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OCEAN THERMAL ENERGY CONVERSION (OTEC)
POWER SYSTEM DEVELOPMENT

Utilizing Advanced High Performance Heat Transfer Techniques

Final Technical Progress Report for August 1—December 11, 1978

December 11, 1978

Work Performed Under Contract No. EG-77-C-03-1570

TRW Systems and Energy
Redondo Beach, California

MASTER

U.S. Department of Energy

Solar Energy

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ACKNOWLEDGEMENTS

This project was conducted by a team consisting of:

- TRW Defense and Space Systems Group, the prime contractor, responsible for power system design and analysis including availability, materials technology, design integration, and project management.
- CF Braun and Company, subcontractor to TRW, responsible for mechanical design and fabricability of heat exchangers and design of ammonia support subsystems. They provided technical support in the areas of rotating machinery, thermal-fluid design of heat exchangers, system safety and installation approach.
- Union Carbide Corporation, Linde Division, subcontractor to TRW, responsible for aluminum corrosion protection, particularly the assessment of the protection technology of Marston Excelsior Ltd.

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- Dr. A.J. Impink, Jr., Dr. J.F. Osterle and Dr. K.P. White, Jr., Carnegie-Mellon University. This team of consultants made major contributions in the areas of off-design and dynamic modeling of the ammonia power loop.
- Dr. R.R. Rothfus, Carnegie-Mellon University, provided basic design data and analyses in support of heat exchanger thermal design.
- Dr. L.L. Ambs, University of Massachusetts, provided turbine design and optimization support.
- Dr. R.T. McLaughlin (ENWATS), provided design and analysis support in the areas of seawater subsystem design including dynamic modeling.

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INTRODUCTION AND SUMMARY

On 1 August 1977 TRW initiated work on the Ocean Thermal Energy conversion (OTEC) Power System Development-I (PSD-I) Phase I project for the Department of Energy (DOE) under contract number EG-77-C-03-1570. This phase of the contract will be complete on 11 December 1978.

The objectives of the program were:

- Development of a Preliminary Design for the full-sized power system module to be used in the 100 MWe OTEC Demonstration Plant by 1984 to demonstrate operational performance and to project economic viability
- Preliminary Design for a proof-of-concept 5 MWe (nominal pilot plant, (Test Article)
- Preliminary Design for proof-of-concept 1 MWe scaled heat exchangers (Test Articles)
- Preparation of a Phase II hardware and support plan (proposal) for the scaled test articles.

The project work was divided into three tasks:

Task 1: Conceptual Design --

Preparation of a Conceptual Design of a full size power system utilizing tube-in-shell evaporators and condensers in which ammonia is flowed on the outside of vertical tubes with sea-water flowing inside. Enhancement of the ammonia side coefficients is achieved by the use of axially fluted tubes with water side enhancement techniques optional. Conceptual designs for the power system development test articles (nominal 5 MWe power system and the 1 MWe heat exchangers) form a part of this task.

Task 2: Preliminary Design --

Preparation of a Preliminary Design of a full size power system module for a 100 MWe OTEC power system based on the concept developed in the Conceptual Design effort and approved by the Government following the Conceptual Design Review. Preparation of Preliminary Designs for the power system development test articles (the nominal 5 MWe power system and the 1 MWe heat exchangers) and special support equipment form a portion of this task.

Task 3: Phase II Plan (Proposal) --

Preparation of a detailed Phase II Plan (Proposal) to provide the 5 MWe power system, and 1 MWe heat exchanger hardware selected in Preliminary Design and Phase II support services.

A surface platform/ship was specified as the basic reference hull to be used during Conceptual Design. The ocean water design point temperature difference was given as 40°F and the major component design life was specified as 30 years. Aluminum was to be considered for use in the heat exchangers.

The Conceptual Design was completed and presented to DOE at a Conceptual Design Review in Washington on 5 December 1977 and, after addressing DOE comments and questions, was documented in the Conceptual Design Report, 12 May 1978.

The project was redirected, effective 1 May 1978:

- The 100 MWe Demonstration Plant was removed from consideration and was supplanted by a 40-50 MWe commercial power system.
- The 5 MWe proof-of-concept test article power system was supplanted by a 10 MWe Modular Application power system.
- The 10 MWe module should employ immersed heat exchangers using titanium tubes with the top tube sheet between zero and 20 feet below sea level.
- The reference containment vessel was to remain a surface platform/ship.
- The pair of 1 MWe heat exchangers was supplanted by a pair of heat exchangers scaled to be most cost effective in obtaining the desired test data.

Accordingly, the Preliminary Design task was modified to:

- Preparation of a Conceptual Design on a power module for the 40-50 MWe commercial power system including costs for prototype, first and eighth production units
- Preparation of a Preliminary Design for the Modular Application power module including costing for prototype, first and eighth production units
- Preparation of a Preliminary Design for the pair of scaled test article heat exchangers.

The Preliminary Design was completed with a draft version Preliminary Design Report submitted, together with the Phase II Plan (Proposal), to DOE on 2 October 1978. Preliminary Design Review and Phase II Plan (Proposal) briefings were presented at the DOE/SAN Oakland CA office on 16 October 1978. The final Preliminary Design Report will be submitted to DOE on 11 December 1978.

TECHNICAL

The Conceptual Design activity concluded that a 12.5 MWe (net) power module was the optimum cost-effective module size responsive to the DOE design requirements. The power system module major components were:

- Two 6.25 MWe vertical tube evaporators
- Two 6.25 MWe vertical tube condensers
- Two 6.25 turbines
- One 12.5 MWe electrical generator
- Four seawater pumps (one per heat exchanger)
- Three ammonia feed pumps (one standby redundant)
- Three ammonia recirculation pumps (one standby redundant)

The evaluation of module size, particularly with regard to costs due to heat exchanger size, was performed and is documented in the Conceptual Design Report. Cost savings accruing to design improvements, manufacturing methods, and the availability of dedicated on-site facilities would apply to heat exchangers of any size and would tend to maintain the cost per KWe constant out to larger sizes. The dedicated facilities would, however, involve large capital facilities investment that could be economically justified only for large scale production. It was questioned that such risk capital would be available for building the Demonstration Plant. Any design that required these expensive, dedicated facilities was concluded to be an impediment to program implementation.

In consideration of the above, and since there were no known compelling forces dictating larger modules, TRW recommended that the power module be approximately 12.5 MWe and that it utilize dual 6.25 MWe heat exchangers in the compact arrangement presented. There were no penalties apparent in this approach and a major advantage was recognized in orderly generation of building blocks for a logical progression from test articles, through pilot plant to the Demonstration Plant with minimum design iteration and risk capital expenditures. Heat exchangers of this size can be manufactured, transported, and installed using a number of existing facilities. Certain advantages of start-up auxiliary power, shut-down, load shedding, and system control accrue with the use of this recommended module size. The major components of the full size power module would serve in both the pilot plant and in the Demonstration Plant. Test article heat exchangers would be conveniently taken as sections from the design of the full scale heat exchangers, thus achieving a most cost-effective test program meeting all test objectives. This can be uniquely accomplished in the vertical, falling film heat exchangers because each tube performs independently. The section was chosen to simulate the full scale liquid/vapor distribution.

All available aluminum corrosion data and surface protective coatings were reviewed with the objective of qualifying aluminum tubes for this OTEC application. We were unsuccessful in achieving this objective and, as a consequence, we recommended titanium for the near future to avoid awkward failures during the test/demonstration program. Further application-oriented aluminum testing was recommended to DOE.

The Conceptual Design Report documents the design, presents supporting trade studies and analyses, cost analysis and projections, and recommendations to DOE for supporting work.

The Conceptual Design was significantly impacted by the Preliminary Design redirection, particularly the stipulation that the heat exchangers were to be immersed using the surface platform/ship reference containment vessel: the implication being that the heat exchangers were to be mounted outboard of the vessel. The immersion alone projected as an immediate power module cost increase of \$200/KWe. In addition, any such outboard arrangement aggravates an inherent problem in the design of a power module without adequate containment vessel interface specification. For example, it was not possible to realistically design for the sea-state condition forces on the heat exchangers or their mountings since it is not possible to calculate the response for the elements of this undefined, coupled dynamic system. Redesign costs on the heat exchangers, their mountings and the vessel itself will add more cost, which at this time is indeterminate. This general situation has caused TRW to maintain its position that extremely close coordination between the power module and the containment vessel designs is essential for a successful system design. Further, we feel that an optimum, in terms of unit energy cost, can only be achieved as a fully integrated design effort.

Considering the redirection to a 10 MWe Modular Application power system, and for essentially the same reasons which dictated the Conceptual Design module size, the Preliminary Design building block module and heat exchanger size were selected at 10 MWe. The major components were:

- One 10 MWe vertical tube evaporator
- One 10 MWe vertical tube condenser
- One turbine
- One Electrical generator

- Two ammonia feed pumps (one standby redundant)
- Two ammonia recirculation pumps (one standby redundant)

These components are to be used in constructing the 10 MWe Modular Application and the 40-50 MWe commercial power system. (By direction, the seawater pumps were eliminated as power module components, but specifications for them are included in the Preliminary Design Report.)

The test article heat exchangers were designed as 200 KWe prototypical pie shaped segments of the full size 10 MWe heat exchangers that exactly duplicate the following characteristics:

- Full length tubes
- Tube to tubesheet joints
- Tubesheets
- Support baffles
- Metering orifices
- Materials
- Open top water box

This design provides the most cost-effective configuration and size to achieve the program objectives of:

- Thermal and hydraulic performance demonstration
- Materials and corrosion effects
- Biofouling and countermeasures effects
- Fabrication techniques.

The performance is directly scalable to full size articles for operation in the ocean environment.

In redesigning the power module from 12.5 MWe to 10 MWe, the question arose as to whether the Conceptual Design dual pair of heat exchangers should be retained; i.e., should the heat exchangers be simply reduced from 6.25 MWe to 5 MWe, or should the module be redesigned to use a single pair of 10 MWe heat exchangers. The immersion requirement, with its resulting piping complexity and number of bulkhead penetrations, forced the decision in favor of the 10 MWe heat exchangers. The penalty accepted in going to these somewhat larger heat exchangers was a reduced number of existing facilities capable of manufacturing them. With the number of heat exchangers per module reduced from four to two, the number of turbines and pumps have been reduced accordingly.

The final Preliminary Design Report submitted on 11 December 1978 documents the design details and presents material addressing the following items:

- System Description and Flow Diagrams
- 10 MWe System Specification
- 200 KWe System Specification
- Performance Calculations
- Control and Instrumentation Functions for Operator and Diagnostic Evaluation
- General Arrangement Drawings
- Subsystem and Component Layout Drawings
- Piping Drawings
- Identification of Applicable Codes and Specifications
- Subsystem and Component Specifications
- Interface Control Drawings and Documentation

- Long lead time purchased items list
- Special Support Equipment Definition
- Operability/Maintainability Plan
- Producibility Analysis
- Fabricability/Installation Approach
- Recommended Materials for Critical Components with Backup
- Identification of Key Safety Issues
- Personnel and Equipment Safety Requirements and Implementation Plan
- Preliminary Stress and Dynamic Analysis
- Engineering Writeups on Developed Computer Codes
- List of Machinery and Spare Parts for Maintenance

- Sensitivity of Design to Key Design Requirements
- Estimate of Nonrecurring Costs
- Trade Studies, Analyses and Rationale Used in Arriving at the Preliminary Design
- Net Energy and Resource Analysis

The Phase II Plan (Proposal) submitted simultaneously with the draft version Preliminary Design Report on 2 October 1978 contains implementation plans for various delivery options for the test article heat exchanger and 10 MWe Modular Application Power System equipment. The plan identifies specific hardware, suppliers and costs, and describes the TRW organization and management approach proposed.

CONCLUSIONS

The conclusions are touched on in the technical section of this report and are detailed in the Conceptual and Preliminary Design Reports. They are highlighted here in summary form.

Aluminum remains the most attractive material for low cost fabrication of OTEC heat exchanger tubes, but, unfortunately, existing corrosion data are insufficient to support its use. Relevant application data do not exist. An intensive engineering research and development program is called for to develop this design data which is essential to the responsible use of low cost aluminum tubes in OTEC.

An optimum OTEC power system can only be achieved as a fully integrated design effort. This is quickly appreciated when attempting the design of a power module without interactive access to the extremely complex hardware, environmental and programmatic interfaces. Lack of coordination of these areas reduced the effectiveness of this conceptual and preliminary design effort. The contract did not address the solution to this problem; it must be concluded however that a strong system engineering and technical direction (SE & TD) function is needed to consolidate the program and to direct a coordinated system design.

Over the range of power module sizes considered (approximately 5 MWe to 25 MWe) and excluding the cost for large special purpose equipment and dedicated facilities, unit energy costs were found to be relatively constant with size. Cost savings accruing to design improvements, manufacturing methods and the availability of dedicated, on-site facilities apply to heat exchangers and modules of all sizes and tend to maintain the unit energy cost constant out to larger sizes. The cost of the large special purpose equipment and dedicated facilities can only be justified, from a cost standpoint, after commitment to a sufficiently large production run has been made. As a result, the performance and economic viability of OTEC cannot be demonstrated with a design or at a scale requiring these special or dedicated facilities. It was thus concluded that the development course to be followed, until the program is on a firm foundation, is an orderly generation of hardware building blocks that permits a logical progression from small scale test articles to the demonstration plant. Commonality of design effort and hardware for the phases of the program reduce risk and cost. This philosophy was the basis for the Conceptual Design; such a philosophy remains valid, and, coupled with an integrated design, is the optimum development course for OTEC.

Finally, we firmly believe that industrial interest and support are essential to program success. These ingredients can only be maintained in a stable program environment with clear objectives and implementation plans.