MASTER

TOTAL ENERGY, DISTRIBUTED COLLECTOR SYSTEMS AND RESEARCH AND DEVELOPMENT PROJECTS

Semiannual Review
26-27 January 1976

THE AEROSPACE CORPORATION

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HIGHLIGHTS OF THE SOLAR TOTAL ENERGY SYSTEMS,
DISTRIBUTED COLLECTOR SYSTEMS,
AND RESEARCH AND DEVELOPMENT PROJECTS
SEMIANNUAL REVIEW
26-27 January 1976
Atlanta, Georgia

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FOREWORD

This report presents the highlights of the Energy Research and Development Administration (ERDA) Solar Thermal Branch Semiannual Review held in Atlanta, Georgia, on January 26-27, 1976. The review covered status and plans for Total Energy Systems, Distributed Collectors, and Research and Development Projects. This report is submitted to the ERDA Solar Thermal Branch by The Aerospace Corporation, Energy and Transportation Division, under Task 6.0 of ERDA Contract No. E(04-3)-1101, Project Agreement No. 2. It was prepared by Mr. Allen F. Latta, Member of the Technical Staff, Energy and Transportation Division. ✓

The author wishes to express his appreciation to Ms. Madge Buckman, Ms. Peggy Crook, and Ms. Bobbie Devaney for typing and assistance in preparing this publication.

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I. INTRODUCTION

The Energy Research and Development Administration (ERDA) has a number of both near-term and long-term objectives for the development and demonstration of alternative solar thermal energy systems. These alternative systems are planned for widespread use in the post-1980 period. During the November 17-19, 1975, Semiannual Review, the 10 MWe Central Receiver Solar pilot plant and associated Test Facility projects were discussed. The purpose of the January 26-27 Semiannual Review, summarized herein, is to provide a similar review of the technical progress made in Total Energy Systems, Distributed Collectors, and Research and Development Projects since the April 30-May 2, 1975, meeting on these subjects.

The review meeting consisted of three sessions during which the various contractors reported their progress and provided copies of an abstract, including viewgraphs of the material presented. This material was summarized to form the input for this document.

Following the technical sessions, the ERDA Solar Thermal Ad Hoc Review Committee met to discuss the results presented and to evaluate the status of the programs and plans for the future. The meeting was chaired by Mr. George Kaplan, Acting Chief, Solar Thermal Branch, Division of Solar Energy. In addition to the chairman, the Committee members present at the review were Walter Christensen (Department of Defense), Daniel Lewis (Federal Power Commission), Harold Spuhler (National Science Foundation), Douglas Elliott (Naval Weapons Center) and Alfred Whatley (Western Interstate Nuclear Board). Also attending the meeting were Lloyd Herwig, Jim Rannels, Lou Melamed, and Robert Hughey, all from ERDA, and Howard Webb of The Aerospace Corporation.

A summary report of the Committee deliberations was transmitted to the Acting Chief of the Solar Thermal Branch on 3 February 1976 by The Aerospace Corporation.

II. THE ERDA SOLAR THERMAL ENERGY PROGRAM*

The early semiannual reviews of the Solar Thermal Energy Program originally covered the activities of the whole program. However, when planning the November review, it became apparent that there was too much material to cover and that the meeting would involve too large a group. Accordingly, the program has been split with each portion reviewed semiannually. The Central Receiver and the related Solar Thermal Test Facility were reviewed in Las Vegas in November 1975. The balance of the program was to be covered during the Atlanta meeting.

The top level ERDA organizational structure (Figure 1) shows, across the upper level, the line management consisting of six Assistant Administrators. In the energy conservation area, shown in the upper righthand portion of the figure, there is work on energy storage that directly complements the activities of the Division of Solar Energy. The three Field Operations Offices that have provided the major support for the Division of Solar Energy Programs are highlighted in the chart by the boxed areas. Additional contracts have also been processed by the other Field Operations Offices.

Figure 2 presents the organization of the Division of Solar Energy. The Solar Thermal Program includes several projects which are concerned with Advanced Research and Technology, Total Energy Systems, and Distributed Collector Systems which will be discussed at this semiannual review. Hybrid Systems are not in

*Delivered by Mr. Howard Webb of The Aerospace Corporation in the absence of Mr. George M. Kaplan, Acting Chief, Solar Thermal Branch.

an active phase of development at the present time, but are being planned for research and development in the future. The Central Receiver effort at the present time is focused on the development of a 10 MWe pilot plant and the associated 5 MWth test facility.

The National Solar Energy Program has shown a continued growth for the past several years, although the solar thermal budget for this year is less than was anticipated. The impact of this lesser amount is not fully understood at the present time. The Solar Thermal Program thrusts can be viewed as long-term plans and short-term plans. The long-term plan calls for the determination of the economic and technical viability of many types of solar energy conversion. The viability of some of these solar conversion types is going to be ascertained in the mid- and late 1980's by actual demonstration plants as in Figure 3.

The near-term effort in Total Energy Systems includes a 2 MWth solar thermal total energy pilot plant installation at the Fort Hood military base, and a 32 kWe total energy test bed being developed at Sandia Laboratories, Albuquerque, N.M. It is about one-half way through the construction phase.

The Solar Thermal Branch of ERDA is confident that by 1990-2000, solar energy conversion systems, both large and small, will make significant contributions toward providing new energy resources which can reduce the fossil fuel demand.

Figure 1. Energy Research and Development Administration

Figure 2. Energy Research and Development Administration
Division of Solar Energy

Figure 3. Solar Thermal Conversion Branch - Milestones

III. Session I: SOLAR TOTAL ENERGY SYSTEMS

CONTRACTOR: The Aerospace Corporation
El Segundo, California

TITLE: Mission Studies

FUNDING AND PERIOD:

\$360,000; 5 January 1975 to December 1975
(This study is a portion of the total funding
given above.)

The contractor reported upon a simple solar total energy (TE) system computer model which allows thousands of different configurations to be simulated and evaluated under a wide variety of conditions. The model adjusts the sizes of a solar TE system's components to maximize the return on invested capital.

The model is dynamic and simulates the interaction of the time varying energy supply and demand and the time-lag effects of thermal storage as can be seen in Figure 4. Figure 5 shows a block diagram of the solar TE system simulation. The thermal input to the turbine generator, the electrical output, and thermal exhaust may be assumed constant during the period of operation. When necessary, solar energy is augmented by conventional fossil fuel to maintain the required input to the turbine generator and to meet any excess thermal demand. The turbine generator, however, may be throttled to match the electrical demand. The various thermal demands (heating, cooling, water heating, etc.) are lumped together into an overall thermal demand.

There are five major variables in a solar TE system: concentrating and flat plate collector sizes, high and low temperature storage capacities, and generator capacity. Large hourly, daily, and seasonal variations in the solar energy supply and demand curves will complicate the design of solar TE systems because an optimal solar TE system may be oversized for part of the year and undersized for part of the year. The important consideration is to balance the overall average operating costs against the overall fossil fuel energy displacement. The optimization program adjusts the five solar TE system variables to maximize the present worth of the net cost savings over the lifetime of the equipment. In short, the optimization program picks the most economical system.

The revenue requirements method is used to compare the overall cost of the on-site TE system versus the cost of purchasing all of the energy from utilities. The term "revenue requirements" means the annual revenue required (as a percentage of the total capital invested) to cover all expenses associated with the investment versus a minimum acceptable percentage profit or return. The present worth of the capital, electricity, and fuel costs over a time horizon of Y years is computed, as is the present worth of purchased energy generated off-site for the same period.

The simulation does not consider the adverse impact of a solar TE system on an electric utility. This impact would cause an increase in both the ratio of peak-to-base load and the required reserve capacity (for cloudy days).

With an understanding of the modeling assumptions, the simulation and optimization program can be a useful tool for determining the optimal configurations and costs of solar TE systems.

Figure 4. Interaction of Energy Supply and Demand

Figure 5. Simulation Block Diagram

CONTRACTOR: Sandia Laboratories, Albuquerque, New Mexico

TITLE: Solar Total Energy Program

FUNDING AND PERIOD:

(1) \$1,975,000; Fiscal Year 1976

(2) \$3,000,000; Fiscal Year 1976

The stated objectives of Sandia's Solar Total Energy Program are (1) to establish the feasibility of the solar total energy concept, (2) to provide a versatile system which can be used as an engineering evaluation center or test bed for component development, (3) to design a system of sufficient size to require realistic integration of all subsystems, and (4) to conduct a demonstration capable of attracting widespread public interest.

The system, depicted in block diagram form in Figure 6, conceptually operates as follows: a heat transfer fluid, Therminol 66* (T-66), is pumped through receiver tubes located at the focus of a series of parabolic trough reflectors (Figure 7) where it is heated to an outlet temperature of 310 C (590 F). The heated T-66 is stored in the high temperature insulated tank. It is then pumped through a heat exchanger in which toluene is boiled and superheated. The superheated toluene is the working fluid for the 32 kWe turbine generator. The turbine generator waste heat is then condensed and becomes the energy source for the heating and cooling components of the system. The supplementary fossil fuel heat supplies for the system are also shown schematically in Figure 6.

A recent overall view of the collector field turbine and control building is shown in Figure 8. The collector field and

*Registered trademark of Monsanto Industrial Chemicals Co.

storage tank are approximately 25 percent of the size required to maintain a 32 kWe output for 11 hours. Visible in the background is the solar project building, an 1130 sq m (12,000 sq ft) office building which constitutes the demonstration load for the solar total energy system.

Details of the collector modules are as follows:

- o Concentrator reflectivity = 0.83.
- o Receiver absorptivity = 0.95, emissivity less than 0.25.
- o Collector module optical constant = 0.71.

Key recent achievements have been:

- o Circulation of Therminol through the collector field.
- o The collected energy deposited in storage (a major program milestone).
- o Tracking and drive systems installed and checked out.
- o High temperature storage tank plumbing and instrumentation completed.
- o Turbine generator acceptance tests completed.
- o Meteorological station installation completed.

In the area of materials development, considerable effort has been expended in determining cost effective coatings for the concentrator solar spectrum reflecting surface and for the absorber emissivity in the near infrared spectral region.

Progress is also being made in the following areas:

- o Temporary conversion of the collector test facility to water for low temperature photovoltaic tests.

- o Optical characterization of reflectors by laser beam techniques.
- o Checkout of instrumentation, fluid flow paths, and valve controls of the loop.
- o Development of test plans, operational procedures, and check lists for operation of the fluid loop at 310 C.
- o Modification of the heater and turbine control circuit.
- o Development of computer programs for data acquisition, reduction, instrumentation readout, performance calculations, and collector field control.
- o Selection of the contractor for collection field fabrication.

Figure 6. Cascaded Solar Total Energy System

Figure 7. Parabolic Collector Modules

Figure 8. Overall View of Collector Field, Turbine and Control Building

CONTRACTOR: Sandia Laboratories, Albuquerque, New Mexico

TITLE: Total Energy Systems Studies

FUNDING AND PERIOD:

\$115,000; included in funding listed
in the previous abstract.

The contractor noted that at the last semiannual review several systems were described along with the performance analysis results from the computer program. Economic studies were reported on the 1000-home model with clear weather and the photovoltaic thermal single home. The 1000-home performance, with actual weather data, was reported at the International Solar Energy Society meeting last August.

A study of the mixed community has been completed recently and is reported in SAND-75-0542. The mixed community as designed by the Department of Architecture at the University of New Mexico is shown in Figure 9, and details of the mixed community and assumptions used are shown in Figure 10. The results of this study demonstrated a net cost advantage through use of a total energy system (Figure 11). The 2000-dwelling unit solar total energy system was changed to maximize the electrical output by lowering the condenser temperature to 100 F and scaling down the entire collector field to provide for more efficient conversion to electricity. When this high density subset was analyzed, however, the savings achieved by converting to electricity only were less than those available by continuing with the solar total energy system.

One interesting preliminary comparison was made with real weather data obtained from the recording pyrheliometer at Omaha. When a mixed load community was sized for Omaha and Albuquerque,

(Table 1) it proved that the collector area was increased only 10 percent. However, the heating load in Omaha is more than 25 percent higher than Albuquerque. This would indicate that a more stable balance is apparent for a total energy system in the colder more northern climates than New Mexico. However, this result is not as yet verified by an economic study.

Table 1. Effect of Location, Mixed Load

	<u>Albuquerque</u>	<u>Omaha</u>
PEAK ELECTRIC LOAD	4.0 MWe	4.0 MWe
HEATING DEGREE DAYS	4300	5000-6000
COLLECTOR AREA	81,000 sq m	89,000 sq m

Figure 9. Mixed Load Community Layout

I. LOAD DESCRIPTION

BUILDING TYPE	DWELLING UNITS	NUMBER OF BUILDINGS
SEPARATE HOUSES	504	504
TOWNHOUSES	800	160
LOW-RISE APT	480	58
HIGH-RISE APT	216	4
COMMERCIAL	-	1
SCHOOLS	-	3

II. FINANCIAL ASSUMPTIONS (29 years)

A. CAPITAL FINANCING

	% HOLDINGS	RATE (above inflation) %*
DEBT (bonds)	60	2.5
EQUITY (stocks)	40	4.5

*THIS IS EQUIVALENT TO 9-1/2% AND 11-1/2% WITH AN INFLATION RATE = 7%

B. FUEL COSTS

LEVELIZED COST OF RESIDENTIAL FOSSIL FUEL = \$3.94/GJ
LEVELIZED COST OF CITY GATE FOSSIL FUEL = \$1.54/GJ

C. CAPITAL RECOVERY FACTOR (CRF) FOR BEFORE TAX

$(0.025) (0.60) + 2(0.40) (0.045) = 0.051$
CRF OVER 29 YEARS = 0.06678

Figure 10. Mixed Load Community Details

	REVENUE REQTS (\$ x 10 ⁻³)			REVENUES (\$ x 10 ⁻³)*	
	CASCADED	NONCASCADED	SAVINGS	THERMAL	ELECTRIC
2000 DWELLING UNIT	2630.7	1840.5	790.2	616.4	901.0
HIGH DENSITY SUB SET **	1151.9	881.9	270.0	295.3	339.2

* BASED ON \$4.00/GJ LEVELIZED COST FOR FOSSIL FUEL, AND
\$10.60/GJ ELECTRIC COST AT RESIDENCE

** HIGH DENSITY SUB SET IS LOW RISE, HIGH RISE, AND COMMERCIAL PART OF
2000 DWELLING UNIT COMMUNITY

Figure 11. Comparison: Total Energy vs. Electricity Only

CONTRACTOR: Sandia Laboratories, Albuquerque, New Mexico

TITLE: Solar Total Energy Campus Study

FUNDING AND PERIOD:

- (1) ERDA; \$93,000
- (2) Dallas Community College District; \$5,000;
October 1975 to June 1976

Sandia Laboratories stated that the objective of this study is to assess the feasibility of providing a solar total energy system for the new North Lake Campus of the Dallas County Community College District. This campus is presently under construction in the Dallas, Texas, suburb of Irving. The assessment will include design and evaluation of several total energy system options, modeling of system performance against campus utilization loads, and economic viability based upon preliminary estimates of both pilot plant and forecast system costs.

The principal aspects of the North Lake Campus are:

- o A site size of 276 acres.
- o First construction phase: 23,250 sq m
(250,000 sq ft).
- o Initial enrollment: 3600 (1800 full-time
equivalent (FTE) day students).
- o Ultimate capacity: 7500 FTE students or more.
- o First Phase projects cost: \$21,000,000.

The site is located near the southeast corner of the Dallas/Fort Worth airport property within the Las Colinas residential area. Currently, the campus is a study candidate for the application of a solar total energy system.

The study began several months ago and involves three participants: (1) Sandia Laboratories for the solar total energy system definition and performance evaluation, (2) Envirodynamics, Inc., for load profile data and architectural support, and (3) a power plant A&E contractor for the power conversion system definition. Highlights of the responsibilities and status of these organizations are discussed in the following paragraphs.

Sandia has defined four candidate total energy systems: (1) cascaded (2) noncascaded, (3) building heating, cooling, and hot water (no electric power generation), and (4) a 1-2 MWe mini-central receiver in lieu of distributed collectors for a cascaded total energy design. The last candidate will be a low level effort in comparison with the first three.

Figure 12 portrays the classic cascaded total energy system using focusing solar collectors,—a high temperature storage system, and a heat exchanger driving a turbine generator. The turbine waste heat is stored in the low temperature storage subsystem for space heating/cooling and hot water. The third candidate would use flat plate collectors and is of interest from the cost effectiveness viewpoint. With some staging and bromide chillers (Figure 13), a coefficient of performance (COP) improvement from 0.60 to about 1.0, and a predominantly high cooling load, the focusing collector area required is about one-third to one-half of that needed for a flat plate system. This tends to indicate that, under these conditions, one could afford to spend two to three times as much for a focusing front end system as for a nonfocusing system, according to the contractor.

Analytical simulations for the four candidate configurations have been completed. The remaining tasks are the heart of the Sandia input to this study. These tasks are to: (1) evaluate

system performance with local weather and insolation, (2) select and size the system, and (3) define the costs.

Researchers at Envirodynamics have found methods of reducing the energy consumption on this particular campus. Figure 14 defines the stated Envirodynamics tasks and status. Also shown are the tasks to be accomplished by the power plant A&E contractor. The selection of this third participant in the study is imminent.

All of the work is planned to be completed by June 1976, and results will include:

- o Estimated costs of candidate solar systems.
- o Forecast energy contributions and savings of candidate systems.
- o Major technical and cost uncertainties of candidate systems.
- o Recommendations for future effort.

Figure 12. Cascaded Solar Total Energy System

Figure 13. Absorption Refrigeration Cycle Efficiencies

ENVIRODYNAMICS, INC

POWER PLANT A&E CONTRACTOR

1. COMPLETED AUTHENTICATED DAILY LOAD PROFILES A. HEATING B. COOLING C. ELECTRIC POWER D. HOT WATER 2. COMPLETED STUDY ENERGY CONSERVATION MEASURES A. SYSTEM OPERATION D. RETROFIT HARDWARE 3. COLLECTOR FARM A. SUPPORT STRUCTURE B. SAFETY C. SECURITY D. MAINTENANCE 4. BUILDING (House Power Conversion/Control Equipment) 5. INTEGRATE SOLAR THERMAL INPUT 6. INSTRUMENTATION AND DATA ACQUISITION 7. COST ABOVE SYSTEMS AND COMPONENTS	1. SELECT THERMODYNAMIC CYCLE 2. DEFINE CONTROL FUNCTIONS 3. DEFINE SWITCHING SEQUENCE 4. DEFINE INTERLOCKS AND CIRCUIT PROTECTION 5. DETERMINE HARDWARE AVAILABILITY 6. COST POWER CONVERSION SYSTEM

Figure 14. Contractor Responsibilities and Status

CONTRACTOR: American Technological University, Killeen, Texas

TITLE: A Pilot Plant Total Energy System for
Fort Hood, Texas

FUNDING AND PERIOD:

- (1) \$140,000; NSF, FY 74
- (2) \$200,000; July 1974 to December 1975
- (3) Total: \$340,000 to September 1976

The American Technological University (ATU) stated that the study objectives were to provide a total energy system for a military base. According to the contractor, Fort Hood is considered to be an appropriate location for an early solar total energy system pilot plant (Figure 15) for several reasons:

- (1) The military has a requirement to have base power and energy independent of utilities to maximize base security.
- (2) A military base can serve as a controlled test environment for the experiment.
- (3) The Fort Hood insolation and climatology are excellent for testing solar total energy systems.
- (4) The Army has designed a modular standard barracks complex for housing military personnel; thus, uniform system requirements for both new and retrofit installations are possible.

- (5) The power level for the barracks complex is approximately 1.3 MWe, 15 MWth, which is an appropriate size for a demonstration system.

The contractor stated that the primary objective of the Fort Hood Project is to display the steady state and transient performance of distributed collector solar total energy systems in an actual operating environment. Secondary objectives are to:

- o Provide a basis for assessing the economic viability of such systems for military and commercial applications.
- o Provide the U.S. Army a basis for assessing the value of solar total energy systems in attempting to make military bases energy independent and to assess their potential in reducing energy use operating costs.
- o Build an initial plant of sufficient size to require significant quantities of solar collectors to stimulate industrial supplier interest in determining the manufacturing reproducibility of reflectors and receivers of at least one type.

The Fort Hood study was initiated with early emphasis on defining the energy requirements of the existing fixed facilities and the potential availability of solar energy at Fort Hood. Detailed studies of the energy requirements have included consumption patterns recorded to the hourly level, analysis of the nature of the loads (i.e., air conditioning, space heating, lighting, domestic hot water, etc.), and distribution of the loads among various buildings or groups of buildings at Fort Hood. The conceptual design is indicated in the schematic diagram in Figure 16.

The investigations concerning the availability of solar energy insolation include pyranometer and normal incidence pyrliometer measurements. These instruments have been installed and operated as a cooperative effort by the U.S. Army. The measurements have been augmented by actual data and simulations for predicting the availability of solar energy under various meteorological conditions. These data have been developed using information recorded by the U.S. Weather Service at Fort Worth, Texas (120 miles north of Fort Hood) over a period of many years.

The 87000 Troop Housing Complex at Fort Hood has been selected as the basis for system design studies. The mean peak electrical load during heavy air conditioning months is approximately 1.33 MW. According to the contractor, the criteria set for developing the conceptual design of a solar total energy system for the 87000 Complex are as follows:

- o The system will provide all electricity required at solar noon on clear days.
- o The high temperature storage will be capable of operating the system at full electrical output for one hour.
- o The system exhaust heat will supply a substantial portion of the thermal energy requirements (space heating and domestic hot water) day and night year around.
- o The waste of useful exhaust heat will be minimized.

Figure 17 depicts the system installation pictorially. The collector field consists of approximately five acres of focusing collectors (shown on the right). Pressurized water is circulated through the collector receivers where it is heated to approximately 500 F and then stored or fed directly to the

turbine generator. The turbine and electrical generator are of conventional design. The turbine shaft output may be varied by controlling the exhaust temperature and pressure to attain an optimum mix of electricity and exhaust heat depending upon the time of year and the requirements for exhaust heat.

A preliminary design is under development. Engineering design is scheduled to begin in 1976 with completion of construction in late 1979.

Figure 15. Total Energy Systems - Major Results and Key Decision Dates

Figure 16. Conceptual Design

Figure 17. Conceptual Design Installation

CONTRACTOR: McDonnell Douglas Astronautics Company,
Huntington Beach, California

TITLE: Industrial Applications of Solar Energy

FUNDING AND PERIOD:

\$247,500; September 1975 to June 1976

The objectives of this program, as stated by the contractor, are to define technically and economically feasible solar energy systems which can satisfy all or part of selected industry demands and to determine the market potential for such systems. The primary emphasis will be placed on the application of total energy systems where industrial process heat, electrical needs, and space heating and cooling requirements can be satisfied with a single solar collector field at maximum possible efficiency. Partial total energy systems and individual systems will be investigated as dictated by the specific energy demand schedules. Only industries within the Southwestern United States are being considered.

Industry selection criteria were applied both nationally and in the Southwest, resulting in the preliminary selections shown in Figure 18. The national survey was made to ensure that the Southwest trends were representative of national trends. More than 500 industries are being surveyed to determine energy demand schedules (hourly, daily, weekly, seasonal), process parameters (state variables, flow rates), and energy (electrical and fossil fuels) required for each step in the industrial process. Also included are the number of square feet of office and plant area, number of employees (office, plant), building characteristics, and land availability. As these data become available, they are reduced to working units, a demand schedule is selected, and a preliminary sizing exercise is conducted. To illustrate the

procedure, data received from a typical industry response are shown in Figure 19. These data were used in the sizing procedure with the exception of the electrical requirements for the mining operations which were believed to be better left on the grid at this point in time. For the conditions stated, approximately 144 acres of collector area were required. A similar exercise is being conducted for the total energy requirements, including storage provisions. Also consideration is being given to an organic Rankine cycle.

The system/subsystem methodology trades illustrated in Figure 20 will be exercised for each industry class where information is obtained (the "P" indicates preliminary and the "F" indicates the final design loop). After the final sizing of each of the industries, the market potential will be determined. This analysis will include energy displacement, the cost of solar versus existing systems, optimum methods for implementation of the solar energy designs, site recommendations, and recommended process facility improvements and their advantages.

INDUSTRY	NUMBER OF ESTABLISHMENTS							
	TEXAS	NEVADA	COLORADO	UTAH	NEW MEXICO	ARIZONA	CALIFORNIA	OKLAHOMA
2033 CANNED FRUITS AND VEGETABLES	25	--	5	8	--	--	160	10
2063 REET SUGAR	1	--	13	1	--	1	10	--
2812 ALKALIES AND CHLORINE	4	1	--	--	8	7	--	--
2911 PETROLEUM	59	--	3	5	4	--	39	15
3241 HYDRAULIC CEMENT	20	--	--	--	--	2	18	3
3251 BRICK AND STRUCTURAL CLAY TILE	38	--	8	6	--	10	17	9

Figure 18. Industrial Applications of Solar Energy -
Industry Selections

ELECTRICAL DEMAND

MINING

17,125 MW-HR/YR:
19.5 HR/DAY: 7 DAYS/WEEK

SURFACE

50,810 MW-HR/YR:
24 HR/DAY: 7 DAYS/WEEK

535 MW-HR/YR: 8 HR/DAY:
5 DAYS/WEEK

TOTAL ELECTRIC DEMAND
68,500,000 KWH/YR

NATURAL GAS DEMAND

STEAM AND PROCESS HEAT

160,000 LB/HR: 24 HR/DAY: 7 DAYS/WEEK
AT 260 PSIG (240°F RETURN WATER)
1,571,830 MCF/YR

GAS-FIRED DRYER

174,650 MCF/YR: 24 HR/DAY: 7 DAYS/WEEK

GAS-BURNING IC ENGINE

10,328 MCF/YR: 24 HR/DAY: 7 DAYS/WEEK

SPACE HEATING

21,596 MCF/YR: 8 HR/DAY: 5 DAYS/WEEK

TOTAL GAS DEMAND
1,768,000 MCF/YR

Figure 19. Typical Potash Facility Annual Energy Demand

Figure 20. System Trades

IV. Session II: DISTRIBUTED COLLECTORS

CONTRACTOR: Argonne National Laboratory, Argonne, Illinois
and the University of Chicago, Chicago, Illinois

TITLE: Nonimaging Collector Development

FUNDING AND PERIOD:

- (1) ANL; \$733,000; July 1975 to June 1976
- (2) UC; \$262,500; March 1975 to February 1976

The Argonne National Laboratory (ANL) and the University of Chicago (UC) are working on the development of nonimaging solar collectors for photothermal and photovoltaic applications. These collectors are identified as Compound Parabolic Concentrators (CPC). In the past six months, subcontracts were let to industry to advance this development. These contracts include the following: (1) Study contracts to Bechtel and A. D. Little, and (2) Collector fabrication contracts to Chamberlain Manufacturing Corporation and American Science & Engineering.

The study contracts to Bechtel and A. D. Little were to: (1) identify applications that can utilize the advantages of nonimaging concentrators, (2) specify critical areas of development needed to make the collector economically competitive, (3) establish goals for timely development of the concept, and (4) review the ANL development program.

The overall annual system efficiency for Rankine cycle power generation may be substantially increased by use of the CPC collector as shown in Figure 21.

As a result of the Bechtel and A. D. Little studies, the thermal program has been directed to the temperature range of 350-450 F for applications to motive power, process heat and air conditioning. The requirements imposed on the collector modules are low-cost reflective surface, good optical and thermal efficiency, and moderate concentration combined with an evacuated receiver with a selective absorber. Potential advantages of the CPC collector are low weight, low precision of manufacture, no diurnal tracking, and a low profile construction.

Fabrication contracts awarded to Chamberlain Manufacturing Corporation and American Science and Engineering (AS&E) were for 20 square foot prototype collectors with two panels each. The Chamberlain units were received in fiscal year 1975 and their performance has been evaluated. The AS&E units will be delivered in April 1976.

Photovoltaic studies have been performed by Mobil-Tyco for primary concentrator applications and by Spectrolab for second-stage applications.

Procedures have been developed for testing prototype collectors. These procedures include measuring optical efficiency, taking precautions to maintain cold mirror surfaces, measuring the thermal performance by heat loss instrumentation, and determining the dynamic performance on the outdoor solar test installation. The results compare well with computer model calculations of Kreider and Kreith.

In addition to the above, a 30 foot long 10X concentration collector with cavity receiver is under construction. This unit will be suitable for daily-cycle testing. In addition, lightweight, low profile (Figure 22) reflectors are being developed and fabricated from thermoformed plastic. These will

be coupled to an evacuated receiver also under development. Optical tests show excellent acceptance characteristics (Figure 23).

Optimal coupling of reflector shapes to specific receiver configurations has been investigated. In addition, design concepts have been developed which are applicable to second-stage concentrators and to concentrators that function entirely by total internal reflection.

Figure 21. Influence of Solar Panel Temperature on Annual Overall System Efficiency Selections

Figure 22. Developmental Collector Configuration

Figure 23. Thermoformed Plastic CPC Angular Acceptance Test

CONTRACTOR: The University of Minnesota and Honeywell Systems
and Research Center, Minneapolis, Minnesota

TITLE: Collector Module Experiments

FUNDING AND PERIOD:

- (1) \$941,300; during the preceding 14 months
- (2) \$426,900; January 1975 to December 1975

The contractor reported that experiments have been continued on the scale model parabolic trough collector module at the desert test site. For these tests, the heat pipe absorber tube treated with the selective absorbing multilayer coating was removed and replaced with a similar heat pipe coated with a nonselective, high temperature black paint. The average solar absorptance was 0.95 and the average emittance was 0.90 at 300 C. The heat pipe configuration had an overall length of 5.2 meters, an outside diameter of 2.54 cm, and a wall thickness of 0.165 cm. The evaporator section was 4.52 meters long and the condenser 0.59 meters long. The wick, located only in the evaporator region, was fabricated from a 100 mesh 347 stainless steel screen spot welded to the inner wall of the tube, which also was constructed of 347 stainless steel. Water was the working fluid. The heat pipe, prior to being coated, was tested for performance at Dynatherm Corporation. The results of these tests correspond closely with the results for the previous heat pipe.

The evaporator section of the heat pipe was coated with a flat black absorber coating. The stainless steel surface of the heat pipe was primed with grey lacquer primer, Campbell No. 954, after thorough cleaning. High temperature black Nextel brand paint, Serial No. 401C-10 made by the 3M Company, was sprayed on the primer to provide a uniform absorber coating.

The power output from the collector was measured using a new variable gas gap calorimeter. The calorimeter consists of a water-cooled brass collar which fits concentrically around the condenser. The collar is 56 cm long and split longitudinally along its diameter. The gap between the inner surface of the calorimeter and the outer surface of the heat pipe can be varied by separating the two halves of the calorimeter and then locking them in place where desired. The calorimeter gap was initially adjusted to provide a heat rejection of 1.5 kW at a vapor temperature of 300 C and with helium in the gas gap. This allowed operation of the heat pipe over large temperature ranges and during those hours when the direct normal solar flux decreases.

Figure 24 presents the system efficiency obtained with the collector oriented in the north-south direction and the absorber tube operating at 300 C. The incident solar flux measured normal to the sun was relatively constant during the test period. A change of 1.0 percent in the efficiency was noted between 1000 and 1200 hours. The collector efficiency was found to be substantially lower with the nonselectively coated absorber tube.

An experiment was conducted to determine the effect of a loss of vacuum in the receiver on the system performance. The space between the absorber tube and the receiver glass envelope was deliberately filled with air. Figure 25 shows the system efficiency for this configuration. Data could be obtained for a period of only a half hour around solar noon as the absorber could not be maintained at a 300 C operating temperature for other times of the day when the solar flux was lower. The lack of vacuum had a dramatic effect on the efficiency as seen in the figure.

To provide a comparison of the collector performance using three absorber configurations, the test results were used to compute the heat flux delivered for a given day. For clear conditions on 15 June 1975, the heat flux delivered by the collector for the three absorber configurations is shown in Figure 26. Although the direct normal flux (Q_{dnf}) is relatively constant for about six hours between midmorning and midafternoon, the collector efficiency falls off at times other than solar noon. This is due to the fact that the efficiency of a trough collector is a function of the cosine of the sun-trough angle (the angle between the incident sun rays and a normal to the concentrator aperture). The cosine curve in the figure illustrates this functional relationship to system efficiency. Figure 26 also shows the effect of the selective coating in that the heat output (Q_{out}) is significantly higher than that for the nonselective black paint.

Figure 24. Performance Data: North-South Orientation, Absorber at 300°C Surrounded by Vacuum

Figure 25. Performance Data: North-South Orientation, Absorber at 300°C Surrounded by Air

Figure 26. Comparison of Results Obtained with Three Different Absorber Configurations; East-West Orientation

CONTRACTOR: The General Atomic Company
San Diego, California

TITLE: Fixed Mirror Solar Concentrator

FUNDING AND PERIOD:

- (1) \$50,000; January 1975 to October 1975
- (2) Additional funding is currently provided by EPRI and three utilities.

General Atomic reported upon recent work with the Fixed Mirror Solar Concentrator (FMSC). This concept is currently undergoing conceptual engineering evaluations to select systems and construction approaches prior to preparing detailed design and cost evaluations. The FMSC consists of a fixed cylindrical array of mirror slats. Although the slats are fixed, each slat has a different surface angle setting. Regardless of the sun angle, the contractor stated that the array of slats produces a sharp line focus, the locus of which is a cylinder of the same radius as the mirror. To collect the solar energy, the heat receiver is mounted on an assembly that rotates about the center of curvature of the mirror. According to the contractor, the most desirable orientation of the collector module is with its axis in the east-west direction. A scale model was built at General Atomic which has an aperture of 3.5 x 10 ft. The model is now at Arizona State University where it is undergoing performance evaluations. A 6.6 ft x 80 ft FMSC (Figure 27) was built under GA license by Scientific Atlanta, Inc., in conjunction with Georgia Tech. It is being tested for potential use with existing systems to heat and cool the Mechanical Engineering Building.

The contractor stated that one of the most important sets of requirements placed on the FMSC is related to the mounting of the

concentrator mirror strips. The strip mounting requirements were specified as follows. The strips must be:

- o Torsionally rigid about longitudinal axis to $\pm .25$ deg.
- o Longitudinal axis coordinates over length accurate within ± 1 in/30 ft.
- o Dynamically stable in winds to 25 mph.
- o Able to survive in winds to 100 mph.

Several options for mounting the strips were presented and are listed in Table 2 along with the associated contractor's comments.

Table 2. Mirror Strip Mounting Options

<u>OPTIONS</u>	<u>COMMENTS</u>
Lay strips in concrete-lined ground troughs	Surface waviness, possible mirror jiggling while filler sets
Lay strips on preformed concrete modules	Accurate concrete surfaces, module alignment required
Lay strips on jigged, bonded aluminum strip structure	Requires external braces
Lay strips on periodic, prealigned, stamped formers grouted in ground	Requires stiff mirrors, former spacing unknown

Preliminary evaluations have been made of three receiver configurations. Performance evaluations show that multiple coolant pipes are preferable, with a single glass cover plate

performing almost as well as two cover plates. Shown in Figure 28 is the heat receiver efficiency for the preferred single plate configuration. The contractor indicated that concentration factors of 50 can be readily achieved, and in the temperature range of 700-1000 F a receiver efficiency of 65-75% can be expected.

A preliminary comparison was made of three generically different fluids (CO_2 , Hitec, and Dowtherm A) to determine their suitability as a heat transport fluid for the FMSC. The study included heat transfer and pressure drop analyses, header and pipe sizing, cost evaluation, and operational considerations. Figure 29 summarizes the major assumptions for the study.

GA has also studied a 100 MWe solar power plant, sections of which are grouped together to form an area of 0.93 miles, measuring 4800 ft by 5400 ft. Fluid from each section would be ducted to a central point for steam production where a steam turbine generator could produce electric power. In addition, collector module studies have been conducted of a concrete substrate collector with a concentrator arc of 120 deg, a radius of 12 ft, a mirror slat width of 3 in and an aperture measuring 21 ft by 200 ft. Conceptually, the module would face south and be tilted 15 deg from the vertical.

Figure 27. Fixed Mirror Solar Concentrator Undergoing Testing on the Mechanical Engineering Building Rooftop at Georgia Tech

Figure 28. Heat Receiver Efficiency
(Single Plate)

FLUID	DESIGN ASSUMPTIONS
CO ₂ , HTS, DOWTHERM A	MIRROR APERTURE FLUX = 154 BTU/FT ² HR 120 DEG MIRROR MIRROR RADIUS = 20 FT
CO ₂	MAXIMUM PRESSURE = 200 PSIA HEAT RECEIVER PIPE I.D. = 8 IN. INLET TEMPERATURE = 600°F OUTLET TEMPERATURE = 1000°F CIRCULATION POWER = 2% THERMAL POWER
HTS	MAXIMUM PRESSURE = 250 PSIA HEAT RECEIVER PIPE 4 IN. X 1/2 IN. INLET TEMPERATURE = 600°F OUTLET TEMPERATURE = 1000°F
DOWTHERM A	MAXIMUM PRESSURE = 160 AND 250 PSIA HEAT RECEIVER PIPE 4 IN. X 1/2 IN. INLET TEMPERATURE = 450°F OUTLET TEMPERATURE = 750°F

Figure 29. Heat Transfer Fluid
Comparison

CONTRACTOR: Sheldahl, Incorporated
Northfield, Minnesota

TITLE: Program to Verify Performance and Cost Effectiveness
of a Segmented Line Focus Solar Collector

FUNDING AND PERIOD:

Cost Sharing Program, ERDA share
\$176,156, November 1975 to November 1976

Sheldahl reported on the program identified above and prior company funded research, development, and collector module testing of a Segmented Linear Array Thermal System (SLATS). Figure 30 illustrates the collector module concept whereby solar energy is reflected from individual segments to a common focal line with each segment providing about a 4:1 concentration ratio. The effective concentration ratio for the collector is then about $4N$ (less focusing and system errors) where N is the total number of segments focused on a common receiver.

The contractor commented that one of the major advantages of the line focusing system is that the receiver (absorber/converter) is small and linear. Because of the small receiver area, Sheldahl stated that the thermal losses by conduction, convection, and radiation can be controlled with relatively small quantities of insulation and radiation barrier. In addition, it was noted that the receiver linearity is comparable with the modular collector design. The receiver can be prefabricated to match collector module size and requires only two connections for each module (typically 400 sq ft of collector area).

In the configuration of Figure 30, two bays of eighteen segments, each segment ten inches wide and ten feet long, have been assembled to provide 150 square feet of collector area. The

two ten foot long bays are driven by a common command and control system mounted on the center pier. The module inclination and receiver location have been arranged to provide maximum annualized output for central Minnesota but can be varied from horizontal to vertical, as required. A test monitoring station is located next to the collector module and is used to house temperature recorders, pumps, and flow meters.

In operation the reflector segments rotate about their longitudinal axis (horizontal, east-west) to track the sun. Drive, command, and control consists of sun tracking about the single axis; and segments are driven with a common linkage once they are individually focused on the receiver at the time of installation. The array shown in the figure is driven by a 1/10 horsepower motor. A basically simple electronic subsystem provides the command and control of the collector module. Focusing is controlled by a dual sun sensor at the receiver. Transient conditions are compensated for in the circuitry so that intermittent cloud cover or other short-term effects do not cause the array to search or shut down. The elements rotate face down to provide protection for the reflector if there is no sun or no demand. If both sun and demand exist, they rotate into focusing position and are then controlled by the null balance between the two sensors at the receiver.

An example of the data obtained from a test run is shown in Figure 31. It should be noted that the efficiency defined is an overall system efficiency, comparing the measured thermal output in the fluid to the normal incident solar flux. In this case, the product of the receiver efficiency (η_r) and the aperture factor (η_{ap}) was determined experimentally to be 0.85. The transmittance through the two Teflon/Air interfaces (η_{tr}) was calculated to be 0.92. The geometric factor

(η_g) was calculated to yield ($\eta_g = 0.954$) at solar noon. Receiver shadowing was 0.953 (η_{rs}).

Thus, at $\Delta T = 0$, the overall receiver efficiency (optical constant) of 0.675 was in reasonable agreement with the measured value of 0.64.

To obtain higher thermal efficiency, a one meter section of a vee-entrant receiver having an aperture of 3 in was fabricated and tested using the 150 sq ft prototype array. This one meter section did not use a circulating fluid or calorimetry. Instead, the absorber was fabricated from a solid piece of copper (1/4 in thick) of sufficient mass (13.5 kg) to provide reasonably long time constants for temperature rise and drop. Five thermocouples were attached on the backside at the center of the copper absorber: one at the apex, one at the middle of each side, and one on each edge. All five readings were averaged for temperature measurements. This receiver was tested by hanging it directly below the 3 in flat receiver of the test module, and manually repositioning the beam downward to align with this new 3 in aperture. Based on the measured performance of the one meter vee-entrant receiver, the predicted performance for a scaled up (4 in aperture) version is shown in Figure 32.

Figure 30. Solar Linear Array Thermal System

Figure 31. Overall Efficiency of SLATS Cell vs. Temperature (Low Temperature Receiver)

Figure 32. Predicted Efficiency of Baseline System

CONTRACTOR: Itek Corporation, Optical Systems Division
Lexington, Massachusetts

TITLE: Solar Power Collector Breadboard Test Program

FUNDING AND PERIOD:

NSF; \$98,800, March 1974 to March 1975

Itek reported on modifications that have been made on the 1 sq m breadboard collector (Figure 33) and new test results obtained since the last Itek review. At that time, Itek indicated that the optical surfaces of the module had become contaminated which reduced the energy intensity at the absorber shown in Figure 34. The contractor noted then that, in the interest of obtaining timely results, a decision was made to proceed with the testing and to extrapolate the measured test results to results which would have been obtained had the collector module been clean. The previously reported optical efficiency constant, as extrapolated, was 75.8%.

Subsequently, Itek removed the concentrator mirror segments, stripped them, and recoated them with a durable aluminum coating rather than the relatively soft silver coating. The absorber was removed from the receiver and cleaned, and design modifications were made to ensure that it would remain clean upon reassembly. An aluminum tube enclosure replaced the originally used Pyrex enclosure. In a further effort to maintain absorber cleanliness, the last step in the assembly process was to slot the aluminum tube to accept the aperture window.

Figure 35 shows the efficiency of the module as extrapolated from the original silver coated mirror tests. It also shows the efficiency measured with the aluminum coated mirrors and the other modifications described above. The 10.2% difference in the

optical efficiency between the two curves compares favorably with the 9% difference in the surface reflectivity of the two coatings (97% for the silver and 88% for the aluminum) integrated over the solar spectrum. A 1.2% difference in these values is well within measurement accuracy and verifies the data extrapolation made when the contaminated system was initially tested. Itek is working on a durable silver coating which is hoped to have application to future collector modules.

Figure 33. Itek 1 Square Meter Breadboard Collector Module

Figure 34. Itek Breadboard Module Absorber System

Figure 35. Breadboard Collector Overall Efficiency vs. Temperature Difference

V. Session III: RESEARCH AND DEVELOPMENT PROJECTS

CONTRACTOR: The University of Minnesota and Honeywell Systems and Research Center (M/H), Minneapolis, Minnesota

TITLE: Research Applied to Solar Thermal Power Systems

FUNDING AND PERIOD:

The funding for these research projects is included in the funding shown in Session II, Distributed Collectors, page 35

The M/H team reported upon a number of tasks which have been completed since the last ERDA review. These tasks include:

- o Reflector surface life tests.
- o Heat pipe fabrication/tests.
- o Auger studies.
- o Solar boiler/heat exchanger performance.
- o Thermal conductivities of candidate insulating materials.
- o Phase change storage analysis.
- o Sensible heat storage experiments.

The reflector surface life tests involved evaluation of numerous reflecting surfaces (Figure 36) subjected to direct as well as accelerated solar exposure. Principal results reported show that samples of second surface aluminum and silver on acrylic, Teflon, and glass underwent negligible degradation for exposure periods exceeding two years. For the fabricated full scale 12 meter heat pipe, the maximum measured transport capability reported was 20 kWth at 300 C vapor temperature and an elevation of 2.54 cm (Figure 37). The main results obtained from using the Auger analyzer and microprobe were the comparisons of

composition versus depth profiles before and after tests at the parabolic collector test site. These results show that black chrome on nickel samples appears to hold promise up to 200 C.

An experimental model of a solar boiler/heat exchanger has been operated and performance data obtained. The experimental apparatus is intended to simulate a boiler/heat exchanger that would be part of a solar thermal collector module in the parallel array transfer loop concept. In each such collector module, the condenser end of a heat pipe would be situated within a boiler/heat exchanger.

In the experimental setup, the condenser end of the heat pipe is modeled by an electrically heated tube. The experiments thus far have been concerned with control concepts for regulating the rate at which feedwater is supplied to the boiler/heat exchanger. The feedwater control concept currently being investigated is of the on/off type, with the opening and closing of a flow control valve being keyed to the level of the liquid water in the boiler/heat exchanger. Liquid level sensing arrangements were employed in which the level was sensed at one, two, or three heights, respectively.

Typical results corresponding to the use of a single sensing point are shown in Figure 38. The feedwater flow rate was set so that both the feedwater flow and the steam generation were fully steady at the maximum power input of 4 kWe. As the power was lowered, the steam rate fluctuated with the maximum fluctuations being about ± 15 percent at the lowest power level of 1.4 kWe. The pressure was found to be constant to within ± 8 psia over the entire range of power levels.

One of the thermal storage concepts studied during the course of the project is based on the use of the latent heat of

fusion during liquid-solid or solid-liquid phase change. A model and the computer program were utilized to study solidification in a rectangular container with convectively cooled walls.

Code	Manufacturer	Mirror Type 1st or 2nd Surface	Original Average Reflectivity	Material
GD/1	General Dynamics	1st	0.85	Aluminized fiberglass with protective coating
GD/3	General Dynamics	1st	0.83	Aluminized fiberglass with protective coating
GD/4	General Dynamics	1st	0.92	Aluminized fiberglass without protective coating
3M/1	3M Company	2nd	0.86	Aluminized acrylic
H/1	Honeywell	2nd	0.76	Aluminized glass
S/3	G. T. Schjeldahl	2nd	0.77	Aluminized Teflon
S/1	G. T. Schjeldahl	2nd	0.79	Aluminized Teflon
S/2	G. T. Schjeldahl	2nd	0.86	Silvered Teflon
R/1	Ram Products	2nd	0.80	Aluminized acrylic plexiglass
AK/1	Alcoa	1st	0.82	Anodized aluminum reflector sheeting (Alzak)

Figure 36. Description of Reflector Samples
vs. Temperature Difference

Figure 37. Evaporator and Condenser Temperature Drop in Full-Scale Heat Pipe

Figure 38. Performance Results: Single Sensor Level Detection vs. Temperature Difference

CONTRACTOR: The University of Arizona, Tucson, Arizona

TITLE: Chemical Vapor Deposition of Spectrally
Selective Surfaces for Photothermal Solar
Energy Conversion

FUNDING AND PERIOD:

NSF; \$446,200; January 1973-June 1975

The University of Arizona reported on the research and development of chemical vapor deposition (CVD) of optical multilayer thin film stacks having the spectral properties required for efficient photothermal solar energy conversion. The two and one-half year program was characterized by three original goals as follows:

- (1) To develop economic techniques for depositing selective coatings in a continuous mode on a long pipe, such as distributed collector absorber tubes.
- (2) To achieve ratios of absorptivity to emissivity on the order of 10-12 at 500 C with an absorptivity in excess of 80%.
- (3) To develop techniques for depositing the coatings as described above such that they withstand long term operation at 500 C without deterioration.

The technical aspects of goal number one were achieved by the successful development of the technology to fabricate optical multilayer coatings by the method of chemical vapor deposition. The continuous CVD process, in principle, is to send a pipe through a sequence of furnaces and deposit the various thin film

components of the stack in one unbroken sequence. Inasmuch as CVD is an open air process, there is no particular limitation with respect to the pipe length. The presenter indicated that costs of the CVD process should not be prohibitively high based on studies performed during the program.

Goal number two was achieved with results as shown in Figure 39. The technology has been acquired to produce selective multilayer coating stacks which could be very important in the solar energy conversion programs. In particular, these coatings, if applied to distributed collectors, would enable efficient operation at working medium temperatures of about 1000 F. As to the current state of the art, Figure 40 demonstrates it very well. After cycling of the stacks for 1000 hours and then soaking from 20 to 100 hours at 600 C, the figure shows that serious deterioration in reflectivity occurs in many of the 30 samples exposed to these conditions. Somewhere between 550 C and 600 C is the temperature limit of selective coating stacks that have been developed under the NSF program.

Finally, the successful achievement of objective number three is shown in Figure 41. The five sets of 32 sample lots each were subjected to long time annealing at temperatures between 500 C and 615 C, plus automatic cycling between 150 C and 500 C. As can be seen, the reflectance loss is minimal for the great majority of the samples.

Thus the solar energy conversion community has available to it selective coatings with good optical properties and long lifetimes at 500 C.

a/e	at 25 C:	15 - 16
a/e	at 500 C:	10 - 12
a	at 500 C:	> 0.8

No deterioration after

100 hours at 615 C 4000 cycles to 500 C

Figure 39. Fabrication of Selective Surfaces on Stainless Steel Substrates

Figure 40. Effects of Automatic Cycling Between 150 C and 500 C

Figure 41. Effects of Long Time Annealing at 500 C

CONTRACTOR: Battelle Pacific Northwest Laboratories
Richland, Washington

TITLE: Comparison of Solar Pond Concepts
for Electrical Power Generation

FUNDING AND PERIOD:

- (1) \$18,300; April to July 1975
- (2) \$16,000; FY 1976

The contractor defined the work as an evaluation study in contrast to a development project. Solar ponds are believed to have potential agricultural and building applications. The objectives of this study are to:

- o Identify the various solar pond concepts for electric power generation.
- o Analyze and compare the performance of these various concepts.
- o Estimate the pond cost and overall power plant system cost for each concept assuming the nonconvective gradient salt pond as the base case.

In operation the solar pond concept captures solar radiation in a shallow pond one to two meters in depth and retains the captured energy in the bottom of the pond so that it is not carried to the top by convection. Essentially the liquid above the trapped energy level serves as a transparent insulator. A basic concept is a nonconvecting salt pond, where a salt gradient ranges for example, from 0.0% MgCl at the top to about 25.0% MgCl at the bottom. The bottom layers of such a pond, being heavier, do not tend to raise to the top when heated as would be the case in a liquid of uniform density. This enables the pond to retain a substantial percentage of the absorbed radiant energy.

However, a potential problem is pond instability. For example, if an object is thrown through a tedlar cover into the pond, it may create a disturbance causing nonuniformity throughout a part of the pond, which in turn could start a convective flow in other parts, and eventually grow sufficiently to destroy the effectivity of the pond.

Solar ponds are generally relatively low temperature systems. The conversion efficiency from thermal energy stored in the pond to electric energy is low. The energy in the pond may be more efficiently used for purposes other than power generation, particularly since the conversion of the pond's energy to electricity requires the development of thermal cycles operating between low temperature levels.

The study approach includes development of a preliminary design for several power plant systems based on the solar pond concept and evaluation of the performance and economics associated with these preliminary designs.

The contractor is developing a computer program to model geothermal power production. The geothermal program considers the geothermal field and power plant economics. For this study, the solar pond was substituted for the geothermal field inasmuch as power plant considerations are comparable. The utilization of this program can provide an extensive analysis of economics for electricity production.

Because temperatures involved in the solar pond are lower than those generally considered for geothermal applications, the program is not directly applicable. Some corrections have been made and some operations have been performed by hand.

Four solar pond concepts were reviewed: (1) nonconvecting salt, (2) nonconvecting salt with membrane (Figure 42), (3) gelled (Figure 43), and (4) shallow convecting pond (Figure 44).

Because there are many technical unknowns in the first three concepts, the results arrived at are uncertain. Assuming that solar ponds are shown to be technically practical, the magnitude of pond costs, illustrated in Table 3, is considered reasonable for a 10 MWe power plant. However, several factors could cause the costs to move up or down by 50% or more. Hence, a comparison of the three concepts is not at all conclusive.

In the case of the shallow convecting pond, costs are based on Lawrence Livermore documents and demonstrated technology. For the gelled pond, a gelling agent was used to reduce the convection. As seen in the table, both flash steam cycles and binary cycles (using isobutane as the working fluid) were evaluated. The binary cycle is considered more realistic at the present time because turbine technology for steam at the low temperatures considered has not been developed. Assuming technical feasibility within the economic framework developed here, solar ponds might produce thermal energy in the range of \$2-4 per million Btu.

General conclusions based on preliminary analysis are:

- o Electrical power production from solar ponds is not cost competitive with other systems, based on current central station power producing technology.
- o The cost of power production with solar ponds is in a range such that additional evaluation may be warranted for unique circumstances such as isolated sites.

- o Based on the cost of Btu's produced by solar ponds, it is quite possible that they can be competitive with other energy systems in some circumstances, if they are technically practical.
- o The technical feasibility of nonconvecting solar ponds is not established.

Table 3. 10 MWe Solar Pond Concepts - Economics Summary

	<u>Nonconvecting</u>		<u>Membrane</u>	<u>Gel</u>	<u>Shallow</u>	<u>Free*</u>
	<u>Steam</u>	<u>Binary</u>				<u>Salt</u>
Pond Cost (\$ x 10 ⁶)	41.6	41.6	28.0	41.4	31.1	11.5
Plant Capital Cost (\$ x 10 ⁶)	17.148	7.107	7.107	7.107	7.107	7.107
Net Power Output (MW)	6.652	7.653	7.653	7.653	7.653	7.653
Installed Cost (\$/kW NET)	8,690	6,366	4,588	6,339	4,993	2,236
Cost of Power (mills/kWh)	203.6	150.2	114.4	149.6	124.9	71.1

*Free salt is the case where the solute for the nonconvecting salt gradient pond is available at no cost.

Figure 42. Membrane Pond Cross-Section

Figure 43. Gelled Pond Cross-Section

Figure 44. Shallow Solar Pond Concept

CONTRACTOR: The University of Houston, Houston, Texas,
in cooperation with the University of Arizona
and Texas Tech.

TITLE: The Utilization of Solar Energy for Feedmill
and Irrigation Projects

FUNDING AND PERIOD:

The National Science Foundation
(NSF-RANN PRP-75-19465), through
the U.S. Department of Agriculture,
Agricultural Research Service

The contractor defined the Feedlot Feedmill (FF) operation, as discussed herein, to be a daylight operation in West Texas well suited for solar energy utilization. The main requirements of an FF are electric power and low temperature steam for feed processing. The contractor stated that the power requirements to date show no unusual peaks during the day and may be met with a properly sized solar plant. Further, it may be desirable to have 3-6 hours thermal storage, such as hot oil, for operational stability, whereas long term thermal storage would be avoided because of cost. Operation on cloudy days could be provided with hybrid operation using conventional stored fossil fuels. For the long term outlook of solar energy utilization, it is believed that one of several possible forms of chemical storage will be developed and may prove economical.

The study included an evaluation of solar collector concepts on a cost per kilowatt thermal $\left[\frac{W_t}{\$ (C_t)} \right]$ vs. temperature (Figure 45). Also, comparisons have been made of the collector area or land required per kilowatt electric $\left[\frac{W_e}{\$ (C_t)} \right]$ for various systems. The analyses included a review of the reported performance estimates of flat plate, slightly concentrating flat plate, linear,

parabolic trough, dish, and solar tower collectors. The solar tower (Figure 46) has been shown to have advantages in the 100 MWe range by a number of investigators, but there has been a very limited consideration of the tower in the smaller MW ratings. Therefore, this study has included analyses of several small tower configurations.

The contractor concluded that the tower system is competitive down to 10 MW thermal level utilizing full size flat heliostats, and down to 1/2 MW thermal level if canted segmented heliostats are used. The contractor noted that cost effective heliostat designs are expected to be available soon. Therefore the tower system was recommended for small total energy systems such as in feedmill feedlot operations and for irrigation purposes. Figure 47 presents the overall results of the study for four representative solar collector systems.

Figure 45. Tower/Heliostat System

Figure 46. Silo and Panel Receiver

COLLECTOR SYSTEM	ESTIMATED BY	OPERATING TEMP. °K AND OTHER COMMENTS	CARNOT EFFICIENCY AT OPERATING TEMPERATURE IN PERCENTAGE	MAX. ELECTRIC POWER POSSIBLE PER \$, $W_e/\$$	COLLECTOR AREA $kW_e (= kW_t \times \text{Carnot } \eta) / m^2$
FLAT PLATE	C.S.U.*	373, Evacuated tubes	13.5	1.74	10.67
	U. Houston (Howell & Bannerot)	517, Trapezoidal grooves	37.5	1.23	6.34
	J.P.L.	477, Vacuum tubes with mirror boosters	32.0	1.32	3.58
PARABOLIC TROUGH	C.S.U.*	423 523	23.5 38.0	2.37 3.75	
	J.P.L.	573 N-S, Single surface 723 Segmented Strips	43.3 55.2	0.70 1.00	
	Sandia*	588.5 E-W, Evacuated Absorber	49.7	1.79	4.16
PARABOLOIDAL DISH	C.S.U.*	475 528 578	31.5 38.2 43.7	3.44 4.35 4.74	4.23
	Honeywell*	603	46.5	1.06	4.9
	J.P.L.	1088 Brayton, distributed type 783 steam, central type	70.2 58.7	2.04 1.53	2.60 3.26
TOWER HELIOSTAT	C.S.U.*	423 473 523 573, MW_t output estimated	23.5 31.5 38.0 43.3	2.60 3.37 3.90 4.35	9.55
	Honeywell*	755	57.3	3.15	3.35
	J.P.L.	Operating temp. unknown Assume 600 & 900°K	45.8 at 600°K 64.0 at 900°K	1.43 at 600°K 2.01 at 900°K	4.35 at 600°K 3.12 at 900°K
	U. Houston	733 450MW _t plant 750 592H-UN, at 85% peak 660 37H-S at 85% peak	59.0 57.0 53.5	3.98 3.90 2.85	2.99 3.22 3.44

* Cost corrected to 1975 dollars

Figure 47. Overall Feedlot Feedmill Evaluation

CONTRACTOR: The Georgia Institute of Technology
(Georgia Tech), Atlanta, Georgia

TITLE: Development and Evaluation of a 400 kWth
Solar Steam Generating plant and Test Facility
in the United States

FUNDING AND PERIOD:

\$475,000; November 1975 to May 1977

The contractor stated that the objectives of this program are to transfer solar energy technology developed in Italy to the United States and to provide an early power tower facility in this country. For about 15 years the University of Genoa in Italy has engaged in the development of solar powered steam generators. The current design has progressed through four generations of development, during which various modifications were incorporated into the receiver and heliostat field.

The existing plant (Figure 48) in Genoa produces 100 kWth of superheated steam at 600 C and 150 atmospheres (1100 F and 2200 psi). The proposed plant to be erected on the Georgia Tech campus will be about three times as large as the Genoa facility, producing approximately 300 kWth of steam at the same output conditions. The Georgia Tech plant will follow the same general design used in Genoa. The 300 kWth system will be supplied by an Italian industrial organization. This company will also supply professional services to assist in the plant startup and in the training of United States personnel. The facility is expected to be in operation in late 1976.

Characteristics of the plant to be erected by the contractor are summarized in Table 4. The major differences between the existing and new plants include: (1) size, (2) provision for a mirror bending device on each heliostat to permit focusing of the heliostats, and (3) addition of a Pyrex antiradiating structure to the receiver.

The requirement for an antiradiating structure arises from the use of focusing heliostats. The focus of a curved heliostat can vary in distance from the heliostat depending on its orientation angle. The geometrical relationships involved are sketched in Figure 49. In aligning the heliostat field, it may be necessary to place the foci of heliostats behind the boiler to obtain the best average coverage of the boiler throughout the day, as shown in the figure for Heliostat 1. However, when the sun is near the horizon, some mirrors will be operating very far off axis, as shown for Heliostat 2. Under these conditions, the Heliostat 2 focal length is shorter than the Heliostat 1 focal length, and the Heliostat 2 focus is in front of the boiler. As the sun angle changes, the Heliostat 2 focus can move through the boiler (Figure 50) causing hot spots in which temperatures up to 1000 C can be attained over areas a few millimeters in diameter. The hot spots cause local overheating of tubes, but the antiradiating structure will diffuse the hot spots to prevent tube damage.

Table 4. Francia Solar Steam Generation Pilot Plant

<u>Description</u>	<u>Existing University Of Genoa Plant</u>	<u>Proposed ERDA- Georgia Tech Plant</u>
Heliostat field	271 heliostats, hexagonal field, 10 m on each side 50% ground coverage	530 heliostats, hexagonal field, 20 m on each side, 50% ground coverage
Heliostats	flat, round, back- silvered glass mirrors, 78 cm diameter, total area 130 sq m	flat, round, back- silvered glass mirrors, 110 cm diameter with bending device on each mirror to permit focused operation total area 504 sq m
Receiver	preheater-boiler- superheater, polished surfaces to assume dark color on heating, no antiradiating structure	preheater-boiler- superheater, polished surfaces, antiradiating structure of Pyrex tubes
Receiver output conditions	steam 150 atm, 600 C, 100 kWth	steam 150 atm, 600 C, 300 kWth

Figure 48. Solar Steam Generating Plant at Genoa, Italy

Figure 49. Relationships of Foci for Concentrating Heliostats

Figure 50. Closeup View of Boiler (Receiver) at Solar
Steam Generating Plant

CONTRACTOR: Lawrence Berkeley Laboratory
University of California
Berkeley, California

TITLE: Measurement of Circumsolar Radiation

FUNDING AND PERIOD:

- (1) NSF; \$93,000; FY 1974
- (2) NSF/ERDA; \$233,800; FY 1975
- (3) NSF/ERDA; \$420,000; FY 1976

The contractor reported that the long term objectives of this research project are to make circumsolar radiation measurements at three southwestern locations. Circumsolar radiation (that radiation which to an observer on the ground appears to come from the sun) results from the small angle scattering of the direct incident light rays by atmospheric constituents such as particulates and aerosols. The dimensions of these scattering particles are on the order of, or greater than, the wavelengths of light. The contracted effort includes measurements of the circumsolar radiation as a function of angular distance from the sun, wavelength, atmospheric conditions, geographic location, and time of year. Standard measurements of the solar radiation are also made. The contractor stated that these measurements are necessary to accurately predict the performance of focusing collectors and to determine whether pyrliometer data are adequate for estimating this performance.

A scanning telescope has been developed to make these measurements. The instrument scans across six degrees of arc per minute, with data digitization of the brightness of the solar and circumsolar radiation every 1.5 minutes of arc as shown in the sketch included in Table 5.

Table 5. Details of Scanning Telescope

SCAN FROM -3° TO $+3^\circ$, ACROSS THE CENTER OF THE SUN

- DIGITIZE IN 1.5' INTERVALS
- 240 POINTS PER SCAN, FROM -3° TO $+3^\circ$
- SCAN PERIOD OF 1 MINUTE PER FILTER POSITION
- 10 FILTER POSITIONS:
 - 8 WAVELENGTH BANDS (0.3 TO 2.5 MICRONS)
 - 1 OPEN POSITION
 - 1 OPAQUE POSITION
- USE 5° ACTIVE CAVITY RADIOMETER FOR ABSOLUTE NORMALIZATION
- USE PYRANOMETER FOR TOTAL SOLAR RADIATION

As shown in the table, an aperture size of 1.5 minutes of arc is used with 0.5° on either side of the center of the sun. Outside this region, where the levels of circumsolar radiation are relatively low, the aperture is increased to 5 minutes of arc to increase the signal level by roughly a factor of ten. A set of measurements consists of one scan at each of the ten filter positions. There are eight optical filters that divide the solar spectrum into eight bands of approximately equal energy content, one open (or clear) position, and one opaque

position. The latter is used to monitor the detector noise. An active cavity radiometer (a type of pyrheliometer) provides an absolute calibration for the telescope. Also the usual normal incidence is measured. Two pyranometers are used, one mounted in the conventional horizontal position and one tracking the sun.

A portable instrument (Figure 51) has been constructed and tested and has been taking measurements at Berkeley for some time. This instrument will be used to take measurements in a variety of atmospheric conditions and geographic locations. Three "fixed-site" instruments are under construction and will soon be deployed at three southwestern locations of interest for solar thermal conversion.

Figure 52 shows a computer generated graph of a sample scan for the clear filter. In this case the circumsolar radiation (C/S) is only 0.5% out of a normal incidence (NI) flux of 981 W/m^2 , which is typical of a clear winter day in Berkeley. The dots are the individual scan digitizations. The scan started at $+3^\circ$, crossed the sun near 0° , and ended as -3° . The discontinuities at roughly one solar radius on either side of the sun are artifacts introduced by the change in aperture size. The computer code searches for the peak point of the sun. The two "edges" of the sun are then empirically defined as the angles at which the brightness is down by 1.5 orders of magnitude from the peak. These edges are indicated on the graph by the two vertical, dotted lines. The center of the sun is then taken as the angle midway between the two edges and is indicated by the solid vertical line. An effective radius is then defined as the true radius of the sun ($\sim 16'$ of arc) plus the radius of the detector aperture ($\sim .8''$ of arc). The effective solar radius is indicated by the solid vertical lines that are at the top and bottom of the graph and that are nearly coincident with the edges of the sun. The brightness is integrated from the center of the

sun to the effective radius to give the intensity of the solar radiation. The brightness is then integrated from the effective radius to the end of the scan to give the intensity of the circumsolar radiation. The ratio of circumsolar to solar radiation is calculated and given at the top of the graph. Also indicated is the normal incidence measurement provided by the pyrliometer.

Figure 53 displays, as a function of the time of day, the output of the pyrliometer (squares), the sun-tracking pyranometer (circles), and the horizontal pyranometer (triangles). These data are for a day of quite high solar radiation levels but with fluctuations around 1200 hours resulting from some atmospheric disturbance. In this figure, noise inadvertently introduced into the pyrliometer accounts for the data scatter.

One of the checks on the quality of the data concerns the linearity of the output of the detector and electronics as a function of the input light level. To investigate the linearity, measurements have been made with the telescope pointed at the center of the sun and the incident light level systematically reduced by placing a series of neutral density filters over the front of the scope. The density of each filter as a function of wavelength was also measured. Using these measurements and taking into account the nominal shape of the solar spectrum, an effective density was calculated for each neutral filter for each optical filter passband. The output of the telescope versus the effective density is plotted for each filter. If the system were exactly linear, then all of the points would lie on a straight line. The agreement with the data is considered satisfactory.

Figure 51. Circumsolar Scanning Telescope

Figure 52. Sample Solar Scan Using Clear Filter Heat Pipe

Figure 53. Comparison of Pyrheliometer and Pyranometer Data vs. Temperature Difference

CONTRACTOR: Sanders Associates, Incorporated
Nashua, New Hampshire

TITLE: A 10 kWth Solar Energy Receiver

FUNDING AND PERIOD:

\$269,995; January 1975 to January 1977

The contractor stated that the objectives of this research and development program are to test a 10 kWth breadboard receiver and to develop a preliminary design for a 1 MWth unit. The design goals for the 10 kWth model are:

Operating temperature:	1600 F
Heat exchanger effectiveness:	80%
Overall conversion efficiency:	70%
(From the solar flux incident on receiver face to the energy transferred to the gas stream)	

Figure 54 is a schematic of an open cycle solar Brayton system. In this system, ambient air is compressed and preheated with waste heat from the turbine exhaust before being fed to the solar receiver where energy is added to raise the gas temperature to meet the turbine requirements (1600-2000 F). The heated air then passes through the turbine where expansion takes place providing power for the turbine generator subsystem. The receiver design employs a window and a honeycomb as the solar energy absorber and as the heat exchanger. The contractor expects this approach to have a low flow resistance (approximately 2-4 inches of water pressure drop across the honeycomb) and low abrasion because the honeycomb will have a large area resulting in low air velocities. The pressure seals will be located in relatively low temperature regions minimizing thermal problems associated with the honeycomb subassembly. In

addition, the honeycomb ceramic is expected to be unaffected by large thermal gradients.

The program schedule for the solar energy receiver development is shown in Figure 55. A simulation program will be used to model the absorption, radiation, and heat transfer properties of the receiver with particular emphasis on the ceramic honeycomb. To provide accurate inputs to the simulation program, emissivity measurements and heat transfer experiments are under way on representative samples of the silicon carbide ceramic honeycomb. Since limited emissivity data is available on silicon carbide, the current measurements are aimed at verifying the existing data and obtaining angular emissivity data at 1700 F. The heat transfer experiments are to determine the silicon carbide tube heat transfer coefficient as a function of temperature.

In addition to the emissivity and heat transfer measurements, a Monte Carlo simulation program has been implemented to provide the input flux distributions for the receiver. With the measured emissivity and heat transfer inputs, the simulation should then provide a reasonably accurate representation of the operation of the receiver. To verify the expected performance, the 10 kWth breadboard receiver will be tested at the U.S. Army Thermal Effects Facility at White Sands, N.M. A flux density of 200 watts/sq cm is available over a 4-inch (10 cm) diameter disk. The 10 kWth receiver will be sized to take advantage of this high incident flux. Inlet air temperature will be maintained at 1150 F to simulate air which would enter the receiver from a recuperator in a Brayton system.

If the receiver concept were integrated into a complete solar thermal conversion system, the net busbar efficiency expected by the contractor would be on the order of

28% as shown in Figure 56. This figure also includes a breakdown of the available estimated overall solar energy conversion losses from the incident solar flux to the deliverable busbar electrical power.

Figure 54. Brayton System with Storage

Figure 55. Program Plan for 10 kWth Receiver

Figure 56. Estimated Brayton System Efficiency Losses