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Line-Focus Solar Thermal Energy Technology Development FY79 Annual Report for Department 4720

MASTER

K.D. Bergeron, R.L. Champion, and R.W. Hunke, editors

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LINE-FOCUS SOLAR THERMAL ENERGY TECHNOLOGY DEVELOPMENT
FY 79 ANNUAL REPORT FOR DEPARTMENT 4720

Edited by

Kenneth D. Bergeron, 4723

Roscoe L. Champion, 4722

Robert W. Hunke, 4725

Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

The primary role of the Solar Energy Projects Department II (4720) is the development, evaluation, and testing of line-focus solar thermal technology. This report of FY79 progress and accomplishments is divided into two parts: (1) Component and Subsystem Development including the design and analysis of collector modules, their components, and associated materials and processes, and (2) Systems and Applications Development, involving larger configurations of solar thermal line-focus systems. The emphasis is on parabolic troughs, but significant efforts on hemispherical bowls, compound parabolic collectors, and dishes for the Solar Total Energy Project are also described.

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SECTION 1: INTRODUCTION

The principal responsibility of the Solar Energy Projects Department II (4720) is the development of line focus solar thermal energy technology. A broad range of activities are associated with this responsibility, but a natural division is to define two general categories:

- (1) Component and Subsystem Development
- (2) Systems and Applications Development

The focus of attention in the first category is the design, development, and testing of materials, structures and devices for parabolic trough collectors ranging from trackers and flexible hoses up to the Engineering Prototype Trough (EPT) collector module. The second category involves the design and performance analysis of complete solar energy systems, consisting of line focus collectors, plumbing, controls, storage, etc. Also included in the second category is system analysis in the larger sense involving studies of the economics and policy issues associated with solar as an alternative energy source.

This report of FY 79 activities is divided into two parts corresponding to these categories. Since the distinction between subsystem and system is not always clear-cut, the assignment of an activity to one category or the other is in some cases arbitrary. However, this was the exception rather than the rule, and a two-part report is a natural vehicle for a description of the department's activities.

The emphasis in this report is on accomplishments during FY 79. However, brief surveys of activities planned for FY 80 are also included in order to provide a better perspective and a sense of the direction in which the program is moving.

Section 2 of this report lists in summary form the significant accomplishments of the year as FY 79 highlights. Sections 3 and 4 constitute the main body of the report, describing past and planned activities for Components and Subsystems Development, and for Systems and Applications Development, respectively. Finally, Appendix A lists publications for the Department as a whole.

SECTION 2: FY 79 HIGHLIGHTS

2.1 COMPONENT AND SUBSYSTEM DEVELOPMENT HIGHLIGHTS

- o Engineering Prototype Trough fabricated and tested to demonstrate improved performance potential of 60% efficiency at 600°F.
- o Large (2m x 6m) steel skinned/aluminum cored honeycomb trough structures demonstrated.
- o Sagged glass and chemically strengthened glass demonstrated in trough structures.
- o Aperture based (hot wire/microprocessor) tracker demonstrated.
- o Sealed/unevacuated receiver demonstrated.
- o Development initiated for sagged glass fabricated with automotive windshield type production tooling.
- o Layouts of troughs utilizing mass-production technologies initiated.
- o Design study initiated for trough field piping layout.
- o Trough foundation design study and testing completed.
- o Development initiated for trough structures of sheet metal and sheet molding compound fabricated with pseudo-production tooling.
- o Optical Measurements Workshop sponsored to develop sources for testing labs.
- o Environmental evaluation of candidate structural materials completed.
- o Thermocline storage subsystem designed and fabricated for engineering evaluation.

- o Improved cogeneration steam turbine assembled for Shenandoah project.
- o SOLTES code documented and distributed.

2.2 SYSTEMS AND APPLICATIONS DEVELOPMENT HIGHLIGHTS

- o Drafts of Fixed Mirror Distributed Focus (FMDF) Technology Development Plan and Industrial Process Heat (IPH) Modular System Project Plan prepared and reviewed.
- o Five site surveys of operating IPH field experiment conducted.
- o Technical reviews conducted through detailed design of seven more IPH field experiments.
- o Planning of the new Modular Solar Thermal Dish Systems Project initiated.
- o Contract placed with McDonnell Douglas (MDAC) for deployment and monitoring of five materials exposure stations.
- o Systems/economics study of Solar Enhanced Oil Recovery completed.
- o Systems studies completed on effects of operating temperature and reflector cleaning.
- o STES optimization code developed and study of relative benefits of STES for a mixed load community completed.
- o MDAC's study of the potential solar IPH market continued.
- o Monte Carlo analysis capability for solar economics developed.
- o "Wireless" data transmission system devised for controlling solar collector fields.
- o Wind tunnel tests of trough collectors conducted at Colorado State University.
- o Technical direction provided for Shenandoah STES project.
- o Design completed and construction begun of Analog Design Verification System (ADVS) at Crosbyton, Texas.

- o Installation of Coolidge irrigation project completed and operation initiated.
- o Willard Irrigation project operated for 1336 hours, including new Solar Kinetics collectors.
- o Numerous tests of collector systems completed at the Midtemperature Solar System Test Facility (MSSTF).

SECTION 3: MIDTEMPERATURE COMPONENT AND SUBSYSTEM DEVELOPMENT

3.1 INTRODUCTION

This section describes the FY79 activities within the Midtemperature Component and Subsystem Development Project of the Department of Energy (DOE) Solar Thermal Power Systems Program.

The overall scope of the project is the development of components and subsystems to support solar systems utilizing midtemperature line-focus solar collection/conversion technologies. The overall objectives of the project are (1) to bring the appropriate technologies to a state of development such that commercialization activities can proceed and (2) to demonstrate with high confidence the performance, durability, and Operation and Maintenance (O & M) characteristics of the components and subsystems which exhibit superior commercialization potential.

Specific elements of the project described herein are the following:

- o Line-Focus Collector/Subsystem Development
- o Materials and Process Development
- o Testing and Evaluation
- o Storage Subsystem Development
- o Power Conversion Subsystem Development
- o Engineering Analysis

3.2 LINE-FOCUS COLLECTOR/SUBSYSTEM DEVELOPMENT

Overview

Line focus collectors have not yet been developed to their full potential in performance, life or cost. The engineering development status of existing technology can be summarized by three major points:

- o Thermal efficiency is not yet at the goal of 60 - 70% peak noontime efficiency at 600°F.
- o Durability is low in relation to lifetime requirements of 10 - 20 years set by economics.
- o Existing technology does not lend itself to low-labor mass-production materials and processes which are required to meet cost goals.

To insure that line-focus collectors have been adequately developed prior to commercialization efforts, the Collector Development Project was initiated in FY78. Overall objectives are to (1) establish, in conjunction with industry, a realistic high-performance, long-life collector as a target for the line-focus collector industry; (2) allow industry to gain insights into mass-production problems; (3) establish reliable estimates of cost and performance of collectors; and finally (4) promote sources for mass-production of components/collectors and design/installation of collector subsystems.

The project consists of four major elements:

1. In-house design of an engineering prototype collector to investigate promising design configurations and to demonstrate the feasibility of 60% peak efficiency at 316°C (600°F). This engineering prototype collector design is based on immediately available technologies and fabrication techniques.

2. Design and demonstration of three parabolic trough collectors to investigate various manufacturing technologies with mass-production potential. These collectors will utilize technologies which require development by industry during the project.

3. Design of a large modular collector field subsystem in order to integrate the design requirements of the collectors and the field. This effort will address such problems as control, piping layout, electrical layout, basic instrumentation, and installation.

4. Continuing technology transfer to industry in order to contribute to the advancement of the state-of-the-art and to promote commercialization of components.

Collector design requirements are presented in Table I. Furthermore, in order to achieve the design efficiency goal of 60%, the error budget presented in Table II with $\theta = 7$ milliradians was established for the Engineering Prototype Trough collector.

Succeeding sections provide summaries of efforts in the following areas:

- o Engineering Prototype Trough (EPT)
- o Structures Development
- o Thermal Analysis
- o Receiver Development
- o Flexible Hose Development
- o Wind Loads Definition
- o Tracker Development
- o Drive Development
- o Foundation and Pylon Development
- o Collector Subsystem Design.

TABLE I. Collector Design Requirements

- o Parabolic trough collector capable of E/W or N/S operation
- o 60% peak noontime thermal efficiency at 316°C (600°F)
- o 2 m aperture width
- o 92° rim angle
- o Glass reflector
- o Structures based on sheet metal, sheet molding compound (SMC) and sandwich technologies
- o Inverted stow position
- o Sealed/unevacuated receiver
- o Black chrome selective coating
- o Computer/aperture based tracker
- o Emergency stow capability; two independent safeties for both rotational and thermal functions
- o Survive 3/4 inch diameter hail
- o Tracking capability to 25 mph wind speed
- o Survive 80 mph wind speed (referenced at 30 feet height)
- o \$10/ft² - \$20/ft² production FOB cost (1978 dollars)

TABLE II. Error Budget for the EPT Collector

<u>TYPE & SOURCE</u>	<u>EFFECTIVE MAGNITUDE</u>	<u>σ^2</u>
	1σ	
Beam Misdirection		
Structure		
Slope	2.5 mr x 2 = 5 mrad	25
Sage and Thermal	2 mrad	
Tracking		
Sensor	2 mrad	4
Drive Nonuniformity	2 mrad	4
Receiver		
Align, etc.	2 mrad	<u>4</u>
2 mm @r = 1 m		$\Sigma \sigma_1^2 = 41$
		$\sigma^1 = 6.4 \text{ mrad}$
Beam Spreading		
Mirror	.25 mrad	.06
Sun (Not Actually Normal)	2.8 mrad	<u>7.84</u>
		$\Sigma \sigma_2^2 = 7.90$
		$\sigma^2 = 2.8 \text{ mrad}$

$$\sigma_{\text{rms}} = \sqrt{\sigma_1^2 + \sigma_2^2} = 7.0 \text{ mrad TOTAL ERROR BUDGET}$$

Engineering Prototype Trough (EPT) Collector

Figure 1 shows the Mod 1 configuration of the Engineering Prototype Trough Collector. This configuration of the EPT utilized a 32 mm (1-1/4 inch) diameter receiver tube. The EPT is fabricated from steel skin/aluminum core honeycomb with dimensions of 2 m x 6 m; chemically strengthened glass is bonded to the trough surface. Steel was used as the face material in order to provide thermal expansion compatibility with the glass and to reduce the utilization of energy-intensive materials. The major development problem formulated from fabrication of the EPT was the bonding of glass to the support structure with techniques suitable to mass-production.

FIGURE 1. Engineering Prototype Trough Collector (Mod 1)

Performance testing has been completed for the Mod 1 configuration. Measured efficiency ranged between 58% at 316°C (600°F) output temperature and 69% at 120° (248°F) as shown in Figure 2.

FIGURE 2. Peak Thermal Efficiency of the EPT (Mod 1)

Efficiency increased to 60% and 72%, respectively, when 10 cm at each edge of the trough was masked. A typical laser ray trace shows slope errors of 5.2 mrad for the whole trough, and slope errors of 2.3 mrad when the area in the receiver shadow and 10 cm at the outside edges are masked. The high slope errors in the masked areas are due to the techniques used in fabricating the honeycomb structure and in assembling the reflector. The error budget allocation was 2.5 mrad. Figure 3 shows a measured all day performance curve for an east-west row. Table III accounts for the differences between measured efficiencies and theoretical design efficiencies.

FIGURE SANDIA PARABOLIC TROUGH-1 EFFICIENCY EVALUATION AT 301.3 °C INPUT

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FIGURE 3. All Day Performance of the EPT (Mod 1)

Observation of the receiver tube as in Figure 4 shows a series of stripes of varying light intensity along the length of the

FIGURE 4. Flux Distribution On The Receiver Of The EPT (Mod 1)

receiver tube. Histograms of receiver intercept positions of reflected rays predicted by the laser ray trace data for the EPT collector indicate that the stripes originate on the reflector; however, it is not yet understood whether the effect is due to an optical or mechanical property of the reflector.

Examination of the reflected light of all of the parabolic reflector structures fabricated over the past several years indicates that all have exhibited this focusing stripe phenomenon to varying degrees. Reflector hardware simply does not conform to a perfect parabola; it oscillates between tolerance zones thus producing the light striations. The effects of the focusing

TABLE III

Measured and Theoretical Components
of Efficiency for the EPT (Mod 1) Collector

Measured Thermal Efficiencies

58% @ 600°F
69% @ 248°F
72% @ 100°F (Est)

Optical Efficiencies

Actual (Thermal Eff + Thermal Losses)	71.5%
Slope Error Losses (5.2 mrad Instead of 2.5 mrad)	3%
Receiver Fittings & Support Losses	2%
Receiver Tube Radial Temp Losses	1%
Glass Area Less Than Aperture Area	1%
Unknown	1%
<hr/>	
Total	80.5%
Theoretical Design Limit Optical Eff	80.6%

effect are being analyzed. This effect may be of more concern, however, in the design of line-focus photovoltaic collectors where a high degree of uniformity of illumination is required.

Tracking using flux sensing along the length of the receiver tube was successful to correct small tracking biases from the computer based tracker. During testing, it was determined that the helically wrapped sensing wire used to sense the concentrated solar flux responds to the flux in a somewhat different manner than does the receiver tube. Initial expectations were that the wire would respond with a simple peaked output centered at the maximum efficiency point; this was not the case. Due to geometric effects, the wire responds in a two-peaked output as shown in Figure 5 along with a measured plot of efficiency as a function of changes in tracking angle. Note that the maximum collector efficiency occurs where the wire output is a minimum between the two peaks.

FIGURE 5. Correlation of Thermal Efficiency and the Response to the Helically Wrapped Wire on the EPT Receiver

The EPT collector was converted to the Mod 2 configuration by replacing the 32 mm receiver tube with a 25 mm diameter receiver tube. Testing will begin early in FY80.

Structures Development

Structural Analyses

Structural analysis and design evaluation has continued on the collector structures development projects described in immediately following sections of this report. Analytical methods have been developed, or are being developed, for the determination of the transverse and longitudinal structural behavior of the several types of parabolic collector panels. The response of these structures to wind, gravity and thermal excitation is being determined and their stiffnesses, dimensional stabilities and strengths are being characterized. Finite element methods are also being applied for analysis of the parabolic collector layouts in their advanced stages of design in order to evaluate stress non-uniformities, local effects and precise load applications.

Sheet Metal Reflector Structure

As the result of a structural materials evaluation program conducted in FY78, sheet steel structures have been identified as candidates for the development of high performance, long life, low cost concentrating solar collectors. On the basis of preliminary screening, a sheet steel monocoque structure was selected for evaluation because of its high structural stiffness to weight ratio. However, a cost estimate for a prototype sheet steel monocoque structure conducted for Sandia by Glitsch Inc. resulted in an estimated cost (for the sheet steel structure only) of approximately $\$76/\text{m}^2$ ($\$5.40/\text{kg}$) for production in quantities of 10^5 m^2 per year or more. This estimate is a

factor of two to three times higher than cost estimates for typical sheet metal items produced in large quantities by automated sheet forming operations such as stamping. The major reasons for this cost premium are the high accuracy required of the completed structure and the labor (or machine operation) intensive assembly required for the monocoque design.

As a consequence of this apparent cost barrier for the monocoque design, alternate sheet steel designs based on automated forming technologies as used in the appliance and automotive industries were investigated. A sheet steel ribbed structure module shown in Figure 6 was selected for further development; the 2 x 1 m size and general configuration of the panel is based on current capabilities of the steel stamping

FIGURE 6. Sheet Metal Structure Concept

industry. The panel design shown in Figure 7 is of two-piece construction; a stamped sheet steel frame panel provides the basic parabolic contour and required structural rigidity, while a flat sheet steel mirror panel completes the closed rib structure and provides a smooth, simply contoured surface for the mounting of the reflective surface. Contour accuracy is provided

FIGURE 7. Sheet Metal Structure Design

by a fixture used to assemble the two-piece module. Assembly will be achieved either by bonding with a structural adhesive or by spot welding. The panel size limitation imposed by stamping capability requires that a collector trough be made up of several individual panels mounted on a spine or torque tube which provides torsional rigidity. Preliminary production cost estimates for this structure are \$30 - \$40/m² for production in quantities of 10⁵ m² per year or more.

The reflective surface to be used on these sheet steel structures may be any one of the mirrored glass or polymer film options which are under development. These reflective surfaces will be bonded to the steel structures; the type of adhesive to be used will depend on the particular structural and contour tolerance requirements of the given reflective surface. The plastic films and the chemically strengthened glass are particularly promising candidates for use as reflective surfaces because they have the potential of being applied to the face of the sheet steel mirror panel while still in the flat. This mirror panel laminate may then be used in the assembly of the two-piece reflector structure module in place of the bare mirror panel. Such a process would produce a completed reflector structure module which is especially attractive from a manufacturing point of view.

A contract has been placed with the Budd Company to develop prototype modules made up from sheet metal panels produced with quasi-production tooling and assembled on quasi-production fixtures. The overall objective of this contract is to provide information and prototype modules which can establish the technical feasibility of producing highly accurate structures

using mass production sheet steel forming technology and to determine the potential cost of such structures. A matrix of prototype modules made up using the various reflective surface options under separate development will be produced for evaluation. First parts are expected in mid-FY80.

Sheet Molding Compound (SMC) Reflector Structure

The design of a 1 x 1 m parabolic trough panel of sheet molding compound (SMC) with an integrally molded glass mirror has been completed, including analysis of stress and bi-material effects. Fabrication of the complete structure with the glass molded in place is felt to be mandatory if the SMC concept is to compete economically with alternative concepts. The panel shown

FIGURE 8. SMC Structure Concept

FIGURE 9. SMC Structure Design

in Figure 8 and 9 is a 1 x 1 m panel which extends from vertex to rim; two panels are fastened together along the vertex to form a full rim to rim trough section. Six of these 1 x 2 m trough assemblies will be mounted on a torque tube to form a 2 x 6 m reflector trough.

The SMC panel has been designed to accept either sagged glass panels or flat, chemically strengthened glass panels which are elastically deformed to the trough contour. Flat glass mirrors (12 x 12") have been shown to survive the molding pressures of 800 psi and temperatures of 300°F; chemically strengthened glass in 2 x 4 ft. sizes have survived molding into parabolic trough sections with a 30" focal length.

The primary problem with the SMC concept is that of thermal expansion mismatch between the SMC ($\sim 10 \times 10^{-6}/^{\circ}\text{F}$) and the glass ($5 \times 10^{-6}/^{\circ}\text{F}$). This mismatch causes the panel to open up as it cools from molding temperature of 300°F. Significant stresses are developed and the panel's focal length increases. Thermal and structural analyses indicate that the tooling can be designed to accommodate the effects of the mismatch; the consistency of the response of various panels remains to be seen.

In searching for potential sources for the SMC development effort, approximately ten SMC molders were visited; several others were contacted by phone to discuss the potential and the problems of this SMC approach. A contract was placed with The Budd Company, Fort Washington, Pennsylvania, for the development of prototype reflector/structures. Design of tooling is underway at Budd with initial units scheduled for mid-FY80.

The objectives of this contract are: 1) to investigate the problems of molding SMC panels, 2) to develop molding techniques and processes for molding glass reflectors into SMC panels; 3) to produce prototype parts for evaluation and 4) to provide information on feasibility and cost of SMC troughs in high volume production.

An interim molding effort is underway at Haveg Industries, Los Angeles, California, to investigate the response of 2 x 4' panels of glass (both sagged and chemically strengthened) to SMC molding conditions. The existing 2 x 4' trough mold is being revised to eliminate multiple ribs on the back side and to incorporate good mold closure to assure proper molding pressures. Panels of both sagged and chemically strengthened glass have been obtained and coated with silver, copper and protective paint. Molding of these units was scheduled for mid-November, 1979. The chemically strengthened glass (Corning's Chemcor TM) is expected to survive; the survival of the sagged and annealed mirrors is the primary factor to be established in this interim work.

Sandwich Reflector Structure

The sandwich reflector structure design approach offers the advantage of fabricating a collector module in one large piece 2 x 6 m as compared to the sheet metal and sheet molding compound (SMC) concepts which are size limited due to current press limitations. Limitations on glass size also have a bearing. The sheet metal and SMC concepts must suffer the economic penalties of assembling 1 x 2 m parts into 2 x 6 m collector modules. It is for this reason that the sandwich structure concept is being evaluated.

A sandwich structure design based on polyurethane foamed in place between two steel skins was initially selected as a follow on to the steel faced-aluminum honeycomb construction used on the Engineering Prototype Collector. Foamed sandwich structures are potentially less expensive than steel faced-aluminum honeycomb sandwich structures. Foamed sandwich test sections were ordered from two different sources for evaluation. However, initial testing of some of these structures in the environmental chamber has proven them to be unstable, thereby requiring a reorientation of the sandwich efforts. This reorientation includes additional work on the steel faced-aluminum honeycomb structure previously developed, improved glass bonding techniques, and determination of quantity production costs. Moderate material development efforts will be continued to determine if stable foam structures can be fabricated.

Laminated Glass Concept

An investigation has been initiated to determine if a structural glass laminate concept should be substituted for the sandwich structure concept. A structural glass laminate supported by a steel framework looks promising as a result of the reduced wind loads determined by wind tunnel testing of collectors. It appears that a 6 mm (approximately) thick glass laminate of about 1 x 1 m size can be supported without large additions to the torque tube already required to support sheet molding compound or sheet metal panels.

The laminate should consist of a thin front sheet of glass which is silvered on the second surface (plus protective copper and paint) and then laminated to a thicker piece of glass with PVB or other adhesive. The resulting structural glass laminate

should withstand wind, hail, etc., loads with a minimum supporting steel framework. Prototypes will be built if a more detailed evaluation continues to appear feasible.

Flat glass laminates have been developed for use with heliostats on the central receiver program. Curved glass laminates will be investigated as part of the sagged glass development program.

Computer Analysis

A computer simulation was developed to provide cumulative all-day performance results for a 90° rim angle, 2 meter aperture parabolic trough solar collector. This computer simulation was used to determine the basic design details for the engineering prototype collector. Testing to date with the engineering prototype collector has confirmed the basic accuracy of the computer simulation. Design problems considered with the simulation include misalignment of the receiver assembly from the focal line, reflector tracking bias, variation in receiver tube operating temperature, and variations in the reflector slope errors. Sensitivity to receiver parameters and wind effects are also analyzed. This computer simulation and the results of the various studies are summarized in SAND78-1026, "Receiver Assembly Design Studies for 2 m 90° Parabolic Cylindrical Solar Collectors."

Collector Assembly Efficiency

FIGURE 10. Theoretical Analysis of Collector Baseline Performance

The computer program was used to establish the baseline performance for the collectors under development. Figure 10 presents the theoretical baseline performance for a collector on June 22, 1962, in Albuquerque. Note that noontime efficiencies of 67% are predicted whereas the program goal as stated previously, is only 60%. Program goals are less than prediction to allow for

practical considerations such as pylon gaps, end losses, receiver support post shadowing, etc.

Receiver Development

Thermal Analyses

Analytical and experimental work was undertaken to quantify thermal conduction and natural convection heat losses in annular solar receiver geometries. Techniques studied for reducing conduction heat losses include evacuation of the annulus gas, oversizing of the annular shape while maintaining slight vacuum levels, and use of gases other than air in the annular space. These techniques can result in total heat loss reductions of 10 to 50%. Heat loss reductions of 10 to 50% can result in noontime collection efficiency improvements of 5% absolute, i.e., from 60 to 65%. However, to achieve these heat loss reductions, costly receiver tube designs are required. SAND78-1769, "Heat Loss Reduction Techniques for Annular Solar Receiver Designs," summarizes the analytical and experimental work.

The net result of the receiver tube heat loss reduction effort was the decision to require the receiver tube to be environmentally sealed but not evacuated or filled with inert gases. However, long term development of receiver tube designs that incorporate heat loss reduction techniques is recommended since only then will it be possible to determine if the complexity (cost) is worth the gain (performance).

Prototype Design

All three of the collectors designed for mass production will utilize the same receiver design. The design presently under

consideration is shown in Figure 11; it was tested in a configuration with a 1.250-in-diameter steel receiver tube on the

FIGURE 11. Prototype Receiver Design

Engineering Prototype Trough. The design incorporates silicone O rings at each end of the glass envelope to seal the annular space which is not evacuated. Laboratory testing of the O ring seal in FY78 confirmed that it would survive and maintain the seal at the high temperatures experienced. The O ring seal design avoids the high cost of glass-to-metal seals and expansion bellows, while allowing relatively easy replacement of broken glass envelopes.

Some of the problem areas of this type of glass envelope design have been (1) the ellipticity of the glass inside diameter at the seal, (2) flaws in the glass, particularly at

the ends which lead to failure due to thermal cycling and major temperature differentials in the glass, and (3) protection of the O ring from concentrated solar flux. Metallization of the I. D. of the seal area is being evaluated as a means of shielding the O ring from the concentrated sunlight.

Several concepts of receiver tube design will be tested for several months during FY80 in the Custom Engineering (9 x 12 ft.) troughs of the MSSTF in order to obtain data on performance, life and maintenance. The concepts include:

1. 12 ft. receiver length with unevacuated annulus, O ring seals with cylindrical glass I. D. and platinum metallization for O ring protection.
2. 24 ft. receiver lengths with mechanical support at the center joint and O rings at the ends of the 12 ft. glass envelopes.
3. 12 ft. receiver with Anti-Reflection coating on the glass envelope.
4. 12 ft. receivers with evacuated and sealed annulus with Code 7740 and Code 7052 glass. To be designed and furnished by Corning Glass Works.

The testing of these designs will confirm receiver tube design requirements, particularly those regarding roundness of the glass I. D. in the seal area, the elimination of flaws at the end of the glass, and survivability of the silicone O rings in actual service.

Flexible Hose Development

Parabolic trough collectors typically utilize a flex hose

at the end of the receiver to accommodate the movement of the parabolic trough. A review of flex hose designs presently being utilized on parabolic trough collectors indicates they are expensive and may have marginal life. Present designs do not protect the inner hose from bending at too small a radius which shortens hose life. The outer sheath requires better sealing against liquid infiltration and improved resistance to high solar fluxes in the areas near the receiver tube. Compound motions in the flex hose are required to accommodate collector rotation and receiver tube expansion. These superimposed motions induce torsion which is detrimental to hose life. Consequently, an effort has been initiated to allow hose manufacturers to design and fabricate insulated flex hose assemblies which meet the following basic requirements:

- o 600°F
- o 100 psi
- o 270° rotation
- o 3 degrees of movement
- o 10 pound max resistance force
- o insulated for less than 100 BTU/hr-ft-°F loss
- o 15,000 cycles
- o \$100 cost goal
- o Environmentally sealed
- o 30,000 W/m² solar flux near receiver tube

Wind Loads Definition

A wind tunnel test of scaled parabolic trough solar collector arrays was conducted in the Meteorological Wind Tunnel at Colorado State University, Ft. Collins, Colorado. The influence of various geometric parameters of single collector modules and

collector field arrays was evaluated. The major conclusions from the testing are the following:

- o The forces and moments on parabolic trough collector modules increase with mounting height above the ground.
- o The peak forces and moments of individual collector modules increase with aspect ratio up to ratios of ten or greater.
- o Intermodule gaps as narrow as six percent of the aperture width between end to end collectors within a row are sufficient to permit collectors to function aerodynamically as individual modules effectively nullifying any long row aspect ratio influence.
- o Collector modules installed within large arrays, even those within the second row of an array, experience an interference effect which provides a significant reduction of the peak lateral and lift forces originating with the wind.
- o The interference-induced load reduction does not apply to the collector pitching moment indicating a pressure distribution change accompanies the interference effect.
- o Appropriate fence or berm configurations can provide reduction of lateral and lift forces in perimeter rows equivalent to the interference effect within collector arrays.
- o A fence or berm height of approximately three-fourths the maximum collector height provides the major fraction of the force reduction achievable.

On the basis of the wind tunnel testing, the following aerodynamic coefficients have been set as design requirements for the collectors.

$$C_L = .5$$

$$C_D = .5$$

$$C_M = .35$$

These coefficients are based on the use of a 25 to 35% porosity wind fence around the collector field.

During FY80 collector pylons and collectors at Willard, N. M. will be instrumented with strain gauges and pressure probes to determine actual wind loads for correlation with the wind tunnel results.

Tracker Development

Three tracking concepts have been screened, i.e., shadow band tracker, computer track, and solar flux sensors. Present shadow band trackers appear to require further development to operate satisfactorily in the long term. Operational experience with computer tracking indicates that it can require site specific corrections or even collector specific corrections in large fields if it is to track satisfactorily throughout the operating day.

Both shadow band tracking and computer tracking have two potential limitations. First, they are both based on the assumption that tracking the sun results in optimum performance of a solar collector. Due to practical limitations about alignment, collector uniformity, etc. in large fields, this may not be true. Second, neither concept integrates an error signal along the complete receiver tube length. They both track the whole length of receiver based on the error signal at one or at most, a few discrete points along the receiver. How important these limitations are has not been completely evaluated primarily because their effect is more apt to show up in large fields than small arrays.

One concept that has the potential to avoid the limitations discussed above is the integrating solar flux tracker. This concept combines computer track together with a flux sensor in order to correct for biases in the computer track. A flux sensor based on a thin wire helically wrapped around the receiver tube and which responds to resistance changes due to solar flux variations has been designed and tested on the Engineering Prototype Trough. Figure 4 shows the thin wire in place on the Engineering Prototype Collector receiver. Efforts to date on this concept are described in SAND79-2163, "Development of a Microprocessor-Based Sun Tracking System for Solar Collectors."

Due to the flexible capabilities of microprocessors, the decision has been made to combine the functions of tracking with fluid control, system safeties, operational control, and status display into a single computer-based control concept for an entire field of collectors. This combined control concept is discussed in more detail under "Collector Subsystem Design" below.

Drive Development

During FY79, the design and demonstration of a cost effective, high performance collector drive system has been initiated. The drive system concept selected for development is that of a singular drive unit operating a linear string of collectors. The drive unit is centrally located in the string and is integral to the drive pylon. The collector structure is made sufficiently stiff to insure tracking accuracy along the entire drive string length and to prevent excessive deflections on glass reflectors. Preliminary cost and performance goals have been established as follows:

- o Nominal cost of \$15 - \$20/m² (15% of collector cost)
- o Standard deviation of drive system positioning errors to be no greater than 2 mrad.
- o Provide 180° of tracking range
- o Provide inverted stow position for collectors
- o Operate in 11 m/s wind speeds
- o Drive to stow in gusts up to 1.5 times the operating wind speed
- o Latch in stow position against wind speeds up to 36 m/s
- o Slew to stow within 5 minutes
- o Include provisions for emergency power supply source.

The drive system functions as part of a closed-loop positioning controller when mated to the tracking and control systems. Control signals to the drive system can be of a simple on-off nature. The drive system as defined herein includes the power source for emergency defocus.

Of the various types of drive systems which have found acceptance in industrial practice, only electromechanical or hydraulic systems lend themselves to this collector drive application which simultaneously requires the capability for fine positioning and the application of high force. In order to perform a more complete comparative evaluation of these drives, preferred designs for each of these two alternatives were defined. For the electromechanical system, the most convenient option consists of an electric motor mated to a gearbox providing the required speed reduction and torque multiplication. For the hydraulic system, a wide range of actuators is available to achieve rotary motion with high torque, including a hydraulic motor/gearbox option similar to the preferred electromechanical option. However, to use hydraulics to best

advantage, a direct drive option to avoid the expense of a high torque gearbox is preferred. Consequently, tightly sealed piston-like actuators capable of both high load levels and precision positioning were selected for further evaluation. Hydraulic power is supplied by individual hydraulic power units located at each individual drive location. These hydraulic power units would be completely preassembled in modular form at the manufacturing source.

A comparison of the attributes of these drive options relative to performance and operational convenience is presented in Table IV. In general, the electromechanical option is more precise but the hydraulic option is more versatile in performance providing its sensitivity capabilities can be established.

A second comparison was performed on the basis of cost. Drive costs of electromechanical verses hydraulic drive were determined through consultations with appropriate commercial sources. Figure 12 compares the relative costs of electromechanical drives and hydraulic drives as a function of torque output. While commercial,

FIGURE 12. Cost Estimates for Electromechanical and Hydraulic Drives

off-the-shelf electromechanical systems tend to be more expensive than hydraulic drives, electromechanical systems custom designed for this particular drive application should be competitive, especially for drives with torque outputs of 5000 N-m or less.

The selection of an appropriate drive string length is a function of both cost and performance. To satisfy the drive positioning criteria listed above, a drive system must be capable of a specific torque output of 70 N-m/m^2 . Based on this drive system size, a second cost comparison between electromechanical and hydraulic drives is presented in Figure 13. This figure shows that

FIGURE 13. Drive Subsystem Cost vs. Drive String Length

either a custom designed electromechanical drive or a hydraulic drive can be made to approach the nominal cost goal of $\$15 - \$20/\text{m}^2$ for drive string lengths of 20 m or more. This result combined with the

results of both structural and control system analyses was used to select a drive string length of 24 m which corresponds to a drive torque output of 3,360 N-m for the specific torque output of 70 N-m/m².

The major issue with hydraulic systems is the ability to achieve the sensitivity required while keeping the system small. To answer this question and have the capability to evaluate fully drive systems in general, a drive test stand has been designed and ordered. The stand should be operational in February, 1980. Commercial hydraulic components for a breadboard hydraulic system have been ordered and will be evaluated on the drive test stand.

During FY80 development contracts will be initiated with industry for a modular electromechanical and a modular hydraulic drive system. Prototypes will be fabricated and evaluated.

Foundation and Pylon Development

Experience with foundations designed for various demonstration projects has indicated that foundations designed using existing conservative standard practices were extremely expensive. As a result, a series of investigations into the minimum foundations required for solar collectors was initiated. This effort to date is summarized in the following three reports.

SAND78-7048, "Study of Low Cost Foundation/Anchor Designs for Single Axis Tracking Solar Collector Systems," evaluated ten preliminary foundation concepts. The reinforced concrete, drilled caisson pier was found to be the most economical design for most sites. The foundations designed in detail per this report are (1) based on estimated wind loads without a wind fence around the edge of the collector field to reduce the wind loads and (2) based on loads for non-drive foundations.

TABLE IV. Comparison Of Electromechanical and Hydraulic Drives

Electromechanical

Advantages

- o Precision through gear reduction
- o Simpler, fewer components
- o Reliability of electromechanical drive generally proven

Disadvantages

- o Bulky for large gear reductions
- o Emergency power supply back up difficult
- o Instantaneous power demands at start up

Hydraulic

Advantages

- o Provides high force at low speed in small size
- o Simple backup for emergency power (hydraulic accumulator)
- o All pumps do not start at once

Disadvantages

- o Sensitivity difficult for compact design
- o Actuator geometry awkward.

SAND79-7016, "Study of Foundation Designs for Single Axis Tracking Solar Collector Systems Under Reduced Loading Conditions", investigated the impact of reduced wind loads, as a result of wind fencing and multiple-row shielding effects, on the design of foundations. This report indicated that reductions in foundation costs of 30 to 50% were possible through wind fencing and multiple row shielding; this is one of the reasons for adopting the requirement of a wind fence for this project. Subsequent wind tunnel testing confirmed large reductions in lift and drag but did not confirm large moment reductions for all the collectors in a field. Hence, the foundation designs described below will be similar to the designs of SAND79-7016 but will be redesigned for loads as determined by the wind tunnel testing.

SAND79-7023, "Analysis of Field Test Results for Single Axis Tracking Solar Collector Foundations", analyzed test results for five reinforced concrete piers, (of the type described in SAND79-7016) to determine eccentric horizontal and vertical failure loads. The results of these tests compared favorably with the theoretical calculations.

The drive pylon must be substantially different from the other pylons as it is required to transfer all the moment on a 24 m drive string to the ground. Consequently, the collectors will be designed for installation in a field with only two types of foundations. The non-drive foundations and pylon interface will all be of the same configuration for economies of installation. The drive foundations will be substantially larger, and the drive pylon will be designed integral with the drive system. Conceptual designs have been undertaken for the support, intermediate and end pylons, based on commonality of design and fabrication.

Collector Subsystem Design

There are two major areas of collector field design which must be resolved before a field can be specified in detail:

(1) layout of the field and (2) control of the field. Field layout includes spacing between collector rows, length of a trough drive string, length of a ΔT string, length of a row, interconnecting plumbing, inlet and outlet manifolds, etc. Field control includes: tracking control, stow control, emergency defocus, overtemperature sensors, safeties, fluid flow control, etc. Both of these areas are under investigation. A typical size collector field has been selected as a model for use in determining specific solutions to field layout and control. Design of this field module will provide a methodology for specific designs for fields of other sizes. The parameters of the model collector field have been selected and are tabulated below:

- o 50,000 ft² field module capable of being combined into a 500,000 ft² system
- o 60° 5°F steady state output temperature
- o 150°F temperature rise per series string of collectors
- o 80 ft collector drive string length
- o 60% collector noontime efficiency
- o 3 to 1 ratio, approximately, between electrical and thermal energy costs.
- o Capital cost amortized at 15% year.
- o 2.25 ratio for field area to collector area.

A contract was placed with Jacobs-Del Engineering Company in FY79 to perform tradeoff studies concerning field layout parameters, and to do the preliminary design of all parts of the field except the collector. Their primary goal is to determine how designing

for a transient thermal system producing expensive heat varies from standard design practice which is currently based on steady state thermal systems utilizing inexpensive heat. Results of the study to date can be summarized as follows:

- o Increased pipe insulation is cost effective to decrease both night cool down losses and component thermal losses.
- o Slightly downsized piping to minimize thermal losses may be cost effective even though cost for parasitic electric power increases.
- o Non-collector field costs are estimated to be 20% of collector costs.
- o Design concepts to minimize heat losses through pipe supports, pipe mounts, valves, and pumps are cost effective.

A preliminary layout for a 50,000 ft² field is shown in Figure 14.

FIGURE 14. Preliminary Piping Layout for 50,000 ft² Collector Field

Techniques for controlling the temperature of the heat transfer fluid in parabolic trough solar collector fields have been studied by computer simulation. A specific control configuration was chosen consisting of a flow control valve and one or more temperature sensors to control the flow in each row of collectors. Figure 15 presents the basic control system. Various control algorithms

FIGURE 15. Collector Field Control Concept

were evaluated for stability and static errors. Time responses to startup transients and to partial and full collector cloud shadowing transients were obtained. The results indicate that temperature control requirements can be satisfied using readily available fluid control components. Experiments are scheduled in FY80 to confirm the computer simulations utilizing collectors at the MSSTF.

Studies of the complete control system required for a 50,000 ft² field of collectors have been completed. The control system combines tracking control, fluid control, system safety monitoring, and routine start-up and shut-down into one control system. The control system selected consists of a central control that handles wake up functions, rough sun position calculations, and authorizes start-up and operation. System turn-on, tracking, fluid control, system safeties monitor, and system shut-down are handled by a series of microprocessors which are located throughout the field. Figure 16 presents some of the functions performed by the control system. During FY80, a prototype of the control system based on the above concepts will be used to control a string of collectors at the MSSTF. Also during FY80, a development contract will be initiated with industry to obtain a production prototype control system which will be used to control several strings of collectors at the MSSTF.

FIGURE 16. Collector Field Subsystem
Control Functions

3.3 TESTING AND EVALUATION

Collector Cleaning

Contamination on collector reflector surfaces will reduce the specular reflectance characteristics of a solar collector. Similarly, contamination on the glass envelope around the receiver tubes will reduce the amount of energy available to the fluid in the receiver tube. Since both of these phenomena affect collector efficiency, it is imperative that effects of contamination be determined and that cost-effective cleaning techniques be established.

A contract was placed with McDonnell Douglas of Huntington Beach, California to identify contaminants, to determine contaminant adhesion mechanisms, and to investigate cleaning techniques. This contract was completed in September, 1979 and the final report SAND79-7052 entitled "Cleaning Agents and Techniques for Concentrating Solar Collectors" is being reviewed. A brief description of the results of this study is as follows:

1. Nonreversible adsorption soil reduced the specular reflectance of glass mirrors by approximately 2%. Acrylic surface mirrors were reduced by 5 - 8%.
2. In addition to the nonreversible contamination, there was an accumulation of dirt which could easily be rinsed off even after being on the surface for several months.
3. The rinsable soil could be removed by the application of 300 to 1000 psi spray of tap water containing a sheeting agent.
4. Each rinsing activity restored the reflectors to the same specularity, i.e., 98% of the original for glass and 92-95% for acrylic. Further soiling and rinsing exercises always

regenerated the same 2% specularity loss. The progressive degradation was observed after 30 soilings and washings.

5. The glass reflector could be restored to 100% of its original reflectance at any time by scrubbing with a detergent. Acrylic reflectors could also be cleaned to 100% of their original specularity with detergents, but scrubbing is not recommended because of the lower abrasion resistance of this material.

6. It was determined that the attachment of the soil to the surface was not the result of chemical interaction, but was simply the result of the intimate molecular contact between the two materials.

Cleaning studies to corroborate the McDonnell Douglas study on additional samples and on actual collector prototypes are scheduled for FY80. The objective is to establish and demonstrate effective cleaning materials, procedures, and equipment.

Laser Ray Trace Testers (LRTT)

The objective of the laser ray trace testers is to characterize solar reflectors by determining their surface slope error and focal length by optical means. A laser beam is reflected off the mirror at a known position. The position of the reflected beam is compared to the theoretical prediction. By sweeping the laser across the mirror, information can be gathered to "map" the collector. The data are used to determine slope error, focal length of the best fit parabola, and deviations from the true parabola. These characteristics can be used to define the accuracy of the reflector, determine errors and establish corrective action in the trough tooling or processing.

Laboratory (Indoor) Testers

The original indoor tester shown in Figure 17 has been used to evaluate the majority of prototype reflectors and structures. These units are typically 2 x 4 ft trough sections with a 30-in focal length. The tester and its software have been modified to allow

FIGURE 17. Indoor Laser Ray Tracer

testing of the half parabola (vertex to rim) specimens of the current advanced trough designs.

Experience has shown that a larger, general purpose laser system is required for indoor testing and inspection of reflector structures. A new lab laser facility has been designed and installed at Sandia in the Nondestructive Testing area; it can accommodate sections as large as 10 x 4.5 ft. This new facility, shown in Figures 18 and 19 is

scheduled to be operational on trough sections in the second quarter of FY80.

FIGURE 18. New Indoor Laser Ray Tracer

FIGURE 19. New Indoor Laser Ray Tracer

Field Laser Testers

The existing outdoor (portable) laser tester shown in Figure 20 has been used in FY79 to evaluate a number of large trough structures. Currently, it is being modified to improve its operation. The carriage and track assembly and the detector have been redesigned. Other parts (the tripod supports and the angular encoder) will be used in the new version, which should be operational in the third quarter of FY80.

FIGURE 20. Field Portable Laser Ray Tracer

Portable Specular Reflectometer

The second generation design of the portable specular reflectometer shown in Figure 21 has been completed together with a detailed set of drawings. Two prototype second generation instruments were fabricated for evaluation. Both of the new instruments have been

assembled and aligned. In addition, the instruments have been calibrated and the reflectance of several materials has been measured.

FIGURE 21. Portable Specular Reflectometer

A major improvement in the second generation instrument is the use of larger optics to allow averaging over a greater surface area of a mirror. The new reflectometer also has the capability of a straight-through beam configuration, allowing determination of a signal corresponding to 100% reflectance. This capability also allows the user to measure the transmittance of materials. Finally, a small microprocessor has been added to the output to allow the operator to take several readings over a mirror area and determine the average reflectance and standard deviation of a series of readings.

Plans for FY80 include use of the portable reflectometer in

dust accumulation studies, mirror cleaning experiments and long-term mirror degradation testing. It is also anticipated that the portable reflectometer drawing package would be made available to optical instrument manufacturers to establish a source or sources for a commercial version of this instrument.

Pump Power Test

A pump power test was conducted which compared the performance of a Dean Brothers centrifugal pump to a Viking positive displacement gear pump over a flow rate range of 70 gpm to 15 gpm using a variable speed controller. The results showed the Viking pump performance to be superior on a power consumption basis. A test was also run operating the Dean Brothers pump at a constant speed with a valve on its outlet to control the flow rate. The latter technique proved to consume the most power. A test report will be published.

3.4 MATERIALS AND PROCESS DEVELOPMENT

Structural Materials Evaluation

The long-range goal of the reflector structural materials program is to provide the analysis and testing background necessary for defining commercially producible, low-cost, accurate, dimensionally stable, and long-life concentrating solar collectors. In FY79, emphasis of the reflector structural-materials program was placed on the following areas:

- 1) evaluation of aged sub-scale structures,
- 2) design optimization studies for ribbed and sandwich constructions,
- 3) development of prototype sub-scale tooling for new concepts,
- 4) determination of silver corrosion mechanisms, and
- 5) thermomechanical characterization of sheet molding compounds.

Previously aged panels were remapped with a modified laser ray trace procedure, which utilized a removable reflective surface. Results showed that a variety of material constructions may eventually meet the operational and lifetime requirements for concentrating solar collectors.¹ Those data are summarized in Table V.

Parametric studies of sandwich structures^{2,3} and ribbed structures⁴ have led to the selection of four additional systems for study. Sample results for sandwich constructions from Ref. 2 are given in Figure 22. Cost, stiffness and thermal compatibility with the glass reflecting surface makes steel the material of choice for sandwich skins.³ Attractive core materials include paper and aluminum honeycomb and reaction injection molded isocyanurate foam. Contracts have been placed to produce 1.22 m x 0.61 m, 45° rim angle (0.762 m focal length) parabolic test specimens from each sandwich construction for future aging studies. In addition, the tooling for producing subscale parabolic test specimens with sheet molding compound has been modified to reflect current designs.⁴ Diagonal ribs have been removed and the number of longitudinal and transverse ribs reduced. Depth of the remaining ribs has been increased to 44.5 mm. Contracts have been placed for specimens with molded-in-place, silvered Chemcor and sagged-glass surfaces, and all sheet molding compound control units.

FIGURE 22. Weight vs. Face Thickness and Material for Various Core Materials at Constant Flexural

Studies of corroded areas on silvered glass reflectors indicated that a variety of degradation mechanisms can be responsible for the loss of mirror integrity, but that moisture appears to be a necessary ingredient. Conspicuous by their absence in the corroded areas were

Types of Structure	Materials	As-Manufactured		Temperature & Humidity Cycling ⁽¹⁾				
		Focal ⁽²⁾ length, mm	RMS slope error, mrad	Time, months	Focal length, mm	Percent change	RMS slope error, mrad	Percent change
Laminates	Plywood 19 mm thick 7 ply	731.1	3.4	25	735.2	(+0.6)	4.4	(+29.2)
Sandwiches	Fiberglass skin, corrugated fiberglass core, 51 mm thick	779.3	2.5	25	could not remove old reflective surface			
	Melamine skin and corrugated paper core, 51 mm thick	742.5	2.3	25	735.6	(-0.9)	4.4	(+91.3)
	Plywood skin and corrugated paper core, 51 mm thick	764.5	2.4	13	760.7	(-0.5)	4.7	(+95.8)
				25	768.5	(+0.5)	5.3 ⁽³⁾	(+120.8)
	Aluminum skin, 0.4 mm, 9.5 mm cell Al honeycomb core 38 mm thick	773.8	1.8	12	781.9	+1.1	2.0	+11.1
Molded	Bent Glass over 136 g/m ³ cellular glass	765.0	1.5	2	structure disintegrated			
	Sheet molding compound, general purpose formulation w/integral 19 mm deep ribs 2.5 mm wide	731.8	2.3	13	729.9	(-0.3)	2.4	(+4.9)

(1) The chamber cycles between -29°C and 49°C with a two hour transition time between temperature extremes and a two hour hold at the temperature extremes. Humidity is controlled to 82 percent at 49°C and 50 percent at 7°C.

(2) mold focal length 762.0 mm.

(3) plywood surface damaged upon removal of polished Al reflector, actual slope error should be somewhat less.

TABLE V. ACCELERATED AGING BEHAVIOR OF CANDIDATE REFLECTOR SUPPORT STRUCTURE MATERIALS¹

known chemical species aggressive toward silver such as chlorine, bromine and sulfur.⁵ These results, when coupled with observations of silver corrosion in fielded systems and accelerated aging specimens, indicate that an intimate bond is necessary between the mirror and reflector support structure, and that care must be exercised in selecting adhesives and edge sealants to exclude species which react with silver. It is also clear that silvering processes and materials developed for indoor use are probably inadequate for solar applications, and that research needs to be conducted to develop improved systems. A specimen to test the glass-silver-copper-paint laminate in shear is being developed to evaluate the effect of materials modifications on laminate strength.

Initial thermomechanical testing of sheet molding compounds has produced some significant results: (1) statistical variations in the material require that large numbers of tests be conducted before significant conclusions regarding material properties may be made; (2) it appears difficult to produce thermal expansion coefficients much lower than $5 \times 10^{-6}/^{\circ}\text{C}$, unless expensive materials such as graphite fibers are added; therefore, the mismatch with molded-in glass reflectors will have to be accommodated in design; and (3) samples from ribbed specimens examined by chemical dissolution show that good fill of the ribs with glass fibers has been achieved. The last result simplified analysis in that uniform properties may be assumed throughout the structure.

In FY80, emphasis of the structural materials program will center on evaluating the aging behavior of the new constructions procured in FY79 and further characterization of sheet molding compounds.

Black Chrome Development

The objectives of this effort are to improve the thermal stability of the black chrome selective coating for operation at 300°C in air for thousands of hours, to provide process information for production electroplating, and to determine degradation mechanisms and optimize substrate materials.

The critical plating bath parameter affecting the thermal stability of black chrome coatings (from Harshaw Chemical Co. Chromonyx bath) is the trivalent chromium (Cr^{+3}) concentration. Reducing the Cr^{+3} level below the nominal 16 g/l to 8 g/l yields coatings whose solar absorptance and emittance properties have remained unchanged after 3900 hrs at 350°C in air.⁶ The significant difference between stable and unstable coatings, as determined from scanning electron microscopy (SEM) studies, appears to be the presence of larger particles (150-200 nm) in the stable coatings.⁷ The larger particle size is felt to result in a reduced amount of oxidation in the stable coating after heating in air, as determined from Auger sputter composition profiling.⁸ Thus the major aging mechanism appears to be oxidation of metallic chromium in the coating to Cr_2O_3 . Additional changes in the coating after the 3900 hr heat treatments are currently under investigation.

A full scale production plating using the low Cr^{+3} bath formulation was carried out at Highland Plating Co., Los Angeles, CA., in April, 1979 as part of the Coolidge Project. Although the Cr^{+3} concentration was constant at 10 g/l throughout the plating operation, the deposited coatings were thermally unstable. A replating at Highland in October, 1979 using the same bath produced coatings that were thermally stable. For the second plating, several conditions were changed in order to improve the coating: (1) higher current densities were used (200 amps/ft²); (2) the plating

time was increased to 6 minutes; and 3) the number of tubes plated on each rack was reduced to improve the coating uniformity. The reason for the difference between these plating runs is being investigated.

During FY80, the following are planned:

- 1) A 20-ft collector installed in the MSSTF will be used for aging tests of black chrome coated receiver tube sections.
- 2) Plating process variables will be studied in Sandia's plating shop using a 160 gallon tank. When successful, the process will be set up at a commercial plating facility.
- 3) Degradation mechanisms will be studied using Auger sputter profiling, SEM, transmission electron microscopy, and possibly infrared reflectance spectroscopy.

Additional characterization of the black chrome plating process has been completed by Honeywell Systems and Research Center, Minneapolis, Minn. The effect of plating bath composition on the thermal stability of deposits was tested, including investigation of the percent Addition Agent, Fe^{+3} concentration, and Cr^{+6} (CrO_3) concentration. These results are being summarized in a plater's guide.

Glass Reflectors

The use of silvered glass has the known advantages of the high reflectance of the silvered reflector and durability of the glass front surface. Producing second surface glass mirrors shaped to meet trough configurations presents a technical challenge due to unique physical properties of glass. During FY79 Sandia investigated three approaches to forming second surface glass reflectors: thin glass laminates, thermally-formed glass, and chemically-strengthened glass.

Thin Glass

Continuing the effort started in FY78, the thin glass structure study advanced through the fabrication of a small number of prototype laminated sheets of glass/steel laminate.

Under the concept employed at Sandia, silvered glass sheets 0.5 mm (.020-in) thick or less are laminated to steel sheets approximately the same thickness. With proper design, subsequent bending of the flat reflector laminate to the trough shape produces only compressive stresses throughout the glass. The neutral bending axis of the laminate is located in the steel backing and will remain there as long as the bond integrity is maintained.

During the March-May, 1979 time frame, several prototype sections .43 m x 2.3 m were fabricated by the Sandia shops. These sections established "proof of concept" characterization and testing of these sections has continued. Test results confirm the feasibility of this approach. However, several processing problems have surfaced; these include:

- 1- Application of a uniform adhesive layer, and methods to obtain void-free bond areas.

- 2- Obtaining straight flat steel backing sheets. Ordinary steel sheets have small ripples and fabrication marks which telegraph through the glass.

- 3- Obtaining a supply of glass sheets .5 mm or thinner with widths greater than .43 m. Some European glass companies, notably Glaverbel, have been producing a soda-lime drawn glass down to a thickness of approximately 0.8 mm.

It was decided to suspend active efforts at Sandia on the thin glass in order to emphasize approaches which show

more immediate promise. It is planned to resume efforts on the thin-glass problems in FY80 with emphasis on adhesive application methods and environmental testing.

Thermally Formed Glass

Prior to FY79 a number of serious issues were outstanding relative to the availability of thermal-forming technology for trough reflectors. These issues are:

1. Availability of glass with low solar absorptivity.
2. Sources for thermally formed glass prototype reflectors in sizes up to 1 m x 1 m.
3. Availability of technology for mass-production of reflectors.
4. Feasibility of achieving desired reflector surface accuracy.

During FY79 efforts were initiated or completed to resolve these issues.

Standard Bent Glass Company has produced approximately 150 units for Sandia and Custom Engineering of thermally-formed glass of 1.47 mm (0.058") thickness. A demonstration Custom Engineering trough unit with a Standard Bent sagged glass sheet showed less than a 3 mr rms contour slope deviation. Reflectance of the silvered aluminosilicate Code 0317 Corning glass was close to 95% with no indication of surface markings caused by the thermal sagging methods. The sagging operation at Standard Bent is designed to accommodate low quantity specialty shapes. The process is labor intensive and does not employ hard tooling. The Standard Bent process, or similar processes, would not be suitable for high quantities from both a rate and cost viewpoint.

In mid-FY79 contracts were initiated with the Ford Aerospace/Ford Glass Division and PPG Industries to study the applicability of automotive windshield manufacturing processes in forming trough reflectors. Figure 23 shows an automotive-type sagging mold known as a ring mold. A version of this mold is being used by Ford and PPG to form the Sandia panels. PPG is also investigating the use of press forming as a forming method. PPG will utilize 60 and 90 mil thick float glass from the PPG Carlisle Plant which has the lowest iron content of any of the PPG production plants; transmittance of the glass will be measured after forming.

FIGURE 23. Ring Mold for Sagging an Automotive Windshield

Ford will utilize 90 mil thick Ford Solar Glass from the run for the Barstow Central Receiver Project; reflectivity of this glass with silver is about 90%.

By mid-FY80 these two contracts will be completed; comparative cost estimates for production techniques and evaluation of the accuracy of the panels will be available.

Chemically Strengthened Glass

The third approach being studied is the use of chemically strengthened glass sheets. This approach is analogous to the thin glass laminate approach in that a flat glass reflector is treated to allow it to be elastically deformed into the required trough shape.

Corning Glass Works (CGW) has developed the process for strengthening their aluminosilicate Code 0317 glass. The glass in sheets as thin as 1.27 mm (.050-in) can be strengthened to have residual compressive stresses of more than 30,000 psi. Since glass fails in tension, the residual compressive stress must be overcome and the glass stressed in tension before it will fracture. These flat glass sheets can be silvered using conventional production methods.

The Engineering Prototype Trough uses chemically strengthened glass. The glass sheets have measured solar reflectance values of approximately 95.8%. After 6 months, the glass panels mounted on this trough show no environmental degradation.

The major issue with this approach is not the potential availability of the technology but rather the production cost. It is currently planned to initiate a cost study during FY80.

Solar Reflectance of Silvered Glass Mirrors

Several PPG low iron float glass mirrors, silvered by a variety of silvering companies were obtained from McDonnell-Douglas (McDAC).

The silvering companies included Buchmin Ind., Carolina Mirror Corp., Binswanger Mirror Products Co., Gardner Mirror Corp. (who used their regular silver formulation and a new Solaflect formulation) and Mechanical Mirror Works, Inc. The solar averaged reflectance values for all but one mirror were between 0.896 and 0.904, which are within the reproducibility of these measurements. One mirror from Mechanical Mirror Works was 0.878, which is 0.022 below the average value of 0.900. Our results are 0.01 lower than solar averaged reflectance data provided by McDAC. From spectral data provided by McDAC, this difference results from lower values measured by us in the portion of the spectrum from 350 nm to 700 nm.

Mirror Degradation Studies

A test program has been initiated to investigate the prevention of mirror degradation in solar applications. The goals of this test program are to:

1. Obtain baseline data against which paints may be evaluated for protection of the copper and silver metallization,
2. Improve or insure lifetime of the mirror,
3. Identify an electrochemical technique for evaluating the mechanism of mirror degradation.

The program consists of three parts:

1. Coated coupons to be exposed to aggressive environments.
- The coupons are copper strips and mirror samples coated with an inhibitor-paint combination; the paints being evaluated are: three PPG mirror paints (lead based), one Glidden mirror paint (also lead based) and Incralac, an acrylic lacquer. The aggressive environments are: (a) 95°F salt spray (5% NaCl), (b) alternating immersion in 5% NaCl (room temperature), and (c) high temperature,

high humidity. In addition, outdoor exposure will be incorporated to correlate lab results with real weathering.

2. Paint properties such as thickness and porosity are measured for general recommendations for paint and inhibitor application.

3. Electrochemical techniques will be used to evaluate the corrosion mechanism in the degradation process.

It should be emphasized that this program is not intended to measure the performance of a large number of paint systems, but is directed at development of a test program which may be used to qualify particular paints or inhibitor paint systems for use in the solar program.

Failure Analysis of Solar Mirrors

The techniques of fracture surface analysis of brittle materials were used to diagnose design problems and determine failure mechanisms in solar mirrors. This technique was used to analyze the failure of a chemically strengthened parabolic mirror which spontaneously fractured without external loading. The location of the source of failure was determined, and fracture surface analysis showed that the fracture was probably caused by the impact of a sharp object which in turn caused a crack to penetrate the compressive surface layer and propagate slowly until catastrophic failure occurred. The tensile stress at failure was calculated from fracture surface features to be ~13,000 psi (90 MPa); the compressive stress at the surface of the sheet (produced by ion exchange) was determined to be ~45,000 psi (310 MPa). Thus, while the ion exchange process offers considerable protection from normal handling and impact damage, it is still possible to penetrate the protective layer with a sharp object such as a screwdriver and cause either immediate or delayed fracture.

Hail and Sand Impact

Since hail and sandstorm damage are potential problems for glass components of solar receivers and concentrators, the equipment and background information necessary for investigation of the problems are being obtained. A spherical projectile accelerator has been purchased and assembled. This gun will simulate hail impact with ice balls of varying diameters. The mechanical properties of hail are not well defined in the literature; thus, more information is necessary. Other materials for simulation are being investigated. Both controlled sand blasting and centrifuge acceleration are being considered to simulate sandstorm damage of solar mirrors.

The investigation of impact and erosion will be continued in FY80. A program has been outlined whose purpose is to evaluate the effect of hail and abrasive grain (sand) impact on solar glass components and to develop general criteria for resistance to hail and sand impact which can be applied to minimum weight structures. The primary goal is to assess the nature and seriousness of damage on components in the field before a comprehensive study of damage is begun.

Polymer Film Reflector Materials

The objective of this program is to develop a reflector material based on a metallized polymer film. Such a material has the potential of being low cost, lightweight, and easily handled. The films presently available suffer from two major disadvantages: (1) their surfaces are easily abraded during cleaning or by wind-blown particles, resulting in a loss of specularity, and (2) their reflectivity is approximately 10% lower than that of silvered glass. Field experience with 3M's FEK-244, an aluminized

acrylic, indicates that UV degradation and adhesion of the film to a substrate may not be critical considerations.

The FY79 effort has been directed towards the search for an abrasion resistant surface. Dow Corning has applied a developmental abrasion resistant coating to FEK-244. The material's reflectivity, abrasion resistance, weatherability and dirt retention properties were excellent and the need for field testing is indicated.

The reflectivities of commercially available metallized films are lower than that of silvered glass because aluminum has a lower inherent reflectivity than silver and because the polymer film absorbs a portion of the radiation. Silver has not been used successfully to metallize films because it degrades very rapidly after being applied. Attempts to protect deposited silver with a plasma polymerized layer of organosilanes were unsuccessful. FEK-244 has a moderately high reflectance (85%) and a promise of possible good weatherability when properly mounted or perhaps protected by an appropriate abrasion resistant coating. Because of the potential cost advantages of FEK-244, a test and evaluation program is planned for FY80. This program will involve lay-down of FEK-244 on various substrates. These samples will then be characterized by testing at Sandia for durability, reflectance, and abrasion.

Coatings

Both front and back surface solar mirrors normally require some type of protection to withstand hostile environments (e.g., weathering, abrasion, cleaning, etc.) for a given lifetime. Polymeric materials are often used to provide this necessary

protection. Past experience has shown that moisture is a contributing factor in the deterioration of solar reflectors. Since polymeric coatings do not generally yield hermetic seals, intelligent choices must be made to provide a satisfactory moisture "stand-off" in order to achieve a desired lifetime.

Several classes of polymeric materials have been empirically evaluated as protective back surface coatings via an artificial weathering chamber. To accelerate the aging process, the respective coatings were either sprayed or painted on silvered mirrors which contained only the sacrificial copper overcoat with no gray paint. The materials were selected for evaluation based on their moisture resistance. The coatings can be ranked as follows: styrene-butadiene copolymer (Kraton), polyurethane (Estane), polyvinylidene chloride (Saran), and polysulfide (Pro Seal 890). The polysulfide coated mirrors exhibited corrosion within a few days, undoubtedly due to attack of the silver by sulfur inherent in the polymer. The polyvinylidene chloride was subject to peeling followed by corrosion in about two weeks. The polyurethane lasted approximately four months, at which time peeling was followed by mirror corrosion. The styrene-butadiene copolymer withstood one year of this accelerated weathering with no evidence of peeling or corrosion at the termination of the test. As a result, this copolymer was spray-coated (toluene solvent) on several field test mirrors (sagged glass) which possessed the familiar gray paint. These mirrors have withstood approximately 5 years of outdoor aging with negligible evidence of mirror corrosion. The evaluated coating should not be confused with adhesives; they were simply moisture barriers to help stem mirror deterioration.

Protective coatings for front surface mirrors have also been investigated. Front surface mirrors possess optical advantages

over back surface mirrors; however, they demand even more protection from hostile outdoor conditions. Conventional methods (e.g., spraying, brushing) of applying optical quality polymeric coatings are inadequate. A promising new technique to produce uniform, transparent, adherent thin films which can conform to either flat or curved surfaces is plasma polymerization. Although plasma polymerization offers the advantage of forming coatings of virtually any organic or organometallic vapor, efforts were concentrated on organosilicone polymers. Additional investigation is required, primarily to improve weatherability of the coatings.

3.5 STORAGE SUBSYSTEM DEVELOPMENT

Thermocline Systems

The first thermal storage subsystem installed in the MSSTF was a thermocline subsystem. This system was designed to evaluate the storage of thermal energy in water at temperatures up to 232°C (450°F), or in Therminol 66^R at temperatures up to 320°C (608°F). The volume of the tank between the diffusers was 5 m³ (1,563 gallons) with a theoretical energy storage capacity of 10⁶ kJ (92 kWh) for Therminol 66 between the temperatures 243° to 311°C (470° to 592°F).

The major difficulty with this system was induced by the thick carbon steel wall of the tank. This 1-in thick wall (designed to withstand the pressures resulting from storing high temperature water) provided a facile path for thermal conduction between the hot and cold layers of the thermocline. As a result, thermoclines established in the tank proved to be unstable and broadened rapidly with time. Additionally, excessive heat loss through the external vacuum jacket made it virtually impossible to perform long-term tests.

Other thermocline storage subsystems are being evaluated by Sandia at Willard, New Mexico, and Coolidge, Arizona. However, these storage units are only subsystems of system experiments. As a result, testing of the storage concepts is limited due to lack of the in-depth instrumentation required for a test facility and the desire to accumulate system operation hours to demonstrate the feasibility of the solar concept.

A new thermocline tank, shown in Figure 24, is presently being installed in place of the old one at the MSSTF. The objective is to produce useful design information for the installation and efficient operation of thermocline storage subsystems for use with line-focusing solar collectors used in various applications. It will be operated as a single medium, direct storage thermocline tank. The capacity will be 4.5 m^3 (1,179 gallons). The tank is made of 4.76 mm (3/16 in) low

FIGURE 24. Thermocline Tank

carbon steel with stainless steel legs to minimize thermal loss due to conduction. Multiple ports at the top and bottom give access for plumbing and instrumentation. The entire top can be removed if required for internal modifications or changes in instrumentation. A 45-cm (18-in) diameter hatch provides personnel access. The installation of stainless steel legs and of the thinnest walls possible is based on past experience.

Various diffuser designs can be installed for evaluation. The tank is instrumented with 350 temperature sensors. Two vertical thermocouples will be attached to both the inside and outside walls of the tank, and there will be thermocouples between each layer of insulation. A displacement-type gauge will measure fluid level. Four turbine flowmeters will measure rate of flow of hot and cold fluid with output data stored by a minicomputer.

Plumbing connections allow hot fluid to be received from either the solar collectors or from the Multiple Tank Thermal storage subsystem. The tank legs will rest on a 5-cm (2-in) pad of load-bearing insulation. The tank will be insulated with 30 cm (15 in) of fiberglass.

Subscale models of diffuser designs will be tested in the laboratory and then fabricated full scale for testing in the system. The first design has been completed and the diffuser fabricated.

Subscale tests are also being conducted in the laboratory to investigate the stability of thermoclines. Full-scale testing of the new tank will begin early in 1980. Testing will include (1) heat loss measurements under steady-state flow conditions at temperatures of 200°, 260° and 315°C (400°, 500°, 600°F);

(2) static heat loss tests with initial temperature at these same levels; and (3) tests of thermocline stability and duration under static conditions, at various charge and discharge rates, and at various temperatures. All these tests will be done with the tank completely filled using an auxiliary tank to accommodate expansion, and then with ullage space in the tank. The difference in performance between laboratory scale models and resulting components of the new thermocline tank will provide a measure of scaling effects.

Heat Loss and Thermal Siphoning

Heat loss testing in the multitank thermal storage subsystem of the MSSTF has indicated far greater than expected heat losses. Instrumentation of the pipes entering the bottom of the tank has indicated that thermosiphoning may be occurring. The suspected mechanism involves establishment of a connection loop in which hot fluid moves along the top of the pipe to a valve, the uninsulated stem of which acts like a fin. The valve thus cools the fluid which in turn drops to the bottom of the pipe and flows back to the storage tank completing the convection loop.

Thermal siphoning operating by such a mechanism has been shown to occur in a 2-in pipe in the laboratory. In the field, temperature measurements on pipes suspected of contributing to thermal siphoning heat losses have shown temperature differences between the top and bottom of a horizontal 2-1/4-in pipe to be greater than 10°C (18°F) under no flow conditions.

In order to fully characterize thermal siphoning within a solar system, tests will be conducted in FY80 to evaluate configurations to determine under what conditions thermal siphoning occurs. The

goal of this work is to provide options to design engineers to allow prevention of unwanted thermal siphoning in solar thermal systems.

3.6 POWER CONVERSION SUBSYSTEM DEVELOPMENT

Solar Rankine Cogeneration Subsystem

Present efforts of the component and subsystem development projects have centered on the development of collector field subsystems for process heat application. Since most process heat applications are less than 350°F and since most midtemperature collectors are capable of much higher temperatures (up to 700°F), a cogeneration system utilizing a Rankine cycle to generate electricity from approximately 600°F to 350°F and utilizing the exhaust from the Rankine cycle system to supply a 350°F process heat requirement is desirable. However, at the present time, an optimum-designed Rankine cycle power conversion subsystem for this application is not commercially available. Consequently, an effort was initiated during the last quarter of FY79 which will establish the system operating parameters and subsystem requirements.

During the last quarter of FY79, a system optimization code has been formulated in order to perform cost/performance tradeoffs. Rankine cycle performance characteristics and component costs have been generated for input to the code.

Steam Turbine for the Shenandoah Project

A high efficiency turbine/generator set is being developed by Mechanical Technology Incorporated of Latham, N. Y. for the Shenandoah Project. The unit will provide up to 400kW_e, 1380 lb/hr of 110 psig process steam and 7500 lb/hr of 5 psig steam for heating and cooling.

High pressure steam at 700 psig and 720°F will enter the turbine inlet through one, two or three admission chambers to achieve efficient part-load as well as full-load performance. The turbine is a four stage axial impulse type with extraction of the 110 psig process steam occurring between the second and third stages. The turbine speed of 42,500 rpm is reduced to 1800 rpm with double reduction gearing to drive an 1800 rpm synchronous generator. The turbine generator and skid assembly is shown in Figure 25.

The history and status of the turbine/generator development is summarized below:

- o Development contract placed in March, 1978.
- o Initial interface control document was signed off by GE, MTI, and SLA in September and released in October, 1978.
- o Electrical and control hardware specifications and design completed in November, 1978 and parts ordered.
- o Mechanical design completed in January, 1979 and long lead items ordered.
- o All of the parts available at the end of September, 1979 and most of the turbine/generator skid hardware assembled. The final assembly of the turbine itself remained. Present plans are that the turbine assembly will be completed and the entire skid assembly will be shipped to MTI's Malta test facility in November, 1979. Hook up of the unit for test should be complete in December, 1979 and testing should commence in January, 1980. Acceptance testing will be followed by several months of characterization testing which will include transient, off-design and start-stop testing. Shipment of the unit to the Shenandoah site is scheduled for October, 1980.

MECHANICAL TECHNOLOGY, INC.
400KW STEAM TURBINE GENERATOR

FIGURE 25. MTI Turbine

3.7 ENGINEERING ANALYSIS

SOLTES

SOLTES (Simulator of Large Thermal Energy Systems) is a computer code which can simulate most systems that use solar energy as an energy source, including process heat, total energy systems and power conversion.

A national workshop was given in September, 1978 in Albuquerque, on the SOLTES code; approximately 60 persons representing 40 companies, laboratories and universities attended. During the preparation of SOLTES for distribution after the workshop, a number of serious problems were discovered regarding the algorithms used in the storage models obtained from SOLSYS. These problems were corrected and the code was sent to Argonne National Laboratories on March 31, 1979 for distribution. A revised document (SAND78-1315 Revised) which contains more explicit documentation of all of the algorithms was issued by Sandia in June, 1979.

SOLTES was also installed and debugged at SLL and at SERI. Two briefings were given to personnel of the Thermal Conversion and Systems Analysis branches at SERI. All other requests for SOLTES were referred to Argonne.

Solar Systems Design Handbook

A handbook to aid in the design of solar thermal systems employing parabolic troughs is under preparation. Primary emphasis during FY79 has been on the completion and verification of computer codes for producing the component and subsystem performance curves necessary for system design.

Figure 26 shows curves of monthly collector output throughout a year. These curves are typical of the performance information to be contained within the handbook. The effect of the resulting shadowing is presented as the collector center to center inter-row spacing is varied from 18 to 10 feet (collector width is 6 feet). Curves such as those in Figure 26 are important in evaluating the effect of land constraints as well as such tradeoff as overall collector field heat loss vs. length of interconnecting field piping resulting from a desire for minimum shadowing. As indicated in Figure 26, little is lost in employing collector aperture to ground area ratios up to about 0.5. The handbook will contain such curves for all latitudes of interest within the continental U. S.

Some verification of the computer code used to compute collector performance as reported in Figure 26 was obtained by predicting hourly performance of collectors in operation in the Sandia CMTF. Figure 27 contrasts computed collector performance using measured hourly solar insolation and weather data with coincident, measured collector performance. Agreement is within 5-10% based upon the integrated daily total solar energy collected. Similar code verifications were made at other times during the year and with different collector orientations. In all tests, agreement between predicted and measured daily performance was within 5 - 10%.

SPACING VARIES FROM
18 TO 10 FT.

MONTHLY COLLECTOR PERFORMANCE

TROUGH SHADOW - ALB

FIGURE 26. Monthly Collector Performance

FIGURE 27. Measured and Computed Collector Performance

Other codes developed during this reporting period include field parasitics codes which include steady state heat losses, overnight cooldown heat losses, and pump power requirements. An experimental test program will be initiated in FY80 to evaluate the effect of uninsulated valve stems and pipe supports on heat loss from pipes. The effect of such items is difficult to model analytically and, as a result, subject to large error. Preliminary tests and calculations indicate that such items contribute substantially to the overall heat loss from insulated field piping.

A preliminary draft of the handbook which concentrates primarily on process heat systems design, will be completed during FY80.

Solar Course

A solar course was prepared and taught as part of the Sandia INTEC* program. The objective of the course was to present to Sandia engineers an overview of solar technology and design. The course was first taught in the fall of 1978 and repeated during the spring of 1979 resulting in 32 hours of video-taped class lectures together with extensive printed notes. Subject matter includes the solar resource, passive and active solar HVAC systems, line focus concentrating systems, central receivers, wind photovoltaics, process heat systems, total energy systems and economics.

*In-Hours Technical Courses

Requests for the course have been received from several industrial organizations and universities.

Angular Effects on Receiver Performance

Recent models of collector performance have included the effect of non-normal incidence upon the solar energy receiver surface. Insights gained by these studies have been included in the total system models for parabolic troughs and bowls. In the latter system, these effects were expected to be important, but have been shown to be less than ten percent.

Hemispherical Bowl Model

A preliminary characterization of a hemispherical bowl has been made and placed in a total system model, which will permit an assessment of the cost of power furnished by a bowl system as the various economic and performance parameters are varied. It will also form the basis for comparison with results from other actual solar collector systems.

Compound Parabolic Collector System (CPC)

The low concentration non-tracking collector typified by the CPC has been modeled for comparison with parabolic troughs. It was determined that a capability to consider the system parasitics was lacking, so this was developed before the model was formulated. Documentation of the model and a parametric study are presently being undertaken. Discussions have been held with Argonne National Laboratories to insure that there is no duplication of effort.

Line-Focus Central Receiver (LFCR)

A model is being formulated for the line focus central receiver. This model will draw upon experience gained on the point focus central receiver and the computer code DELSOL.

In a parallel effort, a rapid approximation to the DELSOL code called SCRAM has been developed and is presently being documented.

SECTION 4: SYSTEMS AND APPLICATIONS DEVELOPMENT

4.1 INTRODUCTION

The objective of this project is to conduct, at the system level, the analytical work, engineering, test, and management activities needed to support the use of solar energy, particularly systems employing line-focus, concentrating collectors, for near-term and mid-term applications with high potential to be commercially attractive. This objective is accomplished by application analysis, performance and cost analyses, conceptual design studies, the testing and evaluation of various system and subsystem configurations, and by technical management and support to field experiment projects. The field experiments are designed to provide focus and feedback to solar R&D, to generate system/subsystem performance and cost data, and to accumulate operating and maintenance experience. All activities are conducted with strong emphasis on private sector involvement and particularly on developing system-level capabilities so that commercial penetration of the energy production market can take place as rapidly as technical and cost readiness permit.

Activities have been divided into four subheadings as follows:

- 4.2 Project Management
- 4.3 Systems Analysis and Engineering
- 4.4 Experimental Systems Management
- 4.5 Systems Tests and Evaluation

Some examples of key activities illustrate the subheadings. In Subsection 4.3 are included application analyses primarily for industrial process heat, solar total energy, and enhanced oil recovery, concept comparison and tradeoff studies, and economic analyses. Subsection 4.3 also includes conceptual design studies

for cogeneration and modular systems for industrial process heat and solar total energy. The activities covered in Subsection 4.4 include technical management of the Shenandoah Solar Total Energy Project (STEP), the Fixed Mirror Distributed Focus (FMDF) Technology Development (which includes the Crosbyton Project), and the Coolidge Solar Irrigation Project in its design and construction phases. Finally, Subsection 4.5 describes the operation of the Midtemperature Solar Systems Test Facility and management of the operating contracts for the experimental solar projects at Coolidge, AZ, Willard, NM, and Gila Bend, AZ.

4.2 PROJECT MANAGEMENT

Drafts of an FMDF Technology Development Plan were prepared and reviewed with DOE/ALO and HQ. This national plan will be a multiyear effort to bring the FMDF solar collector concept to a point of technical and cost readiness for commercialization. This is to be accomplished through system and application analysis, component and subsystem development, and field application experiments. The present Crosbyton Project being conducted by Texas Technological University (TTU) under a DOE contract is an important element of this initiative which is planned for implementation starting in FY 80.

Drafts of an Industrial Process Heat (IPH) Modular System Project Plan were prepared and reviewed with DOE/ALO and HQ. This project, which includes a number of essentially identical (modular) line-focusing solar energy systems for midtemperature IPH applications will be initiated in FY 80. The objectives of the project are to verify the modular system concept, to provide a vehicle for new generation technology, to develop system integrator firms, and to provide a quasi-mass-production opportunity to the solar collector industry.

In August 1979, a meeting was held in Washington, D.C., among representatives of the Economic Regulatory Administration (ERA), DOE Solar Thermal, DOE Solar Applications, and Sandia Laboratories, Albuquerque. The purpose was to provide ERA with technical inputs needed to evaluate a recently submitted analysis of an industrial firm applying for exemption from an ERA requirement to offset part of the thermal load of a new oil-fired boiler with solar energy.

The first five of a series of Sandia site surveys of IPH field experiments were conducted. The surveys resulted from a cooperative agreement between the Solar Thermal (ST) Branch and the Agricultural and Industrial Process Heat (AIPH) Branch of DOE. The purpose of the surveys was to assess the status of the field experiments and to provide recommendations for project modifications or upgrades. Sites visited were York Building Products, Harrisburg, PA; Reigel Textile, LaFrance, SC; Campbell's Soup, Sacramento, CA; Gilroy Foods Co., Gilroy, CA; and Lamanuzzi and Pantaleo, Fresno, CA.

The planning phase of a new project entitled Modular Solar Thermal Dish Systems was initiated by DOE-ALO/Sandia at the request of DOE/HQ. The project was to install a number of small on-site solar thermal electric power stations ranging in size from 3 to 20 kWe and featuring parabolic dish collector systems. Project planning was completed, a Commerce Business Daily announcement was released, and the final draft of the Program Research and Development Announcement for procurement was prepared by ALO and SLA. Programmatic considerations forced the postponement of the project. It will be considered by DOE for implementation in FY 80.

A joint Italian-American solar energy project was outlined in a meeting held at Sandia Laboratories, Albuquerque, on December 11 and 12, 1978. The meeting, chaired by Solar Energy Research Institute, was attended by representatives of the Italian Ministry of Energy, SERI, DOE International Affairs, and Sandia. A 30 month project was outlined, the main feature of which is a 20 kW solar thermal power plant and a 20 kW photovoltaic power plant operating side-by-side at a remote (no electrical grid service) site in southern Italy. The program plan is being submitted to the respective governments.

If the plan is approved, a cooperative agreement will be negotiated and the project would be initiated in FY 80.

Support was provided to DOE/San Francisco Operations (SAN) for the second half of the Line-Focus Solar Central Power Project. The activity for FY 79 consisted of Phase I study contracts with BDM Corporation, General Atomic Company, and Stanford Research Institute. Follow-on activities for this project, if any, will be the responsibility of DOE/ALO with technical management assistance by Sandia Laboratories, Albuquerque.

A meeting was held in Albuquerque in June 1979 with National Park Service personnel who have expressed interest in using concentrating collectors for heating and cooling a visitor center being planned for construction in southwest Missouri. This would be their ninth solar project but their first using concentrators. The project would be funded by the Department of the Interior.

Mr. Jochen Hofmann and Mr. Helmut Zewen of Messerschmitt-Bolkow-Blohm (MBB) visited Sandia on June 1979. Information was exchanged on materials and system design. Their commercial dish collector has a fixed spherical receiver and the concentrator dish rotates around this receiver. The all-day system efficiency was estimated by MBB to be 76%. A cobalt selective surface is used on the receiver. MBB thought meeting the U.S. dish cost goals would be difficult. MBB is in the process of building a 100 kW solar power system in Kuwait. The system is for desalination, irrigation, and electric power. To assure continuous power, the system includes both a diesel-electric generator and a fossil fuel heater as backup. The diesel is also required for start-up as it is a stand-alone system.

A contract was placed by Sandia with McDonnell Douglas Aircraft Company (MDAC) of Huntington Beach, CA, for the deployment and monitoring of materials exposure stations at five IPH process steam sites which were near completion of Phase I design. The stations will contain representative samples of reflective materials and receiver tubes. On a monthly basis for one year, samples will be retrieved and examined and optical properties before and after cleaning will be measured. The effort is being funded by the AIPH Branch; however, the results will be of great interest to the Solar Thermal and Photovoltaic communities in assessing performance/maintenance tradeoffs for various geographical locations.

4.3 SYSTEMS ANALYSIS AND ENGINEERING

Objectives

This task includes general systems analyses and design support activities for the Small Solar Thermal Power Systems Program. The task objective is to develop techniques to evaluate or design solar power systems for defined applications, techniques that will provide guidance for administrative and technical decisions. This activity helps ensure efficient use of program funds to develop and demonstrate solar technologies and provides for transferring solar design technology to commercial and institutional sectors.

Industrial Process Heat (IPH)

IPH Modular System Development Plan

An activity has been initiated to develop for DOE approval an IPH system development plan which would help bring a solar thermal system technology to technical and cost readiness. It is recognized that generating thermal energy is the basic energy product of any solar thermal system. It is also recognized that this must be done economically if solar thermal energy is to have a commercial future.

A project plan has been developed which will stress modularity of solar systems in an attempt to realize these goals. This approach has the potential to minimize engineering costs and improve reliability. The projects will be large enough in scope to realize large production subsystem prices, and for industry to utilize quasi-mass production techniques in fabrication. Industry will do a majority of the project activities.

Focus on Goals

An assessment was made of the cost and value of industrial process heat furnished by parabolic trough and bowls collectors.

The modeling effort included a detailed cost breakdown of the solar thermal system and a total system model. Results were presented to DOE Headquarters and SERI.

Solar Enhanced Oil Recovery

A preliminary analysis of the technical and economic feasibility of Solar Enhanced Oil Recovery (SEOR) was undertaken and it was concluded that this application was well suited to solar energy utilization, in comparison with other industrial applications. Figure 28 shows the breakeven crude oil price above which solar is cost competitive with conventional EOR. (The two cases shown correspond to analysis with and without a guaranteed loan program.)

FIGURE 28. Breakeven Crude Oil Price for Competitiveness of Solar vs. Conventional EOR.

Solar Thermal IPH Market Penetration Strategy

An estimate was made of the likely effects on the U.S. economy of the President's goal of one Quad (10^{15} BTU) of line-focus furnished IPH by the year 2000. It was concluded that this is an ambitious but not impossible goal. Several actions the federal government might take to ensure the meeting of this goal were suggested to Headquarters.

Levels of Decision Relative to Goals

It was determined that a great deal of time has been spent in attempting to meet certain component level goals in order to make solar/thermal energy competitive with alternate energy forms. This approach, which requires a certain cost per square meter of reflector, for example, represents a current opinion of what will be required in the future for solar/thermal to penetrate a certain market sector. A restructuring of the decision-making process has been made in which several levels of "goals" or "bench-marks" are proposed to provide for flexibility in the component and subsystem goals. Work on this project will continue in FY 1980.

Small Electric Power Systems (SPS)

Temperature Effect Upon System Operation

The effect of collector operating temperature upon levelized annual energy cost (LEC) from a solar/thermal SPS has been considered. Because, in general, collector fluid prices increase as the nominal operating temperature increases, the advantage gained in increased turbine performance is largely offset by system economics. The study, which has been presented to DOE Headquarters, concludes that a collector operating temperature of 275°C (527°F) will produce an annualized energy cost that is within ten percent of the optimum value (see Figure 29).

FIGURE 29. Relative Energy Cost for Electrical Power Generation vs. Temperature of Heat Transfer Fluid.

Effect of Reflector Cleaning Upon Energy Cost

A model has been constructed which inputs an idealized reflector weathering curve to a total solar/thermal SPS. The model uses actual data gathered at Sandia Laboratories, Albuquerque, and includes so-called natural cleaning. Individual cleaning costs ranging from \$.05/m² to \$.25/m² were considered to determine optimal cleaning intervals. Results of the study have been presented to SERI, Headquarters, and others and a report is being prepared.

Solar Total Energy Systems (STES)

Kirtland AFB Solar/Thermal Power Plant

A study was made of the feasibility of using a total energy or cogeneration system to furnish the Sandia Laboratories portion of the

Kirtland AFB energy load. The results indicate that at present a fossil fuel total energy system is the most economical. A STES which reduced total energy consumption by 60% appears to be only slightly more expensive if the assumed economic parameters can be met.

Relative Benefits of STES for a Mixed Load Community

This study compared the relative benefits of both present day and advanced technology STES when applied to a 2000 dwelling-unit mixed load community. For reference, small power and district heating loads were also considered. The STES provides energy at a lower annualized cost than either of these two single energy form applications.

A Sandia technical report describing the study has been released.

(SAND79-0346)

Development of STES Optimization Computer Code

A system optimization code which uses a Latin hypercube search to determine minimum LEC for a STES has been developed. The code is extremely versatile in being able to handle different system configurations and load profiles. The STES configuration is diagrammed in Figure 30. Documentation of the code is being carried out at present.

Economic Analysis of the Shenandoah STES

The economic competitiveness of a STES which furnishes energy to an application ten times the size of the Bleyle Plant in Shenandoah, Georgia, was considered. Down payments of 100% and 20% were considered to bracket the values of LEC which might be obtained in an actual plant. Results show that the STES could be economically competitive with conventional plants in the 1990-2005 period if the collector cost goals can be met. Costs for fossil fuels were provided by SERI.

FIGURE 30. Solar Total Energy System Configuration Used in Optimization Study

Ft. Hood Solar Total Energy System

In this study, a series of \$140/m² parabolic troughs were assumed to furnish energy to an application which was sixteen times the size of the LSE #1 at Ft. Hood, TX. Results show that the STES is likely to compete with fossil fuel in about the year 2000.

STES Modularity Study

In an attempt to characterize the light industrial market for STES, McDonnell Douglas (MDAC), Huntington Beach, CA, has been commissioned to survey a number of potential users. The study, which is now in its second year, will determine power levels, duty cycles, and land availability for several types of light industrial installations. SERI is presently coordinating its IPH Data Base study with MDAC so that information obtained by the two studies will not be duplicated.

General Economic Studies

A Stochastic Interpretation of Risk

A study has been made of the relationship between risk and loan leveraging using a Monte Carlo analysis of solar energy system economics. The conventional opinion that leveraging increases risk and therefore requires a higher discount rate has been shown to be invalid in certain circumstances. A better understanding of risk can be gained by calculating the rate of return distribution as all other parameters vary randomly.

Relation Between Utility and Residential/Commercial Economics

There has been a great deal of confusion among the various solar/thermal technology proponents as to what type of economic methodology should be used to determine levelized energy costs. A public utility is a regulated organization whose main purpose is to generate power upon which taxes must be paid. Commercial or industrial installations

on the other hand, produce goods and use power they generate only to displace purchased power. The difference, which is primarily between cost and revenue, has been resolved by showing the correspondence between the two economic methodologies.

Load Leveraging Applied to Solar/Thermal Systems

Because the LEC of a solar/thermal plant is a function of down payment, discount rate and interest rate on borrowed money, it is possible to use loan leveraging to help solar compete with fossil fuel. There are limits to the extent to which a new plant may be "leveraged," but a government loan program could help to overcome the conventional guidelines used. Project financing could result in a loan fraction for a solar/thermal installation which is not restricted by the balance of the parent company.

Systems Engineering

Modular Solar Thermal Dish Experiments

The purpose of the project was to assist in stimulating the development of small on-site solar thermal energy systems using dish type solar collector systems. A project plan and a PRDA document were prepared. The results of the experiments would be used to compare economic viability with other types of solar thermal power systems. The experiments, consisting of both the power generation and the application, were to have ranged in size from 3 kWe to 20 kWe and multiple awards were intended.

This PRDA effort was halted just before it was distributed due to DOE budgetary constraints. The PRDA document exists, and can be used either for future experiments or as a model for new initiatives.

Collector Wind Loads

A wind tunnel test of parabolic trough solar collector configurations was conducted in the Meteorological Wind Tunnel at Colorado State

University. The influence of various geometric parameters associated with single collector modules and with collector arrays was evaluated. A paper minimizing the wind load data on parabolic trough collectors has been prepared. Strain gage instrumented collector support pylons together with hard wire instrumentation has been developed to collect full scale wind forces on the collector array at Willard. The system is currently scheduled for installation during January 1980.

Solar Industrial Cogeneration Project/Small Central Receiver

Preliminary work on the SICP/SCR was performed at SNLA until April 1979, when direction by DOE/HQ placed the responsibility with SAN/SLL. A briefing was given to SAN/SLL and copies of all files on the project were furnished. A CBD announcement was sent to DOE/HQ for review, and a draft PON for site selection has been prepared.

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4.4 EXPERIMENTAL SYSTEMS MANAGEMENT

Solar Total Energy Project, Shenandoah, Georgia

A solar total energy system is an energy system designed to maximize the use of collected solar energy by supplying both low grade (low-temperature thermal) and high grade (electrical and/or mechanical) energy to selected applications. This activity is concerned with systems that collect thermal energy from the sun, convert the energy to electricity, and apply the energy rejected by the conversion process to an appropriate thermal load. The effort is currently focused on the design and construction of a solar total energy system experiment at Shenandoah, Georgia.

The objectives of this project are: (1) to develop within industry the required engineering and development experience on large scale solar total energy systems; (2) to acquire data to reduce the uncertainties of cost and performance predictions; (3) to assess the interactions of solar total energy technology in an industrial application with an electric utility interface; (4) to ensure dissemination of technical data as a basis for expanded growth of solar total energy systems.

Georgia Power Company, Atlanta, Georgia, is providing the site for the project (selected from a DOE/ALO open solicitation) and active utility participation under a DOE/ALO Cooperative Agreement. The Solar Total Energy Project (STEP) system designer (General Electric Company, Space Division, Valley Forge, Pennsylvania) was selected after a competitive conceptual design phase involving three contractors. Sandia Laboratories provides technical direction to participants, management, administration, and technical support to the project.

During FY 79, the STEP, Shenandoah, was rescoped from a 192 collector system with 29.3 MWH storage to a 120 collector system

with 17.6 MWH storage. The rescoping reduces the funding required by the project.

The collector module consists of a 7-meter parabolic dish developed by GE Space Division. The dish reflective surfaces, which were initially coated with a room temperature vulcanizing silicone protective coating (RTV), have been replaced with an aluminized acrylic film surface (FEK-244) to enhance the performance of the dish collector. The loads associated with the rescoped project result in a 3-tank (17.6 MWH, 60 MBTU) storage system rather than the 4-tank (29.3 MWH, 100 MBTU) system associated with the 192 collector system.

The turbine/generator, being procured from Mechanical Technology Inc., is a 400 kWe steam driven energy conversion system which features a steam extraction port to deliver thermal energy at 175°C.

The storage capacity for the low energy Thermal Utilization System will be 2.93 MWH (10 MBTU) to provide the low temperature thermal energy needs of the Bleyle plant.

Shenandoah FY 79 Accomplishments

- o STEP, Shenandoah, was rescoped to reduce funding. The site operation date was advanced from June, 1982, to October 1, 1980.
- o Receiver redesign based on test data of the 5 meter diameter engineering prototype collector tested at Sandia produced significant (>15%) increase in efficiency.
- o Site grading and erosion control modifications were completed at Shenandoah (Figure 32).
- o Design Review was held in Washington, D.C. on November 14-15, 1978.
- o The MSSTF fluid loop was expanded, site improvements made, and the GE-designed 7 meter Shenandoah prototype collectors were

installed (Figure 33). Initial testing was begun subsequent to fluid conditioning.

- o Shenandoah construction cost estimates were reviewed in detail with DOE/HQ.
- o Phase IV, Definitive Design of the Shenandoah Project, was contracted by DOE/ALO with General Electric Company. The period of the contract was from August 1, 1978, to April 30, 1980. Subsequent rescoping plans have changed the completion date for the construction design to January 15, 1980.
- o Three papers related to STEP, Shenandoah, were presented at the ISES conference in Atlanta, Georgia.
- o Shenandoah site solar data were compared with the synthesized Solar Model Year data and were found to compare favorably.
- o Extended column tests of the "trickle-oil" storage concept were completed. The data showed good agreement with predictions.
- o A condensate tank has been incorporated into the system design to return condensed volatiles from the Syltherm 800 silicone heat transfer fluid to reduce fluid loss. Operating cost reductions greater than 50% for fluid replenishment are predicted.
- o Optical tests of a fully assembled 7 meter reflector showed slope errors of less than 0.5 degree. More than 95 percent of the energy fell into an 46 cm (18 inch) diameter aperture.
- o Access to the Quadrant Test Data by GE Valley Forge via long distance telephone and the Sandia Network Operating System (NOS) has been completed.
- o A state of Georgia, Department of Natural Resources, Environmental Protection Division ruling on the environmental effects of silicone oil permits a significant savings in field construction costs to be realized by not requiring full paving of the field for run-off control.

FIGURE 32. Shenandoah STES Site

FIGURE 33. GE Shenandoah Prototype Dish

- o Feasibility of stamping petals with FEK-244 already applied was established and accelerated environmental testing of FEK-244 petals was started.
- o The quadrant test layout of the four collectors has indicated that more distance was required between adjacent collectors to preclude mechanical interference.
- o Construction plans for Shenandoah will follow bid packages based on area activity rather than on discipline to promote consolidation of contractor responsibility.
- o Collector foundation pier tests were conducted on-site at Shenandoah to optimize the foundation design. A single diameter design of greatly reduced length requiring less concrete than indicated by analysis will be utilized.
- o A schedule was established to review construction drawings based on the January 15, 1980 completion date for the definitive design.
- o Various design changes to the GE designed 7-meter parabolic dish collector have been indicated as a result of the quadrant test. Among the changes are receiver structural supports, thermally compatible aperture plates, maintenance of non-laminar flow at all flow rates in the receiver, position indicator mounting, hub to yoke attachment, collector control unit, modifications to handle larger current loads, and a larger pump.
- o Two of the RTV-coated reflectors for the quadrant dish collectors were replaced, the south dish by anodized surface aluminum petals and the west dish by FEK-244 covered petals. This permits comparative data to be analyzed relative to collector efficiency.
- o All three reflector surface candidates are undergoing tests in the environmental chamber.

Shenandoah FY 80 Planned Activities

- o The definitive design phase will be completed by GE during the second quarter of FY 80.
- o Construction drawings will be completed and construction contracts will be awarded during the 2nd quarter of FY 80.
- o Procurement of long lead components will be initiated. Critical components will be procured by the site contractors.
- o Sandia will administer contracts for System Integration, Collector Fabrication and Installation, and for the Control and Instrumentation System.
- o DOE/ALO will obtain the services of a construction inspector to oversee the construction work.
- o Early procurement of the aluminum for the collectors, the computer and integrated circuits (IC) for the Control and Instrumentation System (CAIS), and cabinets and IC's for the Collector Control Unit (CCU) will be initiated by Sandia.
- o Testing of a full scale Shenandoah pre-production collector at Sandia will be conducted to evaluate all modifications from the quadrant test collector.
- o The Sandia Technical Representative will relocate to Shenandoah, Georgia.
- o All interface control drawings between the STES and the Bleyle plant will be finalized.
- o The Georgia Power Company substation location will be determined based on contemplated expansion plans of the Bleyle company.
- o Interface requirements between the turbine generator and the STES will be determined.
- o Turbine generator qualification testing will be initiated and completed during the first half of FY 80. Subsequent transient testing and long term operational testing are planned at

Mechanical Technology, Inc., prior to delivery of the machine to the Shenandoah site.

- o Meteorology station operation at Shenandoah will be maintained as long as possible until construction activities require its relocation.
- o Test and evaluation of the SylthermTM800 heat transfer fluid and reflector surfaces will continue at Sandia.
- o Testing of the Quadrant test collectors will be continue at Sandia.
- o Construction at Shenandoah will start during the second quarter.

Crosbyton, TX, Solar Power Project

The objective of the Crosbyton Solar Power Project is to develop the fixed-mirror, distributed-focus (FMDF) thermal solar collector concept. The project was begun in 1976. It is concerned with evaluation of the FMDF concept and near-term design of a prototype system to demonstrate technical feasibility. The FMDF is a concept in which high temperatures can be achieved by using fixed, non-movable mirrors and a moving receiver to follow the sun. In the FMDF system, a spherical reflector is stationary and a receiver is moved within the reflector bowl to intercept the solar radiation at its focal region. Because the reflector is fixed, it can be constructed in much larger units than movable reflectors, but for the same reason, the system suffers from cosine losses. Thus, the economic advantage of the FMDF system over other high-temperature systems would have to depend upon simplicity of construction.

Texas Technological University (TTU) is the prime contractor to DOE/ALO for the Crosbyton Project. E-Systems and Foster-Wheeler Energy Corporation are major subcontractors.

During FY 77, a conceptual engineering analysis of the performance and cost of an FMDF system was completed. The work included detailed

analyses of the receiver subsystem, transient effects, mirrors, control and tracking subsystems, error budgets, system performance, and economics. A preliminary report in three volumes was issued.

Phase I, Segment I of the Crosbyton Project was completed in February, 1978, and a final report in two volumes was issued. This work resulted in a conceptual design of a 5MWe FMDF solar power system and a 19.8 m (65 ft) Analog Design Verification System (ADVS) proposed for design and construction in Segment II of the project. Segment II was authorized, contracts were negotiated, and work started in the latter half of the fiscal year.

Crosbyton FY 79 Accomplishments

During FY 79, the design of the ADVS was completed, components and subsystems were fabricated, and construction was begun. The preliminary and final designs were reviewed and approved by ALO. The Quality and Acceptance Plan (Q and A) and the Checkout and Startup Plan were submitted by TTU and approved by DOE/ALO. Significant work completed during FY 79 includes:

- o Approximately 500 mirror panels were fabricated. The panels are 31.8 mm (1.25 in) Carolina glass mirrors bonded to impregnated paper honeycomb and backed with a 2.3 mm (0.090 in) steel plate. They have a radius of curvature of 11.4 m (37.5 ft).
- o Two receivers were built, one primary, the other backup. The receivers consist of two parallel 6.35 mm (.250 in) i.d., 12 m (40.0 ft) long tubes wound helically around a cylindrical structure 15.2 cm (6 in) in diameter and 5.64 m (18.5 ft) long. The primary receiver was fabricated from Inconel 617, the backup from a combination of Inconel 600 and 316 stainless steel.
- o The tracking and control system was assembled and tested with the test load and the fluid loop. The system uses quadrant solar sensors and a Bristol controller.

- o The tracking and control system was assembled and tested with the test load and the fluid loop. The system uses quadrant solar sensors and a Bristol controller.
- o Radiant heat tests of both receivers were performed in a facility at E-Systems. In the tests, a simulated solar flux was applied to the receiver, which was connected to the fluid loop and the test load. The system was operated under steady state and transient conditions at temperatures and pressures up to 650°C (1200°F) and 8.3 Mpa (1200 psia), respectively. About 100 hours of operation were accumulated.
- o Hail tests were performed at TTU to determine the resistance of the edges of the mirror panels to hail and to determine the effects on optical characteristics.
- o Work continued at TTU on the detailed model for predicting transient and steady-state behavior of the ADVS. Based on results obtained with the detailed model, the approximate model was modified and improved.
- o Construction of the ADVS (Figure 34) is in process at a site near Crosbyton, Texas. The ADVS is 19.8 m (65 ft) in diameter and will have a peak thermal output of 225 kW.

Crosbyton FY 80 Planned Activity

Construction of the ADVS will be completed and will be followed by an experimental test to measure collector performance. Milestones include reviews of the Q and A results, the checkout results, and the full ADVS test program. Segment IIA is scheduled for completion at midyear to be followed by publication of the formal report for this work.

Segment IIB is scheduled to begin following Segment IIA at the option of DOE and depending upon the results of the ADVS tests.

FIGURE 34. Crosbyton ADVS

150 kW Solar Powered Irrigation Project, Coolidge, AZ

This project has three objectives: first, to prepare a detailed design of a solar-powered experimental facility providing 150 kWe of electric power to the electrical grid for the operation of deep well irrigation pumps; second, to construct the facility in accordance with the prepared design and install it on a farm near Coolidge, Arizona; and third, to operate the facility in an actual farm environment, and to gather and evaluate data on the facility's performance.

The Coolidge Project is the first large-size application of solar energy to pump irrigation water from a deep well. At 150 kW, it is the world's largest solar electric power plant. A preliminary design study was undertaken early in 1977 by three bidders and completed in August 1977. The Dalton Cole farm, south of Coolidge, Arizona, was selected as the project site in February 1977. Acurex Corporation was selected as the prime contractor for this project,

as well as the supplier of the solar collectors. The major sub-contractors to Acurex are Sundstrand Corporation and Sullivan and Masson Consulting Engineers. Sundstrand is the supplier of the organic Rankine cycle power generation unit. The team of Sullivan and Masson and Acurex is responsible for the detailed design task.

Early in FY 78, Acurex began preparation of the detailed design for the system. Detailed design was completed and a design review was held in January 1978, at which time the system design was frozen.

An agreement with the local electric utility was reached in November 1977, whereby the experiment could be connected to the grid and the power generated and power consumed recorded. This reduced project costs by eliminating the need to run separate power lines to the pumps.

The Sundstrand-Acurex contract was signed in September 1978. Sundstrand had received most P.O. items and assembly of the ORC 200 unit was started. The construction contract was approved and site work was started in September 1978.

Coolidge FY 79 Accomplishments

- o Site work and collector foundation construction was completed in December 1978.
- o Production of collector modules began in March 1979 and all collector modules were delivered to the site in May.
- o By May 1979, the Sundstrand ORC 200 turbine/generator, the thermal storage tank, and all major components were in place at the site (Figure 35).
- o During June 1979 all collectors were installed and aligned, and all interconnecting oil piping was installed and leak-tested (Figure 36).

FIGURE 35. Storage and Turbine/Generator System at Coolidge Project

FIGURE 36. Collector and Plumbing Detail at Coolidge

- o Checkout and startup operations were begun, and on September 21, 1979, the turbine/generator was operated for the first time and produced electricity to the grid using solar power (Figure 37).
- o A contract was placed with the University of Arizona for operation and maintenance during FY 80.

FIGURE 37. Coolidge Deep Well Irrigation Project

Coolidge FY 80 Planned Activity

- o The University of Arizona started construction of the visitor center with completion scheduled by November 1, 1979. The dedication of the Coolidge site was in November 1979.
- o The facility will be operated by U of A in accordance with a Sandia coordinated Test & Evaluation plan. Acurex and Sundstrand, the system integrator and turbine/generator supplier, have been awarded U of A subcontracts for continuing technical support.

Industrial Process Heat

Field Experiment Evaluations

Technical reviews of seven Intermediate Temperature Steam IPH Field Experiment projects through detailed system design were conducted. Recommendations of the Technical Review Panel were submitted to the DOE Source Selection Board. Five projects were selected for subsequent funding through Phase II, Fabrication and System Installation.

Participation in the technical review and evaluation process for three new large cost shared solar IPH solicitations was conducted. These solicitations were, a) Solar Systems for Enhanced Oil Recovery, b) Solar Systems for Low Temperature IPH Applications, and c) Solar Systems for Intermediate Temperature Process Heat Applications. Multiple awards for Phase I, System Design have been made for each of these solicitations.

Upgrade of Field Experiment Projects

A review and evaluation of five existing IPH Field Experiments from the Hot Water and the Drying/Dehydration solicitation cycles was carried out. Documentation of the problem areas observed and recommendations for system upgrading will be submitted.

4.5 SYSTEM TEST AND EVALUATION

O&M Contract Management

Willard Irrigation Project

The Acurex collector field was upgraded, the Solar Kinetics field was installed, and the system has been in operation as follows:

Collector Operation	1336 hours
ORC Engine/Orifice Operation	1080 hours
Electricity Generated	1476 KWH

The Barber Nichols turbine has repeatedly had operational problems. During the turbine downtime, the driving fluid is passed through an orifice in order to simulate normal operation.

The collector fields and storage have proven reliable and low in maintenance requirements. In addition, Solar Kinetics continues to use the collector field as a test bed for new ideas related to reflectors and receivers.

New Mexico State University has been under contract for O&M since February 1979. Aside from general O&M, they have conducted numerous storage performance tests. The future operation of Willard will be determined early in FY 80.

Gila Bend Irrigation Project

Battelle Laboratories was contracted to reactivate the 50 HP irrigation system. Between June and October the solar system was operated 282 hours, which was 70% of the time that the facility was manned and solar energy was available. The system operated trouble-free during this period. The future status of Gila Bend will be determined during the early months of FY 80.

Coolidge Irrigation Project

A contract was placed in September 1979, with the University of Arizona, for the evaluation, operation, and maintenance of the of the Coolidge Solar Irrigation Facility.

A test plan for the facility was published on schedule by Sandia in late September. The test plan covers the evaluation of the various subsystems and the facility's operations and maintenance. Following the November 1979 acceptance and dedication milestones, the facility evaluation and operation will begin. An acceptance plan was outlined by Sandia and is being finalized by U of A.

Collector Subsystems

General Atomic FMSC

The evaluation of the General Atomic FMSC collector subsystem (260 m²) was completed. The results of the various performance tests conducted, including all-day tests, along with documentation of the operation and maintenance problems, will be published in the near future. At design conditions, with the oil inlet temperature at 245°C and the oil outlet temperature at 316°C, the peak subsystem efficiency at noon was 36.8%. A total of 517 operational hours have been logged on the subsystem.

The GA system will be maintained as a heat source for the MSSTF facility until a second generation collector subsystem is ready for installation (probably in late FY 80 or early FY 81).

Solar Linear Array Thermal System (SLATS)

The evaluation of Suntec Systems' collector field (260 m²) was completed. The subsystem was operated a total of 380 hours. The heat transfer medium in the receiver tubes was water, initially, and later replaced with T-66 oil. Water was responsible for corrosion products from the carbon steel piping system.

Secondary reflectors were also evaluated on the SLATS receivers. Representative test data (peak thermal efficiencies) are as follows:

η_{WATER} 41%

$\eta_{\text{T-66}}$ 43%

Final results will be published during early FY 80.

Sandia Troughs

Testing has been completed on the Sandia parabolic troughs which were first operated in December 1975. Half of the 100 m² troughs were replaced by Custom Engineering troughs in April 1979. The remaining Sandia troughs will be maintained for heat sources until future programs dictate removal. Total operating time on the Sandia troughs was 922 hours. During the four years of operation, trough efficiency declined from 50% to 30%. A final report will be issued in mid-FY 80.

Raytheon Dish

The Raytheon parabolic dish solar collector has been in operation (92 hours) throughout the year. An all-day operational test was conducted on April 6, 1979. The results indicated a peak collector thermal efficiency of 78% and an average day long efficiency of 74%. A letter report has been published on this test. The construction of a new fluid loop which will allow it to operate along with the other MSSTF subsystems has been completed. Further, all-day tests using this loop are contemplated.

Custom Engineering Troughs

The Custom Engineering Co., under contract to Sandia, provided ten new parabolic troughs to replace the east half of the Sandia collector subsystem. The troughs are of a fiberglass honeycomb structure lined with sagged glass reflectors. They were installed in late June and have been in operation (83 hours) since mid-August

with the original Sandia receiver tubes. Performance data will be published after the new passively evacuated receiver tubes are completed and installed.

GE Quadrant

The GE Quadrant is a prototype array (four collectors) 1/30 of the area of the Solar Thermal Energy Project (STEP) being installed at Shenandoah, Georgia. General Electric, with the help of sub-contractors, prepared the MSSTF site and installed the four 7-meter diameter parabolic collectors, thermal transfer loop and control system. An additional 150 data lines were added to the STF to monitor this test.

A chronology of events, pertaining to the Quad tests, is presented below:

2/79	Site preparation completed
6/6	First RTV-coated reflector installed
6/18	Last RTV-coated reflector installed
7/11	First receiver installed
7/18	Last receiver installed
8/28	First collector thermal test
9/25	Changed one reflector (RTV-coated aluminum to anodized aluminum)
9/27	Changed one reflector (RTV-coated aluminum to FEK 244 covering aluminum)
10/12	First full temperature operation with all four collectors simultaneous

During the full temperature thermal operating tests, receiver output temperatures were between 375° (710°F) and 400°C (750°F) and the temperature rise was about 140°C (250°F). Although this test series will not be completed until well into FY 80, preliminary indications are as follows:

GE Collector Efficiencies (%)

<u>North</u> <u>(RTV)</u>	<u>East</u> <u>(RTV)</u>	<u>South</u> <u>(Anodized)</u>	<u>West</u> <u>(FEK 244)</u>
44-46	46-48	51-53	60-63

Several significant improvements have been incorporated in the Shenandoah STEP design as a result of the Quad installation and testing. These include:

1. Increased spacing between collectors
2. Changed reflector surface from RTV-coated aluminum to FEK 244
3. Added heat shield to the receiver aperture plate
4. Changed fiber optics terminations
5. Changed position of the feedback potentiometers
6. Modified receiver coil design
7. Changed insulated piping supports

Additional testing is planned to complete the characterization of the present design, measure the effects of reflector and receiver design changes and evaluate longer term operation and maintenance conditions.

Total Energy Demonstration

24-Hour Tests

Two 24-hour tests were run at the MSSTF on December 5 and 21, 1978. The subsystems included in the test were the FMSC, SLATS, and Sandia collectors, the multitank storage, the 32 KW turbine/generator, the heating load housed in the control building, and the control/data acquisition equipment. The tests demonstrated the feasibility of simultaneously producing electric power and usable thermal energy from a solar energy source. A report has been published.

These tests helped to identify and quantify problem areas such as:

1. Thermal losses from the prime mover.
2. Thermal energy required to heat up a system after shutdown.
3. Thermal losses from thermal storage and the fluid loops.
4. The need for strategies and possibly some equipment to handle fluid which cools in temporarily unused equipment.
5. Parasitic energy, especially that associated with the turbine.

Additional testing and/or development work has been initiated to minimize these problems before they appear in larger solar installations.

32 KW Turbine/Generator

The old gearbox, which absorbed nearly 40% of the energy output, has been replaced by a more efficient one. Efficiency at 32 KW is expected to increase from 11.5% to 12.9%. Installation and evaluation will take place early in FY 80.

Total Energy Demonstration

The use of the MSSTF facility for total energy demonstration has been concluded and a report is being prepared. The facility is currently being used for subsystem and component testing. However, the total energy capability will be left intact.

Collector Module Test Facility (CMTF)

Collector Characterization

The following systems were characterized:

GE/SA 5-meter EPC dish with five different receiver designs

Acurex with Coilzak reflectors
east/west orientation
north/south orientation
north/south summer solstice

FMC Fresnel Belt

SKI T-700

The above test results (peak noon efficiency) are shown in Figure 38.

FIGURE 38. Comparison of Collector Efficiency vs. Output Temperature

The HP-100 minicomputer data system became fully operational after a complete regeneration by the digital systems development group. Its executive system was updated from RTE-3 to RTE-4 to improve test operations.

Design and fabrication of an "in-line" flow meter calibration system was completed. This addition will permit flow meter calibration checks at actual operating conditions with minimal setup when installation has been completed.

Requests for proposals for design, fabrication, and installation of a new 425°C fluid loop and a rotating collector mounting platform were sent to 33 possible sources. Several proposals were reviewed and evaluated and Custom Engineering Inc., Englewood, CO, was awarded a contract in January 1979. Installation is expected to begin in December 1979. A decision was made to emphasize use of the CMTF to assist Sandia development activities and to test commercial collectors which advance the state-of-the-art, an example of which is the Solar Kinetics T-700 which was installed and tested. As in the past, Sandia will continue to test commercial collectors which have not been tested previously or which have been modified since previous testing. Among these are the GE TC 300 collector, the Suntec collector, and collectors from approximately 10 other contractors.

Yearly Performance

A program is 75% complete to predict yearly performance of collectors as a function of measured peak noon efficiency, incident angle modifier, collector field layout, collector end losses, and location using inputs from weather tapes. These predictions will allow a more meaningful comparison of collectors.

Code Verification

The CMTF data has been used to verify several computer codes currently used at Sandia. The excellent correlation increases confidence in computer data and also enables decisions to be made concerning collector modification without having to run experiments at CMTF.

Energy Display

Two SKI T-500 collectors were set up in demonstration for six months at an Albuquerque museum.

Other Activities

IEA-SSPS Support

Sandia CMTF was requested to perform the qualification test of an Acurex trough module at the CMTF with Glaverbel glass reflector for the the IEA-SSPS Project near Almeria, Spain. Installation began in September and testing followed. The test results will be presented to the IEA Operating Agent, DFVLR, in Cologne, West Germany, in November.

Safety Assessment Document

At the request of DOE, a Safety Assessment Document has been prepared for the energy conversion system and is being reviewed by the Safety Division. The Safe Operating Procedure has been rewritten to include 16 addenda.

IPH Program Support

In July 1979, DOE, CSA, through SERI, requested that Sandia support the IPH program by:

1. Qualifying commercial independent laboratories or testing agencies to test line focusing concentrating collectors.
2. Testing a number of collectors at the qualified facilities or at Sandia's CMTF.
3. Publishing the results of the tests to include predictions of yearly performance for selected locations around the USA.

Five laboratories were contacted concerning commercialization of test facilities; DSET, Wyle, and BDM responded favorably and are currently undergoing evaluation by Sandia. A draft which outlines the requirements for independent laboratories has been written by Sandia and reviewed with SERI in order to comply with future STAM work.

An announcement was published in the September 1979 CBD inviting interested companies to respond with their collector. Four manufacturers responded, three of which were determined eligible. Seven others have been contacted by Sandia and have expressed an interest in having their collector evaluated as part of the program. All efforts will be reported in FY 80.

SERI Support

In February 1979 the personnel operating the test facilities at Sandia (CMTF and MSSTF) and SERI (STAM and SERAPH) mutually began a program of support and coordination to:

1. Speed bringing STAM and SERAPH to operational status.
2. Avoid duplication of effort and gaps in the test program.

Procedures have been developed by means of which SERI has access to test data generated in the MSSTF and applicable data reduction programs stored in Sandia's computers.

A controls test is being conducted on the FMSC Collector Field Subsystem in the MSSTF to verify computer models of controls systems. The results of these tests have shown that the models are generally correct, but that both the controls and the programs require some modifications. After these modifications were made, the tests were reported. Data from the controls test are being used in the development of control strategy and hardware by Sandia.

A pump thermal loss test planned by SERI is to be conducted by Sandia. Design of the test setup is complete and necessary hardware is on order.

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APPENDIX A: PUBLICATIONS AND PRESENTATIONS

A.1 REPORTS

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- C. N. Vittitoe, F. Biggs, L. K. Matthews, and L. O. Seamons, "Helios and Reconcentrators."
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