OTEC OCEAN ENGINEERING TECHNOLOGY DEVELOPMENT

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ABSTRACT

Ocean Thermal Energy Conversion (OTEC) is the principal ocean energy source under development by the U. S. Department of Energy (DOE) because of its potential, state of development, and availability and access of the resource to the U. S. The major features of OTEC are that the source is renewable with minimum impact on the environment, and the constant availability of the resource enhances OTEC acceptability as a power baseload option, with no requirement for additional storage.

DOE has delegated the National Oceanic and Atmospheric Administration (NOAA) to carry out its OTEC Ocean Engineering Technology Development program. This program involves conducting research in critical, high technical risk areas in order to demonstrate technical and economical feasibility and develop a technical information base which can be used by industry to develop commercially viable systems. This program established preliminary baseline designs for floating and fixed systems; developed analytical computer models; conducted laboratory tests of scale models to calibrate analytical models; and is now preparing for sea tests of larger scale models for further validation of analytical models and improvement of baseline designs.

This paper summarizes the technical accomplishments and major findings, mainly reported over the last year, and describes some of the remaining critical needs and the projects underway or planned to minimize the problems and associated risks. This paper covers the ocean engineering technology, viz., platforms, cold water pipe and sea water system, mooring and foundation systems and other areas related to the overall system integration aspects. The development of the electrical umbilical cable and bottom-mounted transmission cable has been managed directly by DOE and is integrated into the ocean engineering system.

1. INTRODUCTION

The Ocean Thermal Energy Conversion (OTEC) concept uses the temperature differences, about 22° C, between the warm surface water (26° C) and the cold deep water (4° C at 910 meters) to operate a heat engine. The resultant output of this engine can be distributed in various ways,

including generation and transmission of electrical power for direct use in the manufacturing of energy intensive products such as aluminum or ammonia. Other by-products such as the nutrients inherent in the cold bottom waters can be used in mariculture facilities co-located with OTEC, and fresh water can be extracted by desalinization or as a direct by-product in open cycle systems considered for future development.

Other countries such as Japan, France, and the Netherlands are active in OTEC development and are considering the multi-product benefits and are looking toward international markets. This topic has been covered each year in the OTEC series of conferences reviewing the market potential for OTEC and the many by-products which may be economically beneficial in various areas of the world (1).

In August 1979, U. S. Industry, through private investment installed and demonstrated MINI OTEC, the world's first operating OTEC plant, a 10 kilowatt net power-producing system located in Hawaii. In September 1981, Japan Industry completed installation of a land-based OTEC plant on the Republic of Nauru which is generating a net power of approximately 30 kilowatts. As technology develops, industry will become more interested in development of OTEC systems for commercial use.

One of the major goals of the OTEC Research and Development Act of 1980 was to develop a pilot plant for operation in 1985. Early this year DOE announced two awards for conceptual designs of pilot plant systems now called Proof of Concept Experiment (PCE). One award was to General Electric for a shelf-mounted plant using a conventional fixed steel tower construction located in approximately 100 meters of water 1600 meters off Kahe Point, Oahu, Hawaii. The other was to Ocean Thermal Corporation (OTC) for a shelf-mounted reinforced concrete plant located on an artificial island in 9 meters of water near an existing shore-based fossil fuel power plant at Kahe Point. The OTEC plant is being designed to use the warm effluent discharge from the condenser of the fossil fuel plant in order to enhance its warm water supply and increase system efficiency.

It is significant to note that both of these are categorized as shelf-mounted type plants. Because of this early trend toward shelf-mounted systems of 40 MW capacity or less, based on the vast island

market, the ocean engineering technology development program has accelerated research in this area over the last year.

Research and development planning over the last 5 years has been directed toward high priority projects in critical areas where essential unknowns were identified. There are critical areas with varying degrees of technical risk for both fixed systems (shelf mounted and land based) and floating systems (moored and grazing) which require further research and validation. These include: large cold water pipes suspended from platforms or installed on steep slopes with requirements for life expectancy requirements on the order of 30 years; foundations to support slope-mounted platforms and cold water pipes for this long duration; materials that withstand long-term corrosion and fatigue for cold water pipes, mooring lines and electrical cables; electrical umbilical cables which demonstrate electro-mechanical integrity to withstand the flexure and other problems and hazards of the ocean environment; deployment, installation and operation of large systems subject to sustained environmental forces over a 30-year period including 100-year survival force conditions; system integration to ensure compatibility of platform coupled pipes, and electrical cables, and foundations or moors to provide the stability for reliable long-term operation; and inspection, maintenance, and repair capabilities over the life of the system. These technical areas are given high priority in the DOE/NOAA ocean engineering technology development program, and projects are underway to minimize these technical risks. The Marine Board, National Research Council, Assembly of Engineering has completed an assessment of OTEC ocean engineering technology; and a final report is in preparation. This report assesses the state of engineering knowledge, technology and practice necessary to design, construct and operate OTEC plants. In addition, this investigative study identifies the additional ocean engineering research and development necessary to meet the projected requirements of the Department of Energy's OTEC program and makes recommendations regarding the content and direction of the ocean engineering R&D in the OTEC program.

2. ACCOMPLISHMENTS AND FUTURE EFFORTS

OTEC plants can be subdivided into two major categories: the floating systems (moored or grazing) and the fixed systems (land-based or shelf mounted). This paper will cover the ocean engineering technology development recently completed, underway, or planned in the following technical areas associated with floating and fixed systems:

- o Platforms
- o Mooring and Foundations
- o Cold Water Pipes and Sea Water Systems
- o System Integration
- o Inspection, Maintenance and Repair

Major accomplishments in the last year, remaining problems, projects underway or planned in each of the above areas will be briefly covered in summary form.

Platforms

Selection of platform type and design characteristics will be influenced by a number of considerations including: net power requirements and the ability to efficiently house and support the heat exchangers, energy conversion equipment and auxiliary equipment; site selection and the attendant environmental loading forces expected over the life of the system including survivability of the 100-year storm; availability of construction facilities and ease of construction, maintenance and repair; and acquisition and life cycle costs involved.

Several configurations for a commercial floating platform/power plant have been investigated, including semisubmersible, spar shapes, ship-like forms, tuned sphere and disc shape (2, 3, 4). In addition, fixed offshore towers, guyed-towers and land-based concepts have also been prepared for commercial OTEC plant applications.

Based on the aforementioned considerations, commercial studies have indicated that larger plants are more cost effective from the standpoint of power production efficiency versus size. Large floating plants also minimize platform motions and consequent stresses induced to the cold water pipe. However, large size has limitations in ease of constructability, transportation and deployment, especially for the platform and cold water pipe.

Baseline designs for 40 MW Pilot Plants have been developed under funding from the U. S. Department of Energy. These include a multiple anchor leg catenary moored plantship (5), a grazing plantship (5), a single point tension anchor leg spar (6), and a shelf-mounted plant (7). The floating plantship concept still needs to undergo a rather extensive hull form development effort for the purpose of optimizing its seakeeping and seaworthiness (survivability) performance characteristics. The single point tension anchor leg spar presents serious technical problems due to its lack of redundancy and the concept may not be suitable in its present form. A critical unknown in the design of shelf-mounted system is the length of the discharge pipes in order to minimize re-ingestion and environmental impact. This will require the development of a valid hydrothermal plume discharge model supported by adequate site data on currents and water stratification (density, salinity, temperature). Another important design problem for shelf-mounted platforms is the ability to analyze the soil-structure interaction for the design of the platform and cold water pipe foundation.

One of the major efforts remaining is the total system integration of the OTEC components with the platform. One problem requiring resolution prior to commercialization is the development of a reliable, long life coupling to connect and perhaps disconnect the pipe from a floating platform. The dynamic action of the platform with a cold water

pipe attached remains to be experimentally validated. The ease of constructability of large platforms/plants (100 to 400 MW size) remains an area of concern for commercialization of large capacity systems.

A project on conceptual design studies of shelf-mounted OTEC systems was recently completed by Giannotti & Associates (G&A) and a final report is in preparation. Eight shelf-mounted platform and cold water pipe configurations illustrated in figures 1A and 1B were examined in a general manner considering advantages and disadvantages in design, construction, deployment and installation, operation, maintenance, repair and survivability. This project included examination of previous design studies viz., the shelf-mounted OTEC system baseline design study conducted by Gibbs & Cox (7) and the shelf-mounted conceptual design study by McDermott, Inc., (8) which proposed a marine railway concept for the cold water pipe.

Based on this preliminary review, all eight concepts were considered technically feasible. Selection of a specific configuration will be influenced by the factors noted in the first paragraph of this section. This report can help a designer in making tradeoff comparisons in a preliminary design stage. Some of the general findings of this study are the following:

- o All personnel facilities should be located above sea level for health and safety reasons, along with significantly reduced structural requirements for compensated systems.
- o Location of heat exchangers, condensers, and ammonia working fluid systems subsea with turbines, generators and related control equipment on a platform above sea level is a convenient layout. Special care must be given to minimize losses in the working fluid piping.
- o Subsea location of heat exchangers, condensers and other major sea water systems components will require a substantial volume of space in the lower section of the shelf-mounted platform. This will provide some blockage to environmental forces due to wave and current loading, especially during storms. This added loading will place greater requirements on the shelf-mounted foundations for the platform and CWP.
- o Platform and cold water pipe foundations located on a sloped shelf are very critical to the long-term structural integrity of the system.

- o Deployment and installation of slope-mounted platforms and cold water pipes is another challenging engineering task.
- o Inspection, maintenance and repair capabilities must be integrated into the basic design and accounted for in life cycle operating costs.
- o Large system construction techniques, which may be applicable to shelf-mounted systems of 40 MW capacity, have been demonstrated by the offshore industry. Much larger offshore structures now exist.
- o A critical problem for all shelf-mounted systems is the length of the discharge pipe required in order to minimize re-ingestion of the cold and warm water effluent.
- o Site selection must take into account the water circulation patterns and the water stratification in the area to ensure a reliable thermal resource.

A literature survey on the state of technology in bottom-mounted offshore platforms and pipes for applicability to OTEC systems designs was completed by G&A and used as a source of reference material for this study, and a final report is in preparation.

The forementioned findings on shelf-mounted systems identified several critical areas that require further research. Plans are being developed to conduct model tests of slope-mounted systems including assessment of the effect of blockage due to the subsea placement of heat exchangers and condensers. In addition, plans and guidelines are being developed to conduct additional at-sea tests on slope-mounted foundations.

As noted in references (2, 3, 4) and in other design studies, a number of concepts have been examined for floating OTEC systems and in most cases the cold water pipe (CWP) was permanently attached to the platform. Even though articulated joints or compliant pipes were used, the stresses induced by the platform motion were frequently excessive and beyond the design limits of the CWP. This was especially noted in the survival mode for the case of the 100-year storm. Based on these considerations, a concept was proposed for a permanently moored CWP that would be decoupled from a platform via a transition section prior to exposure to survival conditions. This concept was the basis for a design study for a Moored Pipe-Mobile Platform (MP-Squared) Project recently completed by G&A, and a final report is in preparation. This project involved conceptual design studies followed by model tests in the HYDRONAUTICS, Inc., Ship Model Basin (HSMB). Two conceptual designs were developed: one was ship-shaped, referred to as the large water plane (LWP) configuration, figure (2); and the other was a catamaran semi-submersible, referred to as

the small water plane (SWP) configuration, figure (3). The LWP provides a more economic surface platform and provides good stability in large sizes. The SWP provides excellent stability at all sizes. A range of platform sizes from about 370 to 660 feet were simulated to cover the 40 to 460 MW capacity range. The LWP and SWP were connected to the cold water pipe (CWP) by means of a transition platform, which is attached to the CWP to provide buoyancy for the pipe and attachments for the mooring lines to maintain the CWP in an upright moored configuration.

In Model tests at HSMB, both versions were subjected to 100-year storm wave loadings (37 ft. significant wave height) representing the Puerto Rico Site and simulated by Bretschneider wave spectra. Test results indicated that both versions would survive the storm loadings while moored and while disconnected. The LWP operated well for the large size plants e.g. 400 MW capacity, but the motions for the smaller sizes e.g. 40 MW, were too extreme for OTEC plant operations. The SWP operated well over the 40 to 460 MW range of sizes. The tests favored the SWP configuration because of the reduced motions. In addition to the advantages of decoupling the CWP to reduce loading forces during a severe storm, the platform can be disconnected to proceed to shore facilities for inspection, maintenance, repair or refit, and the total system need not be designed to withstand the 100-year storm conditions as a permanently moored platform. One disadvantage of this system is the possible need for self-propulsion or towing for the platform. Also platform detachment scenarios providing a safe haven for the platform during the storm and ease of attachment afterwards must be developed.

Mooring and Foundations

During the last year, emphasis has shifted from floating to fixed type platforms; and, therefore, corresponding emphasis has shifted from mooring system development to foundations. The same key problems and unknowns in the mooring area reported one year ago (9) still remain and are repeated below. A project assessing anchor holding capacity and work pertaining to slope-mounted foundations will also be summarized.

Mooring

Offshore floating OTEC platforms/plants, for generating electricity and transmitting power to shore by transmission cable, require deep water mooring systems. Such mooring systems are required to limit the movements of the platform, with coupled cold water pipe, and minimize flexure in the electrical umbilical cable used for power transmission. The sizes of these platforms range from about 70,000 tons for a 40 MW plant, to about 500,000 tons for a 400 MWe Commercial Plant.

Site selection for a moored OTEC power plant requires many tradeoff considerations including: proximity to shore to minimize electric power delivery costs; accessibility of an adequate cold

water source; sea floor terrain profile to avoid going around with the cold water pipe; sea floor conditions for mooring; and overall environmental loading conditions. Several key problems and unknowns still remain in the mooring system area and require further investigation. These are:

- (a) Reliable fatigue data and service life for 5-inch to 6-inch wire rope in the marine environment is not known with any confidence.
- (b) Polyethylene jacketing of wire rope has been proposed as a possible solution for corrosion-fatigue problems, however, its long term survivability and effectiveness is not known.
- (c) Other components such as chain, anchors, winches, and windlasses are not considered off-the-shelf items and quality assurance for the intended usage may be a problem.
- (d) A better method of predicting wave drift forces is desirable to reduce the uncertainty in the prediction of seaway loads to a realistic minimum.
- (e) While subject to environmental forces, the platform, cold water pipe and transmission cable are all moving and interacting. The degree of coupling needs to be more accurately estimated, and a better method for predicting the dynamic response of the total system is desirable.
- (f) Inspection, maintenance and repair procedures for OTEC mooring systems need to be developed.

A series of studies by Det Norske Veritas (10-13) suggested that multiple anchor leg catenary-type mooring systems are the most feasible for moored OTEC platform applications. The use of tension anchor leg systems with a single tension member such as that proposed in (6) is not desirable, based on current practice due to lack of redundancy.

Design of anchoring systems and foundations is highly site specific and, therefore, requires information and data on the engineering properties and characteristics of the sea bottom and sub-bottom of the designated site. Gravity core samples were obtained from the shelf area off of Kahe Point, Oahu during February 1981 as part of a sea bottom assessment program conducted by Lawrence Berkely Lab. (LBL) sponsored by DOE. Eight cores 1.5 meters in length and 2 partial cores 0.8 meters in length were recovered and analyzed by LBL to determine engineering properties including: shear vane strength, permeability, bulk density, grain density and size, and triaxial loading. Additional sea floor survey and sampling is desired at Kahe Point to further develop foundation requirements for the proposed POCE sites and at Keahole Point for the Sea Coast Test Facility. A report on the Geotechnical Analysis of the Kahe Point cores is in preparation.

Based on survey data available at Kahe Point and Punta Gorda, Puerto Rico, the University of Rhode Island, Brian Watt Associates performed a design study to assess anchor holding capacity. Major findings from Phase 1 are noted below:

- o For offshore Hawaii, the most promising procedure would use drilling and grouting of piles.
- o For offshore Puerto Rico, gravity embedment anchors seaward from the OTEC platform could be used in deep water where heavy sedimentation exists; alternatively, drilling and grouting of piles will be required near shore where the bottom is primarily rock.
- o Gravity embedment anchors are ineffective on slopes over 15°.
- o Tension loading on an anchor stock is approximately half the value measured at the surface at the deck handling machinery when the anchor is embedded in heavy sediment.
- o The cost of using very large gravity anchors may be approximately the same as for drilling and grouting.
- o Driven piles can only be used where deep sediments exist. OTEC sites generally have shallow overburden which dictates drilling and grouting piles.

The Naval Civil Engineering Lab is developing a data base on available analytical computer codes for analysis of soil-structure interaction problems in order to develop design procedures for determining the interaction effects between foundations, sea floor and sub-bottom strata. The engineering properties derived from the eight core samples will be used in this analysis. Additional survey data from the Kahe and Keahole Point sites is desirable for developing design guidelines for installing slope-mounted foundations.

Cold Water Pipe and Sea Water System

The OTEC sea water system (SWS) is made up of the warm and cold water pumps, inlet screens, piping, cold water pipe and discharge pipes. The inlet screens prohibit the entry of foreign objects or material into the SWS.

The SWS pumps present challenging design problems due to unprecedented high volume flow rates, low head rise, large SWS mass and capacity, and seaway motions of the platform. Platform heaving motions and/or large amplitude ocean waves can cause significant pressure differences across the pumps, resulting in dynamic effects on pump loading and power requirements.

The SWS piping includes all surge and holding tanks, connecting pipes and fittings, flow control valves, etc., as an OTEC platform-housed system.

Large conduits, fittings and holding tanks are subject to energy dissipative secondary currents and flow reversals and are characterized by slow response to pumping and/or platform motion-induced disturbances. Pressure surges, long response times and energy dissipation within the SWS piping must be addressed during design or they can significantly affect the operations of the other major components of the SWS, including the sea water pumps and heat exchangers.

The CWP is one of the critical major components of the system, mainly because of its size and large moment of inertia when handling during construction, transportation and deployment.

Floating and fixed OTEC systems require pipes of unprecedented dimensions and development of new techniques for construction and installation. For a floating OTEC plant of 40 MW capacity, the pipe would be approximately 10 meters in diameter and 900 meters long. In order to survive cyclic loading over its life, a suspended pipe must be articulated or compliant, and the platform-cold water pipe interconnecting joint or coupling is a critical component. Cold water pipes for shelf-mounted systems encounter problems associated with the installation and long-term stability of foundations and pipes mounted on slopes up to 40 degrees.

Cold water pipes deployed on the slope could be as long as 3000 meters before the desired cold water temperature is reached. Almost all of the CWP research to date applied to pipes suspended from floating platforms, with the present effort emphasizing shelf-mounted pipes.

Six preliminary baseline designs for suspended CWP's were completed for the pilot plant and were processed to supply a range of baseline design data and preliminary cost estimates for constructing these six CWP designs were developed. Results of these design studies are presented in (14) and (15) indicating that the concepts are feasible, but additional development is required to reduce risks. Various types of cold water pipes have been examined including: rigid pipes with flexible joints, compliant pipes, stockade pipes, and bottom-mounted buoyant pipes. Pipe materials considered included: steel, concrete, fiber reinforced plastic (FRP), elastomer, and thermoplastics. Fiber reinforced plastic has emerged as the leading pipe material, especially when combined with a syntactic foam core in a sandwich wall construction. This selection is based on compliancy of the material, relative ease in specifying properties, ease of deployment, corrosion resistance and relatively low cost. The results of preliminary FRP material tests indicated that long-term fatigue is an area which requires further test and evaluation. Adhesion between the core and skins of the sandwich construction after being subjected to long-term cyclic shear loading under tension and hydrostatic pressure needs further examination.

In order to assist in the CWP design process, three analytical computer models were developed to predict CWP responses to hydrodynamic loads and platform

motions. Two of these codes, NOAA/ROTEC and NOAA/DOE operate in the frequency domain, while the third code, NOAA/TRW is a time-domain model. The NOAA/TRW is a three-dimensional analytical code formulated to describe both non-linear beam and shell-like response to pipe loading. The results of laboratory scale model tests and at-sea test measurements of CWP accelerations and stresses (16) have been compared against these analytical models to assess the level of confidence in the existing analytical codes. The data shows reasonably good levels of agreement between model scale data, at-sea measurements and analytical predictions.

Laboratory tests of 1/100th-scale model FRP pipe verified that the full length of pipe can be deployed by horizontal tow-out and vertical upending. The structural response of this test pipe attached to a moored floating platform in operational and extreme sea states was well within design limits.

In order to further refine the analytical codes and obtain experience with larger scale systems, a 1/3-scale CWP at-sea test project was initiated in August 1981. Hawaiian Dredging and Construction Company (HDCC) leads a team consisting of TRW, Ershigs, Inc., Morris Guralnick Associates, Makai Ocean Engineering, Inc., and Edward K. Noda Associates in developing, testing, and evaluating a 10-ft. diameter, 1000-ft. long FRP cold water pipe, which is 1/3 scale of a 30-ft. diameter, 3000-ft. long pipe for the 40-MW plant. Phase I, design phase was recently completed including:

- o CWP design - dynamic loading analysis and vortex suppression design
- o CWP design - laminate design, buckling, joints and internal load analysis
- o Materials testing
- o Fabrication
- o Environmental conditions
- o Mooring design and CWP development
- o Instrumentation
- o Plans, drawings and specifications

Some of the accomplishments and findings of Phase I - Design are listed below:

- o Materials testing: Tensile tests of laminate configurations showed samples to have strength and lap efficiency within specifications; single lap laminates had slightly higher strength than multiple lap laminates; and high elasticity resins had superior strain capability. The proposed core material exhibited requisite compressive characteristics for CWP application. Laminate-core sandwich tests indicated good general strength, compatibility and bonding properties. There is need for examination of strength in tension to prevent transverse cracking. In joint tests, the butt and strap joint performed the best.

- o Instrumentation system specifications were prepared for instrumentation/sensors and data acquisition system.
- o Fabrication plan was prepared and the fabrication procedure is standard practice in the industry, with much experience on record.
- o CWP deployment plan including launch, tow, lowering, and attachment was developed and is similar to the method used for OTEC-1. A mooring system design and deployment plan was also developed.
- o Environmental conditions including current and wave conditions for operational and survival modes were assessed.

The sketch in figure (4) illustrates the design approach for the 1/3-scale at-sea test program and shows a 10-ft. diameter by 1000-ft. long FRP CWP. In order to facilitate handling and construction and to improve cost effectiveness, the dimensions of the CWP to be constructed and tested is expected to be 8-ft. diameter by 400 ft. long. The at-sea test portion of the program, starting in March 1983, is subdivided into Phase II for conducting tests of the CWP suspended from a moored barge; and Phase III to conduct tests of deployment and installation of the same pipe on foundations prepared on the 40 degree (approx.) slope off of Keahole Point.

In both Phases, experience will be gained in at-sea handling and deployment of the cold water pipe. For the suspended pipe test (Phase II), measurements will be made to determine the structural stresses and strains due to motions imparted to the pipe by wave and current loading. Such data will be used to further validate the analytical computer codes. For the slope-mounted pipe test (Phase III) the pipe will be accurately deployed on a previously installed bottom foundation located on the 40 degree slope. The foundation design must be based on the properties and characteristics of the sloped bottom and sub-bottom and must be capable of long-term slope stability. This installation is a precursor for similar future projects involving foundation design and installation on sloped bottoms.

Techniques for geotechnical measurements floor slope stability and sub-bottom survey will also require investigation to ensure that data derived can be accurately stated in engineering parameters needed for foundation design on steep slopes.

In April 1981, the OTEC-1 system terminated operations in Hawaii, and a decision was made to decouple the CWP from the surface vessel and lower it to the ocean floor for storage at a depth of 4500 ft. The sketch in figure (5) illustrates the OTEC-1 CWP in an upright configuration, due to the syntactic foam collar at the top which provides reserve buoyancy. The State of Hawaii expressed interest in using the CWP, consisting of a cluster of three 4 ft. diameter polyethylene pipes, at their Sea Coast Test Facility. This recovery exercise will enable gaining experience in handling the pipe.

Recovery procedures are basically the reverse of installation procedures. Experience in recovery is also applicable for major maintenance and repair scenarios. The Navy plans to participate in this recovery task, since it provides an ideal deep ocean salvage exercise.

Plans to recover the pipe involve severing the 1-3/8" chain at the base of the pipe in order to release it from the anchor clump and allow it to rise to the top. The Navy submersible TURTLE will be used to inspect the pipe and perform the cable sever task. As the pipe ascends vertically, one vessel will be used to attach the pipe collar on the surface. Another vessel with a line attached to the bottom will be used to tow the bottom of the pipe in the opposite direction of the other vessel holding the top of the pipe. Once the pipe is horizontal, it will be towed to the Sea Coast Test Facility for their future installation of the CWP on the slope.

System Integration

The system integration process is crucial in developing a reliable, cost-effective design that is easy to install, operate and maintain. In order to meet physical and operating requirements and achieve overall system performance. It is usually necessary to perform tradeoff analysis between major subsystems including, platforms, power systems, sea water systems, mooring and electrical cable and establish requirements where interfaces exist. Critical interfaces include: the platform and cold water pipe; the moorings and platform; electrical cable and platform and mooring system; and others depending on the system configuration.

The design of the subsystems and the overall system is greatly dependant on utilizing a full range of environmental data including meteorological, oceanographical, and geotechnical. This data must be in a form suitable for engineering use in design. Overall data requirements have been specified by engineers and naval architects involved in the OTEC design process and have been summarized for reference use (17).

Another important consideration is the development of classification requirements for insurability and safety. Very close liaison is being maintained with regulatory bodies such as the U. S. Coast Guard and with ship and platform classification societies such as Det Norske Veritas and the American Bureau of Shipping. Inspection, maintenance and repair requirements must be integrated into the overall system design. A discussion of this important area follows.

Inspection, Maintenance, and Repair

The enormous size and complexity of OTEC systems, deep-water operation, proportionately greater investment risk, and expectations for long-term survivability with a high confidence factor place substantial requirements on the design, deployment, operation, and maintenance of such structures. Preliminary studies of deep-water OTEC platforms indicate that the inspection, maintenance, and repair over a 30 year life could cost as much as half of the total life cycle costs. In order to

minimize the costs associated with IM&R and to minimize catastrophic risk, it also seems logical to improve structural designs, provide sufficient structural redundancy, and integrate IM&R requirements in the design process. There are many trade-off considerations versus cost that must be made.

Assuming that present-day devices in use and under development are suitable for deep-water operation, the main design consideration will be focused on the overall system approach; the strategic location of built-in sensory devices; and integration of systems and techniques which can be remotely operated to perform basic IMR functions.

Floating and shelf-mounted OTEC systems can be developed in various kinds of configurations and involve deep-water operations. Preliminary IMR studies (18) have been performed and have produced the following significant findings which must be taken into account for future OTEC designs:

- o The majority of inspection will be visual, relying on divers to some extent, but due to depth limitations, primarily on remotely operated vehicles (ROV). Existing NDT techniques such as ultrasonics, mag particle, piano wire measurements will be the primary non-visual inspection methods employed.
- o Almost all OTEC inspection tasks requiring only observation and photographic/video recording can use available equipment and techniques.
- o The majority of OTEC inspection tasks requiring the use of NDT to determine the condition of OTEC components and structures can be performed on a routine basis by divers to a depth of up to 300 meters and on a special basis to a depth of 460 meters, employing currently available techniques and equipment.
- o If a multi-anchor-leg mooring system is used, permanent anchoring may be more effectively achieved with the use of piles or piled templates instead of fluke anchors. Otherwise the desired 30-year life requires periodic inspection of the entire mooring system with periodic replacements, including the anchor.
- o Both the divers and undersea vehicle operational ability is severely restricted either where there are significant oscillations caused by vortex shedding of the CWP, or where current velocity exceeds approximately 2 knots.
- o Underwater repair of a suspended CWP must be accomplished by either raising the CWP to the surface for major repair of severe damage; or if the damage is minor, it may be possible to attach a patch or sleeve section.

Based on these several recommendations which appear significant for use in future OTEC work, these items which may impact design, cost or technological risk are as follows:

- o Continuous monitoring of the CWP for bending strain; torsional rotation, tensile strain and deflection, will enable continuous assessment of the CWP forces and facilitate operational control of a floating platform.
- o Below 500 meters water depth, the CWP design should either be sufficient to require no maintenance or should be designed for remote maintenance mainly relying on ROV capabilities. This conclusion is based on current limitations of divers to depths less than 500 meters and the limited capability of manned submersibles. IM&R of the platform/CWP interface is of prime interest. Therefore, a platform-CWP disconnection capability would provide access to the interior of the CWP and facilitate IM&R operations.
- o Any cold water intake screen at the bottom of the CWP should be a coarse mesh in order to limit maintenance and cleaning requirements. Fine screens, if required (e.g., traveling screens, self-cleaning) should be located near the top of the CWP.

In addition to inspection and NDT equipment and methods, present and future needs require that special emphasis be placed on training of inspectors/surveyors and development of a comprehensive data acquisition and assessment program.

In early 1981, Det Norske Veritas completed a study to develop specific requirements for design, fabrication, and inspection/maintenance/repair for OTEC hulls, CWP and mooring systems (19). The study was undertaken to give recommendations for modifying current IM&R requirements so as to obtain an optimal solution considering all critical costs throughout the lifetime of the OTEC plant. Measures for reducing the failure and deterioration susceptibility in terms of improved material qualities, protection against corrosion and abrasion, reduced stress levels, improved construction control, etc., were evaluated and related to the corresponding reduction in inspection, maintenance and repair. In summary, Det Norske Veritas IM&R study (19) developed the information listed below:

- (a) Safety items and their relation to in-service inspection
- (b) Classification of OTEC sub-systems according to their accessibility for IM&R
- (c) Specification of IM&R procedures and hardware for different OTEC sub-systems

- (d) Requirements for IM&R depending on the structural materials of each sub-system
- (e) Definition of levels of redundancy
- (f) Recommended safety criteria in terms of failure mode, sub-system accessibility and level of redundancy.

3. SUMMARY

The material presented in this paper is broad in scope and is by no means an in-depth treatment of the numerous important technical issues being addressed in the development of OTEC ocean engineering in the U. S. Based on the current direction toward shelf-mounted and land based systems, current research and development is emphasizing this area; while work on current projects pertaining to floating systems is being phased down. However, there are critical areas with varying degrees of technical risk for both fixed systems (shelf mounted and land based) and floating systems (moored and grazing) which require further research and validation. These include: large cold water pipes suspended from platforms or installed on steep slopes with requirements for life expectancy requirements on the order of 30 years; foundations to support slope-mounted platforms and cold water pipes for this long duration; materials that withstand long-term corrosion and fatigue for cold water pipes, mooring lines and electrical cables; electrical umbilical cables which demonstrate electromechanical integrity to withstand the flexure and other problems and hazards of the ocean environment; deployment, installation and operation of large systems subject to sustained environmental forces over a 30-year period including 100-year survival force conditions; system integration to ensure compatibility of platform coupled pipes, and electrical cables, and foundations or moors to provide the stability for reliable long-term operation; and inspection, maintenance, and repair capabilities over the life of the system. In FY 83, technical problems associated with shelf-mounted or land-based systems will be given highest priority in the DOE/NOAA Ocean Engineering Technology Development Program.

Current technology development efforts in the U. S. are designed to systematically identify the remaining problems, and conduct research and development to minimize risks, reduce cost, and provide a commercial incentive program to stimulate industry for the rapid implementation of the OTEC concept.

The rapid implementation of new and innovative alternate energy sources, such as OTEC, is of paramount importance to the United States. The rapid depletion of oil and natural gas, and the greater dependence upon foreign sources heighten the urgency of deploying effective and efficient alternate energy sources.

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CONCEPT 1 - SINGLE PLATFORM WITH
SUBMERGED PLANT (G&C
BASELINE DESIGN

CONCEPT 2 - CANTILEVERED TOWER WITH
MODULAR SUBMERGED PLANTS

CONCEPT 3 - MULTIPLE TOWERS WITH
SUBMERGED POWER PACK

CONCEPT 4 - SPM VESSEL WITH
SUBMERGED POWER PACKS

Figure 1A. Shelf-Mounted OTEC Platform Concepts 1-4

CONCEPT 5 - ARTICULATED TOWER
WITH POWER PACK

CONCEPT 6 - GRAVITY STRUCTURE
WITH MOON POOL
POWER PACK

CONCEPT 7 - GRAVITY STRUCTURE
WITH ANNULUS
POWER PACK

CONCEPT 8 - GRAVITY STRUCTURE
WITH CANTILEVERED
TOWER AND MODULAR
POWER PACKS

Figure 1B. Shelf-Mounted OTEC Platform Concepts 5-8

Figure 2. Large Water Plane (LWP) Configuration of Moored Pipe/Mobile Platform and Model Test

Figure 3. Small Water Plane (SWP) Configuration of Moored Pipe/Mobile Platform and Model Test

Figure 4. 1/3 Scale CWP At-Sea Test Program

Figure 5. OTEC-1 Cold Water Pipe and Mooring