontiguous domestic trade excludes trade between ports of the contiguous 48 states. OTEC projects and their servicing vessels are both "eligible" and "qualified" by virtue of Congress's determination in Section 201(a) of the OTEC Act that they shall be deemed to be vessels in the foreign commerce of the United States.

SUMMARY OF BENEFITS

By using existing U.S. Maritime Aids, investors could significantly reduce the amount of capital at risk 6/ in constructing and operating OTEC facilities and plantships. This objective could be accomplished by establishing a separate corporation, limiting the assets of such corporation to the OTEC projects and their servicing vessels, and financing the projects and vessels with one or more of these programs. 7/ Assuming Title XI guaranteed financing, capital at risk would be 12 1/2 percent of the actual cost of the project, or, if the Department of Energy were contributing part of the cost, 12 1/2 percent of the remaining portion of the actual cost. To the extent the equity in the project is funded through withdrawal of tax deferred funds from a CCF, the effective cost of such equity would be cut in half. In addition, vessels documented under the laws of the United States qualify for the investment tax credit and accelerated depreciation.

Given the trend in government policy away from federal involvement in business activities and toward leaving to private enterprise the task of developing adequate sources of energy, it seems likely that the benefits made available by the OTEC Act constitute all of the major financial assistance that the federal government is going to extend toward the development of ocean thermal energy conversion technology. To the extent appropriations are required to fund these programs, it is doubtful given the present atmosphere in Congress that such funds will be appropriated. However, those maritime aids that would be of the most use in financing an OTEC project, i.e., the Capital Construction Fund and Title XI Guarantees, do not require any appropriated funds, and it is now up to industry to

build on the foundation thus provided if OTEC facilities and plantships are to come off the drawing boards and into reality.

FOOTNOTES

1. 46 U.S.C. §1101 et seq.

2. Where monies from a CCF are used to finance a vessel the tax basis of such vessel must be reduced for depreciation purposes. 46 U.S.C. §1177(g). The availability of the investment tax credit is not affected by this, however. See Pacific Far East Line Inc. v. United States, 544 F.2d 478 (Ct. Cl. 1976); O. L. Schmidt Barge Lines, Inc. v. United States, 610 F.2d 728 (Ct. Cl. 1979); Oglebay Norton Company v. United States, 610 F.2d 715 (Ct. Cl. 1979).

3. By stating that vessels providing shipping service to and from OTEC projects shall be deemed to be used in an essential service in foreign commerce for (all) purposes of the Merchant Marine Act, Section 201(b) of the OTEC Act establishes that the corporation operating such a vessel need only meet the 50% citizen-owned test; presumably the 100% citizen board of director requirement still applies to the applicant for ODS. No similar determination was made applicable to the OTEC projects themselves, however. Section 201(a) deems such projects, as well as their servicing vessels, to be used in foreign commerce only for the purposes of Section 607 of the Merchant Marine Act. Query if OTEC projects are to be deemed to engage in any form of commerce at all, other than for the purposes of Section 607, are they to be deemed to engage in foreign commerce or domestic commerce? If domestic commerce, a corporation would have to meet the 75% citizen test in order to operate, and the Maritime Administration would therefore hold it to the 75% test in determining whether the applicant for Title XI assistance is a citizen.

4. The possibility of a vessel's being permanently relieved of operating restrictions upon a total repayment of CDS is not mentioned in the statute. This void has been read as expressing Congress's intention not to interfere with the Secretary's discretion to permit total repayment, the six-month maximum prescribed in Section 506 applying only to temporary as opposed to permanent waivers. Seatrain Shipbuilding Corp. v. Shell Oil Co., 444 U.S. 572 (1980). Total repayment will be permitted only in exceptional circumstances.

5. See the statement of Richard Knutsen, Assistant General Counsel for Ship Finance and Contracts, Department of Commerce, Hearings on S.2492 before the Senate Comm. on Commerce, Science, and Transportation, 96th Cong., 2d Sess. 114-16 (1980).

6. At risk as used herein means merely monies not guaranteed by the United States government and not offset by tax credits, deductions or other benefits. It does not mean "at risk" in the sense used by the Internal Revenue Service to qualify for certain tax benefits. For purposes of this article, it is assumed that 100% of the amounts invested are "at risk" for purposes of the Internal Revenue Code.

7. This assumes that the Maritime Administration would not require a guarantee from the parent corporation. In the past the Maritime Administration has not required parent guarantees where the applicant could meet the minimum net worth and working capital requirements. However, since OTEC would be a new field for the Maritime Administration, they might require greater security in this respect than in the case of a financing for conventional vessels.

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OTEC LEGISLATIVE NEEDS

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During 1980 the Congress recognized the strong potential of ocean thermal energy conversion by passing two new laws.

This paper discusses the process of implementing the two new laws, with emphasis on possible amendments which would clarify the intent of the Congress in passing the OTEC Act of 1980. The adoption of technical amendments to the OTEC Act would simply its implementation and provide a sound legal basis for each step in the OTEC licensing process.

INTRODUCTION

Two new laws were passed by the Congress in 1980:

(1) The OTEC Research,Development and Demonstration Act (P.L. 96-310) which set forth goals for the development of OTEC technology, and

(2) The OTEC Act of 1980 (P.L. 96-320), which resolved legal barriers to commercial use of OTEC and established a simplified single application licensing system for OTEC facilities and plantships.

These two new laws established legislative mandates for two federal agencies primarily involved in the development and commerical aspects of OTEC--the Department of Energy (DOE), and the National Oceanic and Atmospheric Administration of the Department of Commerce (NOAA).

This paper reflects the views of the author as an individual, and should not be interpreted as representing the views of NOAA or of the Executive Branch.

IMPLEMENTATION OF THE NEW LAWS

The federal agency budget cycle takes approximately three years from the time an agency originally plans a funding request to the time the funds are actually received and spent. At the time the two OTEC laws were enacted (during the summer of 1980), federal agencies had already made their initial budget decisions for fiscal year 1982 (October 1, 1981 to September 30, 1982). Administration budget requests for fiscal year 1981, the first full year for implementation of the new laws, had already been submitted to the Congress and the Congress was completing action on them. As a result, there was no opportunity for the two agencies to request additional resources to administer the new laws during FY 1981, and requests for resources for FY 1982 had to compete late in the budget process with other activities which had already been chosen for funding. The first Administration budget request which will reflect full consideration of resource needs to implement the new laws during the entire buget preparation process will be the request for fiscal year 1983.

Federal agencies are relatively accustomed to the long time lags which occur in obtaining resource allocations to implement new responsibilities and they usually do the best they can to implement their new responsibilities by temporarily relocating existing agency resources. The Department of Energy already had an OTEC program with an existing staff and budget when P.L. 96-310 was enacted, and was able to realign some of those resources to issue the cost-shared pilot plant program opportunity notice required by P.L. 96-310.

NOAA had no existing office ready to handle OTEC regulatory and licensing issues when P.L. 96-320 became law on August 3, 1980. NOAA had been assigned regulatory and licensing responsibility for deep seabed mining only a month before passage of the OTEC Act, and decided to create a new Office of Ocean Minerals and Energy to administer both new responsibilities. The office was formed with a small staff which had been working on preparations for deep seabed mining, and temporary resources obtained from other parts of NOAA by reprogramming, detailed personnel, borrowing, and contracts. The rulemaking process began in late October with an environmental impact statement "scoping" meeting, and is expected to be completed on time with issuance of final OTEC licensing regulations by August 3, 1981, as required by P.L. 96-320.

AMENDMENTS TO P.L. 96-320

During the process of analyzing the OTEC Act of 1980 and writing proposed and final regulations to implement it, a number of issues have been discovered which can best be resolved by amendments to the Act. Such issues are often discovered

in the early implementation of new legislation. When the OTEC Act was being considered by the Congress, the final House-Senate conference process was skipped in order to obtain prompt enactment of the legislation, thereby increasing the likelihood that this type of issue might occur.

The issues which can best be resolved by amendments to the OTEC Act can be broken down into five categories: (1) land-based OTEC facilities, (2) antitrust review standard, (3) state programs consistency standard, (4) license application fee phasing, and (5) technical corrections.

Land-based OTEC Facilities

The most important substantive problem in the OTEC Act of 1980 stems from the fact that the possibility of building land-based OTEC plants (with intake and/or discharge pipes extending out into the ocean) was being discussed by very few companies in early 1980 when the legislation was drafted. Although the possibility of land-based OTEC plants is mentiond twice in the House of Representatives committee report on the legislation, the bill itself did not deal directly with all the situations involving land-based facilities.

The law does not specifically state the extent of NOAA's jurisdiction over land-based OTEC plants. NOAA's reading of the definition of "OTEC facility" in the Act and the legislative history is that the definition includes any integral part of an OTEC facility which is seaward of the high water mark. By this reading the seaward portions of the intake and/or discharge pipes of a land-based OTEC plant are included in the definition of "OTEC facility" and must be licensed by NOAA.

Section 101(c)(7) of the OTEC Act requires that an OTEC facility be "documented under the laws of the United States" in order to receive an OTEC license. That phrase is normally used to refer to vessel documentation issued by the United States Coast Guard. The documentation laws administered by the Coast Guard are designed for vessels, not for buildings or pipes. Even though section 108(e)(2)(A) of the OTEC Act gives the Coast Guard authority to require documentation of any U. S. OTEC facility, it is doubtful whether the intake and/or discharge pipe portion of a land-based OTEC plant could meet all the technical requirements of the documentation laws even if the Coast Guard were willing as a policy matter to consider documentation of them.

Unless NOAA were to invent out of thin air some new type of U.S. documentation for this kind of OTEC facility, the OTEC Act must be amended to resolve the difficulty. Three policy options appear possible. First, the definition of "OTEC facility" could be amended to exclude all parts of any OTEC plant located partly on land. Such an amendment would exempt land-based OTECs from licensing requirements, but would directly undermine a major reason why the legislation was needed in the first place--provision of assurance to an OTEC plant owner that no other OTEC plant will be allowed to destroy the economic viability of his operation by changing the thermal gradient used by the owner's OTEC plant. If land-based OTEC plants were to be permitted to operate without licenses, the owner of a moored or Shelf-mounted facility could not be given the assurance he needs that the thermal gradient he uses would not be degraded by a land-based plant.

Second, the Act could be amended to require the Coast Guard to document the portion of a land-based OTEC plant which is located seaward of the high water mark, while waiving any technical requirements (e.g., admeasurement, compartmentation) of the documentation and inspection laws which are found inappropriate. This option would allow the seaward portion of land-based OTEC plant to be documented and licensed as an OTEC facility. It would also preserve the possibility of Martitime Administration Title XI loan guarantees for the seaward portion of the land-based OTEC plant. This would be accomplished, however, at the cost of massive surgery to apply the documentation laws to an entity much different from the entities to which the documentation laws were designed to apply. There is no certainty that the Maritime Administration would make Title XI loan guarantees available to such OTEC facilities.

Third, the Act could be amended to exempt the seaward portion of a land-based OTEC plant from the documentation requirement which is now a prerequisite to receiving an OTEC license. This option would implement the non-interference purpose of the OTEC Act without requiring surgery to the documentation laws. It would, however, make it impossible to obtain Title XI loan guarantees for any part of a land-based OTEC plant, since documentation is one of the prerequisites for such a loan guarantee. If this option is adopted, industry would be giving up the opportunity to convince the Maritime Administration to approve loan guarantees for the seaward portion of land-based OTEC plants, in return for provisions of law which are simply stated and can be easily administered by federal agencies.

Antitrust Review Standard

Sections 101(c)(5) and 104 of the OTEC Act provide for a 90-day review by the Attorney General of antitrust aspects of each OTEC license application. However, the two sections prescribe different criteria for that review. Section 101 (c)(5) states,inter alia, that NOAA may issue an OTEC license unless the Attorney General states that issuance would create a situation "in violation of" the antitrust laws. Section 104(a) allows the Attorney General to submit advice or recommendations to NOAA to avoid action which would create a situation "inconsistent with" the antitrust laws. The existence of two separate standards for antiturst review could lead to difficulty in the licensing process, and it is therefore desirable to have the same standard in both sections of the law.

During Congressional hearings on the legislation which became P.L. 96-320, the Federal Trade Commission's Bureau of Competition pointed out

there are two ways of viewing antitrust aspects of an OTEC license application: one is in the narrow sense of examining whether competitors are joining together in a mutual enterprise, the other is in the broader sense of whether the emergence of a commercial OTEC alternative will increase competition in the overall energy industry. This author believes the broader view should be the controlling view for at least the initial OTEC plants, and would prefer limiting the Attorney General's intervention to situations "in violation of" the antitrust laws.

State Programs Consistency Standard

Consistency of OTEC licenses with State and local laws and/or coastal zone management programs is mentioned in three locations in the OTEC Act (sections 2(a)(8), 101(c)(10), and 105(b)(1)). In each location slightly different language is used. NOAA believes the three different sets of language can be read together to arrive at a single meaning, and wrote that meaning into its proposed licensing regulations. No comments were submitted to NOAA objecting to that formulation.

Notwithstanding the absence of objections to NOAA's proposed regulations on this subject, it is desirable for the law to be amended to use a single set of language in all three places because the Act's language in these locations sets out the procedural rights and duties involved in interactions between NOAA and the States during the OTEC licensing process. It would be unwise to leave any vagueness on procedures, which would only exacerbate any tensions that might arise during the licensing process on a specific license application.

License Application Fee Phasing

Section 102(h) of the Act requires each license applicant to remit a nonrefundable application fee to NOAA at the time the application is filed. The section requires the NOAA administrator to establish by regulation the amount of the fee, which must reflect the reasonable administrative costs incurred in reviewing and processing the application. NOAA has estimated the total of these costs to be $250,000. Although that is much less than the costs for processing a license application for a nuclear power plant, it is not an insubstantial fee to pay before construction begins.

In response to comments on its Advance Notice of Proposed Rulemaking, NOAA decided in its proposed regulations to permit payment of the fee in three installments during the licensing process instead of requiring payment of the entire amount when the application is filed. This phasing of the fee will still insure that NOAA receives payments as costs are incurred, and will present a smaller financial burden to license applicants than having to pay the entire fee when the application is filed. While NOAA's proposed phasing of the fee can be found legal by a very careful analysis of section 102(h), an amendment specifically stating that a phased fee is permissible would avoid any future complications.

Technical Corrections

Because of the speed with which final Congressional action was taken on the legislation in July of 1980, several technical errors occurred which should be corrected before NOAA issues its first OTEC license. These technical errors evidence no substantive disagreement, but need to be corrected in order to avoid possible extensive litigation. The inadvertent omission of the word "not" in a key sentence of the law could, for example, cause extensive litigation with the applicant and NOAA citing legislative history to show that the omission was not intended by the Congress, and the opposing party asserting that under a strict reading of the law the license could not be issued.

Several technical errors of this type crept into the law. While litigation on OTEC licensing is not anticipated at this time, the errors should be corrected before the opportunity for litigation arises.

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THE STATE OF HAWAII PUBLIC SECTOR OTEC PROGRAM

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Hawaii is committed to the development of ocean thermal energy conversion (OTEC). Many factors are essential to successful development. These factors include the state of the technology, the availability of financial support, and the establishment of a legal regime. It is also essential to develop good homes for OTEC plants.

The State of Hawaii wants to be a good home for OTEC plants. The State believes that OTEC will be most successful where it meets the needs of both the industry and the local community. Identifying and meeting these needs is an important task. To develop the potential of this renewable energy resource and to demonstrate our commitment to the democratic process, it is a task which must be done well. Doing it well means that a local community must identify a path—its preferred future—and then clear that path so that it will be an attractive one for industry to follow.

This paper reviews the role which public agencies in Hawaii have played in regard to all the factors essential for OTEC success.

I. A BRIEF HISTORY OF OTEC ACTIVITIES IN HAWAII

The State's commitment to OTEC was demonstrated as early as 1974, when the Hawaii State Legislature established the Hawaii Natural Energy Institute (HNEI) and the Natural Energy Laboratory of Hawaii (NELH). HNEI was established to conduct research on alternate energy technologies. NELH, located on 328 acres of shorefront property at Keahole Point on the Island of Hawaii, was established as a facility for natural energy research.

A study completed in 1975 indicated that NELH was the best site in Hawaii for an OTEC research facility, and OTEC research began there immediately. In 1976, a project was initiated by the National Science Foundation and the Energy Research and Development Administration to investigate biofouling and corrosion problems in OTEC heat exchangers. The test apparatus was mounted on a buoy located 50 feet below the surface in about 200 feet of water directly offshore Keahole Point. Over the years, this project has produced some of the best OTEC biofouling and corrosion information available anywhere in the world.

In 1978 the Seacoast Test Facility Development Group was formed to establish an onshore OTEC test facility at NELH. In September, 1978, Argonne National Laboratory, acting on behalf of the U.S. Department of Energy (DOE), accepted the proposal of the Development Group. The final design of the Seacoast Test Facility was completed in 1979, and the blessing and groundbreaking ceremony took place in February, 1980. The laboratory building and power center have been constructed, and the facility is now pumping warm water for experiments. A cold-water pipe will be deployed in 1981.

Also in 1978, the State entered into an agreement with Lockheed Missiles and Space Company and Dillingham Corporation to fund, construct, and operate an experimental OTEC plant, Mini-OTEC. On August 2, 1979, Mini-OTEC became the world's first at-sea, closed-cycle OTEC plant to generate net energy. Mini-OTEC operated for three and a half months in the NELH ocean research corridor 1.3 miles offshore Keahole Point.

The DOE's first major project, OTEC-1, arrived in Hawaii in late June, 1980. Known as the SS Ocean Energy Converter, it was dedicated at Aloha Tower on July 5, 1980, and deployed 14 miles northwest of NELH in October, 1980. After four months of testing, the project was terminated in April, 1981. The cold-water pipe assembly was left at the operating site, attached to the mooring buoys, and the vessel returned to Honolulu Harbor for further disposition. In May, certain components on the vessel were assigned to Argonne National Laboratory and were removed for continued use at the Seacoast Test Facility.

In the period 1972-1979, the State and private industry contributed $6 million to OTEC development in Hawaii. While this is a major commitment for a State the size of Hawaii, it is a small amount compared with the hundreds of millions of dollars required to scale-up OTEC operations. The scale-up is likely to depend upon funding from the U.S. Department of Energy.

The next step in the DOE program is an OTEC pilot plant. In September, 1980, the DOE issued a Program Opportunity Notice (PON)[1] for the conceptual design, preliminary design, and construction of a 40-MW pilot plant. In anticipation of the PON, an Ad Hoc Committee for the Advancement of OTEC for Hawaii was formed in 1979, under the leadership of Hawaiian Electric Company and Dillingham Corporation, with the support of the University of Hawaii, the Office of the Marine Affairs Coordinator, and the Department of Planning and Economic Development (DPED). The Committee agreed that the best site in Hawaii for a pilot plant would be off the coast of Oahu, the State's most populous Island. In 1980, the Committee produced OTEC for Oahu[2], a report which

sets forth the studies which will be necessary to collect environmental and design data for an OTEC pilot plant offshore Hawaiian Electric Company's generating station at Kahe Point, Oahu.

In his address to Ocean Energy 7 in June, 1980, Governor George R. Ariyoshi made it clear that Hawaii would work with any industrial consortium which wished to bid Hawaii as a site in responding to the PON.[3] The Hawaii State Senate passed a resolution in the 1980 session declaring that it is totally committed to the development of OTEC systems and that the State will compete for, and share the cost with the federal government for, an OTEC pilot plant in Hawaii. The resolution stated that an appropriate in-kind or fiscal contribution will be available at the time Hawaii's contribution is required.[4] The sum of $1,000,000 was appropriated to attract an OTEC pilot plant to Hawaii and conduct environmental baseline data collection at the preferred site. In February, 1981, Hawaii-based bids were filed by Ocean Thermal Corporation, General Electric Company, and Solaramco. Ocean Thermal Corporation bid an onshore plant; General Electric bid a nearshore jacket tower; and Solaramco bid an at-sea grazing ammonia-type plant.

Hawaii's congressional delegation has actively supported OTEC development. U.S. Senator Spark M. Matsunaga introduced S. 1830, the "Ocean Thermal Energy Conversion Research, Development, and Demonstration Act," to provide funding to speed up OTEC development and set national goals. This bill became law on July 17, 1980.[5] U.S. Senator Daniel K. Inouye introduced S.2492, "The Ocean Thermal Energy Conversion Act of 1980," to provide a regulatory framework and financial assistance for OTEC development. This bill became law on August 3, 1980.[6]

The Hawaii State Plan, which calls for ocean energy research and development, was enacted in 1978.[7] In 1980, the DPED published the State Enery Plan,[8] one of 12 functional plans designed to implement the State Plan. The Energy Plan sets forth OTEC-related projects as implementing actions. It was submitted to the State Legislature for consideration during the 1981 Session.

In 1980, the DPED's Hawaii Coastal Zone Management Program initiated an Ocean Management Program to analyze ocean uses, potential conflicts, and community attitudes. This program will analyze OTEC potential in relation to fisheries, mariculture, marine research, marine sanctuaries, nearshore recreation, and coastal energy development. The DPED staff also conducted research on the State and Federal regulation of OTEC plants in Hawaii.[9]

In response to a legislative resolution, the DPED and the Department of Land and Natural Resources commissioned a study of legal issues relating to ocean leasing for mariculture and OTEC activities. This study, Ocean Leasing for Hawaii,[10] was published in January, 1981. The DPED is now beginning work on an Ocean Resources Functional Plan which will be based upon the results of the Ocean Management Program and will integrate existing plans in fisheries, marine education, OTEC, and manganese nodules.

II. THE PUBLIC SECTOR OTEC PROGRAM

DPED has drafted a working document, "The State of Hawaii Public Sector OTEC Program 1980-1985," to map out the planned activities of various public institutions interested in developing Hawaii's OTEC potential. The goal and objectives are as follows:

GOAL

To reduce Hawaii's dependence on imported oil by establishing an OTEC industry which will be environmentally sound, socially acceptable, and economically beneficial to the people of Hawaii.

OBJECTIVES

To promote research

To promote research which will solve scientific and technical problems and accelerate the development of OTEC technology.

To interact with industry

To interact with industry representatives to discuss Hawaii's resources and to identify the requirements of a new OTEC industry.

To facilitate commercialization

To facilitate commercialization by making Hawaii an attractive site for the experimental, pilot, and prototype OTEC plants which are necessary before full-scale commercial plants can be built.

To assess impacts

To assess the environmental, social, and economic impacts which an OTEC industry could have on Hawaii.

To inform the public

To inform government agencies, private businesses, and the public at large as to the nature and potential impacts of OTEC development in Hawaii.

The public sector activities in each of these areas can be described as follows:

1. Research promotion. The purpose of this program element is to identify the research required for OTEC development, obtain the necessary funds, and conduct the research in Hawaii.

The Hawaii Natural Energy Institute (HNEI) is a research institute established by statute and located at the University of Hawaii. It has supported biofouling and corrosion studies, and has provided public information on OTEC potential. In 1981, it prepared an extensive review of OTEC under a subcontract funded by the DOE. This review included resource estimates, the history of OTEC development, closed-cycle technology, ocean engineering, economics, environmental effects, legal issues, political and institutional concerns, sociological concerns, and policy implications.[11]

The Natural Energy Laboratory of Hawaii (NELH) is a non-profit corporation established by statute and governed by a Board of Directors. The Directors consist of

the DPED Director, the Marine Affairs Coordinator, the Chairman of the Board of Land and Natural Resources, two officers or employees of the University of Hawaii appointed by the President of the University, and two County of Hawaii officials appointed by the Mayor of the County. NELH is assigned to DPED for administrative purposes, and is administered under a contract with the Research Corporation of the University of Hawaii. The primary function of NELH is to serve as the "landlord" or facilities manager for the research activities carried out by others at Keahole Point. To date, NELH has been supported by State and County of Hawaii funds, while the first major onshore user, the Seacoast Test Facility, has been funded by the State and Federal government. The next major area of expansion at NELH is in OTEC-aquaculture experiments. NELH is available as a research facility for both public and private sector activities.

2. Industry interaction. Program personnel from various State institutions host industry and government officials who come to Hawaii, and attend workshops and conferences throughout the world. Through this interaction, public sector officials learn of industry's needs and discuss the preferences of the local community. This helps the State clear the path for development.

3. The facilitation of commercialization. The State of Hawaii played a major role in the success of Mini-OTEC, the world's first at-sea, closed-cycle OTEC plant to produce net energy. The DPED and the Marine Affairs Coordinator are now cooperating with Ocean Thermal Corporation, General Electric Company, and Solaramco regarding their responses to the Program Opportunity Notice for the 40-MW pilot plant. The State welcomes the earliest possible involvement by industry in all aspects of OTEC development, and prefers to play a supporting role as industry develops its plans. The State is thus very pleased that the three PON bids from Hawaii have private companies serving as the prime contractors.

State support for industry in Phase I of the pilot plant proposals consists of funding for environmental studies and assistance in obtaining the necessary permits for the construction and operation of the plant. The Governor has committed the full $1,000,000 appropriated by the Legislature in 1980. The State will use $250,000 of this money to conduct a "common-base" environmental study, focusing primarily on bathymetry and sediment sampling offshore Kahe Point. This package will be available as part of the cost-share for each company bidding Kahe as its site. The State will also provide each company with $250,000 for design-specific environmental work, which will be conducted by the company's subcontractors. The $250,000 for "common-base" environmental work and the $250,000 in environmental subcontractor funds will give each company a cost-share of $500,000 for the Kahe site in Phase I.

4. Impact Assessment. Before an OTEC plant is built, the government and people of Hawaii will need to estimate the impacts which the new plant will have. The contractor will be required to obtain a number of permits, and hearings will be held before some of the permits can be issued. At present, impact assessment activities are designed to provide data regarding the area offshore Kahe Point, the State's preferred site for the DOE pilot plant. Work has begun under a Coastal Energy Impact Program grant from the federal Office of Coastal Zone Management to integrate the known environmental data in the Kahe area, and study the pelagic fish and recreational impacts of an OTEC pilot plant located offshore. This initial study will be completed by October, 1981. Proposed impact studies include a public finance study, an infrastructure study, a legal/institutional study, and a socio-economic study.

5. Public Information. Personnel from many public institutions attend community meetings and seminars and provide briefings for Hawaii government officials, citizen groups, and businessmen. The Marine Advisory Program of the University of Hawaii Sea Grant Office and the Curriculum Research and Development Group at the University of Hawaii are developing OTEC materials for community and school use.

III. THE ROLE OF OTEC IN HAWAII'S FUTURE

Hawaii is dependent upon imported oil for 92% of the State's energy needs. At the same time, the state is rich in alternate energy potential: wind, geothermal, biomass, direct solar, and OTEC. The state is developing all of these energy sources.

OTEC has major advantages for Hawaii. With the temperature differential available day and night, all year round, OTEC can provide baseload power to the State's electric system. It appears that negative environmental impacts will be minimal, and OTEC may have a positive impact as a fish aggregation device. Floating OTEC plants would not use Hawaii's precious land resources and could be moved from island to island as energy requirements grow or change, adding flexibility to long-term utility planning. Since many of the best OTEC sites in Hawaii are along the leeward or dry sides of major islands, there is great interest in open-cycle OTEC, which could provide potable water for economic development as well as energy.

Another potential advantage of OTEC for Hawaii is OTEC-aquaculture. The cold deep ocean water brought up during OTEC operations is richer in nutrients than warm surface water. This "artificial up-welling" of nutrients could support an aquaculture operation, either at sea or on land. The cold water could flow through ponds of algae, shellfish, shrimps, lobsters, and seaweed before returning to the ocean.[12] It is possible that OTEC plants will be as important for food production as for energy generation.[13] Hawaii has adopted an aquaculture development plan[14] and currently leads the United States in freshwater prawn farming. The combination of OTEC and aquaculture could stimulate both industries.

The greatest contribution to Hawaii's energy future may come from ammonia production. John P. Craven, State Marine Affairs Coordinator testified before Congress that OTEC will develop in the following four phases:

> (1) The generation of electricity for use by coastal and island communities; (2) The relocation of energy-intensive industry to OTEC sites; (3) The production of hydrogen and ammonia for use as fuel: hydrogen as a fuel for commercial aircraft, and ammonia as a fuel for major power grids relying on the ammonia fuel cell; and (4) The substitution of ammonia as the best synthetic fuel replacement for gasoline and alcohol in internal combustion engines.[15]

He estimated the ocean energy potential of the U.S. Pacific Islands to be 70 quads—equal to the entire nation's energy consumption. He also estimated that "in the Hawaiian Archipelago, including Palmyra Island, it is possible to produce 10 to 15 quads per year—or, in other words to replace the Middle East."[16]

While Hawaii is rich in alternate energy potential, most forms of alternate energy are seen only as substitutes for electricity. At present, however, only 31% of Hawaii's energy demand is for electricity; another 31% is for aviation fuel and 19% for gasoline. With production of both electricity and ammonia, over 80% of Hawaii's energy could someday be supplied by OTEC. This means OTEC may be the key to total energy self-sufficiency in Hawaii.

IV. CONCLUSION

Through its public sector activities, Hawaii seeks to serve as the nation's OTEC laboratory and site for early commercialization. In the coming years, Hawaii will identify its preferred path for OTEC development. This is important, because there is still time for industry to modify its OTEC plant design, location, and method of operation so that commercial-scale plants will fit in with the desires and values of the local community. There is also time for the local community to mitigate any negative impacts associated with development. As a result, OTEC plants will belong to the community and will be supported by it.

We in Hawaii care a great deal about our community, and we care a great deal about the potential of OTEC. We will make Hawaii a good home for OTEC, and OTEC will make Hawaii a better home for us.

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THE FLORIDA OCEAN THERMAL ENERGY CONSORTIUM

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ABSTRACT

In response to congressional initiatives in the area of ocean thermal energy, the state of Florida formed a multi-agency, multidisciplinary team of individuals who set up a non-profit corporation entitled the Florida Ocean Thermal Energy Consortium, Inc. (FOTEC). FOTEC consists of key state agencies, the Governor's Energy Office, the Florida Solar Energy Center, the Florida Institute for Oceanography, a municipal utility coordinating group, and City Electric System of Key West. Formed in late 1980, FOTEC has submitted to the Department of Energy a proposal for the construction of a 40 megawatt pilot plant off shore of Key West, Florida. TRW, Inc. of Redondo Beach, California, was selected as the system integration contractor on this project. The consortium itself is unique, in that it combines the resources of the state and private interests in addressing a common problem: the development of an OTEC pilot plant for the generation of electrical energy in a state that is heavily dependent upon oil for its present electricity.

INTRODUCTION

During the summer of 1980, the U.S. Congress passed and the President signed two bills which moved the nation firmly toward creation of a program to make significant use of ocean thermal energy conversion (OTEC) by the year 2000.

Public Law 96-310, sponsored by Congressman Don Fuqua (Florida) and Senator Spark Matsunaga (Hawaii) called for the creation of an OTEC industry capable of delivering 10,000 megawatts of electric power by 1999. As an interim goal, the law requires 100 megawatts by 1986. Public Law 96-320, sponsored by Congressman Gerry Studds (Massachusetts) provided for environmental evaluation, licensing, and Maritime Administration financing for the activities outlined in PL-96-310.

These two laws, combined with the magnitude of the ocean thermal energy resource surrounding the state of Florida, provided a strong incentive for the present vigorous state government action.

Florida's formal interest in OTEC began in 1976 when the Florida Solar Energy Center (FSEC) began a study of the potential of this technology for energy production in the state. A publication on the state's OTEC research and development capabilities was prepared in November of 1976.[1] FSEC held an OTEC Resource and Environmental Assessment Workshop under ERDA sponsorship in June of 1977.[2] A paper estimating the magnitude of the OTEC potential of the Florida Current at 75,000 MW was published in the Journal of Energy in March 1978.[3] In that same year, FSEC published a brochure which outlined the federal OTEC program, described Florida interests in that program and listed several siting options.[4]

Apart from relatively minor interest in the program on the part of state government leaders, Florida OTEC activities were minimal until late 1980. This was due principally to the slowness of the federal OTEC program and the DOE's stated interest in island sites. Late in 1980, however, DOE issued a Program Opportunity Notice (PON) for the design, construction, testing and operation of one or more OTEC pilot plants. In response to this PON, TRW, Inc. contacted the Governor's Energy Office in October of 1980 and indicated its interest in working with Florida toward establishing a site in the Florida Keys. After some preliminary planning meetings, the state named a multi-agency, multidisciplinary team to begin the complex process of developing what Ezra[5] and Naef[6] have called an OTEC Technology Delivery System (TDS) for Florida. The organization of this team was formalized with the creation of a non-profit corporation named the Florida Ocean Thermal Energy Consortium, Inc. (FOTEC).

The purpose of this paper is to describe Florida's OTEC activities and FOTEC in particular.

FLORIDA'S OTEC POTENTIAL

Florida, with its more than 1,000 miles of coastline along the Atlantic Ocean and Gulf of Mexico and its access to the Gulf Stream, provides the continental United States a unique opportunity for large-scale OTEC utilization. A population of 9 million people and a peak electric generation demand of 21,000 megawatts lend further appeal.

At present (1981), the state derives its electric energy as follows:

Oil	51%
Coal	16
Nuclear	16
Gas	12
Coal by Wire	4
Other	1
	100%

Florida's fragile ecosystem does not encourage the continued widescale use of fossil fuels. Acid rain, caused by coal and oil combustion products, has the potential to seriously damage the state's agricultural interests and vital natural and recreational areas. Also, in terms of long-range planning to satisfy Florida's power requirements, the questionable economics of nuclear facilities simply cannot be ignored.

OTEC provides many attractive features when measured against Florida's requirements. There is no waste disposal problem; the process is environmentally benign; minimum land space is needed; and the process brings important marine nutrients to the surface for exploitation.

While the intensive capital investment necessary to exploit OTEC may appear to be a disadvantage at first glance, it must be remembered that such expenditures can be directed toward exercising important areas of America's technological and economic base. These include maritime construction sites in Florida and along the Gulf coast, the creation of jobs, hardware and advanced technology, all of which can be provided by America's domestic industries.

Florida's heavy dependence on imported fuel oil has contributed to increasing electrical rates throughout the peninsula (Key West actually has one of the highest in the nation: 10.5¢/KWH).

Key West was selected as the site for the first Florida OTEC pilot plant for three reasons: the high price of electricity, its proximity to the resource, and the desire of Key West's City Electric System to participate in the project. This site also offers a capability for early entry of OTEC generated electricity into the mainland U.S. utility grid at a point consistent with Florida's maximum growth. This will be made possible by a 138 KV, 100 MW transmission line presently being constructed from City Electric System of Key West to the Florida Power and Light electricity grid in southern Florida. It should also be noted that Florida Power and Light is presently constructing two 500 KV transmission lines connecting Florida to Georgia Power.

DEVELOPING A TECHNOLOGY DELIVERY SYSTEM

It is in the public interest for OTEC power generation to be brought to commercial feasibility at the earliest possible opportunity. With careful planning, testing and government R&D assistance, large-scale OTEC utilization under accelerated conditions can occur in advance of economic competitiveness. To accomplish this, a number of technical and economic components must be brought together into a Technology Delivery System (TDS).

Assuming that the end goal of the federal OTEC program is a privately owned and operated system of OTEC power plants delivering substantial amounts of energy to various users, there is an obvious need for a mechanism capable of putting a TDS team together. This mechanism, an OTEC Commercialization Task Force, should be capable of performing the following tasks:

1. Identify potential OTEC TDS team members and establish lines of communication between them.
2. Provide educational and information exchange services for potential TDS team members.
3. Determine the specific constraints inhibiting full participation by each potential TDS team member.
4. Develop a series of options for overcoming the constraints and evaluate the feasibility and cost-effectiveness of implementing each of these options.
5. Using the results of the above tasks, develop a strategy for OTEC commercialization involving participation by all the segments of the TDS.
6. Guide and promote the selection or creation of an OTEC owner/ operator capable of taking over responsibility for ownership and operation of the first commercial OTEC power plant.

As this series of tasks is carried out, we expect to see more and more sectors of business, industry, and labor become involved. A formal management structure has already emerged and, in a phased process, will continue to evolve into a well-integrated team capable of carrying the commercialization process forward to a point at which only minimal federal government participation is required.

THE FLORIDA OCEAN THERMAL ENERGY CONSORTIUM

The Florida Ocean Thermal Energy Consortium (FOTEC) was formed in late 1980 as a non-profit corporation, representing all the relevant interests in the state, to respond to the previously mentioned Program Opportunity Notice issued by the Department of Energy.

FOTEC also serves as the OTEC Commercialization Task Force to pursue the six previously enumerated tasks.

The Board of Directors of FOTEC is composed

of one individual identified by each of the following organizations:

Governor's Energy Office
Florida Solar Energy Center
Florida Department of Natural Resources
Florida Department of Veteran and Community Affairs
Florida Department of Commerce
Florida Institute for Oceanography
Florida Municipal Power Agency
Florida Public Service Commission
City Electric System of Key West
Board of Regents

Assisting in the project, as observers, are representatives from the Florida Department of Environmental Regulation, and the Florida Electric Power Coordinating Group.

The chairman of the board is Lex Hester, Director of the Governor's Energy Office. Dr. David Block, Director of the Florida Solar Energy Center, serves as the vice chairman. The secretary of the corporation is John Gilleland of the Department of Commerce, and Thomas Kelley of City Electric System is the Treasurer.

In regard to FOTEC's response to the DOE PON, TRW, Inc. has been selected as system integration contractor. FOTEC's Board of Directors has expressed complete confidence in TRW as the major project subcontractor. As the pilot plant project advances, the specialized knowledge of FOTEC member utility companies, City Electric System of Key West and the Florida Municipal Power Agency, will provide the expertise needed to make the OTEC facility functional. The utilities, involvements will insure the presence of an immediate market for the electricity generated, and a customer for the plant once it becomes available for private ownership.

The Florida Solar Energy Center has been designated as the lead state agency in the program, providing the program manager and deputy program manager.

FOTEC has presented congressional testimony on the Florida OTEC program and on the national program as well. It continues aggressively to seek support from Florida's state and national leadership, and provides frequent briefings to the state's leadership. To date, congressional support has been gratifying. State legislators are also demonstrating an interest in the program. The briefings stress the importance of proving the OTEC principles.

CONCLUDING REMARKS

The offshore OTEC pilot plant site at Key West, Florida offers the following unique advantages:

1) Direct connection to a large utility grid with an enormous demand. This ensures that the Florida OTEC market will never be saturated. An accessible demand exists nearby for nearly any number of OTEC plants which may be sited around Florida.

2) Much of the U.S. OTEC export potential will be to countries with offshore sites that require floating power plants. By developing a floating OTEC for the Key West site, the resulting design will be fully applicable to other sites around the globe.

3) Although the strong current (approximately 3.5 knots) present at the site may pose an initial ocean engineering problem, a plant designed to withstand this current can be operated nearly anywhere on the globe that an adequate ocean thermal resource exists. In addition, nominally quiescent sites can experience sizeable surface currents and current shears in response to tropical storms and hurricanes. Plants sited in low-current areas must be designed to survive these transient events. Thus, maximum OTEC plant versatility is achieved by beginning with a design that not only survives, but routinely operates, in ocean currents having speeds of several knots.

4) By siting in a region of fairly constant current, the thermal effluent re-entrainment problem (which can be experienced at other sites) effectively disappears and the plant's water pumping requirements are reduced.

It is believed that FOTEC provides a mechanism for presenting the proof of concept which is necessary if traditional funding mechanisms are to be made available to the OTEC industry. The utility industry cannot obtain OTEC financing since OTEC has not been demonstrated on a commercial scale and the companies with OTEC expertise are not involved in the utility business. Florida suggests that the consortium approach, coupled with federal support, is a viable one.

The Consortium is concerned that federal support of the program be continued. At the present level of development, no single state could make the necessary commitment to see the program through to its completion. The PL 96-310 was enacted to spark interest in the possibility of ocean thermal energy conversion. As FOTEC pointed out in its testimony before Congress, the existence and vitality of Florida's Consortium is living proof that the spark has struck fire, and Florida stands to play a leadership role in exploiting this energy source.

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PUERTO RICO AND THE PUERTO RICO ELECTRIC POWER AUTHORITY OTEC COMMITMENT

Jose Marina

Puerto Rico Electric Power Authority

ABSTRACT

The Puerto Rico Commonwealth has been supporting the development of Ocean Thermal Energy Conversion (OTEC) for many years. We have identified OTEC as a potential major electric power source in our island's future. Our objective is to assure the Commonwealth an independent source of environmentally clean energy at reasonable cost that will supply our needs through this period of declining energy resources. This paper describes Puerto Rico's current OTEC activities, our expectations for the future, and some possible options in the development of OTEC for Puerto Rico.

Puerto Rico has an ideal situation for the development of OTEC electric power and energy products. Early estimates place our renewable OTEC resource potential at many gigawatts. Our growing demand of some two thousand megawatts today is forecasted to steadily increase through the year 2000 A.D. With dependable OTEC electricity and energy products such as ammonia available, these demand forecasts could be even greater. We see OTEC as having a significant and favorable impact on our island's economy in a period of increasing future energy costs.

In 1979, PREPA proposed cost sharing the development, construction and demonstration of a 100A megawatt Commercial OTEC Electric Power Generating plant to operate in the mid to late 1990's (PROTEC). To reinforce this commitment and update the concept, PREPA is evaluating a modified PROTEC proposal in 1981 calling for larger power modules and an earlier commercial certification date in the 1990-1991 period.

The OTEC DOE work in Puerto Rico has been focused on defining the OTEC resource and the ocean environment adjacent to the southeast end of Puerto Rico. Here, at Yabucoa Bay and Punta Tuna, a sharp sea bottom drop off brings the ocean thermal resource to within less than two miles of land. This field work has been backed up by several economic and financial studies carried out by PREPA and the Consultores Technicos Asociados. PREPA, working with the Governor's office of energy and the University Center for Energy and Environmental Research (CEER) has participated in the response to the DOE Pilot Plants PON. PREPA has assumed both the role of prime contractor and that of joint participant with another consortium. We have offered to build the first OTEC commercial plant or buy electric power from a separate Puerto Rico generating company.

Future Puerto Rico OTEC options envision: a full development (multiple OTEC plants) of the Punta Tuna-Vieques ocean thermal resource for OTEC power; the expansion of close-in OTEC installations (land, fixed platforms and moored plants) at other Puerto Rico locations; the development of distant deepwater moored OTEC electric power generating plants; potential Puerto Rico industrial scenarios appropriate to OTEC Grazing Plants in the vicinity of Puerto Rico; and, a Puerto Rico program to expedite the utilization of commercial OTEC by the islands of the Caribbean, the United States and the third world nations.

INTRODUCTION

General

I am Jose Marina, Director of Planning and Engineering for the Puerto Rico Electric Power Authority (PREPA). I would like to speak not only for PREPA, but for the Commonwealth of Puerto Rico, our people and the many OTEC contractors who have participated with us over the years.

Puerto Rico, through PREPA, can take a somewhat more committed approach to the development of OTEC than most electric power utilities. PREPA is an agency of the Puerto Rico government working closely with the governor's office of energy as well as organizations such as the Puerto Rico Economic Development Administration and our Center for Energy and Environmental Research (CEER). All of us are dedicated to bringing OTEC electric power to our island. We have been participating in OTEC's development since 1967, fourteen years. Figure 1 lists these activities.

Many of you are acquainted with Puerto Rico as a resort and source of excellent rums. Our ocean thermal resources and accessibility to these resources are just as impressive. As you can see in Figure 2,* Puerto Rico is surrounded by year 'round OTEC resource temperatures of 21°C or

*At end of paper

greater. The volcanic nature of the island brings deep, three thousand foot (1,000 meter) cold water within a few miles of our shores in several locations. As can be seen again in Figure 2,* Punta Tuna on the southeast coast, Guayanilla on the South coast, Aguadilla on the Northwest coast, and a considerable portion of the north coast west of San Juan are very close to 3,000 foot cold water.

1967	First joint Puerto Rico Water Resource Authority and University of Puerto Rico OTEC Study. Siting on the east end of the island. Conceptual design completed.
1975	Interagency Committee formed to promote development of OTEC and solar energy.
1975	NSF/UPR OTEC Study near Punta Tuna
1977	University of Puerto Rico Center for Energy and Environmental Research (CEER) formed - 1st priority - OTEC.
1977-1978	Puerto Rico Interagency Committee for OTEC only - lead by Office of Energy of Governor of Puerto Rico
1977 to 1981	Series of DOE/CEER Studies and data gathering at Punta Tuna site.
1980	PREPA 100 MW OTEC Proposal for "PROTEC" power plant.
1980-1981	PREPA DOE OTEC Pilot Plant proposals.

FIGURE 1 - PUERTO RICO AND PREPA OTEC ACTIVITIES

Another very favorable factor in the development of OTEC is the large and growing Puerto Rico demand for electric power. We are in the top three public-owned utilities in the United States. There are not too many United States locations that combine favorable year 'round OTEC resources with a sufficiently large demand for electric power such that large 300-400 MW OTEC power plants can be incorporated in the electrical system as a normal addition. Figure 3 illustrates our electric system load growth and a range of forecasts for the future. Our current PREPA generation acquisition plan includes three 300 MW coal-fired electric power plants sited near Aguadilla on the Northwest coast. Figure 4 lists these planned increases in our system with dates for potential OTEC plant introductions. The design and construction of the first 300 MW coal plant has just been awarded to Brown and Root. Our plans are very realistic responding to greatly increased oil prices and a continually growing demand.

PREPA continues to seek to build diversity and flexibility into our electric power system. OTEC will provide another energy source to our system that is both reliable and renewable. In fact, OTEC as a baseload electric power source may be able to compete with very high price oil-fired peaking plants. PREPA could have as many as five or six different energy sources by the year 2000 including oil, coal, hydro, OTEC, wind and perhaps solar thermal or photovoltaic power. The Commonwealth has decided that the island's energy needs for the foreseeable future can be satisfied without resorting to nuclear power. OTEC is a major option in our future.

On Line	Capacity, MWe	Options
1986-87	300	Coal/Oil
1988-89	300	Coal/Oil
1990-91	300	Coal/Oil/Otec
1994-95	450	Coal/OTEC/Oil
2001	450	OTEC/Coal

FIGURE 4 PLANNED NEW FACILITIES

Puerto Rico, a part of the "Caribbean Frontier" can become a leading element in a United States Caribbean program to bring economic well being to the region. Long term, low cost electric power is a cornerstone of any economic program. OTEC thermal resources abound in the Caribbean and could become positive factors in many of the Caribbean nations economies with our help. Figure 5 maps these areas while Figure 6 taken from the DOE/SAI study of "...The Potential for OTEC in the Developing World," shows the many islands and mainland nations which could benefit from OTEC power.

STRATEGY AND IMPLEMENTATION

The objective of the Commonwealth of Puerto Rico and PREPA is to achieve a large scale 300-400 MWe commercial OTEC electric power generating plant as soon as possible with a continuing addition of OTEC plants to the PREPA system as needed. Our strategy is to support the demonstration of a minimum scale commercial OTEC electric power generating plant or module at Punta Tuna as the building block upon which a 300-400 MW OTEC plant can be built. Such a first commercial plant or module could be 10, 25 or 40 MW in size.

Our tactics include a number of actions to accelerate OTEC development, obtain financing and reduce the cost of OTEC electric power. They include: supporting the DOE OTEC pilot plant PON procurement; cost sharing as appropriate to each project; an open invitation to the OTEC industry to provide the first OTEC commercial power plant to Puerto Rico; a policy of pricing or purchasing the OTEC generated electric power at the avoided cost of oil-fired power during an initial period; comparing OTEC cost of generating electricity with fossil fueled electric power generation on a

*Figures 2 and 3 and 5-13 are at end of paper.

life cycle cost including the cost of fuel with nominal escalation; and, assignment of tax benefits to those industrial firms who bring new business to Puerto Rico through their support and use of OTEC generated electric power or energy products

DIVERSITY

This year, PREPA has taken steps to alleviate a massive dependence on oil by awarding contracts to design the Commonwealth's first coal fired electric power plant. Not only will this new capability help to reduce costs by using a lower cost fuel, but it will also provide a degree of diversity by adding a different fuel, coal, and different suppliers. This will bring to three, the types of PR electric generating plants now using water, oil and coal as their sources of energy. A fourth energy resource is being tapped by a 200,000 kW wind generator in the island of Culebra. Wind energy cannot be counted on to provide dependable baseload power. However, on remote isolated sites such as the island of Culebra wind electric power generation in combination with storage, may provide our future electricity needs.

Our diversity has to match the profile of our electric power generating needs. Both coal and OTEC electric power generation are essentially baseload power generators. In the near future, as both coal and OTEC generating plants come on line, oil fired plants may decline but at least sufficient oil fired peaking capability will be retained in the form of high distillate fired turbines and diesel generators for backup purposes. Future cost improvements and technical accomplishments may see baseload generators feed electric power storage and handle peaking demands without resorting to any oil firing. Puerto Rico has not gone ahead with nuclear power and our limited land area precludes any extensive use of biomass as fuel. Our long term hope for diversity is ocean thermal energy. The next century might well be characterized by total reliance on ocean thermal energy with coal as a backup.

PUNTA TUNA - PUERTO RICO'S FIRST OTEC SITE

Punta Tuna, on the southeast corner of Puerto Rico, was identified early as an ideal OTEC site. A great deal of data has been obtained principally through our Center for Energy and Environmental Research (CEER) which is part of the University of Puerto Rico. OTEC plants have been proposed at that site. Figures 7 through 11 illustrate the favorable characteristics of Punta Tuna. The close to shore, one to three mile, 1,000 meter cold deepwater is most significant together with the year around temperature difference of at least 21°C. currents, both surface and in deep water, are very nominal of the order of 1-1.5 knots maximum. A good harbor adjoins Punta Tuna at Yabucoa Bay. This site can accommodate land shelf mounted or moored deep water OTEC electric power generating facilities. The immediate vicinity of Punta Tuna can support perhaps 1000 MW of OTEC generated electric power from a number of plants.

In the near region between Punta Tuna on the main island and the southwest coast of the much smaller island of Vieques is over ten miles of very close in deep ocean water. This region extended south in the Caribbean can provide considerable ocean thermal resources that might become Puerto Rico's first OTEC field. Vieques is currently tied to the main island by an 18 MW submarine power cable. OTEC could provide Vieques with all its electric power and use the existing power cable to ship energy to the main island. Again, this particular region can extend the first multiple "OTEC plant field" for both commercial electric power generation and additional development and applications data collection. Large volume ocean thermal resource dynamics can be observed not too far from shore.

Figure 12 indicates the principal near shore OTEC areas surrounding Puerto Rico. In addition to the Punta Tuna-Vieques region, they include the southshore Guayanilla region, the Aguadilla Bay in the northwest and most of the northern coast west of San Juan. Further out from the islands, the thermal resource covers thousands of miles including such deeps as the Puerto Rico trench northeast of Puerto Rico and the trench to the northwest. With the development of deeper water submarine power cables, many islands can be connected with OTEC electric power generating sites at some distance. The Virgin Islands particularly St. Thomas can obtain power from Puerto Rico and from St. Croix. Power could be shipped to all the Virgin Islands both British and American. Puerto Rico could provide OTEC power to Haiti until they can begin operating their own OTEC plants. Favorable island configurations, a very large close in ocean thermal resource, and serious energy and economic needs make Puerto Rico a very logical site for the early OTEC commercial operations.

FUTURE OTEC GROWTH

As was outlined in the opening statement, a major portion of Puerto Rico's future generation of electric power could be provided by OTEC starting in the first part of the next century, some 20 to 30 years from now. One most probable scenario would see additional close-to-land or land

OTEC facilities added not only at Punta Tuna, bu new facilities at Punta Vaca on Vieques Island, Guayanilla, Aguadilla and along the north coast as well. These dispersed locations would support a significant part of the PREPA load if only some five to ten OTEC facilities are built (2000-4000 MWe). They would feed the system relatively uniformly around the island and encourage economic and population growth away from the existing urban centers. A subsequent phase in Puerto Rico's OTEC growth would be to locate OTEC facilities at

some distance off-shore (50-20 N miles) when shown to be economically feasible. This phase could also include the operation of grazing OTEC facilities based on Puerto Rico which would be supplying ammonia, aluminum or other high energy products. At some point in these later phases, Puerto Rico would be able to assist other nations in acquiring their OTEC installations. Figure 13 graphically shows such a sequence of OTEC developments.

THE CARIBBEAN FRONTIER AND OTEC

Puerto Rico, as the United States largest and most active island representative in the "Caribbean Frontier," has the opportunity to demonstrate the United States' commercial OTEC capability on the Frontier.

The accomplishments of the last seven years of NSF/ERDA/DOE work and investment can be demostrated and introduced to island nations desparately in need of low cost electric power by one of the "community." Our bilingual English-Spanish society is a positive asset in working with fellow/sister Caribbean nations.

As has been shown in the DOE/SAI International OTEC Study (to be published this summer), the smaller initial OTEC units of some 10 to 40 MW are of a size that can be directly incorporated in many small island electrical systems. The United States can make a very positive contribution to the Caribbean nations encouraging their economic growth and stability. Success in the Caribbean by the United States OTEC industry would be a springboard to the very large OTEC international market. Larger OTEC electric power generating plants could be operating in Puerto Rico in the next decade and be sited at some of the larger Caribbean Islands in the same decade. Jamaica is an excellent example of a nation whose OTEC resource could support an island aluminum production industry. Similarly, Puerto Rico OTEC electric power could produce ammonia and aluminum at Puerto Rico. Puerto Rico and OTEC can be a significant factor in the United States Third Frontier economic development program.

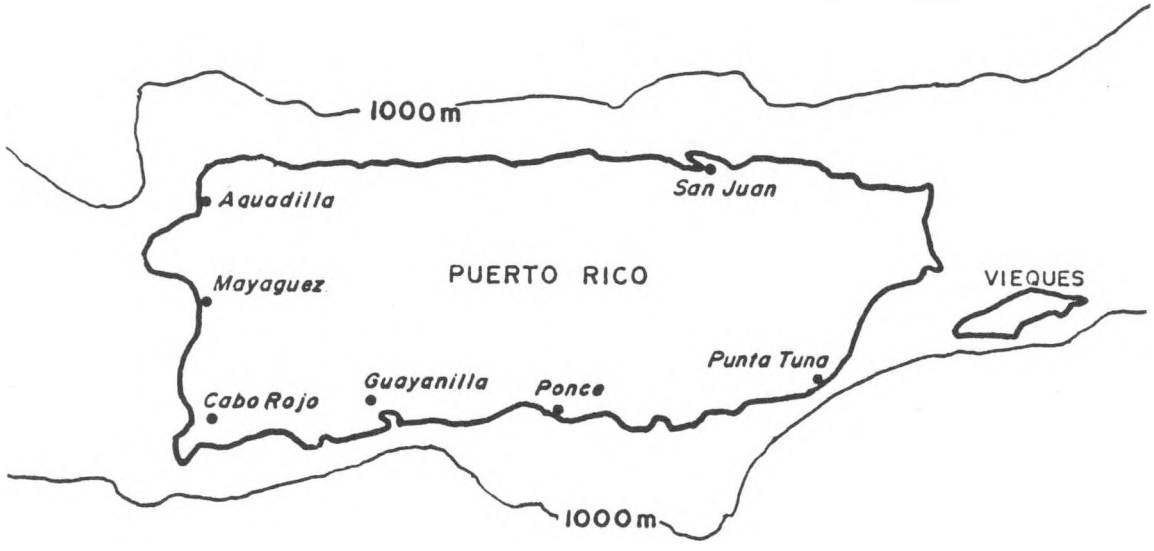


FIGURE 2 - PUERTO RICO

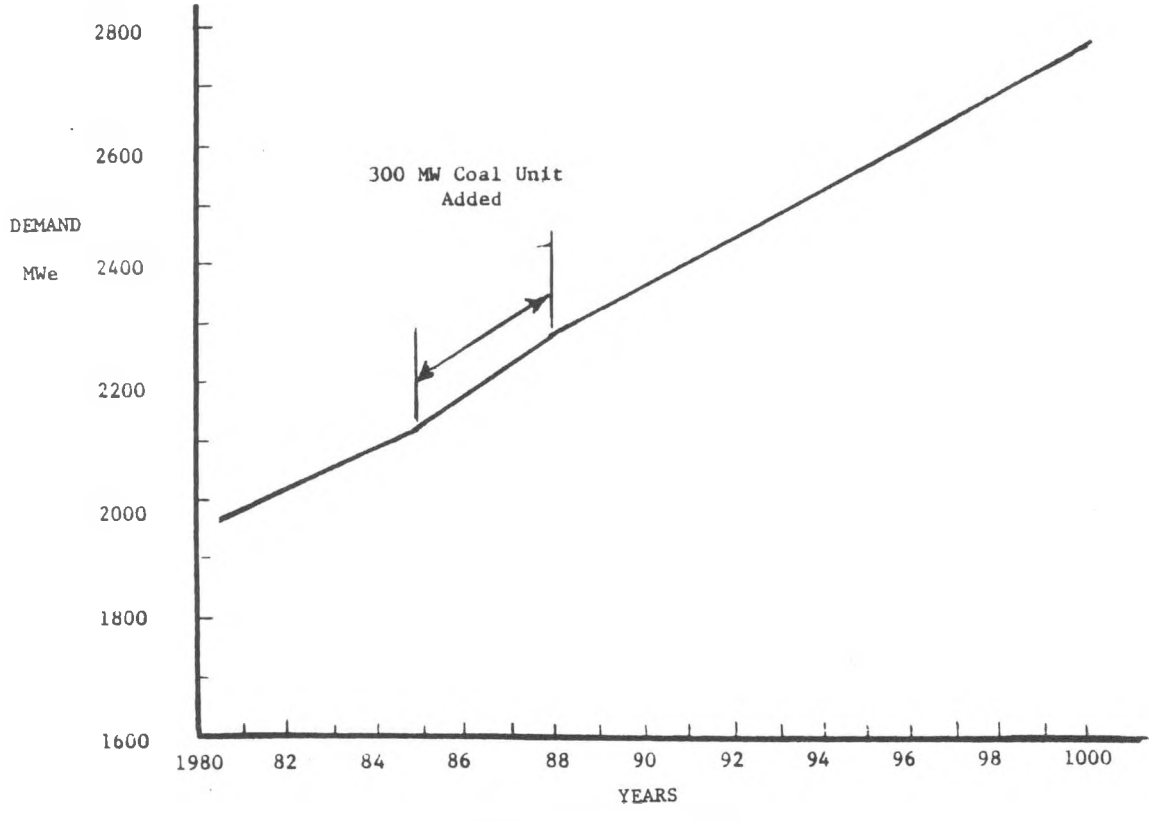


FIGURE 3 - DEMAND GROWTH

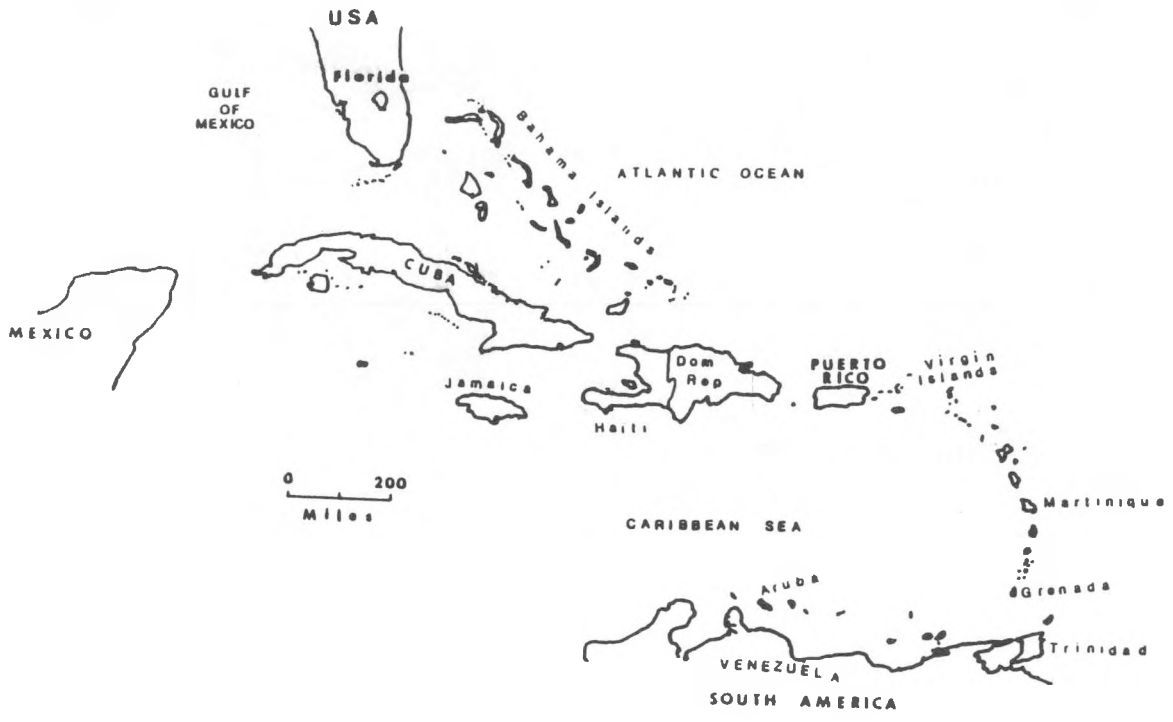


FIGURE 5 - CARIBBEAN OTEC COUNTRIES

Nations and Territories With Thermal Resource (Mean Annual $\Delta T \geq 20°C$ @1000 m Depth

GEOGRAPHICAL AREA	MAINLAND		ISLAND	
AMERICAS	MEXICO	GUYANA	CUBA	GUADA LOUPE (FR)
	BRAZIL	SURINAM	HAITI	MARTINIQUE (FR)
	COLOMBIA	FRENCH GUIANA(Fr)	DOMINICAN REP.	BARBADOS
	COSTA RICA	NICARAGUA	JAMAICA	DOMINICA
	GUATEMALA	EL SALVADOR	VIRGIN IS. (US)	ST. LUCIA
	HONDURAS	BELIZE (UK)	GRENADA	ST. KITTS (UK)
	PANAMA	UNITED STATES	ST. VINCENT	BARBUDA (UK)
	VENEZUELA		GRAND CAYMAN (UK)	MONTSERRAT (UK)
			ANTIGUA (UK)	THE GRENADINES (UK
			PUERTO RICO (US)	CURACAO (NETH)
			TRINIDAD AND TOBAGO	ARUBA (NETH)
			BAHAMAS	

FIGURE 6 - OTEC NATIONS IN THE AMERICAS (DOE/SAE Study)

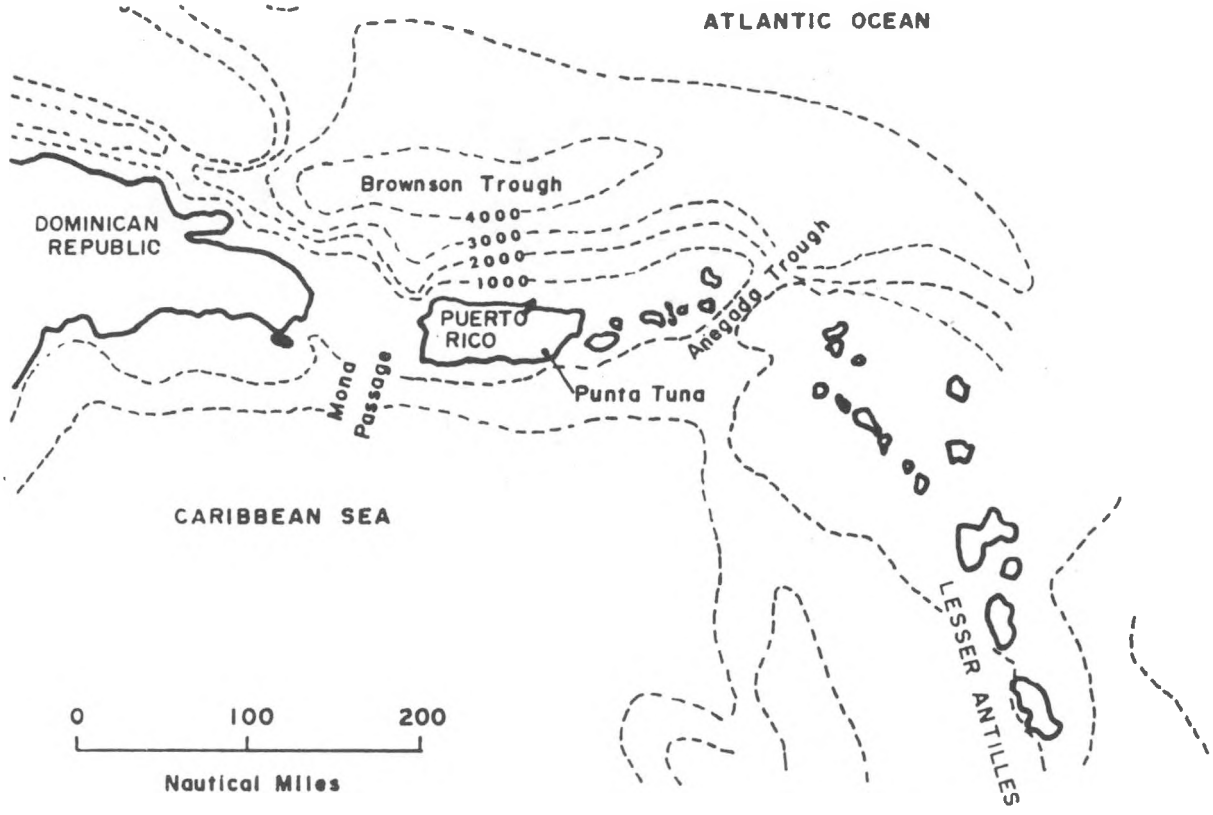


FIGURE 7 - PUERTO RICO

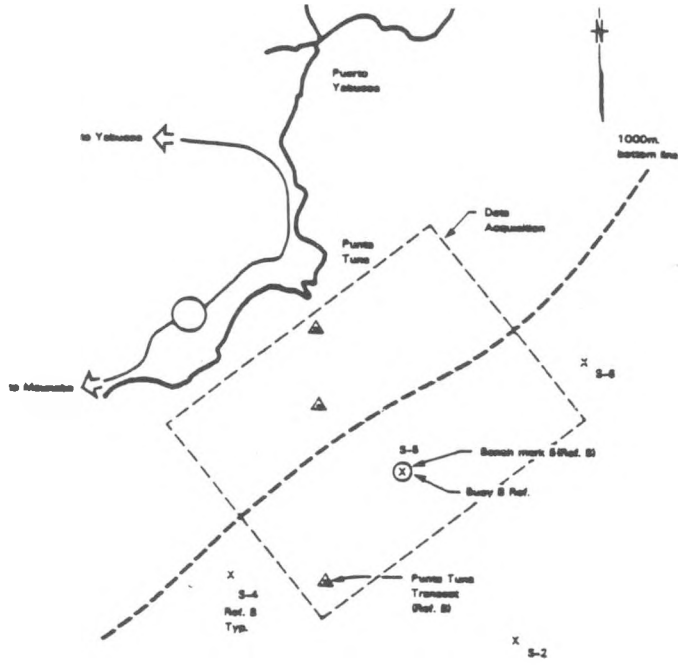


FIGURE 8
PUNTA TUNA SITE

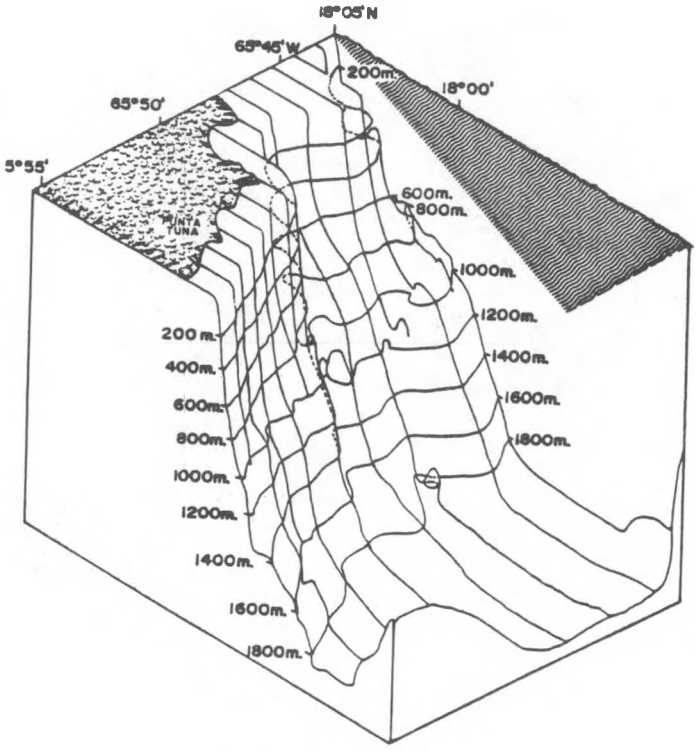


FIGURE 9
PUNTA TUNA AREA TOPOGRAPHY

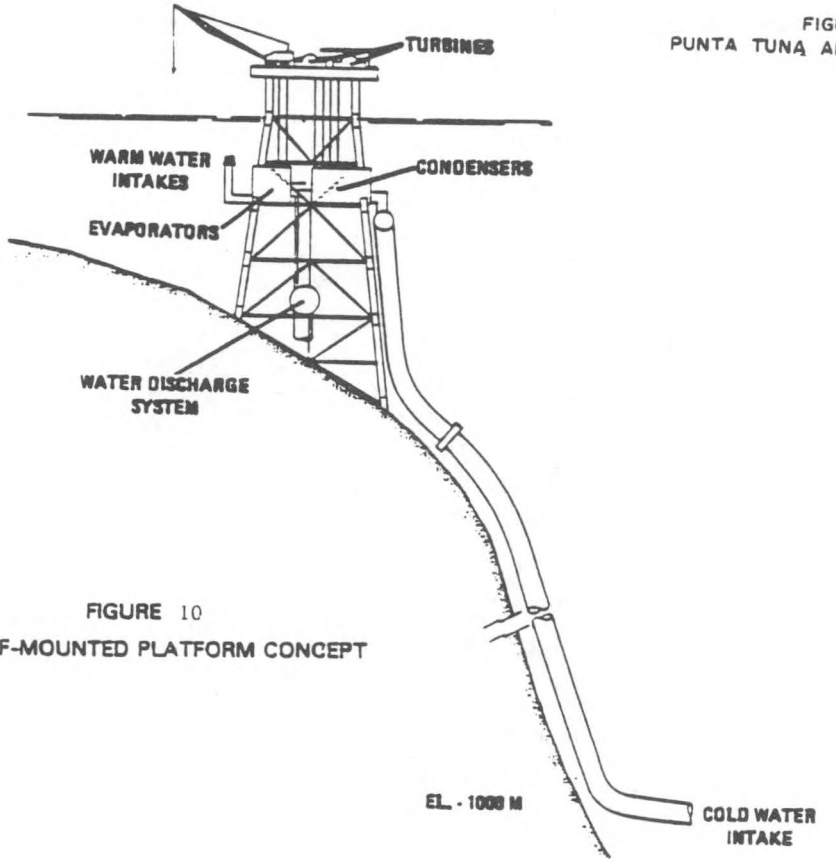


FIGURE 10
SHELF-MOUNTED PLATFORM CONCEPT

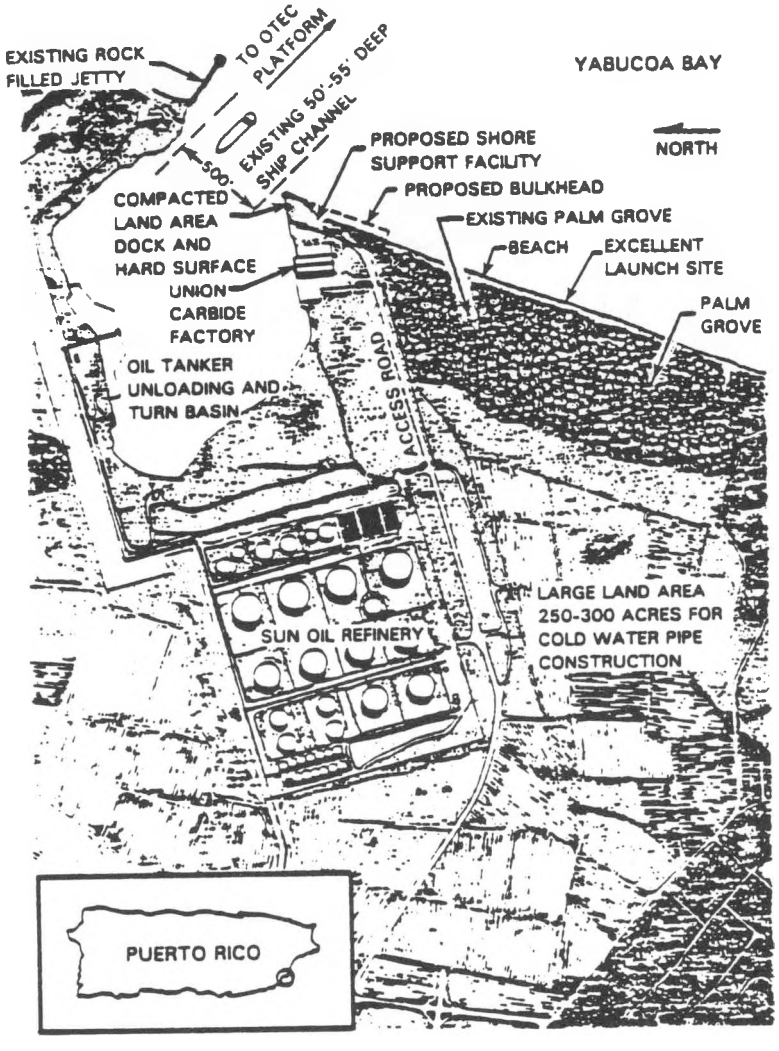


FIGURE 11

CONSTRUCTION/SUPPORT FACILITY

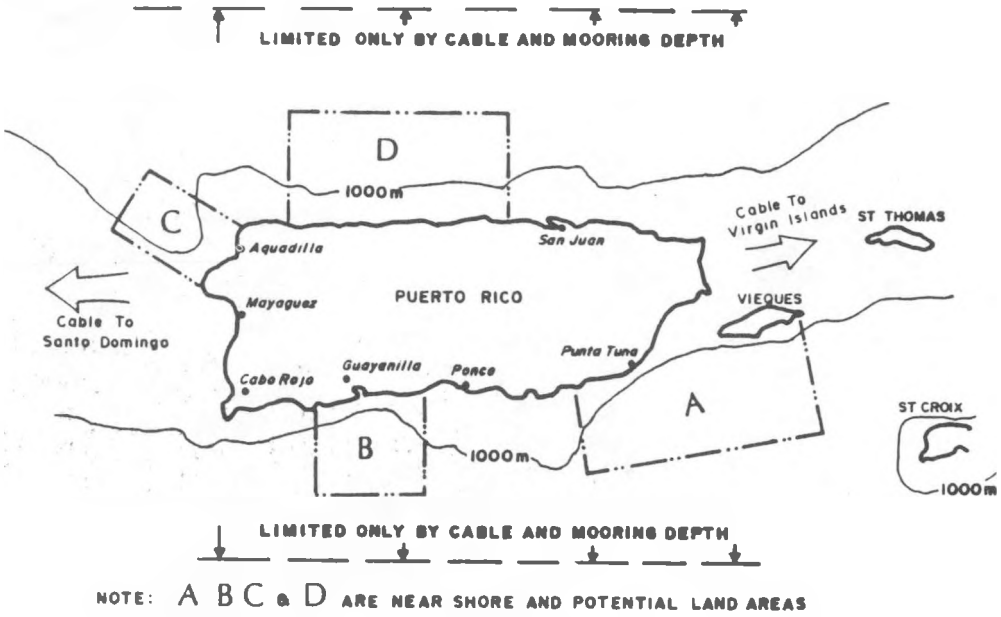


Figure 12 - Puerto Rico OTEC Resources

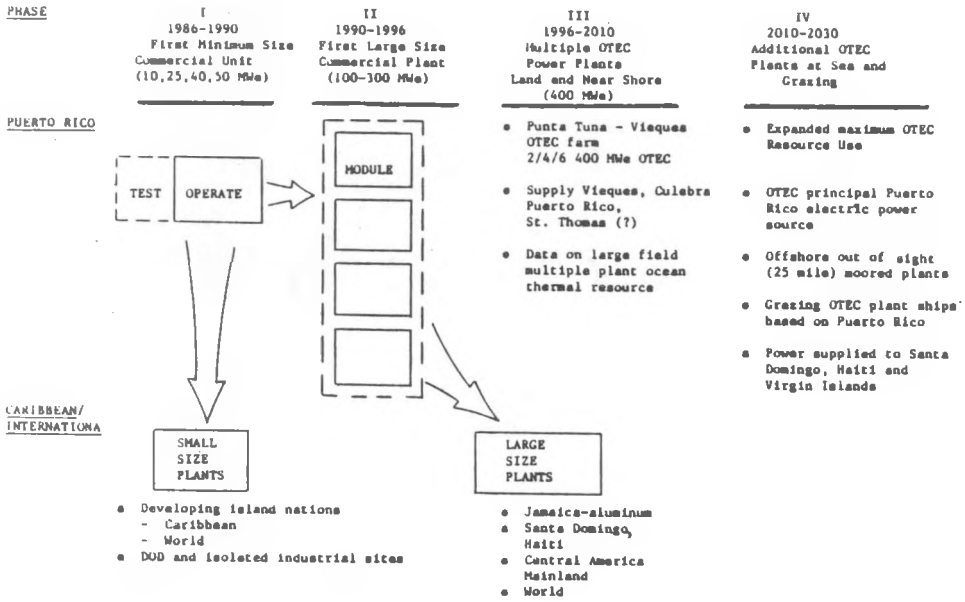


Figure 13 Puerto Rico/PREPA OTEC Growth Phases

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THE IMPACT OF THE OTEC ACT OF 1980 ON OTEC OPERATIONS OUTSIDE U.S. WATERS

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ABSTRACT

The availability of U.S. licenses for OTEC facilities and plantships designed to serve foreign markets raises complex questions of law, development strategy, and national policy. OTEC facilities located outside U.S. waters and not connected to the U.S. by cable or pipeline must be licensed by the U.S. if they are documented in the U.S.; eligibility for documentation depends on U.S. citizen control, which can be readily arranged, rather than beneficial ownership. OTEC plantships must be licensed in the U.S. if a U.S. citizen is engaged in ownership, construction, or operation; consequently the U.S. licensing requirement is difficult for U.S. citizens to avoid. OTEC facility developers should decide whether the benefits of U.S. licensing--regulatory certainty, protection from other OTECs, and diplomatic protection--outweigh the burdens--license conditions, U.S. transport and labor priorities, and diligence requirements. The differential treatment of OTEC plantships as compared to "offshore" OTEC facilities neither promotes exports nor maximizes U.S. control of OTEC units.

I. INTRODUCTION

The size of the market for export of ocean thermal energy conversion (OTEC) units is described in the NOAA preliminary Regulatory Impact Analysis (PRIA) as "vast."(1)* Aside from the potential demand for OTEC-produced ammonia in other parts of the world, the PRIA projects a demand for added electrical power just between 1990 and 2010 in countries where a usable OTEC resource exists equivalent to more than 2800 400-Mw OTEC units. If even a small portion of this demand were actually met from OTEC units, the export market for this equipment would dwarf the market within the United States.

Unfortunately, the Ocean Thermal Energy Conversion Act of 1980 (2) focuses on OTEC units for the United States market and deals only tangentially with the export opportunity. This paper addresses the extent to which a predominantly U.S. owned or foreign-owned facility or plantship destined to serve a foreign market can be made eligible for a U.S. license or can avoid that requirement under the existing law, the benefits and burdens of being U.S. licensed under the OTEC Act of 1980, and the desirability and character of statutory changes that would clarify and broaden the opportunity for choice.

This analysis is necessarily general and may not fit the circumstances of specific cases; moreover, it does not consider the impact that other laws and regulations, such as the Internal Revenue Code or restrictions on the export of certain computer technology, may have on the choice of financial and organizational arrangements. Thorough legal analysis should be a vital element in evaluating these choices.

II. WHEN IS THERE A CHOICE WHETHER TO GET A U.S. LICENSE?

The OTEC Act of 1980 contemplates two licensing alternatives for facilities--a U.S. license, or no U.S. license and instead (presumably) a foreign license--and three alternatives for plantships--a U.S. license, a foreign "compatible" license, or no U.S. license and instead (presumably) a foreign license. The different treatment of OTEC facilities and plantships apparently grows out of the traditionally different approaches to the regulation of offshore platforms and vessels, which are blurred by the OTEC Act's requirement that OTEC facilities be documented like vessels. (Section 108(e)(3)). The distinction in the OTEC Act between facilities and plantships turns on whether the OTEC unit is "standing or moored" (facility) or instead "is designed to use temperature differences in ocean water while floating unmoored or moving through such water . . ." (plantship). "The definition [of plantship] is intended to include all types of OTEC cycles, and all types of OTEC vessels, whether mobile or dynamically positioned."(3) The question of what constitutes a mooring is not addressed. The categorization of an OTEC unit as a facility or a plantship may be of substantial significance to the developer of an "offshore" OTEC unit (one not located in the U.S. territorial sea or connected to the U.S. by pipeline or cable), because a much broader range of choice exists for licensing OTEC facilities as contrasted to plantships.

The availability of and necessity for a U.S. license for an offshore OTEC facility is primarily a function of the rules governing documentation of vessels, which in turn revolve around the

*Numbers in parenthesis refer to References listed at the end of the paper.

definitions of citizenship established by Congress and the Coast Guard. An offshore OTEC facility is covered by the definitional section of the Act, which includes all facilities "standing or moored in or beyond the territorial sea of the United States" (Section 3(11)). Ownership, construction, or operation of an offshore facility by any person is prohibited without a license only if the facility is documented under the laws of the U.S. (Section 101(a)). A citizen (defined in Section 3(18) to include a corporation controlled by individual citizens) may be given a license if the offshore facility is documented (Section 101(b)(2) and (c)) and meets the other license requirements. Thus an offshore OTEC facility located anywhere in the world can be licensed under the OTEC Act if it can be documented under U.S. law; conversely, it need not obtain a license if it need not obtain documentation under U.S. law.

Under the Coast Guard regulations to implement Section 108(e) currently under discussion, OTEC facilities and plantships will be added to the general list in 46 CFR 67.01-5 of classes of vessels entitled to documentation when owned by a citizen. Since neither coastwise trade nor fishing vessles are involved, a corporation incorporated in the United States and whose president, chairman of the board and controlling directors are citizens is itself a citizen, regardless of who the shareholders or beneficial owners are. Foreign investors may well be willing to enter into such an arrangement, which involves a formal loss of control of the corporation, if other benefits accrue. A U.S. citizen that owns an offshore OTEC facility and does not wish to obtain a U.S. license has no obligation to obtain U.S. documentation, so it may simply choose not to do so. Thus, the developer of an OTEC facility designed to serve a foreign market can expect to have substantial freedom of choice about whether to place his facility under U.S. law.

The law governing licensing of plantships is far more restrictive. Any plantship owned, constructed or operated by a citizen must obtain a U.S. license (or a compatible foreign license) and must be documented under U.S. laws to obtain a license. A domestic, foreign, or multi-national group can make itself eligible for a license and thereby bring itself under U.S. law by establishing a corporation that meets the virtually identical U.S. control tests in the documentation regulations and the OTEC Act (Section 3(18)). Avoiding the requirement to obtain a U.S. license is virtually impossible for U.S. beneficial owners, builders, or operators, however. Congress clearly expected that its prohibition that "no citizen . . . may engage in the ownership, construction or operation of . . . [a] plantship" without a license would involve looking through and around the citizenship of a foreign corporation. The House Report sought to clarify and ameliorate the impact of this prohibition by noting, first, that some construction activity, such as supplying components or shipyard work, is outside the scope of the definition of "construction," which is limited to "any activities conducted at sea" (Section 3(6)); and second that

> The Committee does not believe that mere ownership of stock in amounts not sufficient to exercise influence over business decisions, in a business venture whose major activities are other than ownership, construction, or operation of OTEC facilities and plantships, constitutes engaging in ownership, construction, or operation of an OTEC facility or plantship;. . . (4)

These narrow exceptions, apparently designed to avoid outlawing de minimus involvement and protect ancillary U.S. construction opportunities, make clear that the Congress intended to insist on U.S. licensing of every plantship involving significant U.S. participation. Thus the opportunity for a U.S. plantship owner, builder or operator to avoid getting a U.S. license is essentially eliminated by the OTEC Act.

If other nations follow this U.S. example, multinational approaches to plantship development will have to await the negotiation of international agreements establishing one or more international or reciprocal regimes. In the meantime, aside from seeking amending legislation, U.S. developers might try to take advantage of the OTEC Act's loose distinction between plantships and offshore facilities in order to avoid the U.S. licensing requirement.

The range of choice on licensing of OTEC units is subject to two other potential restrictions: First, to the extent that an OTEC unit is located within the territorial sea, exclusive economic zone, or other similar widely recognized assertion of coastal state jurisdiction, or is physically connected to some other coastal state, that state may also impose licensing, ownership or control requirements without regard to the existence of a U.S. license. Such requirements may vitiate the advantages of being a U.S. licensee, or may even impose requirements that render the OTEC unit ineligible for a U.S. license. The Department of State's comments on the House bill noted that under current international law, a coastal state would not have territorial jurisdiction over an OTEC facility standing or moored on the continental shelf beyond the territorial sea and not connected to the shore by pipeline or cable. The Law of the Sea Treaty text would establish coastal jurisdiction for this purpose within 200 miles of shore.(5) Second, the criteria in the OTEC Act prohibit issuance if the Administrator "determines that the construction and operation of the . . . facility of plantship will not be in the national interest and consistent with national security and other national policy goals and objectives, including energy self-sufficiency and environmental quality;" (Section 101(c)(2)). Whether NOAA would invoke this catch-all provision to refuse to license a U.S.-documented facility located and designed to serve a foreign market is unknown. NOAA's Proposed Rules on licensing simply repeat the language of the OTEC Act.(6) For the reasons indicated below, sound national policy argues against denying a U.S. license to

n OTEC unit because of its location.

III. WHY GET A U.S. LICENSE?

As explained above, offshore OTEC facilities can typically be made eligible or ineligible for a U.S. license at the developer's option. The choice for prospective plantship developers is far more restricted. A developer should consider, therefore, whether obtaining a U.S. license offers advantages that outweigh the burdens that accompany such a license.

The benefits of being licensed under the OTEC Act of 1980 fall into two general categories--investment protection and financial benefits. A U.S. license protects the OTEC developers in several ways:

(a) Certainty of Regulatory Standards--Because the Act explicitly authorizes OTEC activities, describes what law applies onboard, and determines which U.S. agencies regulate which activities, and because NOAA, the Coast Guard, and EPA will soon establish rules to answer the inevitable questions of environmental health and safety performance criteria, designers and investors can proceed with some confidence about the acceptability of their efforts.

(b) Protection from other OTEC units--Under Section 101(c)(11) and (13) of the Act, a U.S. licensed OTEC unit is protected from a subsequently licensed OTEC unit impinging upon its operation "so as to degrade the thermal gradient. . ." Under Section 109(b), NOAA is to adopt regulations defining such impingement and "provide for the Administrator to mediate or arbitrate any disputes among licensees . . ." Substantive regulation governing the movement of plantships to prevent impingement are to be promulgated by the Coast Guard under Section 109(c).

(c) Diplomatic protection--A U.S. license and documentation by the U.S. Coast Guard can be expected to result in the treatment of OTEC units as U.S. vessels, and thus the assertion of diplomatic representation and naval protection by the U.S., at least on the high seas as defined by the U.S. Moreover, Section 402 of the OTEC Act provides that the Secretary of State shall "seek effective international action and cooperation in support of the policy and purposes of this Act and may initiate and conduct negotiations . . . to guarantee noninterference . . . [and] to assure protection of such facilities and plantships. . ." The extent to which such protection would be asserted on behalf of beneficial owners who are not U.S. citizens is a matter of State Department discretion, but such owners are unlikely to be any worse off under the U.S. flag (at least in the absence of U.S. involvement in military actions in the relevant area).

More immediate and concrete advantages in the form of financial benefits may also depend upon obtaining a U.S. license. Since other panelists at this Conference are addressing these opportunities in some detail, I will simply note the potential availability, in addition to investment tax credits and accelerated depreciation, of the Capital Construction Fund, the Construction Differential Subsidy and the Operating Differential Subsidy in accordance with Title II of the OTEC Act. Eligibility tests for these financial benefits are not congruent with those for eligibility for a U.S. license, however; some may be available even if no U.S. license is obtained, while others depend on satisfaction of more restrictive definitions of citizenship or on the exercise of discretion by the Secretary of Commerce acting on the advice of the Maritime Administration. The physical location and the nationality of the purchaser of electricity or other products from an OTEC unit have not been explicitly identified anywhere as primary factors for consideration in determining eligibility for these financial benefits.

On the other hand, being licensed by the U.S. carries with it some potentially serious burdens:

(a) License requirements--The most obvious burdens are those inherent in the license itself, including compliance with NOAA, Coast Guard, and EPA standards of performance for health, environmental, and safety protection, non-interference with other OTEC units, amenability to inspection and enforcement, etc. While many of these substantive requirements may be simply good practice and are likely to be imposed by any licensing state, some may impose unnecessarily stringent standards or needless red tape.

(b) American transport and labor requirements--The OTEC Act also imposes some specific burdens that may impose particularly high costs for an OTEC unit far outside U.S. waters. Section 101(c)(8) requires a licensee to agree that all vessels used for "the transportation to the United States of things produced, processed, refined, or manufactured at the" OTEC facility or plantship be documented under U.S. laws. This restriction's importance depends on the planned destination of the products. Section 108(e)(2)(C) in effect imposes the requirement that "any" OTEC facility or plantship (apparently only if licensed under the OTEC Act)(7) be manned or crewed by United States citizens or resident aliens unless such workers are unavailable or the President makes a specific finding with respect to the particular OTEC unit that "application of this requirement would not be consistent with the national interest."

(c) Diligence requirements--Apparently borrow-

ing from the laws involving marine mineral development, Section 106 of the OTEC Act requires the NOAA Administrator to promulgate regulations imposing diligence in the construction and operation of licensed OTEC facilities and plantships, with termination of the license under Section III the mandated penalty. Neither the House Report nor NOAA's Proposed Regulations offer useful guidance on the kinds of diligence requirements or the time intervals that would be appropriate.

Finally, before deciding whether to bear the burdens and take the benefits of a U.S. license for an OTEC plantship, the opportunity for obtaining a license that the NOAA Administrator has found to be "compatible with licenses issued pursuant to this Act" should be considered. Such a license, once obtained, may give most of the investment protection benefits of a U.S. license if the U.S. determination of compatibility is followed by an international agreement providing for mutual recognition and resolution of disputes. Such agreements were contemplated by Congress, as indicated by the House Report.(8) Whether being licensed under foreign law would provide a more favorable investment climate would depend on the substantive and procedural requirements of that law and the willingness of the U.S. to find compatibility if the foreign standards vary significantly from U.S. standards. Moreover, substantial delays might be involved in seeking foreign legislation and the negotiation of a satisfactory international agreement with the U.S. on this subject.

IV. WHAT IS THE RIGHT NATIONAL POLICY TOWARD ALLOWING OR REQUIRING U.S. LICENSES FOR "OFFSHORE" OTEC OPERATIONS?

The OTEC Act's differential treatment of OTEC offshore facilities and plantships is clear. Offshore OTEC facilities may be readily brought under or saved from the U.S. licensing requirement. While OTEC plantships may readily obtain U.S. licenses by establishing formal eligibility for U.S. documentation, they must have U.S. or compatible licenses if there is significant participation by a U.S. citizen in ownership, construction, or operation. This distinction evinces no overarching principle. It does not maximize flexibility for developers in choosing how to be regulated, which arguably would best achieve the OTEC Act's purpose to "establish a legal regime which will permit and encourage the development of ocean thermal energy conversion as a commercial energy technology" (Section 2(a)(4)). Conversely, it does not maximize U.S. control over the design and operation of OTEC units, which arguably would best achieve the OTEC Act's purpose to "provide for the protection of the marine and coastal environment, and consideration of the interests of ocean users, to prevent or minimize any adverse impact which might occur as a consequence of the development" (Section 2(a)(5)), and to "protect the interests of the United States in the location, construction, and operation" of OTEC facilities and plantships." (Section 2(a)(7)). If the former purpose is to be the dominant objective, the U.S. owner, builder, or operator of an OTEC plantship should have the choice whether to proceed under U.S. or foreign flag, just as ordinary merchant fleet operators do. If the latter purpose is to be dominant, U.S. citizens should not be allowed to engage in ownership, construction, or operation of offshore OTEC facilities without obtaining a U.S. license. In either case, the distinction between offshore facilities and plantships makes little sense.

A number of considerations argue for the more flexible approach. Maximum opportunity for marketing OTEC facilities and plantships in areas of the world where they can be most efficient is in the U.S. interest--it will increase the incentive for rapid development of the technology, increase U.S. exports, and reduce the global level of demand for oil. At the same time, our current knowledge about the scale and scope of OTEC's health, safety and environmental impacts suggests that the need to exert global control over OTEC development is far less than, for example, the need to control the development of exported nuclear energy systems and components. The reduced Federal financial commitment to OTEC technology development in the new Federal budget reinforces the view that the barriers to participation by U.S. citizens in OTEC plantship development under foreign flags and licenses should be reduced or eliminated.

REFERENCES

1. National Oceanic and Atmospheric Administration, Office of Ocean Minerals and Energy, Ocean Thermal Energy Conversion Preliminary Regulatory Impact Analysis [and] Initial Regulatory Flexibility Analysis, March, 1981.

2. P.L. 96-320, (August 3, 1980), 94 Stat. 974, 42 U.S.C.A. 9101.

3. House Report No. 96-994, 96th Cong., 2d Session, May 16, 1980, on H.R. 6154, "The Ocean Thermal Energy Act of 1980," p. 40.

4. Id., p. 41.

5. Id., pp. 64-65.

6. Proposed Rulemaking on Licensing of Ocean Thermal Energy Conversion Facilities and Plantships, 46 Fed. Reg. 19425, 37 March 30, 1981.

7. House Report No. 96-994, supra note 3, p. 48.

8. Id., p. 49.

8th Ocean Energy Conference
Washington, DC
June 1981

AN INTRODUCTORY STUDY OF THE ECONOMIC FACTORS FAVORABLE TO AN OTEC ELECTRIC POWER GENERATING STATION ON SAIPAN, COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS

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Commonwealth of the Northern Mariana Islands

OTEC ABSTRACT

This paper discusses factors favorable to Saipan as as ideal site for an OTEC electric power generating station. Since the prime purpose of an OTEC facility is to eliminate the purchase of non-renewable fossil fuel for electric power generation, this paper includes and illustrates how savings in fuel costs could be applied towards amortizing the major part, if not all of the Capital needed for construction of an OTEC electric power generating station.

INTRODUCTION

Saipan, Tinian, and other islands of the commonwealth of the Northern Marianas are not blessed with the potential for generating hydroelectric power, nor do they posses fossil fuel resources. Thus, their total dependence is on residual and diesel fuel oils for power generation. These fuel oils, for reasons of economy, are all of foreign origin, borken down on Guan into small lots for trans-shipment to the point of use.

Since OTEC would displace fuel oil of a high market value, the sum available for amortization of the capital needed for an OTEC station would be maximum. However, the smallness of the demand of Northern Marianas Islands communities, with the exception of Saipan, would preclude OTEC, at least until small land-based installations become feasible.

MAXIMUM DELTA T

Saipan holds promise as an ideal side for the realization of Ocean Energy conversion, in that it is, above all, favorably located within the zone of year-round world-wide maximum delta t realization, as shown on the Map of Ocean Thermal Resources, prepared by Ocean Data Systems, Inc., under Contract No. ET-78-C-01-2898 to the Division of Solar Technology. The foregoing is evident by the close proximity of Saipan to the Marianas Trench, where sub-surface Artic chilled water flows towards equatorial regions.

OCEAN THERMAL PROFILES

In view of Saipan's nearness to Guam (Approximately 150 miles), it is believed that ocean temperature profiles can be expected to reflect approximately the same values as those experienced on Guam. These values are illustrated in Attachment No. 3, prepared by the University of Guam Marine Laboratory. The chart reveals that during the winter months the delta t will average 41° and in summer 43°F, referred to a depth of 2,800/3,000 ft. A decrease in these delta T values has a marked effect on the net power output of an OTEC plant. This is evident, since below a certain value of temperature differential not enough power will be generated to drive the station auxiliares.

NEARSHORE DEVELOPMENT FEASIBLE

In addition to a very favorable delta T, Saipan has the following to offer as a candidate for an OTEC plant:

1. Deep water close to shore - not more than 1½ miles to submarine contours of 3,000 ft. or more
2. Saipan would include Tinian, a very close neighboring island for power service by submarine cable (See attachment No. 1 Map of Saipan and vicinity).
3. Saipan is a near neighbor to Guam (150 miles), where support facilities for construction are available.

SAIPAN'S ECONOMY

Saipan has a total land area of 46.00 square miles, and a population of 17,000 persons. It is one of the most beautiful islands in Micronesia and is a favorite tourist resort, with International hotels fronting on white sand beaches. Thus, tourism dominates Saipan's economy. Agriculture and cattle raising play only a minor role in the economy.

TINIAN'S ECONOMY

Tinian has a total land area of 39.166 square miles. It is a relatively level island exhibiting a greater percentage of flat area than other areas in the Marianas. Population, according to 1978 records, is 900 persons. Principal econimic activities consist of dairying, cattle raising, and tourism. Milk and meat products are shipped to Guam markets. Two-thirds of the land area is under lease agreement with the U.S. Armed Forces.

FUEL OIL SAVED AS CAPITAL AVAILABLE FOR OTEC - SAIPAN/TINIAN

Saipan's annual generation is currently approximately 100,740,000 KWH. With a heat rate of 10,500 BTU/KWH, fuel oil costing an estimated $33.00 per bbl. (light residual), containing an average of 6,169,800 BTU/bbl., the cost of fuel oil will be $5,657,624.00/annum.

Tinian's annual generation is currently approximately 1,400,000 KWH with a heat rate of approximately 12,500 BTU/KWH, fuel oil costing an estimated $42.00/bbl., (No. 2 diesel), and containing an average of 5,670,000 BTU/bbl., cost of fuel oil will be $129,630.00/annum. This saving in fuel oil cost (Saipan and Tinian) would be enough to support a capital investment, amortized in equal payments for 30 years at 12 per cent interest of $46,617,396.00.

OTEC GROSS vs NET POWER GENERATION

It is estimated that an OTEC plant with a 40°F delta T differential will produce a net power output of 50 to 65% of gross generation. In view of Saipan's favorable environment 65% has been estimated for new generation. Thus, the station must have a gross rating of about 31 MW to produce 20 MW of available generation. This represents $1,503.78/KW of "installed capacity" available for plant construction. However, if oil should advance at 12%/annum (the interest rate assumed for plant amortization), this increase, instead of going into the cost of oil could very well be made available for OTEC plant investment. Thus, the break even point for the OTEC plant would be $1,503.78 x 2, or $3,007.56 per installed KW.

The power demand for Saipan/Tinian is presently approximately 15 MW. Thus, a 20% increase in future power demand has been allowed for the 20 MW OTEC plant. This would generate savings in OTEC generation, vs purchase of fuel oil. Although this may be quite substantial, it was not included in the foregoing estimates.

OTEC MODULAR UNITS - SUMMARY

Assuming that 10 MW is the module or component size of a multiple expansible OTEC plant, two 10 MW units would be of the right capacity for Saipan/Tinian power needs. The existing diesel units could remain to support outages of the OTEC units. It would have the following distinct advantages:

1. A one or two unit OTEC plant could serve as the core of an expansible plant. Thus, fabrication and construction could be accomplished in minimum time. We support and indeed endorse the efforts of DOE and others in the mini-OTEC tests and the component tests of OTEC-1, and the many other necessary and related tests and experiments. With these data available, it is confidently expected that a pilot plant would be straightforward procedure with minimum time for fabrication and construction.

2. It would provide all the power needs for two island communities, not just a fractional part of their power requirements, thus, eliminating the need for operating fossil fuel power plants in parallel with OTEC.

3. It would be the first area in the Mariana Islands, or elsewhere, whose total power needs would be generated by OTEC.

4. Fuel oil cost savings would be a maximum, since all fuel is of foreign origin and must be trans-shipped from the refinery on Guam.

5. It would serve as the objective model for other OTEC installations in the Mariana Islands and Western Pacific.

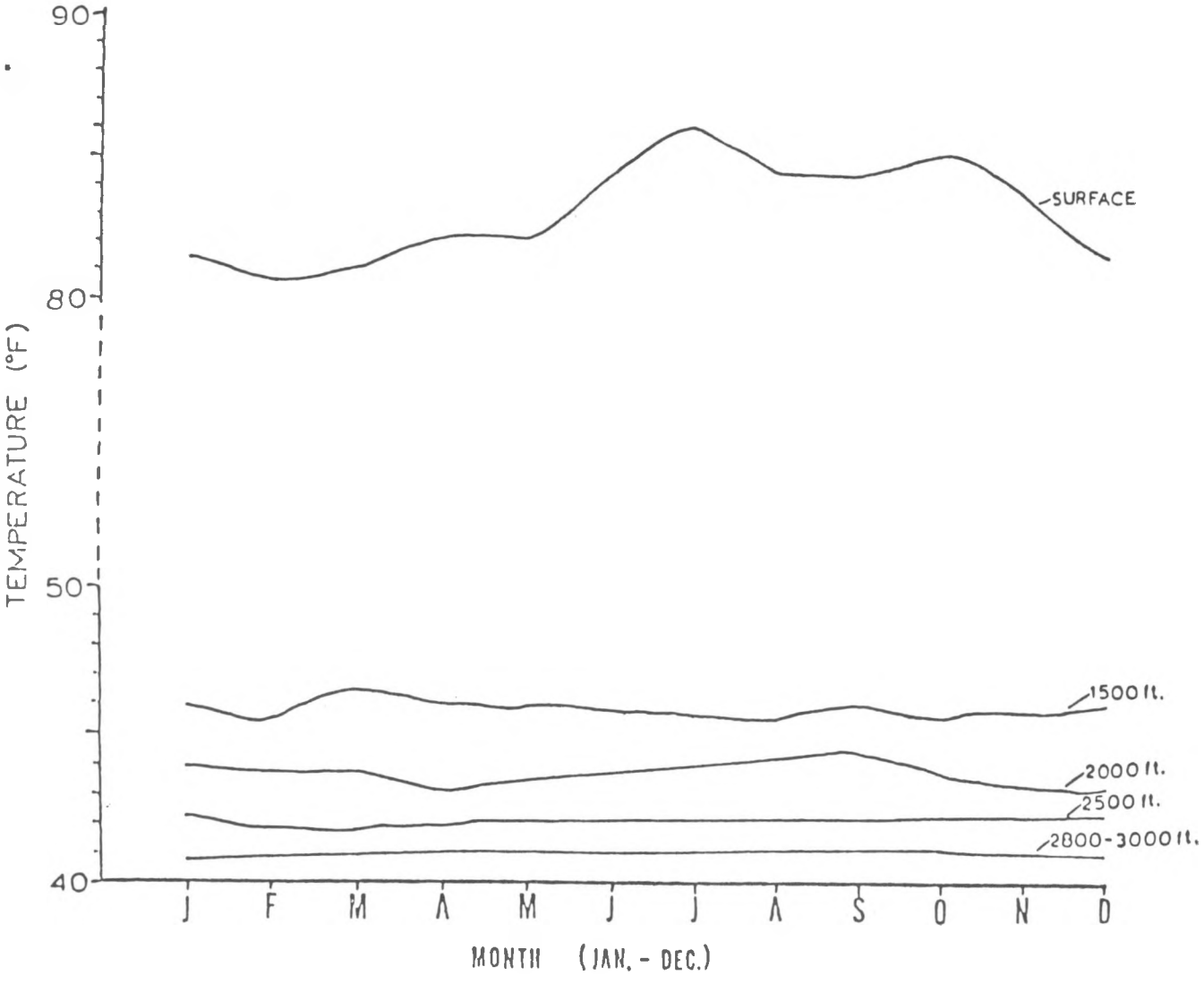
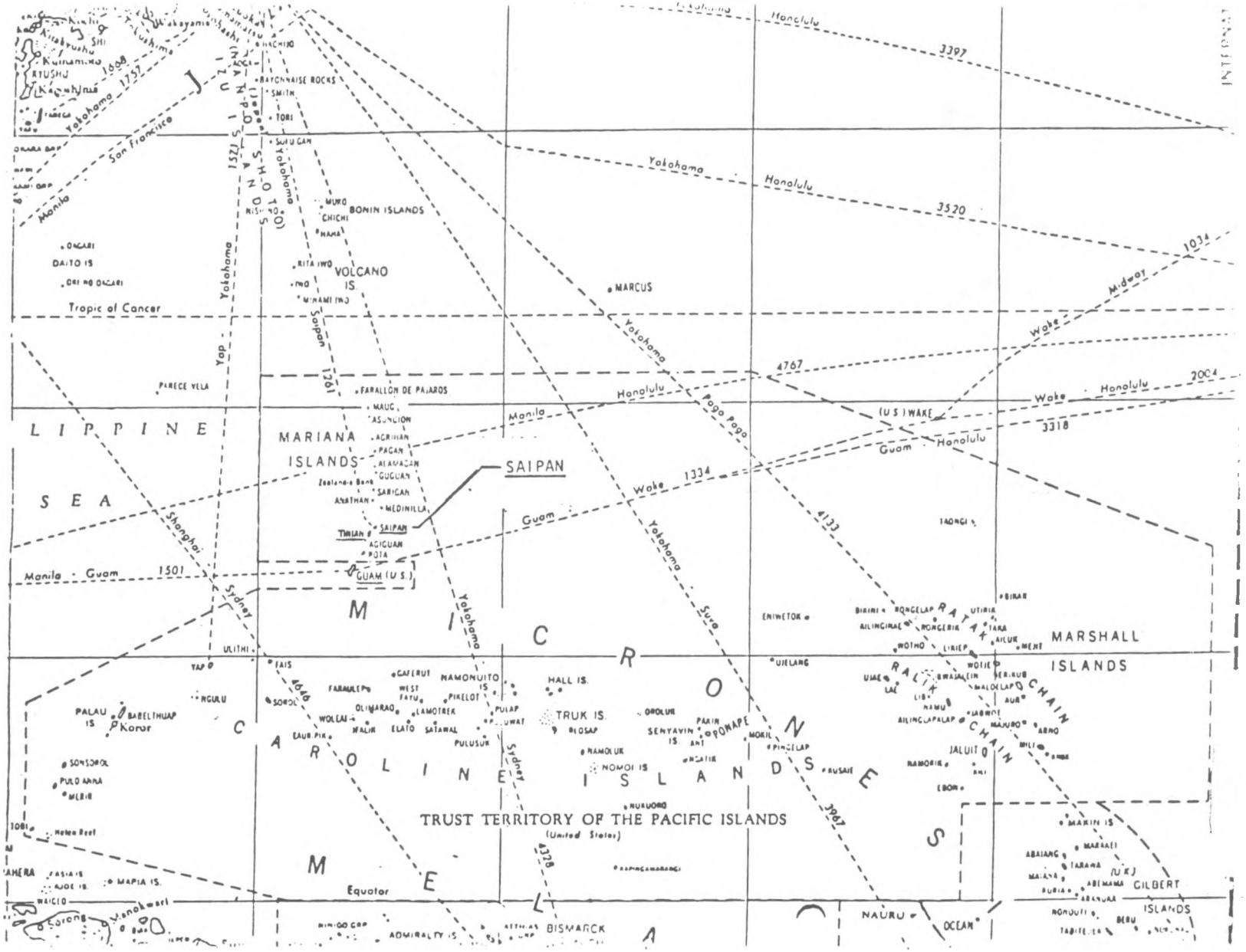


FIGURE 1 Mean monthly temperatures for surface, 1500, 2000, 2500 and 2800-3000 ft. in the vicinity of Cabras Island, Luminao Reef and Glass Breakwater, Guam.


Honolulu
3397
Yokohama
Honolulu
3520
1034
Midway
Wake
Honolulu
2004
Wake
Honolulu
3318
Guam
Honolulu
Wake
1334
Guam
Yokohama
Yokohama
Sydney
Yokohama
Manila
Guam
1501
Shanghai
Yap
Sarpan
1261
Yokohama
Manila
Yokohama
San Francisco
1737
1608
1732
Yokohama
Yokohama
Yokohama

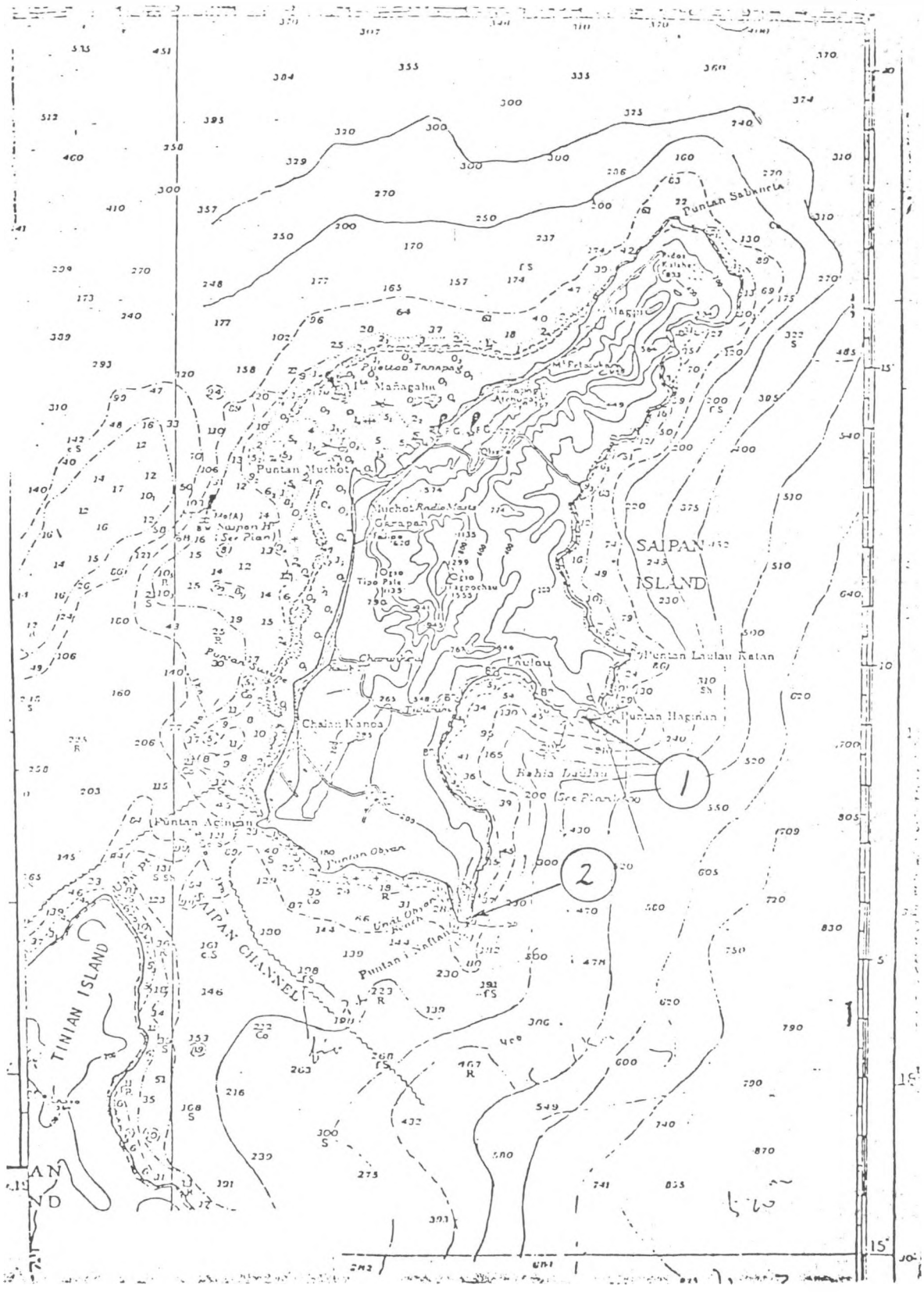


FIGURE 3 Map of Saipan showing submarine power cable shore landing points with respect to nearby deep water contours (in fathoms).

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MARKET POTENTIAL FOR OTEC IN DEVELOPING NATIONS

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ABSTRACT

A comprehensive survey has identified ninety-eight nations and territories with direct access to an adequate OTEC thermal resource within their 200 nautical mile exclusive economic zone. A market assessment study of 67 free market developing nations and U.S. Territories was conducted to evaluate the OTEC market potential and identify those nations with the greatest potential for utilizing OTEC in the 1986-2010 time period. This potential was defined based on assessments of the OTEC technology, resource, market, and barriers and incentives to OTEC implementation.

The results of the study indicate significant market potential for OTEC in the candidate developing nations and territories. The OTEC resource is excellent with as much as 24°C ΔT in close proximity to shore in many of these nations. The broad range in size of electric power systems results in a market for small 10-40 MW commercial OTEC units in the near term 1986-1995 as well as the larger 100-400 MW commercial OTEC units in the 1995-2010 time period.

The overall market potential in the 67 candidate developing nations and territories is represented by the projected addition of 577,000 MWe of new baseload electric power generation facilities between 1990 and 2010. This is equivalent to 50 quads of energy per year or 10,000 mboe in the year 2010 and represents a potential for nearly 3000 OTEC plants in sizes from 10-400 MW. The degree of penetration of this market is dependent on many factors. However, if only 10 percent of the market is penetrated, it represents a potential for about 300 OTEC units by 2010 at an estimated capital cost of about $171 billion (1980 dollars). This is a formidable investment but, if implemented, would result in an estimated cumulative displacement of $343 billion (1980 dollars) of imported oil by 2010.

I. INTRODUCTION

The escalating price of oil on the world market coupled with an increasing demand for energy worldwide has established a framework for development of alternative energy sources. The developing nations have especially been affected by the high cost of imported energy and its negative impact on the developmental aspirations of their people. Many of these nations have few conventional domestic energy resources and are vulnerable to cost and availability of imported energy. However, the locations of many of the developing nations in the temperate zones are compatible with the availability of the Ocean Thermal Energy Conversion (OTEC) thermal resource. Thus, OTEC has the potential to provide an alternative source of energy to developing nations with few domestic alternatives. Although the OTEC potential has been studied extensively for the United States mainland, Hawaii, and Puerto Rico, no comprehensive study of the OTEC potential on a worldwide basis has been reported in the literature. Thus, the United States Department of State (D.O.S.) and Department of Energy (D.O.E.) jointly sponsored a study to assess the potential for OTEC in developing nations.* This paper presents an overview of the results of this study which is still in progress with a scheduled completion date of August, 1981.

The objective of this study was to evaluate the potential of OTEC in the 1986-2010 time period as a source of renewable energy for developing nations for the purpose of supplying OTEC-derived electricity to both conventional electric utility grids and electricity-intensive industries. Initially, a comprehensive market survey of the world OTEC resource and market factors was performed to identify candidate nations and territories for OTEC utilization.(1) Then, detailed market assessment case studies were performed for each of five candidate nations and one U.S. territory selected by the D.O.S./D.O.E. from the survey results--Brazil, Guam, Jamaica, Mexico, Nigeria, and the Philippines.

In the following sections, an overview of the market potential for OTEC in developing nations and territories is presented based on the market survey results of the D.O.S./D.O.E. sponsored study. This market potential is based on assessments of the OTEC resource, technology, market, and an evaluation of barriers and incentives to OTEC implementation in developing nations.

* The views expressed in this paper are those of the author and do not necessarily represent those of the United States D.O.S. or D.O.E.

II. OTEC TECHNOLOGY AND RESOURCE ASSESSMENT

The worldwide OTEC thermal resource(2) was evaluated to identify candidate nations and territories with access to this resource within their 200 nautical mile Exclusive Economic Zone (EEZ). Significant potential for OTEC utilization exists in the temperate zones between 30°S and 30°N latitudes (Figure 1). Potential OTEC sites must meet minimum criteria for the thermal resource - the annual average of monthly temperature difference between the warm surface waters and cold deep waters $\overline{\Delta T}$.

The minimum thermal resource criteria of $\overline{\Delta T}$ greater than 20°C for 1000 meter depth was used to define 98 nations and territories with access to this resource within their 200 nautical mile EEZ (Table 1). These can be categorized as:

1. Developed Nations -- 3 (United States, Japan, and Australia)
2. Territories of Developed Nations -- 29.
3. Nations with centrally planned economies -- 3 (Cuba, China, and Vietnam).
4. Free market economy developing nations -- 63.

The focus of this study was on the 63 free market developing nations plus the four U.S. territories of American Samoa, Guam, Trust Territory of the Pacific, and Virgin Islands.

All of these 67 candidate nations and territories have the potential to utilize OTEC technology based on the availability of the necessary thermal resource. A major factor in the decision to use OTEC is its cost relative to other energy sources. OTEC plant designs, and thus costs, are site dependent. Thus, an assessment is necessary to evaluate the site characteristics which affect OTEC plant design and costs in order to define the best candidate nations for OTEC applications. Key characteristics include:

1. Thermal resource -- magnitude of $\overline{\Delta T}$, size of the thermal resource zone within the 200 nm EEZ, and bathymetry.
2. Storm conditions -- magnitude and frequency of severe tropical storms.
3. Sea state -- surface and subsurface current magnitudes and directions, wave spectrum, and wind speeds.

A dominant plant design parameter is the magnitude of the thermal resource. Power system design studies have typically used a nominal design point of approximately 22°C (40°F) over 1000 meter depth. Variations of 2°C from this design point can result in a 25 percent change in net power output which directly alters the economics of the electricity produced.(3) The parameter of interest is the $\overline{\Delta T}$, the average of monthly temperature differences between the surface warm water and deep cold water. A total of 43 of the 67 candidates have $\overline{\Delta T}$ in excess of 22°C with 6 in excess of 24°C (Table 2).

Another key parameter is the offshore bathymetry at potential OTEC sites. The distance offshore to the $\overline{\Delta T}$ is a critical factor determining the type of OTEC system concept (floating-moored, landbased, shelf-mounted, or grazing), as well as its cost for such items as the electric cable and cold water pipe. A total of 25 of 67 candidates have access to the $\overline{\Delta T}$ within 10 km offshore allowing potential use of landbased or shelf-mounted plants as well as floating plants (Table 2).

The size of the thermal resource zone is an important characteristic which determines the number of OTEC plants which can be installed without adversely affecting the performance of other plants or the surrounding environment. In general, the ocean space between the 1000 meter depth contour and the 200 nm EEZ limit represents the thermal resource zone site for each nation.

However, in practice only grazing plantships can operate in much of this zone. Mooring requirements limit floating-moored concepts typically to 1000-2000 meter. Thus, a measure of the available ocean space for multiple plant sites is given by the length of coastline adjacent to the thermal resource. A total of 38 of the 67 candidates have a coastline length in excess of 250 km and 8 candidates have over 1000 km of coastline (Table 2).

The magnitude and frequency of severe tropical storms (storms with winds in excess of 30-50 m/sec, i.e., hurricane force) are important characteristics in the selection of OTEC plant sites and designs. Although OTEC plants are designed to survive the 100 year storm, the magnitude and especially the frequency of thse storms impacts plant design costs as well as the availability of power due to plant shut-down or temporary thermal resource modifications. Only 2 candidates (Taiwan and the Philippines) have an expected frequency in excess of 3.0 severe storms per 5 degree latitude-longitude square per year. However, there are very few storms in certain areas of the Philippines south of Mindanao. An additional 20 nations have an expected frequency of 1.0-3.0 per year (Table 2). A total of 27 of the candidates have an expected frequency of only 0-0.1 storms. In areas of high storm frequency, land-based or shelf-mounted concepts may be more appropriate than floating concepts.

The technical proof-of-principle for OTEC has been demonstrated in projects such as Mini-OTEC and OTEC-1 as part of U.S. industry and Department of Energy (D.O.E.) OTEC programs. The major obstacles to OTEC commercialization and thus availability for use in developing nations, are demonstrations of the economics of OTEC plants and the engineering development to scale-up to large 100-400 MW-sized units. The currently planned U.S. D.O.E. OTEC Pilot Plant Program will provide the initial demonstration of scale-up and economics for plants in the 10-40 MWe size range. This program will result in a first plant operational by 1986-1987.

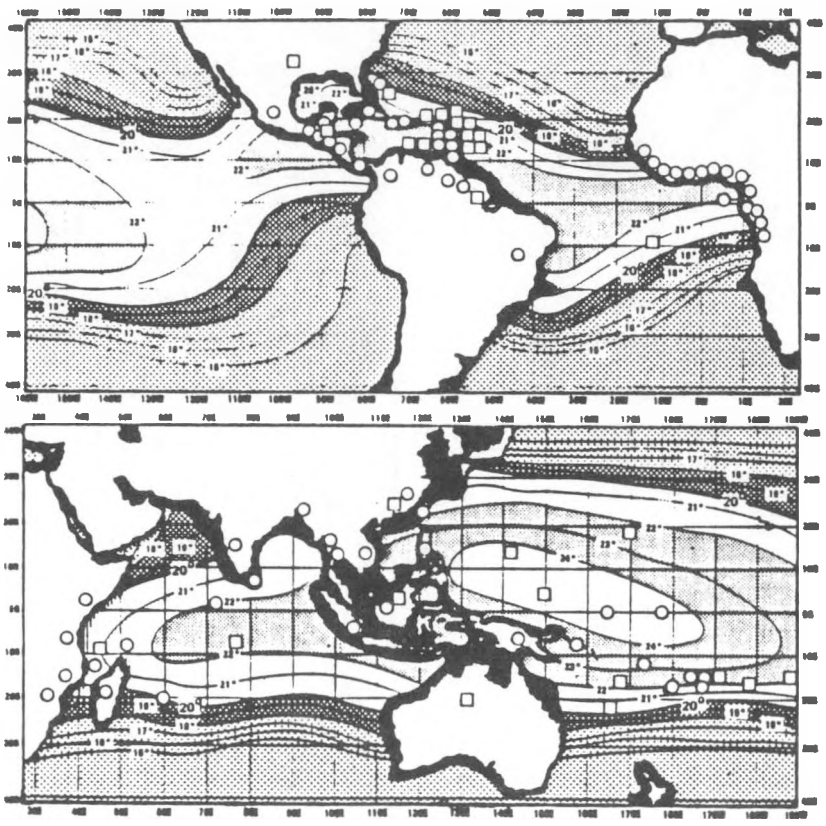


Figure 1. World OTEC Thermal Resource

GEOGRAPHICAL AREA	MAINLAND		ISLAND	
AMERICAS	MEXICO BRAZIL COLOMBIA COSTA RICA GUATEMALA HONDURAS PANAMA VENEZUELA	GUYANA SURINAM FRENCH GUIANA (Fr) NICARAGUA EL SALVADOR BELIZE (UK) UNITED STATES	CUBA HAITI DOMINICAN REP. JAMAICA VIRGIN IS. (US) GRENADA ST. VINCENT GRAND CAYMAN (UK) ANTIGUA (UK) PUERTO RICO (US) TRINIDAD AND TOBAGO BAHAMAS	GUADALOUPE (FR) MARTINIQUE (FR) BARBADOS DOMINICA ST. LUCIA ST. KITTS (UK) BARBUDA (UK) MONTSERRAT (UK) THE GRENADINES (UK) CURACAO (NETH) ARUBA (NETH)
AFRICA	NIGERIA GHANA IVORY COAST KENYA TANZANIA CONGO GUINEA SIERRA LEONE LIBERIA	GABON BENIN ZAIRE ANGOLA CAMEROON MOZAMBIQUE EQ. GUINEA TOGO SOMALIA	SAO TOME AND PRINCIPE ASCENSION (UK) COMOROS ALDABRA (UK) MADAGASCAR	
INDIAN/PACIFIC OCEAN	INDIA BURMA CHINA VIETNAM BANGLADESH MALAYSIA	AUSTRALIA JAPAN THAILAND HONG KONG (UK) BRUNEI (UK)	INDONESIA PHILIPPINES SRI LANKA PAPUA NEW GUINEA TAIWAN FIJI NAURU SEYCHELLES MALDIVES NEW HEBRIDES (UK/FR) SAMOA TONGA COOK IS. (NZ)	AMERICAN SAMOA (US) TRUST TERRITORIES (US) GUAM (US) KIRIBATI FRENCH POLYNESIA (FRANCE) NEW CALEDONIA (FRANCE) DIEGO GARCIA (UK) TUVALU WAKE IS. (US) SOLOMON ISLANDS MAURITIUS OKINAWA (JAPAN) WALLIS & FUTUNA IS. (FR)
TOTALS:	44		54	

* MEAN ANNUAL ΔT>20°C @1000 m DEPTH WITHIN 200 nm EEZ

Table 1. Candidate Nations and Territories with OTEC Resource

Geographical Area	Nation	Thermal Resource (°C)	User Proximity (km)	Thermal Resource Size (km)	* Frequency of Severe Storms	Currents (m/sec)
Indian/Pacific Ocean	Indonesia	22-23	10-50	>1000	0-0.1	0.2-0.4
	Papua New Guinea	23-24	<10	>1000	0.1-0.5	0.4-0.6
	Kiribati	>24	<10	250-500	0-0.1	0.4-0.6
	Tuvalu	>24	<10	250-500	0-0.1	0.2-0.4
	Solomon Islands	23-24	<10	500-1000	0.1-0.5	0.4-0.6
	Nauru	>24	<10	100-250	0-0.1	0.4-0.6
	Trust. Terr. Pacific	>24	<10	500-1000	1.0-3.0	0.2-0.4
	American Samoa	23-24	<10	100-250	0.1-0.5	0.1-0.2
	Samoa	23-24	<10	100-250	0.1-0.5	0.1-0.2
	Philippines	>24	<10	>1000	>3.0	0.2-0.4
	Tonga	20-21	<10	100-250	0.1-0.5	0.1-0.2
	India	21-22	50-100	>1000	1.0-3.0	0.2-0.4
	Guam	>24	<10	100-250	1.0-3.0	0.2-0.4
	Fiji	21-22	10-60	250-500	0.1-0.5	0.1-0.2
	Sri Lanka	21-22	10-50	500-1000	0.5-1.0	0.6-0.9
	Maldives	21-22	<10	500-1000	0-0.1	0.4-0.6
	Mauritius	20-21	<10	250-500	1.0-3.0	0.1-0.2
	Seychelles	21-22	10-50	250-500	0-0.1	0.4-0.6
	Taiwan	21-22	10-50	250-500	>3.0	0.4-0.6
	Burma	21-22	10-50	100-250	0.5-1.0	0.2-0.4
	Malaysia	23-24	100-370	100-250	0.5-1.0	0.2-0.4
	Bangladesh	21-22	200-370	<100	1.0-3.0	0.2-0.4
Africa	Liberia	22-23	10-50	250-500	0-0.1	0.6-0.9
	Ivory Coast	22-23	10-50	250-500	0-0.1	0.6-0.9
	Ghana	22-23	10-50	250-500	0-0.1	0.6-0.9
	Nigeria	22-23	50-100	250-500	0-0.1	0.6-0.9
	Togo	22-23	10-50	<100	0-0.1	0.6-0.9
	Benin	22-23	10-50	<100	0-0.1	0.6-0.9
	Cameroon	22-23	50-100	100-250	0-0.1	0.6-0.9
	Gabon	21-22	50-100	250-500	0-0.1	0.6-0.9
	Mozambique	20-21	10-50	500-1000	0.5-1.0	0.6-0.9
	Sao Tome & Principe	22-23	10-50	<100	0-0.1	0.6-0.9
	Eq. Guinea	22-23	10-50	<100	0-0.1	0.6-0.9
	Tanzania	20-21	10-50	500-1000	0-0.1	0.6-0.9
	Somalia	20-21	50-100	250-500	0-0.1	> 0.9
	Comoros	20-21	10-50	100-250	0.5-1.0	0.6-0.9
	Guinea	20-21	200-370	100-250	0-0.1	0.6-0.9
	Madagascar	20-21	10-50	250-500	1.0-3.0	0.4-0.6
	Congo	20-21	50-100	<100	0-0.1	0.6-0.9
	Kenya	20-21	10-50	250-500	0-0.1	0.6-0.9
	Angola	20-21	50-100	<100	0-0.1	0.6-0.9
	Zaire	20-21	50-100	<100	0-0.1	0.6-0.9
	Sierra Leone	20-21	100-200	100-250	0-0.1	0.6-0.9
	Thailand	22-23	200-370	<100	0.1-0.5	0.4-0.6
Latin America	Brazil	21-22	10-50	>1000	0-0.1	0.4-0.6
	Mexico	22-23	<10	>1000	1.0-3.0	0.2-0.4
	Costa Rica	22-23	10-50	250-500	0.1-0.5	0.4-0.6
	Panama	22-23	10-50	250-500	0.1-0.5	0.4-0.6
	Colombia	22-23	10-50	>1000	0.1-0.5	0.4-0.6
	Honduras	22-23	10-50	250-500	1.0-3.0	0.4-0.6
	Venezuela	22-23	50-100	>1000	0.1-0.5	0.4-0.6
	Haiti	22-23	<10	250-500	1.0-3.0	0.4-0.6
	Dominican Republic	22-23	<10	250-500	1.0-3.0	0.4-0.6
	Jamaica	22-23	<10	250-500	1.0-3.0	0.4-0.6
	Bahamas	20-21	<10	500-1000	1.0-3.0	0.4-0.6
	St. Vincent	22-23	<10	100-250	1.0-3.0	0.4-0.6
	Dominica	22-23	<10	100-250	1.0-3.0	0.4-0.6
	Nicaragua	22-23	100-200	250-500	1.0-3.0	0.4-0.6
	Guatemala	22-23	50-100	100-250	0.1-0.5	0.4-0.6
	El Salvador	22-23	50-100	100-250	0.1-0.5	0.4-0.6
	St. Lucia	22-23	<10	100-250	1.0-3.0	0.4-0.6
	Virgin Islands	22-23	<10	<100	1.0-3.0	0.4-0.6
	Guyana	22-23	200-370	250-500	0-0.1	0.6-0.9
	Surinam	22-23	200-370	250-500	0-0.1	0.6-0.9
	Trinidad & Tobago	22-23	<10	<100	1.0-3.0	0.6-0.9
	Grenada	22-23	<10	<100	1.0-3.0	0.6-0.9
	Barbados	22-23	10-50	<100	1.0-3.0	0.6-0.9

*Number per 5 degree latitude-longitude square

Table 2. OTEC Resource Assessment in Developing Nations

Although there are OTEC programs in progress in other developed countries besides the U.S., plant availability for developing nation applications was based on projections of the U.S. D.O.E. OTEC program. These projections assume a conservative, time-phased scale-up from 10-40 to 100 and then 400 MW-sized units with construction of larger units initiated only when the smaller size has been proven in at least one year of operation. Open cycle technology is assumed to follow closed cycle technology by five years. This assumed OTEC development schedule would result in commercial units available as follows:

1. 10-40 MWe sized closed cycle production units from 1990 with open cycle units by 1995.

2. 100 MWe sized closed cycle production units from 1994 with open cycle units by 1999.

3. 400 MWe sized closed cycle production units from 1998 with open cycle by 2003.

This assumed OTEC development scenario illustrates that large commercial units of 400 MW size may not be available until the latter part of the 1986-2010 time period of interest to this study. However, this is compatible with developing nations which have smaller power systems and can utilize the smaller 10-40 MW units. Thus, key consideration must be given to the applicability and cost of these smaller units in order to adequately assess the OTEC potential.

Major emphasis in the U.S. OTEC program has been on scale-up to the large 100-400 MWe OTEC plants.(4) This emphasis is due to the size of the U.S. power systems and the potential economy of scale effect. However, for many developing nations, particularly island nations, the economy of scale may not be as important as the ability to transition from an imported oil economy to an alternative energy economy. For many of these nations, a 100-400 MW size plant may be much larger than their needs and smaller plants may be more appropriate.

Other considerations in selecting OTEC plant concepts for developing nations in addition to plant size include (1) reliability, availability, maintainability and producibility factors considering the local facilities and labor force and (2) site characteristics such as storm frequency, currents, sea conditions, and bathymetry.

The general state-of-technology for OTEC should not have an adverse affect on OTEC utilization in developing nations in the 1986-2010 time period since they can accommodate the smaller sized OTEC units in their smaller power systems. In addition, the proximity to shore of the thermal resource in many nations allows use of landbased or shelf-mounted system concepts which eliminate the potential cold water pipe or electric cable development issues.

A major factor which must be considered in the selection of OTEC for utilization in developing nations is the relative cost of energy from OTEC compared to alternative energy sources. OTEC plants require large capital investment initially for construction but minimal operating costs since there are no fuel costs. Many engineering design studies(5-12) have produced cost estimates for various OTEC system concepts and sizes typically using a value for the key design parameter $\overline{\Delta T}$ of 22°C (40°F). Costs of OTEC plants will vary for individual developing nations depending on many factors such as construction site, labor, shipping and mobilization costs. However, analysis of cost variables among candidate nations suggests that the dominant variables that impact the OTEC energy cost are the unit size and magnitude of the thermal resource. A 2°C variation can change energy costs by as much as 25 percent. Therefore, the nominal OTEC plant cost values are used along with a correction factor for $\overline{\Delta T}$ variations from 22°C nominal to define OTEC costs in individual nations. The electricity cost estimates for OTEC are based on a levelized busbar cost analysis(21) where the cost of energy (¢/kwh) is a function of capital costs C_c ($/Kw); the fixed charge rate FCR (includes discount rate, insurance, etc.) for capital; the capacity factor for the OTEC plant (CF); and the operations and maintenance costs C_{om} (fraction of installed capital costs):

$$\text{Energy cost (¢/kwh)} = \frac{C_c(\$/Kw)(100\ ¢/\$)(FCR + C_{om})}{CF \cdot (8760\ hr)}$$

Nominal values of CF = 0.8, C_{om} = 0.015, and FCR = 0.10 have been used to define OTEC plant electricity costs as a function of size and $\overline{\Delta T}$ -- the key variables (Figure 3). A variation of +40%, -20% on these nominal costs is expected to cover the range of alternative system concepts and site characteristics.

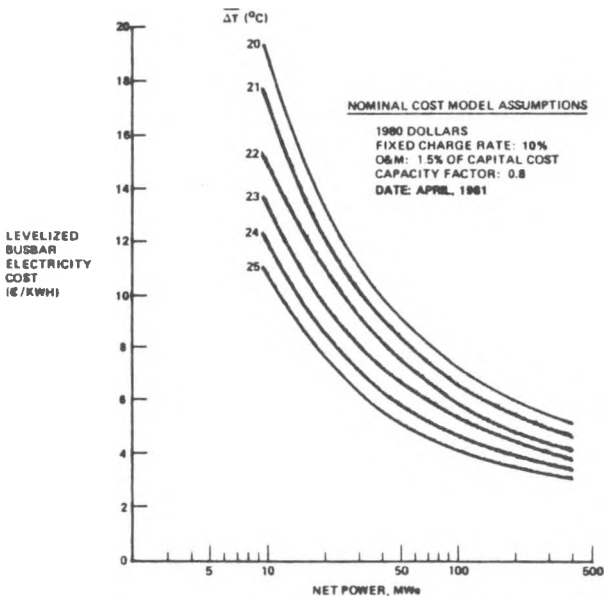


Figure 2. OTEC Busbar Electricity Costs

III. MARKET ASSESSMENT

The market for OTEC in developing nations depends on many factors. However, the primary factors are the demand for OTEC products and the availability and cost of alternative energy sources to provide those products. The primary OTEC products include electricity for applications such as (1) transmission to the power grid; (2) electricity-intensive industrial uses such as ammonia fertilizer or aluminum production; (3) fresh water production; and (4) mariculture applications from nutrient-rich deep water. Key market factors used to assess the potential for OTEC to supply electricity for each of these applications included:

1. Dependence on imported oil
2. Demand for electric power
3. Availability of alternative energy sources
4. Demand for OTEC by-products

The escalating price of oil has placed a severe economic burden on developing nations dependent on imported oil. The price of oil has increased at a 16% per annum rate in real terms since 1972. World Bank estimates(13) project a 3 percent per annum real increase in the 1980-1990 period. This trend is conservative based on recent history but would still result in the price of oil escalating from $30/barrel to $70/barrel over the 1980-2010 time period (in 1980 dollars). Among the 67 developing nations and territories with the OTEC resource, 45 imported 75-100% of their commercial energy demand in 1979.(13) This imported oil bill has had a tremendous impact on the balance of trade and thus economic development. In the Philippines, for example, the oil bill has risen from 11% to 44% of export proceeds and is largely responsible for the trade deficit of $2.29 billion in 1980.(14)

The potential for OTEC to meet the demand for electricity in the developing nations is a function of the installed electrical generation capacity. The magnitude of this installed capacity determines not only the number of potential OTEC plants but also the optimum size of the plant. Typically, an individual power plant should represent no more than 10-15 percent of a nation's power system in order to insure a reliable and available power supply. Information on population and electric power growth projections was assembled for the 67 candidate developing nations. The forecast installed electrical generation capacities in 1990 vary from 0.01 Kw/capita to in excess of 1 Kw/capita with a size variation from 10 MW to 80,000 MW.

The distribution of installed capacities in the 67 nations and territories in 1990 and 2010 shows a wide variation for OTEC plant sizes (Figure 3). Approximately one-half of these nations have capacities less than 1000 MW. This spectrum of installed capacity sizes illustrates the potential for utilization of OTEC plants ranging from the 10 MW to the large 400 MW sizes. Although the smaller 10 MW OTEC units result in higher electricity cost estimates, they will be competing in markets with smaller system sizes where economies of scale are not available and electricity from conventional sources is correspondingly higher in cost than in the larger nations with large installed capacity.

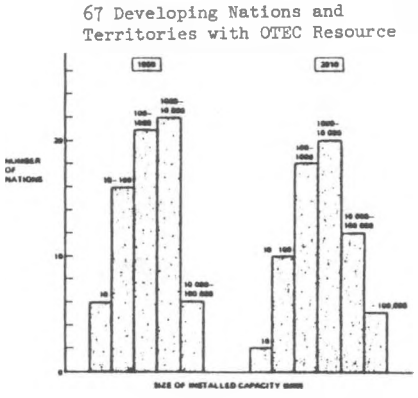


Figure 3. Size of Power Systems

The potential market for OTEC is strongly dependent on the availability and cost of alternative energy sources in the developing nations. As a potential baseload electric power source, OTEC must compete with 1) domestic oil and gas, 2) domestic coal, 3) hydropower, and 4) nuclear power (Figure 4). The dependence on imported oil is the most significant factor for considering alternative energy sources. An evaluation of domestic oil and gas proven reserves (1980) among the candidate OTEC nations shows that 52 of the 67 have no significant reserves and only 11 are net exporters.(13) Coal represents an alternative to oil. Although a total of 46,213 million metric tons of coal reserves are projected for the 67 candidate nations, 58 had no proven coal reserves in 1980.(12) Hydropower is a relatively inexpensive source of baseload electric power. An evaluation of the hydropower potential among the candidate OTEC developing nations shows a total of 738,261 MW of potential.(13) Of the 67 nations, 26 have insignificant hydropower potential (<100 MW) and an additional 20 have potential of 100-10,000 MW. Nuclear power is an alternative baseload electric power source and currently 6 of the 67 candidate OTEC developing nations have plans for nuclear power plants by 1990.(15) However, the size of economical nuclear plants precludes use in nations with smaller power system sizes than about 5000 MW. Thus, 50 of the 67 nations will have power system sizes in 2010 too small to consider nuclear power. In addition to the 6 nations with current nuclear power plans, an additional 11 nations will have sufficient power system sizes to consider nuclear power in 2010.

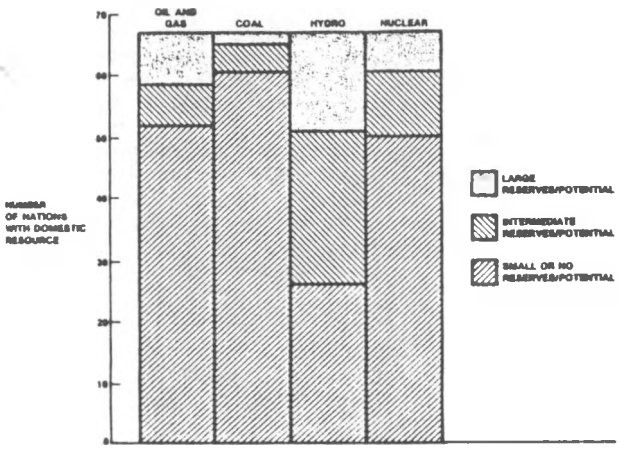


Figure 4. Availability of Alternative Energy Sources

The electricity from an OTEC plant can be used for by-products such as ammonia fertilizer production, aluminum processing, mariculture applications, or fresh water production. Many of the developing nations are well-suited for use of the OTEC nutrient rich cold water for mariculture applications and significant interest exists in this future technology. A number of nations, especially small islands, have fresh water supply problems and could utilize OTEC for this purpose. The use of OTEC plants to produce nitrogen fertilizer has been studied extensively. The potential for this application in candidate developing nations was based on a comparison of recent consumption and production. Among the 67 candidate nations, a net deficit of 2,213,211 metric tons was experienced in 1979.(16) Although this deficit was balanced by imports, it represents a significant potential for domestic production to reduce foreign imports and improve the balance in trade. Aluminum processing is an electricity-intensive application for OTEC which has been studied extensively. Any nation could import bauxite or alumina and process aluminum using domestic electric power sources. However, potential exists in those developing nations which have bauxite deposits and yet process very little aluminum. A total of 30,795,000 metric tons of bauxite was mined in six of the candidate developing nations but less than 1,012,000 metric tons of aluminum was processed in 1976.(17)

The overall market potential for OTEC in the 67 candidate OTEC developing nations and territories is represented by the forecast baseload electrical generating capacity (Figure 5). The estimated baseload in 1990 is approximately 140,000 MW.(1) An average growth rate of 8.5 percent per annum,(15) based on historical trends in developing nations, results in a projected baseload of about 717,000 MW in 2010. The degree of penetration of the market by OTEC is dependent on a number of factors including the Government's policy toward renewable energy sources such as OTEC. Three alternative scenarios, 10, 50, and 100 percent of new baseload capacity from 1990-2010 in OTEC, would result in approximately 60, 300 and 600 GWe of installed OTEC baseload by 2010. This is equivalent to about 5, 25, and 50 quads of energy or 1000, 5000 and 10,000 mboe per year in 2010. Although it is unrealistic to assume 100 percent of baseload in any single technology such as OTEC, it is illustrative of the potential market for about 3000 plants in sizes from 10-400 MW (Table 3).

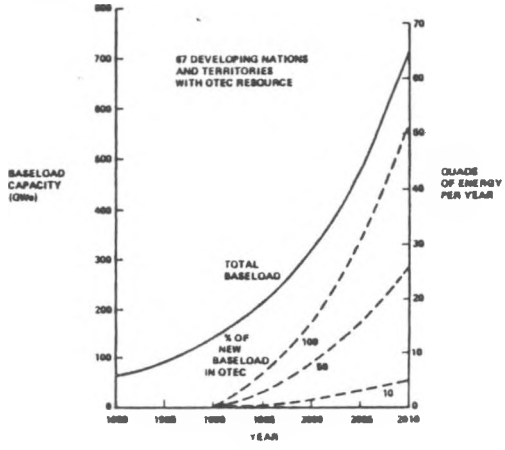


Figure 5. OTEC Baseload Electricity Market Potential

ASSUMED SIZE OF OF OTEC UNIT (MWe)	RANGE IN SIZE OF INSTALLED CAPACITY IN 1990 (MWe)	TOTAL NEW BASELOAD CAPACITY ADDED 1990-2010 (MWe)	NUMBER OF OTEC UNITS
10	10-100	1165	117
40	100-1000	20,400	510
100	1000-10,000	110,750	1108
400	> 10,000	444,685	1112
-	-	577,000	2847

67 DEVELOPING NATIONS AND TERRITORIES WITH OTEC RESOURCE

Table 3. Number of OTEC Plants for New Baseload Electricity

A final key result of this OTEC market assessment is the identification of the market potential for small 5-40 MW commercial OTEC units in the 1986-1995 time period. This market results from three key factors:

1. Small power system sizes in many developing nations can accommodate the small OTEC units.

2. These small OTEC units, although more costly per unit energy than larger OTEC units, are still projected to be cost competitive with the oil-fired steam or diesel in these smaller nations.

3. Commercial 5-40 MW OTEC units are expected to be available in the 1986-1995 time period while larger 100-400 MW OTEC commercial units may not be developed until the 1995-2005 time period.

A total of 53 developing nations and territories have been identified with potential for near term use of small OTEC units. This total encompasses the 27 territories of developed nations including the U.S. territories of American Samoa, Guam, Trust Territory of the Pacific, and the Virgin Islands; the 21 small developing nations with small power system sizes; and the five larger archipelago developing nations -- Fiji, Indonesia, Malaysia, Papua New Guinea, and the Philippines -- which have a large total power demand but widely dispersed individual systems on isolated islands which are not connected to a central electrical grid. The potential demand for these small OTEC commercial units will provide a market for development of an OTEC industry while the large OTEC units are under development.

IV. BARRIERS AND INCENTIVES TO OTEC UTILIZATION

The technology, resource, and market assessments indicate favorable conditions for OTEC utilization in developing nations. However, many factors impact the decision-making process in selecting an advanced technology such as OTEC for applications in developing nations including:

1. Economic Issues
2. Environmental Concerns
3. Political Factors
4. Cultural, Social and Institutional Factors
5. Legal Issues
6. Financial Concerns

Each of these factors was evaluated to identify issues unique to developing nations. Key issues were found to relate to economics and finance.

A major factor in the selection of an OTEC plant is the relative cost of OTEC-derived electricity compared to alternative energy sources. Primary competitors to OTEC as a baseload power source include oil-fired diesel or steam, coal-fired steam, hydropower, nuclear or geothermal. These alternatives have a range of installed capital costs, fuel costs, and load capacity factors. Although costs vary depending on the country, a set of energy costs was assembled for the general class of oil-importing developing countries.(13) Assuming a real escalation of 3 percent per annum in the fuel cost component, projected electric energy costs (in 1980 U.S. dollars) for the 1986-2010 time period of interest show OTEC to be cost competitive with all options except hydropower, gas-fired steam and geothermal for large systems (Figure 6). The large OTEC unit costs of 6¢/Kwh is projected to be competitive with imported oil currently, coal by 1990, and nuclear currently based on cost estimates for small nuclear units. A similar analysis for small 10 MW OTEC units shows a cost of energy of 15¢/Kwh which is competitive with oil-fired steam or diesel units in the 1985-1990 time period (Figure 7). In addition to relative OTEC cost, other economic conditions in developing nations can impact implementation of OTEC. Key issues are financial creditworthiness and economic development potential. However, the use of OTEC may promote energy self-sufficiency and thus contribute to the economic development. The single most important negative economic factor in developing nations is the cost of imported energy and its negative impact on balance of trade. Thus, significant incentives exist for OTEC development to attain energy self-sufficiency and provide a stable base for economic development.

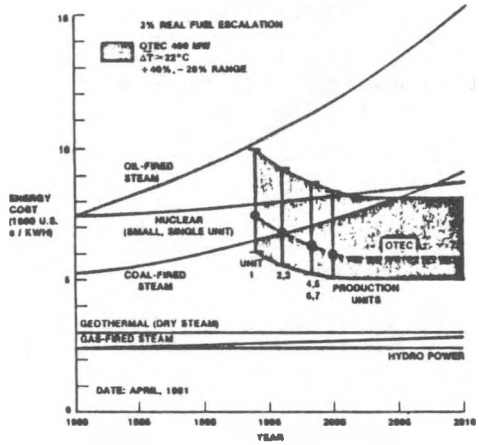


Figure 6. Comparative Cost of Electricity in Developing Nations - Large Systems

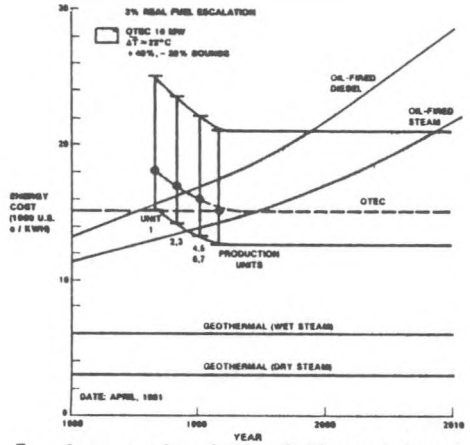


Figure 7. Comparative Cost of Electricity in Developing Nations - Small Systems

A second major factor in OTEC implementation is the financing of capital-intensive projects in developing countries which are short of domestic capital and must rely heavily on foreign credit. This is further complicated by public utilities laws which restrict ownership to government utilities or domestic corporations in many cases. Since foreign technology is required for OTEC implementation, financing approaches and institutional participants must be identified which favorably combine the foreign capital and technology components with the developing nation ownership/investment framework. These institutions include commercial banks and private investment firms,

official government foreign aid programs, official export credits, and bilateral/multilateral agencies. Each of these institutions has different criteria in evaluating suitability of projects.

A key role in the initial OTEC implementation in developing countries could be provided by the World Bank based on their historic role and recent involvement in power development. The World Bank made lending and investment commitments in 1980 for $12.2 billion.(19) Only 4% was in the energy sector but this is expected to increase. However, a substantial increase in World Bank energy sector loans would be required to provide a large fraction of the long-term OTEC requirement. OTEC is not currently an integral part of the World Bank energy projections and plans. If the Bank is to play an initial role in OTEC development in developing nations, it is essential that the World Bank appraise OTEC technology in order to adequately consider its future applications.

In order to realize the OTEC market potential, significant capital investment is required. The 10 percent market penetration scenario results in a required $171 billion (1980 U.S. dollars) in capital investment for the 57 GWe which would be installed by 2010 (Figure 8). This requirement is formidable but it must be compared with the accumulated displaced oil cost of $343 billion (1980 U.S. dollars) assuming a 3 percent real oil price escalation. The reduced "capital" required to import oil provides a source of funds to finance the capital to use OTEC. In addition, this large capital requirement represents a significant market for U.S. exports.

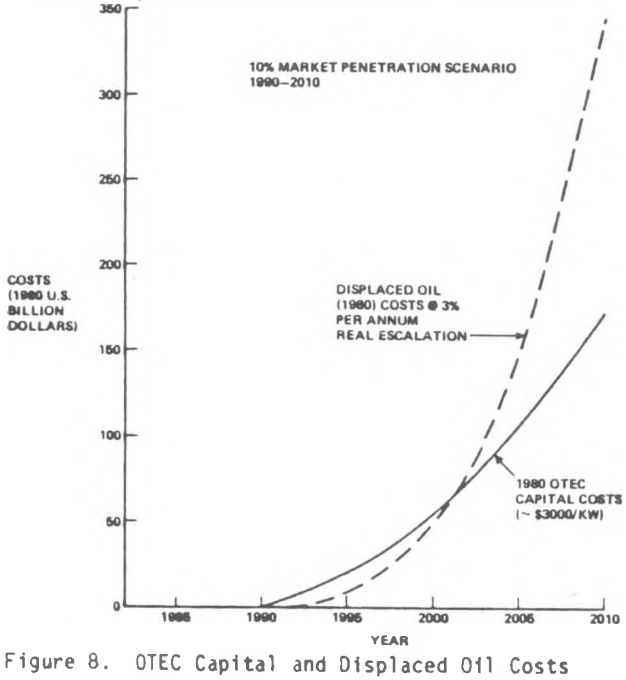


Figure 8. OTEC Capital and Displaced Oil Costs

However, the magnitude of the OTEC capital investment indicates that official foreign aid programs will have a minimum impact in the long-term commercialization and financing of OTEC. Initial funding to initiate OTEC programs in the poorer countries might be expected but not funding of commercial plants. The entire official world foreign aid budget in 1980 was estimated at approximately $16 billion.(20) This is not significant when one 400 MW OTEC plant could cost $1 billion. The bulk of the financing for commercial OTEC plants must come from government equity participation or private commercial bank or investment sources. The expected high level of commercial, foreign investment to implement OTEC in developing countries results in the conclusion that insurance against political and commercial risks is necessary to provide a favorable investment climate and encourage the development of an export market. For U.S. investment, this requires participation of the Eximbank and the Overseas Private Investment Corporation.

As with any emerging technology such as OTEC, there are both barriers and incentives to implementation in developing countries. However, due to the desire to reduce dependence on foreign energy sources and the need for economic development, approaches and institutions to mitigate any barriers will probably be available once the technology is demonstrated to be economic.

V. CONCLUSIONS AND RECOMMENDATIONS

The results of this market assessment clearly illustrate the significant market potential for OTEC in developing nations and territories in the 1986-2010 time period. A total of 98 nations and territories have access to the OTEC resource within their 200 nm EEZ and only 3 of these are developed nations. The OTEC resource is outstanding for developing nations and territories which generally correspond to the OTEC thermal resource zone. The high $\overline{\Delta T}$ of as much as 24°C in conjunction with the close proximity of the resource offshore for many of the candidates allows for more flexibility in selecting a system concept. Developing nations can accommodate OTEC plant sizes ranging from 10-400 MW. Small commercial OTEC units of 10-40 MW size will be available in the 1986-1995 time-frame and many developing nations can accommodate the small sized OTEC units due to the small size of their power systems and high cost of energy derived from oil-fired generation units. Although dependent on many parameters, nominal OTEC levelized busbar electricity costs are estimated at 15¢/KWH for 10 MW to 6¢/KWH for 400 MW units.

The market potential for OTEC is represented by an estimated 577,000 MWe of new baseload electric power facilities between 1990 and 2010 in the 67 candidate developing nations and territories. This is equivalent to 50 quads of energy per year or 10,000 mboe in the year 2010 and represents a potential for nearly 3000 OTEC plant in sizes from 10-400 MW. If only 10 percent of this market is penetrated, a total of $171 billion in OTEC capital costs will be required for the 57,700 MWe of OTEC capacity. However, it will displace $343 billion (1980 dollars) of imported oil. Thus a source of funds exists to finance the capital investment for

OTEC. A final key result of this assessment is the identification of a significant market in the 1985-1995 time period for small 5-40 MW commercial OTEC units which are compatible with the characteristics of 53 smaller developing nations and territories.

It is clear that a significant OTEC potential exists in the near future for developing nations and territories. The successful development and commercialization of OTEC will be highly dependent upon cooperation among developed and developing nations. The developed nations, by providing for the transfer of OTEC technology and assisting with financing, may help begin to reduce the world demand for depletable energy sources. This would consequently moderate the increasing cost of energy and help control escalating inflation rates. For the developing world the potential benefits are much greater. Any incremental advances in economic growth experienced by the developing world in recent years have been negated by the poorer nations' dependence upon imported energy. It is the rapidly increasing cost of this foreign energy which has provided for the majority of negative economic trends. The developing world's objective in promoting the economic growth necessary to improve the welfare of their people lies in their ability to produce large amounts of electricity cheaply and independently. OTEC, if proven commercially feasible and competitive, may represent a major step towards meeting this objective.

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8th Ocean Energy Conference
Washington, DC
June 1981

THE UNITED NATIONS CONFERENCE ON NEW AND RENEWABLE SOURCES OF ENERGY

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United Nations

The United Nations Conference on New and Renewable Sources of Energy (CNRSE) took place in Nairobi, Kenya from 10-21 August 1981. Its objective is to promote the development and use of new and renewable sources of energy, with a view to contributing towards growing overall energy demands, especially those of developing countries.

The Conference was initiated by resolution 33/148 of the United Nations General Assembly and was preceded by an extensive preparatory process which examined fourteen energy sources: Ocean energy (thermal gradient, wave power, and tidal power); solar energy; geothermal energy; wind power; hydropower; biomass; fuelwood and charcoal; oil and tar sands; peat; and energy from draught animals. Eight technical panels were set up to deal with these different sources of energy while six ad hoc groups studied concerns common to all the energy sources: education and training; information flows; research and development and the transfer of technology; industrial issues; rural energy; and financing.

As these panels were progressing with their work, governments were preparing national papers and regional meetings were held to identify regional concerns and draw up plans of action. The Nairobi Programme of Action was a product of these activities as drafted by the Conference Secretariat under the supervision and advice of the Preparatory Committee.

As part of this process, the Ocean Energy Technical Panel met twice and produced a final report during its second session at Geneva from 22-26 September 1980. The Panel was composed of experts from the United Kingdom, Japan, the United States, France, India and Chile. The principal questions discussed were:

(a) What are the technologies which can be utilized significantly in the next 20 years and beyond?

(b) What are the major constraints preventing the development of those technologies?

(c) What are the means of overcoming those constraints and of reinforcing the utilization of the technologies in the next 20 years and beyond?

Although tidal energy is commercially established, there are only a few prime tidal sites in the world where it is probably economic now compared to the cost of fossil fuels. While tidal energy may make a useful contribution to world energy supplies over the next 20 years, the Panel concluded that it is not large by global standards and will not make a major impact on the energy problems of developing countries.

The conclusion on wave energy resources was somewhat similar, though for different reasons. It is larger in extractable form than tidal energy, but is of most interest beyond 30°N and 30°S. Hence, it is applicable to only a few of the developing countries. Even in such countries, it is unlikely to find wide application in the present century because its unit costs are too high; more research was recommended before wave energy economics can be fully assessed.

The Panel focussed primarily on OTEC on the basis of projected conceptual viability, significance for developing countries in the next 10-15 years, and amenability to international action. OTEC is considered a very promising technology of special potential significance for the developing world and that it should be given a high priority. In order for OTEC to overcome the present constraints on its exploitation, the Panel made the following recommendations:

(a) A demonstration project should be initiated in a developing country to demonstrate OTEC reliability and economics, under size and operating conditions appropriate to a commercial operation. It should be open to all who wish to participate. An international demonstration project under United Nations auspices would increase the understanding of OTEC and of the benefits of its application to developing countries.

(b) A special OTEC demonstration fund should be established to finance the project described in (a) above.

(c) An OTEC development fund should be established to support increased international

*The views expressed in this paper are those of the author and do not necessarily reflect those of the United Nations.

awareness of OTEC and early projects in developing countries.

(d) An information, education and training programme should be established, with emphasis on resource and site assessment.

(e) Studies should be undertaken within existing United Nations programmes to address the following subjects:

i. Developing country markets;

ii. Research assessment and network integration;

iii. Long-term OTEC cost/benefit;

iv. Identification of manufacturing opportunities in developing countries;

v. Multiple-use concepts, including the "energy island" concept;

vi. International co-operative plantship projects; and

vii. Refinement of guidelines for resource assessment and site evaluation.

(f) Any demonstration project arising out of recommendation (a) should be linked with activities arising out of recommendation (c). This should be done in such a way as to provide an overall United Nations focus for the participation of all countries interested in OTEC, including information advice and studies aimed at applications and markets, and the establishment of fellowships to advance and train developing country specialists in OTEC technologies.

(g) On tidal power, activities should continue within existing United Nations programmes to help evaluate its prospects in individual developing countries interested in it.

(h) The position on wave power should be reviewed again in about two years.

These recommendations, together with those of the other technical panels were transmitted to the Preparatory Committee and subsequently to the Conference. On the basis of the results of the preparatory process, the Preparatory committee identified five to six broad policy areas for concerted action with the support of the international community according to national plans and priorities.

(a) Energy assessment and planning;

(b) Research, development and demonstration;

(c) Transfer, adaptation and application of mature technologies;

(d) Information flows;

(e) Education and training;

(f) Mobilization of financial resources.

Specific measures within these broad policy areas were identified for each of the energy sources under consideration. For ocean energy, the following specific actions were identified:

(a) Assessment and planning

Assess the ocean energy resource by identifying sites of potential OTEC, tidal and wave energy utilizing archival data and other existing information as well as by undertaking OTEC, tidal and wave energy surveys through the joint efforts of oceanographic and meteorological organizations.

(b) Research, development and demonstration

i. Initiate or continue research and development in such areas as:

- Aquaculture based on nutrient-rich deep waters; floating land-based and shelf-based ocean systems directed to the production of electricity; fresh water and energy intensive products.

- Ocean wave systems including technical solutions suited for the trade-wind belts.

ii. Accelerate the application of ocean energy systems when this appears justified, for example, by:

- An extension of existing facilities, where feasible, for use as regional/international demonstration sites.

- Efforts directed at isolated communities.

The effective implementation of the measures for concerted action on the Programme of Action will require:

(a) The identification of selected priority areas requiring urgent action.

(b) Institutional arrangements for implementation and monitoring, to include:

i. Intergovernmental body;

ii. Co-ordinating mechanisms;

iii. Task forces for implementing specific programmes and projects of the Nairobi Programme of Action;

iv. Secretariat support;

v. Regional and sub-regional action;

vi. Economic and technical co-operation among developing countries; and

vii. Intergovernmental and non-governmental organization.

(c) The mobilization of financial resources for the implementation of the Nairobi Programme of Action.

The adopted Nairobi Programme of Action is to be submitted to the General Assembly of the United Nations at its thirty-seventh session in late 1981. As with its other endeavours, the success of this major United Nations activity will depend upon the will of the participating governments. It was the recognition of the extent of the need for action which gave rise to the Conference. Now this initiative must be translated into concrete programmes in order to realize the ambitious objectives set out in the Nairobi Programme of Action.

8th Ocean Energy Conference
Washington, DC
June 1981

U.S. Plans for the United Nations Conference on New and Renewable Sources of Energy

Csanad Toth
Senior Policy Adviser

Department of State

General U.S. Goals for the UN Conference

Broadly speaking, the U.S. seeks to use the Conference and its preparatory period to:

--Accelerate the Development, acceptance and use of new and renewable sources of energy, taking into account the effects on the Global Environment and Resource Base:

--Elaborate a program for improved and expanded international cooperation in new and renewable energy as part of our over-all strategy of furthering constructive international treatment of energy matters;

--Help educate all countries about the real opportunities new and renewable sources of energy offer in meeting energy needs.

Specific U.S. Objectives for the UN Conference

In pursuit of these general goals, the U.S. should seek the following specific objectives at the Conference:

1. A competent International analysis of current and prospective uses of new and renewable energy sources, obstacles inhibiting their use and recommendations for overcoming the obstacles.

2. A commitment by all countries to include appropriate national new and renewable energy programs within the framework of national energy policies.

3. Improved public and private international cooperation and coordination in research, development and demonstration in new and renewable energy sources.

4. Action to accelerate commercialization of new and renewable energy technology and products.

5. Strengthening information exchange systems in new and renewable energy sources.

6. A commitment to improved education and training in new and renewable energy sources and conservation.

7. Improved bilateral and multilateral financial flows and technical assistance, from capital surplus oil exporting countries as well as traditional sources, for new and renewable energy.

In addition to the foregoing, U.S. has emphasized primacy of national efforts, the significant role of the private sector as a principal instrument of International cooperation in new and renewable energy and better management, efficiency and coordination of existing international institutions active in the

field of new and renewable energy. Moreover, U.S. has stated publicly on numerous occassions its opposition to the creation of new international institutions or funding mechanisms in the field of new and renewable energy.

8th Ocean Energy Conference
Washington, DC
June 1981

RENEWABLE ENERGY RESOURCES IN THE DEVELOPING COUNTRIES

Richard S. Dosik & David Hughart

World Bank

A. The Potential of Renewable Energy in the Modern Sector

Increasing oil prices have stimulated interest in alternative energy sources in developing countries as well as in the industrialized world. The impact of the higher prices on the balance of payments and economic growth of many developing countries has been severe, and the growing demand for energy associated with economic growth has emphasized the need to develop domestic energy alternatives. As in many developed countries, conservation and increased efficiency in energy use are regarded as helpful but not sufficient to meet growing needs.

Renewable energy can substitute for oil in a variety of modern sector uses in transport, industry, and the production of electric power. Quantifying the potential savings in oil, resulting from use of biomass, solar and other renewable energy resources is, however, difficult. The few studies which have attempted to do so suggest the possibility that renewable energy may be able to substitute for some 5 to 15 percent of the oil consumed by the developing countries by the end of the century. Because of differences in coverage, methodology, and critical assumptions (for example, about world oil prices) these results can at best be regarded as indicative. However, they do point to the broad conclusion that renewable energy, while no panacea, can be expected to substitute for a small but significant share of oil consumption in the developing countries over the long run. An earlier and more substantial impact may be possible in regions and countries that are particularly well endowed with biomass.

B. Renewable Energy Needs in the Traditional Sector

Interest in renewable energy has also been stimulated by growing awareness of the existence of a "second energy crisis" brought on by the depletion of forests in many of the developing countries. In contrast to the rise in oil prices, a highly visible modern sector phenomenon, the crisis in traditional energy supplies is a quiet one, but it poses a clear danger in the lives of much of the population of the developing world. Traditional renewable energy resources such as firewood, charcoal, crop residues and animal dung account for virtually all of the fuel used in many rural areas, and may account for about 20 to 25 percent of the total energy con-

sumption in the developing world. Africa is most dependent upon traditional renewable resources, Asia somewhat less, and Latin America is the least dependent upon these resources. About 75% of the population of the developing countries uses traditional fuels, largely within households and primarily for cooking. Most of these people have access to firewood, but roughly 1,000 million people use agricultural and animal wastes to fuel their cooking fires.

The rural energy crisis stems from the fact that the developing countries have been consuming their wood supplies far more rapidly than they are renewing them, with grave environmental, economic and human consequences. Fuelwood harvesting to meet the energy needs of rapidly growing populations, land clearing for agricultural purposes and increased lumbering, together, are consuming the developing countries' forests at a rate of some 1.3 percent or 10-15 million hectares a year. Deforestation, particularly on steep hillsides, has contributed to soil erosion that has reduced upland water storage capacity and increased the siltation of reservoirs (shortening their lives), irrigation canals (raising maintenance costs) and river beds (increasing the danger of flooding). The search for fuelwood has also been an important factor in the destruction of covering vegetation in arid and semi-arid areas, thus contributing to desertification. As fuelwood supplies have dwindled, people have turned increasingly to burning dung and agricultural residues, depriving the soil of valuable nutrients and organic conditioning material. It is estimated that the current use of dung for fuel "costs" some 20 million tons of foregone food grain production annually.

The human cost of the rural energy crisis has also been high, both in terms of its immediate impact on the lives of the poor, and on the long-term prospects for alleviating poverty. The fuelwood shortages that have been felt severely in many parts of the developing world have put a heavy burden on the labor and cash flows of low income groups. Villagers, mainly women and children, who could previously collect fuelwood in the immediate vicinity of their homes, now find in many cases that they must search for it a half a day's walk, or more, away. For example, families in the upland areas of Nepal are spending the equivalent of 60-230 work-days per year on fuelwood collection while in some parts of Tanzania 250-300 work days are required to meet family needs. Nor is the impact limited to rural areas. A recent World Bank survey found poor families in Bujumbura, the capital of Burundi, to be spending upwards of 30 percent of their income for fuel (mainly charcoal).

The development of renewable energy will have its most important impact in helping developing countries meet this second energy crisis. This impact should be measured not only by the quantity of energy produced but also by the contribution made to welfare and development. Small hydro-electric units, wood burning power plants, wind pumps and other renewable sources of mechanical and electrical power, while perhaps not

adding significantly to national energy supplies, can have a major impact on development and touch the lives of large numbers of the poorest people by providing power for agriculture and rural industries.

C. Advantages and Requirements for the Development of Renewable Energy

The developing countries are in some respects at an advantage in developing renewable resources of energy, since they are located in the latitudes that naturally receive the greatest amount of solar radiation. For example, India receives an average of 0.17 tons of oil equivalent (toe), or 1.2 barrels of oil equivalent (boe), per square meter per year, and the Sahelian countries 0.19 toe (1.4 boe), compared with average insolation levels of 0.15 toe (1.1 boe) in the United States and 0.09 toe (0.6 boe) in Western Europe. Where rainfall and soil conditions allow, the biomass produced by this abundance of solar energy gives many developing countries another major renewable energy resource. Unlike fossil fuel deposits, which yield energy in the relatively concentrated and portable forms suitable for large-scale industrial and urban use, solar radiation and biomass are most economically exploited on a small-scale, decentralized basis, and are, thus, well matched to the needs of dispersed rural populations. In addition, much of the equipment needed for many of the renewable energy technologies is suitable for domestic production in even the less industrially advanced of the developing countries.

The relatively high cost of energy from conventional sources in many rural areas of developing countries is likely to make the development of some types of renewable energy economically attractive there sooner than in the urban areas. In developing countries, electricity from large thermal or hydroelectric power stations supplying the national grid now generally costs 5-10 US cents per kWh. However, it is estimated that only about 35 percent of the total population of the developing countries, and about 15 percent of their rural population, is connected to the grid. Where the grid does not reach, the conventional alternative for meeting small-scale needs is usually gasoline- or diesel-generated power. Power from these sources costs, today, roughly 13 US cents per kWh from the units typically used to supply electricity to small towns, and 45 US cents per kWh from the smallest (1 kW) unit used by individual consumers. These estimates are based on an assumed crude oil price of US$30/barrel and "normal" refining and distribution costs; power generated from conventional sources may be much more costly in remote inland locations where high transport charges make fuel substantially more expensive.

While many developing countries have favorable conditions to develop and use renewable energy, the pace at which the full potential of this resource can be developed will be determined by the ability to of the countries to:

-- develop adequate data on sources and uses of renewable energy;

-- enhance their technical capabilities;

-- design systems that can deliver renewable technologies in socially and culturally acceptable forms to large numbers of energy users; and
-- strengthen institutions for energy planning and programming.

Most developing countries lack the data for a realistic assessment of the present and future role of renewable energy in their economies. Hard information on existing resources, uses, and costs of renewable energy is available from only a limited number of case studies, and there have been few efforts to take careful stock of the availability and distribution of national resources for the production of energy from biomass, solar radiation, the wind or small hydro sites. In most countries, systematic efforts to fill the most serious data gaps are a prerequisite for moving beyond pilot projects and isolated investments to the stage of rational selection of development priorities and sound program planning.

As regards technical capabilities, the technologies involved in exploiting renewable energy require varying degrees of scientific and engineering sophistication. A few cases (for example, photovoltaic cells to produce electricity) involve new developments falling in the realm of high technology; others (for example, solar collectors), while also relatively new, demand more in the way of careful engineering than scientific innovations. Developing countries should attempt to build up the capacity to keep abreast of relevant technical developments, to adapt technologies to local conditions, and to apply them successfully. While local capability clearly extends far beyond these areas in some countries, notably Brazil, India, and the Republic of Korea, many countries currently do not have enough trained manpower or material resources to deal with even the less sophisticated renewable energy technologies.

The third major area of concern is the weakness of existing extension services and other delivery systems capable of reaching the rural and urban poor with knowledge about renewable energy and providing them with the technical and other assistance necessary for its application. Popular acceptance is a particularly important and sensitive area. Because households account for the bulk of energy consumption in poor communities, the impact of the renewable technologies will to a large extent depend on the developing countries' ability to make them available in forms compatible with the needs and life styles of their people.

Weaknesses in planning and programming present a formidable obstacle to the realization of the renewable energy potential of the developing countries. While, again, the situation varies widely among developing countries, most of them (like most developed ones) lack coherent national energy plans that can provide a framework for defining the role of renewable energy in the economy, for determining priorities among the various technologies and for assigning resources accordingly. In the first stages of a renewable energy development program, a general sense of

priorities may suffice to shape surveys, technical research and development, and work on extension techniques. Lack of energy planning capacity may not be a major obstacle so long as investment is mainly concentrated on demonstration and pilot projects, but is likely to become more important at a later stage, when renewable energy programs begin to require important budgetary or policy commitments. Many countries lack suitable institutions that can serve as focal points for planning strategies on renewable energy, devising and supporting research and development programs, and promoting commercial applications.

The potential for the utilization of renewable energy in the developing countries, and the problems which must be dealt with in seeking to develop this potential, are discussed in greater detail in the World Bank publication Renewable Energy Resources in the Developing Countries (November, 1980). Other World Bank publications, which discuss specific aspects of renewable energy resource development, include Alcohol Production from Biomass in the Developing Countries (September, 1980) and Mobilizing Renewable Energy Technology in the Developing Countries: Strengthening Local Capabilities and Research (July, 1981)

Session Group VII

OTEC-1 EXPERIENCES AND EVALUATIONS

8th Ocean Energy Conference
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OVERALL OTEC-1 STATUS AND ACCOMPLISHMENTS

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ABSTRACT

The Department of Energy (DOE) has successfully built and operated the world's first at sea ocean thermal energy conversion (OTEC) test facility, OTEC-1. Using a World War II T-2 U.S. Navy tanker, DOE refurbished and converted this tanker into a facility for testing OTEC systems, heat exchangers and components. OTEC-1 operated from mid-December of 1980 to April 1981. OTEC-1 was terminated in April 1981 due to fiscal year 1981 budget cuts.

1. OTEC-1, THE DEPARTMENT OF ENERGY'S OCEAN ENERGY CONVERTER

The Department of Energy's (DOE) OTEC-1 sea based test facility was build by DOE using a former World War II U. S. Navy T-2 SE-A1 class tanker built in 1943 at Sun Shipyards in Philadelphia. The T-2 tanker was designated as T-AO-78 USNS Chepachet by the U.S. Navy. Chepachet was in the Navy mothball fleet at Suisun Bay in San Francisco when DOE acquired the vessel in September 1978 through Global Marine Development, Inc. In February 1979 the vessel was towed from San Francisco to the Northwest Marine Iron Works shipyard in Portland, Oregon for refurbishing and construction/conversion. Construction was completed in June 1980 and Chepachet, renamed SS Ocean Energy Converter by DOE, arrived in Hawaii in July 1980. The vessel and cold water pipe (CWP) deployment plus DOE acceptance was completed in December 1980.

2. SUMMARY OF OPERATIONS

2.1 Seawater Systems

Cold seawater pumping began on December 13, 1980 which represented the start of OTEC-1 operations. Seawater pumping was almost continuous from that date, except for a few brief periods of downtime. A total of 2,565 hours was acumulated for cold water pumping from December through April 1. The warm water system accumulated 2,365 hours in this time period. The combined cold and warm seawater mixed discharge accumulated 2,340 hours from December 13 through March 26 although the deep water discharge pipe was inoperative for most of that time.

2.3 Ammonia Systems

Evaporation of ammonia began on December 31 and a total of 90 tests were accomplished by March 27. The total hours accumulated for these tests was 370.

2.4 Biofouling Control

The primary biofouling control was chlorination. Chlorine was injected into the heat exchangers whenever the seawater systems were in operation. For each 24 hours of operation chlorine was injected into the evaporator and condenser for one hour at a rate of about 0.4 ppm.

In addition to chlorination OTEC-1 used Amertap as a cleaning system. Amertap balls were circulated whenever the seawater systems were running. An average of one ball per tube every 15 minutes was circulated. The usual industry practice is one ball every hour. Amertap was discontinued on March 3 so that the results of no ball cleaning could be observed.

2.5 Sea/Weather Conditions

The CWP was scheduled for deployment in mid summer of 1980. However, this acitivity was deferred by DOE due to a significantly higher 3 knot sub-surface current vs the design value of 1.2 knots. After redesign of the system, adding full instrumentation to the CWP plus added bottom weight, the CWP was successfully deployed in the fall of 1980.

During the time period that OTEC-1 was on site the sea and weather conditions were as follows:

Seas - nominal waves of 3 to 6 feet, maximum waves of 13 feet (on February 27, 1981)

Currents - the only reliable data was obtained from in-the-sea current meters. The following was recorded from September 23, 1980 through December 30, 1980; Average subsurface current of 1/2 knots, maximum subsurface current of 3 knots

Wind - nominal wind velocity of 5 to 10 knots, maximum wind velocity of 35 knots, gusting to 45 knots (on February 25-28, 1981)

Ship motions - nominal roll of 3^{o} to 6^{o} maximum roll of 18^{o} (zero to peak amplitude on February 26-27, 1981), nominal pitch of 1^{o} to 2^{o}, maximum pitch of 6^{o} (zero to peak amplitude on February 27, 1981)

3. SUMMARY OF ACCOMPLISHMENTS

During the brief time period OTEC-1 was deployed OTEC-1 has provided a number of successful accomplishments. A deep mooring in over 4,000 feet of water was set for OTEC-1. In deploying the CWP, the equivalent of a 7 foot diameter CWP was successfully floated 18 miles to the site, down ended, and placed in position. Once in position the ship and CWP seawater systems operated almost continuously from start of operations. Operations continued even during several Kona storms with winds gusting to 45 knots and subsurface currents over 3 knots. The performance of the heat exchangers for the plain tube bundles was found to be in excellent agreement with predicted values.

The CWP was managed to be held to within design limits during a Kona storm by managing the gimbal angles. When the gimbal angle reached 22^{o} in roll the vessel was listed to the opposite side by 12^{o} by water ballast redistribution. This action reestablished a nominal 10^{o} gimbal angle for the CWP. On April 4, 1981 a subsurface current event of over 4 knots occured which pushed the CWP gimbal

angle to its stops of 30^{0}. The scenario which had been developed for such an event was to release the CWP. The CWP would sink and stand off the sea floor bottom in a vertical position for later retrieval.

Since there was no concurrent adverse surface wave action at the time, the decision was made not to drop the pipe. Instead the vessel slipped its moor and went into a controlled drift mode. Drift and heading was controlled by using the ship's thrusters. With the vessel free from the moor the CWP resumed its normal angle. Operation of all the seawater systems was maintained during the period when OTEC-1 was drifting for about one day. This activity established another first - the world's first grazing OTEC plantship!

OTEC-1 drifted for one day. On the following day the seawater systems were stopped, the system dewatered, and ship's power switched to main propulsion. OTEC-1 slowly transited about 5-1/2 miles back to the moor and reattached. With the subsurface current back to normal the CWP/system was also normal and operations were resumed.

4. WHAT WAS NOT ACCOMPLISHED

As a result of fiscal/budget constraints OTEC-1 operations were terminated in April 1981. Although OTEC-1 provided a number of accomplishments several areas remain which need answers. OTEC-1 was not able to successfully maintain operation of the deep water discharge pipe (DWD). The DWD failed each time it was deployed - over 5 times, even though the pipe was redesigned following each failure. Additonal engineering development is needed for a successful DWD.

A better design for instrumenting the full length of the CWP is needed. Although additional time and expense was expended to fully instrument the CWP with linear variable differential transformers (LVDT's) only the upper CWP LVDTs furnished any useful information. The rest of these instruments failed from seawater corrosion and metal fatigue.

In the heat exchangers the long term effects from corrosion were not established since the deployment period was to short. Heat exchanger performance from the enhanced heat transfer surfaces was not fully established, again due to the short deployment time period.

In summary DOE successfully fielded the first large scale OTEC closed cycle experiment, OTEC-1. However, much more engineering research and development remains to be done.

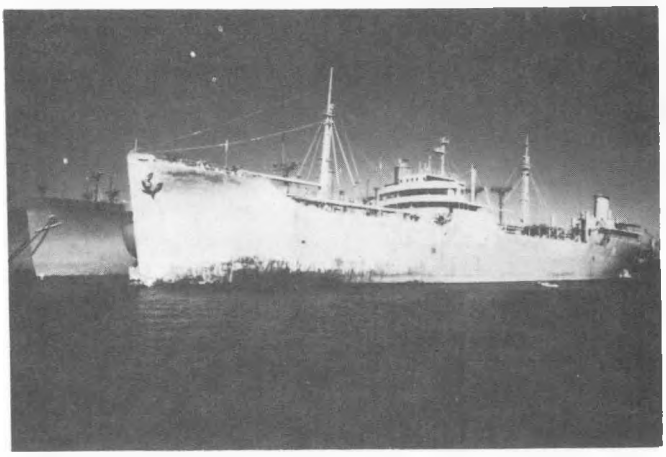
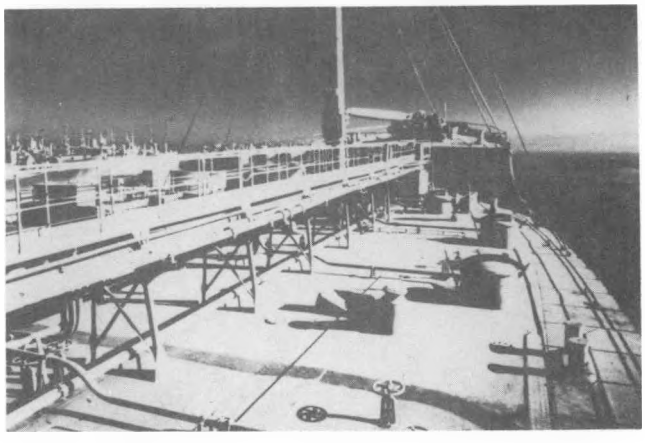


Fig.1 Chepachet in Suison Bay moth ball fleet



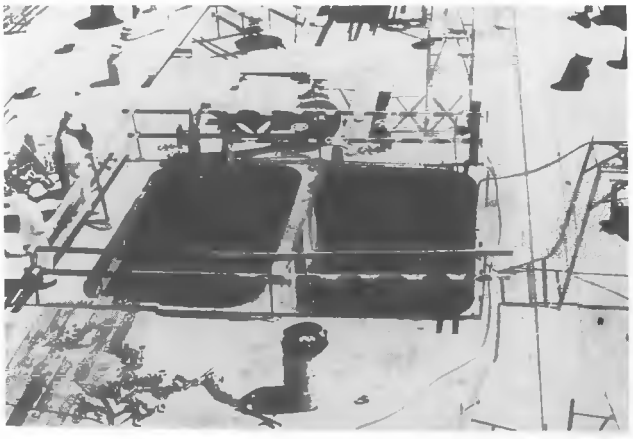
Fig. 2 Chepachet in tow, moving out of San Francisco Bay

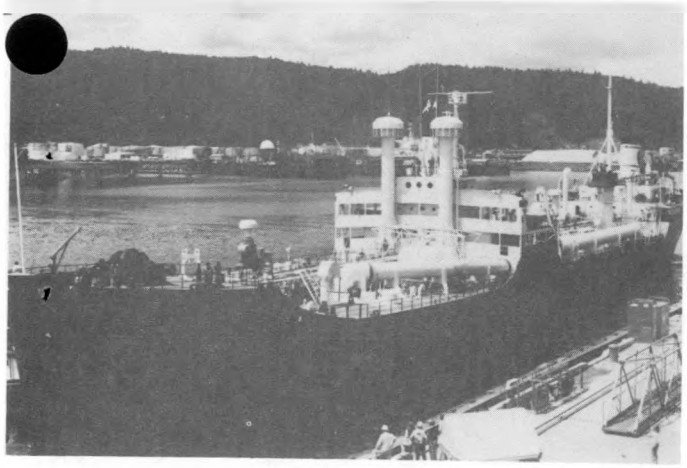


Figs. 3,4,5,6
Some scenes of the conversion of Chepachet to OTEC-1 at the Shipyard in Oregon

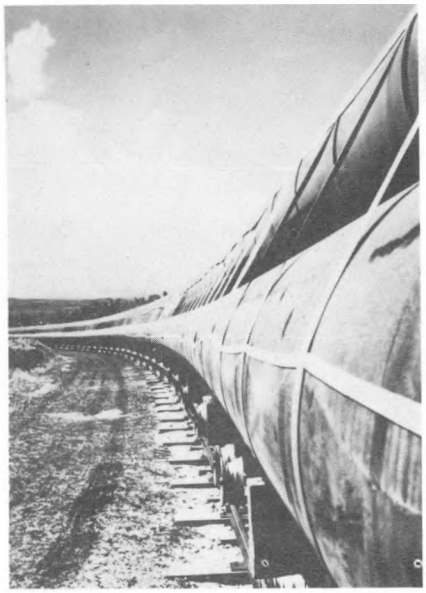


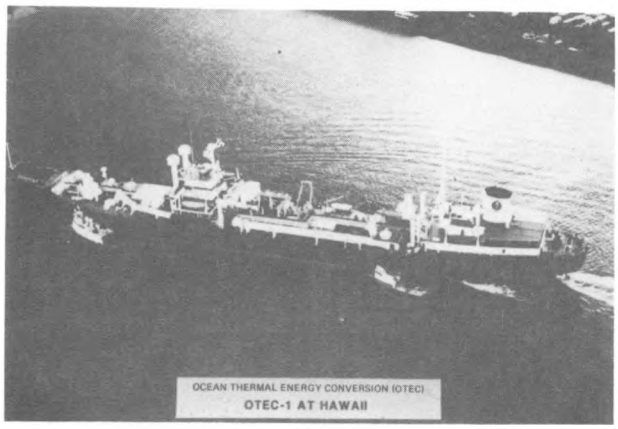




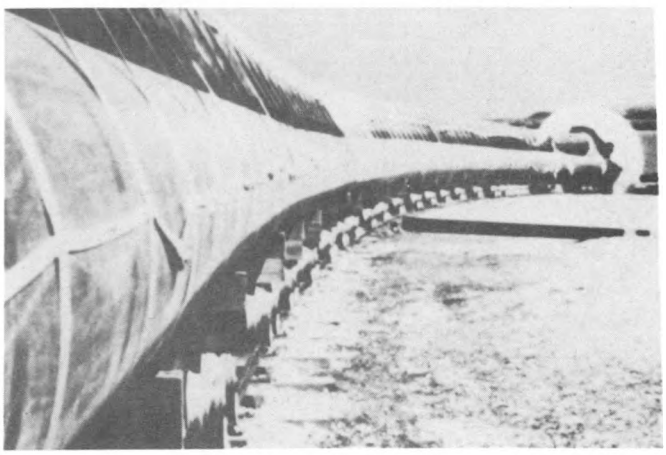


OTEC-1 "SS Ocean Energy Converter," construction completed moving away from dock in Portland, Oregon shipyard





OTEC-1 arriving in Honolulu, Hawaii





Assembly of the CWP



Sliding the CWP into the water at Kawaihae Harbor



Start of tow out of CWP in Kawaihae Harbor

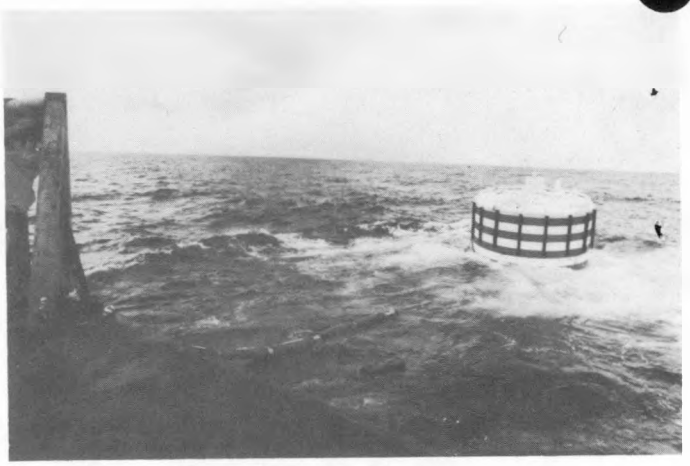
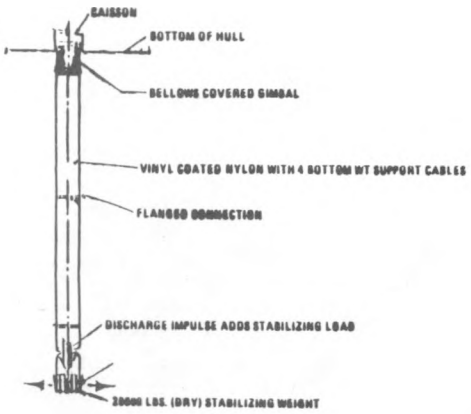


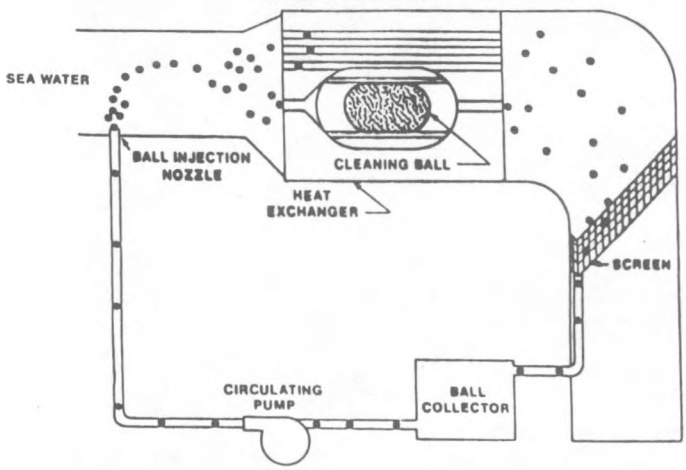
Photo of OTEC-1 surface moor



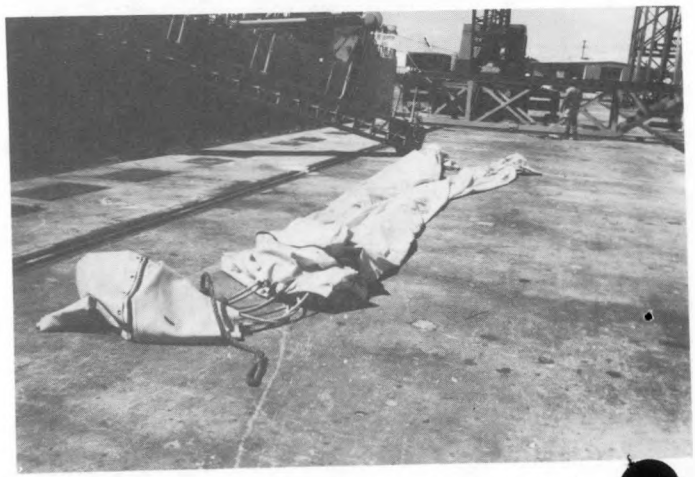
OTEC-1 on site

OTEC-1 MIXED WATER DISCHARGE HOSE ASSEMBLY





Amertap cleaning ball system sketch



Section of deep water discharge hose

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OTEC-1 HEAT EXCHANGER TEST RESULTS

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ABSTRACT

Heat exchanger test results for the first deployment of OTEC-1 are reported. These tests were aimed at evaluating the performance of a state-of-the-art 1MW$_e$, titanium shell-and-tube evaporator and condenser in an ocean environment. The evaporator was unique in that it consisted of both a plain and an enhanced (Union Carbide High Flux) tube bundle, whereas the condenser had plain tubes only. All tests with the evaporator were conducted in the sprayed-bundle mode.

Experimental results for the condenser and plain-tube portion of the evaporator were found to be in excellent agreement with performance predictions--there were no adverse surprises. This result is important because it demonstrates that the thermal performance of large plain-tube heat exchangers can be predicted with a high level of confidence. On the other hand, performance of the enhanced-tube portion of the evaporator was much lower than predicted. Evidence strongly suggested that this poor performance was attributable mainly to fouling of the High Flux surface by corrosion products consisting predominantly of hydrated aluminum oxides.

1. INTRODUCTION

OTEC-1 is a sea-based, Ocean Thermal Energy Conversion (OTEC) test facility constructed by the U. S. Department of Energy for the purposes of evaluating heat exchanger performance, determining the effectiveness of biofouling countermeasures, assessing environmental impacts, and gathering ocean engineering data. A detailed test plan--developed by Argonne National Laboratory (ANL), Lawrence Berkeley Laboratory (LBL), Energy Technology Engineering Center (ETEC), and the National Oceanographic and Atmospheric Administration (NOAA)--defined the goals and priorities of the OTEC-1 first deployment test program [1]. This paper focusses on the heat exchanger performance tests which were conducted as part of that program.

The major objective of the OTEC-1 heat exchanger test program was to evaluate the performance of a state-of-the-art 1MW$_e$, titanium shell-and-tube evaporator and condenser in an ocean environment. The evaporator was unique in that it consisted of both a plain and an enhanced (Union Carbide High Flux) tube bundle, whereas the condenser had plain tubes only. All tests with the evaporator were conducted in the sprayed-bundle mode. Specifically, the OTEC-1 heat exchanger test program included

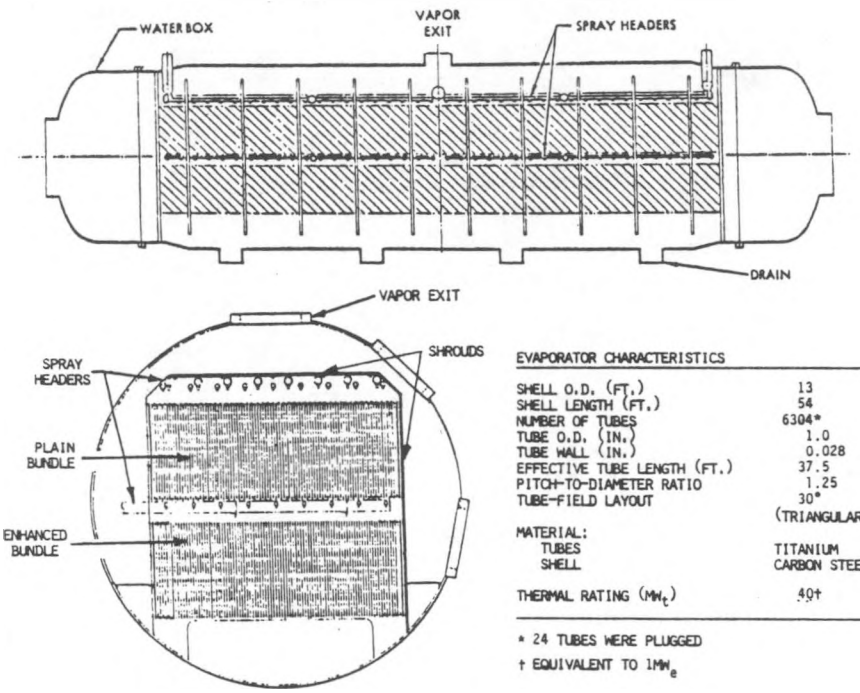
- Baseline performance tests to verify design predictions--evaporator and condenser.
- Variable ammonia feedrate tests to determine the optimum reflux ratio--evaporator.
- Activation and deactivation tests to study the nucleation characterisitics of the High Flux surface enhancement--evaporator.
- Vapor velocity tests to examine liquid entrainment and carryover--evaporator.
- Off-normal performance tests to evaluate behavior at different heat duties and water flowrates--condenser.
- Zonal and local measurements to assess performance variations throughout the bundle--evaporator and condenser.
- Waterside pressure drop measurements to verify design predictions--evaporator and condenser.

Originally, it was planned to conduct a separate series of tests with the evaporator in the flooded-bundle mode, so that thermal performance in both modes (flooded and sprayed) could be compared. However, due to time and budget limitations, tests in the flooded mode had to be deleted.

The purpose of this paper is to present and discuss the OTEC-1 heat exchanger test results. For the sake of brevity, all background and descriptive material is kept to a minimum. Supplemental information on the OTEC-1 heat exchanger test program and experimental hardware can be found in Refs [1, 2].

2. 1MW$_e$ HEAT EXCHANGER TEST ARTICLES

Both the evaporator and condenser are shell-and-tube heat exchangers with seawater on the tube side and ammonia on the shell side.



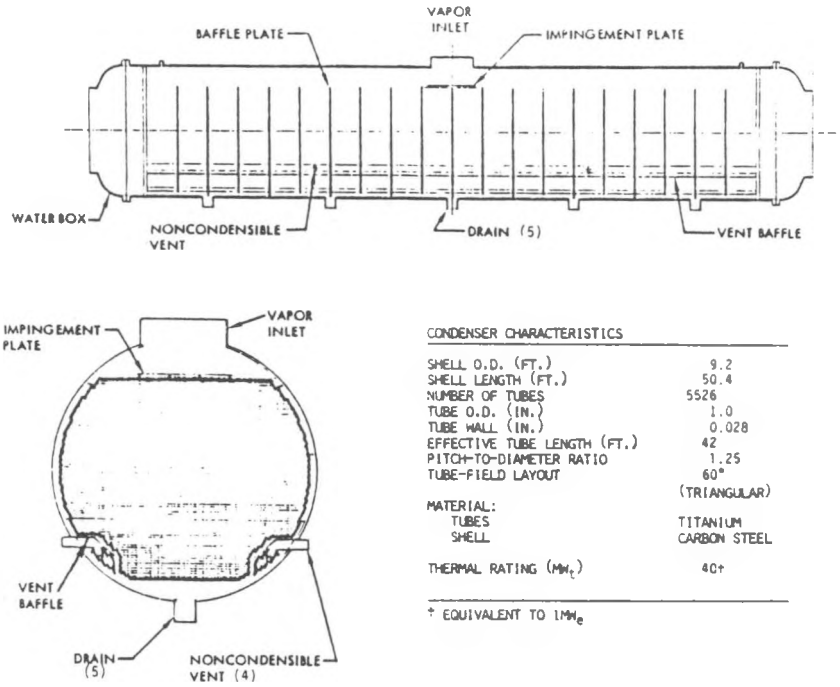
EVAPORATOR CHARACTERISTICS

SHELL O.D. (FT.)	13
SHELL LENGTH (FT.)	54
NUMBER OF TUBES	6304*
TUBE O.D. (IN.)	1.0
TUBE WALL (IN.)	0.028
EFFECTIVE TUBE LENGTH (FT.)	37.5
PITCH-TO-DIAMETER RATIO	1.25
TUBE-FIELD LAYOUT	30° (TRIANGULAR)
MATERIAL:	
TUBES	TITANIUM
SHELL	CARBON STEEL
THERMAL RATING (MW_t)	40†

* 24 TUBES WERE PLUGGED

† EQUIVALENT TO $1MW_e$

Fig. 1 Evaporator Design



CONDENSER CHARACTERISTICS

SHELL O.D. (FT.)	9.2
SHELL LENGTH (FT.)	50.4
NUMBER OF TUBES	5526
TUBE O.D. (IN.)	1.0
TUBE WALL (IN.)	0.028
EFFECTIVE TUBE LENGTH (FT.)	42
PITCH-TO-DIAMETER RATIO	1.25
TUBE-FIELD LAYOUT	60° (TRIANGULAR)
MATERIAL:	
TUBES	TITANIUM
SHELL	CARBON STEEL
THERMAL RATING (MW_t)	40†

† EQUIVALENT TO $1MW_e$

Fig. 2 Condenser Design

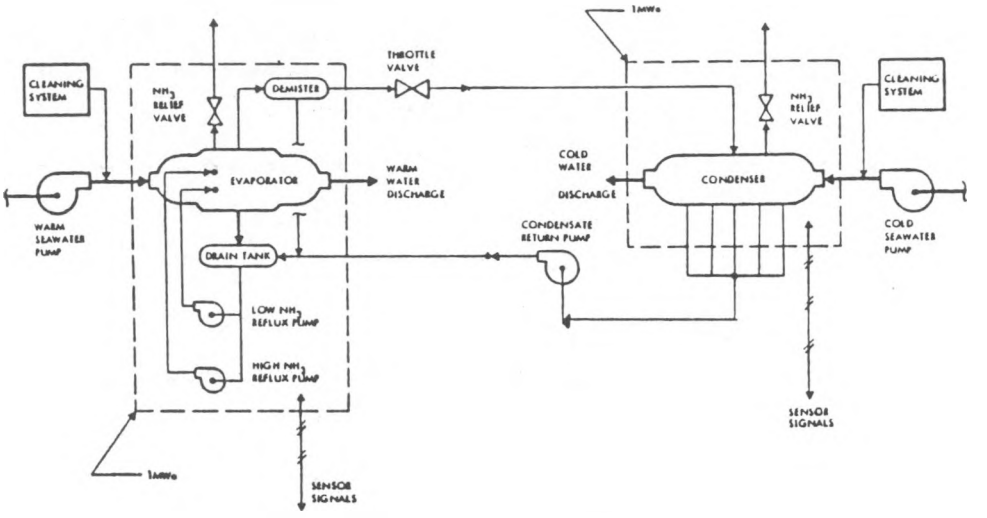


Fig. 3 OTEC-1 Power Loop Interfaces

Geometrical features and design characteristics are shown in Figs. 1 and 2; ammonia-loop interfaces are given in Fig. 3.

The evaporator, Fig. 1, is actually two units in one: a plain-tube upper bundle and an enhanced-tube (High Flux) lower bundle. Performance characteristics of each bundle can be measured separately. The evaporator is designed to operate in either a sprayed or flooded mode. In the flooded mode, the shell of the evaporator is filled with liquid ammonia, such that all or part of the tube bundle is submerged in a pool of ammonia. Nucleate boiling is the primary mechanism of heat transfer on the outside of the tubes. Unfortunately, tests in the flooded mode had to be deleted because of time and budget limitations.

In the sprayed mode of operation, ammonia liquid is directed onto the tubes from nozzles situated at the top plane and mid plane of the evaporator. The top-plane feed system consists of two separate sets of nozzles (a low-pressure, high-flow set and a high-pressure, low-flow set) and the mid plane consists of a single set (high-pressure, low-flow). Thin-film evaporation is the primary mechanism of heat transfer on the outside of the plain tubes and nucleate boiling is the primary mechanism on the enhanced tubes. A side shroud plate, shown in Fig. 1, was installed to constrain the vapor to flow in one direction, simulating the crossflow characteristics of a $4MW_e$ evaporator. All tests were performed with this so-called $4MW_e$ configuration.

The condenser, Fig. 2, has plain tubes only. Ammonia vapor (slightly superheated) enters at the top and condenses in a filmwise manner on the tube surfaces. The condensate falls to the bottom of the shell and is collected in five drain lines, each of which has a turbine flowmeter for measuring the condensate flowrate. Noncondensible gases are removed via four vents located near the bottom of the bundle.

In both heat exchangers, ammonia temperatures and pressures are measured on the shell side, and seawater temperatures and pressures are measured in the inlet and outlet waterboxes. The outlet waterbox of each heat exchanger is instrumented with a rake of Resistance Temperature Detectors (RTDs) for evaluating zonal performance over the bundle cross section. Also each heat exchanger is equipped with special instrumented loops for measuring the performance of individual tubes within the bundle.

Biofouling in the heat exchangers is controlled by intermittent chlorination (0.4 ppm for 1 hour each day) in combination with continuous Amertap (1 ball per 15 minutes per tube). Two ANL Biofouling and Corrosion Modules are used to track the buildup of fouling in the evaporator and condenser--one module for each unit. During the course of the first deployment, there was no evidence of heat exchanger tube-side fouling, as inferred from measurements with the modules. Further evidence of the lack of tube-side fouling was derived from the fact that the overall heat exchanger performance did not degrade with time.

3. INSTRUMENTATION

Prior to the start of testing, most of the critical power loop instrumentation was fully checked out and calibrated in accordance with the OTEC-1 test plan requirements [1]. A special copper-block technique was utilized for end-to-end calibration of the RTDs to within ± 0.125° F. During the test program, the bulk of the OTEC-1 instrumentation functioned satisfactorily, enabling the acquisition of most of the originally-planned test data. There were, however, a number of instrumentation problems which resulted in a loss of data in certain areas. Worthy of mention are failures of (1) the turbine flowmeters and RTDs in the condenser drain lines--resulting

in a loss of data on the axial condensate flow profile, (2) the sonic flowmeter in the demister return line--loss of data on liquid carryover, (3) the instrumented loops in both the evaporator and condenser--loss of data on individual tube performance, and (4) the pressure transducers in the condenser inlet and outlet waterboxes--loss of pressure-drop data for comparison with design predictions.

The most significant instrumentation problem was encountered in the case of the seawater sonic flowmeters (transmission-type), where it was discovered that the transmission signals were being attenuated by bubbles in both the warm and cold seawater systems. Certain corrective actions were taken in an attempt to eliminate the bubbles. As a result of those actions, the population of bubbles was reduced dramatically, but not enough to mitigate the attenuation problem. Later, two other sonic flowmeters were tried: a transmission-type having a higher signal strength and a Doppler-type. Results with these meters, although encouraging, were judged to be unsatisfactory. After exploring a number of alternative means for measuring flow, it was decided to simply calculate the warm and cold seawater flowrates from heat duty measurements on the ammonia side--i.e., equating the ammonia-side heat duty (measured) to the waterside heat duty (unknown) and solving for the seawater flowrate. This technique is expected to yield a flowrate accuracy of ± 5%, but can be employed only when the ammonia system is operational and heat is being transferred. The main disadvantage of not having a direct seawater flowrate measurement is that no independent waterside/ammonia-side heat balance checks can be made.

4. DATA ACQUISITION AND REDUCTION

The OTEC-1 test facility has a mini-computer based data acquisition system (DAS) that can sample and record all channels of data, apply calibration and correction factors to these data, and provide real-time computation and display (with hard-copy) of selected calculated quantities and sensor readings in engineering units. Data can be recorded on disk and tape at independently selectable rates. During first deployment testing, data were generally recorded on tape at a rate of 1 sample/minute. Original data tapes were analyzed on board in real time and duplicate tapes were sent to ANL for more detailed evaluation of the test results.

The data reduction program is based largely on the equations developed in the OTEC-1 test plan [1]. Only a few minor changes had to be made to the original program. For example, heat duty is now calculated solely on the basis of ammonia-side measurements. Also, it is noteworthy to mention that in the prediction of U_o for the lower (enhanced) portion of the evaporator, account is now taken of the fact that only 90% of the active tube length consists of the High Flux enhancement.

5. OPERATING PROCEDURE

The normal start-up procedure for the ammonia system was as follows (seawater system already running): Purge power loop with nitrogen until residual air-to-ammonia ratio is diluted well below explosive limit. Transfer ammonia into evaporator sump. Close throttle valve (V-111) located in vapor line between evaporator and condenser. Start ammonia reflux pump to initiate ammonia spray. As vapor is generated and evaporator pressure begins to rise, open V-111 to allow vapor to flow to condenser. When level of condensate rises in central condenser drain line, start condensate return pump. Monitor ammonia levels in the condensate drain line and evaporator sump. Adjust valve V-111 as required to achieve desired heat duty and allow system to stabilize.

The evaporator pressure, and hence heat duty, is controlled by the setting of valve V-111. The ammonia loop control system is capable of maintaining either constant heat duty or constant pressure in the evaporator. Generally either mode of control is acceptable. However, for the reflux ratio tests it was convenient to hold the evaporator pressure constant and allow the heat duty to vary.

Following initial system start-up, steady-state conditions were generally attained in about 2 hours if the sea state was not unusually high. During rough weather, it was difficult to maintain steady operation of the ammonia system, mainly because of "sloshing" of ammonia in the sumps. Also, cavitation of the ammonia reflux pump was experienced when the ammonia level in the evaporator sump (drain tank) was low.

When a change was made from an established test condition to a new (slightly different) test condition, steady operation at the new condition was usually reached in less than 30 minutes. All tests were conducted for a minimum of 30 minutes. Typically, the duration of a given test ranged from 30 minutes to 2 hours. In a special test to study long-term activation of the enhanced surface, the duration was extended to 35 hours.

6. TEST RESULTS

A total of 95 tests were conducted during 370 hours of ammonia system operation over a three month period extending from January through March 1981. Operating ranges are shown in Table 1 and a tabulation of individual runs is given in Appendix A. Tests No. 1 through 29 were regarded as shakedown runs for the purpose of debugging the system and gaining operational experience. During initial shakedown tests, the water content of the ammonia was unacceptably high ($\sim$ 0.9% by weight); but by distillation, the water content was brought down to a tolerable level (< 0.4% by weight) before proceeding into Tests No. 30 through 95.

6.1 Evaporator Tests

6.1.1 Adiabatic Conditions

To establish confidence in the seawater temperature measurements, the inlet and outlet average waterbox temperatures were compared under adiabatic conditions (i.e., with the ammonia system

shut down), see Fig. 4. The inlet and outlet average temperatures are seen to be in excellent agreement. Also, the individual exit RTD readings agree within the calibration tolerance of ± 0.125°F --except for two RTDs near the center, which read 77.09°F and 77.59°F.

6.1.2 Baseline Thermal Performance

Baseline test results are presented in Table 2. The measured value of U_o for the plain-tube portion of the evaporator is seen to be in perfect agreement with the prediction. Although this perfect agreement is somewhat fortuitous (because the absolute accuracy of the measured U_o is only ± 10%), it shows that the thermal performance of the plain-tube, sprayed-bundle evaporator can be predicted with a high level of confidence--there were no major surprises. The predicted U_o value for the plain-tube bundle was based on a waterside coefficient of 1330 Btu/hr.ft^2.°F from the Petukhov-Popov correlation [3], and an ammonia-side coefficient of 1000 Btu/hr.ft^2.°F from Conti's single-tube data [4]. Zero fouling was assumed.

Table 2 shows that the measured performance of the enhanced-tube portion of the evaporator is considerably lower than predicted. This poor performance is thought to be caused mainly by fouling of the High Flux surface by corrosion products, as will be discussed further in Section 6.1.4. The predicted U_o value for the enhanced bundle was based on the same waterside coefficient used for the plain-tube bundle, and an ammonia-side coefficient of 3800 Btu/hr.ft^2.°F from ANL experiments with a small-scale Union Carbide sprayed bundle [5]. Originally ANL reported an ammonia-side coefficient of 4600 Btu/hr.ft^2.°F, but later that value was revised to 3800 Btu/hr.ft^2.°F based on an improved Wilson plot procedure. In the predictions, account is taken of the fact that 10% of the active tube length did not have High Flux.

6.1.3 Reflux Ratio

The power consumed by the ammonia reflux pump represents a parasitic loss in the system; therefore, it is important to optimize (minimize)

Table 1. Heat Exchanger Operating Ranges

	Evaporator	Condenser
Heat Duty (MW_t)	14 - 46	14 - 46
Seawater Flow (gpm)	57,000 - 91,000	32,000 - 67,000
Seawater Temp. (°F)	76 - 78	41 - 43
NH_3 Feedrate* (gpm)	400 - 3700	N/A
NH_3 Shell-side		
Pressure (psia)	128.8 - 133.4	82.7 - 99.7
Sat. temp. (°F)	70 - 72	46 - 56

* Total combined feedrate from all nozzles

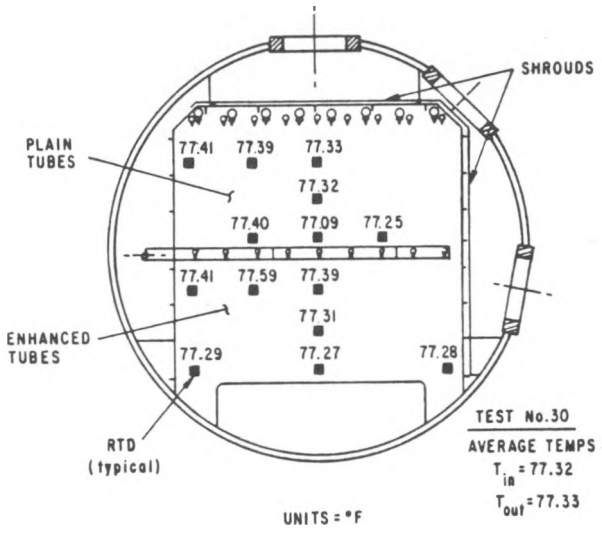


Fig. 4 Seawater Temperatures in Evaporator Outlet Waterbox: Adiabatic Conditions

the feedrate. Figure 5 gives the results for the plain bundle. As the feedrate is reduced, U_o remains constant until a critical (minimum) feedrate of 1000 gpm is reached. Below this critical feedrate, U_o drops sharply as film breakdown and dryout occur on the lowermost tubes in the bundle. At this condition the critical local flowrate on the lowermost tubes is about 45 lbm/hr.ft. This critical flowrate is an important design parameter because it defines the operating limit of any plain-tube spray evaporator for OTEC application: it represents the minimum flow which must be supplied to the lowermost tubes to ensure complete wetting and, hence, optimum performance of the evaporator. As expected, this minimum flowrate of 45 lbm/hr.ft for plain tubes is higher than the value of 20 lbm/hr.ft obtained in tests at ANL with High Flux enhanced tubes because the plain tubes are not as easily wetted and the film breaks down sooner.

Figure 5 shows that the evaporator performance is not strongly affected by the particular spray system used, whether it be top low-pressure nozzles only, top high-pressure only, or a combination of the two.

Results for the enhanced bundle are presented in Fig. 6. The term "effective" ammonia feed refers to the net amount of ammonia liquid reaching the lower bundle. Depending on the method of system start-up, the data fell on either the upper or lower "curve"--further discussion of start-up is given in the next section. The lower curve (deactivated) is similar to the performance of the smooth tube in Fig. 5. Actually the enhanced-tube performance is somewhat poorer than the plain-tube performance (430 versus 490 Btu/hr.ft^2.°F) because the deactivated High Flux surface acts as a "sponge" and holds a stagnant insulating layer of ammonia liquid. An ammonia layer of about 1 mil would account for the difference.

Table 2. Baseline Test Results*

Heat Exchanger	U_o (Btu/hr.ft^2.°F)		Waterside ΔP (psi)	
	Measured††	Predicted	Measured††	Predicted
Evaporator:				
Plain bundle	490	490	2.7	2.5
Enhanced bundle	600†	735	2.7	2.5
Condenser	480	490	**	2.9

* Nominal conditions: heat duty = 40 MW_t, ammonia feedrate = 3000 gpm, warm water flowrate = 83,000 gpm, cold water flowrate = 67,000 gpm.

** Pressure transducer out of calibration.

† Partially activated, see Fig. 6.

†† Measurement accuracy: U_o (± 10%); ΔP (± 2%)

When the enhanced surface was partially activated (by changing the method of start-up), the performance improved, but remained well below the predicted level. Based on a measured value of U_o = 600 Btu/hr.ft^2.°F, the ammonia-side coefficient was calculated to be 1720 Btu/hr.ft^2.°F, compared to the predicted value of 3800 Btu/hr.ft^2.°F--i.e., only 45% of the predicted value. Reasons for the poor performance of the enhanced surface are discussed in the next section.

An interesting hysteresis effect was observed when the surface was partially activated. It was found that the upper curve in Fig. 6 could not be retraced when the feedrate was reduced below about 500 gpm. Instead the data fell on the lower curve when the feedrate was increased, indicating that the surface had become deactivated during operation at the lower feedrates.

6.1.4 Performance of the High Flux Surface

Unless special start-up and operating procedures were employed, the enhanced tubes invariably behaved as plain tubes (i.e., lower curve in Fig. 6). Three different procedures were tried in an attempt to activate the nucleation sites: (1) initially drying out the tubes by shutting off the ammonia feed and opening the throttle valve between the evaporator and condenser for a specified length of time, (2) increasing the excess superheat for nucleation by temporarily reducing the evaporator pressure while maintaining the ammonia feed, and (3) pulling a partial vacuum (15" Hg) for an extended period to evaporate volatile liquid (e.g., water) occluded in the pores. Unfortunately a sufficiently large vacuum pump was not available to pull a harder vacuum. Of these three procedures, the dryout operation proved to be the most successful, but still produced only partial improvement in the expected heat transfer performance of the enhanced surfaces--well below the predicted level, even on a local basis. See Section 6.1.5 for a discussion of local variations of U_o throughout the bundle.

Evidence strongly suggested that the poor performance of the enhanced bundle was attributable mainly to fouling of the High Flux surface. Union Carbide Corporation examined a section of High Flux tubing removed from the OTEC-1 evaporator and found that the tube was fouled with a layer of white crystalline material identified by X-ray diffraction analysis as bayerite or hydrated beta aluminum hydroxide $AL(OH)_3$, with some small amount of iron oxide [7]. These corrosion deposits were embedded in the porous surface and, hence, destroyed the nucleation sites. Union Carbide is trying to identify an effective cleaning method for rejuvenating the surface.

Union Carbide tested a section of the fouled tubing in the as-received condition and made a comparison with data obtained with an original control tube (from the 1979 production run), which was retested at the same time [7]. Water was passed through the inside of the tube and freon-11 was boiled on the outside. Because the tests were conducted with freon instead of ammonia, the relative behavior was more important than absolute coefficients. Test results indicated a substantial degradation of performance of the fouled tube relative to the original (clean) tube. The ratio of boiling coefficients (fouled/clean) was 0.38, which compares favorably with the ratio of 0.45 deduced from the OTEC-1 test data (see Section 6.1.3). These results support the hypothesis that the poor performance observed on board OTEC-1 was due mainly to fouling.

Union Carbide's Metallurgy Department suspects that the corrosion of the High Flux enhancement was produced by prolonged exposure of the tubes to a warm, humid marine atmosphere. An alternate possibility is a chemical reaction between aluminum and ammonia in the presence of small amounts of seawater. A complete analysis of the problem must take into account the entire history of conditions to which the heat exchanger was exposed throughout its lifetime--from initial fabrication through final deployment and testing.

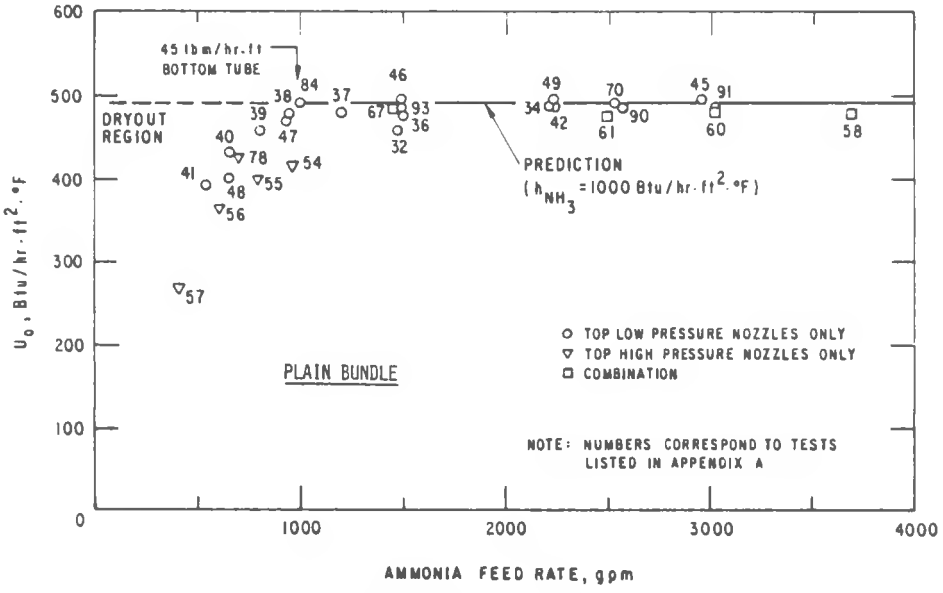


Fig. 5 Influence of Feedrate on Evaporator Performance: Plain-Tube Bundle

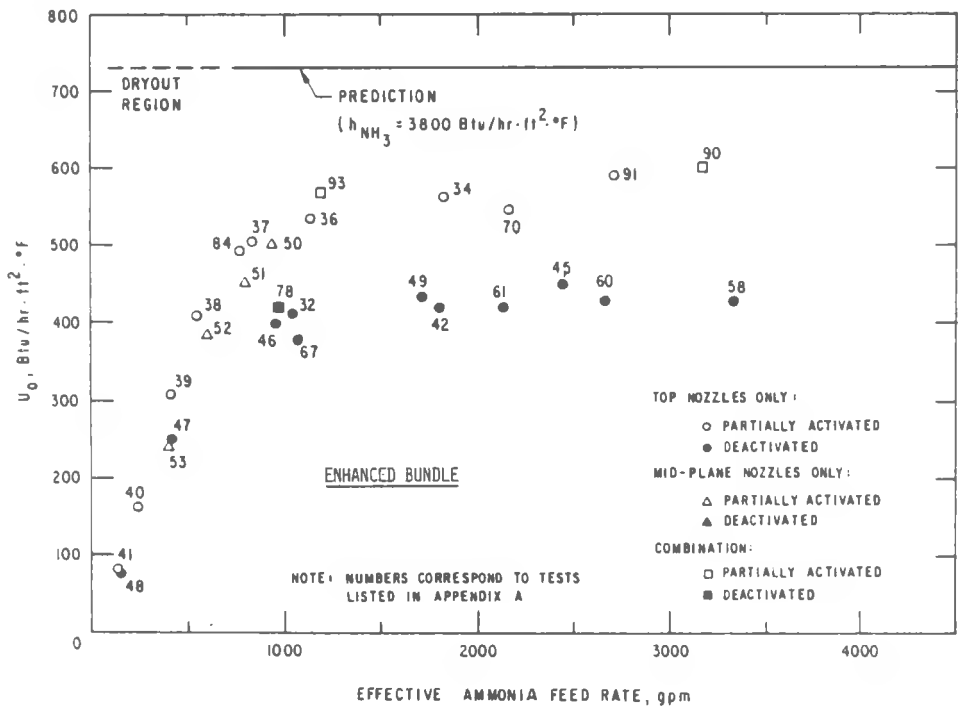


Fig. 6 Influence of Feedrate on Evaporator Performance: Enhanced-Tube Bundle

In any case, one thing is certain: fouling of the High Flux surface must have occurred prior to the start-up of ammonia system operation because the poor performance was detected at the very outset of testing--there was no further degradation with time.

In addition to fouling, there were less-important factors that could have contributed to the poor performance of the High Flux tubes. A post-test inspection revealed widespread plugging of the mid-plane spray nozzles. This should not,

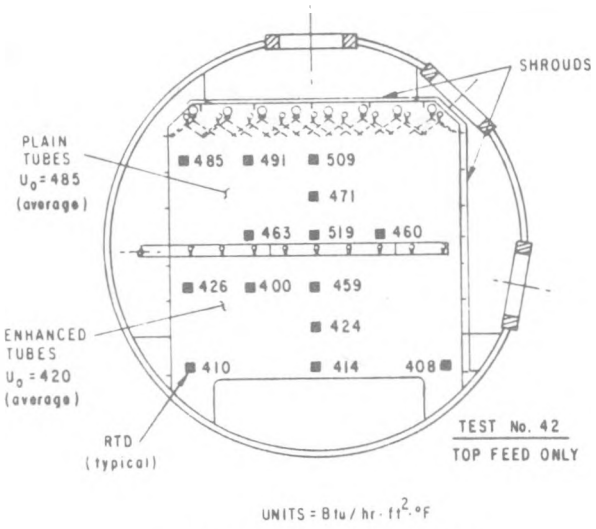


Fig. 7 Distribution of U_o in Evaporator Outlet Waterbox (Lower Bundle Deactivated)

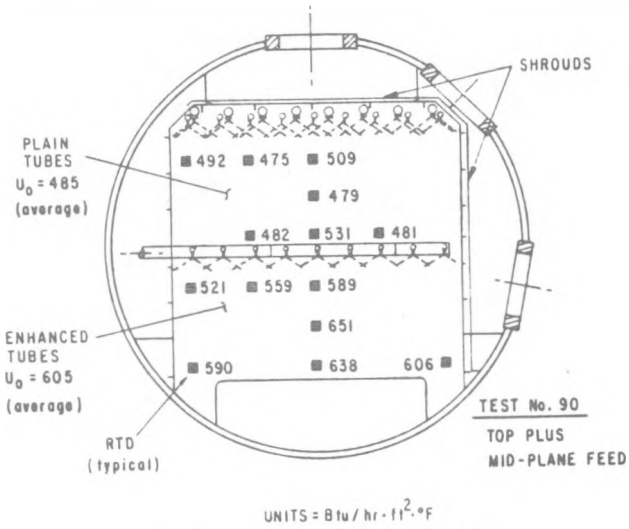


Fig. 8 Distribution of U_o in Evaporator Outlet Waterbox (Lower Bundle Partially Activated)

however, have had a major effect on heat exchanger performance for two reasons: (1) the mid-plane nozzles provided only make-up feed to the lower bundle and (2) the top-plane nozzles, which provided the primary feed to both bundles, must have been functioning properly, as evidenced by the excellent performance of the upper bundle. The post-test inspection also revealed the existence of oily patches on portions of the tube surfaces. Moreover oil was present on the tube sheets, tube support baffles, and on the inside walls of the evaporator shell. Presumably this was ammonia pump lubricating oil which leaked past the pump seal and into the ammonia system.

6.1.5 Bundle-Depth and Vapor Velocity Effects

Figure 7 shows the zonal distribution of U_o in the exit waterbox of the evaporator for a run in which the lower (enhanced) half was deactivated. Observe that the U_o values are fairly uniform within each half of the evaporator. The uniformity in the vertical direction indicates that liquid-loading effects are small, while the uniformity in the horizontal reveals that vapor velocity effects are not significant. The unimportance of vapor velocity also was observed during earlier shakedown runs in which the overall U_o was found to be unaffected when the heat duty, and hence vapor velocity, was reduced to 60% of nominal. This result was expected on the basis of ANL's analysis [6] showing that a crossflow velocity of at least 5 ft/sec is required to deflect the falling film. The maximum crossflow in the evaporator was only 3 ft/sec in the gaps between the outermost tubes. Although the vapor velocity was too low to cause gross entrainment and liquid redistribution within the bundle, there may have been some carryover of small droplets produced by fracture and splashing as the ammonia liquid spray impinged on the uppermost tubes. Unfortunately a failure of the sonic flowmeter in the phase-separator (demister) return line precluded a quantitative assessment of liquid carryover.

Figure 8 shows the zonal distribution of U_o for a case where the lower bundle is partially activated. As in Fig. 7, the distribution of U_o in the upper bundle is fairly uniform. However, the U_o values in the lower bundle range from a high value of 651 Btu/hr.ft².°F in the center to a low of 521 Btu/hr.ft².°F in the upper left hand corner. This variation is considered to be caused not by vapor velocity or bundle-depth effects, but by differences in the nucleation characteristics of the tubes resulting from varying degrees of fouling throughout the bundle.

It was originally intended to study vapor velocity effects by conducting a separate series of tests with the side shroud removed ($1MW_e$ configuration) and making a comparison with results obtained with the side shroud in place ($4MW_e$ configuration). The vapor velocity in the $1MW_e$ configuration would be half that in the $4MW_e$ configuration. However, in view of the fact that tests with the $4MW_e$ configuration clearly showed an absence of vapor velocity effects, separate tests with the $1MW_e$ --having even lower vapor velocity--were deemed unnecessary.

6.1.6 Local Shell-side Temperatures

The evaporator shell-side temperature distribution was found to be uniform both axially and circumferentially, see Fig. 9. Note that the measured shell-side temperatures are in excellent agreement with the saturation temperature calculated at the shell-side pressure. Among other things, the existence of a saturated vapor state indicates that the ammonia is pure. In the early shakedown tests with water in the ammonia, the state of the vapor

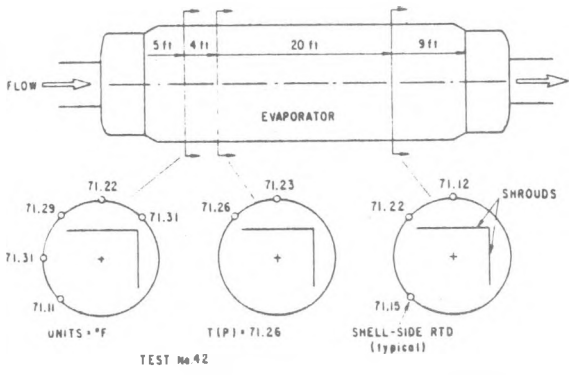


Fig. 9 Local Evaporator Shell-Side Temperatures

was not saturated, but superheated.

6.1.7 Waterside Pressure Drop

The measured pressure drop between the inlet and outlet waterbox agreed favorably with predictions, see Table 2.

6.1.8 Effect of Vapor Bypass to Evaporator Sump

During operation, it was found that the temperature of the ammonia feed was nearly equal to the saturation temperature in the evaporator, suggesting that some ammonia vapor from the evaporator must have been flowing downward through the drain line and condensing directly into the evaporator sump (drain tank). An energy balance on the sump revealed that this bypass flow amounted to about 5% of the total vapor generated within the evaporator. The original data reduction program did not account for the bypass flow and calculated the evaporator heat duty solely on the basis of the vapor exiting at the top of the evaporator (as measured by a Venturi flowmeter in the vapor line). Thus the evaporator heat duty calculated in this manner was 5% low. Also U_o and seawater flowrate were 5% low since they are both calculated from the heat duty. Results given in this paper are based on the original data reduction program and hence do not reflect the 5% correction. Nevertheless, the primary conclusions drawn from the data remain the same.

Vapor bypass is undesirable and probably can be prevented by reducing the diameter of the evaporator drain lines.

6.1.9 Effect of Ship Motion

There was no apparent influence of ship motion on evaporator performance: data taken during high sea states were similar to data taken during calm weather. However, maintaining steady operation of the ammonia system was difficult during high sea states. Also cavitation of the reflux pump was experienced when the ammonia level was low.

6.2 Condenser Tests

6.2.1 Adiabatic Conditions

As in the case of the evaporator, the condenser inlet and outlet average waterbox temperatures were in excellent agreement, and the individual outlet waterbox RTDs agreed to within the calibration tolerance of ± 0.125°F, see Fig. 10.

6.2.2 Baseline Thermal Performance

Baseline results for the condenser are given in Table 2. Typically, ammonia vapor entered the condenser superheated by about 6°F and ammonia condensate left the condenser subcooled by about 1°F. Here, as in the case of the plain-tube evaporator, the thermal performance is predictable to a high level of accuracy--again, there were no surprises. The predicted U_o value was calculated on the basis of a waterside coefficient of 980 Btu/hr.ft^2.°F from the Petukhov-Popov correlation, and an ammonia-side coefficient of 1428 Btu/hr.ft^2.°F in accordance with the original thermal design calculations of C. F. Braun and Company.

6.2.3 Performance at Off-Normal Conditions

Figure 11 shows condenser thermal performance over a range of heat duties from 18 to 47 MW_t and flowrates from 32,000 to 67,000 gpm. Over the entire parametric range, predictions are seen to be in excellent agreement with the measured U_o values. The data exhibit a negligibly small dependence on heat flux, suggesting that the condenser was free of noncondensibles. In tests conducted prior to purging, the U_o value of the condenser was observed to drop markedly at lower heat duties.

6.2.4 Bundle-Depth Effects

The distribution of U_o in the exit waterbox is presented in Fig. 12. As expected, the

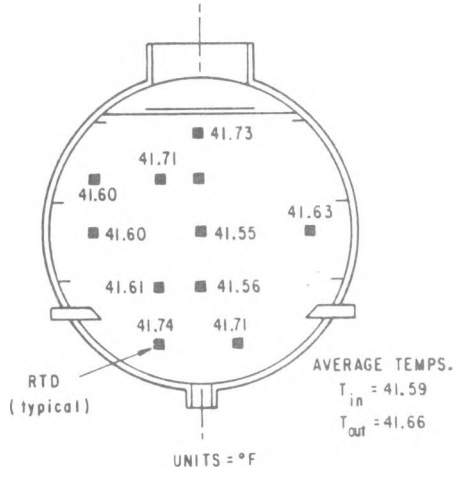


Fig. 10 Seawater Temperature in Condenser Outlet Waterbox: Adiabatic Conditions

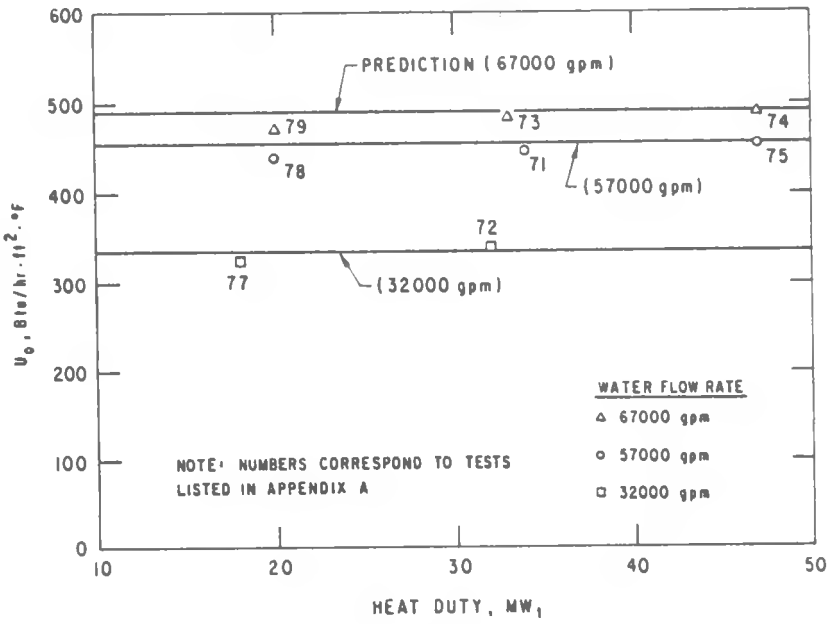


Fig. 11 Condenser Performance Over a Range of Heat Duties and Water Flowrates

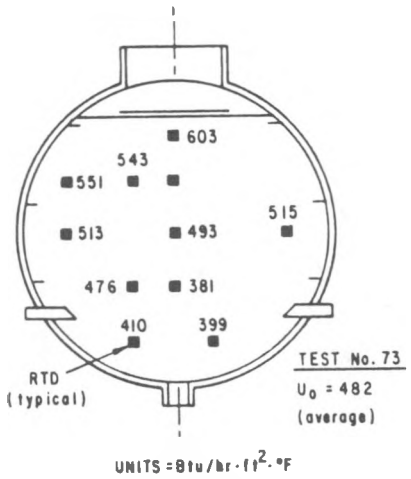


Fig. 12 Distribution of U_o in Condenser Outlet Waterbox (After Purge)

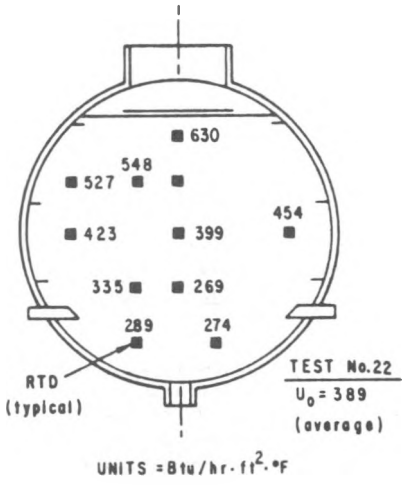


Fig. 13 Distribution of U_o in Condenser Outlet Waterbox (Before Purge)

zonal U_o values are fairly uniform in a given horizontal plane, but decrease with bundle depth as a result of condensate inundation.

6.2.5 Effect of Noncondensibles

Figure 13 shows the distribution of U_o in the exit waterbox before purging. By comparing Figs. 12 and 13, it can be seen that noncondensibles tend to build up in the lower half of the condenser. Generally it was found that several three-minute purges were adequate to remove noncondensibles.

6.2.6 Waterside Pressure Drop

Due to a faulty (out-of-calibration) waterbox pressure transducer, no valid measurements were obtained for comparison with predictions, see Table 2.

6.2.7 Effect of Ship Motion

As was the case for the evaporator, ship motion had no discernible effect on performance, but caused some unsteadiness in the operation of the ammonia system.

7. CONCLUDING REMARKS

During the course of the first deployment of OTEC-1, most of the instrumentation and power loop components functioned satisfactorily, enabling the acquisition of the bulk of the originally-planned test data. There were, however, a number of instrumentation problems which resulted in a loss of data in certain areas. Nevertheless, most of the essential OTEC-1 test objectives were satisfied.

Experimental results for the condenser and plain tube portion of the evaporator were found to be in excellent agreement with performance predictions--there were no adverse surprises. This result is important because it demonstrates that the thermal performance of large plain-tube heat exchangers can be predicted with a high level of confidence. On the other hand, the performance of the enhanced-tube portion of the evaporator was much lower than predicted. Evidence strongly suggested that this poor performance was attributable mainly to fouling of the High Flux surface by corrosion products consisting predominantly of hydrated aluminum oxides.

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APPENDIX A: TABULATION OF INDIVIDUAL RUNS

Test No.	Description	Heat Duty (MW_t)	WW Flowrate (gpm)	EVAPORATOR					CONDENSER	
				NH_3 Feed Rate (gpm)			U_o (Btu/hr.ft^2.°F)		CW Flowrate (gpm)	U_o (Btu/hr.ft^2.°F)
				Top Nozzles Low Press.	Top Nozzles High Press.	Mid Plane	Plain (Upper)	Enhanced (Lower)		
1-29	Shakedown Tests									
30	Distillation & Evacuation	0	78000	0	0	0	N/A	N/A	55000	N/A
31	Surface Conditioning	0	78000	0 for dry 1500 for wet	0	0	N/A	N/A	55000	N/A
32	Baseline	39	78000	1500	0	0	460	410	55000	450
33	Surface Conditioning	0	82000	0	0	0	N/A	N/A	55000	N/A
34	Baseline	37	82000	2200	0	0	485	565	55000	455
35	Deluge	35	82000	2200	0	0	480	560	55000	455
36	Reflux Ratio Tests	35	82000	1500	0	0	475	535	55000	450
37		35	82000	1200	0	0	480	505	55000	455
38		35	82000	950	0	0	475	410	55000	455
39		32	82000	800	0	0	460	310	55000	455
40		28	82000	660	0	0	430	165	55000	450
41		24	82000	550	0	0	390	80	55000	450
42	Baseline	35	82000	2200	0	0	485	420	55000	450
43	Reflux Test	31	82000	950	0	0	Insufficient time to reach steady state		55000	445
44	Surface Conditioning	0	82000	1500 for wet 0 for dry	0	0	N/A	N/A	55000	N/A
45	Reflux Ratio Tests	46	85000	3000	0	0	490	450	55000	445
46		45	85000	1500	0	0	490	395	55000	450
47		39	85000	950	0	0	470	250	55000	455
48		29	85000	660	0	0	400	75	55000	455
49		45	85000	2200	0	0	490	435	55000	450
50	Reflux Ratio Tests: Mid-Plane Feed Only	18	83000	0	0	930	N/A	500	55000	420
51		19	83000	0	0	795	N/A	450	55000	420
52		17	83000	0	0	600	N/A	385	55000	415
53		14	83000	0	0	400	N/A	240	55000	400
54	Reflux Ratio Tests: Top High Pressure Nozzles Only	30	83000	0	960	0	415	285	55000	435
55		28	83000	0	795	0	400	175	55000	435
56		23	83000	0	600	0	365	60	55000	435
57		16	83000	0	400	0	270	Dryout	55000	420

APPENDIX A: TABULATION OF INDIVIDUAL RUNS (Cont.)

Test No.	Description	Heat Duty (MW_t)	WW Flowrate (gpm)	EVAPORATOR					CONDENSER	
				NH_3 Feed Rate (gpm)			U_o (Btu/hr.ft^2.°F)		CW Flowrate (gpm)	U_o (Btu/hr.ft^2.°F)
				Top Nozzles Low Press.	Top Nozzles High Press.	Mid Plane	Plain (Upper)	Enhanced (Lower)		
58	Reflux Ratio Tests: Top Nozzle Combinations	32	83000	2730	965	0	475	430	55000	440
59		32	83000	2370	970	0	480	425	55000	445
60		32	83000	2045	975	0	475	430	55000	445
61		33	83000	1520	975	0	470	420	55000	440
62		34	83000	2525	0	0	480	430	55000	440
63		28	83000	1285	885	0	480	425	55000	440
64		34	83000	1355	900	0	480	425	55000	440
65		41	83000	1410	930	0	475	415	55000	450
66		41	83000	1000	520	0	485	365	55000	445
67		33	83000	950	500	0	485	380	55000	450
68	Repeatability	25	83000	910	0	475	485	420	55000	435
69	Surface Conditioning	0	83000	0	0	0	N/A	N/A	55000	N/A
70	Repeatability	34	83000	2515	0	0	490	550	55000	445
71	Condenser Tests	32	83000	2490	0	0	490	550	55000	445
72		31	83000	2505	0	0	485	550	32000	340
73		31	83000	2510	0	0	485	545	66000	485
74		45	83000	2495	0	0	485	540	68000	490
75		45	83000	2490	0	0	480	540	58000	455
76		44	83000	2495	0	0	470	530	Insufficient time to reach steady state	
77		17	83000	0	610	380	425	410	32000	325
78		19	83000	0	705	475	425	420	57000	440
79		19	83000	0	795	580	425	420	67000	470
80	Repeatability	28	91000	0	600	365	410	375	57000	455
81		24	76000	0	595	450	395	430	44000	400
82	Activation Tests	41	83000	1005	0	0	460	235	44000	395
83		21	83000	1000	0	0	500	425	44000	385
84		22	83000	1000	0	0	495	495	44000	395
85		41	83000	1000	0	0	480	295	44000	405

APPENDIX A: TABULATION OF INDIVIDUAL RUNS (Cont.)

Test No.	Description	Heat Duty (MW_t)	WW Flowrate (gpm)	EVAPORATOR					CONDENSER	
				NH_3 Feed Rate (gpm)			U_o(Btu/hr.ft^2.°F)		CW Flowrate (gpm)	(Btu/hr.ft^2.°F)
				Top Nozzles Low Press.	Top Nozzles High Press.	Mid Plane	Plain (Upper)	Enhanced (Lower)		
86	Miscellaneous Repeatability and Reflux Ratio Tests	38	83000	800	0	0	590	Dryout	44000	410
87		38	83000	0	805	0	495	Dryout	44000	405
88		22	91000	0	490	0	232	Dryout	29000	320
89		17	57000	1190	0	0	430	370	67000	470
90		32	83000	2560	0	920	485	605	44000	405
91		32	83000	3025	0	0	485	595	44000	410
92		32	83000	1490	0	0	485	565	44000	410
93		32	83000	950	0	650	480	555	44000	410
94		29	83000	0	800	810	415	530	44000	410
95		13	79000	0	810	810	445	490	44000	380

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ANALYSIS OF THE UP-ENDING PROBLEM OF OTEC-1 COLD WATER PIPE

E.M. Gershunov, Y.H. Ozudogru*, and J.M. Betts

Global Marine Development, Inc.

ABSTRACT

During 1979-1980 Global Marine Development, Inc. was the prime contractor to the U.S. Department of Energy for design and construction of the Ocean Energy Converter. The project was part of a test program for the investigation of the potential utilization of ocean thermal energy. The Cold Water Pipe(CWP) used on this system was successfully deployed in November 1980. The on-site up-ending of the CWP was the most critical problem in the deployment operation.

This paper describes the analytical approach and the results developed for solving the hydroelastic problems concerning the CWP on-site up-ending. Four different up-ending schemes were studied. Based on this analysis, the most suitable method of the up-ending CWP was determined and carried out during the deployment. The recommended CWP up-ending scenario is also discussed.

FORMULATION OF THE PROBLEM

Prior to formulating the problem, some specific characteristics of the CWP should be mentioned (Fig. 1). The CWP is formed by a cluster of three separate polyethylene pipes held together by ties at regular intervals. Since the polyethylene is a buoyant material having specific weight of 59.3 lb/ft^3, necessary stability is provided by two ballast weights. One ballast, the lower transition, is a steel structure binding the lower ends of the polyethylene pipes and providing an inlet screen. In order to maintain verticality in a current, a second stabilizing ballast is suspended from three steel cables, each of which hangs freely inside each polyethylene pipe and thus applies no tension force on the pipe itself. The upper ends of these cables are attached to a buoyant collar at the upper end of the CWP.

The main characteristics of the CWP are:

- 4 ft - outside diameter of each pipe,
- 2.4 inches - wall thickness,
- 68,000 lbs - wet weight of the lower transition and inlet screen,
- 75,000 lbs - wet weight of the stabilizing ballast at the lower end of the cable system,
- 2,200 ft - total length of the polyethylene pipes,
- 2,500 ft - total length of the cables.

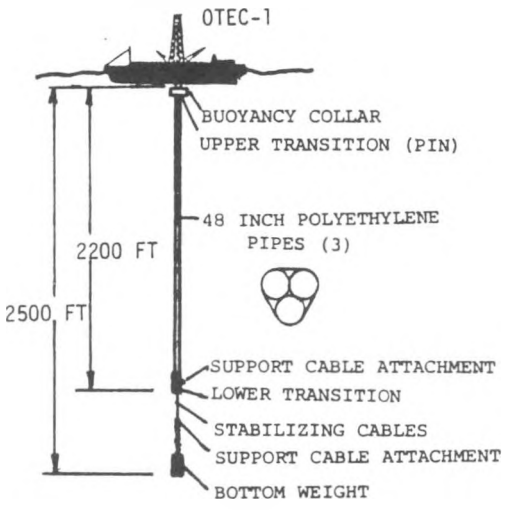


Figure 1
OTEC-1 Cold Water Pipe Assembly

The main objective of the analysis presented in this paper was to investigate various possible up-ending schemes and sequences, and to describe both geometrical and force characteristics governing the up-ending procedure. The 2,200 ft long polyethylene pipe assembly completed with the upper and lower transitions and buoyancy collar was built on the beach and towed on the surface to the test site. The CWP was then up-ended and attached to the OTEC-1 vessel. Figure 2 presents the general arrangement of the CWP up-ending by means of the OTEC-1 vessel and an assisting tugboat. The tugboat cable was attached to the upper transition (pin), while the supporting cables A and B of the OTEC-1 vessel had attachments to the CWP at the lower transition and fish plate, respectively (Figure 1). In

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particular, it is necessary to determine the tension in the supporting cables, the tension which should be applied by the assisting tugboat and the distribution of the bending moment along the CWP. In addition, the desired position and velocity of the tugboat, the duration of the up-ending operation and other factors had to be determined. All of this was used in selecting the most favorable up-ending method.

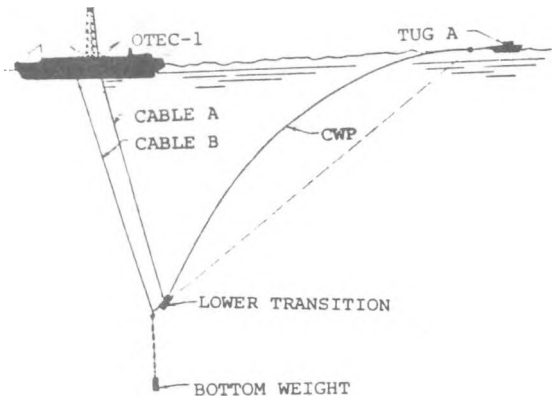


Figure 2
General Arrangement of the CWP Up-Ending
(Up-Ending Scheme No. 1)

It can be noted that the CWP up-ending problem is similar in some respects to the problem of laying a pipeline under tension in deep water. There are, however, unique features of the CWP design and general arrangement which call for deviations from the analytical approach for solving the pipelaying problem.

GENERAL ASSUMPTIONS

The following assumptions are considered in the formulation of the mathematical model:

- The CWP, with a cable system inside, may be simulated as a uniform beam under axial tension,
- Small deformation theory is applicable in describing the CWP behavior during up-ending,
- CWP properties do not vary along its length,
- The current drag forces act in the plane of the CWP curvature,
- When a part of the CWP is floating on the water surface and the other part is submerged, the floating part is tangent to the arc of the submerged part,
- Wave pressure during deployment is neglected,
- The current velocity decays linearly with the water depth.

UP-ENDING SCHEMES

The up-ending schemes investigated are depicted in Figures 2 through 5. These schemes are based on the vessel's handling capabilities and are as follows:

- Scheme 1 - Double cable employed to align the lower end of the CWP along its chord (Figure 2),
- Scheme 2 - Single cable attached to the lower end of the CWP (Figure 3),
- Scheme 3 - Double cable is used to keep the lower transition tangent to the CWP deflected shape (Figure 4),
- Scheme 4 - Free fall of the CWP (Figure 5).

In all schemes, the use of one tugboat is considered as a constraint.

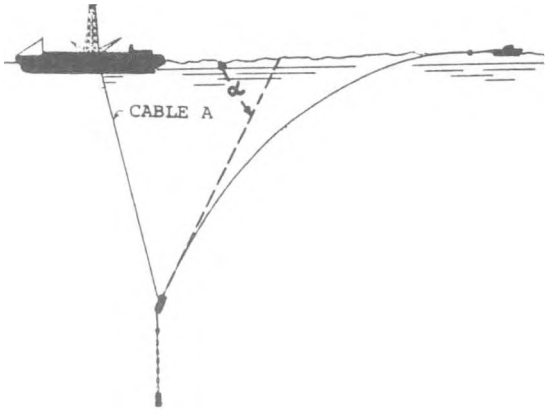


Figure 3
Up-Ending Scheme No. 2

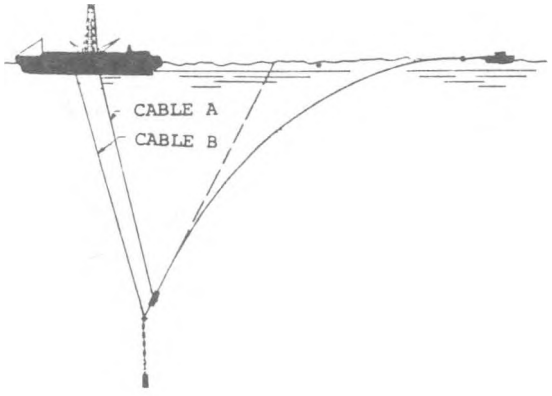


Figure 4
Up-Ending Scheme No. 3

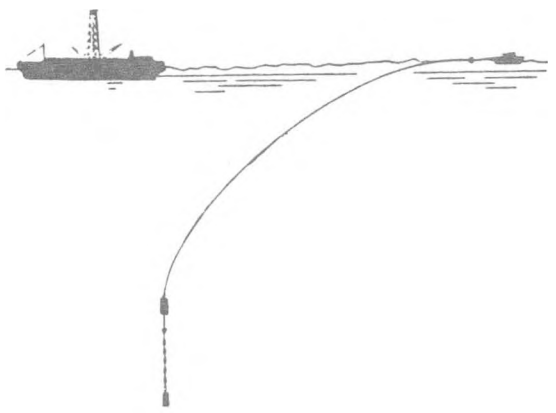


Figure 5
Up-Ending Scheme Corresponding To Free Fall Case
(Scheme No. 4)

MATHEMATICAL FORMULATION

Two coordinate systems are used to describe the up-ending problem (Figure 6).

Both of them have their origins at the upper end of the CWP. Coordinate system $O'\xi\eta$ is used to describe the CWP motion in horizontal direction, while the system Oxy is designed to describe the deflected shape of the pipe at any instant of the deployment situation.

The following set of differential equations and boundary conditions describes the motion and deflected shape of the CWP:

$$M\ddot{\xi} = F_{\xi}(x,\varphi,\omega,\dot{\xi}),$$

$$J\ddot{\varphi} = m_c(\bar{F}),$$

$$EIy^{IV} - Ny'' = f(x,\varphi,\omega,\dot{\xi}), \quad y = y(x,\varphi,\omega,\dot{\xi}),$$

$$y(0,\varphi,\omega,\dot{\xi}) = 0, \quad y''(0,\varphi,\omega,\dot{\xi}) = 0,$$

$$y(L,\varphi,\omega,\dot{\xi}) = 0, \quad y''(L,\varphi,\omega,\dot{\xi}) = -\frac{M_B}{EI},$$

$$\xi(0) = \dot{\xi}(0) = \varphi(0) = \dot{\varphi}(0) = 0.$$

The following notation is used:

- φ = deployment angle, L=CWP length, t=time,
- M = CWP mass including cable mass and added water mass,
- EI = CWP bending rigidity,
- N = mean tension in the CWP,
- J = CWP mass moment of inertia with respect to its center of gravity,
- $F(x,\varphi,\omega,\dot{\xi})$ = resultant force applied to the CWP; it includes all the forces acting at the CWP ends also,
- $F_{\xi}(x,\varphi,\omega,\dot{\xi})$ = projection of this force on the ξ axis,
- $m_c(F)$ = moment of the force $F(x,\varphi,\omega,\dot{\xi})$ with respect to the CWP center of gravity,
- $f(x,\varphi,\omega,\dot{\xi})$ = force applied to a unit length of the CWP at any instant of the up-ending process,
- $\dot{\xi}$ = tugboat velocity toward the OTEC-1 vessel,

$$y'' = \frac{d^2y}{dx^2}, \quad \dot{\xi} = \frac{d\xi}{dt}, \quad \omega = \dot{\varphi}.$$

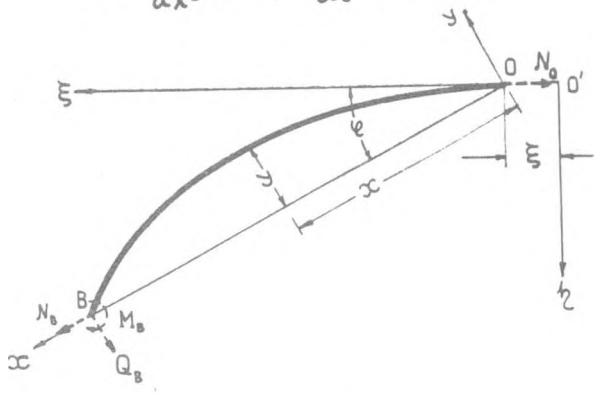


Figure 6
Coordinate Systems and Boundary Conditions

The above set of equations, boundary and initial conditions describes the CWP location and deflected shape regardless of the up-ending scheme considered. The difference in the up-ending schemes results in various magnitudes of the axial force N_B, shear force Q_B and bending moment M_B applied to the lower end of the CWP. N_B, Q_B and M_B depend on the up-ending scheme. The geometry of the lower CWP supporting cables of the different up-ending schemes is used to define these components. It is significant to point out that the forces $f(x,\varphi,\omega,\dot{\xi})$ and $F(x,\varphi,\omega,\dot{\xi})$ include hydrodynamic drag due to current, CWP horizontal translational motion and rotation, CWP and cable wet weight and buoyancy. The Coriolis inertia forces in this particular problem are insignificant and therefore neglected.

The method of integral transforms (1)* was used to obtain solutions. To provide numerical solutions for the various up-ending schemes, a FORTRAN computer program DEPLOY was developed (2).

COMPUTER PROGRAM DEPLOY

Program input includes the ocean current magnitude and its direction, the time duration of the up-ending, the horizontal distance between the OTEC vessel and lower transition, the thrust force applied from the tug to the upper end of

* Numbers in parenthesis refer to References listed at the end of the paper.

the CWP and values of parameters describing the geometry of the supporting cables at the lower end of the CWP. A subprogram of DEPLOY calculates the axial force N_B, shear force Q_B and concentrated bending moment M_B which serve as the input to the main solution.

Computer program DEPLOY is designed to provide a solution of the described equations, boundary and initial conditions over a wide range of independent parameters for any set of input conditions. The program automatically determines the time required for the free fall up-ending, loads and deflections along the CWP, tension in the supporting cables for any up-ending scheme, tension in the CWP and other comprehensive information required.

INPUT DATA

Computations have been performed for a wide range of the input data: no current, 1 and 2 kn current at the surface; up-ending with the current direction and against it; tugboat thruster effect from 20 to 50 kips; up-ending time corresponding to free fall and up to two hours of complete deployment; horizontal separation between the OTEC vessel and lower transition in the range of 5-200 ft.

COMPUTER RESULTS AND DISCUSSION

Each up-ending scheme was examined for various combinations of the input data. It was found that the key factor governing the up-ending problem was the concentrated bending moment at the lower segment of the CWP near the lower transition. Therefore, to obtain a favorable method for implementation, various schemes and different stages of the up-ending were studied.

Some of the numerous results from the analysis (2) are presented in graphical form in Figures 7 through 15. Necessary explanations and additional information are provided in these Figures. Further details are described in Reference (2).

Information presented in these Figures corresponds to an assumed one hour up-ending time. Analysis indicates that this up-ending duration (or longer) is optimal for the tugboat pull force of 20 kips. All Figures show the relationship of several characteristics of the up-ending procedure as a function of the deployment angle.

It is necessary to note that only few parameters on the board of the OTEC vessel could be observed and measured during the CWP up-ending. They were:

- length of the supporting cables,
- tension in them,
- angle of supporting cables with respect to vertical,
- velocity and displacement of the tugboat.

Basically, only the first three of these could be monitored once the thrust force of the tugboat reached its maximum of 20 kips. Consequently, it was important to select a scheme that would yield trouble free up-ending without the necessity of a closely monitored and controlled operation.

Figures 7 and 8 show the tension in the supporting cables and their length at various stages. Figure 9 contains information about the tensile force applied to the top end of the CWP by the tugboat. This force increases to maximum during the initial stage of the up-ending.

Figure 10 provides the variation of the mean tension in the CWP. Concentrated bending moment at the lower end of the polyethylene CWP is a key factor limiting the up-ending scheme and time. Figure 11 presents the absolute value of the concentrated bending moment for deployment Scheme No. 3. The information presented in Figures 12 through 15 refers to the up-ending Scheme No. 2 and one hour up-ending time. These Figures contain maximum deflection along the CWP (Figure 12), tension in the supporting cable (Figure 13), cable length (Figure 14), and slope (Figure 15).

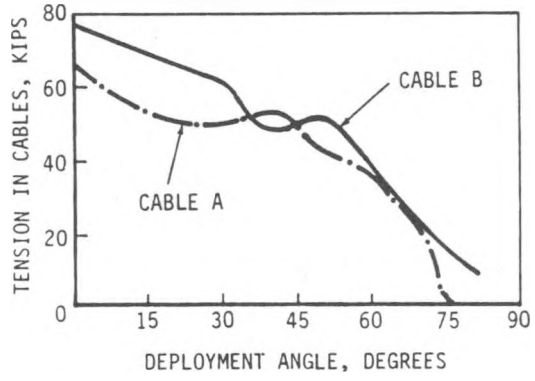


Figure 7
Tension in Supporting Cables A & B for Deployment Scheme No. 3

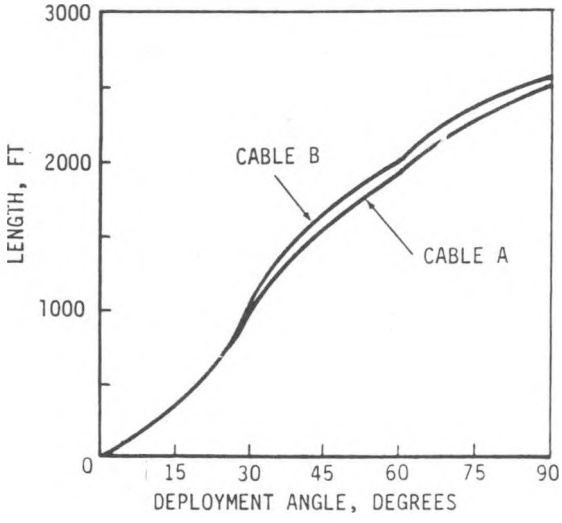


Figure 8
Length of Supporting Cables A & B for Deployment Scheme No. 3

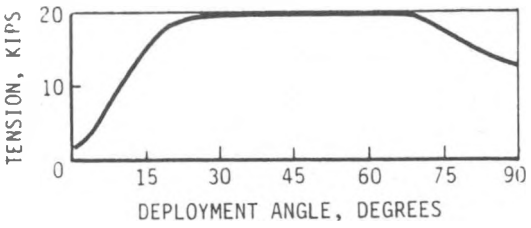


Figure 9
History of the Tugboat Tension for Deployment Scheme No. 3

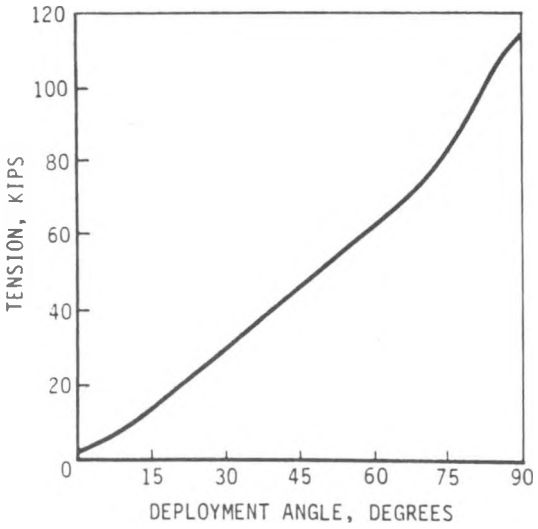


Figure 10
Mean Tension in the CWP System for Deployment Scheme No. 3

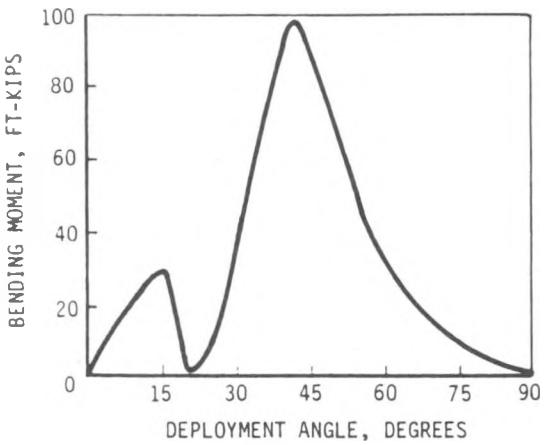


Figure 11
Absolute Value of the Concentrated Bending Moment at the Lower End of the CWP for Deployment Scheme No. 3

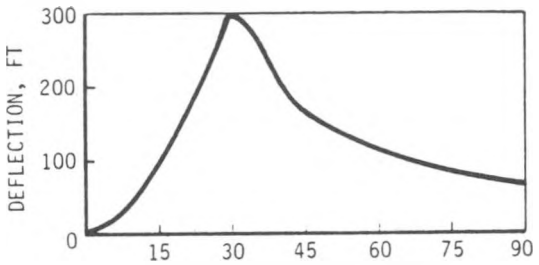


Figure 12
Maximum Deflection of the CWP for Deployment Scheme No. 2

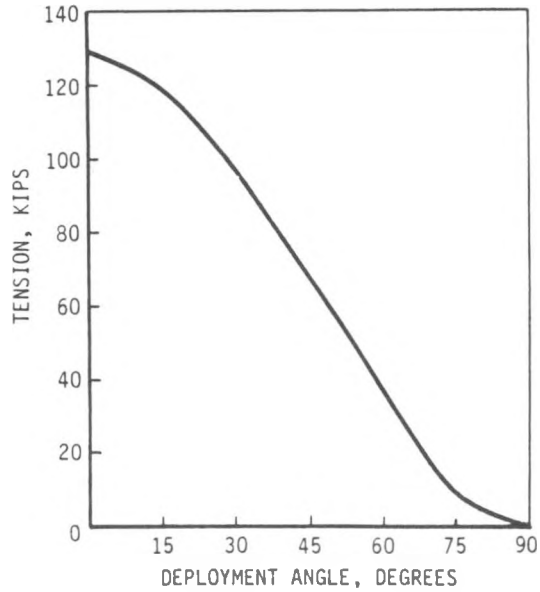


Figure 13
Tension in the Cable A for Deployment Scheme No. 2

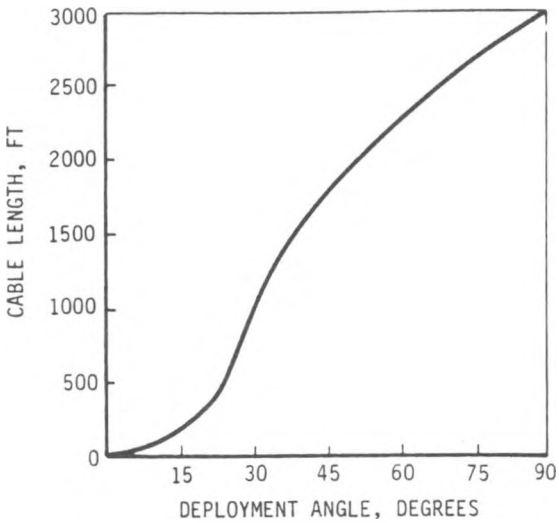


Figure 14
Cable Length as a Function of the Deployment Angle for Deployment Scheme No. 2

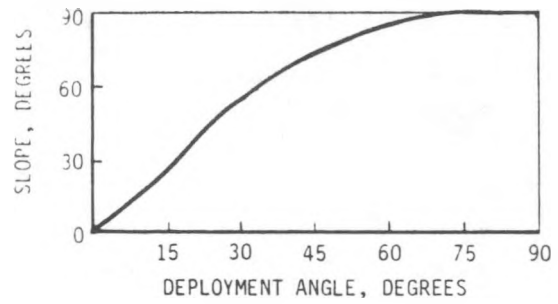


Figure 15
Slope α for Deployment Scheme No. 2

The tugboat displacement as a function of deployment angle is shown in Figure 16. When the deployment angle becomes approximately 30°, the thrust of the tugboat reaches the maximum and, consequently, it starts moving toward the OTEC-1 vessel. For solving this part of the up-ending problem, it was assumed that the drag force applied to the tugboat was small compared to the maximum thrust. The maximum tugboat displacement was estimated to be 650 ft. The maximum tugboat velocity was determined to be in the range from 12 to 14 ft/sec for the CWP up-ending against a 1 knot current.

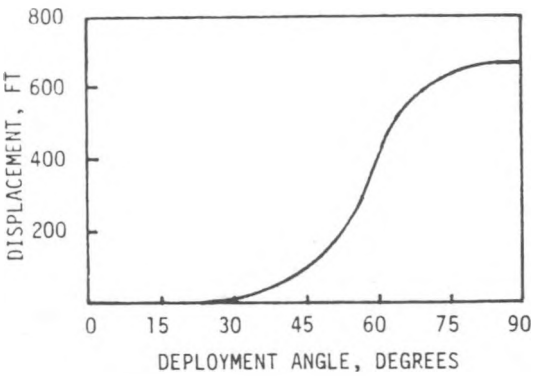


Figure 16
Tugboat Displacement Toward the OTEC-1 Vessel

UP-ENDING SCENARIO

Based on the results obtained from this study, the following up-ending scenario was recommended for implementation (3):

- Follow the Scheme No. 3 until the deployment angle reaches 45°,
- Implement Scheme No. 2 while the deployment angle is in the range of 45° to 70°,
- Allow free fall (Scheme No. 4) when the deployment angle exceeds 70°.

The maximum tugboat pull required is 20 kips and the duration of up-ending is one hour (or longer). The deployment of the CWP was performed, following these recommendations, without encountering any significant problems.

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2. GMDI Technical Report "CWP Deployment Analysis for OTEC-1," RPT-04086-C812, Revision 0, 20 November 1979.

3. OTEC-1 Cold Water Pipe Deployment and Installation Sequence, GMDI Drawing Transmittal, A-4086-LL26, Alt 1, 27 May 1980.

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BUBBLE ENTRAINMENT ON OTEC-1: IMPLICATIONS FOR FUTURE OTEC DESIGNS

Ted E. Goetz

ROCKWELL INTERNATIONAL : ENERGY TECHNOLOGY ENGINEERING CENTER

ABSTRACT

Problems were experienced in seawater flow measurements aboard the OTEC-1 vessel. Gas bubbles in the seawater systems prevented proper operation of the flowmeters. Air entrainment in the sump and gas evolution were identified as bubble sources.

Remedies included increasing the sump water level and system backpressure. Neither resulted in proper flowmeter operation, however, bubble presence was significantly reduced by the increased sump water level.

Gas evolution and air entrainment can be prevented by appropriate system and sump design such as those provided by Hydraulic Institute Standards. Non-standard sump designs can be verified by scale model testing. Degassing can be minimized by limiting piping elevations and pressure drops. The benefits of bubble elimination must be balanced against the costs of preventing bubbles.

INTRODUCTION

During operation of the OTEC-1 test experiment, problems were experienced in measuring flowrates in the warm, cold, and discharge seawater systems. The ultrasonic flowmeters, designed to measure seawater flowrate to 1% accuracy, were unable to function properly. It was postulated that proper operation of the flowmeters was prevented by gas bubbles interfering with sonic signal transmission through the seawater. Since the gas bubbles could also impact water side heat transfer coefficients and heat exchanger performance, an investigation was initiated to determine the source of the bubbles, methods of bubble elimination, and design practices to prevent similar problems in future installations. The results of the investigation have been detailed in this paper.

BUBBLE SOURCES

The OTEC-1 warm and cold seawater systems, rated at 92,600 gpm and 68,170 gpm respectively, were each driven by a single stage pump taking suction out of a sump. Both warm and cold systems discharged spent fluid to a mixed discharge sump which was emptied by the mixed discharge pump. Ultrasonic flowmeters failed to function in all three systems, however, emphasis was placed on eliminating bubbles in the warm water system where bubble presence was most significant.

Four mechanisms were proposed to account for the presence of bubbles in the warm water system. These were:

1. Air entrainment due to turbulence at the sump water surface.
2. Air entrainment due to vortexing in the sump.
3. Evolution of dissolved gas.
4. Pump cavitation.

Observations of the warm water sump during operation indicated that air entrainment due to surface turbulence was substantial. This entrainment was due to high water velocities and abrupt flow direction changes in the sump.

Warm water entered the sump area through a 5 foot diameter vertical standpipe that extended from the ship's keel to 13 feet (all elevations relative to keel datum). Operating water level in this section of the sump was 22 feet, insufficient to prevent water, exiting from the standpipe, from geysering into the air above the sump surface level resulting in air entrainment (Figure 1). The water then passed through two vertical screens, one in the port direction and one in the forward direction from the standpipe (Figure 2). Downstream of the screens there was additional turbulence and air entrainment particularly downstream of the forward screen where the flow took a sharp left turn to reach pump suction. The seawater experienced a 1 foot head loss across the screens resulting in an operating level of 21 feet downstream of the screens.

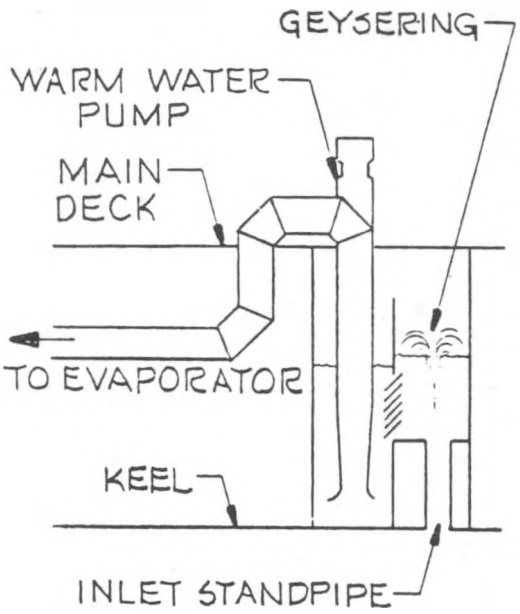


Figure 1
Warm Water Sump Schematic

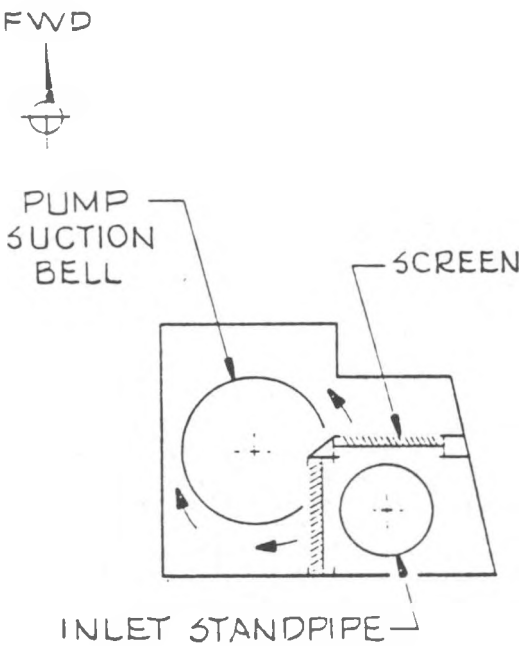


Figure 2
Plan Of Warm Water Sump

At nominal warm water flowrates, the velocity of water through the screens was about 3 feet per second, too high to allow entrained air bubbles to escape. Velocities downstream of the screens were also sufficiently high to keep air bubbles entrained.

Vortex formation around the pump column could not be observed because of difficulty in seeing through the turbulence induced froth on the sump surface. However, there is some evidence that air entraining vorticies could have been forming. Hydraulic Institute Standards (1)* recommend 14 to 15 feet of submergence over the suction bell to prevent vorticies in a sump designed per Hydraulic Institute Standards. Although the nominal water level above the bell was in the 14 to 15 foot range, the design of the sump varied considerably from Hydraulic Institute Standards and consequently the submergence may have not been sufficient.

Vortex formation was also encouraged by uneven flow distribution to the pump suction bell. Observation of the sump showed that the forward side of the pump was "starved" relative to the aft side resulting in high velocity flow around the pump column. Transverse and longitudinal ship support structures below the pump suction bell (Figure 3) may have also contributed to flow disruptions and subsurface vortex formation in the sump. Flow splitters, such as the transverse plate underlying the pump suction bell parallel to incoming flow, normally act as vortex suppressors. However, because of the small clearance between the plate and the suction bell, this plate may have acted to disrupt flow. The "starved" conditions on the forward side of the pump may have been encouraged because this plate prevented flow to the forward side of the pump from the aft side. Flow blockages by the inlet screen support structure provided additional disruptions.

The release of dissolved gas from solution may have also accounted for some of the gas bubbles in the system. Pressures at the center of strong subsurface vorticies may have been low enough to evolve gas from solution in the seawater. The decrease in pressure and severe agitation experienced by the warm water in the piping would also encourage gas evolution.

The water pressure upstream of the flowmeter and evaporator ranged from +24 feet of seawater at the keel (standpipe inlet) to -10.7 feet (gauge) of seawater at the top of pump discharge. The low pressure at the top of pump discharge was a result of the relatively high elevation of the discharge (48 feet above the keel, 24 feet above the nominal sea level). Tests performed aboard the vessel showed that gas came out of solution from seawater under a similar reduction in pres-

*Numbers in parentheses refer to references listed at the end of the paper.

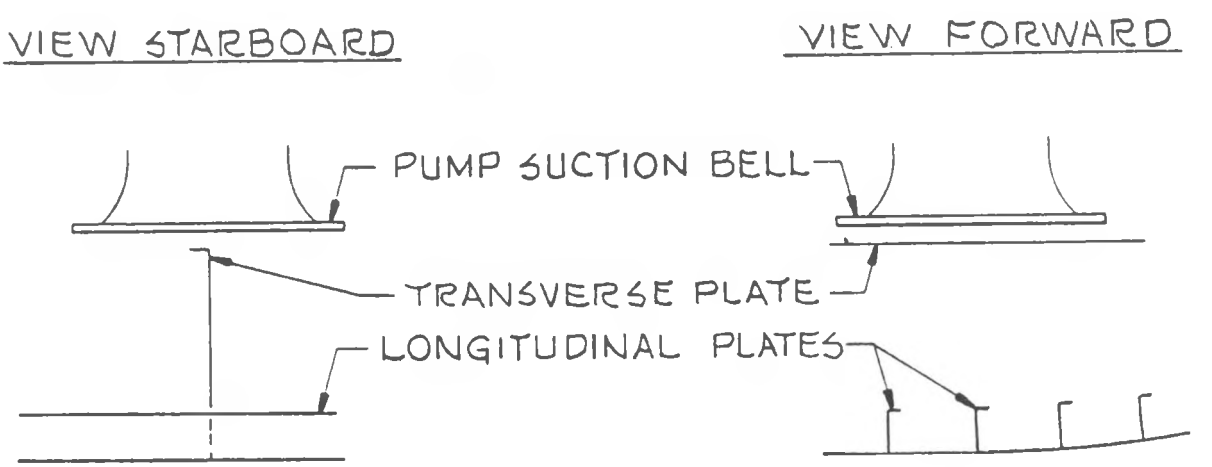


Figure 3
Transverse And Longitudinal Plates Below Pump Suction

sure with mild agitation. Although warm water system pressure increased above atmospheric pressure before reaching the flowmeter due to the drop in warm water pipe elevation, kinetics of gas evolution dictate that gas evolves much quicker than it redissolves and therefore most of the evolved gas would not have redissolved.

Pump cavitation was considered an unlikely source of bubbles since vapor bubbles produced by this phenomena would collapse before reaching the higher pressure region upstream of the ultrasonic flowmeter, and thus not impact flowmeter operation.

ATTEMPTED SOLUTIONS

Since the source of the bubbles was thought to be most likely multifold, a variety of solutions were considered to eliminate the bubbles. Methods that could be implemented relatively quickly with the ship on station were emphasized. However, due to the limited remaining operating time of the vessel, and the desire to accumulate the maximum amount of OTEC operating experience, only two of the proposed solutions were attemped.

The most successful of these solutions was to increase the submergence of the pump suction by pulling a vacuum on the warm water sump. The water level above the suction bell was increased by approximately 11 feet to a 32 foot elevation. The result was a considerable decrease in the warm water system bubble content. The success of this sump level increase indicated that air entrainment, due either to vortexing or surface entrainment, was the major contributor to the bubbles. The increased separation between the pump suction bell and the sump surface was sufficient to calm surface waters and eliminate the geysering above the inlet standpipe. However, the decrease in bubble content was not sufficient to allow proper flowmeter operation.

The second solution, applied to eliminate bubble evolution, was to increase the operating level of the discharge sump. The level rise resulted in an increased warm water system pressure. Qualitative observations indicated little reduction in bubble content and little improvement in flowmeter readings. However, since the resulting pressure rise was insufficient to eliminate all the negative gage pressure areas in the warm water piping, bubble evolution may not have been sufficiently discouraged. In addition, gas evolution in localized low pressure areas such as a subsurface vortex would not be impacted by the discharge sump level rise.

IMPROVED SUMP AND SYSTEM DESIGN

Prevention of gas bubbles in systems such as the OTEC-1 seawater loop can best be accomplished by appropriate sump and system design. Hydraulic Institute Standards provide design guidelines for pump sumps. The recommended design for an 82,600 gpm rated pump is shown in comparison to the actual configuration of the OTEC-1 warm water sump in Figure 4. The most significant difference is the long straight approach channel recommended by the Standards that was nonexistant in the OTEC-1. The long approach channel provides uniform approach velocities, discourages vortex formation, and allows for damping of flow disturbances at the sump inlet. Considerable differences in suction bell to sump floor clearance between the

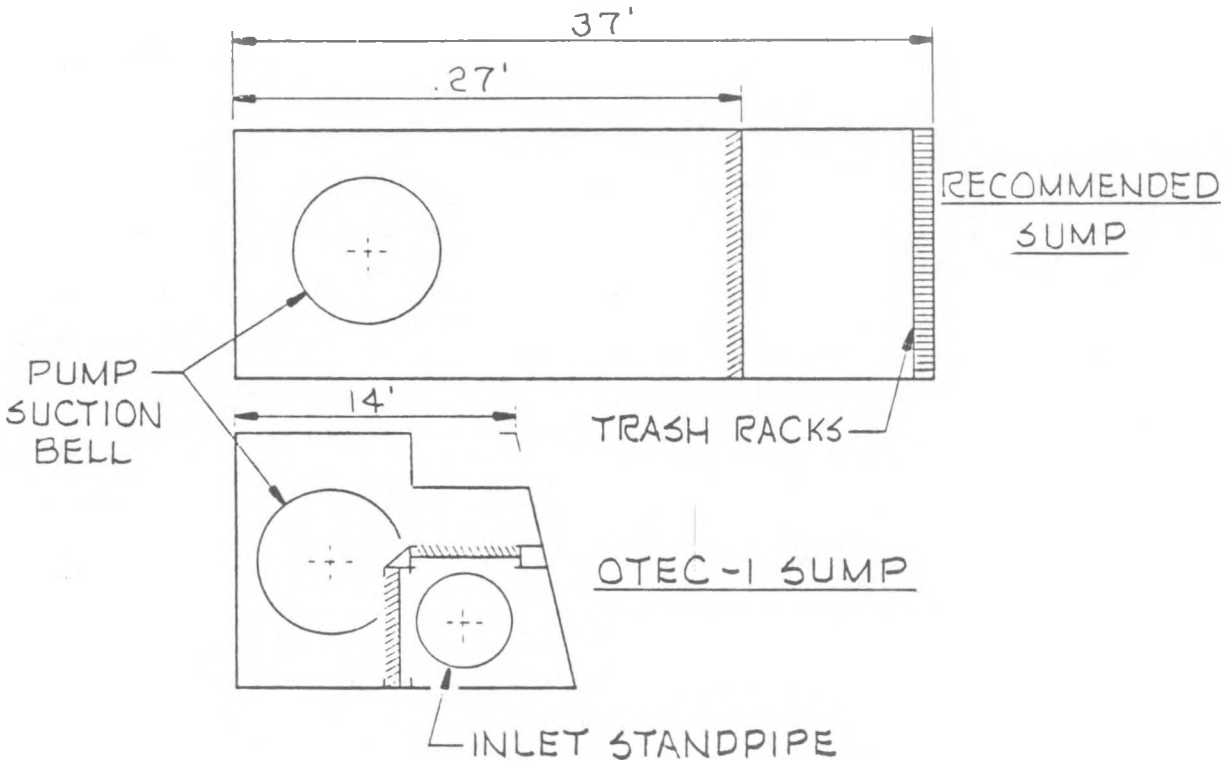


Figure 4
Comparison Of Recomended Sump With OTEC-1 Sump

Hydraulic Institute Standards and the OTEC-1 design were also evident. The OTEC-1 suction bell clearance was about 7 feet as opposed to approximately 3 feet recommended by Hydraulic Institute Standards and clearances of 1/2 the suction bell diameter or 4 feet recommended by others (2, 3,4). The increased floor clearance may have encouraged poor flow distribution and vortex formation at the suction bell inlet. Hydraulic Institute Standards also recommend maintaining sump velocities less than 2 feet per second and minimizing abrupt flow direction changes. Both of these criteria were violated by the OTEC-1 sump design.

Sump design guides such as those provided by Hydraulic Institute Standards may be difficult to follow in ocean based systems due to size and cost limitations. Possible alternatives for a system such as OTEC-1 are elimination of the sump by direct immersion of the suction pipe in the ocean or utilization of a non-standard sump design. Direct immersion of the pump suction pipe could impose pressure fluctuations on the seawater pumps due to the wave induced motion between the ship and the ocean. Constant flowrate would be difficult to maintain even during mild sea states. Hence, this method is not recommended. A non-standard sump design might contain flow baffles, diverters or other fixtures to insure calm and uniform suction bell approach flow. However, these designs are difficult to evaluate analytically and scale model testing is usually required to verify prototype sump adequacy. Sump models commonly range from 1/10 scale to 1/25 scale. Pump flow must be scaled down in the model so that the main flow patterns in the model duplicate those of the prototype. Model pump flow is commonly scaled to maintain the same Froude Modulus in both the model and the prototype. The Froude Modulus relates gravity and inertia forces, both of which can be predominant in open channel flow systems. Scaling flow based on Froude Modulus results in model velocities directly proportional to the square root of the scale factor. However, by basing model velocities on Froude Modulus the assumption is made that other effects such as surface tension and viscosity are unimportant. Some modelers (5, 6, 7) have found better duplication of prototype flow patterns if model flow veloc-

ities are increased to prototype values thereby compensating for scale effects. In general, it is prudent to evaluate model sumps at Froude Modulus velocities and higher. Scale values of velocities, flowrates, and areas, based on both Froude and constant velocity criteria, for a 1/10 scale model of the OTEC-1 warm water pump are shown on Table 1.

System designs that minimize piping elevation changes will minimize seawater degassing. To avoid impacting the integrity of bulkheads, OTEC-1 warm and cold seawater piping was routed above the main deck before descending into the condenser and evaporator compartment. This design resulted in low pressure areas that probably encouraged bubble growth in the high elevation piping. If large piping elevation changes cannot be avoided, utilization of an increased pumping head may suffice to eliminate the low pressure regions, however, this option reduces system efficiency by increasing pump parasitic loads.

CONCLUSIONS

Evidence gained from sump observations and the applied solutions suggest a multisource gas bubble origination. Air entrainment due to vortexing and/or surface turbulence predominated but contributions from gas evolution in system low pressure areas also contributed enough to prevent flowmeter operation.

Improved sump and system designs can prevent similar occurrences in future OTEC facilities. Design verification can be obtained by scale model testing. However, the costs associated with designing to eliminate gas bubbles may exceed the benefits derived from bubble elimination. If so, proper test techniques require that provisions for measuring gas bubble content in the fluid streams should be taken.

ACKNOWLEDGEMENTS

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TABLE 1

1/10 SCALE MODEL PARAMETER VALUES FOR FROUDE AND CONSTANT VELOCITY MODEL CRITERIA

PARAMETER	OTEC-1	FROUDE	CONSTANT VELOCITY
LINEAR DIMENSIONS	1	1/10	1/10
AREAS	1	1/100	1/100
VELOCITIES	1	1/3.16	1
FLOW (GPM)	1 (82600)	1/316 (261)	1/100 (826)

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OTEC-1
Environmental Monitoring Program

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ABSTRACT

Environmental monitoring for OTEC-1 operations consists of an on-board program conducted by Aecos, Inc., and an oceanographic sampling program, conducted from research vessels, by EG&G and the University of Hawaii. Both programs are directed by the Marine Sciences Group of the Lawrence Berkeley Laboratory. The goal of these programs is to develop environmental data for use in the various OTEC-1 experiments, to maintain the operating permit issued by EPA and to provide the basis for estimating potential effects of larger scale plants.

Work to date includes the six initial oceanographic cruises to the OTEC-1 site (HOTEC-01-06) prior to deployment at approximately two month intervals, followed by three oceanographic cruises in the summer of 1980, January 1981 and April 1981. Current meter arrays have been operated near the site since June 1980. On-board monitoring has been continuous since the deployment of OTEC-1 from late October 1980 to April 1981.

On-board measurements in excess of the environmental permit requirements have been developed in conjunction with the ANL-operated joint test group. Additional current profile measurements from the OTEC-1 platform useful for design requirements and ship handling characteristics were planned and augmented through discussions of the needs of the Ocean Engineering group and the ship's operators.

INTRODUCTION

The OTEC-1 environmental monitoring program began in October 1978 with the first in a series of six oceanographic cruises to the proposed site prior to deployment of the OTEC-1 platform. The information collected on these cruises (HOTEC 01-06) was primarily cruise oceanographic work including hydrocast and net tow information. Serial current measurements did not begin until June 1980 and continued through the OTEC-1 platform deployment until April 1981. Oceanographic cruises continued after the initial HOTEC bi-monthly occupations during deployment. In addition, in April 1981 a plume study was conducted in conjunction with the oceanographic cruise. During deployment on-board platform measurements were made using the environmental van.

This paper will briefly summarize the significant findings of the environmental program based on analyses completed to June 1981. More completed specific studies are found in these proceedings in papers by Hartwig (Biology), Hunt and others (Chemistry) and Harms (Physical and Ocean Engineering). Final reports and other specific papers based on OTEC-1 work will be published beginning in the summer of 1981. All qualified environmental data will be deposited with the National Oceanographic Data Center (NODC) in Washington.

PHYSICAL OCEANOGRAPHIC DATA

Water currents speed and direction measurements from current meter moorings in the vicinity of the OTEC-1 site off Hawaii between June 1980 and April 1981 are summarized below:

26 June - 20 July 1980 Deployment

Depth M	MAX	MEAN	SD	DIR	% OBS
177	58.60	18.88	11.64	30^{o}-120^{o}	58.4
281	47.12	14.06	8.23	315^{o}-090^{o}	62.1
924	18.35	6.06	3.28	180^{o}-225^{o}	29.1
24 July - 19 September 1980 Deployment					
56	151.95	44.12	36.25	0^{o}-90^{o}	72.3
73	133.85	42.12	30.13	345^{o}-90^{o}	82.2
90	117.98	34.84	25.44	345^{o}-90^{o}	83.3
113	89.05	29.02	21.06	345^{o}-75^{o}	69.7
166	81.02	22.98	18.71	345^{o}-60^{o}	55.3
811	26.89	7.77	3.98	255^{o}-330^{o}	27.7
23 September - 20 December Deployment					
45	75.61	27.26	14.28	15^{o}-090^{o}	53.7
70	73.00	25.10	12.20	15^{o}-090^{o}	51.2
155	50.97	13.96	8.02	0^{o}-075^{o}	31.9
811	37.90	7.96	4.76	180^{o}-240^{o}	26.5
26 December 1980 - 14 April 1981					
54	94.46	29.27	17.03	$300^{o}90^{o}$	64.4
101	84.38	22.87	13.24	285^{o}-90^{o}	74.3
151	71.50	18.87	10.23	330^{o}-105^{o}	61.9
350	32.86	10.81	4.73	315^{o}-90^{o}	49.8
771	31.93	8.53	4.44	165^{o}-270^{o}	39.1*

*At 771 meters, 41.43% of directions range from 285°-60°, a spread of 135° azimuth; but 39.1% of directions range from 165°-270° a spread of 105° azimuth.

Currents in the upper 300m had a mean northerly or or northeasterly component. Current speeds were highest near the surface both in the average and during extreme events, and decreased gradually with depth to at least 289 meters. Typically speeds decreased about 50% between the 50m level and the 150m level. Between 177 and 281m, mean and extreme speeds decreased about 25%. Below 300m, current measurements were available only at about 800 or 900m depths where the mean currents are low (8 cm/sec), with a net southwesterly drift. Most of the energy in the current record from these depths was due to the mixed semidiurnal and diurnal tides.

Maximum current episodes were observed in early September throughout the upper part of the water column (to at least 166m depth). During this interval, which lasted about 2 weeks, maximum currents of 152 cm/sec (56m depth), 118 cm/sec (90m depth), 89 cm/sec (113m depth), and 81 cm/sec (166m depth) were observed. At the 56m level, speeds in excess of 100 cm/sec were observed on thirteen consecutive days. The maximum speed observed at the 800m (or 900m) depth was observed in late November when magnitudes of 38 cm/sec were recorded. The duration of these relatively high speed events at 800m was shorter than 12 hours.

Tidal currents are observed in the records from all depths at both the diurnal and semidiurnal frequencies. At both frequencies, the tidal flows were rotary and directed in a clockwise direction with typical speeds between 5 and 15 cm/sec. Currents associated with the tides were largest at above 100m and had a maximum speed associated with them of the order of 25 cm/sec. A portion of this energy was the result of internal tides, probably generated by the barotropic tide moving across the steeply shelving bottom east of the OTEC-1 site. The amplitude (1/2 of the height) of these internal tides, as deduced from temperature variations at the semidiurnal frequency, may be as large as 50m or more, with the largest amplitudes observed at the deepest measurement depth (811m).

The most important feature of the currents observed at the OTEC-1 site was the variability of the mean flow in the upper several hundred meters of the water column. The observed currents in this layer ranged from northerly flows at 150 cm/sec to southerly flows at 60 cm/sec. This variability was present over time scales of a few days to a month or more. Associated with high current speed and northeasterly flow was temperature lowering, cyclic at tidal frequencies, observed in the near surface meters. Such temperature depressions seen for example, in the late November 1980 event at 45 and 70 meters are in excess of that produced by bending the array to deeper (colder) depths in the current.

CTD casts made from the R/V Holokai at 12 stations (14 casts to 350 meters, 2 casts to 800 meters and 1 cast to 560 meters) taken in the vicinity of the OTEC-1 site from 3-5 August 1980 show:

Surface temperature	25.977-27.215°C
Salinity Maximum Depth	13-190 meters
Value	34.96-35.00%
Salinity Minimum Depth	460 meters
Value	34.1%
800 Meter Temperature	5°C

Such data is consistent with historical observations of surface North Pacific subtropical water overlying North Pacific intermediate water.

Expendable bathythermographs taken in the Alenuihaha Channel from the R/V Holokai in two parallel transects (8 XBT's 19 December 1980 and 13 XBT's 28-29 December 1980) from the OTEC-1 site to south of Kahoolawe show:

Surface Temperature	25-26°C
Mixed Layer Depth	60-90 meters
800 Meter Temperature	5°C

CHEMICAL OCEANOGRAPHIC DATA

(See Hunt and others, this volume for details)

Dissolved Oxygen

Dissolved oxygen averages about 5.3 mL/L at the surface ranging from approximately 5.0 to 5.8 mL/L.

A subsurface maximum is observed near 50-100m, the depth of the maximum depending on the time of year. On the November and December cruises (HOTEC's 06 and 01), the maximum appears at greater depths than in the April, June, July and October cruise (HOTEC's 02-05). From about 100m to the oxygen minimum, at approximately 500-600m, the concentration declines steadily to about 1 mL/L. On the December cruise (HOTEC-06), an extremely low minimum was observed - 0.2 mL/L. It was observed two separate casts at two depths, so the observation cannot be easily rejected as an analytical anomaly. There is a fair degree of variability in the data ± 0.5mL/L to the depth of the oxygen minimum, then relatively low variability ± 0.2 mL/L.

The HOTEC profiles are in fair agreement with the profile from GEOSECS station 235 (16°45'N, 161°23'W) which shows a minimum of 0.6 mL/L at 500m. The subsurface maximum at 130m at GEOSECS station 235 was deeper than that observed on HOTEC-06 at 100m.

Phosphate

At the surface, the phosphate concentration averaged about 0.3 -at/L which immediately decreased to about 0.15 -at/L. Below 100m the concentration increased to about 3.0 -at/L at 400-450m. The concentration then remained c

stant. The variability of the data remained about ± 0.02 -at/L throughout the profile. No variation could be linked directly with seasonality or time of data. The profile of the phosphate data at the surface agrees with the GEOSECS data from station 235.

Nitrates

At the HOTEC site, nitrate remains virtually undetected until 100m; at greater depths the concentration increased to about 43 -at/L. Variability was about ± 2.5 -at/L near 100m increasing to ± 5 -at/L in the nutricline. No fluctuations could be attributed to seasonality. The data is in good agreement with the GEOSECS, station 235 results and with Gundersen and Palmer's data from Keahole Point.

Silicate

Silicate concentrations averaged 2-3 -at/L at the surface to a depth of about 100m.

The concentration gradually increased to an average of about 90 -at/L. Although the variability in deep water was quite high, nearly 10 -at/L at 900m, no correlation could be made with the seasons. Agreement was good with the GEOSECS data.

BIOLOGICAL OCEANOGRAPHIC DATA

(See Hartwig, this volume for details)

Phytoplankton

At the HOTEC site large temporal and vertical variations in phytoplankton biomass and primary productivity were observed. Over a year, phytoplankton biomass (chlorophyll a) varied threefold, and primary productivity, although always nutrient-limited varied more than 25-fold (Table 1). Vertically, the profiles of phytoplankton biomass were similar over time showing low and uniform levels in the upper 40-60m, with a chlorophyll a maxima centered at 85m. Photosynthetic rates were highly variable over time and productivity: biomass ratios were consistently low and indicative of strong nutrient limitation. The large variation in photosynthetic activity was far in excess of the accompanying changes in the physical properties of the system, and could not be explained by variations in phytoplankton biomass or the prevailing nutrient gradients. We found significant correlations ($P<0.01$) between depth-integrated phaeopigment stocks and primary production, and between phaeopigments and ammonium levels. Phaeopigments are produced by the digestion of chlorophyll. Variations in the supply of regenerated nutrients by grazers is believed to account for most of the observed temporal variability in photosynthesis.

Macrozooplankton

The HOTEC site shows a diel vertical migration pattern, with zooplankton migration into the surface waters during the night and back into the deeper waters during the day.

One can not make the sweeping generalization that copepod abundance increases at night and decreases in the day. Day/night copepods abundance distributions are site dependent, time dependent and depth dependent.

The diel variation with depth of zooplankton biomass in two size categories (0.2-0.5mm and greater than 0.5 mm) was examined. HOTEC-05 showed evidence of diel vertical migration of biomass while HOTEC-06 did not. This is in contrast to the abundance data where both cruises showed diel vertical migration. This points out the problem of parameter selection for examining events or impacts. An investigator must choose that (those) parameter(s) which most succinctly or simply explains the event or impact under study.

On HOTEC-05, diel vertical migration occurred in smaller and larger zooplankton. The depth distribution of biomass at the HOTEC site, was similar for both size classes.

Nekton

The macronekton although capable of avoiding entrainment are attracted to structures (e.g., OTEC) in the ocean thereby increasing the number subjected to the probability of entrainment and impingement. The effect on macronekton will be highly species dependent. Experience at OTEC-1 showed that although sharks (white tips) and large adult fish (yellow fin tuna, dolphin fish) were attracted to the structure, none appeared to be impinged. However, as impingement was not studied directly, smaller species may have been impacted.

Micronekton would be much more susceptible to entrainment and impingement. Visual sightings in the OTEC-1 moon pool revealed entrainment of micronekton.

FISHERIES

(see Ryan and Jones, this volume for details)

Hawaii principal fisheries are carried on by a variety of techniques including: pole-and-line, midwater longline, trolling, handline, seines, gillnets and traps. Use of the live-bait, pole-and-line method generally results in a catch composed of at least 90% (by weight) skipjack tuna (aku) the remainder of the catch may include such offshore pelagic species as mahimahi (dolphin fish), small yellowfin tuna (ahi), and little tuna (kawakawa). Large yellowfin tuna (about 250 pounds) and large bigeye tuna (about 300 pounds), are the principal catch of the longline or flagline fishery. Flaglines also catch lesser quantities of large albacore tuna (up to 90 pounds), bill fishes, ono (wahoo), mahimahi, sharks, and other pelagic species. Trollers catch ahi, (primarily yellowfin tuna), billfishes, ono (wahoo), mahimahi and smaller species of tuna. Handlines are used to catch bottomfishes such as snapper and goatfish. They are also used at night with lights to catch coastal pelagic schooling species such as, akule (bigeyed scad), and opelu (mackerel scad). Seines and gillnets are used in shallow waters for skule,

opelu, mullet, reef-fishes and inshore bottom fishes. Traps are used in shallow water to catch reef fishes.

Source of the Data

Since the late 1940's, the State of Hawaii, Division of Fish and Game has required all licensed commercial fishermen to submit monthly catch reports. From these reports the Division tabulates data in three basic areas: 1) catch weight and numbers, 2) time and place of capture, and 3) fishing effort. This section of the report uses fisheries data made available by the Hawaii Division of Fish and Game.

For ease in reporting the place of capture the Hawaii Division of Fish and Game has divided the waters around Hawaii into Fishing Areas. A proposed OTEC site off the Island of Hawaii (HOTEC) is located in Area 122. The composition of the landings varied during the period examined, but generally skipjack tuna, yellowfin tuna, blue marline, and snappers were the most important groups in terms of pounds landed. On the average, skipjack tuna comprised 62% of the landings, yellowfin tuna 10%, blue marlin 9%, and snappers 5%.

During the 20 years from 1959 to 1978, the weight of the total landings varied considerably. The fluctuations are primarily due to fluctuations in tuna landings, especially the amount of skipjack. The landings of skipjack tuna range from a low of 123 pounds in 1966 to a high of 407,453 pounds in 1974. The only catch per unit of effort (CPUE) data made available from Area 122 are for blue marlin catches from 1966 to 1978. The catch of blue marlin per unit of effort varied during this period, indicating that the density of blue marlin in Area 122 varied from year to year.

In 1978, the annual landing from the fishing area (Area 122) off Keahole Point was valued at $272,150. The 10-year average was $141,000 (1969-1978).

ON-BOARD MONITORING

Monitoring of the effluent of the OTEC-1 platform during deployment was done by Aecos, Inc., using the environmental van as a base of operations. The purpose of the measurements was to maintain the NPDES Operational permit and to provide basic data for the environmental program and for the various heat exchanger tests. The permit requirements were maintained, with the expected operational problems, to the satisfaction of EPA. The experiment essentially was that of a surface discharge as the mixed discharge pipe was never successfully deployed to the design depth of 70 meters.

Standard analyses were taken either daily, weekly or monthly. The results reported here are summaries of the preliminary data.

Daily Measurements

Routine daily measurements for ammonia and residual oxidants were made during operations at the evaporator, the condenser and in the mixed discharge. Chlorine demand was measured daily for about one month from late December into Jan 1981, then weekly until the end of February. T time-consuming analysis was stopped as the values were low and uniform during the measurement interval. Summary of the ammonia, residual oxidants and chlorine demand data are given in Table XX.

Weekly Measurements

Standard oceanographic parameters such as dissolved oxygen, salinity, as well as nutrients, pH, suspended solids, and total organic carbon were scheduled on a weekly basis. Table YY gives a summary of such observations.

Monthly Measurements

Trace metals, aluminum, copper, iron and titanium were measured as both particulate and soluble fractions monthly from the evaporator mixed discharge, and condensor flows. Such data showed high variability within replicate samples to make either the validity or the meaning of the data questionable at this time. Accordingly no summary data are given here awaiting further interpretation. Other monthly measurements for permit requirements such as discharge/sump oil and grease and standard discharge monitoring showed values within EPA guidelines and will not be given here as such measurements are of compliance value and do not pertain to OTEC specific concerns.

Other Measurements

A two day study of volatile organic compounds potentially due to chlorination of sea water was made in early April 1981. Bromoform, dichloromethane, benzene, chlorobenzene, xylene, and dibromochloromethane were detected. Analyses of that data is incomplete at this time but will be the subject of a separate report.

A comprehensive plume study was conducted in April in co-operation with the ship-board program and the cruise program using dye tracers. Data from this operation appears in part in Harms and others (this volume) and in reports in press by Noda and others.

Profiling current meter surveys were made at intervals from the platform in support of ship's operations in maintaining station. Summary of this data is reported by Harms and others (this volume).

TABLE 1

Daily Measurements - OTEC-1 Platform

SYSTEM	Ammonia (µg-at/L)	Residual Oxidants (mg/L)	Chlorine Demand (mg/L) 2 min	Chlorine Demand (mg/L) 5 min
Evaporator-Intake				
Range	ND[a*] - 0.71	ND - 0.52	0.08-0.13	0.10-0.15
Mean	0.24	0.25	0.12	0.13
Standard Deviation	0.14	0.14	0.01	0.01
Number	66	108	14	11
Evaporator-Discharge				
Range	ND-1.19	ND-0.54	-	-
Mean	0.30	0.27	-	-
S.D.	0.19	0.10	-	-
Number	112	102	-	-
Mixed Discharge [b**]				
Range	ND - 1.30	ND - 0.46	0.06-0.11	0.05-0.13
Mean	0.24	0.14	0.09	0.09
S.D.	0.14	0.06	0.02	0.02
Number	130	217	14	11
Condenser-Intake [b]				
Range	ND - 1.98	ND - 0.91	0.03-0.10	0.03-0.10
Mean	0.26	0.37	0.06	0.08
S.D.	0.24	0.13	0.02	0.02
Number	74	110	29	26
Condensor-Discharge				
Range	ND - 1.12	ND - 0.70	-	-
Mean	0.32	0.30	-	-
S.D.	0.21	0.11	-	-
Number	98	103	-	-

* ND = None Detected

** On 3/28 the ammonia concentration in the condensor discharge was 21.1 µg-at/L and in the mixed discharge was 9.4 g-at/L. These are anomalously high,and although real were not considered in the neons.

TABLE 2
Weekly Measurements - OTEC-1 Platform

System	SAL 10^{-1}	DO mL/L	pH	TOC mg/L	Suspended Solids mg/l
Evaporator					
Range	34.391-34.986	3.74-6.67	8.10-8.38	0.869-1.876	0.2-1.86
Mean	34.74	4.63	8.27	1.22	0.83
Standard Deviation	0.22	0.97	0.05	0.35	0.4
Number	16	17	16	5	14
Mixed Discharge					
Range	34.38-34.667	3.88-1.36	7.622-8.228	.765-1.075	0.13-0.8
Mean	34.51(mix 34.49)	2.55(mix 3.03)	8.06	0.91	0.44
S.D.	0.13	0.76	0.13	0.13	0.2
Number	14	16	15	5	12
Condensor					
Range	34.192-34.283	0.8-2.92	7.51-7.97	0.491-0.989	0.5-0.4
Mean	34.25	1.43	7.64	0 82	0.24
S.D.	0.02	0.55	0.15	0.18	0.13
Number	16	17	15	5	13

TABLE 2
Weekly Measurements - OTEC-1 Platform (cont.)

Evaporator	NO_3 µg-at/L	TN µg-at/L	PO_4 µg-at/L	TP µg-a/L	Si µg-at/L
Range	0.1-.29	5.75-42.4	0.09-0.25	0.05-1.77	0.62-7.35
Mean	0.13	14.3	0.16	0.50	3.43
Standard Deviation	0.09	10.9	0.05	0.38	1.94
Number	13	13	7	14	16
Mixed Discharge					
Range	0.32-36.3	6.07-58.8	0.93-2.90	.48-3.18	2.13-79.3
Mean	16.6	20.9	1.29	1.71	34.3
S.D.	8.0	9.2	0.55	0.69	17.0
Number	11	10	10	11	11
Condensor					
Range	29.8-42.2	44.2-80.7	2.25-2.86	2.49-3.78	44.2-80.7
Mean	35.16	56.2	2.59	3.03	61.3
S.D.	3.27	7.3	0.17	0.76	12.4
Number	16	14	16	15	16

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Plenary Session

Charles McC. Mathias, Jr.; Senior United States Senator, Maryland was introduced by Dr. H. Guyford Stever, Chairman of the Assembly of Engineering of the National Research Council

Edwin M. Hood, President and Board Chairman; Shipbuilders Council of America

William E. Richards, Director, Division of Ocean Energy Systems, Office of Solar Power Applications, Department of Energy

Robert W. Knecht, Director, Office of Ocean Minerals and Energy, NOAA

J. Bill Young, Deputy Asst. Administrator for Maritime Aids (Trade), U.S. Maritime Administration

American Oceanic Organization/National Energy Resources Organization Luncheon

Dr. John B. Slaughter, Director, National Science Foundation was introduced by Congressman John B. Breaux, (D-LA)

Arsene d'Arsonval Centenary Banquet

Dr. John P. Craven, Coordinator of Maritime Affairs State of Hawaii, Dean of Maritime Resources, University of Hawaii, was introduced by Mr. Phillip Eisenberg, President, Hydronautics, Inc.

For text of speeches see Preliminary Report of 8th Ocean Energy Conference

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