HIGHLIGHTS OF THE SOLAR THERMAL CONVERSION PROGRAM

Semi-Annual Review

April 30-May 2, 1975

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HIGHLIGHTS OF THE SOLAR THERMAL CONVERSION PROGRAM
SEMI-ANNUAL REVIEW
30 APRIL - 2 MAY 1975

Prepared for:
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FOREWORD

This report presents the highlights of the Solar Thermal Conversion Program Semi-Annual Review Meeting held in Houston, Texas, from April 30 through May 2, 1975. The report was prepared by the Energy Programs Group of the Energy and Transportation Division of The Aerospace Corporation under Task 5.0 of ERDA Contract No. E(04-3)-1101, Project Agreement No. 2.

Mr. George Kaplan was the ERDA Program Manager for this contract, and Mr. Robert Hughey was the technical coordinator for the ERDA San Francisco Operations Office. Dr. M. B. Watson is the Associate Group Director of the Energy Programs Group. The work was performed under the supervision of Mr. H. M. Webb, the director of the Solar Thermal Conversion Management Support Program.

This report was prepared by Dr. Frederick C. Finlayson. In addition, the author wishes to acknowledge the diligent efforts of the other personnel in the Energy Programs Group who have aided in the preparation of this document.

The author also wishes to acknowledge the many ERDA and NSF contractors and grantees that have provided information, cooperation, and counseling in the formulation of this report.

The author expresses his sincere appreciation to these people and organizations: to Mr. F. C. Eggers for technical editing and to Ms. Mari Bythway and Ms. Bobbie Devaney for typing and preparing this document.

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I. INTRODUCTION

This report highlights results of ERDA and NSF studies that were presented at the Solar Thermal Energy Conversion Program semi-annual review meeting held at the University of Houston on 30 April through 2 May 1975. In January 1975 most of the Solar Thermal Energy Conversion Research Studies previously started under the National Science Foundation's (NSF) Research Applied to National Needs program were transferred to the newly-formed Energy Research and Development Administration (ERDA). The status of the ERDA and NSF studies was presented in the first two and half days of the meeting. The remaining portion of the third day was set aside for the Solar Thermal Energy Ad Hoc Review Committee deliberations. The work reported on in two of the presentations had been supported by contracts with the National Aeronautics and Space Administration. These included: (1) a Lewis Research Center contract with Honeywell and Black and Veatch which included a study of central receiver solar thermal conversion plants; and (2) a JPL preliminary survey of a parabolic dish collector combined with a Brayton cycle engine.

The review meeting agenda started with a program overview of the ERDA program plan, the Electric Power Research Institute (EPRI) program plan, and the progress in the mission analysis study by The Aerospace Corporation. The total energy, distributed collector, surface technology, and central receiver studies followed. The same order of presentation has been used in the body of this report which highlights the individual project results.

The second section of this report, titled "Recommendations and Conclusions," is a compilation of the informal oral comments, recommendations, and conclusions of the Ad Hoc Review Committee

relative to the information presented at the semi-annual review. The review committee members or their representatives are listed below. Due to the fact that proposals would soon be under evaluation on an ERDA RFP for "Subsystem Research Experiments and Preliminary Design of a Central Receiver Pilot Plant," the various central receiver studies were not discussed by the Ad Hoc Review Committee. The announcement relative to this RFP, made prior to the three-day meeting, is reproduced in full below. The meeting was chaired by J. Rannels and E. Doering of ERDA.

ERDA Solar Thermal Ad Hoc Review Committee Members

P. Bos	Electric Power Research Institute
D. Elliott	Naval Weapons Center
A. Greenberg	The Aerospace Corporation
W. Christensen*	Defense Energy Office
N. Lutkefedder*	Federal Energy Administration
C. Selvage	Sandia Laboratories
H. Spuhler	National Science Foundation
A. Whatley	Western Interstate Nuclear Board

* Committee member unable to attend Semi-Annual Review meeting.

Announcement by ERDA Representative Mr. E. Doering

"A situation exists in which your cooperation is requested. The Request for Proposals, RFP 75-124, for a Central Receiver Solar Thermal Power System (Phase I), which is part of the Solar Thermal Program, is in the competitive stage. Formal review and evaluation of proposals received in response to the RFP will begin in the near future. Several members of the Contractor Selection Board and the Technical Review Panel are in attendance at the Semi-Annual Solar Thermal Review. Accordingly, there will be no discussion of this procurement and it will be understood

that there will be no discussion of any proposals or of the contents of any proposals submitted in response to the RFP 75-124 during formal presentations or informal conversations by either contractor representatives or government representatives, except for work which is being performed or has already been performed under existing or past contracts and grants, and then only during the formal presentations."

II. RECOMMENDATIONS AND CONCLUSIONS

The recommendations that follow reflect the majority opinion of the Ad Hoc Review Committee members present at the review. However, the summary presented here has not been circulated for review or revision by the individual committee members. The recommendations are intended to provide the basis for overall program direction or specific recommendations to individual contractors.

General Observations

Central Receiver Concept

Significant progress has been made in the various studies over the past two years with the greatest emphasis placed on the central receiver concept.

On the systems level, considerable effort has gone into design, which has evolved as the economically most viable system concept based on long-term considerations. Much of the economic and technical performance data substantiate this choice, even though significant differences exist between the cost estimates made by the various contractors. However, although estimates of costs and technical performance differ between the several contractors studying this concept, there seems to be general agreement that central receiver systems are superior both economically and technically to distributed systems. The consensus supports the choice of a central receiver concept for further development. To achieve this, competitive proposals are currently being evaluated for "Subsystem Research Experiments and Preliminary Design of a 10 MWe Central Receiver Pilot Plant," and

two or more contracts are to be awarded in June 1975 with the preliminary design completed in June 1977. The progress and the risk associated with the central receiver development will, to a large extent, depend upon the availability of the 5 MW Solar Thermal Test Facility. A major portion of the subsystem research experiments can be accomplished utilizing an electrically heated facility; however, certain aspects of the central receiver design (e.g., verification of the receiver design under actual solar irradiation) can only be demonstrated in a solar thermal facility. The delay in the selection of the test facility site may ultimately impact the program by increasing the development risks. The committee did not feel it was necessary to postpone the central receiver effort if progress on the test facility were delayed, but rather everything possible should be done to accelerate the facility availability once the site has been selected. This can be accomplished by proceeding with an A&E test facility conceptual design and then once the site has been selected, give the site personnel enough contracting flexibility and freedom to move rapidly on procurement. Procurement should include incremental A&E design and construction packages (i.e., first phase--site grading and underground utilities; second phase--foundations and roads; and third phase--tower and building construction).

The solar energy developments are very capital intensive and require a sophisticated econometric model to assure adequate market capture potential with a reasonable return on investment. The model developed by The Aerospace Corporation for evaluation of the central receiver and distributed collector thermal electric power plants was patterned after models utilized by the electric utility industry including energy production from fossil fuel, nuclear, and hydroelectric power plants. It was recommended that ERDA require each of the contractors to conduct their economic analyses in a consistent way. The model developed

by Aerospace should be utilized and forwarded to each of the central receiver contractors. All data/cost/economics done on the program should be forwarded to ERDA and reviewed for consistency by Aerospace before release to the public by ERDA.

Solar Total Energy Systems

The application of solar thermal conversion to total energy concepts has received little emphasis as compared with the central receiver electric power system application. Most of the work reported was from the Sandia Laboratories, Albuquerque (SLA) effort. This effort is mainly a test bed (currently limited to a rather specific concept). The total energy systems level studies needed to support the SLA total energy concepts are missing. Additional efforts in the systems analysis area are required to establish the market potential for the various categories of total energy systems (residential, commercial, industrial, institutional, military base, etc.). System level studies are also required to define the technical goals, cost, and performance levels best suited for each category of total energy systems. This work has been initiated by The Aerospace Corporation as part of their systems definition work.

Distributed Collector Systems

The mission analysis and distributed collector studies performed to date have indicated that the distributed collector subsystem was not competitive with the central receiver concept for the economic production of electrical power for large (greater than 50 MWe) intermediate load power plants. Work is proceeding with many point designs of distributed collector systems with a current lack of understanding of the mission or applicability of these collectors. It is not presently evident that these point designs will benefit electrical power, process

heat, total energy systems, or hybrid energy systems. The technical goals, performance levels, and cost requirements have yet to be defined. The point designs will identify what can be achieved but will not establish the overall requirements or market potential for the distributed collector systems.

Hybrid Systems

Some of the central receiver solar electric power plant studies were initially evaluated as hybrid systems. The Sheldahl/Foster Wheeler/University of Minnesota/Northern States Power Company concept was designed to operate as a hybrid with a conventional fossil fuel system. The Martin Marietta/Georgia Tech. central receiver design was designed as a hybrid with hydroelectric storage. The committee was intrigued with the notion that hybrid systems offered near term opportunities and, therefore, the committee recommended that ERDA prepare request for proposals for different types of hybrid systems and then award competitive contracts with industry in the most promising areas.

Process Heat

The solar thermal program should include some effort to define the market for process heat, but in doing so the survey should also include the electrical and chemical energy demands that exist in these industrial facilities (e.g., do not lose sight of process heat as a product of the total energy plant). In conjunction with this effort the solar thermal program needs to specify the optimum solar collector for each type of application (e.g., efficiency vs. cost of collectors as a function of process heat temperatures).

Selective Coatings

The need for more basic research on selective coatings at high temperatures will not be known until the program tests a high temperature solar flux (1000 suns) on the current coatings utilizing large surface areas. This part of the test program is still two years off; therefore, some effort must continue in the most promising research areas. However, there is a trade-off of coatings versus solar traps. The trade-off is one of economics and stability of coatings at high temperatures. Consequently, each coating research effort must be examined individually as to its merit relative to the total solar program.

Identification of Problem Areas

American Technological University (ATU)

The ATU evaluation of a solar total energy system for Fort Hood lacked depth. No analysis was evident, either systems or economics, to justify or verify their approach. Energy conservation, building heating and cooling and the total energy requirements can not be tackled separately. To solve the Fort Hood energy problem requires a modular approach with the proper balance of each of the elements. If the work is to continue, the committee recommends a site visit to gather more facts, and then probably ATU will need to select some acceptable solar consultants and/or contractors to assist them in completing the study.

Helio, Incorporated

At the Semi-Annual Review in August 1974 the committee questioned the value of Helio selective coating work to the solar thermal program. A site visit was made and recommendations were given to the contractor on how the work should be structured to be of value to the Solar Thermal Program. Although some improvement was evident, not enough progress has been made to justify continuation of this effort due to the low temperature coatings being evaluated and low efficiencies achieved with these coatings.

Sandia Laboratories, Albuquerque

The system level studies required to support the Sandia Laboratories Total Energy System point design are missing. Further point design efforts should not be undertaken until the system studies identifying market requirements and market penetration potential are established (see Total Energy System Summary). The committee was surprised that Sandia found the need for digital controls to point the distributed collector while the industrial contractors were able to satisfy the requirement with a less complex analog system. It was recommended that Sandia call in one of the industrial members to assist them with this problem.

III. HIGHLIGHTS

A. Program Overview

Energy Research and Development Administration

Solar Thermal Energy Conversion Program Summary

An overview of the Energy Research and Development Administration (ERDA) program plan for Solar Thermal Energy Conversion was presented. The role of solar thermal electric production, relative to the overall ERDA organization, was shown in terms of the ERDA organizational structure shown in Figure 1. A perspective was provided for the ERDA solar thermal energy budget relative to the national solar energy program, as shown in Figure 2.

Long and short term objectives of the program were discussed. The long-term objectives are to develop and demonstrate the technology required to establish the technical feasibility and indicate the economic viability of:

- (1) Solar thermal conversion electric power systems including:
 - a first-generation central receiver system (by the mid-1980's),
 - distributed collector subsystem technology, and
 - hybrid solar thermal subsystem technology;
- (2) Solar thermal total energy systems; and
- (3) solar thermal process heat systems.

The near-term objectives are to design, fabricate, check out, and test:

- (1) a 10 MWe central receiver type solar electric power pilot plant tied to a utility network;
- (2) a 5 MWt solar thermal test facility; and
- (3) a 200 kWe, 2 MWt solar thermal total energy pilot plant.

In the development of first-generation systems to meet these objectives, ERDA will concentrate on the central receiver concept for electrical power generation. ERDA will, however, continue studies and subsystem tests for other system concepts in order to resolve uncertainties relative to their cost-effectiveness comparison with the central receiver concepts. In the area of total energy systems, studies of alternative applications will continue, closely coupled to the program to provide a test facility. Support will also be provided for component development efforts in the areas of advanced research and development. All second generation applications are considered part of the advanced research and development efforts. Work in this area will include the development of improved materials and coatings and the investigation of hybrid and process heat systems. A schedule of the ERDA Solar Thermal Branch proposed activity is shown in Figure 4.

The managerial organizational structure for meeting the ERDA Solar Thermal Branch objectives is presented in Figure 3. It can be seen that program coordination, review, and planning are structured by major project elements. These project elements have been organized on the basis of major pilot plant and demonstration activities for technology development. It is intended that the major efforts will be carried out by industry in these project element subdivisions. Specific detailed project

management will be conducted by the ERDA or other government laboratories and The Aerospace Corporation. Major hardware development will be performed by industry with plans calling for only limited engineering testing to be conducted in-house by ERDA labs.

Figure 1. ERDA ORGANIZATIONAL STRUCTURE

\$ MILLIONS

	NSF				ERDA	
	FY 71	FY 72	FY 73	FY 74	EST FY 75	PROPOSED FY 76
<u>SOLAR ELECTRIC APPLICATIONS</u>						
SOLAR THERMAL	0.06	0.55	1.43	2.2	11.0*	13.2
PHOTOVOLTAIC	-	0.33	0.79	2.4	8.0	12.8
WIND ENERGY	-	-	0.20	1.0	7.0	11.5
OCEAN THERMAL	-	0.14	0.23	0.7	3.0	3.2
	(0.06)	(1.02)	(2.65)	(6.3)	(29.0)	(40.7)
<u>DIRECT SOLAR CONVERSIONS</u>						
HEATING AND COOLING	0.54	0.10	0.40	5.9	17.2*	26.0
BIOCONVERSION	0.60	0.35	0.65	1.0	5.0	3.6
WORKSHOPS AND PROGRAM ASSISTANCE	-	0.19	0.25	-	-	-
	(1.14)	(0.64)	(1.31)	(6.9)	(22.5)	(29.6)
TOTALS	1.20	1.66	3.96	13.2	51.2*	70.3

*Funding includes both NSF and AEC for solar energy

Figure 2. NATIONAL SOLAR ENERGY PROGRAM BUDGET

Figure 3. SOLAR THERMAL BRANCH MANAGEMENT ORGANIZATION

MILESTONES

(1) DECISION TO BUILD BENCH MODEL/TEST FACILITY	(7) SECOND GENERATION PLANT IN OPERATION
(2) DECISION TO BUILD PILOT PLANT	(8) DEMONSTRATION PLANT IN OPERATION
(3) BENCH MODEL/FACILITY IN OPERATION	(9) DECISION TO BUILD COMMERCIAL PLANT
(3a) PARTIAL CAPABILITY	(10) COMMERCIAL PLANT IN OPERATION
△ PILOT PLANT CHECKED OUT AND OPERATING	(11) DECISION TO BUILD ADVANCE COMM. PLANT
(5) DECISION TO START SECOND GENERATION PILOT PLANT	(12) ADVANCE COMMERCIAL PLANT IN OPERATION
(6) DECISION TO BUILD DEMONSTRATION PLANTS	

Figure 4. SOLAR THERMAL BRANCH OBJECTIVES

Electric Power Research Institute

Solar Thermal Program Overview

An overview was presented of the solar thermal program to be sponsored by the Electric Power Research Institute (EPRI). The EPRI program, as it was outlined, is designed to be complementary to the ERDA program. However, in accordance with EPRI's mission, their program will emphasize work more directly applicable to the problems of the electrical utilities throughout the country. Since the EPRI program, as it was presented, had not been approved by their Board of Directors at the time of the presentation, its details have not been included here. The overall program will be a matter of public record when it is finalized and approved.

The Aerospace Corporation

Solar Thermal Conversion Mission/System Analysis

The Aerospace Corporation presented the initial results of an extension of the mission analysis program to the entire continental United States. Previous Aerospace studies have applied the mission analysis principles to the Southern California area and the Southwestern U.S. region. The mission analysis studies have examined and compared alternative applications or missions for solar thermal systems. The missions investigated included the production of electricity in central station power plants used for base, intermediate, or peaking operations and the production of combined electrical and thermal energy in total energy systems. The mission analysis methodology has been applied on a consistent basis to the evaluation of alternative solar thermal conversion concepts for providing electrical power under realistic operating environments. Previous studies have shown economic and technical advantages for the central receiver solar power system in comparison with distributed collector systems.

The current study of central station power missions has been concentrated initially on extending the climatological data and analyses and electrical power demand analyses to more complete coverage of the contiguous 48 United States. Twenty-two representative, relatively uniform, climatological regions tentatively have been defined within the U.S. The boundaries of these regions were tentatively selected on the basis of climatic variables such as summer and winter insolation, degree days of heating and cooling, and humidity. These regions along with newly-selected locations for insolation data and preliminary selections for electrical demand analysis regions are shown in

Figure 5. The extension of the insolation data base and electrical demand characteristics information to the remainder of the contiguous U.S. will permit the evaluation of solar plant performance under actual day-to-day weather conditions and power requirements over representative portions of the entire country.

The objectives for the subsequent activities of the present contract are: (1) to refine the methodologies for assessing solar plant performance and economics as well as those for assessing margin requirements for various mixes of solar and conventional power plants; and (2) to extend the comparison of solar and mixed plant performance and economics to the different climatic regions in terms of the specific local demand profiles selected (also shown in Figure 5), different mixes of solar and conventional power plants, and over a wider variety of assumptions for fuel cost, mode of operation, and thermal storage requirements representative of the conditions and requirements of the extended geographic coverage.

To accomplish these objectives, previously developed simulation and analysis models are being refined to be more representative of the wider variety of utility systems and operational requirements outside of the southwestern U.S. These newly-refined models will permit more consistent evaluation of technical and economic trade-offs for solar power relative to more conventional power plant concepts. This study will determine whether different solar thermal power plants (in terms of optimized storage and collector field sizes) are appropriate for areas outside the Southwest than have tentatively been determined to be preferred within the Southwest. The potential market penetration in electrical power production by solar thermal conversion systems will also be investigated. The use of selected hybrid solar/fossil fueled power plants will be explored in the areas outside of the southwestern U.S. Losses and power

output limits associated with thermal storage will also be explored.

Investigations of total energy systems will be concentrated at three levels. First, system concepts and methods of analyzing and modeling them will be developed. Concept development will involve selections of size, configuration, siting, and utilization of total energy systems. Next, applications will be explored of the most attractive concepts, for which performance and costs will be analyzed and compared. Finally, the resources required for large-scale implementation of total energy systems will be examined.

Figure 5. UNITED STATES CLIMATOLOGICAL REGIONS
SHOWING LOCATIONS FOR INSOLATION DATA COLLECTION AND
ELECTRICAL DEMAND ANALYSIS REGIONS

B. Total Energy Systems

CONTRACTOR: Sandia Laboratories, Albuquerque, New Mexico

STUDY: Solar Total Energy Program

FUNDING AND PERIOD:

\$1,975,000 (ERDA), \$100,000 (NSF);

30 June 1974 to 30 June 1975

The primary objective of the Sandia Laboratories Solar Total Energy Program is the determination and demonstration of the technical and economic feasibility of solar total energy systems, through the design, development, construction, test, and analysis of a test bed total energy system. The project, currently conceived as a seven year effort, was initiated by the Atomic Energy Commission (AEC) in July 1972, and the first three phases of the project are now complete. Progress on Phase III, the FY/75 program, was reported at this meeting. Phase I was a background study covering nine months. Phase II consisted of preliminary system design, analysis, and economic evaluations. Phase III, exploratory development, included the completion of a collector test facility, completion of a computer program to mathematically model a proposed baseline total energy system, and completion of distributed trough type collector tests. Phase IV of the project started in July 1974. This is planned as a two year effort to test and evaluate the components and to fabricate and assemble a development model of the baseline total energy system. Phase V, which overlaps the second year of Phase IV, is the operational phase of the development model. This effort is intended to validate the total energy computer simulation program.

An artist's rendition of the preliminary concept for the Solar Total Energy Test Bed is shown in Figure 6. It was reported that by this reporting period, the test bed design had been frozen and all major hardware items had been ordered and many received. Two 9' x 12', N/S, tilted collectors have been installed at the collector test facility, and the full-scale prototype 9' x 12' E/W reflectors have been received. An energy storage test facility has been completed and testing initiated on the TES storage tank. The solar collector field and the turbine/control building construction has been initiated.

System analysis and subsystem testing is currently in progress. A program for a loop analysis of transient collector response with dynamic fluid storage requirements and time varying solar insolation has been developed and exercised. Utilizing the program, basic control strategy and preliminary designs for control operational subsystems have been developed. Collector receiver tube parameter testing has been performed, and a selective black chrome surface (absorptivity = .95, emissivity = .21 at 315 C) has been selected for receivers. On this basis, a baseline design was selected with a power "budget" as shown in Figure 7.

A systems analysis of several applications of TES has been initiated. The analysis will evaluate results for TES application to a 1000 home residential unit, a mixed community of 2000 dwelling units (including single family homes, low- and high-rise apartments, schools, and commercial buildings), military load centers, as well as evaluation of the baseline test building to be built as part of SLA's overall Solar Total Energy Program. Thus far, the studies have concentrated on developing models for evaluation of the electrical, heating, cooling, and hot water loads for residential elements of the community as a function of external environments, and development of a solar

radiation model to use as input to the systems analysis. A study of the architectural aspects of using solar collectors in construction of a variety of community buildings has been initiated. An architectural rendition of a portion of a community designed around a solar TES is shown in Figure 8.

Figure 6. PROPOSED TEST BED

POWER BUDGET AT 315°C (600°F)
FOR SOLAR TOTAL ENERGY SYSTEM
BASELINE DESIGN

Figure 7. POWER BUDGET

Figure 8. TYPICAL APPLICATION

CONTRACTOR: American Technological University,
Killeen, Texas

STUDY: Solar Energy Conversion Program for U.S. Army
Installations

FUNDING AND PERIOD:

- (1) \$140,000, 10 June 1974 to 10 September 1975
- (2) \$100,000, FY 76 (8 months' duration)

The overall objectives of the American Technological University study call for the conceptual design of a load following solar thermal energy conversion system to meet the energy needs of U.S. Army installations. The specific approach will include: (1) definition of the projected energy requirements for Fort Hood, Texas, in the mid-1980 time frame, (2) initiation of an insolation measurement program at Fort Hood, and (3) definition and analysis of various conceptual designs of solar thermal conversion total energy systems to meet projected demands.

Energy requirements have been estimated for Fort Hood in the 1970 to 1985 period, as shown in Figure 9. A rate of increase in energy consumption of approximately 10% per year was used over the entire period -- with a resultant doubling period for both gas and electric energy consumption of about 7 years -- a rate substantially in excess of the national average.

Solar radiation measurements were conducted at a Fort Hood location using four Eppley pyranometers with spectral filters and one Eppley normal incidence pyrliometer. Daily total insolation measurements for the period 5 September 1974 to 10 November 1974 were presented, as shown in Figure 10.

Various concepts for solar conversion have been considered including a concept for hydroelectric power production using solar powered pumped water storage with pools located on the Belton Reservoir, on site at Fort Hood. The schematic electrical generation system shown in Figure 11, using both thermal and fluid storage, was suggested for conversion of solar energy to electrical energy with the pumped storage-hydroelectric concept shown.

Figure 9. ENERGY REQUIREMENTS: 1970-1985

Figure 10. MEASURED INSOLATION AT FORT HOOD

Figure 11. ELECTRICAL GENERATION SYSTEM

C. Distributed Collector/Surface Technology/Other

CONTRACTOR: General Atomic, San Diego, California

STUDY: Testing of Scale Model and Preliminary Design of
Full-Scale Mirror Collector

FUNDING AND PERIOD:

\$50,000; 8 months, FY76

General Atomic (GA) reported on the systems studies which they have conducted on a distributed parabolic reflector concept with fixed mirrors and movable (solar tracking) heat absorber pipes. Figure 12 shows an artist's concept of such a system. In the concept described, air is circulated through the collectors as the working fluid. A "pebble-bed" storage system is used to collect and store energy for demand delivery to a secondary cycle steam generator supplying steam to conventional steam turbine-generators for electrical power production.

Specific costs for collection systems were not developed, but a concept was proposed in which the fixed primary mirrors would be "molded" into the ground. The ground surface would be prepared with earth moving equipment and covered with a 3 in. supporting layer of asphalt, so that a "shiny metallic foil" could be hot pressed into the asphalt to act as the reflector. Pebble-bed heat storage units have been conceptually designed using concrete pressure vessels filled with pebbles.

General Atomic's program has been partially supported by the following utilities: Arizona Public Service, Southern California

Figure 12. PROPOSED DISTRIBUTED COLLECTOR SYSTEM

Edison, and Utah Power and Light. A working model of a fixed mirror solar concentrator (of a different design than that proposed by GA) has been built at the Georgia Institute of Technology as part of the program to explore the technology of the concept for heating and cooling buildings. GA's plans call for testing by Arizona State University of a one-tenth scale working model which has been fabricated. This study will support the test program and provide a preliminary design of a full-scale mirror and collector.

CONTRACTOR: Cornell University, Laboratory of Atomic and Solid
State Physics

STUDY: Optical Properties of Small Particles and
Particulate Coatings

FUNDING AND PERIOD:

\$100,000; 12 months, FY75-76

In order to obtain better wavelength selectivity for solar collectors, both theoretical and experimental investigations are being conducted of the optical properties of composite coatings containing small particles. Small metal particles in dilute concentration (where the wavenumber of the radiation times the particle diameter is much smaller than 1) have very different optical properties from those of the bulk metal itself. In this limit the particles behave as Lorentz oscillators. The resonant frequencies of these oscillators are in the visible region of the electromagnetic spectrum. For concentrated arrays of particles, a self-consistent model has been developed at Cornell which describes quite generally the optical properties of a metal particle-dielectric particle composite in the concentration regime where percolation is possible so that the resultant material conducts electricity. It was reported that preliminary calculations support the results of previous experiments and indicate that the lowest frequency electronic resonance of the composite structure can be adjusted to occur in the center of the solar spectrum. The calculations show that the important parameters for metal particles embedded in a dielectric matrix are the metal particle density, the dielectric matrix, and also the composite medium thickness.

The theory is able to describe the optical properties of granular metals, cermet, doped metals and metal composites in terms of the optical constants of the bulk ingredients. In all of these metal-insulator systems, strong optical absorption will occur in the visible portion of the spectrum because of the submicroscopic texture. This conclusion is quite general and small metal particles are not needed to obtain the desired optical absorption characteristics. For example, submicroscopic voids in a metal substrate also produce absorption resonances in the visible region. Thus, it was reported that a mechanically tough selective surface can be constructed by plasma spraying equal concentrations of transition metal and dielectric particles. This composite will absorb in the visible because of the texture and reflect in the infrared because of the metal-like conductivity. Finally, a hybrid thermal-photovoltaic system was described which makes use of selective surfaces to transform the solar spectrum to a narrow frequency distribution. This receiver, as shown in Figure 13, by stepping down the spectral distribution of energy, as shown in Figure 14, provides a better matching of the incident radiation to the absorption band gap of PbS and increases the number of carriers produced in the solar cell for a given incident flux. A maximum theoretical room temperature efficiency of 14% is calculated for such a system. By reducing the temperature of the PbS to 120 K with a Carnot refrigerator, a maximum theoretical efficiency of 40% is estimated to be achievable for the total system.

Figure 13. HYBRID THERMAL PHOTOVOLTAIC RECEIVER

Figure 14. SOLAR SPECTRUM TRANSFORMER

CONTRACTOR: Perkin-Elmer

STUDY: Application of Inhomogeneous Metal Dielectric
Mixture Films as Solar Absorbing Surfaces

FUNDING AND PERIOD:

\$86,000; 12 months, FY75-76

The Perkin-Elmer presentation described a proposed absorbing or selective surface film comprised of a vapor phase mixture of metal and dielectric materials graded in composition from 100% metal to 100% dielectric in the thickness direction, such as that shown in Figure 15.

Analyses have shown that the inhomogeneous film can be made a selective surface through control of the thickness over which the metal-dielectric mixture composition gradient occurs. The concept was initially used to provide specular radiation sink surfaces giving absorption values greater than 90% over broad frequency ranges. The film is not an interference device such as the multilayer surface shown in Figure 16. This provides advantages in that the inhomogeneous films spectral properties are unaffected over a broad range of solar incidence angles (up to 60 degrees incidence) and also in that it can be applied to non-specular surfaces.

The process for depositing the film can be readily automated and the film can be constructed from a broad range of materials. Surfaces with broad band absorption characteristics have been fabricated to date using titanium and magnesium oxide; titanium and aluminum oxide; chromium and silicon dioxide; and chromium

and magnesium oxide. Typical reflectivity spectral response characteristics for inhomogenous films are compared with multilayer films in Figure 17. Substantial improvements in spectral absorptivity are obtained by appropriate selection of the metallic/dielectric composition in the film, as shown in Figure 18.

It was reported that in the coming year combinations of other refractory metals and dielectrics will be explored. The dependence of the spectral properties on the composition gradient will be investigated along with the stability of the film at high temperatures in air and vacuum.

Figure 15.
INHOMOGENEOUS FILM

Figure 16.
MULTI-LAYER STRUCTURE

Figure 17. SPECTRAL RESPONSE

Figure 18. TEST RESULTS

CONTRACTOR: University of Arizona, Optical Sciences Center

STUDY: Chemical Vapor Deposition Research for Fabrication
of Solar Energy Converters

FUNDING AND PERIOD:

\$346,000; 8 February 1974 to 8 February 1975

This project involves the fabrication (deposition), test, and analysis of a variety of spectrally selective, solar-energy absorbing coatings for concentrating receivers. Spectral selectivity is achieved by depositing a semiconductor absorber (such as silicon) which is spectrally matched to the incident solar radiation spectrum, over a thin metal film reflector (such as silver) which reflects radiation at much lower spectral energy levels. The special aspect of this study is the investigation of methods of successive chemical vapor deposition (CVD) for all elements of the multi-layered absorber, one upon another as shown in Figure 19. CVD fabrication of multilayered optical elements has the advantages of economic availability of materials, the utilization of sequential flow-through fabrication methods, deposition by open-tube processes at atmospheric pressures, with fabrication at temperatures greater than 650 C. Potential obstacles to successful CVD fabrication of absorbers are:

- 1) Adaptation of existing technology to produce optical grade coatings of unlimited lateral dimensions;
- 2) Obtaining uniform deposits despite thermal and mass flow gradients during fabrication;
- 3) Evaluation of the effects of high deposition temperatures on film interfaces (diffusion, agglomeration, thermal stresses, etc.).

Results of experiments to determine optimal silicon deposition rates were presented. Concepts for commercial CVD production facilities were shown. It was estimated that a commercial facility could produce silicon coated pipe at a throughput rate of about 1000 meters/day.

A variety of materials for coatings are to be studied in this investigation. Typical absorption/reflectance results are shown in Figure 20 showing high absorption (low reflectance) in the spectral range less than 1 micron -- the most important portion of the solar radiation spectrum. Coating stability was shown under repeated thermal cycling (up to about 2000 cycles in 1000 hours -- with temperatures up to 625 C). Results of preliminary optimization investigations for different layer materials have shown absorptions of 80-85% at 500 C.

Figure 19. MULTI-LAYER TANDEM ABSORBER

Figure 20. SPECTRAL REFLECTANCE OF CVD COATING

CONTRACTOR: Itek Corporation, Optical Systems Division

STUDY: Solar Power Collector Breadboard Tests

FUNDING AND PERIOD:

\$98,000; 1 June 1974 to 29 March 1975

Results were presented of a program in which a breadboard solar power collector system (about one square meter in area) was designed, manufactured and preliminary testing conducted. The program objectives also called for the performance of a preliminary cost analysis. In a previous program, Itek had investigated linear distributed systems and designed, developed, and tested a linear cavity type of absorber. This cavity, combined with Itek's concept for a linear, segmented, tracking mirror system was combined into the breadboard apparatus shown in Figure 21 for investigation in this study. The system was considered a breadboard apparatus because no mechanism was provided for transferring heat from the collector to a thermal working fluid for energy production.

The collector apparatus was exercised and measurements made of the efficiency of collector performance (in terms of the energy absorbed by the collector relative to the energy delivered to it after adjustment for heat losses). Results are shown in Figure 22.

A conceptual system design and analysis was made in order to determine representative costs for commercial application of the system. Results of the preliminary analysis are shown in Table 1. Detailed design and analysis would be required before thoroughly accurate cost estimates could be made.

Figure 21. BREADBOARD TEST CONFIGURATION

Figure 22. COLLECTOR EFFICIENCY

Table 1. ESTIMATED COST

<u>ITEM</u>	<u>COST</u> <u>(DOLLARS/METER²)</u>
COLLECTOR MIRRORS	33.33
ABSORBER SYSTEM (INCLUDING FLOW CONTROL)	31.76
SUPPORT FRAMES	11.33
MIRROR DRIVE COMPONENTS	12.73
ELECTRICAL CONTROLS	10.05
SITE & FOUNDATION PREPARATION	18.75
MAINTENANCE	5.00

TOTAL COST \$122.95/METER² → \$123/METER²

CONTRACTOR: University of Minnesota/Honeywell

STUDY: Research Applied to Solar-Thermal Power Systems

FUNDING AND PERIOD:

- (1) \$374,200; 1 July 1973 to 30 June 1974
- (2) \$427,000; 1 July 1974 to 31 December 1975

The objectives of this continuing effort include the design, analysis, fabrication and testing of parabolic trough collectors utilizing heat pipes for transporting thermal energy from the solar collector to the water working medium.

The review presented test results for the collector shown in Figure 23. Typical results, for an east-west orientation of the collector are shown in Figure 24. Results for the effects on system efficiency of variations in a number of parameters were shown (e.g., solar position relative to the collector, absorber temperature, and north-south orientation). A relationship for heat loss as a function of absorber temperature was also derived.

The status of experimental work on heat pipe performance and the evaluation of steam generators for collector modules was also presented. Results were shown of analyses of thermal storage concepts using phase changes from solid to liquid for various materials, and an experimental facility described for studying the phenomena. Results of experimental measurements of the thermal conductivity of hollow glass microsphere insulation were presented, as shown in Figure 25. An investigation of solar absorber coatings was also described.

Figure 23. PARABOLIC TROUGH DISTRIBUTED COLLECTOR

Figure 24. EAST-WEST ORIENTATION TEST RESULTS

Figure 25. INSULATION TEST RESULTS

CONTRACTOR: Colorado State University/Westinghouse

STUDY: Solar Thermal Electric Power Systems

FUNDING AND PERIOD:

(1) \$511,500; 1 May 1973 to 31 October 1974

(2) \$100,000; FY 76, 6 months

The objective of this study was to determine design parameters for thermal-mechanical systems in order to convert solar energy to electric energy at the minimum cost per kilowatt/hour of electrical generation for electric utility systems. The individual tasks for the study, shown in Figure 26, require optimization at the subsystem level, as well as the system level (lowest cost electricity) which sometimes produced ambiguous results. Systems analyses in the study were also constrained to concepts utilizing relatively low temperature (150 C to 250 C) saturated steam which influenced overall system efficiencies.

Various collector concepts were evaluated. On the basis of delivered thermal power costs for distributed systems, point focusing collectors using Fresnel reflectors were shown to be lowest in cost, as shown in Figure 27. Also investigated were desirable aspect ratios for collector fields, the relative cost of using steam or pressurized water as the energy transfer fluid for collectors and comparisons of central receiver and distributed systems. The distribution of system costs by subsystem elements is shown for representative examples of the two systems in Figure 28. For the relatively low temperature systems considered, the electrical generation costs for central receiver (tower/heliostat) and distributed systems are shown in Figure 29. In terms of 1972-1973 cost figures, busbar costs for

solar generated electricity were estimated to be as low as 23 to 24 mills/kWh for central receiver and distributed systems respectively [operating at the highest temperatures (250 C) investigated].

- DEVELOP PERFORMANCE AND CAPITAL COST MODELS FOR SOLAR COLLECTORS AND OPTIMIZE DESIGN AND OPERATING PARAMETERS FOR LEAST-COST THERMAL ENERGY OUTPUT.
- CHOOSE COST EFFECTIVE FIELD LAYOUTS FOR ENERGY TRANSPORT TO CENTRALIZED LOCATION AND OPTIMIZE FOR LEAST-COST THERMAL ENERGY DELIVERY.
- DESIGN HEAT STORAGE SUBSYSTEMS AND DEVELOP PERFORMANCE AND CAPITAL COST MODELS.
- DETERMINE PERFORMANCE OF HEAT ENGINES FOR CONVERSION OF THERMAL TO MECHANICAL AND ELECTRICAL ENERGY.
- DETERMINE PERFORMANCE AND COSTS OF COMPLETE SOLAR ELECTRIC GENERATING SYSTEMS UNDER REAL SOLAR RADIATION AND ATMOSPHERIC WEATHER CONDITIONS AND OPTIMIZE FOR LEAST-COST ELECTRICITY FROM EACH SYSTEM.
- EVALUATE THE NEEDS FOR RESEARCH AND DEVELOPMENT FOR CONSTRUCTION OF THE PROTOTYPE SOLAR POWER SYSTEM HAVING THE MOST ATTRACTIVE POTENTIAL.

Figure 26. STUDY TASKS

Figure 27. COLLECTOR COST COMPARISON

Figure 28. SYSTEM COST COMPARISON

Figure 29. IMPACT OF PLANT SIZE

CONTRACTOR: Helio Associates, Inc., Tucson, Arizona

STUDY: Air Stable Selective Surfaces for Solar Energy
Collectors

FUNDING AND PERIOD:

\$216,800; 1 April 1974 to 30 September 1975

This project has as its objectives: (1) the evaluation of selective coatings for solar collectors that would have a long lifetime for operation at temperatures of 150 °C (300 °F); (2) the evaluation of the optimal use of selective coatings in solar collectors with simple, low concentration geometries and their cost performance ratios; and (3) the design of a test module to demonstrate collector performance.

The selective coating production and optical measurements tasks have concentrated on the design, production and measurement of selective coatings with high absorptance ratios (of order 1) for the solar radiation spectrum (from about 0.3 to 3 microns), and low emittance ratios (of order 0.1) for long wave length radiation (from about 4 to 25 μ m). Coatings with absorptance of at least 90% and emittance of less than 3% have been produced and evaluated. Figure 30 shows typical design ranges for various types of coating materials.

In coating lifetime investigations, coatings have been tested for 3000 hours in air without change in their absorptance and emittance characteristics. The coating utilization and collector performance studies have indicated that absorptances of greater than 90% will be necessary for flat plate collectors. However, it is expected that cost effective collectors will require at least low levels of concentration. Studies are

under way to determine optimal low concentration collectors. A variety of concepts for such collectors are being considered ranging from evaluation of Winston type parabolic cusp collectors to "double cusp" collectors of in-house design as shown in Figure 31.

Region A - Al-SiO Designs
 Region B - Cu-CuS Designs
 Region C - Ag-Dielectric Designs
 Dashed line shows former design trend.

Figure 30. DESIGN RANGES OF COATING MATERIALS

Figure 31. DOUBLE CUSP COLLECTOR

CONTRACTOR: Lawrence Livermore Laboratory

STUDY: LLL/Sohio Shallow Pond Solar Process Heat Project

FUNDING AND PERIOD:

\$100,000; June 1974 to June 1975

A report was presented on the LLL/Sohio Solar Process Heat Project, describing the prototype shallow solar pond facility now under construction at the Sohio site in New Mexico. Experimental performance data were presented for one of the LLL shallow solar ponds. Improved pond and system designs were discussed as well as some recent developments in weather-resistant plastics.

The no-funds-exchanged agreement between the Standard Oil of Ohio (Sohio) Petroleum Co. and ERDA, was briefly described which provides for the Lawrence Livermore Laboratory to design a shallow solar pond facility for the Sohio uranium mining and milling complex now under construction near Grants, New Mexico.

A parametric performance and cost analysis of a combined shallow solar pond-fuel oil system for the Sohio plant has just been completed and is available on request from the authors. Figure 32 is an artists's drawing of the proposed six-acre shallow solar pond facility, consisting of 112 pond modules, each 12 feet wide by 200 feet long, cold water storage tanks, and underground insulated hot water storage reservoirs (the black covered trenches between the rows of pond modules).

The on-site Sohio Project work will be carried out in two phases, the prototype phase and the final system phase. Construction has begun on the prototype system which will include the construction, operation, and evaluation of at least three

full size (12' x 200') pond modules, each containing some parametric variations in design features. Site preparations are complete, including the excavation of both hot and cold water storage reservoirs. The polyvinylchloride (PVC) bays are completely assembled and plans called for their installation in May.

Measurements of daily heat collection were made on breadboard test facilities (a 12' x 50' three-layered PVC pond) at LLL, over a 14-day period in March 1975. The average daily heat collected was 867 BTU/sq ft with a range of from 200 to 1150 BTU/sq ft. Average daily collection efficiency varied from 38 to 62 percent, with an average over the period of 55%. Collection efficiency was defined as the ratio of daily heat collected to the integrated (measured) daily insolation.

Figure 32. SKETCH OF SOHIO SHALLOW POND PROCESS HEAT PROJECT

CONTRACTOR: Lawrence Berkeley Laboratory

STUDY: Measurement of Circumsolar Radiation

FUNDING AND PERIOD:

- (1) \$93,600; April 1974 to September 1974
- (2) \$234,000; October 1974 to June 1975

The objective of this project is to provide special solar radiation measurements potentially necessary for accurate prediction of the performance of solar thermal conversion systems using focusing collectors. These measurements consist of determining the flux profile from the sun in the circumsolar region (the small-angle region around the sun) as a function of angle, wavelength, and atmospheric conditions.

Presently, calculations of the expected system performance of ground-based focusing collectors assume that the solar flux is contained within the $1/2$ degree angle subtended by the sun. This assumption would be justified if the only atmospheric effect were absorption of the sunlight. However, the sunlight is also scattered by molecules (Rayleigh Scattering), particulates and aerosols (Mie Scattering). While the molecular scattering is nearly isotropic, the particulates and aerosols scatter the sunlight predominantly through small angles, resulting in circumsolar radiation (also referred to as the solar aureole). Pyrheliometers, the standard instruments used to measure the "direct" solar flux, typically have a 6 deg field of view. Thus circumsolar radiation is included in the measurement of the pyrheliometers. The amount of energy that would be collected by focusing devices with small fields of view could be overestimated. Prior to this project, little data existed on the amount of circumsolar radiation and its dependence on atmospheric

conditions. The instrumentation for acquiring such data was also lacking.

The presentation described the details of a "scanning telescope" developed by LBL which makes the required angular and wavelength dependent measurements of the flux of radiation from the sun and circumsolar region. The preliminary results show the expected sharp cutoff of radiation with a subtended total angle of approximately 0.6 deg, with radiation delivered at angles greater than 0.8 falling by about 4 orders of magnitude. (See Figure 33)

Figure 33. PRELIMINARY MEASUREMENT OF CIRCUMSOLAR RADIATION

CONTRACTORS: Argonne National Laboratory
University of Chicago

STUDY: Solar Energy Conversion -- Compound Parabolic
Concentrator Collector Program

FUNDING AND PERIOD:

- (1) ANL; \$186,000; October 1974 to June 1975
- (2) UC; \$63,000; October 1974 to February 1976

The Compound Parabolic Concentrator (CPC) collector development study is based on a cylindrical adaptation of an ideal conical collector developed in 1966 by Hertenberger and Winston to concentrate Cherenkov light in high energy physics experiments. The cylindrical application of the collector may offer an attractive low cost, low solar concentration, fixed trough collector suitable for total energy systems, photovoltaic systems, or the heating and cooling of buildings.

The approach uses light concentration without imaging, where the concentration factor is $1/\sin \theta_c$ (Figure 34). The CPC has a theoretical advantage in concentrators. It can be shown that for a given concentration aspect angle (controlled by the collector/absorber relationship), corresponding to θ_c for the CPC, that conventional concentration ratios are reduced by at least a factor of $1/\pi$ compared to the CPC.

The optical properties of CPC were investigated. In general, as long as incident radiation falls upon the CPC within the critical angle for the receiver (θ_c) the radiation at the exit is diffuse and collection efficiency is essentially uniform over the entire angular range. Results for two other cases are shown in Figure 35. In the case where the incident angle is

greater than θ_c , radiation at the exit is peaked and efficiency falls off rapidly, decreasing by a factor of 3 to 4 within about one degree of θ_c .

A number of modifications of collector design and applications of the CPC were presented. Figure 36 shows the application of a CPC as a second stage concentrator for the receiver of a central receiver power plant.

A comparison of the performance of CPCs with flat plate collectors was given. Typical results for low powered (3X) concentrations are shown in Figure 37.

The goals for the study include the investigation of the problems associated with the technological development of the CPC and the evaluation of the economic viability of commercial fabrication of the collectors for photothermal and photovoltaic applications. Within this broad framework, the contractors intend: (1) to identify the principal areas of application of the concept; (2) to identify and evaluate the significant program areas requiring early participation in research and development by commercial fabricators and design engineering companies; and (3) to prepare and scope the work to be performed in later study phases which would provide a more detailed and complete goals study for the CPC development.

Figure 34. COMPOUND PARABOLIC CONCENTRATOR

Figure 35. ENERGY DISTRIBUTION AT EXIT APERTURE

Figure 36. CPC AS SECOND STAGE CONCENTRATOR

Figure 37. PERFORMANCE COMPARISON, X3 CPC VS. FLAT PLATE

CONTRACTOR: Jet Propulsion Laboratory

STUDY: Comparison of Terrestrial/Orbital Solar Energy
Conversion Systems

FUNDING AND PERIOD:

NASA; \$350,000; June 1974 to June 1975

The NASA Office of Energy Programs is presently conducting a study of the potential utility of large orbital central power stations. As part of this study, JPL is performing a survey of potential terrestrial solar energy conversion systems for comparison with orbital central power stations. The candidate terrestrial options being reviewed include both solar thermal and photovoltaic conversion. Among the solar thermal options, the following are being studied: low temperature flat plate collectors, medium temperature parabolic cylinder collectors, and high temperature dispersed parabolic dish and central tower heliostat collectors. A report was presented of a preliminary survey of the parabolic dish collector combined with a closed cycle Brayton engine. An example was given of a 100 MWe distributed system, consisting of approximately 6000 parabolic collectors (each 36 feet in diameter). Each of the 6000 individual units was designed to have its own turbine-generator, producing electric power which was collected and conditioned for delivery from the field to the main utility grid. As indicated in Figure 38, estimated generation costs were \$1465/KWe, with an energy cost of 73 mills/kWh at an overall system efficiency of 22.5%.

100 MW_e - DISTRIBUTED GENERATION

- OVERALL EFFICIENCY _____ 22.5%
- TOTAL COST (1975 \$) _____ 1465 \$/KW_e
- ENERGY COST _____ 73 $\frac{\text{MILLS}}{\text{KW-HR}}$
- (AT SIMPLE 15% ACF _____ 55.7 $\frac{\text{MILLS}}{\text{KW-HR}}$)

Figure 38. PARABOLIC DISH SOLAR PLANT COST SUMMARY

CONTRACTOR: McDonnell Douglas Astronautics Co.

STUDY: The Elimination or Control of Material Problems in
Water Heat Pipes

FUNDING AND PERIOD:

\$189,500; 1 January 1974 to 31 March 1976

The objective of this study is to determine the most effective combination of materials, fabrication methods, and operating procedures for a water heat pipe that will provide satisfactory performance when used as a local absorption solar thermal energy collector. The heat pipe materials and design characteristics being evaluated are shown in Table 2, while operating results obtained to date are shown in Figure 39. Life testing of the various heat pipe materials is continuing. Problems from oxidation associated with diffusion of dissociated hydrogen gas through heat pipe walls have contributed to performance reduction. Studies are under way to determine the diffusion rate of hydrogen gas through each candidate material at 300 C. Two heat pipes will be fabricated and tested to evaluate designs with end caps of a material which has a high diffusion rate for hydrogen but contains a low cost stainless steel body. Heavy walled, self-venting, and relatively low cost heat pipes will be tested in the immediate future as part of an investigation of the potential for cost reduction in full-scale heat pipes.

Table 2. MATERIALS AND DESIGN CHARACTERISTICS

MATERIAL	NOMINAL CHEMICAL COMPOSITION	OUTSIDE DIAMETER		WALL THICKNESS	
		CM	IN	CM	IN
316	Fe + 18 Cr + 14 Ni + 3 Mo + 2 Mn + .08C	1.27	.500	.124	.049
347	Fe + 19 Cr + 13 Ni + 1 Mn + [Cb + Ta] + .08C	1.27	.500	.124	.049
430	Fe + 18 Cr + 1 Mn + .12C	1.91	.750	.165	.065
CDA 715	68 Cu + 30 Ni + 1 Mn + 1 Zn + .5 Fe	1.27	.500	.124	.049
MONEL 400	66 Ni + 31.5 Cu + 1.3 Fe + .9 Mn	1.27	.500	.124	.049
INCONEL 600	76 Ni + 15.5 Cr + 8 Fe + .25 Cu + .25 Si + .5 Mn	1.27	.500	.089	.035
INCOLOY 800	46 Fe + 32 Ni + 20.5 Cr + .4 Ti + .4 Al	1.27	.500	.124	.049
304 SS/CU	BIMETAL TUBE	1.27	.500	.124 .038	.049 .015

Figure 39. HEAT PIPE PERFORMANCE CURVES

D. Central Receiver Systems

The material presented by contractor teams in this session was restricted at ERDA request. Proposals for participation in prototype development (Phase I) for a Central Receiver Solar Thermal Power System had been prepared, and delivered to ERDA, by essentially all of the teams represented in this portion of the presentation. Since members of the Contractor Selection Board and Technical Review Panel for evaluating the proposals were in attendance at the meeting, contractors were requested not to discuss any of the proposals (or any new work on their contracts) during formal presentations in order to avoid any potential conflicts of interest. The ERDA announcement relative to this request has been quoted in full in Section I.

CONTRACTOR: University of Houston
McDonnell Douglas Astronautics Co.

STUDY: Solar Thermal Power Systems Based on Optical
Transmission

FUNDING AND PERIOD:

- (1) \$216,900; 15 June 1974 to 14 June 1975
- (2) \$112,800; 1 May 1974 to 31 May 1975
(Model Heliostat Tests, China Lake, Calif.)

The objective of this study was to perform a preliminary technical and economic feasibility study of a central receiver solar-thermal electric power system. In this concept, solar radiation is reflected from a relatively large number of steered (fixed location) mirrors to a common target receiver located on a central tower. An artist's conception of a typical layout is shown in Figure 40. The objective has been supported through work on the following tasks: (1) analysis of the solar flux concentration system, including a system geometric analysis of the optical characteristics, guidance and control system studies, and reflector designs; (2) investigation of the receiver and energy transfer system, including conceptual designs of the tower; (3) system definition and evaluation with particular attention to economic analysis of the collection, energy transfer, and energy conversion systems; and (4) construction and testing of an operational 14 square meter heliostat in a desert environment to evaluate tracking accuracy and beam dispersion for the heliostat subsystem.

Results of a study of collector field optimization were presented. Based upon calculations of heliostat-to-heliostat shading and blocking in the winter season, an optimized rectangular array was developed (with non-uniform spacing of rows

and columns designed to minimize shading and blocking for all portions of the field). Though based upon the motion and relative position of the sun and collectors in the winter, the array was also designed to minimize variations in peak energy over the year, maximize redirected power per heliostat over the year, while maintaining the largest practical mirror density for the field. Figure 41 shows the results of this study. The shaded region shows the elements of a rectangular array which can be "trimmed" (eliminated), since their effectiveness is less than 85% of average heliostat effectiveness for the field -- integrated over the entire year. Note the off-center (southern) location of the receiver tower (designated by the T). The variation in the "broad-shouldered" diurnal thermal power curves for the system over a period of a year are shown in Figure 42. With a field distribution of this type, the flux distribution for reflected thermal power at the central receiver is shown in Figure 43. Results for a single (central) aim point are shown at the left, while a two-aim point (near the upper and lower thirds of the receiver) are shown at the right of the figure.

A review was presented of the overall system trade-off studies which are being conducted. The relative variation on heliostat cost with its size was discussed. Costs generally decrease with increasing size, but are not very sensitive for heliostats larger than about 16 by 16 ft. A number of variations in shapes of receivers have been considered. These variations, along with their relative advantages and disadvantages, are shown in Figure 44.

A review was presented of the results of a solar energy receiver design study conducted under subcontract by the Rocketdyne Division of Rockwell International. Results of a trade-off on receiver shapes indicated that the aspect ratio (length/diameter) should be of order unity; that wide vanes were

a higher risk design element, because of wind loads and restrictions on internal space within the receiver envelope; and that noncylindrical shapes presented additional risks. A specific preliminary design study was conducted for the receiver shown in Figure 45. Its design characteristics are given in Table 3.

The model heliostat test program conducted at the Naval Weapons Center/China Lake, Ca. has been completed and results of the investigation were presented at the meeting. The purpose of the program was to:

- 1) Design, fabricate and test a representative, full-scale heliostat;
- 2) Determine heliostat tracking accuracy for candidate servodynamic control techniques;
- 3) Obtain data on servodynamics;
- 4) Obtain data on reflector surface accuracy and intensity distribution for a range of field positions.

A photograph of the heliostat and test equipment in operation is shown in Figure 46. Results of the experiment are presented in Table 4.

Figure 40. CENTRAL RECEIVER CONCEPT

Figure 41. HELIOSTAT FIELD EFFECTIVENESS

Figure 42. SYSTEM THERMAL POWER

Figure 43. RECEIVER FLUX PATTERNS

	CYLINDRICAL	HEMICYLINDRICAL RECEIVER	STAR	CAVITY
ABSORPTIVITY				
UNCOATED	0.85	0.85	0.94	0.97
COATED	0.94	0.94	0.98	0.99
RELATIVE COST	1.0	—	1.5	2.5
REMARKS	<ul style="list-style-type: none"> • Minimum wind load • Minimum system cost 	<ul style="list-style-type: none"> • No place for structure • High wind load • High wind torque 	<ul style="list-style-type: none"> • Medium cost • High wind load on points • No impact on collector field 	<ul style="list-style-type: none"> • High wind load • High wind torque • Major impact on collector field

Figure 44. RECEIVER COMPARISONS

Figure 45. RECEIVER ASSEMBLY

Table 3. RECEIVER DESIGN SUMMARY

SIZE	- 18 M DIA - 25 M LONG
CONSTRUCTION	- 24 INDEPENDENT PANELS - ONE PASS
ATTACHMENT	- HUNG FROM TOWER TOP
TUBING	- 0.50 IN. O.D. - 0.064 IN. WALL - INCOLOY-800
TUBE JOINING	- BRAZED TO LATERAL STRUCTURAL BANDS PLASMA SPRAYED INCONEL ON INTERIOR-LIGHT TIGHT
TUBE RESTRAINT	- FREE LATERAL GROWTH SLIDING JOINT TO ALLOW LONGITUDINAL GROWTH
CONTROL	- EACH PANEL CONTROLLED INDEPENDENTLY

Figure 46. MODEL HELIOSTAT TEST SET-UP

Table 4. MODEL HELIOSTAT TEST RESULTS

- **VERIFICATION OF OVERALL CONCEPT**
 - CLOSED LOOP BEAM SENSOR WITH COORDINATE TRANSFORMATION CENTRAL PEDESTAL SUPPORTED REFLECTOR; SEPARATE SENSOR SUPPORT PEDESTAL
- **DETERMINED HELIOSTAT TRACKING ACCURACY AND SERVO DYNAMIC RESPONSE**
 - LINEAR AMPLIFIER WITH BUZZ ~ 0.6 MR
 - LINEAR AMPLIFIER WITHOUT BUZZ ~ 2-3 MR
 - PULSE WIDTH MODULATED AMPLIFIER ~ 1-2 MR
 - POLE-POSITION RESPONSE ~ 0.6 TO 5 MR AT $B_N = 90^\circ$
 - SERVO DYNAMIC COMPUTER PROGRAM RESULTS COMPARED WITH TEST DATA
 - DEMONSTRATED TRACKING RESPONSE TO OFF-NOMINAL CONDITIONS
- **DETERMINED REFLECTOR FLUX PATTERNS, FLATNESS, REFLECTIVITY**
 - FLUX PATTERN ~ OVERLAPPING CIRCULAR PATTERNS, APPARENTLY INCLUDED BY SURFACE WAVINESS
 - FLATNESS ~ <0.6 MR
 - FLUX PATTERN DATA OBTAINED AT 300' TO 3,000'
 - REFLECTIVITY DECREASED 5 TO 6% BY DUST
 - VIDEO DIGITAL IMAGE RADIOMETER MEASUREMENT TECHNIQUES CONFIRMED
- **FIELD TEST TECHNIQUES**
 - MOBILE HELIOSTAT TESTING TECHNIQUE CONFIRMED
 - HELIOSTAT FIELD POSITIONS SIMULATED THROUGH USE OF TOWER AND TARGET
 - FLUX PATTERNS READILY PHOTOGRAPHED USING RETRO-REFLECTING BEADED GLASS SCREEN TARGETS
 - TRACKING ACCURACY/RESPONSE DATA FROM BEAM SENSOR WITH SOLAR IRRADIANCE READ-OUT

CONTRACTORS: Sheldahl, Inc., Northfield, Minnesota
Foster Wheeler Corp., Livingston, North Dakota
University of Minnesota, Minneapolis, Minnesota
Northern States Power Co.

STUDY: Hybrid Central Receiver Solar Energy Conversion
Systems

FUNDING AND PERIOD:

\$260,000; 15 November 1973 to 15 November 1974

The primary objectives of this investigation were the estimation of the performance and economics of a Central Receiver Solar Thermal Conversion System operated as a hybrid with a conventional fossil fuel system. Analyses and testing to evaluate use of stretched membrane reflective materials for heliostat surfaces were performed. The efforts have been conducted generally along the following organizational lines: Sheldahl, Inc., project organization, materials evaluation (membrane reflectors), concentrator (collector) subsystem analyses; Foster Wheeler Corp., thermal conversion (receiver analyses); University of Minnesota, hybrid vs. stand-alone configuration considerations and mirror steering analysis.

As one of the competitors for the Phase I portion of the Central Receiver Solar Thermal Power System, no formal presentation of the work of this contractor team was made, in accordance with the previously described ERDA request.

CONTRACTOR: Martin Marietta Corporation, Denver, Colorado
Georgia Institute of Technology, Atlanta, Georgia

STUDY: Solar Power System and Component Research

FUNDING AND PERIOD:

- (1) \$229,500; 15 January 1974 to 31 January 1975
- (2) \$599,000; 12 months (1 MW Cavity Receiver Design and Test in Odeillo, France)

The objectives of the initial phase of this program were to evaluate the potential utilization of Solar Thermal Conversion Central Receiver-Hydroelectric Hybrid Power Systems and to define the requirements for a bench model Cavity Receiver Test Program using the Centre National de la Recherche Scientifique (CNRS) Solar Furnace at Odeillo, France. The major elements of this phase of the program included: the system analysis for a base line 100 MWe Central Receiver Solar Thermal/Hydroelectric Hybrid power plant; the thermal design and analysis of a bench model boiler and superheater consistent with the available power at CNRS Solar Furnace while preserving the technical features of the base line 100 MWe system; the definition of the necessary facility modification at CNRS; and the preparation of test plans for performing the tests on the boiler and superheater bench models at CNRS. Design and testing of the cavity receiver at CNRS are to be performed in the indicated follow-on portion of the study.

In accordance with the ERDA request, the contractor team limited its presentation of their system analysis and development work for central receivers to material which had previously been presented. No new work related to their competitive proposal to

ERDA was presented, to avoid a potential conflict of interest between government and contractor representatives.

However, a presentation was made on the status of the work on the 1 MWt bench model cavity receiver test at the CNRS solar furnace. Work has been completed on the analysis and design drawings made for the bench model boiler-superheater subsystems. Support equipment needs have been determined and specified along with interface requirements at the CNRS solar furnace. Scale models of the CNRS focal building and bench model equipment have been built to assure that interface specifications are adequate. Photographs of the models were presented. Plans for operational tests at CNRS have been formulated.

In the program now beginning, the same team members will construct, assemble, and proof test the model receiver before shipping it to France. Following shipment to CNRS, a flux redirector modification, required for operation at the French facility, will be incorporated and operational tests conducted.

CONTRACTORS: Honeywell, Inc., Minneapolis, Minnesota
Black and Veatch, Kansas City, Missouri

STUDY: Dynamic Conversion of Solar Generated Heat to
Electricity

FUNDING AND PERIOD:

A report was presented on the work performed by Honeywell/Black and Veatch for NASA/Lewis Research Center, Cleveland, Ohio, under Contract NAS3-18014, "Dynamic Conversion of Solar-Generated Heat to Electricity." The objectives of this study program were to: (1) establish criteria and methods for the selection of sites for central solar thermal power plants and use the criteria to evaluate potentially suitable sites within the Continental United States; (2) develop a set of candidate systems configurations which typified the large number of possible design approaches for the collection and conversion of solar energy to electricity; (3) specify analytically the performance of all solar power plant subsystems, such as the mirrors, receivers, energy transport, turbine-generator, heat rejection, steam generator, and storage; and (4) conduct systems studies for the candidate design configurations and provide a technical and economic comparison from which the most promising concepts for large-scale conversion of solar-generated heat to electricity could be identified. The effort undertaken during the program led to the selection of the water-superheated steam (850 psig/900 F) crescent central receiver system as the preferred concept from among 11 candidate systems.

This result was attained after a systematic technical and economic evaluation of both distributed and central receiver solar thermal power systems which included flat plates, parabolic

troughs at three different orientations, paraboloid-of-revolution dishes and four central receiver concepts. The polar mounted trough and the dish concepts were evaluated for saturated steam and pressurized water as thermal transport fluids.

To perform the analytical specification of the components of these systems and to carry out the required systems studies, an extensive software capability was needed. A versatile software program utilizing a Monte-Carlo simulation code was developed to simulate the performance of the focusing collector systems. For the central receiver, the code has the unique capability of time-dependent flux mapping and yearly power integration.

The solar power plant designs were investigated in the range of plant capacities from 100 to 1000 Mw(e). The investigations considered the impacts of plant size, collector design, feed-water temperature ratio, heat rejection equipment, ground cover, and location on solar power studies showed that plant capacities less than 100 Mw(e) may be best. Although the size of central receiver concept was not parametrically investigated, all indications are that the optimal plant capacity for central receiver systems will be in the range from 50 to 200 Mw(e).

Engineering cost estimates were made for two baseline concepts evaluated in detail in the study: a pressurized water, paraboloid of revolution "dish" collector system; and a water/superheated steam, Rankine cycle central receiver system. Tables 5 and 6 present the results of the cost estimating exercises for the dish and central receiver baseline systems respectively. It can be seen that with estimated costs of \$1,266/KW, and energy cost estimates of 50.6 mills/kWh, the central receiver system enjoys a substantial apparent cost advantage over the baseline dish system where estimates were made of capital costs of \$1,784/KW and energy costs of 73.2 mills/kWh.

Solar thermal power plant site selection criteria and methodology were also established and used to evaluate potentially suitable sites. The result of this effort was to identify a site south of Inyokern, California, as typically suitable for a solar thermal power plant. The criteria used in the selection process included insolation and climatological characteristics, topography, and seismic history as well as water availability.

In performing the system study, a variety of problems were identified for which additional work was recommended. Foremost among these was the recognition that design details of the receiver require special attention. It was observed that if configurations could be identified which would permit complete usage of the high-flux and high-temperature capabilities of the magnification of the solar flux in the central receiver concept, that some gas turbine concepts with upper temperature limits of about 1800 F would make improved system efficiencies possible. A recommendation was made for the investigation of high temperature-high performance receivers, possibly using ceramics, to improve system performance capacities. An investigation of low-cost heliostat design concepts was also recommended, since the heliostats are the dominating cost item in the overall central receiver system.

Table 5. CENTRAL RECEIVER SYSTEM BASELINE CAPITAL COST SUMMARY
(March 1974 Dollars)

SYSTEM PARAMETERS	
PLANT CAPACITY, PEAK	215 MW(e)
AVERAGE OUTPUT OVER 4000 HOURS	147 MW(e)
ANNUAL ENERGY PRODUCTION	588 X 10 ⁶ KWH
ESTIMATED DIRECT COST (THOUSANDS OF DOLLARS)	
LAND	600
HELIOSTATS	118,300
PIPING/HEAT EXCHANGERS	1,500
TOWER/RECEIVER	12,000
TURBINE-GENERATOR/HEAT REJECTION/PUMPS	12,200
BALANCE OF PLANT	9,200
TOTAL DIRECT COST	153,800
ESTIMATED INDIRECT COST	32,300
TOTAL CAPITAL COSTS	186,100
UNIT CAPACITY COST (DOLLARS PER KILOWATT OF AVERAGE (4000 HOURS) OUTPUT)	1,266
CONTRIBUTION OF CAPITAL INVESTMENT TO ENERGY COST (MILLS PER KILOWATT-HOUR (16% FCR))	50.6

Table 6. DISH SYSTEM BASELINE CAPITAL COST SUMMARY
(March 1974 Dollars)

SYSTEM PARAMETERS	
PLANT CAPACITY, PEAK	143 MW(e)
AVERAGE OUTPUT OVER 4000 HOURS	100 MW(e)
ANNUAL ENERGY PRODUCTION	0.39 x 10 ⁶ KWH
ESTIMATED DIRECT COST (THOUSANDS OF DOLLARS)	
LAND	300
HELIOSTATS	108,000
PIPING/HEAT EXCHANGERS/PUMPS	26,700
TURBINE-GENERATOR/HEAT REJECTION	7,200
BALANCE OF PLANT	5,200
TOTAL DIRECT COST	147,400
ESTIMATED INDIRECT COST	31,000
TOTAL CAPITAL COSTS	178,400
UNIT CAPACITY COST (DOLLARS PER KILOWATT OF AVERAGE (4000 HOURS) OUTPUT)	1,784
CONTRIBUTION OF CAPITAL INVESTMENT TO ENERGY COST (MILLS PER KILOWATT-HOUR (16% FCR))	73.2