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OCEAN THERMAL ENERGY CONVERSION POWER SYSTEM
DEVELOPMENT

Phase 1: Preliminary Design
Final Report

December 4, 1978

Work Performed Under Contract No. EG-77-C-03-1569

Westinghouse Electric Corporation
Power Generation Divisions
Lester, Pennsylvania

U.S. Department of Energy

Solar Energy

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POWER SYSTEM DEVELOPMENT**

**Phase 1
Preliminary Design**

Final Report

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Contract No. EG-77-C-03-1569

**Department of Energy
Division of Solar Technology**

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FOREWORD

This is Volume 1, Executive Summary, of a three-volume final progress report entitled Phase I Preliminary Design, submitted to the Department of Energy under contract number EG-77-C-03-1569. Volume 1 is an abridged version of Volume 2. The other documents in this report are:

- Volume 2 Technical Details
- Volume 3 Appendices

In Volume 2, the technical aspects of Phase 1 preliminary design are given; in Volume 3, appendices that substantiate or complement certain information in Volume 2 are presented.

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1. INTRODUCTION

This report summarizes the preliminary design portion of Phase I (conceptual and preliminary design) of the Power System design for the Ocean Thermal Energy Conversion (OTEC) Demonstration Plant project.

The scope of Phase I was the conceptual design of:

- Full sized power system module.
- Scaled (5 MWe nominal) proof of concept power system.
- 1 MWe heat exchanger test article

Included were all components and subsystems specifically involved with the generation of power (warm and cold seawater pumps, heat exchangers, turbine/generator, etc.)

The scope of Phase I preliminary design is:

- Conceptual design of a commercial size power system between 40-50 MWe(net) with costing on prototype, first production, and eighth unit.
- Preliminary design of a 10 MWe net modular application power module with tube material of titanium, and analogous to the commercial size power module. The heat exchangers are to be immersed and costing data should be provided for first unit and eighth unit.
- Preliminary design of a heat exchanger test article.

The project approach is diagrammed in Figure 1.

The results presented herein represent Westinghouse's best estimates based upon present knowledge.

Westinghouse was responsible for major component design, systems engineering and economic analyses.

Westinghouse was supported in this study by Carnegie-Mellon University, Union Carbide Corp. (Linde Division), Gibbs and Hill Inc., Middle South Services, Inc., and Dr. A. E. Bergles (Iowa State University). Carnegie-Mellon University provided advanced technology heat exchanger experience and a control system dynamic model. Union Carbide Corporation also provided advanced technology heat exchanger experience along with tube enhancement techniques. Middle South Services, Inc. contributed knowledge of electric utility practices and operating procedures. Dr. A. E. Bergles provided tube enhancement experience. Gibbs and Hill Inc. contributed the skills and knowledge of integration of major equipment for a total power plant.

The work was performed for the Division of Solar Energy of the Department of Energy under Contract Number EG-77-C-03-1569 and was begun on August 1, 1977. The preliminary design report consists of the following three volumes which document the study approach and results:

- Volume 1 - Executive Summary
- Volume 2 - Technical Details
- Volume 3 - Appendices

2 CONCEPTUAL DESIGN OF 100 MWe PILOT PLANT

2.1 Economic Optimization

The system design in the conceptual and preliminary stages of this contract was based on an economic optimization supported by technology assessments and producibility analyses. The procedure is shown in Figure 2. The central optimization computer model is composed of heat balance, mechanical design and cost models. This computer program uses pattern search to find the optimum cost design using the models of the entire power system. The specific optimum designs are further qualified by a dynamic response analysis and technology and producibility assessments. Off design data is provided by a steady state analysis program.

The results of the cost studies showed that the power system cost is most affected by module size. Figure 3 plots the conceptual cost of the heat exchangers and power module and indicates that the optimum cost is at the 50 MWe level.

Seventeen types of enhancement were studied, along with the entire range of tube diameters. Only those enhancements that had manufacturing experience and available correlation data were considered. A summary of results is shown in Figure 4. The optimum enhancement selection is currently the Linde High Flux coating on the evaporator with plain inside surfaces and plain tubes in the condenser. While many of the enhancement options had higher heat transfer coefficients, they did not provide the lowest system cost when initial cost and operating losses were considered.

2.2 Technology Assessment

The major technical issues addressed were the tube material selection, biofouling control and potential availability. All have critical impacts on the ultimate competitiveness of the OTEC concept.

While titanium has a significantly higher cost than aluminum or copper nickel tubing, it is the only material that has been qualified for sea water and ammonia service and was selected as the material for a demonstration plant. The requirement of reliability of the modular experiment also leads to the use of titanium. Long term commercial cost goals, however, led to an effort to qualify aluminum for commercial plants. Therefore, a variety of aluminum configurations are proposed for the test article to lead toward qualification of an aluminum configuration.

Biofouling also has a significant impact on OTEC viability. Chlorination provides the lowest cost option if it can be used in concentration low enough to keep the effluent within EPA limits. The current design is based on a fouling resistance of $0.00025 \text{ Hr-}^{\circ}\text{F-Ft}^2/\text{BTU}$ although a resistance of $0.0001 \text{ Hr-}^{\circ}\text{F-Ft}^2/\text{BTU}$ is a strong potential. Amertap is selected as the back up mechanical system. Toxic coatings, foamed solvents, ozone, MAN brushes and manual cleaning methods were considered but were not as effective as the chosen methods.

Analysis of the operating environment and design strategies indicate that an availability of over 90% is obtainable.

2.3 Producibility

In order to use the large size economical power modules, very large heat exchangers are required. In order to provide the large size heat exchangers while allowing use of existing automated drilling and tube welding equipment currently in existence in the heat exchange industry, a modular heat exchanger

design was developed. The concept is illustrated in Figure 5 showing the rail shippable bundles and the arrangement in the shell. The detailed tube plate assembly is shown in Figure 6.

The 100 MWe demonstration plant platform was designed to allow construction in a number of existing U. S. facilities. Heat exchanger water boxes were made an integral part of the hull to minimize sea water pressure drops. A diagram of the conceptual 100 MWe hull is shown in Figure 7 .

3 TEST ARTICLE

3.1 Test Article Selection

The proposed test article is shown in Figure 8 . It is designed to provide data to allow scale up to any size heat exchanger. The test article heat exchangers are designed using the same construction aspects as the 10 MWe modular experiment and the 50 MWe commercial size power module. The evaporator shown in Figure 9 and the condenser shown in Figure 10 are both constructed using modular bundles, explosively clad tube sheets, an integral separator and hotwells in similar configuration to the larger plants. The size of 0.13 MWe is compatible with resources on OTEC-1. In addition, devices are provided to allow simulation of the full size bundles to verify performance and mechanical characteristics.

3.2 Aluminum Qualification

An important goal of the test article is to qualify aluminum as a suitable material for commercial OTEC plants in sea water and ammonia service. A number of aluminum alloy and coating configurations will be included to evaluate corrosion, erosion and biofouling cleaning impacts.

The tube configurations include:

Al 3003, Al clad ID

Al 5052

Al 5052, Al clad ID

All configurations will also have selected teflon coated samples and both seamless and welded tubing included. These selections represent the best opportunities to qualify the lower cost aluminum for use in commercial size plants.

3.3 Performance Verification

The test article system has been designed with provisions to vary the fluid and vapor flow characteristics to simulate the performance of any size tube module foreseen beyond the commercial size plants. The variable features in the evaporator include:

- Variable vapor flow through use of a vapor recycling blower in the evaporator.
- Variable liquid recycle to simulate tube loadings.
- Adjustable low baffle to simulate vapor flow past a bundle.
- Compartmentalized collection trays to evaluate liquid distribution.

The condenser model has a two-dimensional tube field and orificed non-condensable core pipe to simulate venting and condensing phenomena. A flow diagram of the test article system is shown in Figure 11.

The normal ASME power test code for separating tube fouling effects is not practical because continuous monitoring is necessary. A clean water circulating loop shown in Figure 12 is provided for both evaporator and condenser to provide biofouling measurements.

4 10 MWe MODULAR EXPERIMENT

4.1 System Operation

A performance summary of the 10 MWe modular experiment design is shown in Figure 13 and component efficiencies are shown in Figure 14.

An important aspect to the performance of the unit is the control system. The system diagrammed in Figure 15 was selected to provide redundant turbine overspeed protection without the losses associated with conventional turbine control and stop valves. The control system makes use of extremely large bypass valves and feed-valves. Each acting by itself will prevent the turbine from exceeding the 100% overspeed criteria for which it was designed.

4.2 Arrangement

Arrangement of the optimally sized and configured 10 MWe OTEC I power module achieves maximum practicable packing density in a surface platform/ship, minimizes heating and cooling water management problems and ammonia working fluid piping runs, offers innovative space utilization to facilitate construction and maintenance, and is readily adaptable to all alternative platform configurations. A profile view in Figure 16 shows the consolidation of components, the submerged heat exchangers and the downstream location of seawater pumps to allow for diffusers in the exhaust pipes. The equipment can be mounted in a variety of hulls in addition to the reference hull that we have selected, and similar mounting can extend to the 50 MWe modules as well.

The end views of the condenser and evaporator in Figures 17 and 18 show that the square tube modules allow placing the moisture separator and the evaporator drain tank and condenser hotwell integral to the shell to reduce cost and piping runs.

4.3 Modeling of Commercial Plant

The heat exchangers in the 10 MWe plant, model larger heat exchangers in commercial plants because the tube modules are thermodynamically and structurally equivalent to the larger plant. The turbine is a one-half size double speed version of a 40 MWe turbine and exactly models the thermodynamic, structural and vibration characteristics of the larger turbine. A modest extrapolation of this size leads to the 50 MWe commercial version.

5 50 MWe POWER MODULE

5.1 Power System Adaptability

The evaporator arrangement for the 50 MWe power module is shown in Figure 19 . The increased number of tube modules, integral separators and drain tank analagous to the 10 MWe configuration is shown. The incorporation of these power modules into a 400 MWe barge in Figure 20 and a spar type platform in Figure 21 indicates the flexibility of arrangement of these modules.

5.2 Forecast Power System Cost

The estimate of power system module cost is shown in Figure 22. The cost is bounded by aluminum tubed units with expected replacement with current technology as an upper limit. A lower bound is an aluminum unit assuming tubing costs to be included at the simple strip cost without corrosion allowance and assuming negligible manufacturing cost for producing the welded tubing. The assumption in all these curves is that potential cost improvements in technology will be balanced by contingency factors that are not included.

CONCEPTUAL ——— PRELIMINARY ——— PROJECTED
COMMERCIAL

- ECONOMIC OPTIMIZATION
- TECHNOLOGY ASSESSMENT
- PRODUCIBILITY ANALYSIS

- COST EFFECTIVE
- ALUMINUM QUALIFICATION
- PERFORMANCE VERIFICATION

- RELIABLE SYSTEM
- COMPACT ARRANGEMENT
- EFFECTIVE MODELING

- ADAPTABLE POWER SYSTEM
- COST IMPROVEMENT

FIGURE 1
PROJECT APPROACH

FIGURE 2
DESIGN LOGIC

FIGURE 3
COST MODULE

FIGURE 4
TUBE ENHANCEMENT SELECTION

FIGURE 5
MODULAR HEAT EXCHANGER DESIGN

FIGURE 6
TUBE BUNDLE INSTALLATION

FIGURE 7
SHIP-SHAPE 100 MWe ARRANGEMENT

FIGURE 8
TEST ARTICLE

FIGURE 9
TEST ARTICLE EVAPORATOR

FIGURE 10
TEST ARTICLE CONDENSER

FIGURE 11
TEST ARTICLE FLOW DIAGRAM

FIGURE 12
BIOFOULING MEASUREMENT LOOP

10 MWe POWER MODULE

21

EVAPORATOR		CONDENSER	
INLET TEMPERATURE, °F	59.7	INLET TEMPERATURE, °F	49.1
EXIT TEMPERATURE, °F	70.5	EXIT TEMPERATURE, °F	49.0
TUBE VELOCITY, FT/SEC	6.5	TUBE VELOCITY, FT/SEC	5.6
WATER FLOW, 10 ⁶ LB/HR	305.	WATER FLOW, 10 ⁶ LB/HR	263.
Δ P FLOW, PSI	2.90	Δ P FLOW, PSI	3.72
TURBINE		AUXILIARY POWER (MW)	
INLET TEMPERATURE, °F	70.2	COLD WATER PUMP	2.30
EXIT TEMPERATURE, °F	49.1	WARM WATER PUMP	1.52
RPM	3600.	NH ₃ PUMP	0.28
NH ₃ FLOW, 10 ⁶ LB/HR	3.0	RECYCLE PUMP	0.05
POWER	14.4	HYPOCHLORITE GENERATOR	0.17

FIGURE 13
PERFORMANCE SUMMARY

TURBINE	.827	BLADING EFF	= .9
		EXHAUST LOSS	= 2.4%
		MECH. LOSS	= 0.2%
		MOISTURE LOSS	= 5.5%
GENERATOR	.967	HYDROGEN COOLING	
SEA WATER PUMPS	.670	PUMP	.895
		DIFFUSER	.900
		A.C. MOTOR	.832
AMMONIA PUMPS	.75	PUMP	.83
		MOTOR	.9

FIGURE 14
COMPONENT EFFICIENCIES

**TURBINE FLOW CONTROLLED BY
LIQUID FEED & RECYCLE FLOW &
BY-PASS VALVES**
FAST TURBINE FLOW RESPONSE
MINIMUM PRESSURE DROP IN VAPOR LINE
**LIQUID VALVES CLOSE AND
BYPASS VALVES OPEN DURING TRIP.**

FIGURE 15
CONTROL SYSTEM, 50 MWe

FIGURE 16
10 MWe POWER SYSTEM

U.S. DEPARTMENT OF ENERGY OTEC TEST ARTICLE WESTINGHOUSE STEAM TURBINE DIVISION CONTRACT NO. EG-77-C-33-1589	
10 MWE INTEGRAL PLATFORM	
GENERAL ARRANGEMENT	
SECTION 3-3
Caterpillar Inc. ENGINEERING DEPARTMENT P.O. BOX 100 JOLIET, ILL. 61701 JOB NO. 11-2651	SCALE: 3/32"=1'-0" ARI-M-30

FIGURE 17
10 MWe EVAPORATOR

FIGURE 18
10 MWe CONDENSER

FIGURE 19
50 MWe EVAPORATOR

FIGURE 20
400 MWe SHIP-TYPE PLATFORM

FIGURE 21
400 MWe SPAR PLATFORM

FIGURE 22
ULTIMATE POWER MODULE COST