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**OCEAN THERMAL ENERGY CONVERSION POWER SYSTEM
DEVELOPMENT-I**

Phase I—Final Report

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December 18, 1978

Work Performed Under Contract No. EG-77-C-03-1568

**Ocean Systems
Lockheed Missiles & Space Company, Inc.
Sunnyvale, California**

U.S. Department of Energy

Solar Energy

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FOREWORD

The Lockheed Missiles & Space Company, Inc. (LMSC), together with corporate team members and subcontractors, has completed all requirements of the Power System Development-I (PSD-I), Phase I, Contract (EG-77-C-03-1568) for the Department of Energy, Division of Solar Energy. This report presents a summary of the 16-month study project that consisted of the following tasks:

- o Task 1, Conceptual Design for a nominal 25-MW(e) power system module applicable to the 100-MW(e) Demonstration Plant, a 5-MW(e) scaled proof-of-concept power system, and 1-MW(e) heat exchanger test articles
- o Task 2, Preliminary Design including a 50-MW(e) commercial plant size power module Conceptual Design, and 10-MW(e) Modular Application Power System and Heat Exchanger Test Articles Preliminary Designs
- o Task 3, Phase II Plan (Proposal) for the detail design, fabrication, checkout, delivery and installation, and test operation support of the 10-MW(e) Modular Application Power System and Heat Exchanger Test Articles

The corporate team members were:

- o Lockheed Electronics Co. (LEC), Houston, TX
- o Lockheed Shipbuilding and Construction Co. (LSCC), Seattle, WA

The subcontractors were:

- o AIRCO Cryogenics, Newport Beach, CA
- o Bechtel National Inc. (BNI), San Francisco, CA
- o Foster Wheeler Energy Corp. (FWEC), Livingston, NJ
- o General Electric, Medium Steam Turbine Division, Lynn, MA
- o Rotoflow Corporation, Los Angeles, CA

This Final Report includes the following:

1. Attachment 1, Conceptual Design Report LMSC-D566744
2. Attachment 2, consisting of
 - o Volume I - Preliminary Design Report, LMSC-D630248
 - o Volume II - Appendixes A, B, and C
 - o Volume III - Appendixes D, E, and F
 - o Volume IV - Appendix G
 - o Volume V - Appendixes H, I, J, and K

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Section 1
INTRODUCTION AND SUMMARY

The objective of the Ocean Thermal Energy Conversion (OTEC) Power System Development-I (PSD-I), Phase I, study was to develop conceptual and preliminary designs of closed-cycle ammonia power system modules for the 100-MW(e) OTEC Demonstration Plant, the 400-MW(e) Commercial Size Plant, and Heat Exchanger Test Articles representative of the full-size power system module design.

1.1 INTRODUCTION

The PSD-I, Phase I, effort was performed from August 1, 1977 through December 4, 1978 under the United States Energy Research and Development Administration (later the Department of Energy, Division of Solar Energy), Contract EG-77-C-03-1568. The three tasks performed were:

Task 1: Conceptual Design. Develop conceptual designs for the following: the full size [25-MW(e) nominal] closed cycle ammonia power system module for the 100-MW(e) demonstration plant; the scaled [5-MW(e) nominal] proof-of-concept power system; and the 1-MW(e) heat exchangers (evaporator and condenser), representative of the 25-MW(e) design. The major issues for conceptual design are (1) the heat exchanger thermal size, material and tube water-side fouling countermeasures, (2) the power system module net power output size, availability and reliability, and busbar power cost, and (3) internal and external power module configurations and heat transfer enhancement techniques.

Task 2: Preliminary Design. Develop conceptual designs for a 40- to 50-MW(e) closed-cycle, ammonia commercial size plant power system module whose heat exchangers are immersed in seawater and whose ancillary equipments are in

a shirt-sleeve environment. Develop preliminary designs for a Modular Application Power System (MAPS) sized at 10-MW(e) whose design and construction is to be analogous to the 50-MW(e) module, except for heat exchangers which are to be designed and fabricated using titanium tubes. Develop preliminary designs for heat exchanger test articles (HETA), an evaporator and condenser, representative of the 50-MW(e) heat exchangers, designed and constructed of aluminum alloy suitable for seawater service, to be tested on the OTEC-1 platform.

Task 3: Phase II Plan (Proposal). Provide a detailed Phase II Plan (Proposal) for providing Heat Exchanger Test Articles to be installed and tested on the OTEC-1 platform, and for providing power system(s) for the planned Modular Application plant(s).

1.2 STUDY SUMMARY

Selection of power module and equipment configurations, materials, and fabrication methods was based on a number of trade studies, the OTEC environment, power system availability, cost, technology state-of-the-art, and manufacturing state-of-practice and techniques. The results of these studies are as follows:

1. Heat exchangers were found to decrease in cost per unit of power with increasing size within the study range. At the 50-MW(e) size, heat exchanger costs per unit of power were approximately 10 percent less than at the 25-MW(e) size.
2. Aluminum heat exchangers were found to be less expensive on a life-cycle basis than titanium or stainless steel heat exchangers.
3. For the immersed configuration, the selected depth of the heat exchanger top is 20 ft below the water line, to minimize containment vessel costs.
4. Spherical shell heat exchangers are cost effective and minimize system complexity through the use of the generous vapor gallery.
5. Multi-level liquid ammonia distribution using irrigation tubes ensures optimum tube wetting while avoiding tube flooding.
6. Ammonia-side heat transfer enhancement is slightly cost effective. Seawater-side heat transfer enhancement appears not to be cost effective.

7. High operational availability of the power system is provided by redundant critical equipment and by access for scheduled maintenance.
8. Variable-flow pumps are cost effective at sites where there is a moderate seasonal ΔT variation.
9. Multiple seawater pumps reduce the length of the seawater path and improve system availability.
10. Radial inflow turbines are slightly lower in cost than axial flow turbines and are not appreciably affected by power system vapor quality.
11. The biofouling countermeasure schemes (chemical and mechanical) of chlorination and M.A.N. brushes are effective and compatible with the heat exchangers.
12. Equipment state-of-practice provides low development and minimum schedule risks.
13. Fully integrated power modules externally adaptable to spar-type platforms are least expensive, lend themselves most readily to scheduled maintenance, and require least capital for construction facilities.
14. The Modular Application Power System module is a self-contained design especially planned for the modular experiment. It provides flexibility in equipment and equipment arrangements, demonstration of technical feasibility and verification of OTEC economics.
15. Heat Exchanger Test Articles are representative of full-sized heat exchangers. The vapor augmentation and liquid distribution control designs provide the ability to verify thermal and fluid dynamic performance and mechanical characteristics, and the test articles can be used to obtain operating characteristics.

The Conceptual Design Report (LMSC-D566744) and the Preliminary Design Report (LMSC-D630248) are included as Attachments 1 and 2 to this report. These attachments present the conceptual design of the 25-MW(e) and 50-MW(e) power system modules, and the preliminary design of the 10-MW(e) modules and the heat exchanger test articles.

A Phase II Plan (Proposal) was submitted to DOE under LMSC-D626994, 2 October 1978 to perform the detail design, to fabricate and manufacture, to checkout and deliver, and to support the installation and test operations of the 10-MW(e) module and the test articles.

1.3 PROJECT TEAM

Bearing in mind the importance of the OTEC Power System Development projects, the best qualified team members (subcontractors) were selected. An overview of the project team as it was during the contract period ending 4 December 1978 is given in Fig. 1-1. They are listed as follows:

Foster Wheeler Energy Corporation (FWEC). FWEC was responsible for verifying heat exchanger thermal performance and the overall heat exchanger design.

Fig. 1-1 PSD-I, Phase I, Project Team

Bechtel National, Inc. (BNI). BNI was responsible for the design of the ammonia cycle, ammonia auxiliaries, and power control and distribution systems.

Turbine Subcontractors. The choice of a single turbine-generator supplier was not determined at contract start. The availability of axial and radial inflow turbines, and the fact that one subcontractor specializes in only one type of turbine, made it prudent to have two subcontractors. During Task 1, General Electric provided data on the axial flow turbine performance. During Task 2, AIRCO provided axial turbine performance data.

The radial inflow turbine is the first choice with the axial inflow machine as a backup.

- o Rotoflow Corporation. Rotoflow was responsible for the radial inflow turbine and turbine control design, and the selection of its matching electrical generator.
- o AIRCO Cryogenics. AIRCO was responsible for the axial flow turbine and turbine control design and the selection of its matching electrical generator.

Lockheed Electronics Company (LEC). LEC, a company of the Lockheed Corporation, was responsible for the design of the PSD-I Data Acquisition and Control System (DACS).

Lockheed Shipbuilding and Construction Co. (LSCC). LSCC, a company of the Lockheed Corporation, was responsible for the establishment of requirements for facilities and equipment, and schedules and costs for the assembly of power system modules.

1.4 PROJECT SCHEDULE

Figure 1-2 presents an overview of the PSD-I, Phase I schedule. The total period of performance was 16 months, 1 August 1977 to 18 December 1978. Task 1 (Conceptual Design) was performed from August 1977 through January 1978,

Fig. 1-2 Power System Development Schedule

culminating in delivery to DOE of the Conceptual Design Report, LMSC-D566744, dated 30 January 1978.

Task 2 (Preliminary Design) was performed from February 1978 through 18 December 1978, the closure of the contract period. This effort resulted in the Preliminary Design Report, LMSC-D630248, a draft of which was delivered to DOE on 2 October 1978. The final report with DOE's comments incorporated, is attachment 1 to this report.

Task 3 (Phase II Plan) was started in June 1978 and culminated in a Phase II Plan Proposal, LMSC-D626994. This technical proposal was delivered to DOE on 2 October 1978.

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Section 2

PROJECT REQUIREMENTS AND GUIDELINES

This section presents the program requirements from the commencement of the contract, through evolutions and changes, to the final requirements for contract completion.

Task 1, Conceptual Design, was successfully concluded, following DOE groundrules and guidelines as presented, and the Conceptual Design Report was delivered to DOE (see also Attachment 1) on 30 January 1978. Task 2, Preliminary Design, was initiated in early February 1978 under the basic ground rules. On 10 March 1978, some of these ground rules were modified by DOE directive, "OTEC PSD Preliminary Design Guidance," which was incorporated in the design tasks. Additional clarification was received in a meeting between LMSC and DOE representatives, and was documented through a conference report (PSD-CR-78-01) dated 22 March 1978 (see section 2.2 for guidelines). Task 3, PSD-I Phase II Plan (Proposal), guidance was received June 19, 1978 and completed with the proposal submitted on October 2, 1978.

2.1 TASK 1: GROUND RULES AND GUIDELINES

The DOE groundrules and guidelines for Task 1 were to

1. Include only those basic elements in the power module required for a power generating system, i.e., the heat exchangers, turbine-generator, seawater pumps, ammonia plumbing and pumps, ammonia and electric power auxiliaries, and the control system, excluding platform-related components.
2. Design the heat exchangers as horizontal shell and tube types, with heat transfer enhancement, if cost effective.

3. Design the power system with a temperature difference (ΔT) of 40°F , $+4^{\circ}\text{F}$ or -10°F between warm and cold water.
4. Size the power module to 25-MW(e) net, with the objective of determining the size of the power plant and its components, to minimize the cost of delivered electricity.
5. Modularize the power system such that a complete plant could grow to 100-MW(e) net by the addition of more modules.
6. Incorporate a thirty-year design life with 1,000 start/stop cycles and 6,000 hr/year operation. (This was interpreted to mean periodic replacements of components if economically feasible.)
7. Design the warm seawater subsystem with a pressure drop of 10 ft of water, and the cold seawater subsystem with a pressure drop of 15 ft of water. These values may be varied if shown to be technically and economically feasible.
8. Use ammonia as the working fluid.
9. Design for a biofouling heat transfer resistance not to exceed

$$0.0005 \frac{\text{hr-ft}^2\text{-}^{\circ}\text{F}}{\text{BTU}}$$

10. Ensure module operability of 90 percent at a 60 percent confidence level.
11. Evaluate configurations of modules internal to the platform and detachable modules external to the platform.

2.2 TASK 2: GROUND RULES AND GUIDELINES

The DOE groundrules for Task 2 were to

1. Size the Commercial Plant Power system module at 50-MW(e) net.
2. Designate "Modular Application" as the new nomenclature for the previous Proof-of-Concept pilot plant. The Modular Application power system module size is to be 10-MW(e) net (at a ΔT of 40°F), instead of 5-MW(e), and its design and construction is to be analogous to the 50-MW(e) module.

3. Select the heat exchanger test article size (to be tested on OTEC-1) based, in part, on the following:
 - a. Compatibility with the OTEC-1 system specification for cold and warm water, and ammonia supplies
 - b. Ability to generate data for design of larger heat exchanger including liquid entrainment, pressure drop, and working fluid (ammonia) distribution
 - c. Consideration of a reduction of the test article cost by significantly reducing its size, as long as the desired data can still be obtained
4. Immerse the Modular Application and Commercial Plant power system heat exchangers in seawater with the ancillary equipment maintained in a shirt-sleeve environment. The depth of water at the top of the heat exchangers will be between 0 and 20 ft.
5. Determine power system costs, with consideration given to the heat exchangers being constructed at facilities dedicated to OTEC.
6. Limit the predicted overall plant availability to 0.9 with subsystem allocations of reliability to achieve this overall system availability.
7. Construct the heat exchanger test article (for testing on OTEC-1) of aluminum alloy suitable for seawater service.

In addition, the following guidelines were provided by DOE:

1. Evaluate the Modular Application and Commercial Plant power system and include consideration of mineral scaling, corrosion, stress corrosion, and corrosion fatigue caused by surface enhancement and other factors.
2. Expand the analysis of flow-induced vibrations in the preliminary design beyond what appears in the Conceptual Design Report.
3. Assess safety code aspects of rolled and welded 5052 aluminum tubing and also that of the tubesheet.
4. Consider the heat exchanger waterboxes to be integral with the containment vessel in the preliminary design effort and reflect this change in the power module cost.

5. Establish the sensitivity of the power system cost to the turbine cost for turbine costs in the range of \$40 to \$100/kW with efficiencies of 83 to 86 percent
6. Explore a modular approach to the heat exchanger design for the 50-MW(e) power system

Conference notes dated 22 March 1978 also stated scope and schedule for Task 3 Evaluation Criteria, Preliminary Design Report and Final Report, and questions or clarifications on the subject. Lockheed submitted a set of questions on 5 June 1978 to the Government Technical Representative (GTR) in order to clarify the study bases. The GTR answers were received by letter dated 5 July 1978, and were incorporated in the reports.

Summarizing the letters, and subsequent DOE direction, Task 2 supplemental objectives were to

- o Develop conceptual designs for a 40- to 50-MW(e) net closed-cycle ammonia commercial plant power system module whose heat exchangers are immersed in seawater and whose ancillary equipments are in a shirt-sleeve environment.
- o Develop preliminary designs for a MAPS sized at 10-MW(e) net whose design and construction, including material selection, is to be analogous to the 50-MW(e) module, except for heat exchangers which are to be designed and fabricated using titanium.
- o Design the 10-MW(e) MAPS to be self-contained and self-sufficient, except for ocean systems and power transmission.
- o Design the 10-MW(e) MAPS to have a 30 year life.
- o Base power system availability on 8,760 hr/yr.
- o Develop heat exchanger test articles (an evaporator and condenser) representative of the 50-MW(e) heat exchangers, designed and constructed of aluminum alloy suitable for seawater service, and to be tested on OTEC-1.
- o Design the heat exchanger test articles to have an operating life of 4 years and a total "shelf life" of 10 years

The reference ocean platform was specified by DOE as a surface vessel with the heat exchanger immersed in seawater to a design depth of 0 to 20 ft measured from the top of the heat exchanger. For the 50-MW(e) module, the OTEC 400-MW(e) Plant Ship, defined in the Platform Configuration and Integration Study, was used as the reference platform.

2.3 TASK 3 GROUND RULES AND GUIDELINES

The Scope of Work for Task 3 Phase II Plan (Proposal) consists of two tasks:

- o Task 1, Heat Exchanger Test Articles (and associated effort to design, build, deliver, etc).
- o Task 2, 10-MW(e) Modular Application Power System (and associated effort to design, build, deliver, etc).

Note: Task 2 module is to be self-contained and without seawater pumps.

Each Task of Phase II had five defined activities:

1. Detailed design
2. Develop, fabricate, checkout, deliver and provide installation support
3. Design, fabricate and deliver any special ancillary equipment
4. Participate in designated working groups
4. Provide support to test operations

In addition, Task 1 had one delivery point (San Francisco) while Task 2 had two delivery site options (San Francisco and New Orleans) and two Schedules (B - starting Jan 1979, and C - starting April 1980).

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Section 3

POWER SYSTEMS TECHNICAL STUDY AND RESULTS

This section highlights the end results of the PSD-I, Phase I, study. Cost and technical trades were performed leading to significant design decisions, such as module size, test article size, material selection, heat transfer enhancement, heat exchanger shape, biofouling countermeasures, and operational guidelines. LMSC selected state-of-the-art heat transfer techniques for this study. Standard commercial practices of the Lockheed team members were used in arriving at a concept for an OTEC commercial power system which would be life-cycle cost-effective and would minimize developmental risks. Through the stages of design, conceptual and preliminary, the objective was to use present state-of-the-art practices. Therefore, the OTEC power cycles use equipment and components which have been extensively proven in the chemical and refinery industries.

The features of the derived power systems, their major equipment, and alternative power system modules are discussed in this section. Each will be discussed as to the design evolution throughout the contractual period, and resultant baseline design configurations.

Configurations. The baseline power system configuration is designated as the "immersed-segmented power system," with "immersed" describing the 20-ft design depth for the heat exchangers, and "segmented" indicating the several power system segments (major hardware subsystems), which are installed separately on the ocean platform to collectively form the power system. These subsystems can be removed as separate segments for major overhaul or replacement. The alternative immersed power system concept combines all the power system components, including the heat exchangers, into one integral module designated

as the "immersed-unitized power system." This complete module is attached to the ocean platform as a unit and is removed as a unit for major overhaul or refurbishment.

An alternative power system conceptual configuration is the "submerged power system" in which the heat exchangers are deeply submerged, up to a depth of 300 ft, as for installation on a spar platform. The deeply submerged heat exchangers are more nearly pressure balanced, thereby reducing the structural loads, and hence weight and cost of the heat exchangers. The operating environmental conditions for the heat exchangers are also reduced with a spar platform. Seawater circuit dynamics are reduced for a spar as compared with a surface platform using immersed heat exchangers. The submerged concept uses components identical to the immersed configuration.

Heat Exchangers. Monolithic spherical shell aluminum heat exchangers were selected. They reduce system complexity and cost by providing space within the shell for installation of the mist extractors, all liquid-ammonia distribution piping, and integral sumps.

- o Location of the hook-and-vane mist extractors internal to the heat exchanger shell eliminates a separate pressure containment vessel and allows simple gravity drainage of the collected liquid ammonia into the evaporator sump.
- o Improvement of the vapor flow distribution and flow loss reduction with the large gallery of the spherical shell.
- o Attachment of intersecting cylindrical structures to the spherical shell (Fig. 3-1) eliminates the need for complex, doubly curved ring forgings.
- o Difference in cost between a spherical shell and a cylindrical shell with appropriate ring stiffeners is not significant.

Methods to ensure optimum heat transfer to the ammonia working fluid were studied, resulting in improved control of the liquid ammonia film by gravity irrigation of the tube bundle in sections with an optimum number of tubes per

Fig. 3-1 Conceptual Design — Baseline (Immersed-Segmented) 50-MW(e) Power System

column. Adequate tube wetting is obtained with this method and is provided at a reflux rate which reduces the cost and the parasitic power of the ammonia distribution pumping system.

Experimental evaluation of heat transfer enhancement techniques resulted in the selection of circumferential fins on the exterior of the tube which significantly increase ammonia heat transfer rates with no increase in parasitic power. The fins also improved the uniformity of flow of the thin film.

Optimum tube size was selected after consideration of total power system cost, overall performance, tube material and fin configuration. For aluminum 5052, the tube selected is 1.5-in. OD, has a nominal wall thickness of 0.1025 in., between 15 to 20 fins per inch, and a fin height of 0.025 in. Aluminum is the most cost-effective tube material over the 30-year life of the power system, allowing for heat exchangers replacement at intervals of 10 years or more.

Incorporation of double tubesheet reduces the thickness, weight, and cost of the tubesheets. Structural analysis has confirmed that the inner tubesheet can be annular, using only the outer tube rows for stiffness.

Control of biofouling in heat exchangers is ensured by a combination of chemical and mechanical systems. Low level chlorination is used to control biofouling, and a M.A.N. brush device in each tube is used periodically to clean the tubes by reversal of the seawater flow direction.

Rotating Machinery. Redundancy of equipment, components, or circuits is used to ensure continuous operation in case of a failure of components in a critical function. Multiple ammonia condensate and distribution pumps are incorporated to ensure continuous ammonia feed. Multiple seawater pumps for each heat exchanger allow a high level of power system output in the event of

a single pump malfunction. Two types of turbines (radial inflow and axial flow), each capable of meeting all requirements of the turbine-generator system, have been carried throughout the conceptual and preliminary designs. These turbines are adaptations of existing commercial hardware. First choice is the radial inflow machine, with the axial inflow unit as a design backup.

Power System. Existing commercial practices have been used so that the design ensures minimum developmental risk coupled with a high confidence in manufacturing schedules. Maintainability has been carefully considered throughout all facets of the power system concept. Routine maintenance has been accommodated by a shirt-sleeve environment and physical access to all machinery. Equipment removal and replacement is readily accomplished in all configurations. Ancillary equipment is also in the shirt-sleeve environment. Economy of scale indicates that a 50-MW(e) net output would be the most cost effective for a commercial OTEC plant with a 400 MW(e) overall output.

3.1 25-MW(e) POWER SYSTEM MODULE (TASK 1)

Trade studies were performed on heat exchangers, seawater pumps, turbine generators, power module construction, and ammonia plumbing as a function of heat exchanger size to determine minimum cost per kW. A 10 percent cost reduction per unit of power was obtained by increasing the module size from 25- to 50-MW(e). Using 5-MW(e) building blocks to obtain a 25-MW(e) unit increases the cost by 40 percent over that of a single 25-MW(e) unit. Ammonia heat transfer enhancement at a ΔT of 36 °F decreases the cost by 3 percent. Seawater-side heat transfer enhancement did not appear to be cost effective.

The number of seawater pumps for the condenser and evaporator was the subject of a trade study concerned with cost and power loss in case of pump failure. Multiple pumps are definitely favored over a single unit.

Turbine-generator cost per unit of power decreases with an increase in power output. However, the cost reduction becomes almost zero for 20-MW(e) or larger radial machines.

Ammonia system trade studies revealed that plumbing and heat exchanger costs are at a minimum for vapor velocities of 140 to 160 fps and condensate velocities of 20 to 25 fps.

3.2 50-MW(e) COMMERCIAL POWER SYSTEM MODULE (TASK 2)

Conceptual design of the 50-MW(e) power system module for the OTEC commercial plant was based on minimizing life-cycle costs. State-of-the-art heat transfer technology and existing commercial fabrication practices were used in the design of the heat exchangers. Horizontal shell-and-tube heat exchangers satisfy these requirements. This approach resulted in a commercial power system concept with predictable hydraulic and thermodynamic characteristics. These heat exchangers could be manufactured today. Conceptual design features for the 50-MW(e) module are shown in Fig. 3-1.

The 50-MW(e) module was based on the basic work performed for and reported in the Conceptual Design Report (Attachment 1). The size was increased from the previous 25-MW(e) conceptual module to a 50-MW(e) module. Module power output and allocations are given in Table 3-1. The Reference Baseline column provides data for the 10 ft warm seawater system head loss and the 15 ft cold seawater system head loss. The Optimized Geometry column represents the conditions for the 400-MW(e) surface platform.

Three power module configurations for the 50-MW(e) evolved from the studies:

- o Immersed-Segmented
- o Immersed-Unitized
- o Submerged-Unitized

The selected baseline arrangement for the immersed heat exchangers (DOE guideline), is the segmented module. Heat exchanger data for the horizontal shell-and-tube evaporator and condenser are given in Tables 3-2 and 3-3 respectively. Arrangement drawings, platform interfaces and assembly sequences and facilities are presented in Attachment 2.

Table 3-1

50-MW(e) COMMERCIAL POWER SYSTEM
MODULE-POWER ALLOCATIONS

<u>Item</u>	Power (MW) (except as noted)	
	<u>Reference Baseline P (a)</u>	<u>Optimized Geometry (b)</u>
Turbine Power	68.3	67.8
Generator Power	67.3	66.8
Warm Water Pumping Power	6.7	6.7
Cold Water Pumping Power	8.7	8.2
Ammonia Pumping Power	1.4	1.4
Controls, Hotel, Internal Losses, etc.	0.4	0.4
Chlorination Power ^(c)	0.08 (to 0.64)	0.08 (to 0.64)
Mechanical Cleaning Power ^(d)	—	—
Net Power Out	50.0	50.0
Turbine Gross/Net Power (ratio)	1.37	1.36

(a) Reference baseline includes 10 ft warm (evaporator) and 15 ft cold (condenser) seawater head losses

(b) Optimized geometry represents surface platform estimated seawater head losses

(c) 0.2 mg/liter to (1.6) mg/liter dosage

(d) System sized with added heat exchanger pressure loss; cleaning system operated by seawater flow reversal

Table 3-2

HEAT EXCHANGER DATA - HORIZONTAL SHELL-AND-TUBE
(EVAPORATOR) 50-MW(e) MODULE

<u>Item</u>	<u>Reference Baseline ΔP (a)</u>	<u>Optimized Geometry (b)</u>
Thermal Rating (MBtu/hr)	7280	7200
Water Flow Rate (gpm)	2,666,500	2,726,600
Ammonia Flow Rate (lb/hr)	20,746,400	20,500,000
Design Pressure (psi) ^(c)	168	168
Total Number of Tubes	89,000	89,000
Tube OD (in.)	1.5	1.5
Tube Wall (in.) ^(d)	0.1025/0.090	0.1025/0.090
Fins (#/in.) ^(e)	15-20	15-20
Fin Height (in.)	0.025	0.025
Tube Length (ft)	55.2	52.8
Tubesheet Diameter (ft)	55.3	55.3
Number of Tube Supports	10	10
Tube Support Spacing (ft)	5.0	4.8
Shell OD (ft)	78.7	77.0
Shell Thickness (in.)	6.5	6.5
Tube Material (Aluminum) ^(f)	A1 5052	A1 5052
Shell Material (Aluminum)	A1 5083	A1 5083
Baffle Material (Aluminum)	A1 5083	A1 5083
Design Outlet Quality (%) (with internal mist extractor)	99	99

(a) Reference baseline includes 10 ft warm (evaporator) and 15 ft cold (condenser) seawater head losses

(b) Optimized geometry represents surface platform estimated seawater head losses

(c) Burst

(d) Mean/Minimum

(e) Heat transfer enhancement shell side

(f) Current investigation indicates Alclad 3004 to be superior to 5052

Table 3-3

HEAT EXCHANGER DATA - HORIZONTAL SHELL-AND-TUBE
(CONDENSER) 50-MW(e) MODULE

<u>Item</u>	<u>Reference Baseline ΔP (a)</u>	<u>Optimized Geometry (c)</u>
Thermal Rating (MBtu/hr)	7053	6972
Water Flow Rate (gpm)	2,305,000	2,598,000
Ammonia Flow Rate (lb/hr)	13,831,000	13,666,300
Design Pressure (psi) ^(c)	168	168
Total Number of Tubes	103,000	103,000
Tube OD (in.)	1.5	1.5
Tube Wall (in.) ^(d)	0.1025/0.090	0.1025/0.090
Fins (#/in.) ^(e)	15-20	15-20
Fin Height (in.)	0.025	0.025
Tube Length (ft)	55.2	52.8
Tubesheet Diameter (ft)	55.3	55.3
Number of Tube Supports	10	10
Tube Support Spacing (ft)	5.01	4.80
Shell OD (ft)	78.7	77.0
Shell Thickness (in.)	6.5	6.5
Tube Material (Aluminum) ^(f)	A1 5052	A1 5052
Shell Material (Aluminum)	A1 5083	A1 5083
Baffle Material (Aluminum)	A1 5083	A1 5083

(a) Reference baseline includes 10 ft warm (evaporator) and 15 ft cold (condenser) seawater head losses

(b) Optimized geometry represents surface platform estimated seawater head losses

(c) Burst

(d) Mean/Minimum

(e) Heat transfer enhancement shell side

(f) Current investigation indicates Alclad 3004 to be superior to 5052

For the 50-MW(e) module, aluminum was selected for the heat exchangers and tubes, with M.A.N. brushes for mechanical tube cleaning and chlorine for biofouling countermeasures.

These 50-MW(e) modules are producible with present state-of-the-art techniques. Equipment for cutting, welding, and moving bulky items is available in shipyards. A special facility would be required for final assembly and floating the power modules to the platform.

The cost of power module production units will be about \$1,900/kW(e) for the first unit and about \$1,800/kW(e) for the eighth unit.

3.3 10-MW(e) MODULAR APPLICATION POWER SYSTEM (TASK 2)

The 10-MW(e) MAPS represents a major step toward actual commercial hardware in its total demonstration of OTEC technical and operational feasibility. This power system is large enough to supply a useful amount of energy and small enough to be manufactured in existing facilities while providing the necessary projections of commercial plant cost effectiveness. This is the result of state-of-the-art designs and the use of existing time-proven, commercial technology throughout the power system design.

The phenomenological features of ammonia (liquid and vapor) and seawater are well understood so that the thermal and hydraulic performance may be scaled between the 50-MW(e) commercial and the 10-MW(e) unit.

Existing performance models, correlated with the results of the heat exchanger test articles, and refined with the actual performance data of the 10-MW(e) power system, will serve to project commercial OTEC performance. These performance models, used to optimize the commercial power system, were applied to the sizing of the components for the 10-MW(e) power system. Figure 3-2 illustrates the design features of the immersed-segmented 10-MW(e) power system.

Fig. 3-2 Conceptual Design - Baseline (Immersed-Segmented)
10-MW(e) Power Module

Specific features of the 10-MW(e) power system, which are different from the 50-MW(e) commercial power system configuration, are as follows:

- o Self-contained power module incorporating all ammonia and electrical auxiliaries, safety and operational equipment except for ocean systems and power transmission.
- o Titanium Tubes to ensure confidence in the heat exchanger life.
- o Carbon steel heat exchanger shells to be compatible with the titanium tubes. The tubesheets are titanium-clad carbon steel.

Note: A sacrificial anode protection system is incorporated to ensure compatibility between the steel and the titanium-clad tubesheets.

The 10-MW(e) segmented power system configuration offers sufficient flexibility to adapt to platform configurations in the conduct of modular experiments. With this arrangement, various hardware candidates can be installed, usually with little adaptation, and operated with the total system.

The manufacturing plans for the 10-MW(e) heat exchangers and rotating machinery have shown that all tooling is standard shop practice design, requiring neither advanced technology nor development work. Facilities and equipment exist to fabricate, handle, deliver, and assemble all components.

Module power output allocations are given in Table 3-4, estimated weights and buoyancy in Table 3-5 for the immersed segmented module, and heat exchanger data for the horizontal shell-and-tube evaporator and condenser are given in Tables 3-6 and 3-7, respectively.

Chlorine was selected to prevent biofouling, with chlorine to be manufactured onboard the module at a cost savings over bulk transportation.

The design of the MAPS 10-MW(e) module was carried to the preliminary design level with detailed drawings shown in Attachment 2.

Table 3-4

10-MW(e) MODULAR APPLICATION POWER SYSTEM
POWER ALLOCATIONS

<u>Item</u>	Power (MW)	
	<u>Reference Baseline P (a)</u>	<u>Optimized Geometry (b)</u>
Turbine Power	14.8	14.0
Generator Power	14.6	13.8
Warm Water Pumping Power	1.7	1.3
Cold Water Pumping Power	2.2	1.8
Ammonia Pumping Power	0.3	0.3
Controls, Hotel, Internal Costs, etc.	0.4	0.4
Chlorination Power ^(c)	0.02 (to 0.16)	0.02 (to 0.16)
Mechanical Cleaning Power ^(d)	—	—
Net Power Out	10.0	10.0
Turbine Gross/Net Power (ratio)	1.48	1.40
(a) Reference baseline includes 10 ft (evaporator) and 15 ft (condenser) of seawater head losses		
(b) Optimized geometry represents surface platform estimated seawater head losses		
(c) 0.2 mg/liter to 1.6 mg/liter dosage		
(d) System sized with added heat exchanger pressure loss. Cleaning system operated by seawater flow reversal		

Table 3-5

ESTIMATED WEIGHT AND BUOYANCY
10-MW(e) Segmented Power Module
(With Operating Space)

Condenser Module

<u>Item</u>	<u>Weight (lb)</u>	<u>Buoyancy (lb)</u>
Condenser	1,004,000	1,500,000
Pump Room	100,000	613,000
Pump Room Access Trunk	93,000	335,000
Ammonia Condensate Pumps (3)	42,000	-
Condenser Inlet Transition	21,000	3,000
Condenser CW Discharge Pipe	24,000	-
Condenser Plumbing	12,000	-
Turbine Exhaust Diffuser	33,000	40,000
Turbine and Generator Foundation	5,000	-
Structure Support	32,000	4,000
Operation Space (Platform)	365,000	1,521,000
Operation Equipment	<u>1,319,000</u>	<u>-</u>
Total	3,050,000	4,016,000
Fixed Ballast	966,000	

Evaporator Module

Evaporator	940,000	1,610,000
Pump Room	100,000	613,000
Pump Room Access Trunk	93,000	335,000
Ammonia Distribution Pumps (4)	48,000	-
Ammonia Vapor Plumbing	96,000	54,000
Structure Support	32,000	4,000
Operation Space (Platform)	383,000	1,659,000
Operation Equipment	<u>510,000</u>	<u>-</u>
Total	2,202,000	4,275,000
Fixed Ballast	2,073,000	

Table 3-6

HEAT EXCHANGER DATA - HORIZONTAL SHELL AND TUBE (EVAPORATOR)
10-MW(e) MODULAR APPLICATION POWER SYSTEM

<u>Item</u>	<u>Reference Baseline ΔP (a)</u>	<u>Optimized Geometry (b)</u>
Thermal Rating (MBtu/hr)	1,562	1,440
Water Flow Rate (gpm)	677,500	712,750
Ammonia Flow Rate (lb/hr)	4,455,300	4,104,000
Design Pressure (psi) ^(c)	168	168
Total Number of Tubes	51,400	51,400
Tube OD (in.)	1.0	1.0
Tube Wall (in.) ^(d)	0.028	0.028
Fins (#/in.) ^(e)	15-20	15-20
Fin Height (in.)	0.025	0.025
Tube Length (ft)	26.2	24.8
Tubesheet Diameter (ft)	29.3	29.3
Number of Tube Supports	7	6
Tube Support Spacing (ft)	3.8	3.7
Shell OD (ft)	39.4	38.4
Shell Thickness (in.)	2.0	2.0
Tube Material	Ti	Ti
Shell Material (carbon steel)	A516, Gr 70	A516, Gr 70
Baffle Material (steel)	A36	A36
Tubesheet Cladding Material	Ti	Ti
Design Outlet Quality (%)	99	99
(a) Reference baseline includes 10 ft warm (evaporator) and 15 ft cold (condenser) seawater head hoses		
(b) Optimized geometry represents surface platform estimated seawater head losses		
(c) Burst		
(d) Minimum		
(e) Heat transfer enhancement shell side		

Table 3-7

HEAT EXCHANGER DATA _ HORIZONTAL SHELL AND TUBE (CONDENSER)
10-MW(e) MODULAR APPLICATION POWER SYSTEM

<u>Item</u>	<u>Reference Baseline ΔP(a)</u>	<u>Optimized Geometry(b)</u>
Thermal Rating (MBtu/hr)	1,514	1,395
Water Flow Rate (gpm)	589,000	641,500
Ammonia Flow Rate (lb/hr)	2,970,200	2,736,000
Design Pressure (psi) ^(c)	168	168
Total Number of Tubes	64,200	64,200
Tube OD (in.)	1.0	1.0
Tube Wall (in.) ^(d)	0.028	0.028
Fins (#/in.) ^(e)	15-20	15-20
Fin Height (in.)	0.025	0.025
Tube Length (ft)	26.2	24.8
Tubesheet Diameter (ft)	29.3	29.3
Number of Tube Supports	7	6
Tube Support Spacing (ft)	3.9	3.7
Shell OD (ft)	39.4	38.4
Shell Thickness (in.)	2.0	2.0
Tube Material	Ti	Ti
Shell Material (carbon steel)	A516, Gr 70	A516, Gr 70
Baffle Material (Steel)	A36	A36
Tubesheet Cladding Material	Ti	Ti

(a) Reference baseline includes 10 ft warm (evaporator) and 15 ft cold (condenser) seawater head losses

(b) Optimized geometry represents surface platform estimated seawater head losses

(c) Burst

(d) Minimum

(e) For Heat Transfer Enhancement

The cost of the self-contained, titanium-tubed MAPS first production unit will be about \$3,000/kW(e) and about \$2,800/kW(e) for the eighth unit. The cost may be reduced approximately \$600 to \$800/kW(e) by going to a platform integrated module with aluminum-tubed heat exchangers.

3.4 HEAT EXCHANGER TEST ARTICLES (TASK 2)

The heat exchanger test articles will provide cost data, performance and operating experience. The heat exchanger test articles were designed to verify thermal, hydraulic, and mechanical characteristics of horizontal shell-and-tube heat exchangers (Table 3-8). Cost effectiveness and compatibility with the OTEC-1 system were paramount in the designs of the heat exchangers.

Configuration. The test article heat exchangers were designed to fulfill all the test objectives cost effectively. The design is compatible with the specifications of OTEC-1. The design is analogous to the physical and structural arrangements of the 50-MW(e) CPM and 10-MW(e) MAPS heat exchangers. Hence, the cost data from this hardware design and procurement will be readily applicable to the cost models for the commercial power system. The features of the heat exchanger test articles are described below and the evaporator is illustrated in Fig. 3-3.

Size of the heat exchangers was based on the following:

- o Consideration of the seawater pumping capacity on the OTEC-1, assuming parallel operation with the 1-MW(e) heat exchanger test articles at their nominal requirement.
- o The minimum size required to represent adequately the vapor flow in the evaporator.
- o The cost of the heat exchangers.

Dual tube bundles, separated by a vertical bulkhead, provide for the simultaneous testing of enhanced tubes on one side and smooth tubes on the

Table 3-8

BASIS FOR DESIGN OF HEAT EXCHANGER TEST ARTICLES

Area	Objectives	Features*
Demonstrate Mechanical Features	Design to Include Critical Mechanical Features	<ul style="list-style-type: none"> o Spherical Shell o Aluminum Shell, Tubes o Internal Mist Extractors and Sumps o Structural Dynamically Scaled Tube/Supports
	Tube Vibration	<ul style="list-style-type: none"> o Instrumented Tubes o Variable Vapor Velocity
Demonstrate Fabrication Techniques	Design, Fabricate, Inspect, and Repair With Existing Technologies	<ul style="list-style-type: none"> o Shell Forming and Assembly o Tube/Tube Shell Weld
Evaporator and Condenser Heat Transfer	Liquid Ammonia Distribution System	<ul style="list-style-type: none"> o Segmented Tube Bundle o Variable Flow to Each Segment o Irrigation Distribution
	Tube Wetting	<ul style="list-style-type: none"> o Tube HT Measurements
	Vapor-Liquid Entrainment	<ul style="list-style-type: none"> o Separator Flow Measurement
	Heat Transfer Enhancement	<ul style="list-style-type: none"> o Tube HT Measurements o Variable Vapor Flow o Plain-Enhanced Comparison o Variable Liquid Flow o Overall HT Coefficient
	Platform Motion	<ul style="list-style-type: none"> o Operation in Various Sea States
	Tube Bundle Inclination	<ul style="list-style-type: none"> o Tube HT Measurements o Overall HT Coefficient
Determine Aluminum Corrosion and Scaling Effects	Remove Tubes and Inspect	<ul style="list-style-type: none"> o Aluminum Tubes and Tube Sheets, Alloys o Accessible for Interior Manned Inspection
Determine Biofouling Effects and Countermeasures	Measure Heat Transfer Performance With and Without Biofouling Control	<ul style="list-style-type: none"> o Chlorination o Brushing o Heat Transfer Measurement Device o Simultaneous Tests of Smooth/Enhanced Tubes
Demonstrate At-Sea Operations	Full Range of Possible Operational Procedures and Environment	<ul style="list-style-type: none"> o Simulate Platform Motions o Operations in Rough Sea o Output at Small Temperature Differential

*HT - Heat Transfer

Fig. 3-3 Configuration of Heat Exchanger Test Articles
(0.2-MW(e) Nominal Evaporator)

other side of the heat exchangers under identical thermal conditions. Based on estimates of the OTEC-1 system losses, the heat exchanger test articles are capable of 0.37-MW(e) output with both sides operational, and 0.22-MW(e) nominal output with the enhanced tube only.

The mist extractor and ammonia sump are internal to the spherical shell of the evaporator. Control of evaporator tube liquid ammonia film thickness is obtained by separately controlled liquid distribution lines (not shown in Fig. 3-3). Additional ammonia vapor is injected from outside the evaporator through perforations in the separating bulkhead to flow outwardly through the left and right tube bundles to simulate the vapor flow rate of larger heat exchangers.

Off-vertical performance of the heat exchangers, simulating platform configurations or motions, can be accommodated by adjustment of the length of supporting legs or of the thickness of the leg foot pads. The characteristics of the tube irrigation can be explored by this convenient mechanism.

Material for these heat exchangers is aluminum for the shell and tubes. The size of the heat exchanger was determined by the thermal and fluid dynamic parameters which lead to minimum size while still being able to produce the required test data.

Test article and OTEC-1 interfaces will have to be finalized during the detail design task. Manufacturing and assembly of these heat exchangers presents no problems with facilities presently available.

For evaluation of tube life and corrosion, different aluminum alloys will be incorporated into the tube bundles. Candidates include Alclad 3003, Alclad 3004 and Al 5052. Every three or four months during heat exchanger operation, four or six tubes are to be extracted for metallurgical examination and analysis.

Section 4

RECOMMENDATIONS

The recommendations resulting from the findings and conclusions of this study are presented here.

1. Broaden the scope of the preliminary designs to evaluate 50-MW(e) power module for platform configuration other than the reference surface ship/platform. The restrictions in this study did not necessarily lead to the lowest power module cost.
2. Optimize plant cost and performance by integrating power module control systems and equipments with the platform control system and equipments (e.g., ammonia storage, ammonia cleanup, chlorine production, etc.).
3. Continue the investigation of aluminum alloys (Alclad 3003 and Alclad 3004) as OTEC heat exchanger material. Lower cost with a life expectancy at least equivalent to Al 5052 seems feasible.
4. Continue development of both radial and axial inflow turbines in order to verify performance, operational characteristics, and manufacturing costs. The distinction between the radial and axial machines is not sufficient to warrant a final choice at this time.
5. Conduct a preliminary design of the ammonia turbine drives for seawater pumps in order more precisely to define cost, performance, and advantages for this arrangement compared with the more conventional drive options.