SAND76-0205

Unlimited Release
UC-62

Solar Total Energy Program Semiannual Report October 1975 - March 1976

Solar Energy Projects Division

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT(29-1)-789

Printed June 1976

Sandia Laboratories
energy report

1-2

SF 2900-QQ8(3-74)

Issued by Sandia Laboratories, operated for the United States Energy
Research and Development Administration by Sandia Corporation.

SAND76-0205
Unlimited Release
Printed June 1976

Distribution
Category UC-62

SOLAR TOTAL ENERGY PROGRAM SEMIANNUAL REPORT
October 1975 - March 1976

Edited by
George W. Treadwell
and
Leroy E. Torkelson
Solar Energy Projects Division, 5712
Sandia Laboratories
Albuquerque, NM 87115

ABSTRACT

This report describes the activities of the Sandia Laboratories Solar Total Energy Program during the 6-month period, October 1975 through March 1976. Included are highlights of the period, descriptions of the system and its components, including recent modifications, and the results of systems analyses and component testing.

Printed in the United States of America

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy $5.50; Microfiche $2.25

CONTENTS

CONTENTS (cont)

TABLES

FIGURES

SOLAR TOTAL ENERGY PROGRAM SEMIANNUAL REPORT
October 1975 - March 1976

SECTION I. INTRODUCTION

The primary objective of the Sandia Solar Total Energy Program is to determine and demonstrate the technical and economic feasibility of solar total energy systems for a variety of sites and loads. In support of the primary objective additional objectives of the program are (1) to construct a system (Solar Total Energy System Test Facility) which is sufficiently versatile to be used as an engineering evaluation center or test bed for further development of individual components or other solar energy subsystems (2) to encourage private sector participation in the program and in the development of components for the system, (3) to determine those areas of research and development that offer the greatest payoffs, and (4) to develop and validate a systems analysis computer program capable of evaluating the great number of possible combinations of total energy system configurations.

The Solar Total Energy System, depicted in block diagram form in Figure 1-1 and as an artist's concept in Figure 1-2 (also in a photo, Figure 3-1), will operate as follows: A heat transfer fluid (Therminol 66) is heated in the receiver tubes of the solar collectors by reflected and focused solar radiation. This fluid is pumped to the high-temperature storage tank. On a demand basis, fluid is extracted from this storage and pumped to the heat exchanger which produces superheated toluene vapor to power the turbine/generator. The boiler can also be operated from a fossil-fuel-fired heater to insure continuity of operation during extended cloudy periods. Turbine condenser coolant is pumped to the low-temperature storage tank and becomes the energy source for the heating and air-conditioning components of the system.

The overall Sandia Solar Total Energy Program consists of five phases with the work reported in this document being part of Phases IV and V. The program, which began in 1972 with background research and exploratory analysis, has progressed to the present hardware stage in which the Solar Total Energy System Test Facility is being built to evaluate solar energy subsystems and to provide energy for an 1100 m^2 office building, the Solar Project Building.

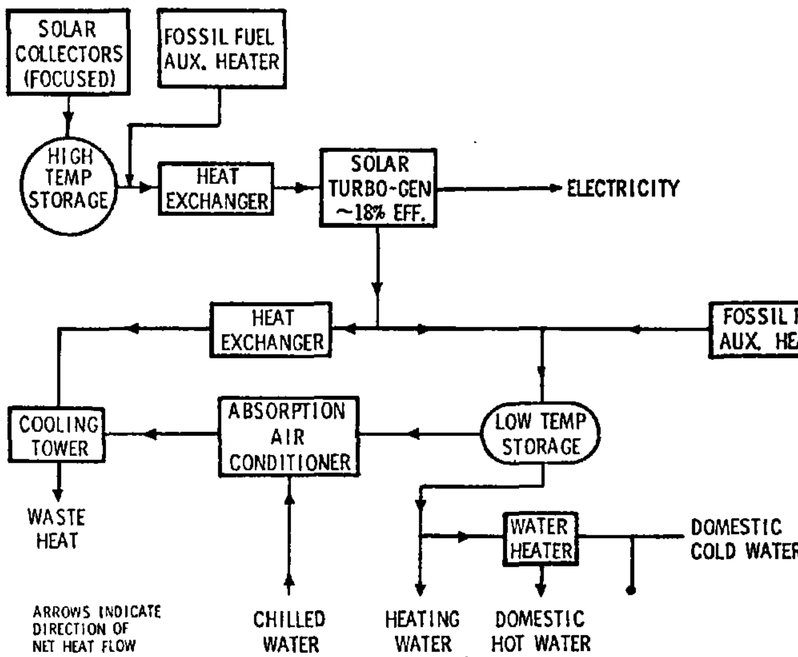


Figure 1-1. Solar Total Energy System Simplified Schematic

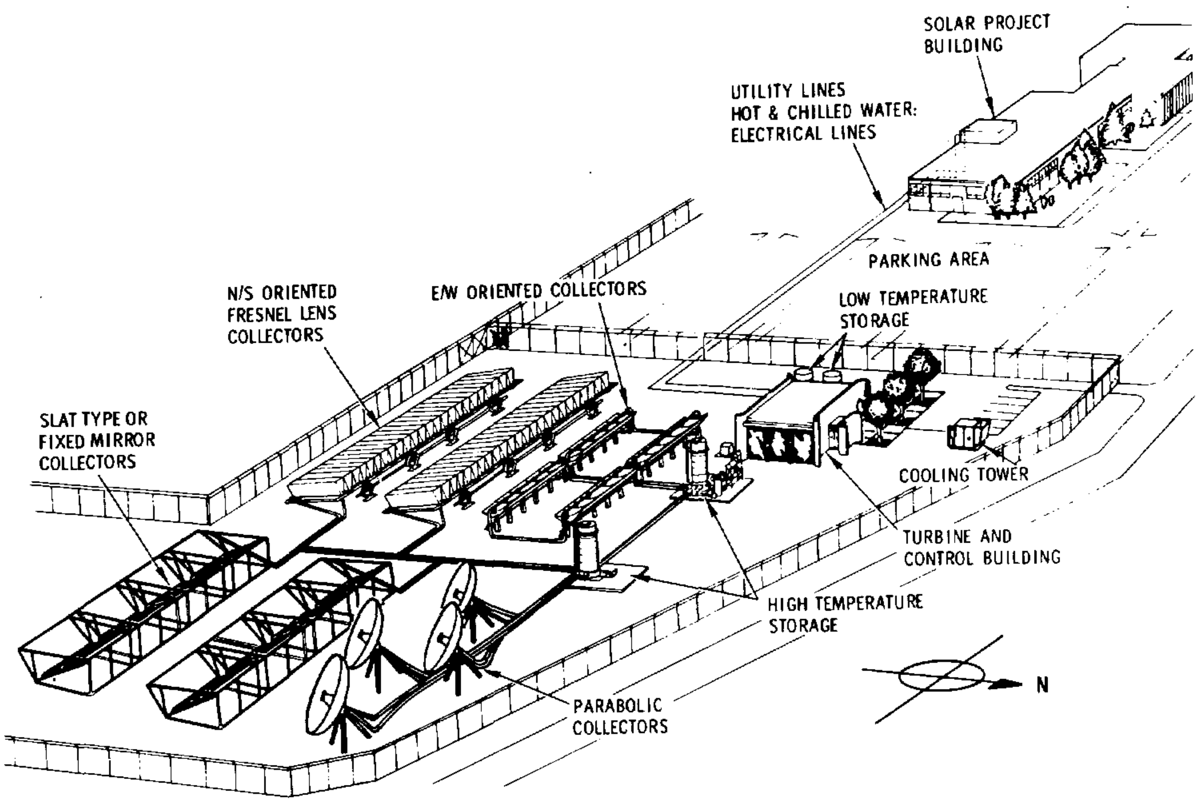


Figure 1-2. Solar Total Energy System Test Facility

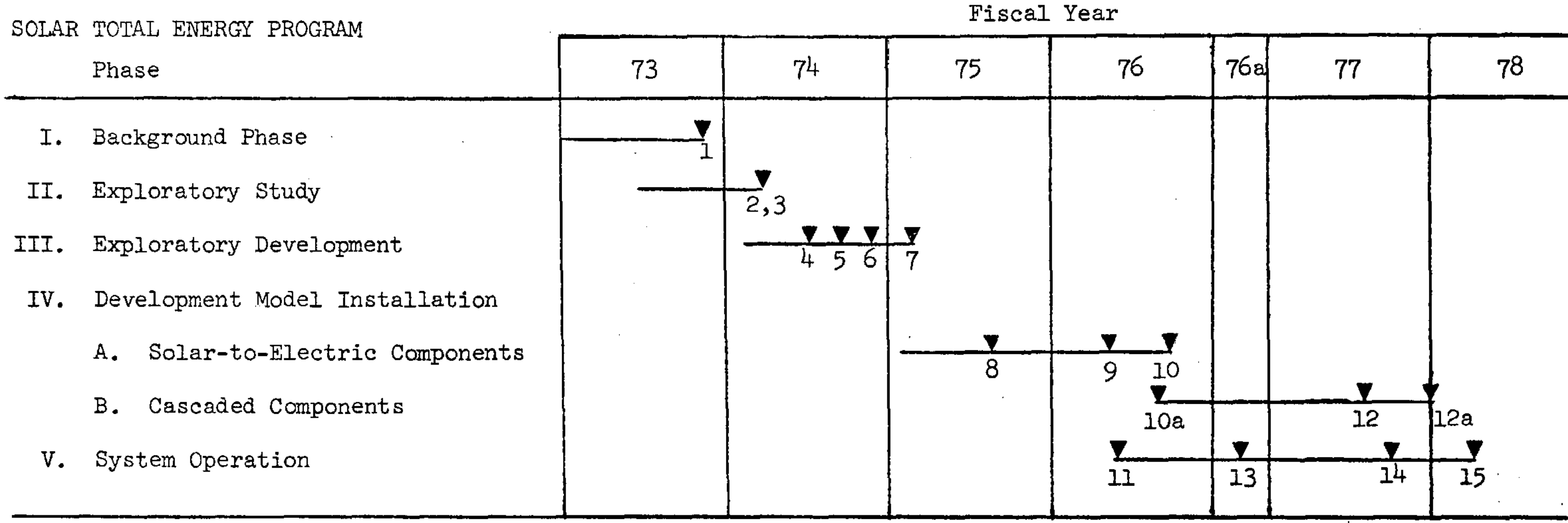
Phases I, II, and III, which emphasized preliminary studies and designs, have been completed. Phase IV-A began in July 1974 and ended during this reporting period. Phase IV-A marked the transition from the analysis and design effort to the hardware and construction effort. About 25% of the high-temperature, solar-to-electric portion of the system was put into operation during this phase.

During Phase IV-B, which started in July 1975, the remainder of the collector field and storage capacity will be added, and the cascaded low-temperature portion of the system will be designed and installed. Much of the Phase IV-B effort is being subcontracted.

Phase V, which started in January 1976, will consist of operating the test bed under various conditions to gather and analyze engineering data which can provide a basis for the design of large-scale experimental plants and for future solar energy systems. During this phase, the electric power, heat, and cooling for the Solar Project Building will also be demonstrated. (See Figure 1-3.)

Phases VI and VII, which had been envisioned to consist of the design, construction, and operation of a large-scale prototype solar total energy power plant, will no longer be conducted under this program but rather will be pursued within the overall national Solar Thermal Energy Conversion Program.

Because Phase IV-A was concluded during this reporting period, this semiannual report will serve not only as an overall program progress report but also as a Phase IV-A "closeout" report. To give somewhat more detail than mentioned above, Phase IV-A consisted of the design, fabrication, installation, and checkout of the first 200 m^2 collector field quadrant, an interim sized high-temperature stratified storage tank, a 32 kW organic Rankine cycle (ORC) turbine/ generator and its Therminol-to-toluene heat exchanger, an instrumentation and control subsystem, a cooling tower, the turbine and control building, and all necessary pumps and fluid loops to interconnect these subsystems. A description and status of each subsystem will be included in the body of the report.



Milestones:

1. Completion of Phase I
2. Preliminary system design complete
3. Economic evaluation complete
4. Collector evaluation facility complete
5. System analysis program (SOLSYS) operational
6. Baseline system design complete
7. Phase IV-A proposal submitted
8. Phase IV-A design freeze
9. Partial collector field, storage, and turbine-generator test bed complete
10. Phase IV-A complete, system 100 percent operational

10a. Subcontracts for collector field subsystems placed

11. Initial operation of partial Solar Total Energy System Test Facility
12. Low-temperature components of Solar Total Energy System Test Facility installed.

12a. Subcontracted collector field subsystems completed

13. System analysis program (SOLSYS) refined and revalidated
14. Demonstration of Solar Project Building
15. Operation of complete Solar Total Energy System Test Facility

Figure 1-3. Solar Total Energy Program Schedule and Milestones

SECTION II. OVERVIEW OF ACTIVITIES

Highlights

The following activities and milestones highlighted this reporting period:

- Contracts for preliminary design of collector field subsystems placed with General Atomic, McDonnell Douglas, Sheldahl, and Raytheon.
- All subsystems have been operated singly at full rated capacity.
- Collector field output of 320°C (608°F) achieved with 10-collector string.
- Twenty-collector string operated at interim temperature output.
- Instrumentation, control, and data acquisition system operational.
- Thermocline established in high-temperature storage tank, 310° to 240°C (590° to 470°F).
- Therminol-to-toluene heat exchanger and turbine/generator operated together at 32 kW generator output.
- Tracking and drive system operated both on sun sensor and by computer-controlled digital techniques.
- Therminol heated by supplementary fossil-fuel heater.
- All fluid loops leak-checked and insulated.
- Laser ray-trace facility developed for optical characterization of reflectors.
- Development of field laser ray-trace unit underway.
- High-pressure water loop being added to collector test facility.
- Black chrome selective coating process proves reliable. The 24 tubes coated with it have an $\alpha \geq 0.94$, $\epsilon \leq 0.26$ at 300°C.
- Temperature-humidity cycle tests on parabolic structures continuing.
- Dust and hailstone damage tests on reflective surfaces continuing.
- Diffuse-to-direct solar radiation component correlation study completed.

Reports and Presentations
September 1975 - April 1976

Publications

L. G. Rainhart and W. P. Schimmel, Jr., "Effect of Outdoor Aging on Acrylic Sheet," Solar Energy, 17, 4, p. 259, September 1975.

R. P. Stromberg, "A Status Report on the Sandia Laboratories Solar Total Energy Program," Solar Energy, 17, 6, p. 359, 1975.

D. M. Mattox, "Solar Energy Materials Preparations Techniques," Journal of Vacuum Science and Technology, 12 (September-October), p. 1023, 1975.

E. C. Boes, "Estimating the Direct Component of Solar Radiation," SAND75-0565, Sandia Laboratories, November 1975.

R. W. Harrigan, "Application of Solar Total Energy to a Mixed Load Community," SAND75-0542, Sandia Laboratories, December 1975.

D. M. Mattox, "Coatings and Surface Treatments in Solar Energy Application," in Plating and Surface Finishing, p. 55, January 1976.

D. M. Mattox, "Application of Thin Films to Solar Energy Utilization," Journal of Vacuum Science and Technology, 13, (January-February), p. 127, 1976.

E. C. Boes, "Solar Radiation Availability to Various Collector Geometries: A Preliminary Study," SAND76-0009, Sandia Laboratories, February 1976.

A. F. Veneruso, "Tracking Angles and Rates for Single Degree of Freedom Solar Collectors," SAND76-0027, Sandia Laboratories, March 1976.

R. B. Pettit and R. R. Sowell, "Solar Absorptance and Emittance Properties of Several Solar Coatings," Journal of Vacuum Science and Technology, 13 (March-April), p. 596, 1976.

R. L. Champion and M. W. Edenburn, "Solar Total Energy Program Semiannual Report, April 1975-September 1975," Solar Energy Projects Division 5712, SAND76-0078, April 1976.

Presentations

B. W. Marshall, "Solar Energy Research, "American Defense Preparedness Association, Albuquerque, New Mexico, October 1, 1975.

J. A. Leonard, "Solar Total Energy Project," Interagency Mechanical Operations Group Conference, Albuquerque, New Mexico, October 8, 1975.

J. A. Leonard, "ERDA Solar Energy Programs," Air National Guard Civil Engineering Conference, St. Louis, Missouri, October 9, 1975.

J. A. Leonard, "Sandia's Solar Total Energy Program," Society for Advancement of Materials and Process Engineering Conference, Albuquerque, New Mexico, October 15, 1975.

R. L. Champion, "Approaches to Fabrication of Parabolic Trough Reflectors," SAMPE Conference, Albuquerque, New Mexico, October 15, 1975.

B. W. Marshall, "Solar Energy Research," Building Contractors Association, Albuquerque, New Mexico, October 16, 1975.

J. A. Leonard, S. Thunborg, and G. W. Treadwell, "Solar Total Energy Program," ERDA Solar Total Energy Semiannual Review, Washington, D. C., October 23, 1975.

R. P. Stromberg, "Sandia Solar Total Energy Program," New Mexico State University, Las Cruces, New Mexico, October 23, 1975.

D. M. Mattox, "Materials for Solar Energy Utilization," Material Science Seminar, University of Wisconsin, Madison, Wisconsin, October 24, 1975

B. J. Petterson, "Things Not To Do (Collector Materials Considerations)," New Mexico Solar Energy Association Meeting, Las Cruces, New Mexico, October 25, 1975.

D. M. Mattox, "Thin Films and Coatings for Solar Energy Applications," National American Vacuum Symposium, Philadelphia, Pennsylvania, October 28-31, 1975.

R. P. Stromberg, "Applications of Solar Energy," Bell Laboratories, Denver, Colorado, October 29, 1975.

R. P. Stromberg, "Introduction of Sun School," Sun School, Las Cruces, New Mexico, November 11, 1975.

M. W. Edenburn, "A Solar Heating System for a Northern New Mexico Adobe House," 1975 ASME Winter Annual Meeting, Houston, Texas, December 2, 1975.

R. W. Harrigan, "Solar Residential Solar Heating and Cooling," short course, University of New Mexico, Albuquerque, New Mexico, December 5, 1975.

J. A. Leonard, "Sandia Solar Total Energy System," Florida Solar Energy Center, Cocoa Beach, Florida, December 19, 1975.

G. E. Brandvold, "Sandia Energy Programs," New Mexico Institute of Chemists, Albuquerque, New Mexico, January 9, 1976.

J. A. Leonard, "Solar Total Energy Program," ERDA Solar Thermal Program Review, Atlanta, Georgia, January 26, 1976.

R. P. Stromberg, "Total Energy Economics," ERDA Solar Thermal Program Review, Atlanta, Georgia, January 26, 1976.

D. M. Mattox, "The Economic and Technical Aspects of Coatings for Solar Energy," American Vacuum Society, Tampa, Florida, February 2-5, 1976.

J. A. Leonard, "Energy Programs at Sandia Laboratories," American Vacuum Society, Tampa, Florida, February 2-5, 1976.

R. P. Stromberg, "Solar Energy Research," Santa Fe Contractors Association, Santa Fe, New Mexico, February 17, 1976.

R. W. Harrigan, "Sandia Laboratories Solar Total Energy Program," Chemical Engineering Department Seminar, University of New Mexico, Albuquerque, New Mexico, February 17, 1976.

R. P. Stromberg, "Sandia Laboratories Solar Programs," American Institute of Architects Meeting, Albuquerque, New Mexico, February 19, 1976.

D. M. Mattox, "The Economic and Technical Aspects of Coatings for Solar Energy," American Optical Society Topical Conference on Optical Interference Coatings, Pacific Grove, California, February 24-26, 1976.

A. F. Veneruso, "Sandia Labs Solar Total Energy Program," 7th Conference on Surface Studies, Los Alamos, New Mexico, March 9, 1976.

B. L. Butler, "Solar Reflector Analysis Using Laser Ray-Trace," Graduate and Faculty Seminar, New Mexico Institute of Mining and Technology, Socorro, New Mexico, March 23, 1976.

G. E. Brandvold, panel member, "Space and Marine Science Contributions to Solving the Energy Problem," Thirteenth Space Congress, Cocoa Beach, Florida, April 7, 1976.

J. A. Leonard, "Solar Total Energy at Sandia Labs," Thirteenth Space Congress, Cocoa Beach, Florida, April 8, 1976.

R. B. Pettit, "Optical Properties of Materials for Solar Energy Applications, Graduate and Faculty Seminar, New Mexico Institute of Mining and Technology, Socorro, New Mexico, April 20, 1976.

SECTION III. PROGRAM DESCRIPTION AND STATUS

Task 1. Program Management

The Sandia Solar Total Energy Program has been organized into a work breakdown structure of tasks and subtasks. This complete structure is given in the Contents for this section. The detailed status of each program task is described in the subsections below, organized for convenience along the lines of the work breakdown structure. A chart illustrating complete program staffing is shown in the Appendix. The technical contributions of these individuals to the Solar Total Energy Program as well as their written inputs contained in this semiannual status report are gratefully acknowledged.

Task 2. System Management

2.1 System Engineering

Future Quadrants of the Collector Field -- As of the end of the last reporting period, 52 RFP's had been sent to companies in the solar industry for the Phase I portion of the Sandia Collector Field Subsystem Program. Sixteen technical proposals were received on or before October 31, 1975. After a review by a seven-man technical review committee lasting three weeks, six companies were selected to continue the competition. They were asked to submit cost proposals by January 12, 1976. Before the receipt of the cost proposals, each of the six companies were visited by two members of the review committee. The company visitations together with the cost proposals from the final six companies provided the committee with the information it needed to choose companies to be given contracts. The following four companies were chosen:

General Atomic Company
McDonnell Douglas Astronautics Company
Raytheon, Inc.
Sheldahl Company

On February 26, 1976, a contract was placed with McDonnell Douglas Astronautics Company for the development of their north-south fresnel lens concept illustrated in Figure 2-1. Contracts were placed with the other three companies on March 31, 1976. The Sheldahl concept shown in Figure 2-2 is an east-west arrangement with a fixed receiver and tracking mirrored slats. Figure 2-3 illustrates the General Atomic concept of a fixed reflective trough oriented in the East-West direction with a tracking receiver tube. The parabolic dish concentrator being developed by Raytheon is shown in Figure 2-4.

The Phase I contracts now in effect will be completed by October 1, 1976. At that time two or three of the contractors will be chosen to proceed with the Phase II portion consisting of final design work, construction, and installation of their collector field subsystems.

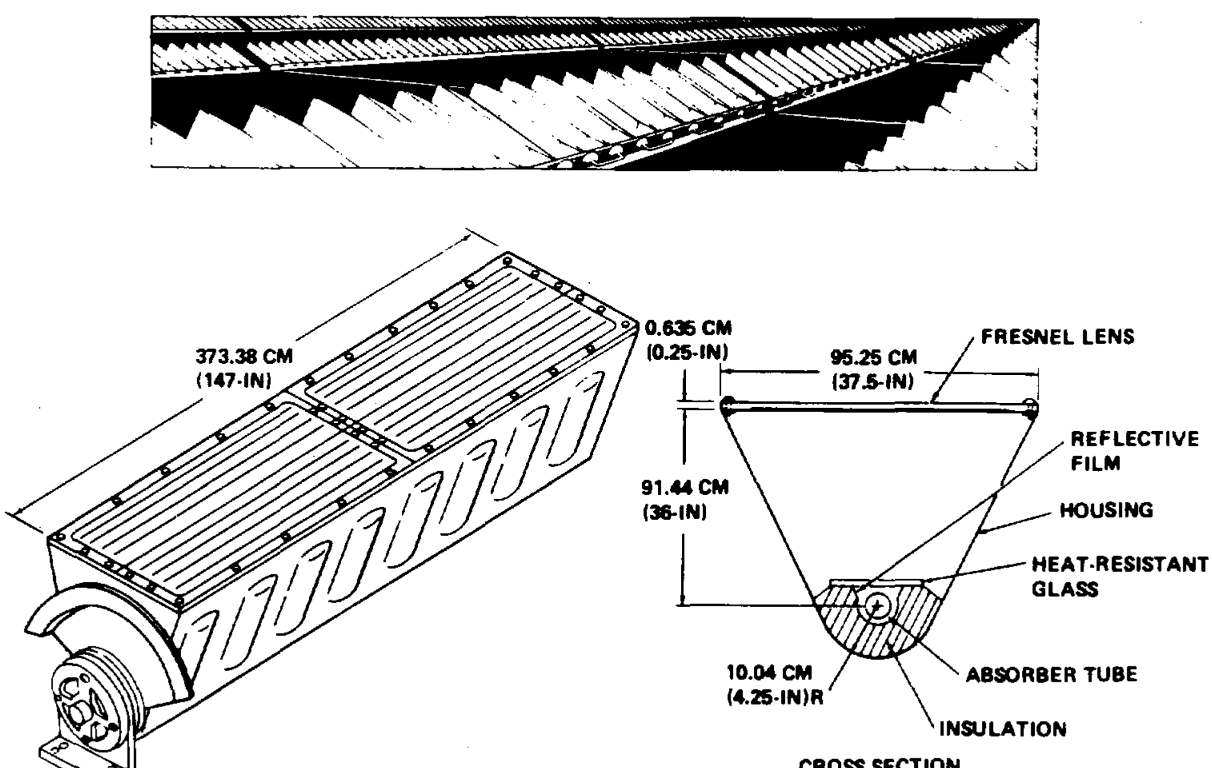


Figure 2-1. McDonnell Douglas Collector Field Concept

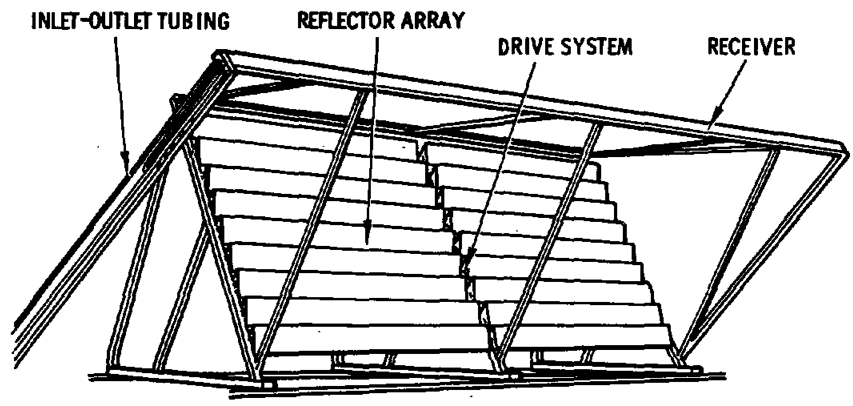


Figure 2-2. Sheldahl Solar Linear Array Thermal System 13.9 m^2 (150 ft^2) Array

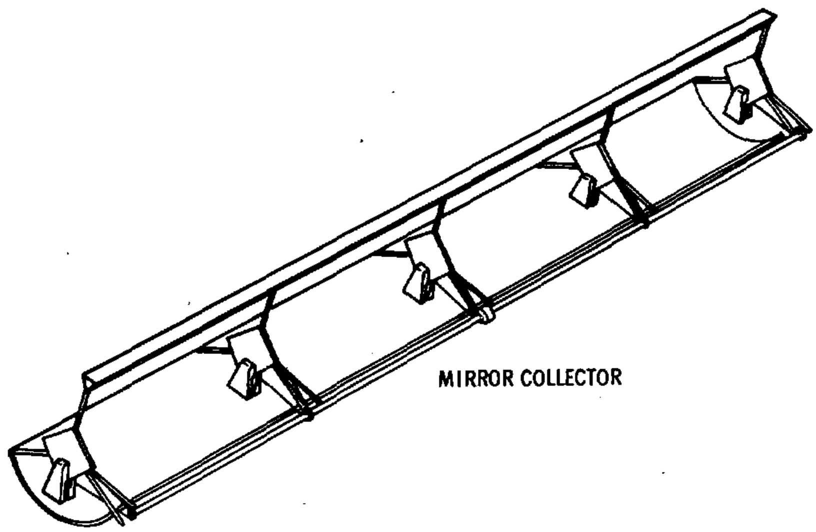


Figure 2-3. General Atomic Fixed Reflective Trough

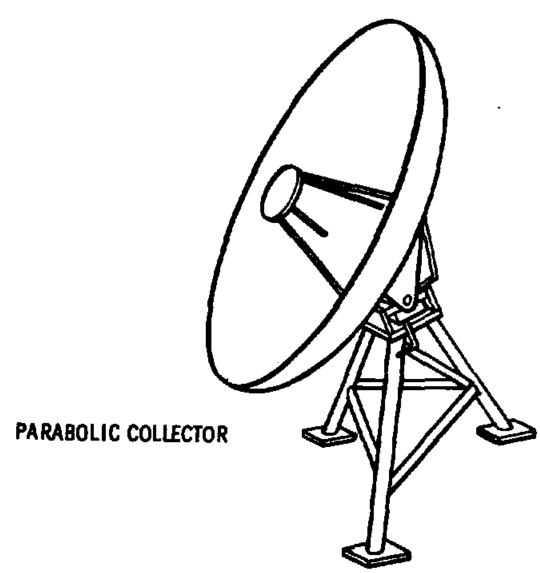


Figure 2-4. Raytheon Dish Concentrator

System Requirements -- The system schematic, Figure 2-5, has been revised to reflect the increased heat-flow rates required for the ORC efficiencies obtained in initial testing at Sandia. These revisions are based on using commercial power for the ORC parasitic load.

As a consequence of the lower than expected ORC efficiencies, the previous semiannual report described anticipated changes in: collector area, storage capacity, boiler, storage fluid transfer system, condenser fluid transfer system, turbine load heat exchanger, and cooling tower system. ORC testing to date indicates that no changes will be required to the boiler, turbine load heat exchanger, or cooling tower system. The changes required and/or made to the other subsystems as a result of the increased energy rates are summarized below.

> Required collector area is increased by 16%.
>
> Operating time from storage is decreased from 48 to 41 minutes at full load ORC conditions.
>
> A new pump motor, gear box, and motor controller has been added to the storage fluid transfer system in order to increase the Therminol 66 pump rate from 151 to 170 litre/min (from 40 to 45 gpm).
>
> A new higher speed motor and pump impeller has been received, but not yet installed, for the condenser fluid transfer system pump. This will increase the pump capacity from 284 to 333 litre/min (from 75 to 88 gpm).

Organic Rankine Cycle -- Performance tests on the energy conversion system in the direct gas-fired mode were conducted in December. These tests, which are discussed in more detail in Section 5.2, confirmed ORC performance and the adequacy of the cooling water system, i.e., the condenser-water and cooling-tower fluid loops. Performance tests on the energy-conversion system, using Therminol 66 heated by the fossil-fuel heater as the toluene heat source, were conducted in March. These tests, also discussed in more detail in Section 5.2, confirmed that the energy-conversion system performed adequately when operated in the mode required for full solar operation. In addition, they confirmed the adequacy of the boiler, heater, and Therminol 66 fluid transfer system to operate the ORC at full load conditions.

As anticipated in the last semiannual report, the actual efficiencies are lower than predicted earlier. The results of these lower efficiencies were discussed fully in that report. The actual operating efficiencies are summarized in Table 2-II.

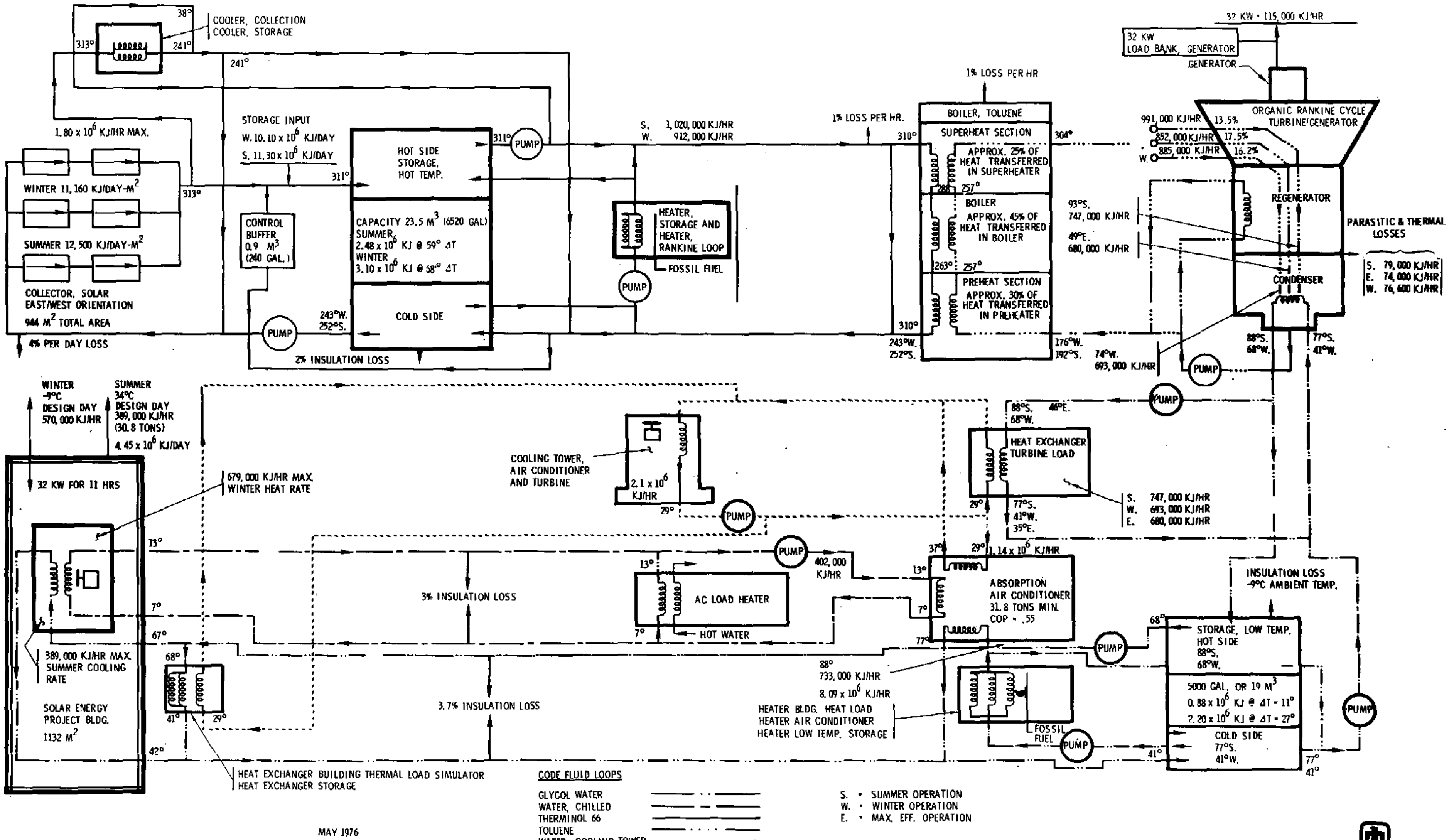


Figure 2-5. Solar Total Energy System Schematic

TABLE 2-I

Rankine Cycle Efficiencies
(%)

Cycle Temperature Limits (°C)	Cycle Temperature Limits (°F)	Predicted Efficiency w/parasitics	Actual Efficiency: Supplier Testing w/parasitics	Actual Efficiency: Supplier Testing w/o parasitics	Actual Efficiency: Sandia Testing w/o parasitics
296/93	565/200	13.6	10.6 to 10.9	11.6 to 11.9	11.6
296/74	565/165	16.2	12.2 to 13.3	13.3 to 14.5	13.0
296/59	565/138		13.0	14.2	
296/49	565/120	17.5			13.5

Phase IV-B -- The requirements for the heating and cooling subsystem to be constructed as part of Phase IV-B have been established. The subsystem will have the nine operational modes described below.

Heat Simulator/Storage Mode

Heat the Bldg. 832 load simulator heat exchanger with heat from storage.

Heat Building/Storage Mode

Heat Bldg. 832 with heat from storage.

Heat Building/Heater Mode

Heat Bldg. 832 with the fossil-fuel water heater.

Air Conditioner/Storage Mode

Operate the air conditioner with heat from storage.

Air Conditioner/Heater Mode

Operate the air conditioner with the fossil-fuel water heater.

Air Conditioner/Storage/Heater Mode

Operate the air conditioner with heat from storage and simultaneously operate the air conditioner load heater with heat from the fossil-fuel water heater.

Air Conditioner/Load HE/Heater Mode

Operate the air conditioner and air conditioner load heater simultaneously with the fossil-fuel water heater.

Heat Storage Mode

Heat storage with heat from the fossil-fuel water heater.

Cool Storage Mode

Cool storage with the Bldg. 832 load simulator heat exchanger.

The above nine operational modes are subject to the following system requirements:

- The system must sense when storage is full or empty and switch back and forth between Air Conditioner/Storage Mode and Air Conditioner/Heater Mode automatically. This switching should be unaffected by the simultaneous use of the fossil-fuel heater to heat the air conditioner load heater as in the Air Conditioner/Storage/Heater and the Air Conditioner/Load HE/Heater Modes.

- The system must sense when the storage is full or empty and switch back and forth between the Heat Building/Storage Mode and the Heat Building/Heater Mode automatically.

- Bldg 832 is typical of many commercial buildings which, at certain times of the year, require heating and cooling in the same day but not simultaneously. Under these conditions the storage tank will be maintained at 88°C (190°F). Consequently the heating system must be able to use energy at 88° or 68°C (190° or 155°F).

- Primary mode of operation for the fluid transfer system is with a two-tank, hot- and cold-storage mode. However, the system should be capable of operating from one tank operating in a thermocline mode.

- The system shall not be required simultaneously to heat the building and operate the air conditioner.

- Air conditioner load heater and building load simulator shall have controls capable of duplicating typical system loads, i.e., the fluid flow rate to them will be varied and they shall be capable of returning the fluid at set temperature.

A contract has been awarded to a consulting engineering firm to design the system per the above requirements with construction to be completed in November 1976. This contract provides for the heating and cooling subsystems up to the Solar Project Building. The contract to modify the building to meet the system requirements has been awarded and modifications are underway. The contract will be completed by November 1976.

Operating Procedures -- Following is an outline of the Safe Operating Procedures (SOP), Pressure Safety Analysis Reports (PSAR), and Operating Procedures to be written for the solar total energy testbed.

The overall philosophy is to write an SOP for the collectors and for each complete fluid loop in the system and interlock these fluid loops by means of the SOP and operating procedures to ensure no damage to the system during operation. The loops can be operating individually or simultaneously. Where the operation of one loop effects the operation of another loop, the operating procedures tie them together.

Collector SOP

This SOP will cover all hazards associated with the collectors (receivers, reflectors, structure and tracking) in the tracking or nontracking mode. It will specify that the procedures in the therminol loop SOP must be in effect if the collectors are tracking in order to prevent damage to the system.

Therminol Loop SOP

This SOP will cover all hazards associated with the Therminol 66 fluid loop. Within this SOP will be detailed setup and operating procedures for all regular operational modes. This SOP will be the one that covers operating procedures for the collector tracking system and will be so written that fluid flow through the collectors is attained before tracking is engaged.

This SOP will specify that if the collectors are operated the collector SOP must be followed, and if toluene is heated in the boiler the toluene loop SOP must be followed.

The PSAR for the Therminol fluid system will be a part of this SOP and will discuss all safety interlock systems which are a part of this fluid loop.

Toluene Loop SOP

This SOP will cover the hazards and give the operating procedures necessary for the toluene fluid system, i.e., the organic Rankine cycle. It will specify that when the toluene fluid loop is operated, the SOP for the Therminol fluid loop and the operating procedures for condensing water fluid loop systems must be followed.

The PSAR for the toluene loop will be a part of this SOP and will discuss all toluene system automatic safeties.

Condenser Water Fluid System Procedures

Since this system is no different from those existing in most buildings today, it will require no formal SOP or PSAR. However, a set of operating procedures for the regular operating modes will be written.

Cooling Tower Fluid Loop Procedures

Since this system is similar to those in everyday use through the country, it will require no formal SOP or PSAR. However, a set of operating procedures for the regular operating modes will be written.

Chilled Water Procedures

Since this system is similar to those in daily use throughout the country, it will require no formal SOP or PSAR. However, a set of operating procedures for the regular operating modes will be written.

Test Plans -- The following test plan has been compiled with the goal of achieving steady-state operation of the solar total energy test bed at the earliest date. Steady-state operation means operating the turbine from heat collected by the collectors at 315°C (600°F). The problems associated with transient operations resulting from such things as clouds, early morning startup, changing electrical demand, preheat of system components such as heater and storage cooler, determinations of when to switch from storage to heater operation, etc., will not be solved at this time. These problems require operating experience and data for their resolution. Another test plan is being formulated to gather this data.

The tests required to achieve steady-state operation are:

1. Heater Checkout - March 23

Operate heater to heat empty toluene boiler to determine heater flow limitations and check out control.

2. 10 Collectors at 315°C (600°F) - March 24

Operate 10 collectors at 315°C (600°F) to determine problems, adjust controls, and determine limitation flow and radial Δt. Testing done on these 10 collectors because they are heavily instrumented.

3. Heat Storage - March 31

Heat storage to establish a 243°/315°C (470°/600°F) thermocline at the middle of tank. Set up automatic cooling mode to cool tank when thermocline is at middle of tank. Continue heating storage tank to exercise automatic cooling system. Determine thermocline stability.

4. Reheat Storage - April 13

After above testing, reestablish clean thermocline with heater for ORC collector testing.

5. 20 Collectors at 315°C (600°F) - April 20

Operate 20 collectors from 243°/315°C (470°/600°F) storage thermocline to check out and adjust controls. Also check out automatic cooler-control system.

6. ORC Operation - March 25, 149°C (300°F) - April 21, 315° C (600°F)

Operate ORC from heater to check out controls and determine minimum temperature of operations. (Required to establish storage thermocline requirement.)

7. Steady-State Operation - April 30

Operate 20 collectors to heat storage and use storage to run ORC cycle under steady-state conditions.

To date, test numbers 1, 2, 3, and test 6 to 149°C (300°F) have been satisfactorily completed. Test reports for these tests are being written.

2.2 System Analysis

Program SOLSYS, Sandia's solar energy system simulation computer code, has been packaged and sent to the Argonne code dissemination center for release.

Argonne Code Center
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Task 3. Collector Field

3.1 Reflectors and Structure

The 200 m^2 (2160 ft^2) field of east-west collector troughs was completed and fully functional in February 1976. The final major parts to be assembled were the reflector sheets which were mechanically clamped on the concave surfaces of the troughs. The reflector sheets were installed in December on two of the 18.3 m (60 ft) troughs and in January and February on the other two troughs. The two western troughs were used for the initial functional field testing on December 31, 1976, when collected solar energy was deposited in storage.

The collector field consists of four continuous 18.3 m (60 ft) troughs in two rows aligned on east-west axes. See Figure 3.1 for an overall view of the completed collector field. Center-to-center spacing between rows is 7.6 m (25 ft). Each of the 18.3 m troughs consists of five 2.7 x 3.7 m (9 x 12 ft) trough units, mechanically connected at the ends to form a single structural trough.

Stress analyses of the structure have indicated adequacy in 13.4 m/s (30 mph) continuous wind with 40.3 m/sec (90 mph) gusts. Wind tunnel tests recently conducted on 1/10 scale trough models indicate that drag and lift forces used in the analyses are reasonably correct. The wind tunnel tests are discussed in Section 9.3.

Figure 3-1. Solar Total Energy System Test Facility (collector field lower left)

Drive System -- Although each 18.3 m trough is mechanically connected to form a single rigid structure, driving torque is applied to each of the five units from a single motor by means of a common shaft which runs the length of the trough. This design approach prevents major torsional stresses and deflection down the length of the trough. The drive shaft includes a right angle worm gear reducer (40:1) at each pylon to tap off power to a second worm gear reducer (100:1) which drives a chain-and-sprocket assembly (10:1) connected to the trough structure. The motor-to-trough reduction ratio is 40,000:1, providing a tracking rate of 9°/min with a 1000 rpm input.

The worm gear reducers, which contained summer-weight lubricating oil installed during summer assembly, were first operated in the winter months when nighttime temperatures were near -5°C (23°F). The significant viscosity increases in the oil at these temperatures produced motor torque loads significantly higher than expected.

The 1/2 hp 50 Vdc electric motor previously selected to provide a large torque safety factor proved necessary to drive the 10 worm gear units of each 18.3 m trough. Measurements were made of actual driving torques as the troughs were driven through 170° of rotation. The torques varied from 16 to 28 in.-lb at 400 to 800 rpm, depending on temperature and trough position. Since the troughs are pivoted about an axis approximately 0.38 m (15 in.) from their center of gravity, the torque loads due to gravity increase as the troughs move toward the horizon.

With a change to lower viscosity oil, the torque loads were reduced by 50 percent, but they remain higher than originally anticipated. The probable cause of the high torque is the added pressure on the gears caused by gravity and the offset CG. Required torques are now 11 to 13 in.-lb at 1100 rpm (0.21 hp) -- even with gravity aiding the trough's downward rotation.

Counterbalancing of the troughs to move the CG to (or near) the axis of rotation was considered but discarded primarily because of cost and impracticality. In addition, the torque loads due to a 30 mph wind were equal to or exceeded the torque loads due to the gravity and the offset CG. The motor and gear train had to be sized for the wind loads as well as dead weight loads. No doubt the normal (light wind) operating power requirements could be reduced by counterbalancing. Factors influencing this design problem and possible solutions are discussed in Section 9.3.

Reflector Materials -- Reflector materials for the present Phase IV-A application are discussed in this section. Development efforts and evaluation data on reflector materials for future applications are discussed in Section 9.2.

The reflector material for the 200 m^2 field was originally planned to include both front- and second-surface reflector films. Reflector sheets for half of the field (plus spares) were produced and shipped to Sandia in July 1975. In October 1975 the supplier visited Sandia to discuss problems encountered in the production and environmental capability of the protective coating to go over the metal of the two front-surface reflector films. Due to schedule commitments, a decision was made to use second-surface aluminum on Teflon for the entire collector field. Reflector sheets for the second half of the field were shipped in November 1975.

These reflector sheets are 0.025 mm (.001 in.) aluminized Teflon, laminated to polyester (Mylar or Melenex), and bonded to a flat 0.64 mm (0.025 in.) thick aluminum sheet of 2024-T3.

Reflector sheet installation involved the use of springloaded outer edge clamps plus a 25.4 x 6.4 mm (1.0 x 0.25 in.) aluminum strip down the center of the troughs. The center strip, found to be necessary in preliminary assembly checkout, is held by screws into the plywood. After the wind damaged one sheet, four screws were installed—two on each side—on each reflector sheet, about 0.25 m (10 in.) from the trough rim.

After installation of the reflector sheets, problems of wind and cleaning have required attention. Weather conditions involving winds of 20 to 45 mph have been relatively common through the winter and spring seasons. Winds of these velocities incessantly pull at any small gaps or overhangs of the reflector sheets or other materials, such as insulation, sheathing, etc. Aerodynamic smoothness must be a conscious and continuous effort in collector design. Metallic foil tapes have been used successfully in sealing some of the wind-vulnerable gaps and slits, but it is only an interim measure which requires further attention. Optimum design will foresee and eliminate the requirement for these stop-gap measures.

With the film reflectors, the wind also appears to aggravate the problem of cleaning. In addition to combining with precipitation to put dirt and moisture together on the reflector surfaces, the wind appears to be producing an electrostatic charge on the reflectors which attracts and holds noticeably more dirt and dust than was evident on earlier troughs which used Alzak. This is just an observation at the present time; however, it requires further investigation. The evaporated aluminum is sandwiched between Teflon and Mylar, which isolates it from the 2024-T3 structural sheet; the two conductors and the separating Mylar form a very large area capacitor.

Cleaning -- The cleaning requirements for a large array of reflectors is an important facet to be investigated in the operation of the Solar Total Energy System. Water has been provided throughout the area to allow washing operations. The troughs spent several weeks during the winter with the focal plane in vertical position. Rain and snow fell, melted, and drained down the vertex. A film or scum has accumulated along the vertex because of the thorough wetting and then drying of contaminants. A clean Teflon surface should not be "wetted" but should produce only beads of water on the surface, the center of the troughs is now dirty enough to produce wetting.

Therminol was spilled on the reflector surfaces during changing of some of the receiver tubes. Several solvents were used for cleaning with little success. The best cleaning agent was warm water, detergent, and a soft cloth rag rubbed gently over the soiled area to avoid scratching of the Teflon with either the rag or the accumulated grit. Although this installation is sufficiently small to allow manual washing of the entire reflector area, the program must aim at developing cleaning methods which are suitable for very large fields as well as determining the frequency of cleaning required and the degradation produced by dirty reflectors.

A flow-through cartridge which produces deionized water has been ordered for the final rinse of the reflectors to avoid residual mineral deposits from the evaporation of hard water droplets inevitably left on the reflectors after washing. Removal of these beads of water is impractical by squeegeeing, wiping with soft cloths, or any other method because of the soft texture of the Teflon and its vulnerability to scratching; labor costs would also probably be prohibitive. Perhaps a blower of some sort could be devised for rapid, efficient drying. This problem illustrates a need for an abrasion-resistant reflector or coatings.

Other methods of cleaning besides merely rinsing with a stream or spray of water are under investigation. One is a chemical cleaning solution (acidic, detergent, or other) which can be sprayed on, left a short time to dissolve or loosen the dirt, followed by water or deionized water to rinse it away. The reflector as well as all other portions of the system which will come into contact with the washing solution must be virtually unaffected by it in order not to degrade the system over the lifetime of its operation.

3.2 Receivers

The receiver tube design has been described in previous reports.

All receiver tube assemblies required for the collectors have been completed and installed. Two spare units are available as well as piece parts for several partial assemblies. Because of some difficulties in maintaining an integral glass/Kovar fusion seal near a welded joint, several of the receiver tube assemblies have been fabricated with an expansion bellows at each end of the assembly. The flanges and bellows are sources of thermal loss and will be insulated.

The thermocouple egress port has been difficult to seal to maintain a vacuum in the glass jacket annulus. In some cases, exposure to the temperatures associated with 315°C (600°F) fluid operation has caused minute cracking of the epoxy seal around the stainless-steel-jacketed thermocouples.

Easy installation and removal of the receiver tube assemblies has been demonstrated. This has been aided by the optical alignment of all receiver tube assembly support brackets through the use of an alignment telescope. The relationship of the receiver tube assembly line to the focal line(s) of the reflectors is not yet known.

The western quadrants of receiver tubes have been exposed to service operating temperatures with ambient pressure within the glass jacket. The mechanical behavior was within predictions. A sufficient expansion range is available in the support bracket design, and bending of the receiver tube due to the asymmetric flux input was not significant. The internal turbulence generator assisted in maintaining a small temperature gradient in the liquid cross section. The hollow metal "O" ring seal between receiver assemblies prevents Therminol 66 leakage and the expansion bellows compensates, at all air pressures, for the glass/steel differential expansion. The metal/glass fusion joints have retained structural integrity.

3.3 Tracking and Control

Active System -- The active sensor/servo system, described in some detail in the last two semiannual reports has been tested on the solar test bed during this report period. The sun sensor is presently being modified. The four silicon photovoltaic cells (two on each side of the shadow-board) are being replaced by two cells. These cells are mounted at an angle of 30° with respect to the East-West axis as shown in Figure 3-2. This design eliminates the electrical output balancing of the two cells on each side. The tilt angle allows for better off-axis "viewing" of the cell.

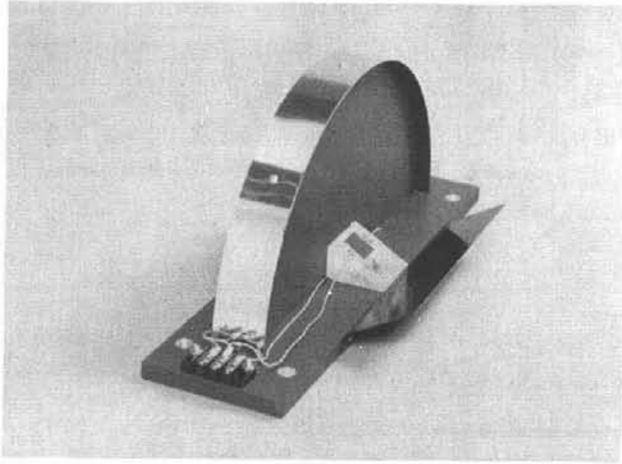


Figure 3-2. Sun Sensor Unit

Passive System -- The digital shaft-encoder/computer-command tracking system has been installed and checked out. This system is used to evaluate, the active sensor system or, alternatively, may be used actually to command the drive train to correctly track the sun. This system is discussed further in Section 6.

Safety Features -- In the event that fluid flow rate is too low or has stopped there is the probability of overheating damage, first to the heat transfer fluid and then to the receiver tubes. The parameters selected to sense or preclude this event are:

1. Loss of power to the trackers
2. Loss of power to the controller rack
3. Loss of power to the minicomputer
4. Over-temperature detected on receiver tubes
5. Loss of fluid flow at flow meter
6. Excessive thermal expansion of the receiver tubes
7. "Inattention" by the minicomputer as detected by the "watchdog timer".

The corrective action taken when one of these parameters is detected is to command the pump to maximum speed and command the trackers to defocus. In case the event is caused by loss of commercial power, the trackers will switch to backup battery power. There is no backup power for the pump motor.

Event Nos. 5 and 6 above are additions which were not discussed in previous reports. Events 3 and 7 may be overriden if the minicomputer is not actively commanding some part of the system. Number 2 will command pump speed to a preset minimum (no signal).

3.4 Fluid Transfer System

The fluid transfer system interconnects the collectors, the blending tank, the cooler, the high-temperature storage, and the toluene boiler. This fluid loop consists of valves, pumps, piping, insulation, and instrumentation.

During this reporting period the remaining undelivered hardware was received and the construction contract for the fabrication and installation of the system was completed. On March 15 the installation of the insulation was finished to permit the start of high-temperature operation throughout the system.

As reported earlier the fluid transfer system has many modes of operation. The entire fluid loop has been operated in each of the various modes under steady-state conditions. During the next few months tests will be conducted under transient operating conditions to check out and refine the control systems.

Before the installation of the insulation each portion of the fluid loop was pressurized with nitrogen to 1379 kPa (200 psig) at ambient temperature and checked for leaks by using a "soap-bubble" test. During assembly of the loop all pipeline joints, including the attachment points at the valves were heliarc welded. This proved to be very satisfactory as the only leaks found were at bolted flange joints. Subsequent operation with high-temperature Therminol 66 flowing through the pipelines revealed no additional leaks.

3.5 Cooler

The cooler acts as a thermal load on the collector/storage system in the three primary modes discussed below.

> Director Collector Cooling Mode - In this mode, the heated fluid returning from the collector field can be diverted directly to the cooler rather than going to the storage tank, allowing the collector field to be independently operated.

Automatic Cooler Mode - In this mode the status of the storage tanks is monitored by thermocouple sensors within the storage tank connected to controllers. When these sensors indicate storage is full of hot fluid, they activate a pump and control valve and allow the hot fluid to be pumped through the cooler, cooled to the desired temperature of 243°C (470°F) and returned to the bottom of the storage tank.

Cool Storage Only Mode - In this mode the coolers are used to cool the storage tank to any desired temperature including ambient.

All three of these modes have been operationally tested at design conditions under steady-state conditions. The "transient loads" and "preheat of the system" problems will be addressed later after actual operational experiences have been obtained. It appears these problems will be minor and can be solved, if necessary, by the procedures discussed in the previous semiannual report.

3.6 Collector Field Tests

The western quadrants of collectors (10 in series flow) have collected energy to attain a 315°C (600°F) output temperature with flow through the blending tank (mixing mode) to confirm the mechanical and thermal aspects of the design. Glass jacket vacuums were not used. All expansions, bending, and sag were within predicted limits. All receiver seals functioned properly without leakage. This 282°C (540°F) increase in liquid temperature required about two hours of solar tracking (9 to 11 a.m. MST). Approximately 0.28 m^3 (75 gallons) of Therminol 66 liquid were used in the test.

All 20 collectors have been operated in series in the same mode to about 150°C (300°F) with no difficulty.

Task 4. High-Temperature Storage

The high-temperature storage tank described in the last semiannual report was installed and insulated during this reporting period. The vacuum jacket operates at a pressure of less than 0.5 mm Hg under normal operating conditions. Because of extensive outgassing of the material within the vacuum jacket, the jacket is always operated open to the vacuum pump to insure maximum insulation properties. The top and bottom of the tank are insulated with 20 cm (8 in. minimum) Kaowood bulk insulation against the tank, with 15 cm (6 in. minimum) of rock wool batts forming an outer layer of insulation. The tank is sealed to prevent moisture from entering the insulation.

The tank has been operated up to 260°C (500°F) as of the end of this reporting period. There has been no attempt to establish and test the stability of thermoclines during this period, although such tests are slated for the first part of the next reporting period. Initial indications have been that thermoclines do indeed form in T-66, but their long-term stability remains to be determined.

Task 5. Turbine/Generator System

5.1 Toluene Boiler

The heat exchanger to transfer the heat from the Therminol 66 (T-66) fluid to the toluene working fluid for the turbine/generator was delivered and installed during the summer of 1975. The heat exchanger consists of four separate elements--one for preheating, two for boiling, and one for superheating. A 5.1 cm (2 in.) thick ceramic fiber blanket has been added to the boiler to achieve the design heat loss rate of 1 percent. The boiler has been used to furnish heat to the toluene at maximum load conditions. With a T-66 input temperature of 309°C (588°F) and an output temperature of 243°C (469°F), the boiler transferred 977,000 kJ/hr (926,000 Btu/hr) to the toluene. That fluid's exit temperature was 308°C (586°F). This test showed that the boiler will adequately meet the needs of the ORC even though, as discussed in the previous semiannual report, these needs are in excess of the design loads.

5.2 Turbine/Generator

The turbine control console and instrumentation hookup was completed the latter part of October and the unit was operated for the first time at Sandia on October 31. The unit was operated essentially as received from Sundstrand in the direct gas-fired mode. Initial operation lasted only a few minutes before shutdown because of several problems such as leaky fittings, a nonfunctioning load bank, and a clogged filter in the condenser cooling loop.

The month of November was spent primarily in initial shakedown trials of the turbine system and the test facility. Numerous small but time-consuming problems were encountered, such as the condenser piping was found to be reversed, the condenser cooling water flow meter clogged repeatedly until a strainer was installed immediately upstream, numerous shorts and open circuits were found in the test facility instrumentation and control lines, etc.

With the majority of the initial problems corrected, the turbine was tested extensively during the first week in December using fossil fuel. The test results are given in Table 5-I. The tests were run with the cooling water-glycol return temperatures nominally controlled at 88°C (190°F), 68°C (155°F), and 43°C (110°F), representing the design use conditions for summer, winter, and fall/spring operation, respectively. The superheater exit temperature was nominally controlled at 304°C (580°F) and the turbine inlet pressure at 1586 kPa abs (230 psia) for all tests representing the design conditions. The loads were applied from the facility load bank and were chosen to correspond to the nominal half-load and full-load tests run at Sundstrand, with the internal system parasitic electrical loads ($\sim$ 3 kW_e including 1 kW_e for the combustion air blower) being carried by the system. The internal parasitic electrical loads were carried by the building power for the Sandia tests. The efficiency numbers in Table 5-I are based on gross generator electrical power out divided by heat into the toluene. "Station" or "busbar" efficiency would be reduced depending on what parasitics are charged to the system and if the heater losses (either Sundstrand or Graham) are considered. In general, the test data verified previous test results obtained at Sundstrand and indicated that the unit is approximately 2 to 3 percentage points lower in efficiency than previously projected by Sundstrand (e.g., 11.0% vs. 13.4% at the summer full-load conditions). The lower than expected efficiency of the turbine/generator affects several other major components in the test facility, such as the collector field, the high-temperature thermal storage, the boiler system, and the cooling loop. However, preliminary analyses indicate that the test facility will be capable of accommodating the decreased turbine system efficiency.

Sundstrand, in January, presented their analysis of why the turbine system produced lower than expected efficiency. In summary, they concluded that the major items contributing to the lower efficiency were (1) The alternator manufacturer inadvertently installed an oversized cooling fan resulting in a constant power loss of 2 kW_e; (2) the feed pump, regenerator, and turbine nozzle ring did not meet design goals because of compromises made in adapting the original Sundstrand 100 kW_e system to the Solar Total Energy System operating requirements. The alternator fan was replaced with a proper size unit during January when the turbine system was down for replumbing for operation with the Therminol 66 loop. Sundstrand's suggested improvements in the turbine nozzle ring, etc., are not being incorporated at this time. They will be considered for retrofit at a later time.

Along with the completion of the replumbing required to allow operation of the turbine from the Therminol loop, the revised control philosophy and logic diagrams were finalized in January. The required control system hardware changes were completed in February. Also in February, rough draft versions of a new Safe Operating Procedure and Pressure Safety Analysis Report for the turbine system were completed.

The collector and storage Therminol loops were debugged in early March, allowing operation of the turbine in the indirect heated mode on March 24. Initial operation was short lived because of several problems. The first problem encountered was an equipment malfunction in the load bank which caused a transformer, power meter, and several wires to overheat after approximately 10 seconds of operation. After the load bank was disconnected, several attempts at starting the turbine generator were made but operation could not be sustained because of shutdown signals from the underpressure/underspeed and undervoltage sensors. These were found to be caused by a rather mysterious shift in the set levels of the turbine throttle valve's enable and underpressure shutdown pressure switches which prematurely opened the throttle valve on startup before sufficient boiler pressure was present and which then caused the underpressure safety to shut down the unit.

TABLE 5-I

Turbine System Performance Test Data Summary

Test No. (a)	Water-Glycol(b) T_{in}	Water-Glycol(b) T_{out}	Load (kW_e)	Efficiency (%)	Toluene(b) Superheater Exit Temp.	Superheater Exit Pressure	Turbine Inlet Temp.	Turbine Inlet Pressure	Condenser Inlet Temp.	Condenser Inlet Pressure
1	76 (169)	89 (192)	20.1	8.43	303 (578)	1606 (233)	291 (555)	1475 (214)	90 (194)	48 (6.90)
2	71 (159)	88 (191)	20.2	8.95	309 (589)	1655 (240)	299 (571)	1524 (221)	92 (197)	47 (6.76)
3	71 (160)	88 (190)	20.2	9.11	312 (594)	1730 (251)	301 (574)	1620 (235)	92 (196)	46 (6.62)
4	78 (172)	89 (193)	20.2	8.30	300 (572)	1524 (221)	291 (551)	1455 (211)	91 (195)	49 (7.14)
5	79 (174)	89 (193)	20.2	8.25	317 (602)	1662 (241)	299 (570)	1524 (221)	92 (197)	50 (7.30)
6	75 (167)	87 (189)	34.5	11.7	303 (578)	1799 (261)	294 (561)	1606 (233)	92 (197)	46 (6.66)
7	75 (167)	87 (189)	34.5	11.7	300 (572)	1772 (257)	291 (555)	1606 (233)	92 (197)	45 (6.58)
8	68 (155)	81 (178)	34.6	12.0	302 (576)	1813 (263)	289 (553)	1648 (239)	87 (188)	39 (5.66)
9	75 (167)	87 (188)	34.6	11.4	303 (578)	1813 (263)	294 (562)	1634 (237)	88 (190)	47 (6.76)
10	78 (172)	91 (196)	34.6	10.5	299 (571)	1703 (247)	291 (556)	1503 (218)	92 (197)	53 (7.68)
11	58 (136)	67 (152)	20.2	9.29	308 (587)	1724 (250)	294 (561)	1620 (235)	75 (167)	22 (3.14)
12	54 (130)	67 (152)	20.2	10.3	304 (580)	1689 (245)	293 (559)	1579 (229)	76 (168)	21 (3.02)
13	57 (135)	69 (156)	20.2	10.1	297 (567)	1620 (235)	284 (543)	1531 (222)	75 (167)	22 (3.26)
14	57 (135)	69 (156)	20.2	9.98	304 (579)	1703 (247)	289 (552)	1593 (231)	75 (167)	23 (3.40)
15	58 (136)	69 (156)	20.2	10.2	305 (581)	1703 (247)	290 (554)	1606 (233)	75 (167)	23 (3.38)
16	47 (117)	72 (161)	20.3	9.75	302 (576)	1689 (245)	294 (562)	1558 (226)	76 (168)	29 (4.28)
17	52 (125)	73 (163)	34.5	12.9	301 (574)	1717 (249)	290 (554)	1579 (229)	74 (165)	27 (3.90)
18	44 (112)	67 (152)	35.8	13.4	306 (582)	1772 (257)	292 (557)	1627 (236)	72 (161)	21 (3.10)
19	54 (129)	68 (155)	34.6	12.6	303 (578)	1786 (259)	293 (560)	1655 (240)	76 (168)	29 (4.26)
20	56 (132)	69 (157)	34.6	12.5	309 (588)	1806 (262)	296 (565)	1675 (243)	76 (169)	30 (4.36)
21	58 (136)	72 (161)	34.6	12.4	303 (577)	1744 (253)	289 (553)	1593 (231)	77 (171)	32 (4.62)
22	61 (141)	74 (165)	34.6	12.3	304 (580)	1662 (241)	292 (558)	1524 (221)	78 (173)	33 (4.88)
23	36 (96)	44 (111)	20.1	10.3	313 (595)	1758 (255)	298 (569)	1634 (237)	58 (136)	8.4 (1.22)
24	36 (96)	44 (112)	20.1	10.4	310 (590)	1765 (256)	297 (566)	1648 (239)	57 (135)	8.1 (1.18)
25	36 (97)	45 (113)	20.1	10.5	308 (586)	1751 (254)	294 (561)	1648 (239)	57 (135)	8.4 (1.22)
26	33 (92)	44 (111)	35.8	13.2	303 (578)	1772 (257)	289 (552)	1634 (237)	61 (141)	1.5 (2.18)
27	32 (90)	44 (111)	34.4	13.5	305 (581)	1662 (241)	291 (555)	1565 (227)	56 (132)	8.0 (1.16)
28	33 (91)	44 (111)	34.4	13.4	304 (579)	1682 (244)	290 (554)	1558 (226)	56 (132)	8.4 (1.22)
29	34 (93)	44 (112)	34.5	13.3	301 (573)	1772 (257)	289 (553)	1648 (239)	57 (134)	9.0 (1.30)
30	34 (93)	45 (113)	34.4	13.3	302 (575)	1772 (257)	291 (555)	1641 (238)	57 (134)	8.7 (1.26)

Notes:

a. Tests performed at Sandia on December 3-5, 1975, in direct gas-fired mode without parasitic loads.

b. Temperatures in °C (°F), pressures in kPa abs (psia).

After recalibration of the system instrumentation, the ORC was operated at design turbine inlet temperatures and pressures and at power output levels of 5, 10, 15, 20, 25, 30, and 32 kW_e on March 25. Total operation time was about one hour. Very little effort was made to obtain stable operating conditions during these runs, since our primary objective was to determine the joint operating characteristics of the ORC and the T-66 heater and to get a feel for manual control of the two. The only significant problems encountered were instability of the flow (pressure) control valve, which had also happened during the December runs, and a problem with the turbine control logic in latching in the load bank.

On March 26, the control logic problem with the load bank was fixed, but subsequent operation of the unit indicated that the fix caused other minor problems with the automatic control logic for the auxiliary boost pump (it had to be turned on and off manually) and the lube oil start pump (it ran continuously)--these problems did not interfere with testing of the ORC. The unit was operated for about 1-1/2 hour at power levels of 8, 16, 24, and 32 kW_e. Except during startup and with the exception of the flow control valve, the ORC, the T-66 heater, and the cooling loop were operated successfully together under automatic control. The flow control valve was operated manually during the tests. Comparison of efficiency calculations based on energy into the toluene indicate that the ORC efficiency in the indirect heating mode is at least as good as in the original gas-fired mode (see Table 5-I). Detailed performance tests will be performed as soon as possible.

5.3 Turbine Heat Exchanger

The turbine load heat exchanger is the interface between the condenser cooling loop and the cooling tower loop. This exchanger is to keep the cooling tower water, which becomes contaminated by the evaporation process, out of the condenser and low-temperature storage. It was installed in August 1975.

The turbine heat exchanger has been used in support of the ORC system. To date it has satisfactorily handled the required maximum heat rate of 799,000 kJ/hr (757,000 Btu/hr). However, the heat exchanger was not sized for maximum heat flow conditions, i.e., summer operations. The most stringent operating conditions occur when there is a minimum driving ΔT between the cooling tower water and the condenser water, i.e., equinox operations. The most stringent testing has been a 718,000 kJ/hr (681,000 Btu/hr) heat rate at a 17°C (30°F) ΔT. This required a fluid flow rate of 291 litre/min (77 gpm). To meet the required load of 718,000 kJ/hr at a 5.5°C (10°F) ΔT will require approximately a 340 litre/min (90 gpm) fluid flow rate as anticipated in the previous semiannual report. To meet this requirement a new motor and pump impeller will be added to the condenser fluid transfer system; they have been delivered but have not yet been installed.

5.4 Cooling Tower

The cooling tower used to dissipate the heat rejected from the ORC turbine and the absorptive air conditioner (simultaneously as necessary) is an induction-type cooler supplied by Baltimore Air Coil, Inc. The unit is shown in Figure 5-1. The tower is capable of cooling 1324 litre/min (350 gpm) of water from 36° to 29°C (96.5° to 85°F) with a summer day ambient temperature of 36°C (96°F) and a wet-bulb temperature of 21°C (70°F). This cooling capability is equivalent to 2.1×10^6 kJ/hr (2×10^6 Btu/hr). The tower uses an induction spray for evaporative cooling and consequently does not require fans with their attendant noise. The basic cooling tower, pumps, and connecting plumbing from the remote tower to the turbine building were installed and functional in September 1975.

Since then the tower has been used in support of the ORC system. To date it has satisfactorily handled a load of 799,000 kJ/hr (757,000 Btu/hr), which is well below its design load of 2.1×10^6 kJ/hr. It will not be possible to test it under full load until the absorptive air conditioners and project building thermal load simulator are added to the project in Phase IV-B.

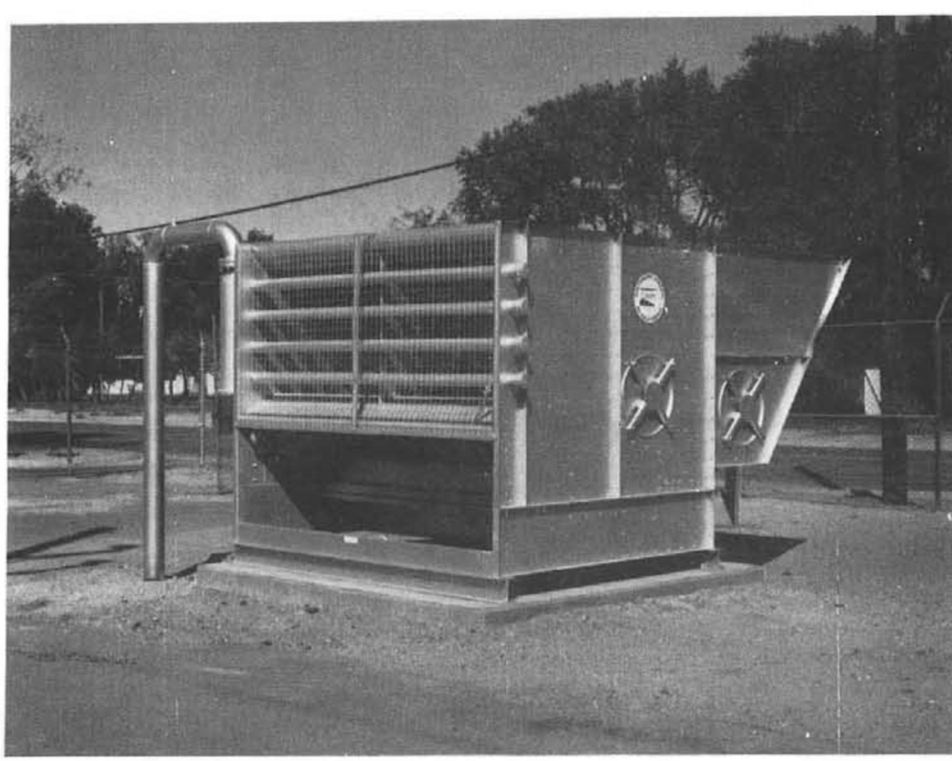


Figure 5-1. Induction-Type Cooling Tower

5.5 Condenser Fluid Transfer System

The condenser fluid loop is the fluid system that interconnects the turbine condenser with the turbine load heat exchanger (Section 5.3). In Phase IV-B, the loop will also interconnect the low-temperature storage, the low-temperature storage heater, the Solar Project Building, and the project building thermal load simulator. The fluid used in this loop is a 30 percent ethylene glycol/water solution. The requirements for the system have been established as follows:

1. Maintain constant cooling water output temperature from the ORC system condenser regardless of system load. Have the capability of changing system control to maintain instead constant ORC fluid output temperature from condenser.

2. Use the turbine load heat exchanger to cool low-temperature storage, bypassing condenser when so doing.

3. Sense when storage is full and automatically divert flow to the turbine load heat exchangers.

4. Have the capability of blending flow from cold side of low-temperature storage with flow direct from condenser to maintain any desired condenser supply temperature (needed when temperature of low-temperature storage is lower than desired condenser supply temperature).

The parts of this system necessary for Phase IV-A, i.e., requirement No. 1 above, were completed in early FY 76. Provisions have been made so that those parts required for Phase IV-B (Nos 2, 3, and 4) can be easily added.

The system has been used in support of Rankine cycle testing. When the ORC system was generating 32.6 kW, the condenser fluid transfer system satisfactorily transferred 799,000 kJ/hr (757,000 Btu/hr) from the condenser to the cooling tower water. The input cooling water temperature to the Rankine cycle was 75°C (167°F) and the output temperature was 86°C (187°F). However, to accomplish the above cooling rate the fluid pump had to deliver 303 litre/min (80 gpm) whereas its rated capacity is 284 litre/min (75 gpm). This was expected and is a consequence of the lower than expected Rankine cycle efficiency discussed more fully in the previous semiannual report. As reported there, the pump motor and pump impeller will be replaced with larger units to prevent excessive heating of the motor and give a large flow capacity, thereby giving more flexibility in operation of the toluene load heat exchanger.

5.6 Cooling Tower Fluid Transfer System

The cooling tower fluid transfer system presently connects the cooling tower (Section 5.4) with the turbine load heat exchanger (5.3). This fluid transfer system was constructed as part of the test facility control building and became operational in September. The system has been used in support of the ORC system. To date it has satisfactorily handled a load of 799,000 kJ/hr (757,000 Btu/hr) which is well below its design load of 2.1×10^6 kJ/hr (2×10^6 Btu/hr). It will not be possible to test the system under full load until the absorptive air conditioners and project building thermal load simulator are added to the system in Phase IV-B.

Task 6. Instrumentation and Control System

6.1 Control and Equipment Center

A 140 m^2 building was constructed to house system components and control equipment. This building, completed in July 1975, houses all major system equipment except the collector field, high- and low-temperature storage, and cooling tower. The control room of the building is shown in Figure 6-1.

Figure 6-1. Control Room in Control and Equipment Building

6.2 Control and Instrumentation

Operational control of the system is primarily a matter of controlling fluid transfer, i.e., controlling pump speeds and valve position for operation.

During this reporting period we achieved stable, but not optimal, operation of controllers in the turbine cooling loop, the storage cooling loop, and storage heating with fossil fuel.

The Delta® system was used for changing set points on the turbine cooling loop controllers and for acquiring status and temperature data associated with this loop.

Turbine Controls -- The ORC turbine controls have undergone major modifications to separate the natural-gas-fired heater and the turbine for independent operation of either system (Figures 6-2 and 6-3). The turbine has been integrated into the solar total energy system so that it receives its heat input through the Graham heat exchangers and rejects its heat output to the glycol-water cooling loop. Flow and pressure sensors provide inputs to safely interlock the turbine's operation with proper flow conditions in those input and output loops. The gas-fired heater can be used as a backup heat source to run the turbine or heat thermal storage.

The system safeties, originally supplied as a combined unit by Sundstrand, have been separated as to heater- or turbine-related functions. These safeties monitor various temperatures, pressures, and flow conditions and execute appropriate actions, such as turbine or heater shutdown, if hazardous conditions occur. Primary safety conditions such as unit over-temperatures, stack over-temperature, flammable vapor pressure, and condenser overpressure result in immediate shutdown of both turbine and heater. A complete safety checkout test series has been completed to verify proper performance of all safety circuits. During these tests a unit over-temperature was simulated by a heat gun, causing the CO_2 fire extinguisher to function. Minor changes were made in aiming the CO_2 nozzles to direct the flow properly over the turbine and heater components. This test also established that no further hazard was created by the extinguisher system to personnel in the turbine room. All exits from the room remained visible and no streams of CO_2-induced fog impeded movement to any exit.

Other progress --

- Completion and checkout of the "watchdog timer" (a safety device to detect "inattention" by the mini-computer).
- Data acquisition and presentation programs have been developed for the turbine and the collector field.
- An "ephemeris" program has been developed which computes sun azimuth and elevation and the proper solar collector elevation to be in focus. This program is used to (1) evaluate the active tracker (actual collector angles are measured by shaft encoders), and (2) provide inputs to a minicomputer tracking algorithm (next item).
- A tracking control algorithm has been developed which will keep the solar collectors within 0.05 degree of perfect focus. Inputs to this algorithm are the "ephemeris" program and shaft-encoder outputs.
- Completion of the instrumentation and control wiring.

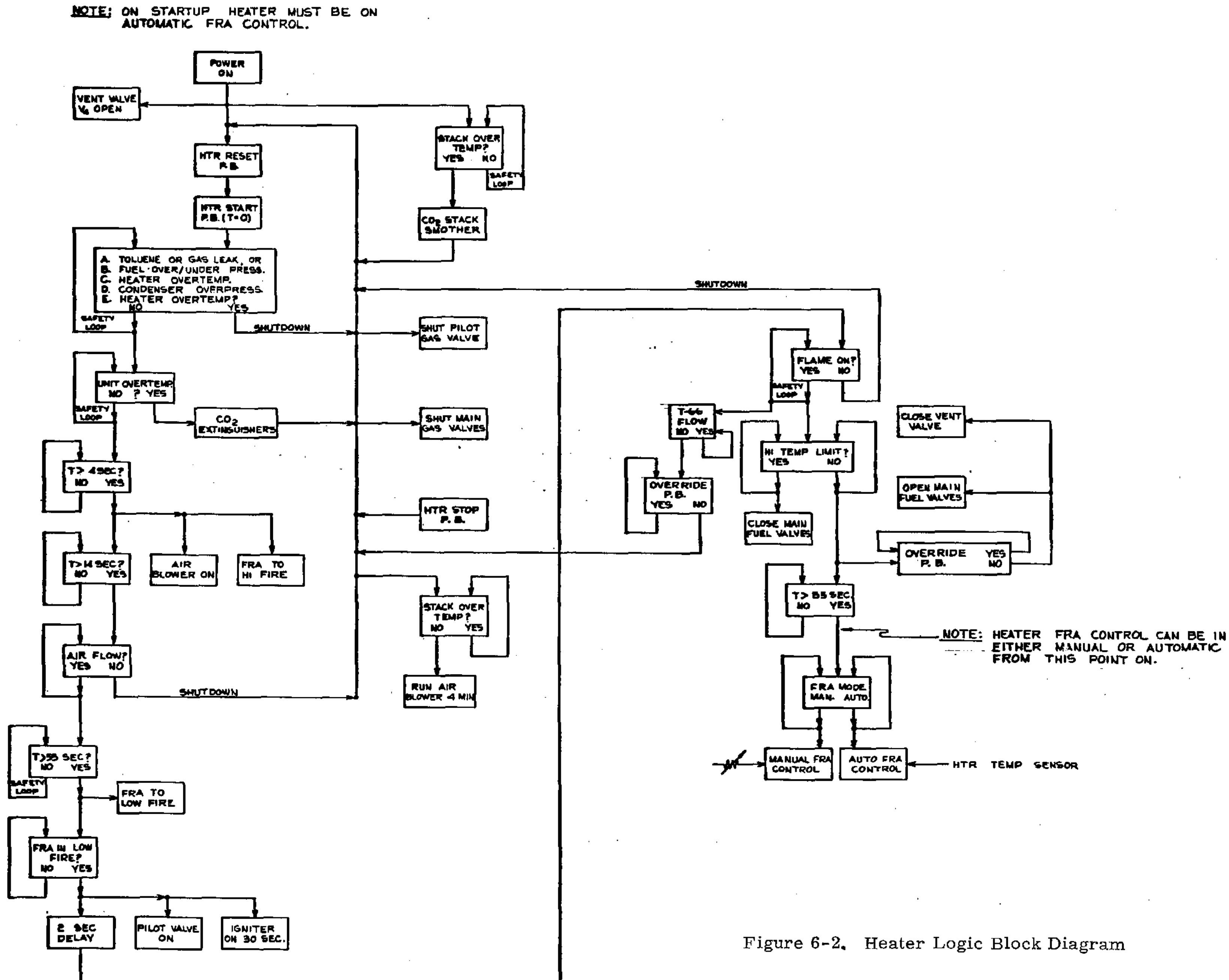


Figure 6-2. Heater Logic Block Diagram

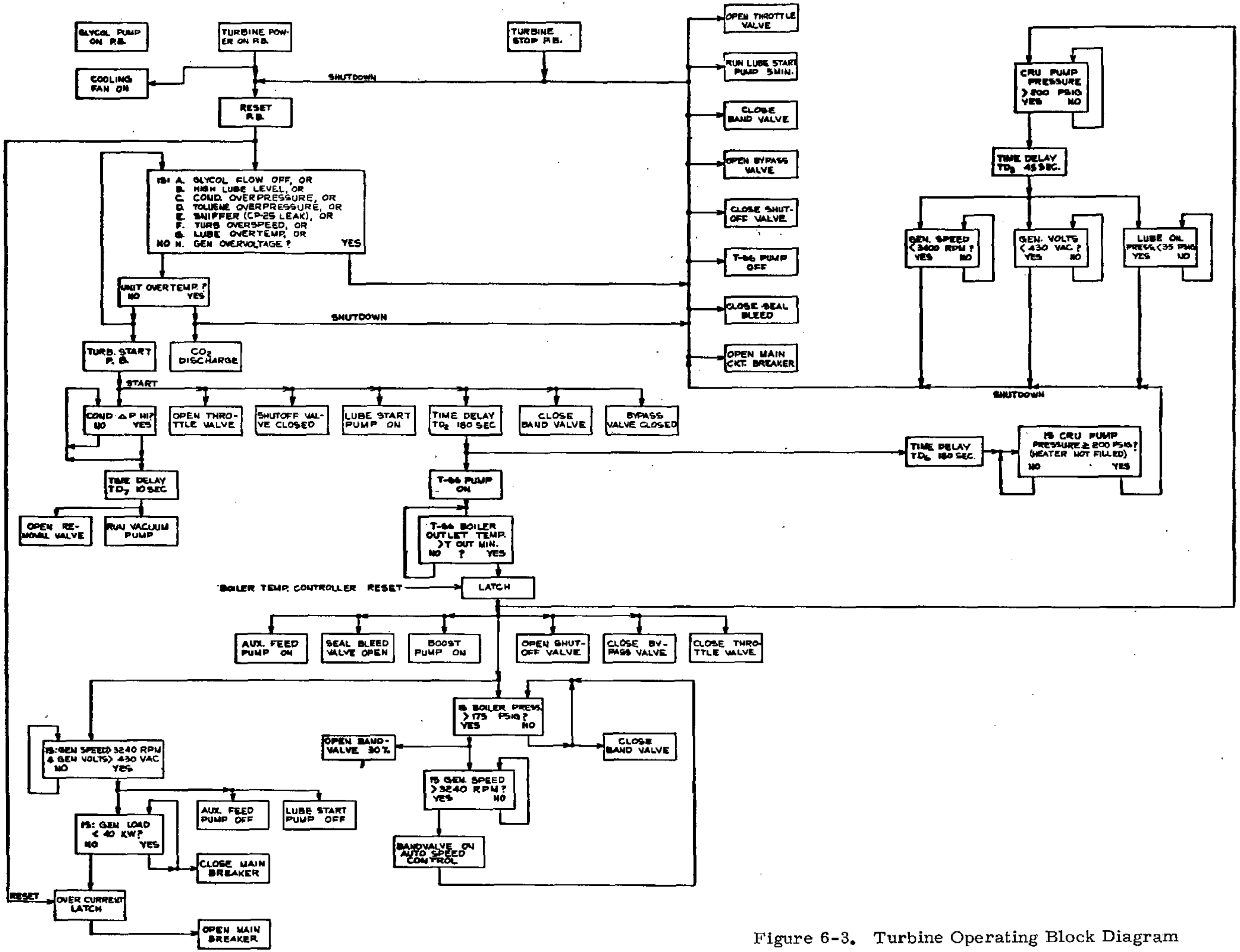


Figure 6-3. Turbine Operating Block Diagram

6.3 Data Acquisition, Recording, and Presentation

Programs were separately developed for the turbine and the collector field. We expect to combine these programs during the next reporting period. These programs are modified nearly every day they are used to add features, change nomenclature, streamline the presentation to facilitate fast comprehension of critical data, or to present printed data in units more familiar to the engineer who is involved in the testing.

Both programs acquire data continuously. The minicomputer switch register is used to select actions upon demand such as:

Printout collector field temperatures, flow rates, efficiencies, ambient weather conditions, etc.

Take 10-point averages of data essential to efficiency calculations

Take minicomputer control of solar collector tracking

Force mistracking of the solar collectors, up or down

Print raw data as it is acquired

Print temperatures of the storage tank skin temperatures

Run the slide display

Print the data and status conditions monitored by the Delta® system

Store raw data on disc.

Task 7. Collector Test Facility

The experiments to evaluate different turbulence generators for asymmetrically heated receiver tubes have been halted because of the inability of the three-zone electric tube furnaces to deliver the required asymmetric energy flux about a receiver circumference. The limited results prior to the halt of testing corroborated previous work on symmetrically heated tubes.

Limited analytical attempts are underway to determine the influence of asymmetric flux and film coefficients on liquid local film coefficients. Should these attempts be unsuccessful, equipment modifications to obtain asymmetric flux will be examined. The importance of turbulence generators is treated at more length in a subsequent section of this report.

Task 8. Improved Data Base Compilation

Solar and Weather Data

The task of preparing hourly solar and weather tapes for 1962 and 1963 for eight U. S. locations has been completed. The locations are: Albuquerque, Blue Hill (Massachusetts), Fort Worth, Los Angeles, Miami, Nashville, Omaha, and Seattle. These data tapes contain hourly values for both total horizontal and direct normal solar radiation. In addition to providing a data source for solar systems studies at Sandia Laboratories, these data tapes will be made available to any other interested individuals or firms.

Task 9. Phase IV-B Supportive Energy Research

9.1 Collector Fabrication Development

As described in previous reports, a pair of precision metal parabolic molds have been used to fabricate a variety of 0.6 x 1.2 m (2 x 4 ft) parabolic test sections for evaluation of production processes and environmental capabilities. Table 9-I describes the construction of a major portion of the test sections which have been produced. Each of these units has been inspected with the laser inspection technique described in the previous semiannual report to establish their baseline optical characteristics. These parabolic test sections have been placed in accelerated or real-time environmental testing for evaluation. The effects of these tests, plus a series of simulated hail tests, will be evaluated by reinspection of the units with the laser system and detailed comparison with the initial data.

The data also provide a means of comparing the various trough structures produced from standard materials by conventional manufacturing processes. It should be stressed that these units represent the first attempts by the various suppliers who have not had the opportunity to optimize their fabrication procedures or to develop new techniques. These data are representative of current technology; future improvements in both part quality and cost can be expected.

The laboratory laser inspection technique has been refined in the areas of data collection and reduction to provide the optical characteristics listed in Table 9-I. The "focal length" column tabulates the focal length of the least-squares fit to a true parabolic contour of the test section; the desired focal length is of the mold which is 762 mm (30 in.). An increase in focal length indicates an opening of the trough section; a decrease focal length indicates a closing of the trough producing a shorter radius of curvature than that of the mold.

TABLE 9-I

Parabolic Test Section Fabrication and Laser Inspection Data

Sandia Identification	Manufacturer	Parabola Construction: Reflector	Parabola Construction: Front Skin	Parabola Construction: Core	Parabola Construction: Back Skin	Reflector Attachment	Remarks	Focal Length[a] (mm)	Slope Error σ, One Standard Deviation[b] (mrad)
SL-21	Brunswick	Alzak	-	7-ply 1/10 Lauan	-	During lamination	Plywood high forming pressure	+ 8.9	2.9
SL-22	Brunswick	Alzak	-	7-ply 1/10 Lauan	-	Vacuum held	Plywood high forming pressure	-30.9	7.9
SL-23	Brunswick	Alzak	3-ply 1/10 Lauan	2-in. paper honeycomb	3-ply 1/10 Lauan	During lamination	3/8 cell honeycomb	+ 2.5	4.5
SL-24	Brunswick	Alzak	Mel	7-ply 1/10 Lauan	Mel	During lamination	High pressure forming	-37.9	3.8
SL-25	Brunswick	Alzak	3-ply 1/10 Lauan	2-in. paper honeycomb	3-ply 1/10 Lauan	During lamination	3/8 cell honeycomb	- 2.5	2.2
SL-26	Brunswick	Alzak	-	2-in. paper honeycomb	0.025 Al	During lamination	Al skinned paper	- 7.9	2.5
SL-27	Brunswick	Alzak	-	1-in. Al honeycomb	0.025 Al	During lamination	May be paper honeycomb	+11.7	2.3
SL-29	Brunswick	-	Mel	2-in. paper honeycomb	Mel	Vacuum held		+ 4.9	1.9
SL-30	Brunswick	Alzak	Mel	2-in. paper honeycomb	Mel	During lamination		-19.4	2.4
SL-32	Parabolite	Alzak	Micarta	2-in. fiberglass honeycomb	Micarta	After lamination	Low pressure	+ 5.8	2.0
SL-33	Parabolite	Alzak	Fiberglass	2-in. fiberglass honeycomb	Fiberglass	After lamination	Fiberglass-polyester skins	+17.3	2.5
SL-35	Parabolite	Alzak	Micarta	2-in. paper honeycomb	Micarta	After lamination		+31.8	2.0
SL-36	Parabolite	Alzak	Mel	2-in. paper honeycomb	Mel	After lamination		+24.1	1.9
SL-52 (Top)	Parabolite	Alzak	Fiberglass	2-in. fiberglass honeycomb	Fiberglass	After lamination	This is one 4 x 4 ft reflector	+ 5.1	1.6
SL-52 (Bottom)	Parabolite	Alzak	Fiberglass		Fiberglass	After lamination		+ 6.3	2.1
SL-53 (Top)	Parabolite	Alzak	Fiberglass	2-in. fiberglass honeycomb	Fiberglass	After lamination	This is one 4 x 4 ft reflector	+ 2.8	2.3
SL-53 (Bottom)	Parabolite	Alzak	Fiberglass		Fiberglass	After lamination		+ 2.8	2.7
SL-54 (Top)	Parabolite	Alzak	Fiberglass	2-in. fiberglass honeycomb	Fiberglass	After lamination	This is one 4 x 4 ft reflector	+ 7.9	2.1
SL-54 (Bottom)	Parabolite	Alzak	Fiberglass		Fiberglass	After lamination		+ 3.4	2.4
SL-55	Del Mfg.	Ag-glass	-	6-in. foam glass	-	During lamination	Back surface Ag-glass	+ 3.1	1.3
SL-56	Del Mfg.	Ag-glass	-	6-in. foam glass	-	During lamination	Back surface Ag-glass	+ 3.1	1.5
SL-57	Hexcel	FEK-163	0.014 Al	1.5-in. Al honeycomb	0.014 Al	After lamination	3/8 ox ACG honeycomb	+ 9.8	1.8
SL-58	Hexcel	FEK-163	0.014 Al	1.5-in. Al honeycomb	0.014 Al	After lamination	Double sheet adhesives	+11.4	1.3
SL-59	Hexcel	FEK-163	0.016 Al	1.5-in. Al honeycomb	0.016 Al	After lamination	Thicker skins and double adhesives	+ 2.1	1.0
SL-60	Hexcel	FEK-163	0.016 Al	1.5-in Al honeycomb	0.016 Al	After lamination	Thicker skins and double adhesives	+ 9.7	1.3
SL-63 (Top)	Parabolite	Alzak	Fiberglass	2-in. fiberglass honeycomb	Fiberglass	After lamination	This is one 4 x 4 ft reflector	+12.6	1.5
SL-63 (Bottom	Parabolite	Alzak	Fiberglas		Fiberglass	After lamination		+15.3	1.5

Notes:

a. Mold focal length and desired trough focal length is 762 mm (30 in.)

b. Slope error is measured only in the trough transverse direction. Longitudinal slope error is ignored. See text for explanation.

The "slope error" column lists a single number for each unit which is one standard deviation (σ) of the overall unit slope-error distribution. This slope error has been measured only in the trough's transverse direction. The reason for limiting the slope-error measurement to the transverse direction is that longitudinal slope errors have negligible effect on collector performance; longitudinal slope errors merely move the reflected energy longitudinally along the receiver tube. However, transverse slope errors result in deflection of reflected rays to one side of the receiver tube, thereby missing it and degrading collector performance. The standard deviation slope error is given in milliradians because slope error is defined as the angular difference between the actual reflector surface slope and the theoretical slope of the least-squares fit parabolic curve at the particular inspection point. The data base includes 9680 data points on a grid with intervals of 5.1 mm (0.2 in.) and 10.2 mm (0.4 in.) in the longitudinal and transverse directions, respectively.

The purposes of the laser inspection are:

- to determine the trough focal length and its variation
- to determine the overall accuracy of the slope contour plus detailed slope error data for a grid of inspection points.

These inspection data can be used in a wide variety of ways, including:

- evaluation of development units, as initially fabricated and after environmental tests
- aiding in design of receiver tube size and specification of tolerances on receiver tube locations through collector performance calculations
- checking molds and initial parts in setting up process and quality controls for a production run
- establishing acceptance criteria for production units.

The environmental test chamber, seen in Figure 9-1 behind and to the right of parabolic test sections, is used in a severe overtest of the sections in order to accelerate the aging process. Each temperature/humidity chamber cycle is 8 hours long and cycles between -29° and 54°C (-20° and 130°F), spending 2 hours at each extreme and 2 hours in transition from one extreme to the other. The chamber relative humidity is controlled between 50 and 85 percent. As the temperature goes below freezing, frost is formed on the test troughs.

This test cycle was devised as a means of accelerated aging of test items. The low temperature of -29°C was selected as typical of minimal which might be encountered during severe winter nights. (Albuquerque recorded -17°F a few years ago). The 54°C temperature was selected to accelerate aging without producing material phase changes. There is no direct relationship of this cycle with a specified number of months of actual outdoor environment. A crude comparison could be made by observing that one month in the chamber (90 cycles) is slightly more severe than 90 days of a very cold winter. Similarly the same 90 cycles to 54°C are perhaps equivalent to a very hot desert summer.

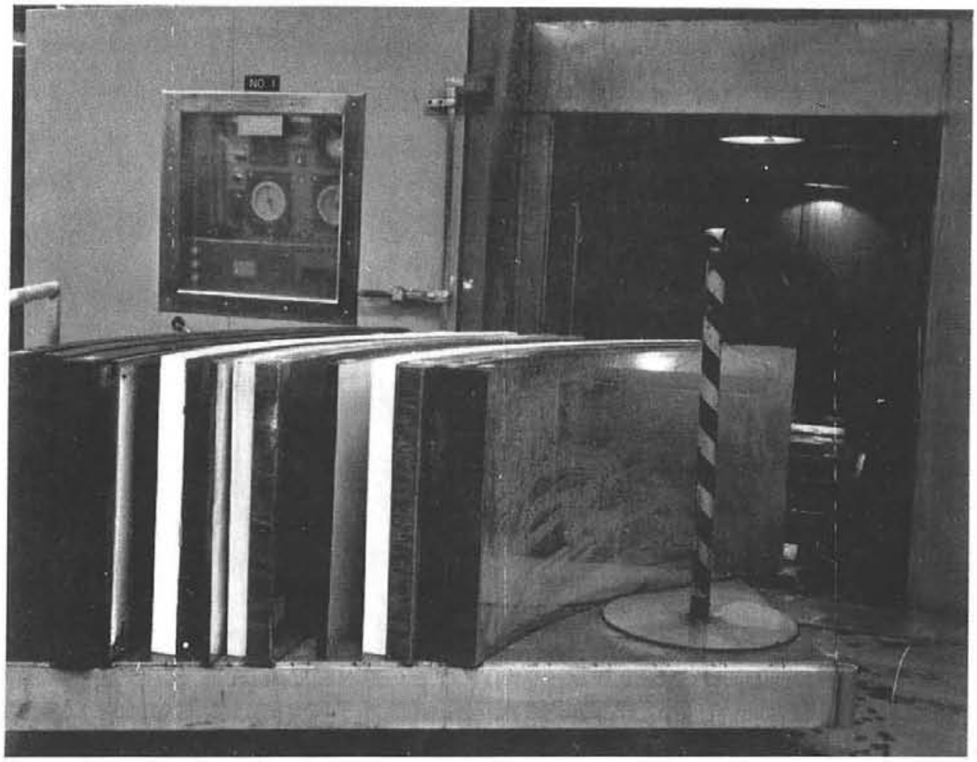


Figure 9-1. Parabolic Trough Sections and Environmental Test Chamber

9.2 Reflector Materials and Measurement Techniques

Specular solar reflectance measurement procedures and data analysis techniques have been considerably improved. Data have been obtained and analyzed for a variety of currently available solar reflectors supplied by G. T. Sheldahl, 3M Company, Alcoa, Kingston Industries, and Metal Fabrications, Inc.

A bidirectional reflectometer was constructed to measure the absolute specular reflectance of flat mirrors at discrete wavelengths from 400 to 900 nm. Reflectance data were obtained as a function of the reflected beam width from 1.0 to 16.9 mrad (0.057 to 0.97°). In cases where the reflectance was still significantly increasing at the maximum aperture of 16.9 mrad, the asymptotic value was determined from hemispherical reflectance values measured with a Beckman DK-2 spectroreflectometer. In addition, the hemispherical reflectance data, which covered the wavelength range 320 to 2500 nm, were used to normalize the spectral reflectance results to obtain solar averaged values. Both measurements were referenced to NBS aluminum and gold specular reflectance standards.

In analyzing the data, it was first assumed that the mirror would scatter the reflected beam according to a normal distribution of the form

$$R(\theta) \propto \exp\left[\frac{-\theta^2}{2\sigma^2}\right] \quad , \tag{1}$$

where θ is the deviation of the reflected beam from the specular direction and σ is the standard deviation of the distribution. There were two reasons for assuming a normal distribution: first, in describing surface roughness properties of materials, it is generally assumed that the average surface height distribution can be characterized by a normal distribution and, secondly, the energy distribution computer program describing the parabolic reflector system requires a standard deviation for the reflected beam in its calculations.

For some of the materials, Eq. (1) was adequate in describing the reflected beam profile. An example of the agreement is shown in Figure 9-2 for 3M Scotchcal 5400 laminated to 25 mil backing sheet. This material is described by the parameters R_s (solar reflectance) = 0.85 and σ = 1.9 mrad. R_s and σ values of additional materials are listed in Table 9-II.

However, for some of the other reflectors, the reflectance profile could not be described by a single normal distribution. In this case the measured profiles appeared to be composed of a sharp central peak together with a broad background. Therefore, it was assumed that the reflectance profile might be characterized by the sum of two normal distributions according to the equation:

$$R(\theta) \propto R_1 \exp\left[\frac{-\theta^2}{2\sigma_1^2}\right] + R_2 \exp\left[\frac{-\theta^2}{2\sigma_2^2}\right] \quad . \tag{2}$$

With this assumption, four parameters are necessary to describe the reflectance profile, (R_1, σ_1) and (R_2, σ_2), with the constraint that $R_s = R_1 + R_2$. An example of curve fitting to Eq. (2) is shown in Figure 9-3 for silvered Corning microsheet glass 0.11 mm (0.0045 in.) thick mounted on an optically flat plate. The parameters describing the reflected beam profile are R_1 = 0.78, σ = 1.1 mrad and R_2 = 0.18, σ_2 = 6.2 mrad. The values of these parameters for additional reflectors are listed in Table 9-II. All materials measured to date can be described by either a single distribution or the sum of two normal distributions.

It should be noted that, for all the materials mounted on the optically flat plate, a significant amount of scattering due to dust particles trapped between the plate and the reflector is present in the data. A mounting technique which removes this additional scattering is being developed so that the intrinsic properties of the reflector material can be determined.

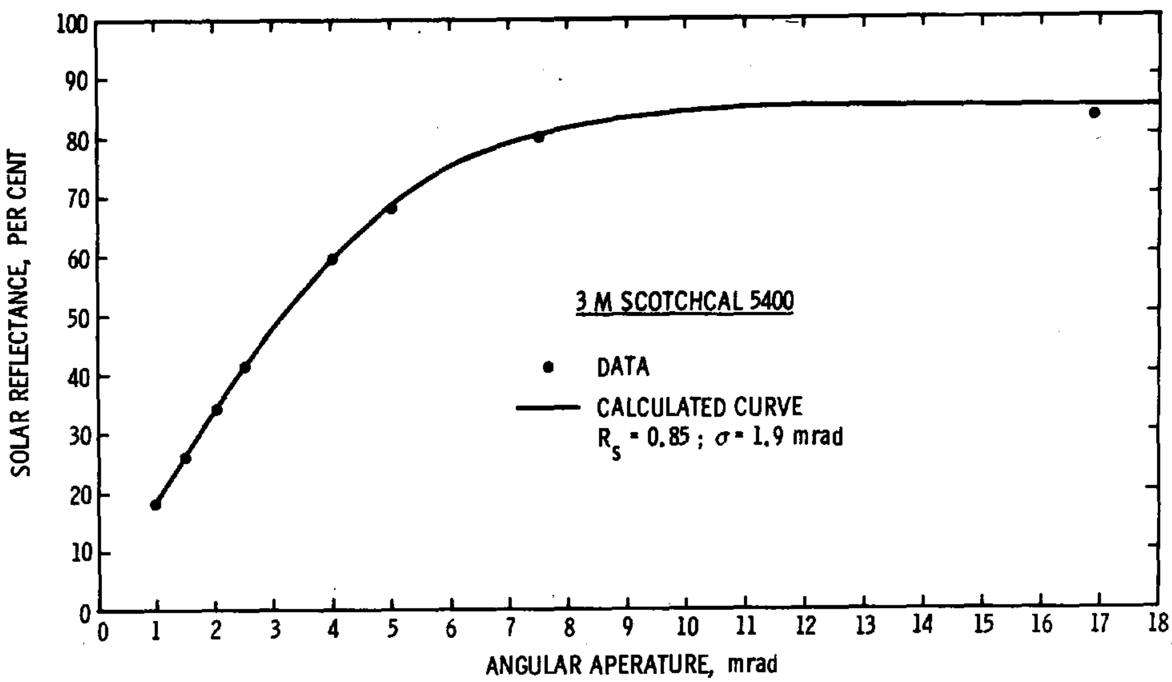


Figure 9-2. Solar Reflectance vs Angular Aperture (normal distribution)

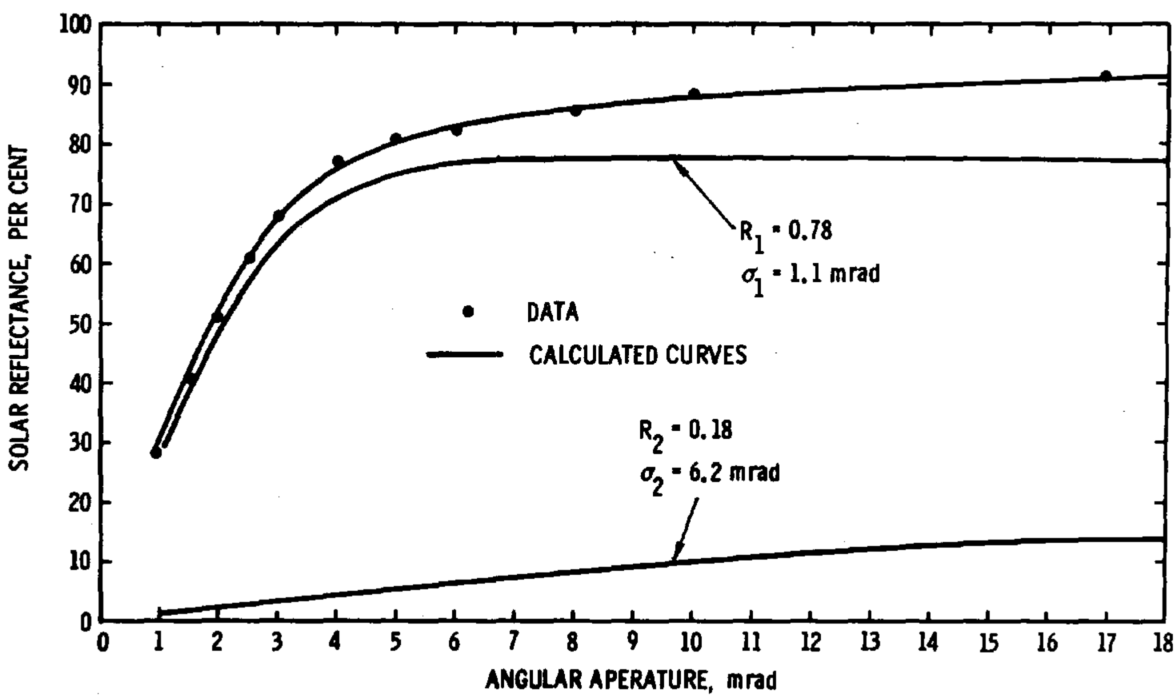


Figure 9-3. Solar Reflectance vs Angular Aperture (dual normal distribution) Silvered Corning Microsheet 0.11 mm (0.0045 in.) (mounted on vacuum plate)

TABLE 9-II

Specular Reflectance Properties of Various Mirror Materials

Material	Supplier	Wavelength (nm)	R_1	σ_1 (mrad)	R_2	σ_2 (mrad)
Alzak	Alcoa	670.	0.65	0.39	0.20	9.7
perpendicular to rolling marks		505.	0.54	0.42	0.31	10.1
		407.5	0.44	0.53	0.41	9.8
parallel to rolling marks	Alcoa	670.	0.68	0.24	0.17	7.7
		505.	0.60	0.29	0.25	7.1
		407.5	0.53	0.40	0.32	7.0
3M 5400 laminated to 0.64 mm (0.025 in.) Al sheet	3M	550.	0.85	1.9	-	-
3M 5400 special mounting on 0.64 mm (.025 in.) Al sheet	3M	690.	0.85	0.87	-	-
		550.	0.85	0.87	-	-
		410	0.85	0.89	-	-
Al-Teflon laminated to 0.64 mm (0.025 in.) Al sheet	Sheldahl	690.	0.87	1.2	-	-
		550.	0.87	1.2	-	-
		410.	0.87	1.3	-	-
Silver - 2 mil (0.05 mm) Teflon, mounted on optically flat plate	Sheldahl	550.	0.69	0.77	0.28	6.9
Silver - 5 mil (0.127 mm) Teflon, mounted on optically flat	Sheldahl	690.	0.77	0.26	0.20	4.7
		550.	0.75	0.26	0.22	7.0
		410.	0.62	0.33	0.35	8.2
Silvered Corning Microsheet 0.0045 in. (0.11 mm) mounted on optically flat plate	Sandia	550.	0.78	1.1	0.18	6.2
Double coat acrylic-Al-mylar on 0.64 mm (0.025 in.) Al sheet	Sheldahl	550.	0.49	0.89	0.37	12.7
Double coat acrylic silver on glass	Sheldahl	550.	0.93	0.21	-	-
High purity Al bright	Metal Fabrication, Waterbury, Conn.	550	0.38	1.2	0.46	9.6
Kinglux reflector sheet	Kingston Industries	498	0.62	0.37	0.23	16.1

The advantages of this method of analyzing the reflectance profiles include:

- The measured properties of reflector materials are not dependent upon characteristics of the measurement technique, a problem with all previously reported data.
- Scattering profiles down to 0.2 mrad in width can be determined although the incident beam is 1.0 mrad in width.
- The results are in the proper form for the energy distribution computer program being developed at Sandia.
- The results are in a form which can be easily compared to other beam-spreading errors, such as tracking errors or mirror-slope errors.

9.3 Wind Tunnel Tests

Perhaps the most important factor governing the structural design of parabolic troughs for solar collectors is the loading produced by wind. Trough designers must consider the forces and moments induced by winds and incorporate sufficient strength to survive high winds. Early in the design phase of the 2.7 x 3.7 m (9 x 12 ft) troughs, an inquiry was made of Sandia's aerodynamics group regarding expected wind loads on large parabolic structures. After a literature survey produced no specifically applicable data, estimates were made of drag and moment curves for worst-case wind loading. The worst case was defined as a 90 mph wind perpendicular to the trough (yaw = 0°) with the trough rotating through 180° (pitch = 0° to 180°).

The design of the troughs for Phase IV-A was completed using the estimated drag and moment curves plus appropriate safety factors. The aerodynamics group recommended that a series of wind tunnel tests be conducted with model troughs to provide typical lift, drag, and yaw forces plus moments about the three mutually perpendicular axes. The recommended tests included the complete range of yaw and pitch combinations.

During development of various methods of trough fabrication, it became increasingly apparent that specific, accurate wind-loading data would be required for optimization of trough structures. Optimization includes minimizing materials and labor costs in production of reflector troughs which will meet the environmental (wind) criteria.

Preliminary discussions were held in September and October 1975 regarding the scope of a proposed wind tunnel series and the parameters to be investigated. The outgrowth of these and subsequent discussions, plus informal liaison with LTV, was definition of a test series for 1/10 scale models of a 2 m (rim-to-rim) trough.

The purpose of the test series was to develop force, moment, and pressure data for parabolic troughs for virtually all combinations of pitch and yaw for winds which might impinge on trough collectors. The results of these tests should provide accurate data for use in design of three vital solar collector components: (1) the trough structure, (2) the driving mechanism, and (3) the support system including the pylon(s) and the foundations. It is expected that the test data will be published in the near future as a separate report which will be given wide distribution for use in other parabolic trough development programs.

Five test configurations were planned and fabricated, all of a 2 m trough with a 93.6° rim angle to 1/10 scale. Four were models of different lengths to investigate the effects of aspect ratio (length to width ratio); the lengths ranged from 0.24 to 1.95 m for aspect ratios of 1.25 to 10.0. The fifth configuration was a duplicate of the 0.73 m unit with front and backside pressure instrumentation. The purpose of this unit was to produce a grid of data of pressure differentials across the trough thickness so that the resultant forces might be determined for use in structural analysis. Force and moment data of the pressure unit (which was not aerodynamically clean due to the pressure tube installation) could be compared with the clean unit of the same length.

The model configurations were not exactly representative of real world collector trough installations in that each configuration was supported by a single strut; this arrangement was necessary to adapt to wind tunnel support structure and instrumentation for measuring resultant loads. However, the basic aerodynamic forces on a trough were established and these can be resolved analytically to apply to the support structures used in actual installations.

The wind tunnel tests were conducted at the Vought Corporation at Grand Prairie, Texas, during the week of March 8, 1976. The raw data have been resolved into wind axes and body axes forces and moments and into nondimensional coefficients for drag, lift, yaw, and appropriate rotational moments.

A Sandia report presenting the data is being prepared for unlimited distribution.

9.4 Requirements for Reflector Trough Continuity

In the design of the Phase IV-A east-west collectors which are now operational, the rotation axis was located at a point outside the trough, but near the vertex. The reason for selecting this axis was to allow the reflective surface of the trough to be continuous for its entire length. If the pivot point were within the trough, gaps between the individual trough units would be required to provide clearance for the supporting pylons. The continuous trough design provides continuous illumination on the receiver tube, with no end plates, pylons, or drive mechanisms projecting into the trough to cause shadowing. Also there are no gaps in the reflector to produce similar lengths of unilluminated receiver tube at regular intervals along the trough. Both shadowing and non-illumination decrease input energy to the receiver and allow increased thermal losses from it.

A brief computer analysis was conducted to investigate the effects of noncontinuous reflector surfaces on energy collection. The daily energy output was calculated for a 2 m wide trough array with 48 m^2 of aperture.

The results of the study indicated that a 0.15 m (6 in.) gap between individual reflector units of 3 m length will not decrease the trough's energy output by more than 1 to 2 percent. This study did not consider the effects of the additional losses which will occur as a result of shadowing of the reflector surfaces by the structural components which might project into the trough volume. A brief look at the projected area of the pylons, trunnions, etc., required to support a trough array indicates that this structure can be designed to keep such shadowing to a minimum; estimates are 1 to 2 percent. However, a major factor influencing the choice of trough mounting configuration now becomes the design of the driving mechanism and the troughs.

In previous designs, the driving torques have necessitated use of a large diameter (~1 m) chain disc or sprocket centered on the rotational trunnion. Moving the location of this type of mechanism to a point within the trough would effectively block a significant amount of the incoming energy beam, particularly at low sun angles in morning and evening hours. If the driving mechanism can be designed to eliminate such large-area devices, then trough-mounting configurations can be governed by economics or other considerations. If the driving mechanism design cannot be modified to eliminate the shadowing, then a rotational axis outside the trough and a continuous reflector trough may be necessary.

Mounting and rotation of an east-west trough about an axis which is outside the trough has some notable disadvantages; the most important is the offset center of gravity and the resultant high bearing pressures and high torque loads required to drive the trough at low angles of elevation. Counterbalancing can be used to limit these effects but that becomes expensive.

Future mounting configurations offer a major design challenge with many trade-offs. The goal is a simple configuration with minimal gaps in receiver tube illumination.

9.5 Laser Inspection Systems

The laser inspection system used for the 0.6 x 1.2 m parabolic test sections included two linear translation devices at right angles to achieve full (or nearly full) coverage of the trough. The small (45°) rim angle allowed a single linear detector to be placed at the focus to detect transverse slope errors. This inspection setup is shown in Figure 9-4, the laser mounted on the horizontal traverse and the trough section mounted on the vertical traverse. The size and rim angle limitations indicated the need for a more versatile inspection system.

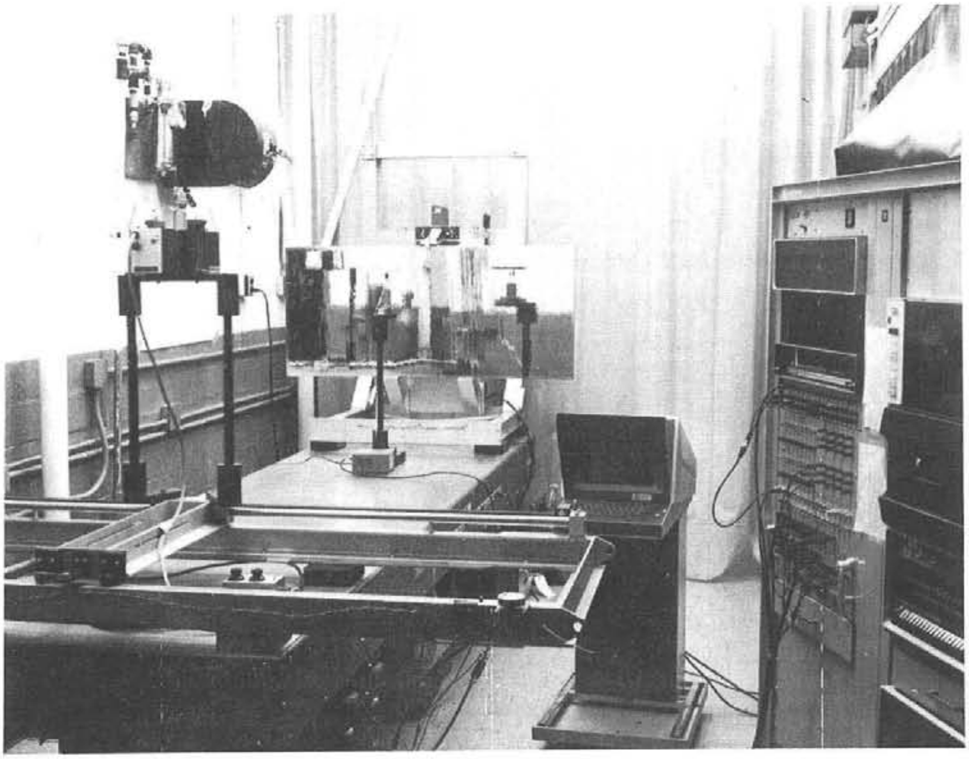


Figure 9-4. Laser Inspection Setup

A second generation laser system is now in final development with two important innovations:

- Rotation (instead of translation) of the laser beam will be used to scan across the trough from rim to rim.
- Rim angles up to ~100° and trough lengths of 3.7 m or smaller will be accommodated. The conceptual design of this system is shown in Figure 9-5.

This inspection system makes use of the similarity of contour of a parabolic cylinder and a right circular cylinder of a properly chosen size. As illustrated in Figure 9-6, a laser is mounted at the center of a circle with a radius of about 2.7 times the focal length of the parabola to be inspected. The center of the circle is placed in the focal plane of the parabola so that the vertex of the parabola and the circle coincide. The two curves lie very close together and have similar transverse slopes.

A laser beam emanating from the center of the circle would be reflected from a perfect cylinder back to the center of the circle. Errors in cylinder slope would produce a deflection of the reflected beam to one side or the other of the center of the circle where it could be detected by the photo detector mounted at right angles to the laser. Thus, a rim-to-rim scan could be accomplished by merely rotating the laser while recording the detector output. The parabolic trough can be inspected in the same fashion except that a computer must be used to calculate the difference between the theoretical slope of the parabola and that of the circular cylinder as a function of the rotation angle of the laser.

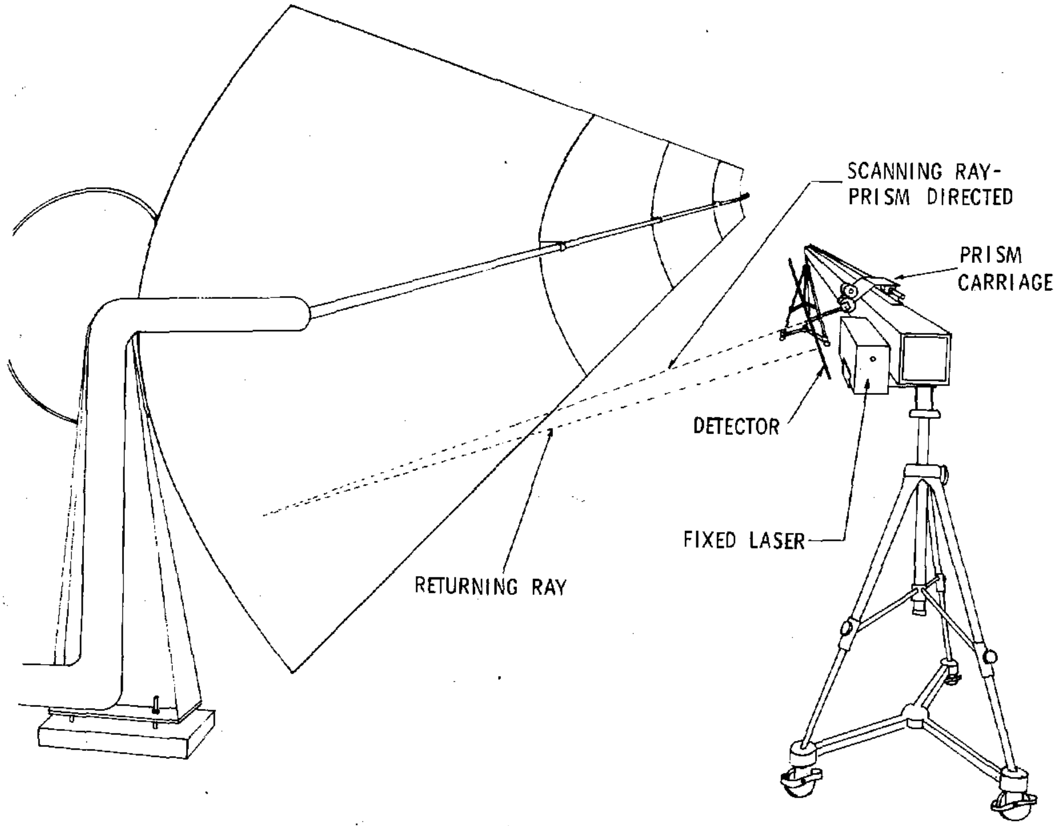


Figure 9-5. Large Radial Scan Laser Ray-trace

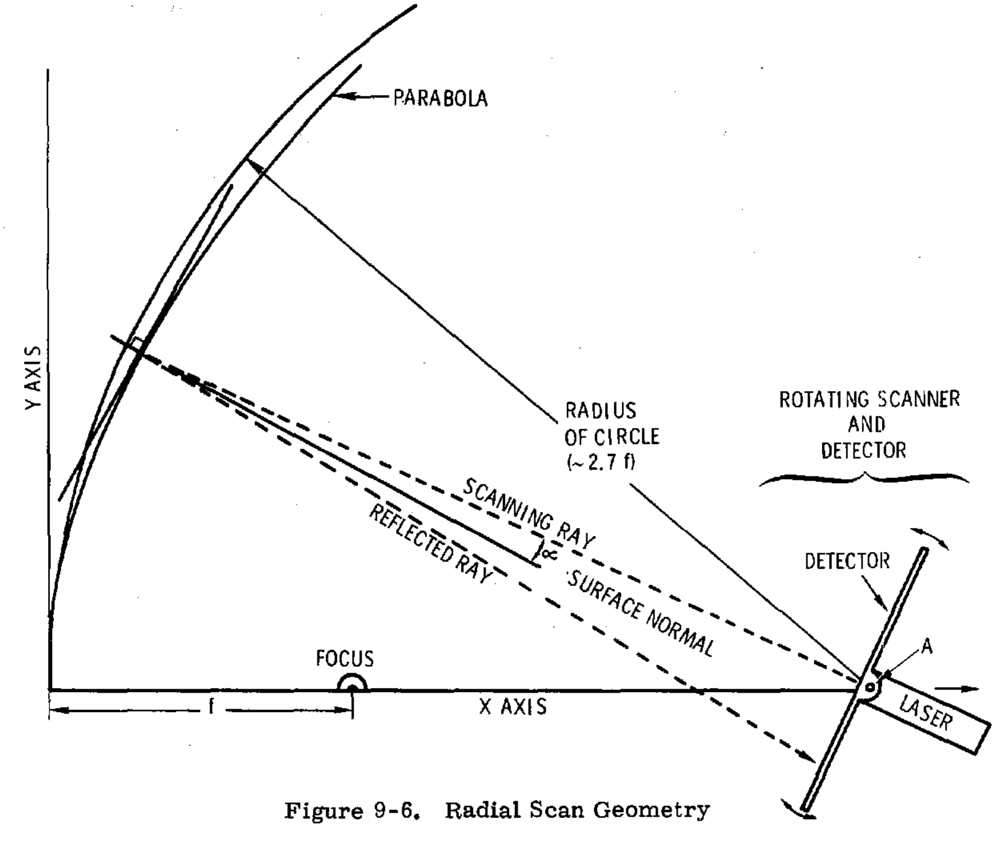


Figure 9-6. Radial Scan Geometry

The reflected ray position on the detector is compared with its expected arrival point and the slope error is determined point by point over the trough surface. The errors of the parabola can then be plotted in the same manner that the previous inspection system data was plotted.

The system still requires translation of the laser beam longitudinally along the trough to offset each sequential rim-to-rim scan by a predetermined interval. A further simplification of this requirement has been achieved by mounting the laser to "look" down the longitudinal translation axis and by use of a lightweight, rotatable mirror to reflect and "rotate" the laser beam through its rim-to-rim scan. The differences in geometry of the two laser inspection systems are accommodated by appropriate computer programming and data reduction.

This second generation radial scan laser inspection system offers several important advantages:

- The data can be taken with the receiver tube in place; it can also be taken in situ for large troughs without requiring disassembly if the unit can be rotated to place the laser assembly in the focal plane.
- The rotation-translation geometry is significantly simpler in set up than a translation-translation system, and therefore less costly.
- The system is adaptable to parabolic troughs of different equations by changing only software.

Procurement of components for the radial scan system suitable for the 2.7 x 3.7 m units in the field is nearly complete. It should be in operation during the next reporting period.

The application of the laser inspection technique to large heliostats for central receiver solar systems is also being investigated. This system cannot be used when the rim angle of the trough is greater than 100° because the parabolic curve and the circular arc diverge and the reflected beam misses the detector.

9.6 Storage Technology

Four storage concepts are being evaluated for use in Phase IV-B. These are mixed-rock/oil storage, phase change storage employing sodium hydroxide, oil thermocline, and multiple tank systems. The latter two were discussed in the last semiannual report.

Rock/Oil Storage -- Rock/oil storage is being developed as part of the central receiver program. Detailed design of this concept has been completed and a test facility is scheduled for operation in August. This facility operation will encompass most of the operation modes encountered in a solar total energy facility and thus should provide an evaluation of the potential of rock/oil storage for such applications. Detailed status of this project can be found in the Detail Design Review, Central Receiver Solar Thermal Power System, Phase I, March 1976, by McDonnell Douglas. Of particular interest in this project was the observation of good thermal stability of Caloria HT 43 at 315°C (600°F). This heat transfer fluid, available from Exxon Co., currently costs about 1/6 as much as Therminol 66.

Phase-Change Storage -- As discussed in the last semiannual report, the application of phase-change storage to our facility has been studied. A commercial unit known as Thermkeep® was investigated and judged incompatible with a total energy system. During this reporting period, the engineering staff at Comstock and Wescott* proposed a modified storage system employing pure NaOH as the phase change material. Thermal analysis of this redesigned storage system has indicated its compatibility with the Solar Total Energy Systems Test Facility. The cost projected for such a unit would be about $1.36/MJ while the cost of sensible heat storage in Therminol 66 is about $9.50/MJ. Engineering development would be required to adapt the commercial Thermkeep system to a solar total energy system.

9.7 Receiver Tube Technology

Receiver Tube Assembly Alignment -- The technique and equipment for characterization of parabolic surfaces is described elsewhere in this report. The technique permits the determination of the parabola focal line and the mirror slope errors. For continuous east-west axis collectors, the locus of focal points will not form a line although the axis of the receiver tube assemblies will be, of necessity, a single line. If the receiver mounting position and the focus of the reflector do not coincide, the amount of flux which strikes the receiver will not be optimum. Figure 9-7 illustrates the influence of off-focus mounting of a receiver tube assembly. If the receiver can be mounted within ±2.5 mm of the true focus, the loss of collector efficiency is minimal. Measurements of model reflectors described in this report suggest that individual mirrors may not have such closely controlled foci. In situ measurement of the reflectors in the first quadrant of the collector field remains to be done.

*Comstock and Wescott, Inc., Cambridge, Mass. 02138.

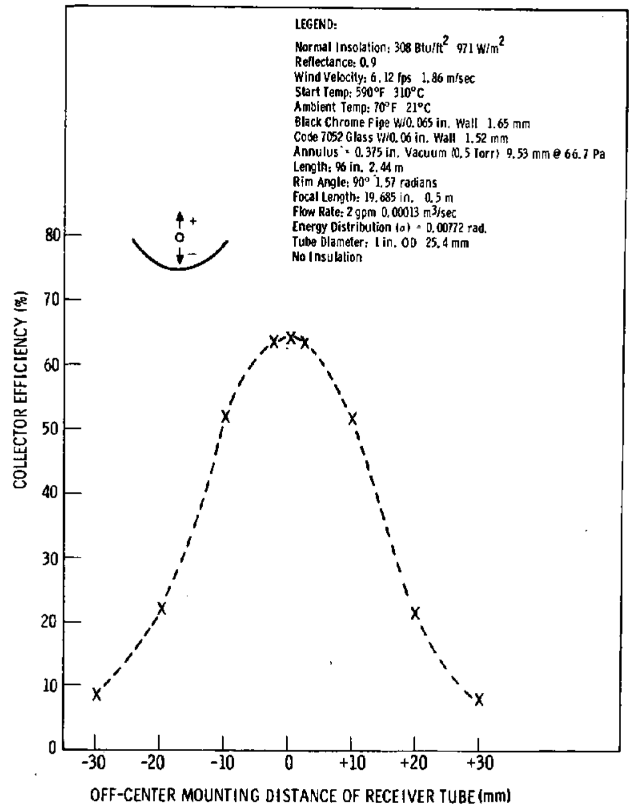


Figure 9-7. Influence of Off-Center Receiver Tube Mounting

Liquid Film Temperatures -- The use of organic liquids in concentrating collectors poses overheating problems which may ultimately require replacement of the liquid. The trade-offs between receiver size and optical dispersion were described briefly in the last semiannual report and, with a given optical dispersion and reflector aperture, an optimum receiver diameter can be selected. Once the collector field outlet temperature is established and the flow rate to obtain the temperature is determined, the flow rate to obtain the temperature rise through a collector can be tentatively calculated by assuming a symmetrical solar flux.

Since the flux is asymmetrically distributed around the receiver, the liquid film temperatures nearest the reflector might exceed the maximum allowable film temperature of the organic liquid, 375°C (705°F), although the bulk of the liquid would remain within allowable limits. Exposure of the liquid to temperatures greater than 340°C (645°F) decreases the "life" of the liquid. Its viscosity increases and specific heat decreases.

The introduction of a cylindrical pipe in the receiver to force annular liquid flow results in more effective heat transfer into the liquid and more uniform temperatures for a given flow rate. The influence of a 25 mm (1-in.) diameter plug in a 38 mm (1.5 in.) internal diameter receiver is illustrated in Figure 9-8. Under the conditions stipulated (solar noon), the minimum allowable flow is half of what it would be without a plug and the liquid pump controls can be adjusted to always deliver more than the minimum. If the liquid bulk temperature rise cannot be obtained, the liquid would be recycled through the blending tank.

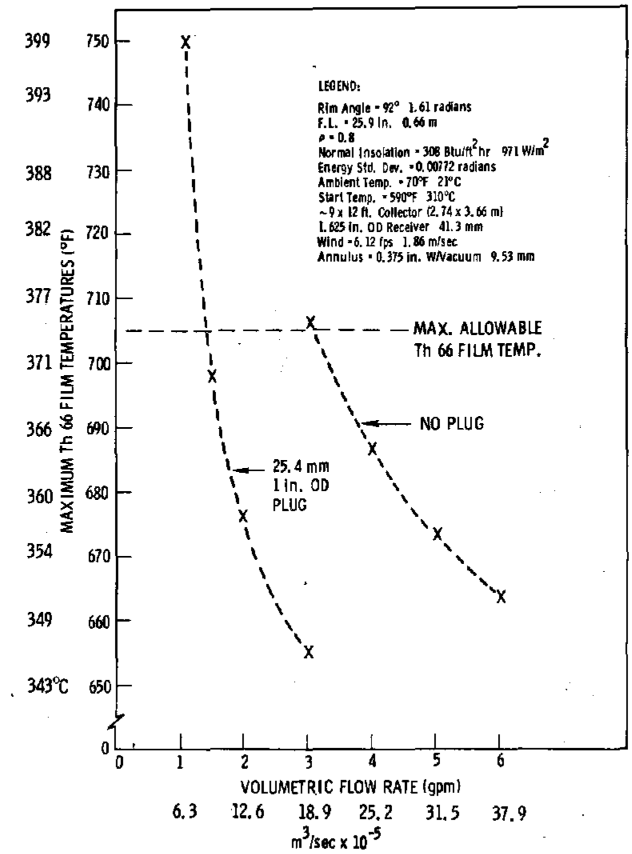


Figure 9-8. Influence of Plug on Predicted Maximum T-66 Film Temperatures (Phase IV-A Northwest Quadrant)

Conditions other than solar noon are similarly illustrated in Figure 9-9. The pump set-points can be modified to allow lesser flow at times other than solar noon without exceeding the allowable film temperature.

Optical Considerations -- The degradation of collector performance due to less than perfect optics is partially illustrated in Figure 9-10. The visible reflectance of the borosilicate glass and black-chrome absorber coating are closely approximated within the optics code used to model collector optical performance. The value in having a glass antireflection coating for east-west collector axis orientation can be construed from these data. If possible, antireflection coatings will be applied to replacement receiver tube assemblies.

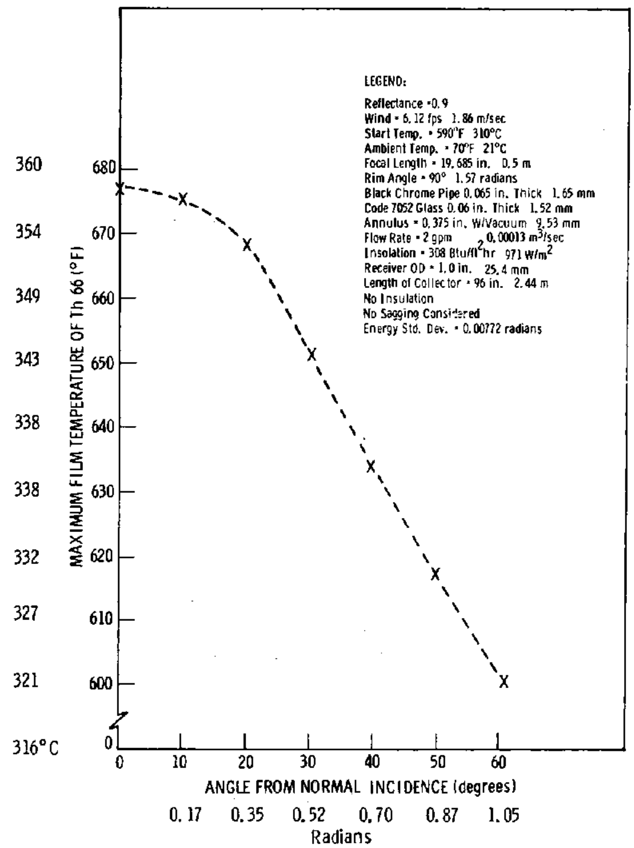


Figure 9-9. Predicted Maximum T-66 Film Temperatures

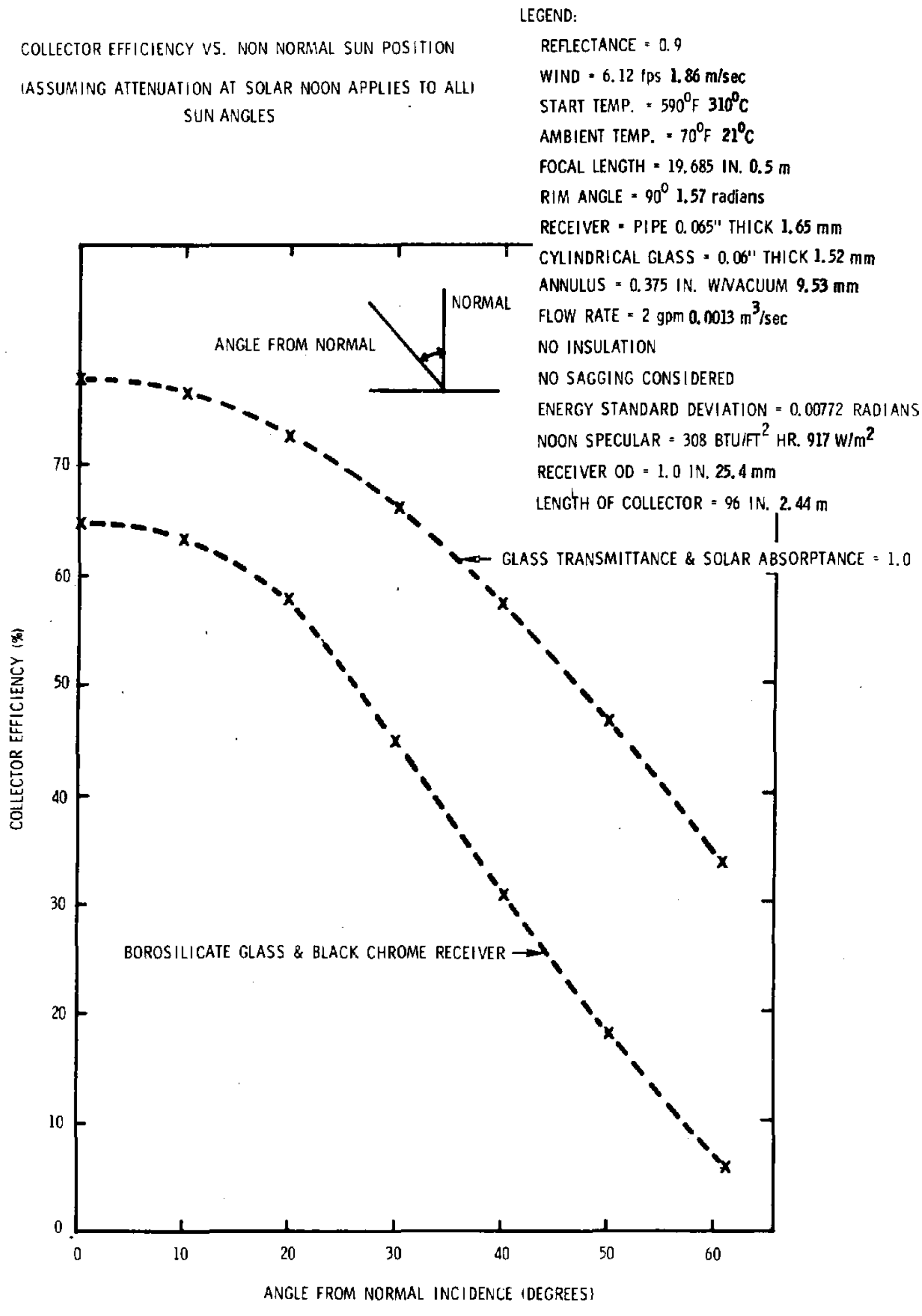


Figure 9-10. Collector Efficiency vs Nonnormal Sun Position (Assuming attenuation at solar noon applies to all sun angles)

Task 10. Coating Evaluation

Six black-chrome plated collector pipes, which were found to have low solar absorptance values, $\alpha < 0.95$, were returned to Bendix, Kansas City, for reworking. Sandia personnel, with portable Gier-Dunkle infrared and solar reflectometers, were at Bendix to determine if the pipes could be reworked by overplating the surfaces or if stripping off the black chrome and replating would be required.

Several pipes were overplated for various times (1 to 3 minutes) and current densities (165 to 260 A/ft^2). In all cases, the solar absorptance and emittance increased, but remained below the required value of $\alpha = 0.95$. As a check on the plating bath, several nickel-plated panels were black-chrome plated at a current density of 195 A/ft^2 for different times. Measured values were $\alpha = 0.925$ for both 3 and 4 minutes plating. Therefore, it was concluded that some change not reflected by chemical analysis had occurred in the plating bath between the time the last acceptable pipes were plated in early August and the six unacceptable ones were done in late September.

A fresh black-chrome bath was prepared and several test panels were plated to determine whether acceptable coatings could be obtained. The receiver tubes were stripped and replated; the solar selective properties of the six replated receiver tubes are listed in Table 10-I. The average solar absorptance was 0.95 ± 0.01 and the average emittance at 300°C was 0.21 ± 0.01.

TABLE 10-I

Solar Selective Properties of Replated Receiver Tubes

Pipe	α (m = o) Gier Dunkle	ϵ at 300°C Gier Dunkle Sapphire Filter
12-13	0.94	0.19
12-14	0.97	0.22
12-15	0.96	0.20
12-16	0.97	0.21
12-17	0.96	0.21
12-18	0.97	0.21

SECTION IV. APPENDIX

Program Technical Contributors*

Advanced Energy Project Department

G. E. Brandvold

Solar Projects Division

J. A. Leonard

- System Engineers
  - R. L. Champion
  - R. W. Harrigan
  - B. J. Petterson
  - S. Thunborg
  - L. E. Torkelson
  - G. W. Treadwell
- Technicians
  - T. J. Bauman
  - C. W. Matthews
  - G. L. McCoach

Program Support

- System Analysis
  - M. W. Edenburn
- Thermal Analysis
  - W. H. McCulloch
  - C. E. Hickox
- Data Processing
  - L. C. Bennett
  - W. W. Shurtleff
- Turbine Generator
  - J. P. Abbin
  - J. D. Cyrus
- Air Conditioning
  - A. V. Farnsworth
- Structural Analysis and Design
  - J. T. Finger
  - P. P. Stirbis
- Plant Engineer
  - C. K. Rudy
  - E. E. Rush
- Theoretical Analysis
  - F. Biggs
  - J. F. Banas
- Instrumentation and Control
  - A. F. Veneruso
- Materials Development
  - Reflector Structures
    - B. L. Butler
    - C. B. Frost
    - H. R. Sheppard
  - Reflector Materials
    - T. M. Meyer
    - G. D. Miller
    - R. B. Pettit
  - Receiver Materials
    - E. K. Beauchamp
    - D. M. Mattox
    - R. R. Sowell
- Testing and Evaluation
  - T. P. Conlon
  - D. W. Miller
  - L. G. Rainhart
  - D. W. Tipping
- Aerodynamics
  - J. A. Stark
  - R. E. Tate
- Electronics and Wiring
  - E. Rankin

*This list includes part-time contributors.

DISTRIBUTION:
TID-4500-R64, UC-62 (274)

American Gas Association
1515 Wilson Boulevard
Arlington, VA 22209
Attn: P. Susey

Argonne National Laboratory (2)
9700 South Cass Ave.
Argonne, IL 60439
Attn: M. L. Kyle
Office of the Director
Attn: S. Zwerdling
Director of Solar Energy Programs

Battele Memorial Institute
Pacific Northwest Laboratory
P. O. Box 999
Richland, WA 99352
Attn: K. Drumheller

Associated Universities, Inc.
Brookhaven National Laboratory
Upton, NY 11973
Attn: J. Blewett

Institute of Energy Conversion
University of Delaware
Newark, DE 19711
Attn: K. W. Boer

Edison Electric Institute
90 Park Avenue
New York, NY 10016
Attn: L. O. Elsaesser
Director of Research

Energy Research and Development (13)
Solar Energy Division
20 Massachusetts Ave.
Washington, DC 20545
Attn: H. Marvin
R. Blieden
G. Kaplan (10)
S. Gronich

Energy Research and Development Adm. (5)
Albuquerque Operations Office
Albuquerque, NM 87115
Attn: D. L. Krenz (3)
R. R. Malone, SAO
D. K. Nowlin

Envirodynamics, Inc.
3700 McKinney Ave.
Dallas, TX 75204
Attn: J. E. Guthrie

Environmental Factors and Public Utilities Div.
Department of Housing and Urban Development
Washington, DC 20410
Attn: A. R. Siegel, Director

University of Idaho
Moscow, ID 83843
Attn: H. Silha

Deputy to the Science Advisor
U. S. Department of Interior
Room 5204
Washington, DC 20204
Attn: M. Prochnik

Intertechnology Corporation
Box 340
Warrenton, VA 22186
Attn: G. C. Szego, President

Lone Star Gas Company
901 S. Harwood St.
Dallas, TX 75201
Attn: L. H. Sutherland

University of California
Lawrence Livermore Laboratory
P. O. Box 808
Livermore, CA 94550
Attn: W. C. Dickinson

Congressional Research Service
Library of Congress
Washington, DC 20540
Attn: H. Bullis
Science Policy Division

Midwest Research Institute
425 Volker Blvd.
Kansas City, MO 64110
Attn: J. O. Bradley

New Mexico State University
Las Cruces, NM 88001
Attn: R. L. San Martin

University of New Mexico
Department of Mechanical Engineering
Albuquerque, NM 87113
Attn: W. A. Cross
For: M. W. Wilden

Northern Natural Gas Co.
2223 Dodge St.
Omaha, NB 68102
Attn: J. M. De La Castro

DISTRIBUTION (Cont.):

Oak Ridge National Laboratory (2)
P. O. Box Y
Oak Ridge, TN 37830
Attn: J. Johnson
R. Pearlstein

Office of Science and Technology
Executive Office of the President
Washington, DC 20506
Attn: R. Balzhizer

Office of Technology Assessment
Old Immigration Building, Rm 722
119 D. Street, NE
Washington, DC 20002
Attn: R. Larsen

Jet Propulsion Laboratory
Bldg 277 Rm 201
4800 Oak Grove Dr.
Pasadena, CA 91103
Attn: V. C. Truscello

Omaha Public Power District
1623 Harney
Omaha, NB 68102
Attn: A. R. Spangler

The Pentagon
Room 3E114, Mail Stop 103
Washington, DC 20540
Attn: G. Dorough
Deputy Director for Research and Advanced Technology

Raytheon, Inc.
Missile System Division
Spencer Laboratories
Wayside Avenue
Burlington, MA 01803
Attn: L. Paradis

Southern California Gas Co.
P. O. Box 3249
Terminal Annex
Los Angeles, CA 90051
Attn: S. Cunningham

Southern Union Gas Company
Fidelity Union Tower Building
Room 1537
1507 Pacific Avenue
Dallas, TX 75201
Attn: J. O. Carnes

Southern Union Gas Company
723 Silver SW
Albuquerque, NM 87103
Attn: B. D. Daugherty

Sundstrand Electric Power
4747 Harrison Avenue
Rockford, IL 61101
Attn: A. W. Adam

Carroll V. Kroeger, Sr.
Director, Tennessee Energy Office
Suite 250
Capitol Hill Bldg.
Nashville, TN 37219

Watt Engineering Ltd
RR 1, Box 183 1/2
Cedaredge, CO 81413
Attn: A. D. Watt

Texas Electric Service Co.
P. O. Box 970
Fort Worth, TX 76101
Attn: J. A. Harris
Marketing Services Manager

Commanding General
White Sands Missile Range, NM 88002
Attn: STEWS-TE-NT
M. Squires

1100 C. D. Broyles
Attn: J. D. Kennedy, 1110
G. E. Hansche, 1120
1280 T. B. Lane
1283 H. C. Hardee
1284 R. T. Othmer
1300 D. B. Shuster
1330 R. C. Maydew
1400 A. Y. Pope
2300 L. D. Smith
2320 K. L. Gillespie
Attn: L. W. Schultz, 2324
2541 G. W. Gobeli
3622 T. P. Conlon, Jr.
3700 L. S. Conterno
3720 L. E. Fuller (3)
Attn: E. G. Dylo, 3721
5000 A. Narath
Attn: J. K. Galt, 5100
5110 F. L. Vook
5130 G. A. Samara
5150 J. E. Schirber
5200 E. H. Beckner
5231 J. H. Renken
5420 J. V. Walker
5700 J. H. Scott
5710 G. E. Brandvold
5711 R. P. Stromberg
5712 J. A. Leonard (100)
5715 R. H. Braasch
5719 D. G. Schueler
5730 H. M. Stoller

DISTRIBUTION (Cont):

5735	M. M. Newsom
5740	V. L. Dugan
5800	R. S. Claassen
	Attn: R. L. Schwoebel, 5820
5830	M. J. Davis
	Attn: D. M. Mattox, 5834
5840	D. M. Schuster
	Attn: R. C. Heckman, 5842
	F. P. Gerstle, 5844
	E. K. Beauchamp, 5846
8100	L. Gutierrez
8180	C. S. Selvage
	Attn: A. C. Skinrood, 8184
9300	L. A. Hopkins, Jr.
9330	A. J. Clark, Jr.
	Attn: J. V. Otts, 9336
9340	W. E. Caldes
	Attn: J. L. Mortley, 9344
9400	H. E. Lenander
9410	R. L. Brin
	Attn: R. K. Petersen, 9412
9515	J. T. Hillman
9700	R. E. Hopper
	Attn: H. H. Pastorius, 9740
	R. W. Hunnicutt, 9750
6011	G. C. Newlin
8266	E. A. Aas (2)
3141	C. A. Pepmueller (Actg) (5)
3151	W. L. Garner (3)
	For ERDA/TIC (Unlimited Release)

Org.	Bldg.	Name	Rec'd by*	Org.	Bldg.	Name	Rec'd by*
3141-1/804/100							

*Recipient must initial on classified documents.