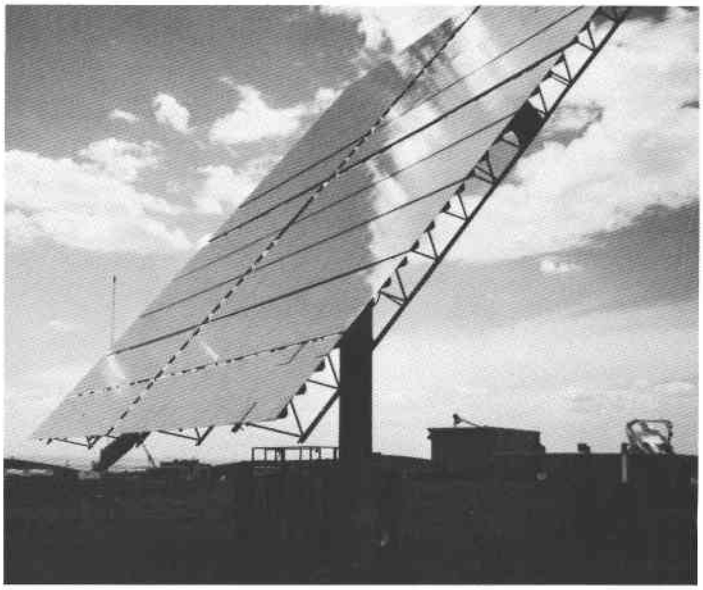
Solar Thermal Technology Annual Report



On the cover: Clockwise from top right: ARCO's ATS large-area heliostat design, Luz Solar Electric Generating Systems (SEGS) with 10-MW_e Solar One in the background, and SKI stretched membrane mirror.

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Solar Thermal Technology Annual Report

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Preface

The research and development (R&D) described in this document was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology (STT) Program. The goals of the STT Program are to advance the engineering and scientific understanding of solar thermal technology and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates the solar flux by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point- and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Dishes track the sun on two axes and use mirrors to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multimodule system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from as high as 400°C in troughs to more than 1500°C in dish and central receiver systems.

The STT Program is directing efforts to advance and improve each system concept through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories that work with private industry. Together these laboratories have established a comprehensive, goal-directed program to improve performance and provide technically proven options for eventual incorporation into the nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must become economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to ensure a successful program.

This annual report describes the accomplishments and progress of government-funded activities initiated, renewed, or completed during Fiscal Year (FY) 1987 (October 1, 1986, through September 30, 1987). It highlights the program tasks conducted by participating federal laboratories and by industrial, academic, or other research under a subcontract. The emphasis of the Solar Thermal Technology Program during the year was (1) to perform research and development leading to the economic viability of two primary solar thermal concepts, central receiver and parabolic dish, and (2) to explore applications of national significance where the special attributes of concentrated sunlight are appropriate.

The report includes three appendices that cover principal contacts and sources of additional information (Appendix A), acronyms and abbreviations (Appendix B), and a glossary of terms (Appendix C). A bibliography of relevant publications from Sandia National Laboratories and the Solar Energy Research Institute completes this annual report.

Acknowledgments

This document was prepared under the guidance of the Solar Thermal Technology Division, Office of Solar Heat Technology, U.S. Department of Energy (DOE). The work described was carried out for DOE by various research organizations and government laboratories, including Sandia National Laboratories and the Solar Energy Research Institute, their contractors and suppo[illegible] universities; and through the DOE field operations office in Albuquerque, N. Mex. This report was coordinated and published by the Solar Energy Research Institute for DOE.

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Executive Summary

Introduction

The nation faces many difficult challenges in developing an effective and responsible policy on energy production and use. The many vital issues include energy security, energy cost, international balance of trade, international competitiveness, and environmental quality. Energy security requires maintaining assured access to sufficient energy resources at a cost that does not disrupt our standard of living. It is essential in terms of national defense, the trade deficit, and political stability that we limit our dependence on foreign energy supplies. Pervasive and growing problems with atmospheric and water pollution, acid rain, and the greenhouse effect also make it imperative that we limit the burning of fossil fuels. Most experts agree that, unlike the past when we relied on a primary energy source such as coal or oil, a mixture of energy sources will have to be developed for the future.

Solar thermal technology is an integral part of the U.S. Department of Energy's (DOE) strategy to help the nation achieve energy security and solve the other energy-related problems. As part of a balanced national energy strategy, the widespread implementation of solar thermal energy systems has the potential to increase our domestic energy supplies, reduce our dependence on imported oil, and help U.S. industry respond to increasing international competition for domestic and overseas markets for solar energy systems.

Solar thermal systems use concentrating collectors to focus sunlight so that useful energy at high temperatures can be produced. Three types of concentrating collector systems are being developed in DOE's Solar Thermal Technologies (STT) Program. These are parabolic troughs, which focus at low concentration ratios and are used for mid-temperature applications, and parabolic dishes and central receivers, which are capable of achieving high concentration ratios and very high temperatures. Concentrated sunlight is a versatile and high quality form of energy. Therefore, solar thermal technology has a broad spectrum of applications that includes industrial and commercial uses of process heat, electrical power generation, hazardous waste destruction, and a variety of other advanced applications that take advantage of the unique attributes of highly concentrated sunlight.

Research, development, and analysis of solar thermal systems performed by the Sandia National Laboratories Albuquerque, the Solar Energy Research Institute (SERI), and industrial organizations suggest that state-of-the-art systems are likely to produce power at about 12¢/kWh. The Solar Thermal Technology Program is improving the performance and reducing the cost of solar thermal components and systems to reach energy delivery costs of about 5¢/kWh — the long-term goal. Further, increased attention is now being placed on reliability, availability, and system operational considerations to assist industry and end users in developing a self-sustaining market in the future.

Research to explore the special attributes of concentrated sunlight provided new insight and supporting evidence that these attributes can be put to effective uses beyond generating heat and electricity. High heating rates, concentrated high energy photons, and the broad spectral distribution of solar energy are the attributes of particular interest. New application potential was explored in laboratory experiments for waste detoxification, surface transformation of materials, and chemical synthesis.

Central Receiver Technology

During FY 1987, central receiver technology activities fell into five tasks: concentrators, receivers, balance of plant, central receiver systems, and system experiments. The most important activities in these tasks were stretched membrane and large glass/metal heliostat development; molten salt-in-tube and falling-film direct absorption receiver development; utility power plant system designs; operation of the Central Receiver Test Facility (CRTF); and the completion of power production operation and evaluation of Solar One, the 10-MW_e solar thermal central receiver pilot plant.

Concentrators

To achieve the long-term cost goal of $40/$m^2$ for heliostats, researchers are continuing the development of stepwise improvements in glass/metal technology while pursuing innovative designs that have the potential for dramatic cost reductions. During FY 1987, to further reduce costs and improve performance, the concentrator technology development activities were principally in four areas: (1) development of stretched-membrane heliostats, (2) development of large-area heliostats, (3) development of a low cost heliostat drive, and (4) development of cost-effective approaches to heliostat cleaning.

During FY 1986, Solar Kinetics, Inc. (SKI), and Science Applications International Corporation (SAIC) completed two independent studies on feasibility of stretched-membrane heliostats. The studies, which built upon prior work at SERI and Sandia, emphasized the design, fabrication, and costs of a commercial-scale, stretched-membrane heliostat.

The SKI and SAIC studies showed that in mass production, the simplicity and low weight of stretched-membrane mirrors result in heliostat costs that are more than 20% lower than current glass mirror designs. In addition, both contractors designed and built 50-m^2 prototype mirror modules that were as representative as possible of a commercial, stretched-membrane mirror design. The prototypes were installed in April 1986 for testing at the CRTF. During FY 1987, researchers began a 1-year evaluation of the optical performance of SKI's prototype mirror module. Major issues addressed in the test program include the optical performance of the stretched-membrane mirror, the performance of the mirror's focus control system on windy days, the reflective film, and the applicability of alternative methods for cleaning the polymer mirror.

Measurements of the optical performance during FY 1987 show the beam shape produced by SKI's mirror module is at least as good as current glass mirror designs. The measured beam shape and total beam power are close to theoretical values calculated with the HELIOS computer code. The observed image shape is indicative of the total heliostat beam dispersion. This reflected beam dispersion was estimated to be about 2.6 mr. This value is comparable to those for the second-generation glass/metal heliostat designs. After 14 months of outdoor exposure, the clean reflectivity of the silvered-acrylic film was over 92.8%, which is close to the 93.5% measured when the mirror was new. In calm conditions, the mirror defocus system can reduce the power on the target by over 80% in about 6 sec.

Also during FY 1987, researchers at Sandia began development of second generation stretched-membrane mirror modules. Researchers responsible for the design and construction of the first prototype mirror modules identified a number of areas where design improvements or additional cost savings might be possible. SAIC and SKI are developing an improved design for a mass-producible, commercial, stretched-membrane heliostat. In addition, each contractor will design and build a second 50-m^2 prototype mirror module. The prototypes will be installed in FY 1988 at the CRTF for testing.

Two large-area heliostat designs are under development. Advanced Thermal Systems Company (ATS) has fabricated a 148-m^2 glass/metal heliostat and has installed it for testing at the CRTF. Solar Power Engineering Company (SPECO) is building and installing a 200-m^2 glass/metal heliostat. Studies indicate that the heliostat cost per unit area of reflective surface decreases as heliostat size is increased. However, the use of larger heliostats causes a small reduction in performance because of optical defects, and concern exists over the ability of large heliostats to survive wind loads over an extended period. Evaluation of the optical performance of these heliostats is under way and will be completed in FY 1988.

Heliostat cleaning is highly cost-effective for central receiver power plants. Studies have shown that a 1% increase in mirror reflectivity produces more than a 1% increase in net energy produced by the plant. During FY 1987 researchers began to develop cost-effective methods of keeping heliostats clean.

Sandia began developing low cost heliostat drives in FY 1[illegible] The purpose of this activity is to reduce costs of the drives in mass production, which previously have ranged from \$18 to \$25/m^2 of heliostat area, to \$11/m^2. A contract was awarded to Peerless-Winsmith, Inc., to design the drives and fabricate prototypes. During FY 1987, the design of the drive was completed. Projected drive costs in mass production were estimated to be between \$11 and \$14/m^2. Fabrication of the prototype heliostat drives is under way.

Receivers

During FY 1987 Sandia continued efforts to improve reliability and decrease fabrication costs of molten nitrate salt receivers and components. Activities included testing an advanced 5-MW$_t$ molten salt-in-tube receiver and commercial-scale pumps and valves for molten salt service, testing flow characteristics of a falling-salt-film direct absorption receiver (DAR) using water, and designing a solar panel research experiment to test the DAR concept. These activities are an important step toward achieving the receiver long-term efficiency goal of 90% and cost goal of \$30/m^2 (expressed in dollars per square meter of heliostat area).

The Molten Salt Subsystem Component Test Experiment (MSSCTE, also called the Repowering Category B Project) is a hardware development and test program being conducted at the CRTF. The objective of the program is to resolve technical uncertainties related to components and subsystems of molten salt central receiver technology. The goals are to test an advanced molten salt receiver and to determine which commercially available pumps and valves are suitable for molten salt applications.

During FY 1987 the first phase of the 5-MW$_t$ molten salt receiver (a C-shaped cavity that incorporates features of a 60-MW$_t$ receiver) characterization was performed except for the optimization tests.

In addition, Sandia completed construction of the molten salt pump and valve test loops. The test loops will demonstrate the effectiveness of full-scale hot and cold salt pumps and qualify valves and packing materials under operational conditions expected in commercial solar power plants. Testing with salt will begin in early 1988. Completion of testing is expected by the end of 1988.

The falling-salt-film DAR was proposed in the mid-1970s to simplify and reduce the cost of central receiver systems. Potential advantages of the DAR include simplified design, improved thermal performance, increased reliability and operating life, and reduced capital and operating costs. Recent studies show that the cost savings and improved performance can result in reductions in levelized energy costs of 17%-26%. A number of technological uncertainties affecting DAR feasibility require resolution before the concept can be considered a commercial alternative.

To allow flow testing with nitrate salt and provide a test bed for DAR testing in an actual solar environment, researchers are designing a 3-MW_t salt flow loop. Work has been initiated to examine receiver-specific aspects of a commercial DAR, emphasizing differences between salt-in-tube receiver designs and the DAR. Major issues being addressed include panel and support design alternatives, thermal stress and deformation analyses of the receiver panels, salt containment and blackener issues, and costs relative to more conventional receiver designs. An 8 m by 1 m water panel test apparatus is in operation to support the design of the salt loop and DAR panel.

Balance of Plant

The development of two central receiver dynamic simulators continued during FY 1987 as part of an effort to optimize the design and operation of molten nitrate salt plants. ESSCOR Corporation, under contract to Sandia, developed a simulation model of the MSSCTE system currently being tested at the CRTF. Sandia's researchers developed a model of a hypothetical DAR. Both models run real time on a portable computer. These models are being used to accomplish the following objectives: 1) to understand central receiver system performance during transients, 2) to test, optimize, and design central receiver control algorithms, 3) to understand component response to component failures, and 4) to optimize annual energy production from central receiver plants. Work during FY 1987 concentrated on the first two objectives.

Comparisons of the predictions of the CRTF model with experimental results indicate the model gives good performance predictions. The model also produced qualitative insights regarding system dynamics that were subsequently verified by experimental results.

Central Receiver Systems Study

This task continued during FY 1987 to focus on the conceptual designs of commercial-scale central receiver power plants. A group of western electric utilities in a cooperative effort with DOE led efforts to assess the component and system progress that has been made and decide what power tower design options could best fit their future generating needs. Leaders of the two team efforts were the Pacific Gas and Electric Co. (PG&E) and Arizona Public Service Co. (APS). Both teams had participated in designing conceptual utility-scale solar central receiver plants prior to the current studies.

At the end of the year-long study both teams came to essentially the same conclusion about the preferred option for the plant and agreed on the best configuration for a commercial power tower. The teams concluded the first few plants may be 100-MW_e size to reduce the financial risk and uncertainty. The mature plants will be about a 200-MW_e size. The teams predicted annual performance to be about 320-330 GWh net per year for the first 100 MW_e plant at a cost of about $0.11-$0.12 per kWh. The operating capacity was projected to be about 38%.

A second major activity of the Central Receiver Systems Study task in FY 1987 was the initiation of a multiyear study aimed at improving the annual efficiency of central receiver plants. The annual energy improvement study will identify design and operation improvements that will bridge the gap between the current efficiency prediction of 15% and the long-term goal of 22%.

During FY 1987 a computer code called SOLERGY was developed to predict annual energy from central receiver power plants. The code uses a measured record of insolation at 15-min intervals to predict annual energy output. SOLERGY was used in a validation study against the actual performance of the Solar One power plant for 1985. SOLERGY was also used to identify the most important causes of system inefficiency at Solar One.

System Experiments

During FY 1987, the only system experiment under way was the Solar One 10-MW_e Solar Thermal Central Receiver Pilot Plant. Solar One produced power throughout the year and demonstrated its operational capability to supply power reliably to a utility grid. In July 1987, Solar One completed the third year of its power production phase. On July 23, 1987, the plant set a new daily production record of 97.4 MWh_e net. Another record was set on July 14, 1987: the plant operated for its 38th consecutive day.

Solar One started the semi-commercial phase on August 1, 1987. The goal of the semi-commercial phase is to operate the plant in the most cost-effective manner. To this end, Southern California Edison (SCE) is currently operating the plant 5 days a week and is attempting to operate the plant with a minimum number of operating and maintenance personnel.

The Solar One collector subsystem has been operating since November 18, 1981. The overall performance of the collector field has been excellent and very reliable. One panel was severely deformed because of a problem with the drain valve; however, the receiver operated successfully throughout FY 1987. During the entire 3-year power production phase, the heliostat availability was greater than 97%.

During FY 1987 SCE performed an analysis that showed that continuous cleaning of the heliostat field was cost-effective. (Continuous cleaning requires the maintenance crew to clean the heliostats one at a time and, when finished, to start over again with the first heliostat). Consequently, SCE implemented continuous cleaning at the plant using an acid wash that restores reflectivity to the heliostats' design values.

Distributed Receiver Technology

Most of the work in distributed receiver (DR) technology development during FY 1987 was directed toward developing the components of distributed concentrating solar collector systems and testing and analyzing the performance, cost requirements, trade-offs, and applications of such systems. The distributed receiver technology development studies fell into seven tasks: concentrators, receivers, engine conversion technology, transport and storage, controls, DR systems, and systems experiments.

Concentrators

Four areas constitute the major emphasis of point-focus concentrator development: the DOE innovative concentrator development, the stretched-membrane dish collector development, the concentrator materials development, and the line-focus concentrators.

The DOE innovative concentrator development is a two-phase program in which detailed concentrator designs are developed in phase I, and prototypes are fabricated and tested during phase II. The concentrating collectors designed in this project are required to meet specific performance and survivability criteria; be modular and mass producible; be easy and economical to manufacture, assemble, and operate; and have a 10- to 20-year life. Two contractors, the Acurex Corporation and the LaJet Energy Company (LEC), fabricated and delivered dish collectors to the Distributed Receiver Test Facility (DRTF) for testing and evaluation during FY 1987.

The Acurex Innovative Concentrator is a continuous, 15-m diameter, paraboloid of revolution constructed from 18 pie-shaped gores. The predicted thermal output of this dish at 91% optical efficiency is 161 kW_t at 1 kW/m^2 solar input. The collector was assembled at the DRTF in October and November of 1986. A sheet metal concentrator such as the Acurex collector has the potential for lightweight, high performance and could be closer than other dish-type collectors to commercial-readiness. The concentrator suffered severe wind damage in December 1986, and Sandia and DOE continue to evaluate various options for reassembling and testing the collector.

The LEC innovative concentrator uses 95 polymer membrane facets 1.5 m in diameter to concentrate the sun's energy. The curvature of the facets is maintained by a vacuum between the front reflective membrane and a back membrane. The LEC concentrator is 19.3 m in diameter and is predicted to have an optical efficiency of 90% and a thermal output of 145 kW_t. The collector was delivered to the DRTF and assembled during July and August of 1987. Testing is scheduled to begin following the installation of thermal protection for structures near the focus in early December 1987.

The stretched-membrane dish collector development is organized into three phases. Phase I is the preliminary design of an optical element and experimental evaluation of facet fabrication techniques and performance. Phase II is the detailed design of the complete collector including the support structure, drives for tracking, and the control system. Phase III is the construction and testing of the collector. The goals are to build a large (approximately 150-m^2) stretched-membrane dish collector with a focal-length-to-diameter (f/D) ratio near 0.6. The optical membrane must be of high optical quality, having an average slope error of less than 2.0 mr, a collector mass of from 30 to 45 kg/m^2, and a peak optical efficiency of 91%.

At the completion of a competitive procurement process in October 1986, SKI and LEC were awarded contracts to pursue phase I of the stretched-membrane dish collector development. The contractors will complete phase I designs in November 1987, and the phase II award will most likely be placed in February 1988.

The concentrator materials development emphasis in FY 1987 was to adapt the sol-gel protective coating technology used with the structural mirrors to thin-foil mirrors that can be used for stretched-membrane applications. A problem inherent in the use of silvered metal foils as mirrors is the lack of a surface finish suitable for mirror applications. The application of sol-gel as a planarizing layer between the steel foil and the silver reflective layer prevented galvanic coupling between the silver and the steel and improved the reflectance (from 71% to 95% with four coats of sol-gel). Researchers began efforts to apply a suitable protective overcoat for environmental protection.

Testing of line-focus concentrators continues for the evaluation of improved components. During FY 1987 the following component improvements were evaluated: Acurex direct-embedded pylons with self-aligning bearings, Acurex evacuated receivers, and SKI stainless-steel receivers. Results were encouraging and mark the gradual incremental improvement of trough performance and durability.

Receivers

The primary objective of the receiver task is the development of efficient, low cost, reliable solar receivers for Stirling engines and thermochemical transport applications. Sandia developed concentrator and receiver modeling codes in FY 1986 as a first step in establishing a comprehensive and versatile point-focus receiver design capability.

During FY 1987, a computer code called CIRCE was validated with experimental data. This code was developed as a dish-specific optics simulation package for predicting incident solar flux distributions. It provides an understanding of the behavior of dish receivers, including heat loss, and simulates dish performance.

The U.S. Sandia-Israel Reflux Receiver/Reactor was designed in FY 1986. The "reflux" receiver concept as a viable receiver option was developed as part of a bilateral agreement between the United States and Israel. During FY 1987 the receiver was fabricated at Sandia and tested at the Weizmann Institute of Science solar furnace in Rehovot, Israel. The tests in Israel successfully demonstrated that the receiver provides efficient transport to the reactors. The temperature distribution within the heat pipe was extremely uniform, and good agreement with computer models on the process was obtained. This was the first on-sun test of this important receiver concept.

The main thrust of heat engine development is for Stirling cycle machines and reflux heat-pipe receivers. The STT Program is sponsoring several activities to develop and investigate reflux heat-pipe receiver options for kinematic and free-piston Stirling engines. During FY 1987 researchers initiated the detailed design of a reflux heat-pipe solar receiver for the Stirling Thermal Motors STM 4-120 kinematic Stirling engine. In FY 1988 this design will be completed with fabrication testing at Sandia on the test bed concentrator (TBC) to follow. After this testing, the receiver will be coupled to the engine for a total system test.

Engine Conversion Technology

The objective of this activity is the evaluation and development of the heat engine technologies applicable to distributed receiver systems.

Current heat engine development is focused on the Stirling cycle. Particular emphasis is being placed on the development of engines in the 20-50 kW_e size range to match current and future parabolic dish thermal capacities. In addition, the thermally regenerative electrochemical systems, the liquid metal thermal electric converters (LMTEC), are being investigated and developed.

Through an interagency agreement between DOE and NASA, Sandia is coordinating with NASA Lewis Research Center (LeRC) to develop an Advanced Stirling Conversion System (ASCS) based on free-piston Stirling and reflux heat-pipe receiver technology. During FY 1987 contracts were placed with Mechanical Technology, Inc. (MTI) and Stirling Technology Corporation (STC) for conceptual design of two ASCSs.

Stirling Engines. Heat engine development at Sandia is focused on the kinematic and free-piston Stirling engines. Because of the few moving parts, the free-piston Stirling engine is ideally suited for solar application; it requires less maintenance and operates longer than the reciprocating combustion engine, while retaining high thermodynamic cycle efficiency.

During FY 1987 under technical management by LeRC, MTI and STC completed their phase I conceptual design of the free-piston Stirling engine. Both contractors used the basic free-piston Stirling concept. However, each applied a different approach for converting the engine's mechanical power to electrical power. MTI introduced a linear alternator while STC choose to operate a conventional rotary generator via hydraulic fluid converter in the engine.

Phase II of the ASCS program will be detailed design and hardware manufacture. It will begin in late FY 1988 or early 1989.

Liquid Metal Thermal Electric Converter (LMTEC). Since FY 1985, Sandia has been actively engaged in the evaluation and development of heat engine technologies applicable to a dish electric system. This ongoing effort identified the LMTEC concept as promising for the STT Program's long-term cost and performance goals.

During FY 1987, significant progress was made in the evaluation and development of the LMTEC concept. Sandia completed construction, testing, and post-test analysis of the LMTEC bench test model (BTM). Motivated by the results of the first BTM, Sandia developed a new thin-film electrode permeability test. In addition, contract work at the University of Pennsylvania and the University of Wisconsin has resulted in continued progress towards the successful production of single and polycrystalline samples of the mercury analog of sodium-alumina solid electrolyte.

Transport and Storage

The objectives of this task are to identify, develop, evaluate, and demonstrate high efficiency, low cost energy transport and storage systems suitable for high temperature solar thermal distributed receiver applications. In implementing these objectives, the emphasis has been on developing and demonstrating the technology of thermochemical (TC) transport for point-focus central engine applications. TC transport involves the transport of latent heat of reaction from an endothermic chemical reaction in the receiver of a dish to a centralized exothermic reactor at a distant point of use. TC energy transport appears to provide a cost-effective alternative to sensible heat energy transport from a field of point-focus solar thermal collectors.

FY 1987 activities included complementary modeling and experimental studies to demonstrate the feasibility of TC energy transport for DR applications. The SOLTES steady-state sensible energy transport performance code was modified in FY 1987 by incorporating TC transport models obtained from the Closed Loop Efficiency Analysis (CLEA) code. Model development activities were also undertaken as part of a catalyst evaluation and development study being performed at the University of Houston. Two CO/H_2 methanation models and a closed-loop CO_2/CH_4 reforming/methanation model were completed during FY 1987.

Experiments continued during FY 1987 in the CLEA thermochemical energy transport facility (2.5 kW_t). An endothermic reactor capable of reaction temperatures between 900° and 1000°C was designed and fabricated for the CLEA facility during FY 1987. A two-stage methanator, the first stage adiabatic and the second stage isothermal, was also designed and fabricated during this period.

Catalyst evaluation and development studies have continued at the University of Houston in support of the CO_2/CH_4 TC transport system. Accomplishments in FY 1987 include: (1) preliminary determination of rate equations, heat transfer parameters, and deactivation rates and mechanisms for rhodium-based catalysts in pellet form, and (2) modification of existing computer models.

Closed Loop Operations Experiment (CLOE) is based on the CO_2/CH_4 reforming/methanation chemical system and will be conducted in two phases. Phase I involves conservative, state-of-the-art receiver/reactor designs. Phase II involves advanced receiver/ reactor design concepts capable of operating at higher temperatures; at least one of these units will be mounted on a parabolic concentrator to demonstrate operation in a true solar environment. A contract was placed early in FY 1987 with Resource Analysis International (RAI), Inc., to perform a detailed design of the CLOE phase I system. A significant accomplishment during the fourth quarter of FY 1987 was the completion by RAI of stage II (Chemical Engineering) of the CLOE phase I design. RAI supplied Sandia with a design package that included a process flow diagram, piping and instrument diagrams (P&IDs), design drawings, equipment, piping and instrument specifications, and a preliminary plot plan.

Controls Study

Control system failures are a major cause of downtime in solar power facilities. During FY 1987 a study was undertaken to identify central needs for distributed receiver systems. The study concluded that greater emphasis should be placed on developing intelligent tracking controls, improving system models, and producing inexpensive flow regulating devices.

Distributed Receiver Systems

Two projects constituted the major emphasis of the distributed receiver systems task: systems engineering and analysis, and the Shenandoah Solar Total Energy Project (STEP).

Systems Engineering and Analysis. During FY 1987 the systems engineering and analysis project concentrated on completing phase II of the central engine study. This study investigated the viability of using current large Rankine turbines for conversion along with two types of heat transport methods: sensible and thermochemical.

The results of phase II of the central engine study were encouraging for systems comprising a 50-MW_e steam Rankine turbine, a thermochemical transport system, and an appropriate number of near-term technology dishes. The study, in fact, indicated that the optimum size of such a plant might be larger than the 50-MW_e size studied.

Shenandoah Solar Total Energy Project. The objective of STEP is to evaluate a solar total energy system that provides electric power, process steam, and air conditioning in a realistic industrial environment. During FY 1985 a series of 29 system tests were completed. Substantial facility upgrades were completed, and title to the project was turned over to the Georgia Power Company as scheduled. Continuous operation testing was completed by the end of FY 1985. Solar field heat loss experiments were conducted in FY 1986, as were system performance tests related to turbine performance. During FY 1987 Georgia Power revamped the entire collector field control system to simplify the operation and reduce labor requirements. Modifications were also made by Sandia early in FY 1987 to improve the performance.

Testing of the improved output of the STEP plant has continued throughout FY 1987. The final reports of the results will be published in FY 1988.

Small Community Solar Experiments

The Small Community Solar Experiment (SCSE) projects were undertaken to evaluate solar electric 100-kW_e plants. In prior years DOE selected Osage City, Kans., and Molokai Island, Hawaii, as the sites for these experiments. Each SCSE will use point-focus concentrators and heat engines. DOE/Albuquerque selected Barber-Nichols Engineering as the prime contractor for the SCSE #1 at Osage City, Kans. Power Kinetics, Inc. (PKI) is a subcontractor to Barber-Nichols and will provide the concentrators for the electric generating modules. By the close of FY 1985, the SCSE #1 module verification test unit was being installed at the DRTF for preproduction evaluation testing.

During FY 1987 Barber-Nichols recommended that PKI's collector be replaced by the LaJet Energy Company's collector because of the low performance of the PKI concentrator. In August 1987 the subcontract between LEC and Barber-Nichols was approved and the Barber-Nichols engine will be tested on the LEC concentrator. The Barber-Nichols organic Rankine cycle (ORC) engine was installed on a 100-kW electric solar simulator at the DRTF for contined testing until the LEC innovative concentrator is qualified. Testing of the second ORC engine for the Osage City verification module began.

In 1985 DOE/Albuquerque selected PKI as the prime contractor for the SCSE #2 at Molokai, Hawaii. This system will feature five collectors with 50-kW_e steam engines to provide a 250-kW_e system capacity. The PKI contract became effective late in FY 1985. The design of this system is nearing completion.

The Verification Test Module, originally scheduled to begin testing in March 1987, was delayed for approximately 12 months while detailed design drawings were prepared and a complete structural analysis performed. Verification testing will begin in February 1988.

Research

The STT Research Program involves analysis, evaluation, modeling, experimentation, and measurements that are performed for the purpose of defining and developing options for all solar thermal technology. The research identifies and verifies the technical feasibility of new concepts that could lead to a significant reduction in cost or an increase in the efficiency and reliability of solar thermal systems. The research program is also exploring new ways for converting solar thermal energy into useful products. The research, furthermore, seeks to obtain additional data on materials, mechanisms, operation, and performance of concepts so that analyses can be performed to determine the potential for such ideas in the future. The work also characterizes components, materials, and subsystems required for new or existing concepts that have not reached engineering development.

In FY 1987, research at SERI centered on silver-polymer research, membrane concentrators, DARs, and the effective use of unique attributes of the concentrated solar spectrum.

Silver-Polymer Research

The two primary goals of the silver-polymer research are to develop and verify the technical feasibility of at least one silver-polymer reflector material applicable for low cost, lightweight concentrators, and to develop durable, stable, ultraviolet-resistant polymer reflectors. These materials must have a reflectance of at least 90% and maintain this optical performance for at least 5 years.

The principal objectives of the FY 1987 research were to improve the durability of the promising silver-polymer reflectors identified earlier. Another objective was to identify and characterize ultraviolet stabilizers for polymers to protect them in prolonged environmental exposure.

Because concentrators account for 40%-60% of the cost of a solar thermal system, durable, low cost, novel reflector materials are important for reducing concentrator cost (hence, reducing the solar thermal system cost), improving their expected useful lives, and increasing their optical efficiency.

During FY 1987 research concentrated on optical characterization of silvered polymers and on the chemical modification of polymer-stabilizer systems. Additional efforts involved industrial-scale fabrication and testing of flexible silvered acrylic mirrors by 3M Company and studies on factors limiting the performance of laminated constructions. Researchers also conducted laboratory-scale studies at the University of Akron on the effects of processing variables on the surface optical properties and durability of silvered polymers, and on the mechanical properties of polymer films for all-polymer membrane mirrors.

Significant progress occurred in several research areas. Researchers have shown that (1) the initial optical performance is well within the long-range goals and is maintained for over 4 years outdoors, (2) the polymer films perform satisfactorily in an outdoor environment, (3) performance outdoors is site dependent and at least one site causes reflectances to fall below the 5-year goal within a 2-year time interval, and (4) the silver/polymer interface is the major point of degradation, and experiments are identifying the main causes of degradation.

During FY 1987 the emphasis of the ultraviolet-resistant polymer materials research was on synthesizing and testing various polymeric stabilizers of the hydroxy-benzotriazole, hydroxy-benzophenone, and hindered amine classes to be included in the host polymer (polymethylemthacrylate) of interest.

Researchers demonstrated that polymeric stabilizers are good candidates for further improvement in mirror durability. Weathering tests demonstrated that both optical performance of stabilized glazings and photolytic stability of stabilizers depend strongly on the accelerated weathering mode selected. Photolytic deactivation of the stabilizers is slow enough to allow required outdoor lifetimes of mirrors for at least 5 years; however, it may become a factor after more prolonged use.

Membrane Concentrators

Concentrator research in FY 1987 focused on stretched-membrane dishes. The major goal was to define the cost-performance potential of using stretched-membrane technology for parabolic dish applications. Significant advantages, similar to those that have accrued for stretched-membrane heliostats, are possible for dishes using the membrane design. In carrying out this research, researchers have extended existing data bases developed for stretched-membrane heliostats.

In developing the description for the potential cost-performance benefits of stretched-membrane dishes, SERI has defined and pursued several major areas of investigation. These include research on the structural-optical response, the optical performance of the dish subsystem, the membrane material fabrication, and the experimental testing of prototypes.

In FY 1987, several structural models of a membrane shape were developed and applied to determine the proper initial shape of a membrane prior to vacuum stabilization. In addition, a model to determine overall dish thermal efficiency was developed. Also in FY 1987, research continued that evaluated various composite materials for several membrane reflector concepts usable with either dish or heliostat applications.

Direct Absorption Receivers

The goal of the research on the DAR is to advance the state of theoretical and experimental knowledge so that information for the design of a DAR, including the specification of feasible configurations, working fluids, and operating modes, is sufficient for an experienced designer to design a near-commercial scale receiver.

The objectives of the DAR research task in FY 1987 were to study both experimentally and analytically many of the remaining heat transfer and fluid dynamics issues needed for understanding the phenomena of direct absorption of concentrated solar flux in doped nitrate salt. The major research accomplishments of the task in FY 1987 included the following.

SERI conducted small-scale laboratory experiments using the DAR test loop to understand the nitrate salt film behavior with and without dopant. In addition, water-film experiments were conducted to study the flow distribution over alternative surfaces and multiflow zones. Installation modifications of the DAR test loop were completed at SERI's Field Test Laboratory Building. Testing with the 250-kW radiant heater began. A method for calibrating the flux produced by the heater, in the plane of the DAR test panel, was developed. Results of the calibration showed that the heater produces peak flux as high as 700 kW/m^2 and that the flux distribution was quite uniform.

Researchers completed an apparatus that enables them to observe the behavior of long films of falling water. An instrument was designed and fabricated that allows researchers to measure a time series of the film thickness in any location on the lucite tube, thus providing information on the roll wave height, spacing, and other important parameters. This enables the characterization of the wave patterns expected in a nitrate salt DAR.

Researchers succeeded in containing molten nitrate salt at the edges of open channels in a no-flux environment. A number of different configurations were tested. A special C-shaped edge configuration succeeded in containing the salt. Tests show that the molten salt was totally contained on the Inconel DAR test panel (15 cm wide by 60 cm long) at Reynolds numbers up to 20,000 (the maximum for the DAR flow loop). This edge containment configuration proved effective during flux tests. Also a commercial DAR will operate most likely at higher salt flow rates. This method of salt containment appears to work well beyond a Reynolds number of 40,000 and, if necessary, further refinements would allow the method to work at any flow rate.

Researchers at the Northwestern University developed hydrodynamic models of the flux-induced film dryout problem. This model considered a horizontal, quiescent salt film exposed to a lateral flux gradient (100 kW/m^2 m) and a flux distribution meant to simulate the effect of waves on the salt film. Both clear and doped salt were considered. The lateral flux gradient had negligible effects on the salt film. A disturbance simulating a ripple developed a depression of about 37% of the undisturbed film thickness. The model revision will begin in FY 1988.

The goals of materials research are to identify materials (heat transfer fluids and containment materials, in particular) and collect information on materials properties for use in the design and development of effective, durable, and economically feasible DARs. Key issues are the optical performance, durability, and compatibility of the materials involved. Two categories of DAR materials were subject to this research. The first category involved salts to be used as heat transfer fluids; the second included containment materials. These materials are subjected to a rather severe environment in DAR use: working temperatures to 600°C with possible excursions to more than 700°C because of receiver hot spots; solar fluxes to at least 500 suns with some design goals to several thousand suns; uneven and cyclic heating; mechanical, hydraulic, and thermal stresses, both static and dynamic; and chemical effects such as corrosion and decomposition because of environmental effects and material interactions.

The work during FY 1987 addressed issues related to the properties of dopants for addition to the molten salt and compilation of data on the physical and chemical properties of draw salt. These efforts consisted of two major activities. One was to identify materials that could be added to the molten salt to increase the absorbance of the solar energy; the other, to review literature to collect data on the physical and chemical properties of molten nitrate salts.

During FY 1987 system analysis studies compared the DAR concept with the salt-in-tube receiver, and an internal film receiver concept with a salt-in-tube receiver. An earlier comparison of the cost and performance of the DAR receiver with a salt-in-tube receiver in the context of a solar thermal system for electricity production was updated to include a receiver designed by the recent Utility Central Receiver Study. The study concluded that the DAR continues to offer the potential for significant (16%) improvements in the levelized cost of delivered electricity. A comparative evaluation of the internal film receiver (IFR) concept versus salt-in-tube receiver showed that the IFR has many of the advantages of the DAR, but of a lesser magnitude.

Solar Regenerative Thermoelectrochemical Conversion

Researchers at the Hughes Aircraft Company have invented and are researching a Regenerative Thermoelectrochemical Converter (RTEC) for efficiently converting concentrated solar thermal energy to electricity. The RTEC concept appears to have significant potential for both dish and central receiver applications. The engine has the potential for high efficiency (up to 40%), good reliability (40,000-100,000 h lifetime) and good maintainability because simple pumps are its only moving parts. It also provides high-energy-density chemical storage.

Direct Conversion

The goal of direct conversion research is to establish the feasibility of using concentrated solar energy beneficially for addressing important national energy needs such as detoxifying chemical waste products, producing transportable fuels and high value chemicals, and modifying the properties of materials.

Most of the work in direct conversion research was directed toward photoenhanced solar detoxification of hazardous wastes, conversion of chemicals, and solar enhanced material processes.

Researchers at the University of Dayton have shown that certain hazardous chemical groups [such as polychlorinated biphenyls (PCBs) and dioxins] are destroyed more efficiently using concentrated solar flux than by strictly thermal methods. The advantage evidently stems from the high energy portion of the solar spectrum causing non-equilibrium processes that lead to chemical bonds being broken. In FY 1987 researchers ran additional experiments, with higher light intensities, to show the destruction of a dioxin isomer to 99.9999% destroyed for a thermal system with simulated sunlight in both oxidative and pyrolytic environments. Pyrolysis is partial combustion where the reaction is starved for air and sunlight provides the energy for destruction. Using sunlight this way would result in a substantially reduced investment in the plant, reduced operating costs, and enhanced performance.

Another objective of this research is to show that direct use of concentrated solar flux will enhance the conversion of chemicals or materials to high value forms that are difficult or impossible to produce by using fossil fuels. The enhancements are expected to be an improvement in yield, an improvement in product selectivity, or a substantial increase in the rate of conversion.

Researchers at the University of Houston are experimentally investigating the photoenhancement of chemical reactions, with emphasis on catalytic reactions that use solids to absorb the direct flux. These experiments are accompanied by an activity to build a data base of chemical reactions that are of industrial significance and that are amenable to photoenhancement. This data base is especially aimed at chemical transformations that substantially increase the value of the products compared to the reactants. These activities will lead to a goal definition of the potential of photoenhanced conversion of chemicals.

During FY 1987 the solar-enhanced material process task efforts were directed to using concentrated solar flux to increase the strength and abrasion resistance of strategic materials — materials that could lead to high efficiency, high temperature engines and turbines. Researchers at Georgia Tech Research Institute are setting up experiments to compare the effects of solar irradiation of materials in a solar furnace with those of pure thermal effects obtained in an electric furnace. Materials chosen for study include carbon fibers; advanced carbon-carbon composites; and zirconium and hafnium carbides in the form of powders, whiskers, or coatings. Researchers have successfully enhanced the oxidative resistance of commercial carbon fibers by direct flux processing in the solar furnace. Tests are under way to actually produce fibers and to test for beneficial changes in other properties. Experiments have resulted in production of hafnium carbide whiskers. Further experiments are under way to define the solar enhancement in this chemical vapor deposition process.

SERI's materials research emphasized the use of highly concentrated solar radiation to produce high quality and high-value-added metallurgical coatings on materials. Significant progress has been made in research on systems that appear to be good candidates for this technology. A sample holder was designed and made to specifications for the solar furnace at Sandia. Samples of various substrate materials were purchased, cut, lapped, polished, and coated with appropriate materials for the experiments. Seventy-six samples were exposed to the high solar flux in either air or flowing nitrogen gas. Numerous samples were analyzed by metallurgical cross section, microscopic examination, microhardness testing, and by the methods of surface science and composition-in-depth profiling. The results of these experiments are encouraging, and industrial interest in the process is growing.

Chapter 1
Introduction

The Program Goal and Objectives

The goal of the Solar Thermal Technology (STT) Program is to establish the technology base for commercial applications of solar thermal energy, thereby allowing the private sector to produce and deploy systems capable of meeting the range of energy demands typical of U.S. industry and utilities. This goal focuses on developing, in cooperation with industry, the materials, components, subsystems, and processes capable of meeting specific energy cost targets. The program, therefore, fosters research and development (R&D) to increase system efficiency and reliability, reduce the cost of delivered energy, and develop new applications where the solar thermal technology has high strategic or economic value.

To achieve this goal, the following objectives were defined:

- Complete the R&D required to support the mid-term needs of industry and utilities for electric, cogeneration, and process heat applications.
- Conduct the long-term R&D needed to expand the technology base of solar thermal energy into new high risk, high payoff solar concepts with deployment beyond 1990.

Since 1975, substantial progress has been made in solar thermal technology. Advances are reflected in terms of improved performance, reliability, and economics. A collaborative effort by industry, academia, and government over the next 5 years is essential to work toward achieving the program technical and cost targets. Two such targets are to deliver electrical energy at $0.05/kWh and heat energy at $9/MBtu or less. The long-term technical and cost targets, established in cooperation with private industry during preparation of the 5-year plan*, are shown in Table 1.1.

The strategy for meeting the program objectives is to pursue government-sponsored and cost-shared R&D aimed at achieving a sufficient level of technical maturity for the various solar thermal technologies. With this approach, decision makers within the private sector will find risks acceptable should they choose to manufacture, market, or use the technologies.

Organization

The program, conducted by the U.S. Department of Energy (DOE), comprises three major subprograms: central receiver technology, distributed receiver technology, and solar thermal technology research. These subprograms are responsible for R&D of solar thermal materials, components, subsystems, and systems. Day-to-day research activities are conducted on an in-house or contract basis by two national laboratories. Figure 1.1 shows institutional relationships.

R&D Activities

During FY 1987, the most important activities in the central receiver technology areas were stretched-membrane and large glass/metal heliostat development; molten salt-in-tube and falling-film direct absorption receiver development; utility power plant system designs; operation of the Central Receiver

*National Solar Thermal Technology Program, *Five-Year Research and Development Plan 1986-1990* — September 1986 (DOE/CE-0160).

Table 1.1 Solar Thermal Long-Term Targets

Target	Electricity	Heat
System factor cost efficiency, %	22-28	56-68
System capital cost (1984$)[a]	\$1300-\$1600/kW_e	\$390-\$470/kW_t
Capacity factor	0.25-0.50	0.25-0.30
System factor cost (1984$)[b]	\$0.05/kWh_e	$9/MBtu

[a]Normalized to turbine or process capable of handling peak field thermal output; includes indirect costs.

[b]Energy costs levelized in real dollars; economic assumptions differ between electric and heat systems.

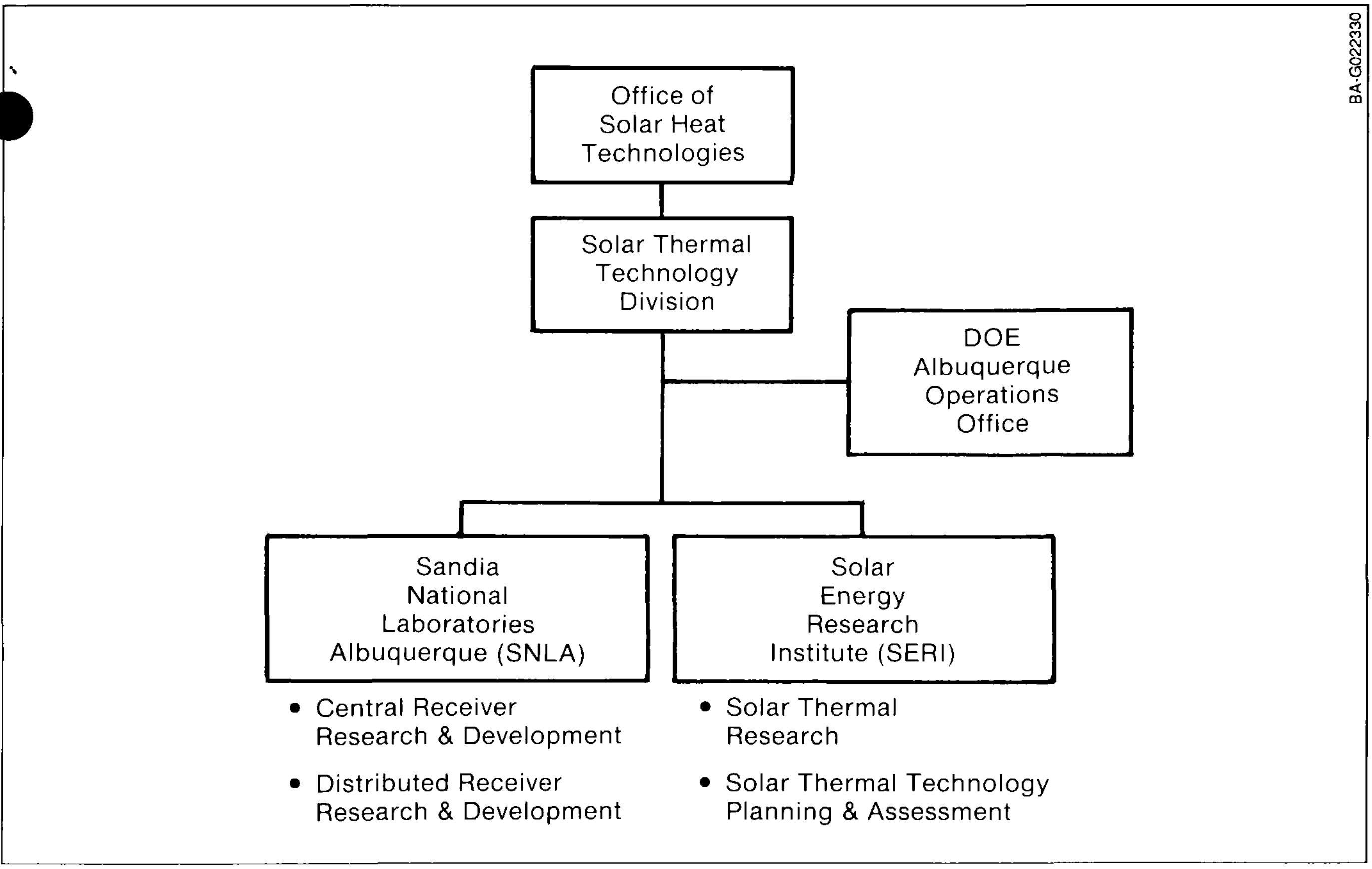

Figure 1.1 Solar Thermal Technology Organizational Structure and Responsibilities

Test Facility (CRTF); and the completion of power production operation and evaluation of Solar One, the 10-MW_e solar thermal central receiver pilot plant.

Most of the work in distributed receiver (DR) technology development during FY 1987 was directed toward developing the components of distributed concentrating solar collector systems and testing and analyzing the performance, cost requirements, trade-offs, and applications of such systems.

In FY 1987, solar thermal research emphasis was on increasing the durability and lifetime of reflectors, optical and structural analysis and evaluation of membrane concentrators, and phenomena of thin-film salt flow in direct absorption receivers. Research was also under way to explore new applications of concentrated solar energy. Thus far, nearly all solar thermal applications have converted the concentrated solar energy into electricity or into heat to be used in industrial processes.

Use of the unique attributes of solar flux can lead to new applications. For example, a university research team found that certain toxic chemicals can be efficiently destroyed with concentrated solar energy. Other potential applications explored include treatment of materials to make them more valuable by making them wear and corrosion resistant. Strategic chemicals, using photon enhanced chemical synthesis, can also be produced from concentrated solar energy.

The balance of this report contains the description, objectives, and FY 1987 accomplishments of all elements of the STT Program. Also included, where appropriate, are the issues and technical barriers that still need to be overcome.

Chapter 2
Central Receiver Technology

In a solar thermal central receiver system, large sun-tracking mirrors called heliostats concentrate and focus incoming solar energy on a tower-mounted receiver (Figure 2.1). In the receiver, the solar energy is captured as high temperature thermal energy. Thermal energy can be converted to electric power, used to provide industrial process heat, or stored for use as required. Having thermal or chemical energy storage allows solar central receiver plant operation during periods of low or no solar insolation.

This chapter describes the accomplishments and progress of central receiver research and development activities in FY 1987. In FY 1987, central receiver activities fell into 5 of the 11 task categories described in the plan: concentrators, receivers, balance of plant, central receiver systems, and system experiments.

The most important activities were stretched-membrane and large glass/metal heliostat development; molten salt-in-tube and falling-film direct absorption receiver development; utility power plant system designs; operation of the Central Receiver Test Facility (CRTF); and the completion of power production operation and evaluation of Solar One, the 10-MW_e solar thermal central receiver pilot plant.

Concentrators

The heliostat field comprises 35%-45% of the total capital cost of a central receiver system. Therefore, reducing the cost of heliostats while maintaining optical performance is crucial to the successful commercialization of central receiver technology. Current heliostat technology is based on the use of silvered-glass mirrors. Sandia estimates the costs for these glass mirror heliostats to be about \$200-\$300/m^2 at moderate production rates. Mass production and further improvements in glass mirror heliostat designs could reduce the cost to less than \$100/m^2.

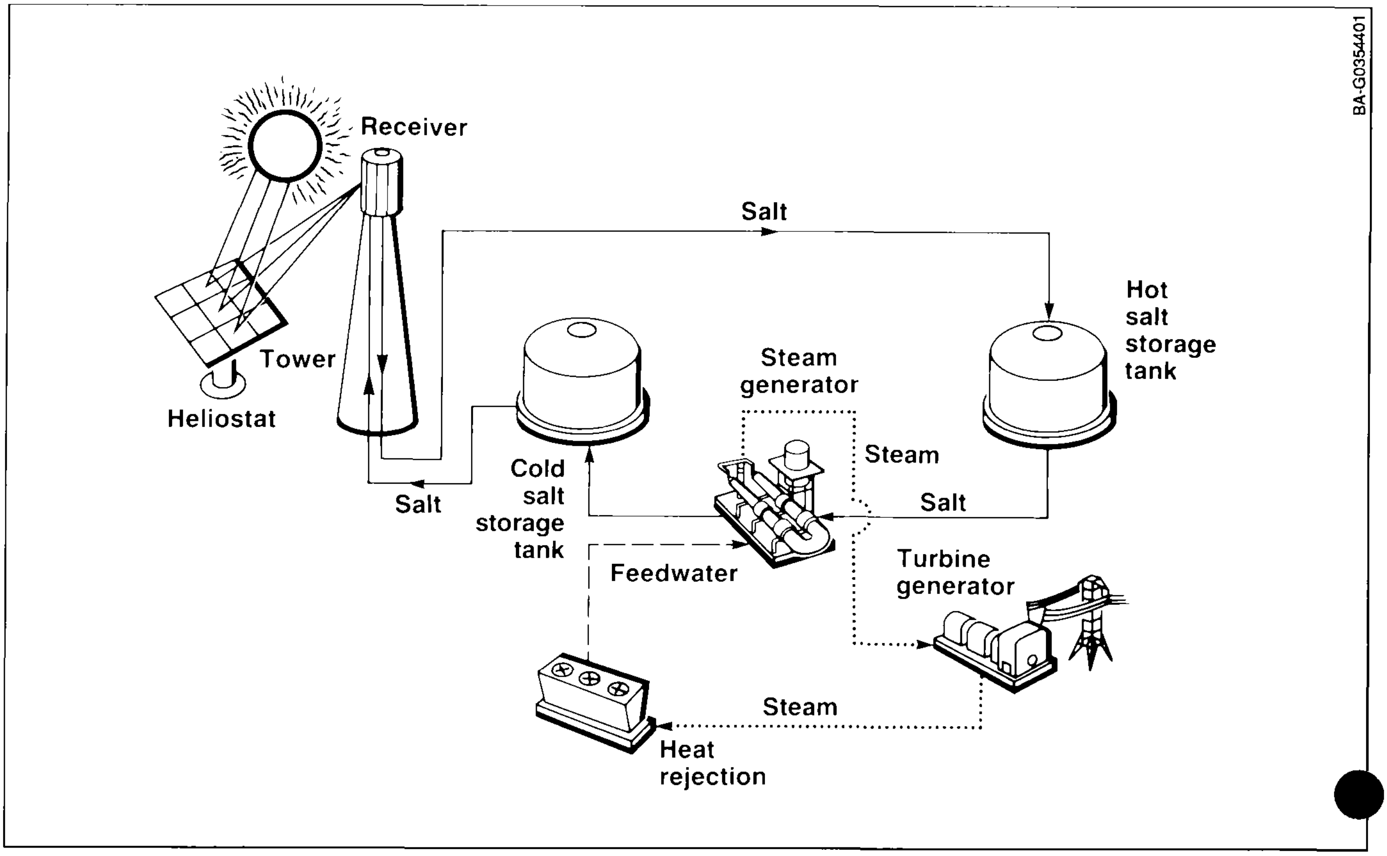

Figure 2.1 Flow Schematic of a Molten Salt Central Receiver System

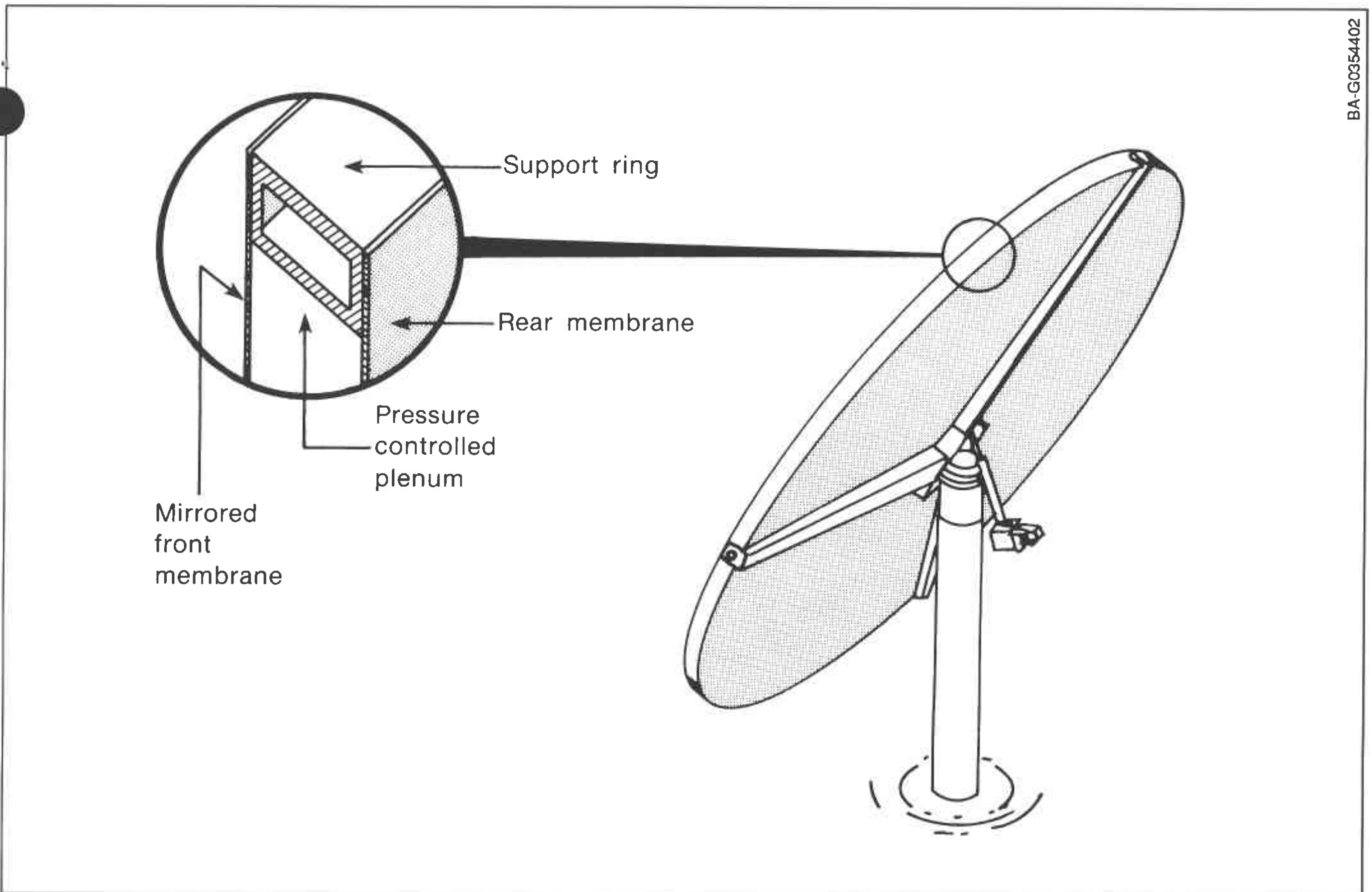

Figure 2.2 Stretched-Membrane Heliostat Design

To further reduce costs and improve performance, researchers are continuing the development of glass mirror technology while also pursuing innovative designs that have the potential for dramatic cost reductions. Technology development activities in FY 1987 were principally in four areas: 1) stretched-membrane heliostats, 2) large-area glass mirror heliostats, 3) a low cost heliostat drive, and 4) cost-effective approaches to heliostat cleaning.

Stretched-Membrane Heliostats

A stretched-membrane heliostat is radically different from familiar glass mirror designs. Stretched-membrane mirrors are simpler and lighter than glass mirrors because of more efficient use of materials for the mirror and its support structure. Thus, stretched-membrane heliostats have the potential to be significantly less expensive. A stretched-membrane mirror module consists of two thin, metal membranes (foils) stretched over both sides of a large-diameter metal ring (Figure 2.2). The reflective surface is a silver-polymer film adhered to the front membrane. A slight vacuum is maintained in the space between the two membranes to provide a concave, focused shape to the reflective surface. The space between the two membranes can be quickly repressurized to defocus the mirror in an emergency.

In FY 1986, Science Applications International Corp. (SAIC) and Solar Kinetics, Inc. (SKI), under contract to Sandia, completed two independent studies addressing the feasibility of stretched-membrane heliostats. These studies emphasized the design, fabrication, and costs of a commercial-scale, stretched-membrane heliostat. Both studies concluded that in mass production, the simplicity and low weight of stretched-membrane mirrors result in heliostat costs that are more than 20% lower than current glass mirror designs. In addition, both contractors designed and built 50-m^2 prototype mirror modules that were as representative as possible of a commercial design. The prototypes were installed in April 1986 for testing at the CRTF. Figure 2.3 shows the prototype mirror module built by SKI.

During FY 1987, Sandia began a planned 1-year evaluation of the optical performance of SKI's prototype mirror module. (The prototype developed by SAIC did not produce a viable beam image and could not be fully analyzed.) Major issues addressed in the test program include the optical performance of the stretched-membrane mirror, the performance of the mirror's focus control system on windy days, the performance of the mirror's defocus system, the durability of the reflective film, and the applicability of alternative methods for cleaning the polymer mirror.

Measurements of the optical performance during FY 1987 show the beam shape produced by SKI's mirror module is at least as good as current glass mirror designs. Figure 2.4 shows an example of measured isoflux contours of the reflected beam. The measurement was made with the new beam

Figure 2.3 Prototype Stretched-Membrane Mirror Module Built by SKI

characterization system in use at the CRTF. The measured beam shape and total beam power are very close to theoretical values calculated with the HELIOS computer code. The observed beam shape is indicative of a reflector with a nearly ideal parabolic contour. The total mirror-normal mirror slope error is estimated to be about 1.3 mr. A 1.3-mr slope error is comparable to second-generation, glass mirror designs. After 14 months of outdoor exposure, the clean reflectivity of the silvered-acrylic film was over 92.8%, which is very close to the 93.5% measured when the mirror was new. In calm conditions, the mirror-defocus system can reduce the power on the target by over 80% in about 6 sec.

Sandia will measure the optical performance of the mirror on windy days next year. The measurements will be used to estimate any increased spillage (light that misses the target) that would occur on windy days. Alternative methods for cleaning the mirror will also be assessed. Measurements of the optical performance of SKI's mirror module verify that stretched-membrane mirrors promise lower cost heliostats without degradation in performance. The two prototypes confirm that all required materials and technology are currently available, with the possible exception of the reflective film. Researchers do not expect current reflective films to maintain the necessary high reflectivity for the 30-year heliostat life. SERI is working with industry to develop and test improved reflective films. In addition, Sandia is developing first-surface, silvered-metal mirrors with a sol-gel silica coating to protect the silver.

Also during FY 1987, development of second-generation, stretched-membrane mirror modules began. The design and construction of the first prototype mirror modules identified a number of areas where design improvements or additional cost savings might be possible. The two contractors, SAIC and SKI, are developing an improved design for a mass-producible, commercial heliostat. In addition, each contractor will design and build a second 50-m^2 prototype stretched-membrane mirror module. The prototypes will be installed in FY 1988 at the CRTF for testing by Sandia.

Large-Area Glass Heliostats

Large-area glass heliostats have reflective areas greater than 100 m^2. Studies show that increasing the size of a heliostat's reflective area provides the economies of scale that reduce the cost per unit area of reflective surface. Two major concerns about large-area heliostats are: 1) the possible degradation of optical performance compared to smaller designs and 2) their ability to survive wind loading over an extended period of time. To address these issues, Sandia purchased two large-area, glass mirror heliostats from industry. The heliostats were made by Advance Thermal Systems (ATS) and Solar Power Engineering Company (SPECO) and have reflective areas of 150 and 200 m^2, respectively. These heliostats, shown in Figures 2.5 and 2.6, have reflective areas that are more than three times larger than those evaluated in the second-generation heliostat

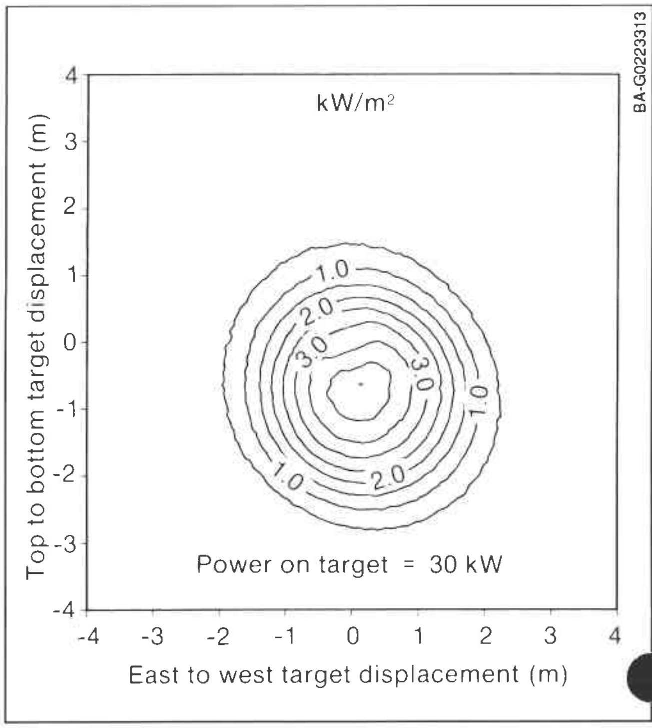

Figure 2.4 Isoflux Contours of the Reflected Beam from SKI's Mirror Module

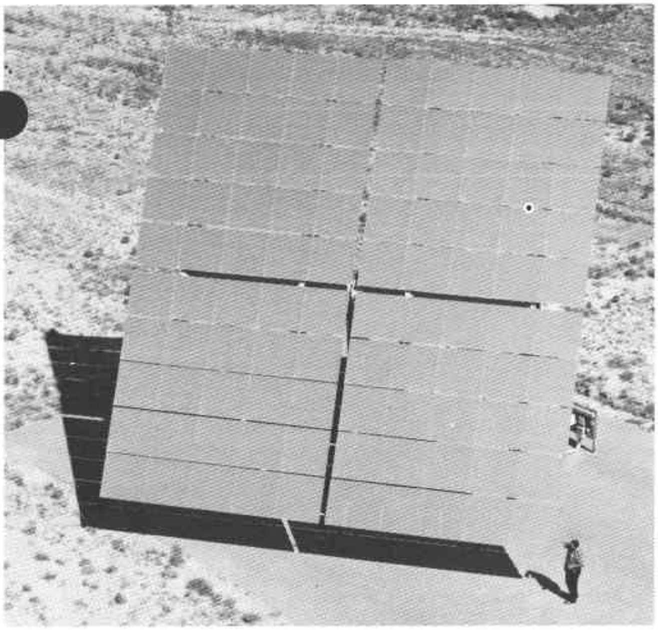

Figure 2.5 ATS Large-Area Heliostat Design

program. Evaluation of the optical performance of these heliostats is under way and will be completed in FY 1988.

Low-Cost Heliostat Drives

During FY 1986, development of a low cost heliostat drive began. The objective of the development program is to reduce the costs of heliostat drives in mass production to about $\$11/m^2$ of reflective area. The costs of previous designs are projected to be from \$18 to $\$25/m^2$ for $150\text{-}m^2$ heliostats.

Peerless-Winsmith, Inc., was awarded a contract to design a low cost drive mechanism and to fabricate drive prototypes for testing. They completed the design of the drive in FY 1987. The drive consists of an elevation and azimuth mechanism. The elevation drive is a ball-worm gear with an exposed worm; the azimuth drive uses an orbiting plate to achieve the necessary gear reduction. Projected drive costs in mass production were estimated to be between \$11 and $\$14/m^2$. Fabrication of the prototypes is under way. This innovative drive will be functionally tested in FY 1988 by installing the drive on the ATS $150\text{-}m^2$, large-area heliostat, currently being evaluated at the CRTF.

Heliostat Cleaning

Studies show that heliostat cleaning is highly cost-effective for central receiver power plants. A 1% increase in mirror reflectivity produces more than a 1% increase in net energy produced by the plant. At the Solar One plant, heliostats are cleaned regularly with a wash truck. Using commercially available cleaning agents, crews at Solar One have demonstrated that mirror reflectivity can be returned to nearly 100%. However, with the advent of larger heliostats, development of cleaning equipment capable of reaching the great heights of these heliostats (over 14 m) is needed. Moreover, stretched-membrane heliostats use a silvered-acrylic reflector that is easily scratched by any contact cleaning method. During FY 1987, Sandia began a joint project with SERI to develop cost-effective methods of keeping heliostats clean. The goals of the program are: 1) development of cost-effective surface treatments for glass, acrylic, and other promising solar optical materials that will reduce the adherence of soil to the surface, and 2) development of cost-effective, noncontact methods of applying, conserving, and/or recycling deionized water or other cleaning agents for large solar collectors. These methods will be useful in distributed receiver and photovoltaic as well as central receiver programs.

Receivers

Receivers convert concentrated solar radiation into thermal energy. Receivers have been designed, built, and tested using a variety of heat transfer fluids: water or steam, air, molten nitrate salt, and liquid sodium. Over the past decade, receivers have been developed with operating temperatures as high as 816°C but the focus of the development has been on moderate operating temperatures below 593°C.These moderate-operating-temperature receivers continue to be the primary focus of our research because they enable the use of conventional Rankine-cycle steam turbines or use in intermediate temperature industrial processes. Higher temperature cycles currently offer no advantages for electricity production.

In FY 1987 Sandia continued efforts toward improving the reliability and decreasing the fabrication costs of molten nitrate salt receivers and components. The activities included testing an advanced $5\text{-}MW_t$ molten salt-in-tube receiver and commercial-scale pumps and valves for molten salt service, testing flow characteristics of a falling-salt-film direct absorption receiver (DAR) using water, and design of a solar panel research experiment to test the DAR concept. These activities are an important step toward achieving the long-term efficiency goal of 90%

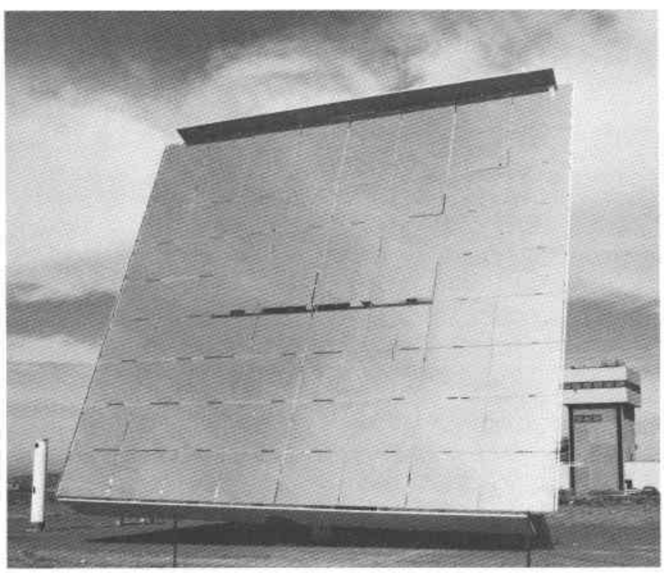

Figure 2.6 $200\text{-}m^2$, Large-Area Heliostat Built by SPECO

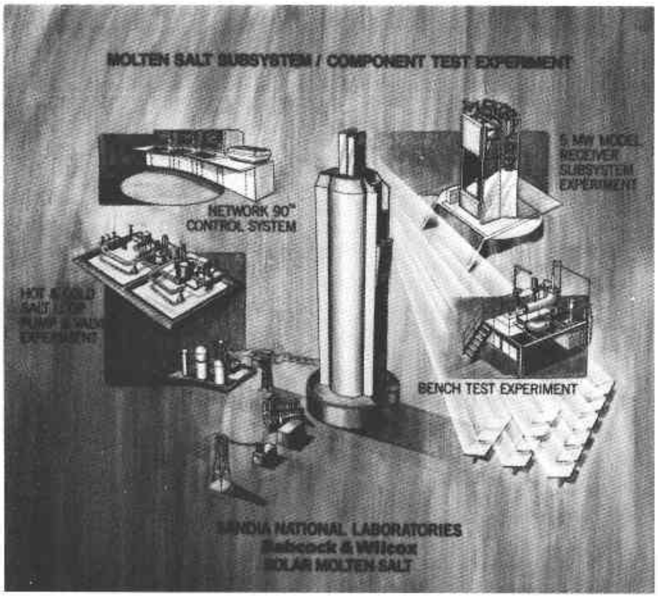

Figure 2.7 Molten Salt Subsystem Component Test-Experiment

and cost goal of \$30/m^2 for receivers (expressed in dollars per square meter of heliostat area).

Molten Salt Subsystem Component Test Experiment

The Molten Salt Subsystem Component Test Experiment (MSSCTE) is a hardware component development and test program being conducted at the CRTF. The objective of the program is to resolve technical uncertainties related to components and subsystems of molten salt (60% sodium and 40% potassium nitrates) central receiver technology. The goals are to test an advanced molten salt receiver and to demonstrate that commercially available pumps and valves are suitable for full-scale molten salt applications (Figure 2.7).

Receiver Test. The molten salt receiver is a C-shaped cavity that incorporates features of a 60-MW$_e$ commercial plant design. Sandia incorporated two different panel designs, one by Babcock & Wilcox and one by Foster Wheeler Development Corporation, into the receiver. The panels differ mainly in their support and header arrangements.

During FY 1987 Sandia performed the first phase of the receiver characterization except for the optimization tests.

Steady-state testing at a rated power of 4.5 MW$_t$ has confirmed the receiver operation. Thermal performance of the receiver was evaluated both experimentally and analytically. Using flux-off and flux-on loss tests, researchers determined the thermal efficiency of the receiver to be 95% ± 4%. They analytically calculated the receiver efficiency to be 89% ± 9% and the expected design efficiency to be 90%. The receiver temperature control algorithm worked well and is being tuned to reduce thermal transient induced stresses in tubes and headers. Sandia demonstrated receiver capabilities for maximum power production and start-up. The receiver produced 36 MW during a 9-h period around solar noon on a day near the spring equinox. The receiver reached rated outlet temperature within 70 min after sunrise, using the heliostats to warm the cold absorber panels. Start-up was achieved sooner when an electric cavity heater was used to prewarm the panels.

Some of the receiver tubes developed pin-hole leaks at the tube-clip welds. These leaks did not prevent operation; they only caused some degradation of the paint on the receiver panel. The cause of the leaks was poor quality of welds at the tube clips and can be prevented in future tube receivers.

In a second phase of the characterization testing researchers will obtain additional thermal loss data, refine the receiver control algorithm, and provide annual performance and thermal cycling data.

Bench Test for Valve Packing Materials. The purpose of the bench test was to select valve packing materials for use with molten salt. The test demonstrated that graphite fiber with interspaced glass-reinforced Teflon washers and an extended bonnet successfully seals valve stems against salt leakage at cold salt conditions of 285°C and 9.13 MPa and hot salt conditions of 565°C and 2.24 MPa.

Pump and Valve Test Loops. The molten salt pump and valve test loop is intended to demonstrate the performance and reliability of full-scale hot and cold salt pumps and qualify valves and packing materials under the operational conditions expected in commercial solar power plants. The pump and valve test setup contains two separate loops; the cold loop operates at 285°C and the hot loop operates at 565°C. Each loop contains a pump and six representative valves. During FY 1987, researchers completed construction of both loops and performed water flow tests on both loops. The completed loops are shown in Figure 2.8.

Testing with salt will begin in early 1988. Completion is expected by the end of 1988.

Falling-Salt-Film Direct Absorption Receiver

The falling-salt-film DAR was proposed in the mid-1970s to simplify and reduce the cost of central receiver systems. Rather than flowing through tubes that are exposed to the concentrated solar flux, the heat absorbing fluid (a blackened molten nitrate salt) flows in a thin film down a flat, near-vertical panel and absorbs the flux directly. Potential advantages of the DAR include simplified design, improved thermal performance, increased reliability and operating life, and reduced capital and operating costs. The cost savings and improved performance can result in reductions in levelized energy costs of 17%-26%.

Figure 2.9 is an artist's concept of a DAR in an external cylinder configuration. Cold salt (285°C) is introduced onto the DAR panel at the top of the receiver. The salt flows in a thin, wavy film down the panel surface at velocities of several

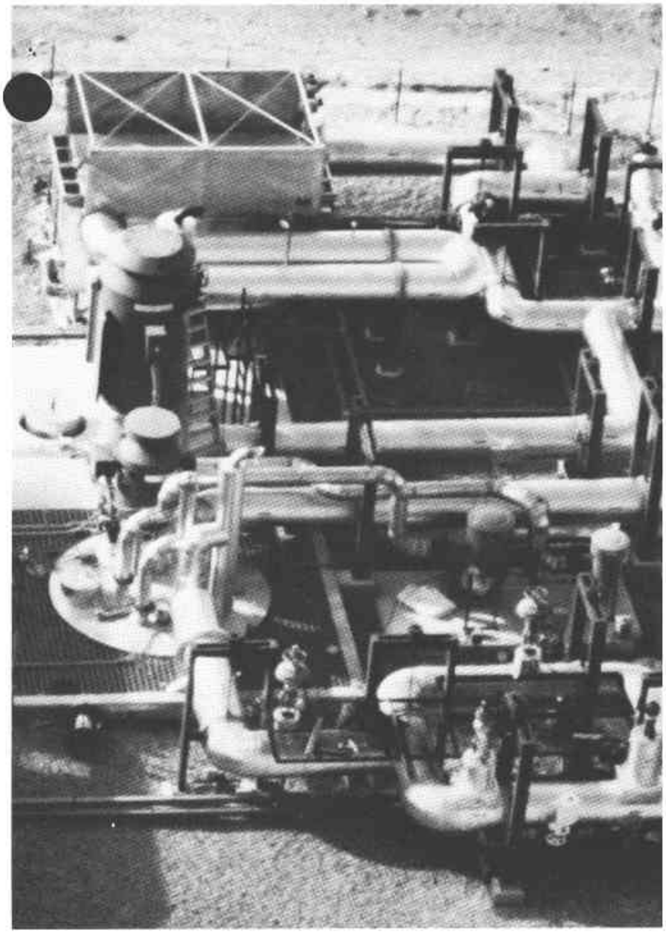

Figure 2.8 Pump and Valve Loops

meters per second, through the solar beam focused on the receiver. The hot salt (565°C) is collected at the bottom of the panel and piped down the tower. The ability of the flowing salt film to absorb the incident solar flux depends on the panel design, fluid flow characteristics, and blackener properties.

Some technological uncertainties affecting DAR feasibility require resolution before the concept can be considered a technological alternative. Among these are the stability of the flowing salt film in high, nonuniform fluxes and in wind; the stability and performance of blackening agents; effects of long-term, high temperature exposure of the salt to the atmosphere; and the optical and thermal efficiency of the absorbing film. In addition, a number of system-related advantages of the concept need to be quantified. Based on previous small-scale experiments, none of these appears to pose major problems, but performance and practicality of the DAR will be confirmed in the planned large-scale testing.

Water Flow Testing. As part of the DAR program, Sandia has conducted water flow tests to evaluate fluid flow performance under DAR-like conditions. Because the flow properties of water at ambient temperature are similar to those of hot nitrate salt (565°C), flowing water films provide a good representation of flowing salt films. A laboratory-scale water system (1 m wide by 3.5 m high) was used to develop DAR inlet and outlet manifolds and to investigate wave phenomena in the flowing film, wind effects on film stability, and control characteristics of multiple control zones. A 2 m diameter by 10 m high external cylinder water flow test apparatus (see Figure 2.10) was built to evaluate these effects on a scale similar to that of a commercial DAR.

Sandia developed manifolds that effectively distribute and collect the flow from the panel over a large (at least 10 to 1) turndown ratio. Flow measurements on the panels show that the initial flow distribution on the panel can be maintained along the length of the panel, providing the capability for flow control in regions of varying flux without need for physical separation between control zones. High speed photography and other techniques were used to provide data on fluid film and wave characteristics, including film thickness and wave frequency, velocity, and height. The observed wave phenomena do not appear to be detrimental to DAR operation.

Panel Research Experiment. To allow flow testing with nitrate salt and to provide a test bed for DAR testing in an actual solar environment, a 3-MW_t salt flow loop is being designed as illustrated in Figure 2.11. The loop is capable of accommodating DAR panels up to 1 m wide by 6 m long at flow conditions typical of a commercial-sized DAR. Once fabricated, salt flow tests will verify similarity with results of the water flow tests and enable us to refine manifold and panel designs for use with molten salt. Water-cooled shielding around the panel and an air-cooled heat rejection system will be added to allow solar testing of the panel on the CRTF tower.

External DAR Design Studies. Sandia has initiated work to examine receiver-specific aspects of a commercial DAR, in consideration of the differences between salt-in-tube receiver designs and the DAR. Major issues being addressed include panel and support design alternatives, thermal stress and deformation analyses of the receiver panels, salt containment and blackener issues, and costs relative to more conventional receiver designs.

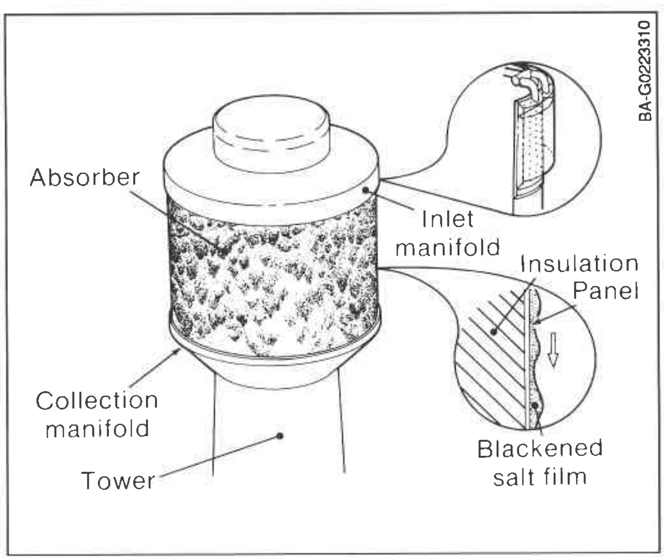

Figure 2.9 External Molten Nitrate Salt DAR

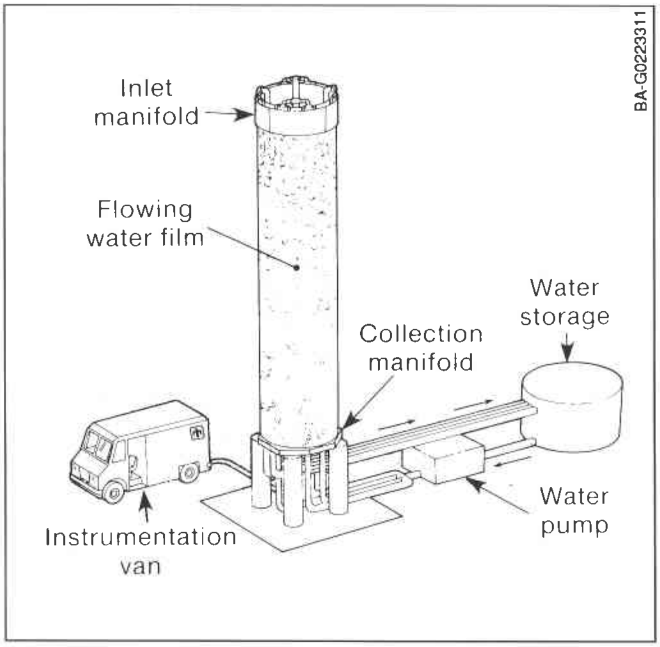

Figure 2.10 DAR Large Water Flow Test

Volumetric Receiver Testing

The volumetric air receiver concept is being studied in Europe to provide higher fluid temperatures to improve efficiency in the process or cycle, or for use in initiating particular chemical reactions. During FY 1987 a metal wire mesh volumetric receiver was developed and tested under the International Energy Agency (IEA)/Small Solar Power System (SSPS) Task VII.

Though the United States is not directly involved in the Task, Sandia provided support by developing a computer model (HOTAIR) of the volumetric receiver process to predict the performance and to evaluate other volumetric receiver designs. The computer code results are in general agreement with the test results. The testing and evaluation of this volumetric receiver is expected to be completed in January 1988.

Receiver Materials and Fluids

Tube Receiver Materials and Design. Sandia held a workshop this year to help develop design criteria for tube receiver design, incorporating all newly available material, design methodology, and weather information. It was decided to use 20,000 design cycles for a 30-year plant life (based on the results of real weather data analysis) and a design methodology based on ASME code case N47. Even though this code case does not apply to solar receiver tube conditions, accounting for thermal fatigue but neglecting creep effects results in minimal changes to the N47 methodology.

Thermal fatigue is the phenomena wherein the measured lifetime of a material exposed to a constant mechanical loading during temperature cycling is shortened relative to the life during cyclic mechanical loading at a constant temperature. Data and design criteria are generally much more readily available for isothermal mechanical fatigue, although for solar thermal receivers, thermal fatigue is the dominant failure mechanism. To provide the necessary data for tube life prediction, Sandia conducted thermomechanical fatigue studies 316 Stainless Steel, Incoloy 800, and modified 9Cr-1Mo steel this year to test their expected performance in a receiver environment. Testing has confirmed the existence of thermal fatigue degradation in properties in Incoloy 800 of about a factor of 10, while for 316 Stainless Steel the thermal fatigue degradation effect is about a factor of 2. Modified 9Cr-1Mo testing showed poor performance of this alloy at temperatures above 600°C, indicating it is probably not suitable as a receiver material except possibly for low temperature panels. For solar receiver service, 316 Stainless Steel appears to be the preferred material.

Advanced Heat Transfer Fluid Development. The current molten salt working fluid in use in central receiver systems (60 wt % sodium nitrate, 40 wt % potassium nitrate) melts at temperatures near 240°C. All component and piping in contact with the salt, except the solar-heated receiver panels, must be heated to avoid salt freezing or severe thermal shock. If a working fluid with a lower melting point (preferably below 150°C) could be identified, heating requirements could be reduced or, for larger components, eliminated. Heating to 150°C would allow the use of steam or hot water tracing rather than the expensive and low reliability electric heating that is now used.

Recently Sandia has identified several potential techniques for reducing the freezing point of molten salt working fluids.

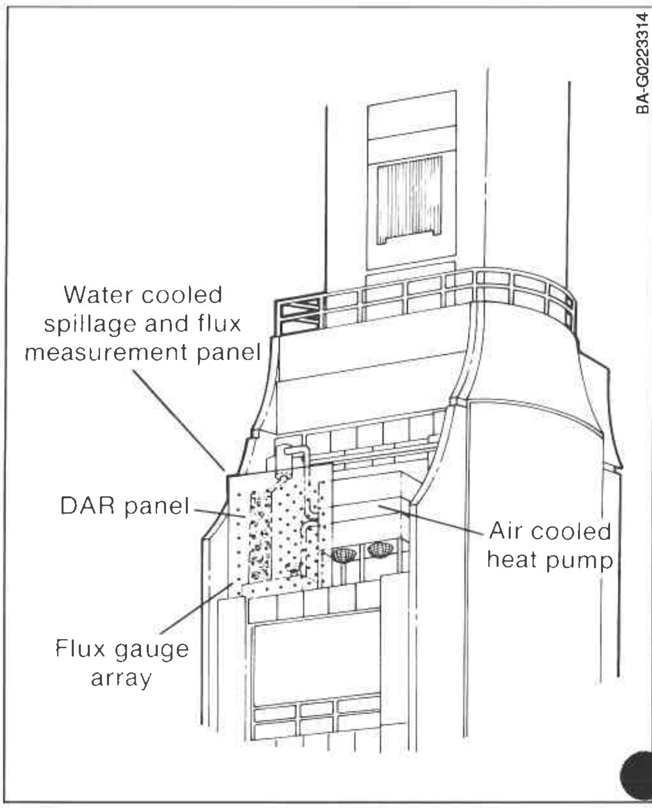

Figure 2.11 Molten Nitrate Salt DAR Panel Research Experiment

Dilution of the salt with water, for example, can reduce the freezing point of the mixture to near ambient temperatures. This technique has limited application (to the receiver for overnight cooldown, for example), because the water must be removed for high temperature operation. Alternatively, addition of about 30% calcium nitrate to solar salt would reduce the melting point to well below 150°C according to the literature and some preliminary testing. Although calcium nitrate is inexpensive, and might actually reduce the cost of the working fluid, the effects of calcium nitrate addition on high temperature performance, material corrosion, and pumping costs are not yet known. Finally, recent commercial advances in the handling of Hitec salt (50% potassium nitrate, 40% sodium nitrite, 7% sodium nitrate, melting point 142°C) may make its use at central receiver system temperatures feasible by reversing degradation reactions in a small, side-stream regeneration loop. The cost-effectiveness of such systems and their ability to limit corrosion problems is not yet known, however. Because of their potential benefits to central receiver systems, these alternatives will continue to be investigated.

Balance of Plant

The balance of plant task addresses research and development on the nonsolar components necessary to construct, operate, and maintain a complete central receiver plant. Efforts are directed towards reducing balance of plant capital, operating, and maintenance costs, and minimizing parasitic power requirements. Activities include the design and optimization of plant controls, characterization and optimization of site construction, plant service facilities, power conditioning equipment, and spare parts inventory. In FY 1987 the focus of this task was the study of advanced controls. The goal is to reduce operating and maintenance costs and to improve plant performance by operating with a minimum of personnel. The development of two central receiver dynamic simulators continued during FY 1987 as part of an effort to optimize the design and operation of molten nitrate salt plants.

Dynamic Simulation of Central Receiver Plants

ESSCOR Corporation, under contract to Sandia, completed construction of a model of the molten salt cavity receiver system currently being tested at the CRTF. A model of a hypothetical DAR was developed. Both models run real time on a portable computer. These models are being used to accomplish the following objectives: 1) to understand central receiver system performance during transients, 2) to test, optimize, and design central receiver control algorithms, 3) to understand component response to component failures, and 4) to optimize annual energy production from central receiver plants. Work during FY 1987 concentrated on the first two objectives.

The CRTF system model simulates the cavity receiver, the molten salt thermal storage system, and the process control system. The user interacts with the simulation while it is running via menus and several color graphic mimics of the system hardware.

Comparisons of the predictions of the CRTF model with experimental results indicate the model gives good performance predictions. The model also produced qualitative insights regarding system dynamics that were subsequently verified by experimental results. The model correctly predicted that all of the control loops must be operable to prevent overheating of the molten salt during severe cloud transients. The model also identified possible receiver temperature ramp rates during severe cloud transients that exceeded allowable values established by the receiver designers. Sandia modified the receiver operation and/or the control algorithm to alleviate this problem.

The DAR model predicts average salt temperatures, back plate temperatures, and film thicknesses along the length of the flow channel as a function of time during cloud transients. A control algorithm was developed that is capable of preventing salt overheating during typical and severe cloud transients. The algorithm developed was found to be much simpler than the one developed for the CRTF cavity receiver. The DAR will enhance system reliability and performance. This simplified design will enhance the reliability and performance of the DAR.

Central Receiver Systems

Central receiver system activities include the design and analysis of complete solar central receiver plants. Sandia performs cost and performance trade-offs at the component, subsystem, and system levels to understand the interactions of the plant elements and to integrate these elements into a complete system. The activities also include the operation of the CRTF in Albuquerque, N. Mex., and U.S. participation in international central receiver projects.

A major activity continued during FY 1987 to develop the conceptual designs of commercial-scale central receiver power plants. A group of western utilities is participating in a cooperative effort with DOE to study paths to the eventual commercialization of solar thermal central receiver technology. Plant costs and performance are being established for advanced system designs using molten nitrate salt and liquid sodium technologies. The team is exploring financing and technology development strategies to identify the most promising path for meeting the long-term cost and performance goals for electricity production.

A second major activity in FY 1987 was the initiation of a multiyear study aimed at improving the annual efficiency of central receiver plants. The annual energy improvement study will identify design and operation improvements that will be required to bridge the gap between the current efficiency prediction of 15% and the long-term goal of 22%.

Predicting Annual Plant Performance

One important requirement for the commercialization of central receiver technology is the ability to reliably predict the annual performance of a plant. Confidence in a technology will be increased if the expected plant performance revenue can be predicted accurately before the plant is built. Moreover, having a computer code that predicts annual energy allows alternative plant configurations to be analyzed and the optimal plant to be selected. Existing tools that predict annual energy proved to be unreliable. For example, the original estimates of the annual energy production of Solar One proved to be overly optimistic. Using the operating and performance data learned from a large number of systems experiments (Solar One, receiver tests, etc.), a computer code was developed to predict annual energy from central receiver power plants. The code, called SOLERGY, uses a measured record of insolation at 15-min intervals to predict annual energy output. SOLERGY was completed and released to the public in FY 1987.

One major use of SOLERGY in FY 1987 was in a validation study against the actual performance of the Solar One power plant for 1985. Data used as input to SOLERGY were developed from the extensive Solar One data base. These data include observed insolation for 1985, plant design parameters, and plant operational characteristics. To model the water/steam system used at Solar One, Sandia made a number of changes to the SOLERGY code. In addition, a new model was developed for parasitic power using a regression fit to plant data. It was found that SOLERGY provided good estimates of time-dependent power production on reasonably clear days (Figure 2.12). However, SOLERGY predicts too much net energy on days with intermittent insolation because of passing clouds. The poor predictions on partly cloudy days are due to: 1) the inability of the 15-min time steps used in SOLERGY to capture insolation transients lasting less than 15 min but sufficient to cause the turbine to go off-line, and 2) unpredictable human operator actions on cloudy days. Time-dependent power predictions were found to improve when 3-min insolation data were used. Though SOLERGY predictions using 15-min data are fairly poor for partly cloudy days, these days contribute only marginally to total annual energy production. Moreover, in current plant designs using molten-salt energy storage, passing clouds would not cause the turbine to shut down as is the case at Solar One. Therefore, 15-min insolation data are probably adequate for molten salt central receiver design studies. Figure 2.13 shows the calculated annual energy

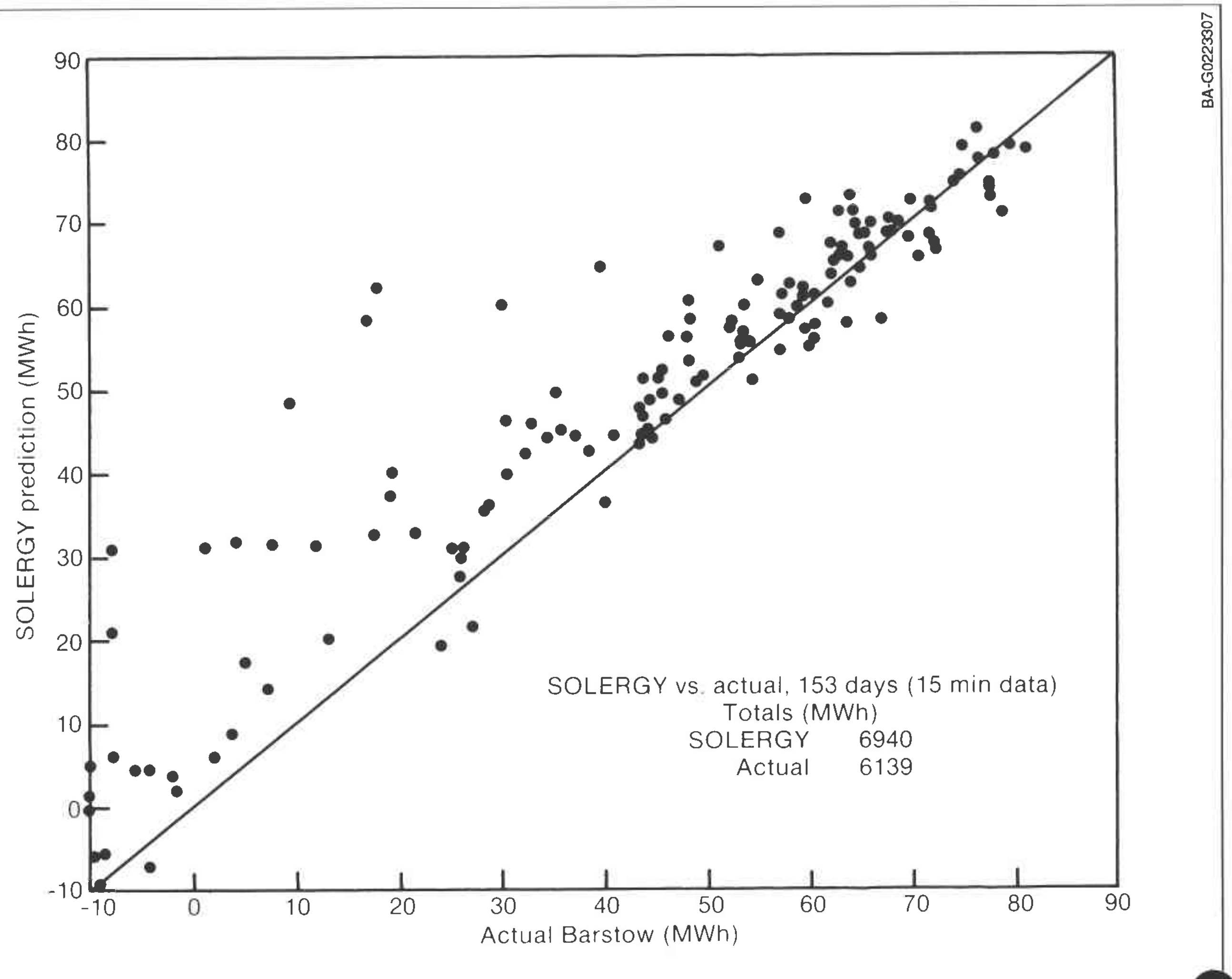

Figure 2.12 Comparison of Daily Net Energy Produced by Solar One and the Energy Predicted by SOLERGY. The 153 selected days during 1985 represent days when the plant functioned normally (no forced or scheduled outages) and the data acquisition system was operational.

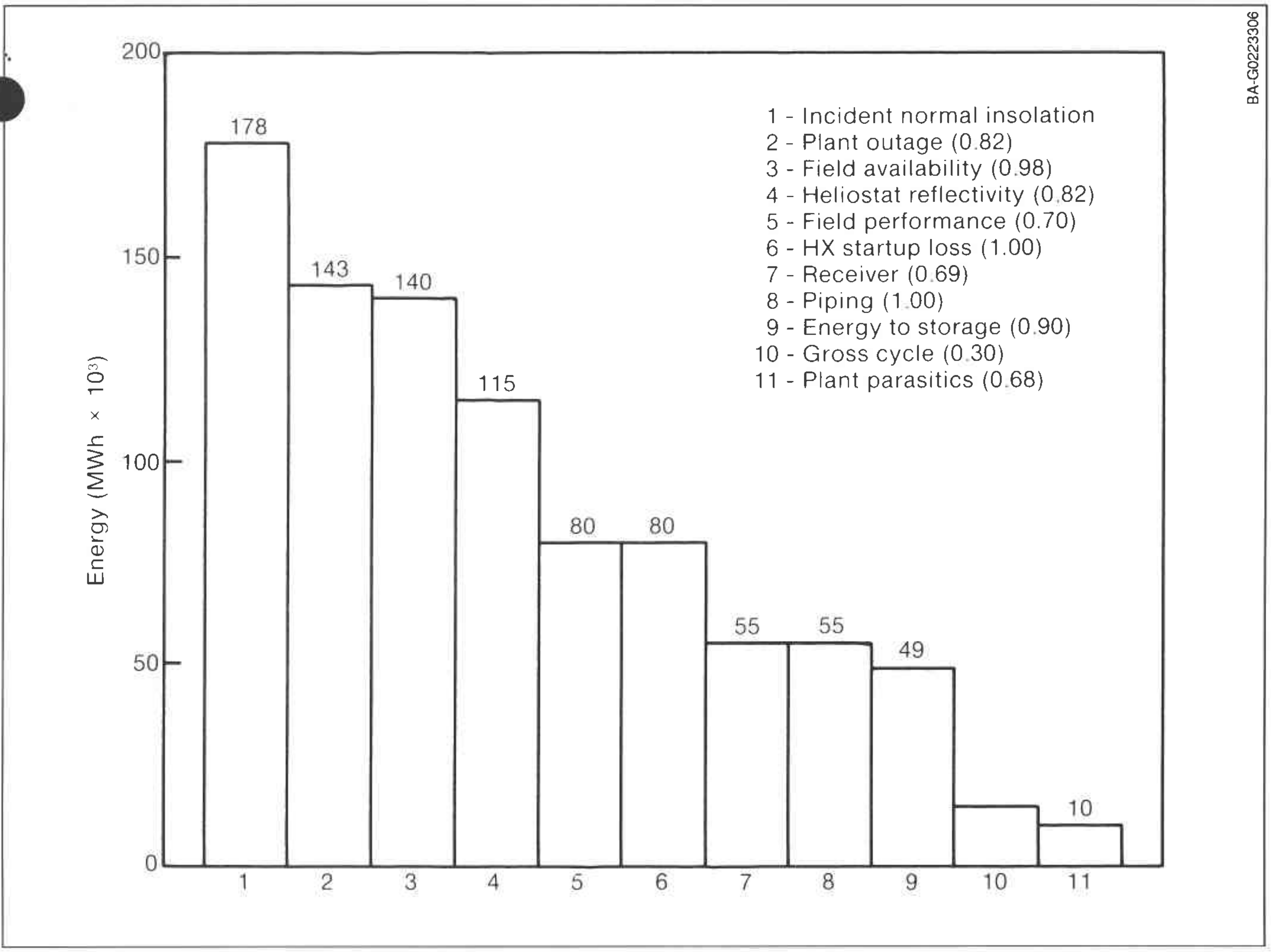

Figure 2.13 Annual Energy Efficiency of Solar One for 1985 Predicted with the SOLERGY Computer Code

efficiency for Solar One. The predicted annual energy is within 16% of the actual performance for 1985.

Also as part of the SOLERGY validation study, SOLERGY was used to identify the most important causes of system inefficiency at Solar One. Sandia identified three issues in particular that are also concerns in current-generation solar plant designs: 1) plant reliability, 2) reduction in parasitic power, and 3) heliostat cleanliness.

Electric Utilities Study of the Solar Central Receiver

During late 1986 and through most of 1987, two electric utilities led team efforts to assess the component and system progress that has been made and to decide what central receiver design options could best fit their future generating needs. The two study team leaders were the Pacific Gas and Electric Co. (PG&E), located in northern California, and Arizona Public Service Co. (APS), located in central Arizona. The cost of the two year-long studies was paid in part by DOE and in part by the team members. Both teams had participated in designing conceptual utility-scale solar central receiver plants prior to the current studies. The team members included experts on all the subsystems and experienced designers and consultants.

The teams entered this effort with component and subsystem preferences that were the result of their earlier work. The strategy was for the teams to work independently to develop a state-of-the-art conceptual plant design that could best fit their needs for capacity, modularity, and performance. The program goal was to have both teams agree on the best configuration so that resources could be concentrated on developing that plant design. To achieve the goal, the teams agreed to extensive common data bases and a list of ground rules. In general, these consisted of design and configurations criteria, cost data and size-scaling relationships for the plant, the site, and for each of the subsystems. For example, the site was selected to be Barstow, Calif., because the solar insolation is well characterized. This is not necessarily the best site for a solar power tower plant but was chosen to assure comparability of construction costs, labor costs, and performance data at a well-defined site.

Both teams independently made technical, performance, and economic trade-offs. A technical advisory group of consultants

Table 2.1 Preferred Power Plant Configuration

Plant size – 200-220 MW electric	
Operating capacity – 37%-38%	
Solar multiple – 1.8	
Thermal storage – 6 h	
Solar receiver shape – External cylinder	
Solar collector – 150 m^2 heliostats	
Heat transport fluids	
	Receiver – molten nitrate salt (60% $NaNO_3$, 40% KNO_3)
	Turbine – water and steam
Fossil hybridization – None	

and national laboratory experts guided the process with monthly reviews. At the end of the year-long study both teams came to essentially the same conclusion about the preferred options for the best configuration for a commercial power tower. Figure 2.11 is a representative schematic of that plant. The characteristics of the plant are summarized in Table 2.1.

As part of the design and selection process, the teams estimated capital costs based on available data from existing pilot plants and cost projections for the components as the power tower reached design and construction maturity. They developed costs for the first commercial plant and for a plant that would be built much later when all of the manufacturing and learning cost reductions had been achieved. The first few plants may be a 100-MW_e size to reduce the financial risk and uncertainty. The mature plants will be about 200 MW_e. The capital cost estimates were similar from the two teams. A condensation of the teams' results gives the approximate costs in Table 2.2. These costs are higher than might be expected because of the high solar multiple and large capacity of the thermal storage system. Nevertheless, plants with these characteristics will provide the highest value to these utilities over their 30-year operating life.

A key factor in determining whether a utility can afford the capital investments indicated in Table 2.2 is the cost of energy the plant produces over its 30-year design lifetime. Because of the variable solar insolation, it is important to accurately predict the performance (net output) of the plant over its life. The Sandia-developed computer code, SOLERGY, was used by the teams to predict the annual net output of the hypothetical first and mature commercial plants. Component performance was modeled based on experience with the Solar One pilot plant and other experimental data obtained for components or systems chosen for the commercial plants. Using the code and 1 year of solar insolation and meteorological data from Solar One, researchers predicted the annual performance to be about 320-330 GWh net per year for the first 100-MW electric plant at a cost of about \$0.11-\$0.12/kWh.

The annual efficiency of converting collected sunlight to net electric output is about 14%-15%. For a mature 200-MW plant the annual net output would double to 650 GWh, the operating capacity would be about 38%, and the conversion efficiency would be the same. The cost of electricity would be reduced to \$0.07-\$0.10/kWh because of the lower capital cost per kilowatt and smaller, per MW, operating crew of the 200 MW_e plant.

These projected costs for electricity were leveled over the 30-year design life of the plants and include recurring operation and maintenance expenses.

Central Receiver Test Facility

The CRTF located at Albuquerque, N. Mex., is used to test, evaluate, and develop components and systems for solar central receiver technology. The major activities undertaken at the CRTF in FY 1987 were the MSSCTE, which includes an advanced molten salt receiver test and a molten salt pump and valve test; large-scale water flow experiment assembly; advanced heliostat installation and testing; maintenance and upgrade of the CRTF heliostat control system; the continued operation of the solar furnace; and the performance of many reimbursable experiments. The first three items are discussed in other sections of this chapter; the last three items are discussed here.

The operation and maintenance of the CRTF heliostat field is increasingly affected by the age of the control computers and field electronics. Two projects continued during the year, one to replace the host computer and a second to develop replacement heliostat control electronics. Sandia has assembled the new heliostat control system, developed software, tested an upgrade heliostat line, and held training sessions for the operations personnel. The system installation will be completed when an appropriate period of time (approximately one month) is available with no field operations scheduled. Sandia has developed and specified the replacement heliostat control electronics. The specified units will require the new heliostat host computer for control and interfacing; therefore, final implementation of this project is delayed until the new control system is installed.

The CRTF includes a solar furnace that is used to calibrate instruments for measuring the flux density of concentrated sunlight and to evaluate high temperature materials for solar thermal technology applications. Specific projects at the solar

Table 2.2 Installed Cost for First and Mature Plants

Subsystem	Installed Cost (1987\$/kW) 1st Plant (100 MW_e)	Mature Plant (200 MW_e)
Collector field	925	725
Receiver-tower	350	275
Thermal storage	225	200
Steam generator	150	125
Turbine generator	550	450
Controls	25	25
Balance of plant	50	50
Indirect costs	500	275
Cost of money	275	250
Rounded total \$/kW_e	3100	2400

furnace this year included recalibrations of all receiver flux gages for the MSSCTE program, materials tests of high temperature bondings of ceramics to metals, and operation of test bed for evaluating distributed receiver codes accuracy in predicting cavity heat losses.

The CRTF also provides solar testing to nonsolar thermal development users on a non-interference, cost-reimbursable basis. In FY 1987, the major reimbursable test activity was the program to simulate aerodynamic heating effects on full-scale defense missile radomes. This program entered the routine testing phase, requiring over 150 pulses on six different test units. Other reimbursable experiments consisted primarily of material tests under high heat fluxes.

System Experiments

System experiments provide valuable data on the cost, performance, operations, and maintenance of a complete solar central receiver system. The data were used to establish the technical feasibility of the central receiver system, provide information to support private sector decisions regarding designs and economics of future central receiver systems, and identify areas where future central receiver research and development may lead to significant performance improvements and increased capabilities.

In FY 1987 the only system experiment in operation was the Solar One 10-MW_e solar thermal central receiver pilot plant. Solar One operated in a power production mode through most of the year to demonstrate the operational capability of the plant to supply power reliably to a utility grid.

Solar One

Solar One, shown in Figure 2.14, is the world's largest solar central receiver electric generating station. The plant, located in the Mojave Desert near Barstow, Calif., is designed to supply 10 MW of electric power to the Southern California Edison (SCE) utility grid.

Solar One has 1818 heliostats that reflect the sun's energy onto a receiver mounted on top of a tower. Water in the receiver absorbs the solar energy and is boiled and converted to high pressure steam. This steam powers a turbine for the generation of electric energy.

Power Generation Summary

Solar One completed the 3-year power production phase in July 1987. The important statistics for the entire phase are summarized in Table 2.3. The performance of the plant showed a significant increase in the second and third years compared with the first year results. The increase resulted from improved insolation, improved maintenance, and refined operating procedures.

On July 23, 1987, the plant set a new daily production record of 97.4 MWh_e net. The previous high achieved during the second year of the power production phase was 88.1 MWh_e net. Another record was set on July 14, 1987: the plant operated for its 38th consecutive day.

Figure 2.14 Solar One: The 10-MW_e Solar Thermal Central Receiver Pilot Plant Located Near Barstow, Calif.

Table 2.3 Solar One Power Production Data

Item	First Year	Second Year	Third Year
Insolation (kWh/m^2 day)	6.55	6.97	6.70
Number of heliostats available	1758	1746	1796
Plant availability without solar available — effects of weather (%)	80	83	82
Plant availability with effects of weather (%)	52	60	54
Gross energy (MWh$_e$)	11,754	15,345	15,300
24-h plant load (MWh$_e$)	4731	4880	5320
Net energy (MWh$_e$)	7024	10,465	9980
Power production hours	1601	1863	1913
Thermal storage charging hours	208	184	4
Unscheduled plant outage hours	292	340	471
Scheduled plant outage hours	371	175	110
Weather outage hours	1217	963	1183

Solar One started the semi-commercial phase on August 1, 1987. The plant is currently operating five days a week. Southern California Edison (SCE) is attempting to operate the plant with a minimum number of operating and maintenance personnel. The goal of the semi-commercial phase is to operate the plant in the most cost-effective manner.

Collector Subsystem

The Solar One Collector subsystem has been operating since November 18, 1981. The overall performance of the collector field has been excellent and very reliable. For example, during the entire 3-year power production phase, the heliostat availability was greater than 97%.

A portable specular reflectometer is used to measure mirror cleanliness at Solar One. Mirror cleanliness is the fraction of the perfectly clean reflectivity, expressed as a percentage. Measurements are made at intervals of about two weeks.

During FY 1987 SCE performed an analysis which showed that continuous cleaning of the heliostat field was cost-effective. (Continuous cleaning requires one person to clean the heliostats one at a time and, when finished, to start over again with the first heliostat). Consequently, SCE implemented continuous cleaning at the plant using an acid wash that restores the reflectivity to the heliostats' design values. This cleaning program allowed the plant to achieve the daily power production record described in a previous section.

Receiver Subsystem

Panel Deformation

During early January 1987, the plant was shut down for 17 days because panel 9 was found to be severely deformed. The panel was damaged because of overheating that resulted from a leaking drain valve that reduced the flow in the panel by shunting flow to the drain. The valve was repaired but the panel was left deformed. Insulation was installed around and behind the panel during the outage so the plant could continue to operate. The deformed panel has not affected performance measurably.

Inspection of other panels on the receiver indicated that panel 16, located in a symmetric position to panel 9, was also more deformed than others. McDonnell Douglas and Sandia performed analyses which indicated that these panels experienced severe temperature gradients during start-up and cloud transients. Changes were made to the operating policy during cloud transients and start-up to maintain temperature gradients and ramp rates within acceptable limits.

Inspection of the panel thermal expansion system also revealed mechanical problems at these and the other panels. It was postulated that problems with this system contributed to the panel deformation. Several recommendations were made by Babcock & Wilcox and Foster Wheeler to improve the thermal expansion system but were not implemented because of budget limitations. Despite the panel deformation, the receiver continued to operate successfully throughout FY 1987.

Receiver Absorption

The receiver panels are coated with black Pyromark paint to increase the absorption of solar energy by the receiver surface. In December 1985 the receiver was repainted with Pyromark since the absorptance of the paint on the receiver panels had decreased with time from 0.95 (the design value) to about 0.88. Solar absorptance measurements were made on the receiver in March and August 1986 and in October 1987. The results showed that the average solar absorptance of the receiver was about 0.96 and did not change, within experimental accuracy, over this entire interval. Because the solar absorptance of the receiver is an important parameter in meeting receiver performance goals, an understanding of its degradation mechanisms is necessary. Testing and analyses are continuing to identify the degradation mechanisms that caused the reduction in the paint absorptance and to determine the economic intervals for repainting.

Chapter 3
Distributed Receiver Technology

A solar thermal distributed receiver system consists of one or more line-focus or point-focus collectors, each of which uses a concentrator to focus the sun's energy and a receiver to absorb the energy and convert it to heat. The heat collected by these systems may be converted to electricity by an engine/alternator directly coupled to the receiver or it may be moved by a thermal transport system to a central location for conversion to electricity, used for process heat, or for both (cogeneration). Increasing the number of modules integrated into the system increases capacity. The modules integrated into the system can be identical and therefore adaptable to mass production methods.

Parabolic trough systems concentrate sunlight onto a receiver tube located along the focal line of the reflecting parabolic trough collector. A heat-transfer fluid flowing through the tube is heated to temperatures that are typically 300°C or less. The trough usually rotates about one axis to follow the sun.

Point-focus solar collectors, usually in the form of a parabolic dish with two-axis tracking, concentrate sunlight onto a receiver located at the focal point of a parabolic reflector. Temperatures exceeding ~~1500°C~~ are possible using point-focus parabolic dishes. Current emphasis is on the dish-electric concept in which a small heat engine is located at the focus of a collector. Thermally interconnected collector arrays that power a large heat engine or serve a thermal application are also of interest.

Concentrators

The objective of the distributed receiver technology program concentrator task is to develop efficient, cost-effective methods for concentrating solar energy. This objective is sought through the design, analysis, and testing of concentrating collectors and collector components. The primary thrust of this task during FY 1987 is point-focus (dish) concentrator development, although some testing on line-focus system components continues.

Point-focus Concentrators

Point-focus concentrating solar systems may be used for high quality thermal applications to generate electric power. The major emphasis of point-focus concentrator development are the DOE innovative concentrator project and the stretched-membrane dish collector development project. The concentrator materials development project supports these two projects.

Innovative Concentrator Project. The DOE innovative concentrator project is a multiphase project to develop detailed concentrator designs and to build and test prototype collectors. The collectors designed in this project are required to meet specific performance and survivability criteria; be modular and mass producible; be easy and economical to manufacture, assemble, and operate; and have a 10- to 20-year life. Two contractors, the Acurex Corporation of Mountain View, Calif., and the LaJet Energy Company (LEC) of Abilene, Tex., fabricated and delivered dish collectors to Sandia's Distributed Receiver Test Facility (DRTF) for testing and evaluation.

The Acurex innovative concentrator, shown in Figure 3.1, is a continuous, 15-m diameter, paraboloid of revolution constructed from 18 pie-shaped gores. The panels are made from steel backing sheets that have been stamp-formed into the shape of a paraboloid and bonded to a reflective top sheet of steel covered with 3M ECP 300 silver film. The predicted thermal output of this dish at 91% optical efficiency is 161 kW_t at

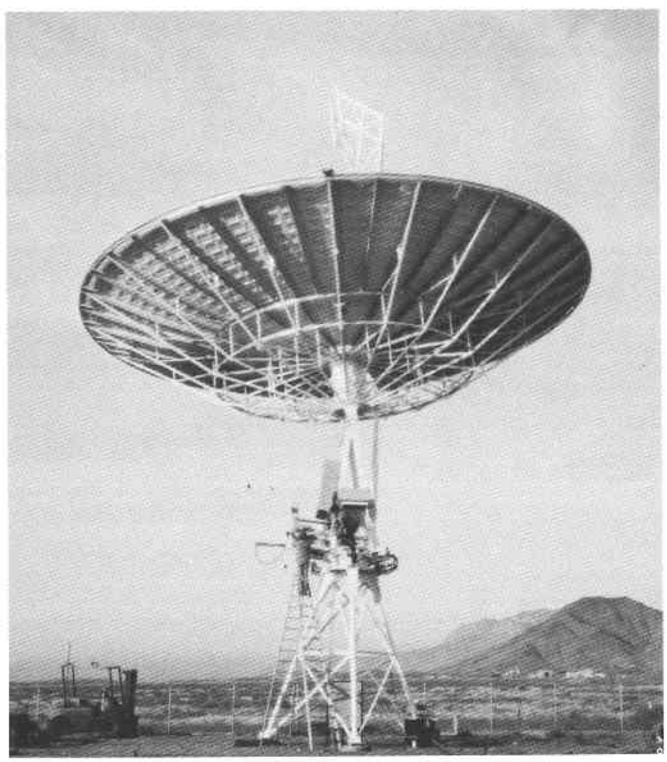

Figure 3.1 Acurex Innovative Concentrator

1 kW/m^2 solar input. The collector was assembled at the DRTF in October and November of 1986 and, on December 9, 1986, it came down in a wind when a substandard weld in the south tripod leg failed. Funding was not available to rebuild the collector but, because of the failure, Acurex did redesign the base support structure. Sandia and DOE continue to evaluate various options for reassembling and testing it.

Figure 3.2 shows the LEC innovative concentrator, which uses 95 polymer membrane facets 1.5 m in diameter to concentrate the sun's energy. The curvature of the facets is maintained by a vacuum between the front reflective membrane and the back membrane. The LaJet concentrator is 19.3 m in diameter and is predicted to have an optical efficiency of 90% and a thermal output of 147 kW_t for a 1 kW/m^2 solar day. The collector was delivered to the DRTF and assembled during July and August of 1987. Testing is scheduled to begin following the installation of a thermal protection system for a structure near the focus in early December 1987.

Stretched-Membrane Dish Collector Development Project. A stretched-membrane dish concentrator is made by attaching two thin metal or polymer membranes to a rim and drawing a vacuum between the membranes to stabilize the concentrator contour. The outer surface of one of the membranes is the highly reflective material that forms the concentrator. This approach has the potential to substantially reduce the weight and cost of dish concentrators while maintaining the high performance of faceted silvered glass concentrators such as the two test bed concentrators (TBC) and the Vanguard (or McDonnell Douglas Astronautics Corp.) dishes.

The stretched-membrane dish collector development project is organized into three phases. Phase I is the preliminary design of an optical element and experimental evaluation of facet fabrication techniques and performance. At the completion of a competitive procurement process in October 1986, contracts were awarded to SKI and LEC to pursue phase I. Phase II is the detailed design of the complete collector including the support structure, drives for tracking, and the control system. Phase III is the construction and testing of the collector. The goals of the project are to build a large (approximately 150 m^2) stretched-membrane dish collector with a focal-length-to-diameter (f/D) ratio near 0.6. The optical membrane must be of

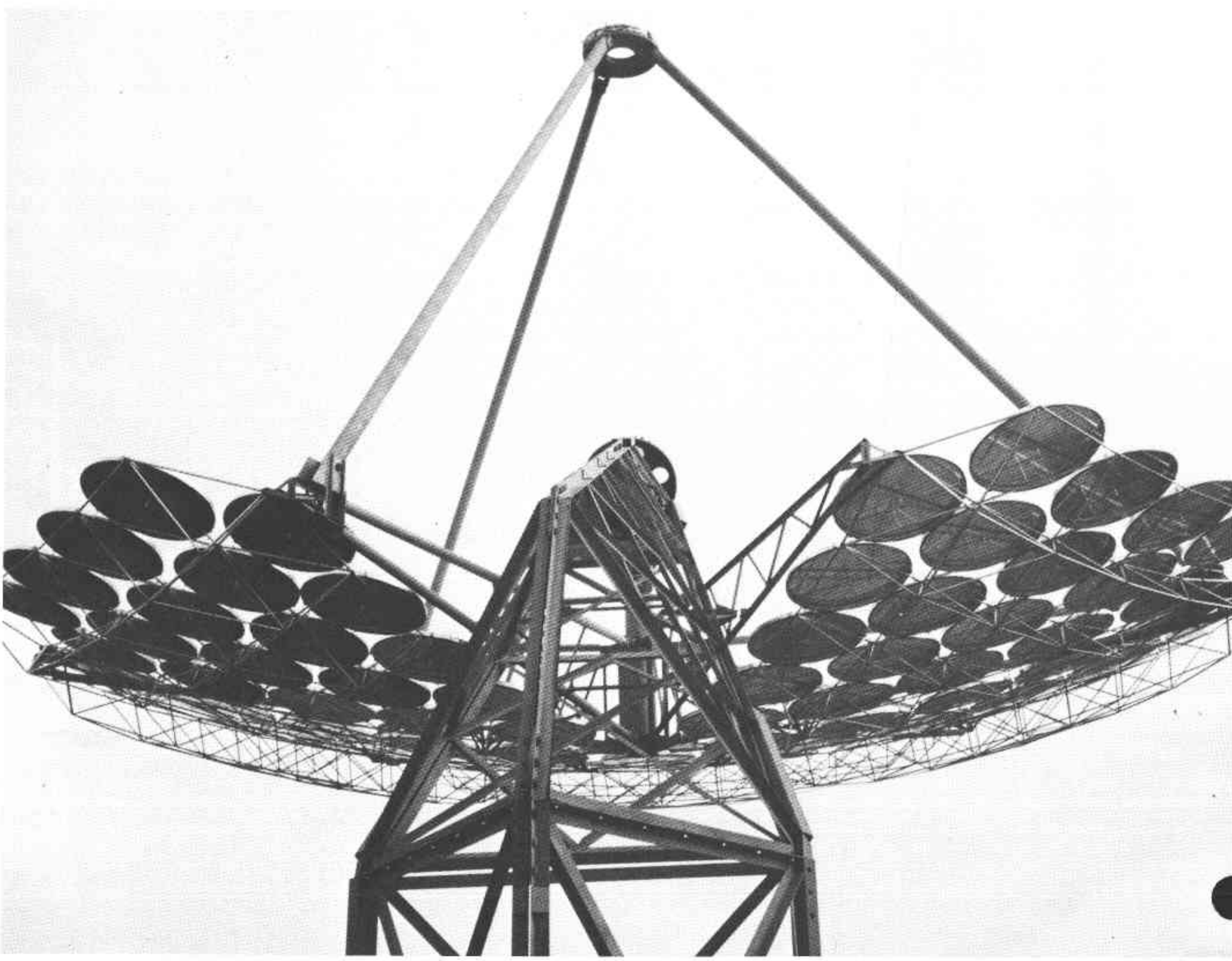

Figure 3.2 LaJet Energy Company Innovative Concentrator

very high optical quality having an average slope error of about 2.0 mr, a collector mass of 30-45 kg/m^2, and a peak optical efficiency of 91%.

The SKI design, conceptually represented in Figure 3.3, uses an annular support ring attached to an axial support post with tensioned cables. The ring properties are enhanced by the cables decoupling the ring stiffness from the membrane. SKI uses a free-form yielding approach to fabricate experimental aluminum membranes. Through the application of nonuniform loading to the membrane during the forming process, SKI has been able to achieve a square-root-of-sum-of-squares deviation from a paraboloid of 3-4 mr over 97% of the membrane surface.

LEC is developing a composite stretched-membrane concentrator. The membrane is comprises four layers of fiberglass impregnated with vinylester resin and a layer of polyethylene terephthalate (PET) with ECP 300 silver film on the top. The purpose of the intermediate PET layer is to minimize substrate print through to the optical silver layer. LEC is fabricating the required membrane contour on a highly accurate, tool plaster mandrel. Experimental results have shown that the application of circumferential rings of optical material are more compliant with the mandrel shape than radial gores and result in a reduction in the total length of PET seams on the concentrator surface. Finite element analysis has also shown that a biasing of the initial shape or a radial adjustment of the membrane-ring attachment is required to achieve the paraboloid of revolution for the final concentrator contour.

The contractors will complete phase I designs in November 1987; the phase II award will most likely be placed in February 1988.

Concentrator Materials Development. In support of the stretched-membrane dish collector development project, as well as the stretched-membrane heliostat project, the emphasis in FY 1987 was to adapt the sol-gel protective coating technology used successfully with the sheet metal mirrors to thin foil mirrors that can be used for stretched-membrane applications. A problem inherent in the use of silvered metal foils as mirrors is the lack of a suitable surface finish adequate for mirror applications. An innovation introduced was the application of sol-gel as a planarizing layer between the steel foil and the silver reflective layer. Besides the prevention of galvanic coupling between the silver and the steel, a significant improvement in the reflectance (from 71% to 95% with four coats of sol-gel) has been achieved. Sandia also initiated efforts to apply a suitable protective overcoat for environmental protection, which will be the main emphasis during FY 1988.

Line-Focus Concentrators

Testing of line-focus concentrators continues for the evaluation of improved components. During FY 1987 Sandia evaluated the following component improvements: Acurex direct-embedded pylons with self-aligning bearings, Acurex evacuated receivers, and SKI stainless-steel receivers.

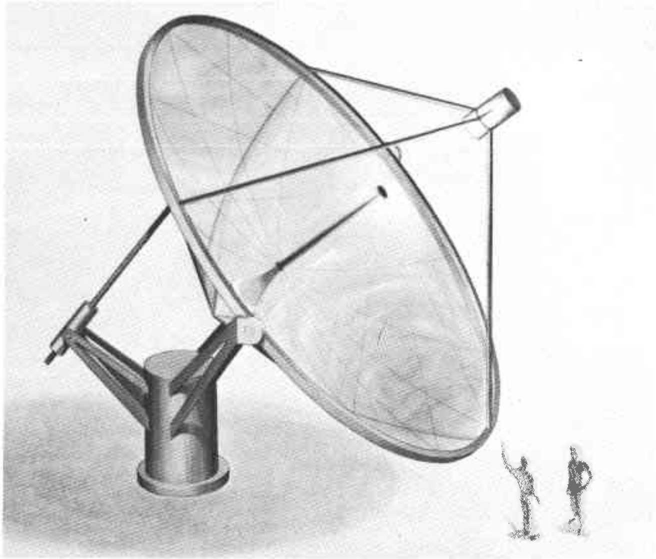

Figure 3.3 Solar Kinetics Stretched-Membrane Concentrator Concept

Acurex Line-Focus Direct-Embedded Pylons. A drive group of six collector modules on direct-embedded pylons with self-aligning bearings was installed at the DRTF in 1986. The pylons use Acurex's direct-embedded design that permits installation with only a single alignment step. The collector pylon extends into the concrete pier. After the holes for the piers are drilled, the pylon is positioned in the hole with a tripod-base alignment fixture. This fixture permits alignment of the pylon before the concrete is poured and holds the pylon until the concrete is set. In traditional designs the pylon is mounted to the concrete pier with anchor bolts, and two alignment steps are required. The alignment of the direct-embedded pylon in the fixture is accomplished more easily than either of the two alignment steps in the traditional design. This design reduces the cost of labor and material required for field installation of trough-type solar energy systems. This technique may also be applied to some dish and heliostat designs as well.

The pylons also incorporate self-aligning bearings that are being evaluated through life-cycle testing. Failures of the original pillow block bearings began after 1000 cycles; all had failed before 2000 cycles were completed. The new self-aligning bearings have completed 1531 cycles through FY 1987 without any failures.

Line-Focus Receivers. Six Acurex evacuated receivers, each 6 m long, were installed on the above drive group of Acurex collectors at the DRTF in January 1986. This drive group is being operated on weekdays, when weather permits, to evaluate reliability of the assemblies. Of the six assemblies, two were damaged during shipping or installation, and the vacuum in a third has degraded during operation. The other three have maintained a good vacuum. Tests at the DRTF have accumulated a total of 913 h of operation to date. Collector performance has improved because of the evacuated receivers, but has not yet been quantified. An additional evacuated receiver will be installed at a later date on a collector on the rotating platform to evaluate the effect of the design on performance. A nonevacuated, black-chrome-on-stainless-steel receiver manufactured by SKI has been evaluated on the rotating platform to provide a baseline for comparison to the evacuated receivers as well as the usual black-chrome-on-mild-steel receivers evaluated in the past.

Receivers

The primary objective of the receiver task is the development of efficient, low cost, reliable solar receivers for Stirling engines and thermochemical transport applications. The approach is to develop receiver hardware in support of heat engine and thermochemical transport application experiments and to improve our understanding of receiver heat transfer by experimentation and computer code development.

Receiver Analysis

Receiver design requires an understanding of energy exchange mechanisms inside cavity receivers. All three modes of heat transfer are involved and are usually interrelated in complex ways. Development of concentrator and receiver modeling codes has been a priority effort as a first step in establishing a comprehensive and versatile point-focus receiver design capability. In addition to providing a capability for understanding the behavior of receivers and simulating their performance, these codes allow the design engineer to identify loss mechanisms and make cost-effective trade-offs.

In FY 1987 Sandia validated with experimental data a computer code called CIRCE, which was developed as a dish-specific optics simulation package for predicting incident solar flux distributions. Figure 3.4 shows a typical comparison of the CIRCE simulation with experimental data from one of the TBCs at Sandia. The peak flux intensities were found to agree within about 30% with the simulation peak intensities. This discrepancy is easily explainable by uncertainties in several of the input variables and is of the same magnitude as the day-to-day variations. Of greatest importance is CIRCE's ability to predict complex morphological characteristics of flux distributions in target planes behind the aperture. When this capability is eventually combined with a thermal analysis model that will incorporate reflection, heat transfer to the working fluid, and losses through the aperture, it will represent a major capability for the design and understanding of dish solar receivers. The CIRCE code was distributed to several other labs and private solar design firms that use the code daily.

Receiver Development

Receiver development involves the design, fabrication, testing, and analysis of receiver hardware for heat engine and thermochemical transport applications.

Thermochemical Receiver/Reactors

For thermochemical energy transport, three fundamental types of receiver/reactors were identified that can be used to effect chemical reactions near the focus of a dish concentrators. These are (1) tube receiver/reactors which have tubular reactor elements that are directly heated by solar energy in the receiver, (2) indirect receiver/reactors that use an intermediate heat transfer fluid between the receiver and reactor, and (3) direct absorption receivers/reactors that absorb sunlight directly on the catalyst.

All three types of receiver/reactors have their own set of limitations, risks, and advantages, but the reflux heat-pipe receiver/reactor (a kind of indirect receiver/reactor where

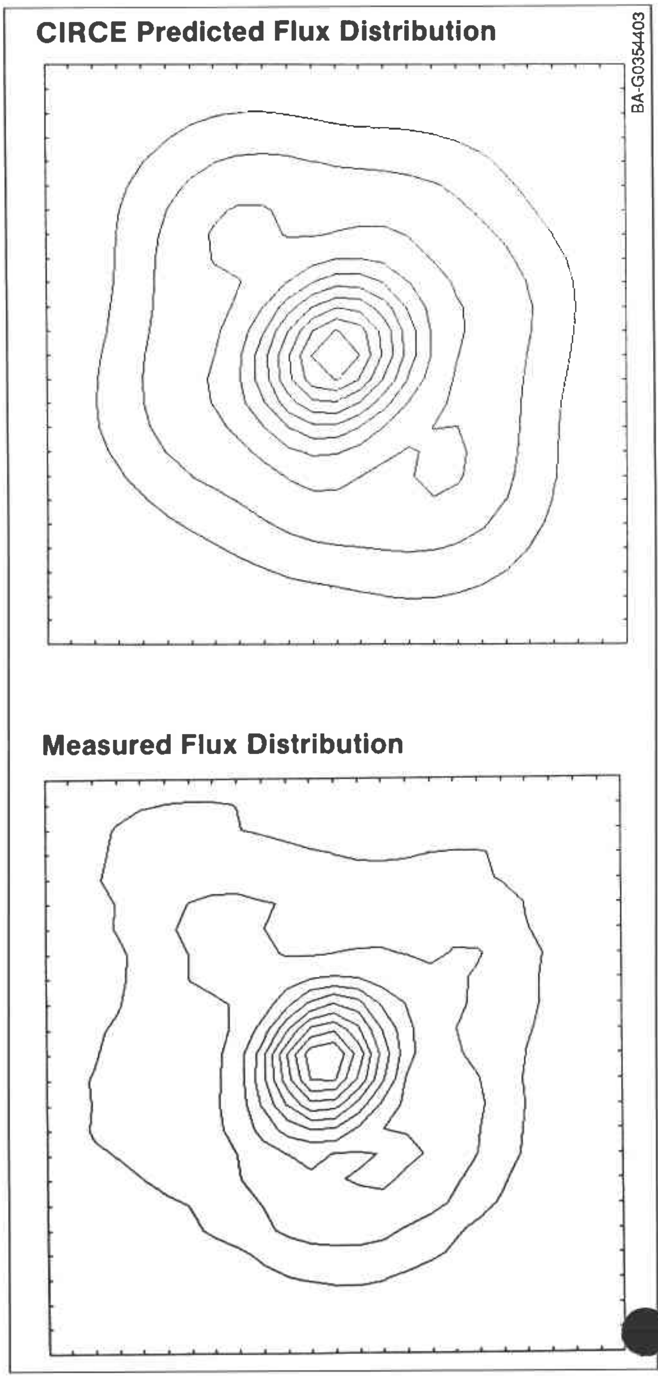

Figure 3.4 Incident Solar Flux Distributions Predicted by CIRCE (top) and Measured on TBC-1 at Sandia

sodium is the intermediate fluid) and the direct catalytic absorption receiver/ reactor are especially promising.

Figure 3.5 shows the Sandia-Israel reflux receiver/reactor and illustrates the principle of operation. The receiver was fabricated at Sandia in FY 1987 as part of a bilateral agreement between the United States and Israel and was tested at the Weizmann Institute of Science (WIS) solar furnace in Rehovot, Israel. The receiver is located just behind the focal plane of the WIS 7-m diameter horizontal-axis solar furnace and packaged in high temperature insulation. Sunlight is directed onto the receiver/absorber, which causes sunlight to evaporate from the back surface of the wicks. The sodium condenses on the reactor tubes and liberates heat for the chemical reaction. Liquid sodium is then returned to the back of the receiver/absorber by return channels and distributed by wicks.

The tests in Israel successfully demonstrated that the receiver provides efficient transport to the reactors. The temperature distribution within the heat pipe was extremely uniform, and good agreement with computer models on the process were obtained. This was the first on-sun test of this important receiver concept.

The other receiver concept that promises even better performance at a lower cost for thermochemical transport is the direct catalytic absorption receiver/reactor (DCAR). The DCAR uses a window that permits the direct absorption of sunlight on the catalyst. The advantage of this design is that it avoids the heat transfer limitations that are inherent in conventional tubular chemical reactors (see Figure 3.6). This exciting receiver concept, which was first explored by researchers at the University of Minnesota is potentially very efficient, inexpensive, and capable of operating at much higher temperatures than conventional tube or reflux receivers. The DCAR represents a truly unique solar capability for performing reforming and other chemical reactions.

Stirling Engine Receivers

The main thrust of heat engine development is Stirling cycle machines and reflux heat-pipe receivers. The STT Program is sponsoring several projects to develop and investigate reflux heat-pipe receiver options for kinematic and free-piston Stirling engines.

In FY 1987 the detailed design of a reflux heat-pipe solar receiver was initiated for the Stirling Thermal Motors (STM) STM4-120 kinematic Stirling engine. In FY 1988 fabrication and testing at Sandia on the test bed concentrator will be conducted. After this testing, the receiver and the engine will be tested as a total system.

Figure 3.7 shows a mock-up of the engine with the heat pipe solar absorber/evaporator. Note that unlike the geometry of a conventional tubular heat pipe, the evaporator has been modified for the efficient collection of solar energy. Its principle of operation is identical to that of the Sandia-Israel reflux heat-pipe receiver/reactor except that heat is transferred to the heater tubes of a Stirling engine rather than to a chemical reactor. This receiver has also been configured for operation on a dish rather than on a solar furnace. The gravity-assisted return of liquid sodium to the solar absorber is thus more readily accommodated with the dish-mounted receiver. Figure 3.8 shows a schematic of the engine-receiver and auxiliaries. The relation of the receiver absorber to the aperture and insulation housing can be seen. Another advantage of the reflux heat-pipe receiver is that it can be readily hybridized (the gas-fired heat-pipe can also be seen in Figure 3.8). Long-range plans call for the integration of this receiver with a gas-fired heat pipe also being developed by STM with funding from the Gas Research Institute.

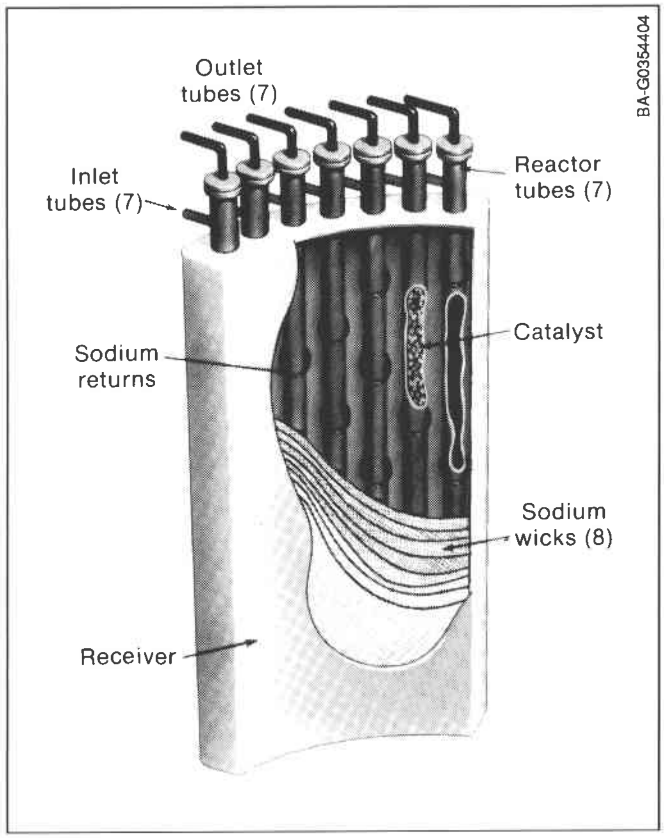

Figure 3.5 Sandia-Israel Reflux Heat-Pipe Solar Receiver/ Reactor

Through an interagency agreement between DOE and NASA, Sandia is coordinating with NASA Lewis Research Center (LeRC) to develop an Advanced Stirling Conversion System (ASCS) based on free-piston Stirling and reflux heat-pipe receiver technology. In FY 1987 contracts were placed with Mechanical Technology Inc. (MTI) and Stirling Technology Corporation (STC) for the conceptual design of two ASCSs. Figures 3.9 and 3.10 show the MTI and STC conceptual designs. The MTI heat pipe receiver features a sintered nickel powder wick that incorporates circumferential and radial arteries to facilitate the return of liquid sodium to the solar absorber. The STC receiver is a reflux boiler and uses potassium instead of sodium as the heat transfer fluid. Liquid return to the absorber is assured by an inventory sufficient to submerge the absorber in orientations from vertical to horizontal. The engine heater tubes are always located in the vapor space above the pool.

Engine Conversion Technology

Heat Engine Development

The objective of this activity is to evaluate and develop heat engine technologies applicable to distributed receiver systems. Current heat engine development is focused on the Stirling cycle. In particular, the DR Project emphasizes the development of engines in the 20-50 kW_e range to match current and future parabolic dish thermal capacities.

Stirling Engines

The main thrust of heat engine development is the Stirling cycle. Several projects are being done to bring kinematic and free-piston Stirling engines to hardware test.

In early FY 1987 Sandia was scheduled to take delivery of a kinematic Stirling engine, STM4-120 (Figure 3.7), currently under development by STM. However, because of setbacks in completing full operational testing at STM, the STM4-120 will not be delivered until FY 1988. This engine has several features that are beneficial for solar application. These features include heat pipe technology for efficient energy transport, pressurized crankcase to extend piston seal life, and power control via a variable swashplate for simplified power control. With these features, STM has designed an engine that has the potential to operate 50,000 h between major overhauls. At the design point of 25 kW_e the cycle efficiency will be 40%-45%. Integration of a heat rejection system, controls, generator, and heat input scheme will be completed in FY 1988. Also, during FY 1988 a reflux heat pipe solar receiver will be designed, constructed, and installed with the STM4-120 system on a TBC for on-sun testing.

The interagency agreement between DOE and NASA discussed in the receiver section will result in the development of an ASCS based on free-piston Stirling engine (FPSE) technology. The FPSE offers the same advantages as the kinematic Stirling engine plus the potential of even longer life and lower operating and maintenance costs (O&M). The longer life and lower O&M are due primarily to fewer moving parts in a FPSE. Under technical management by LeRC, MTI (Figure 3.9) and STC (Figure 3.10) completed their phase I conceptual designs of an ASCS in FY 1987. Both systems utilized the basic FPSE; however, different approaches were taken for converting the mechanical energy of the engine to electrical energy. MTI designed a system that used a linear alternator while STC designed a system in which a rotary generator is operated by a hydraulic fluid converter in the engine. In addition to the phase I designs, both contractors used the expertise of Pioneer

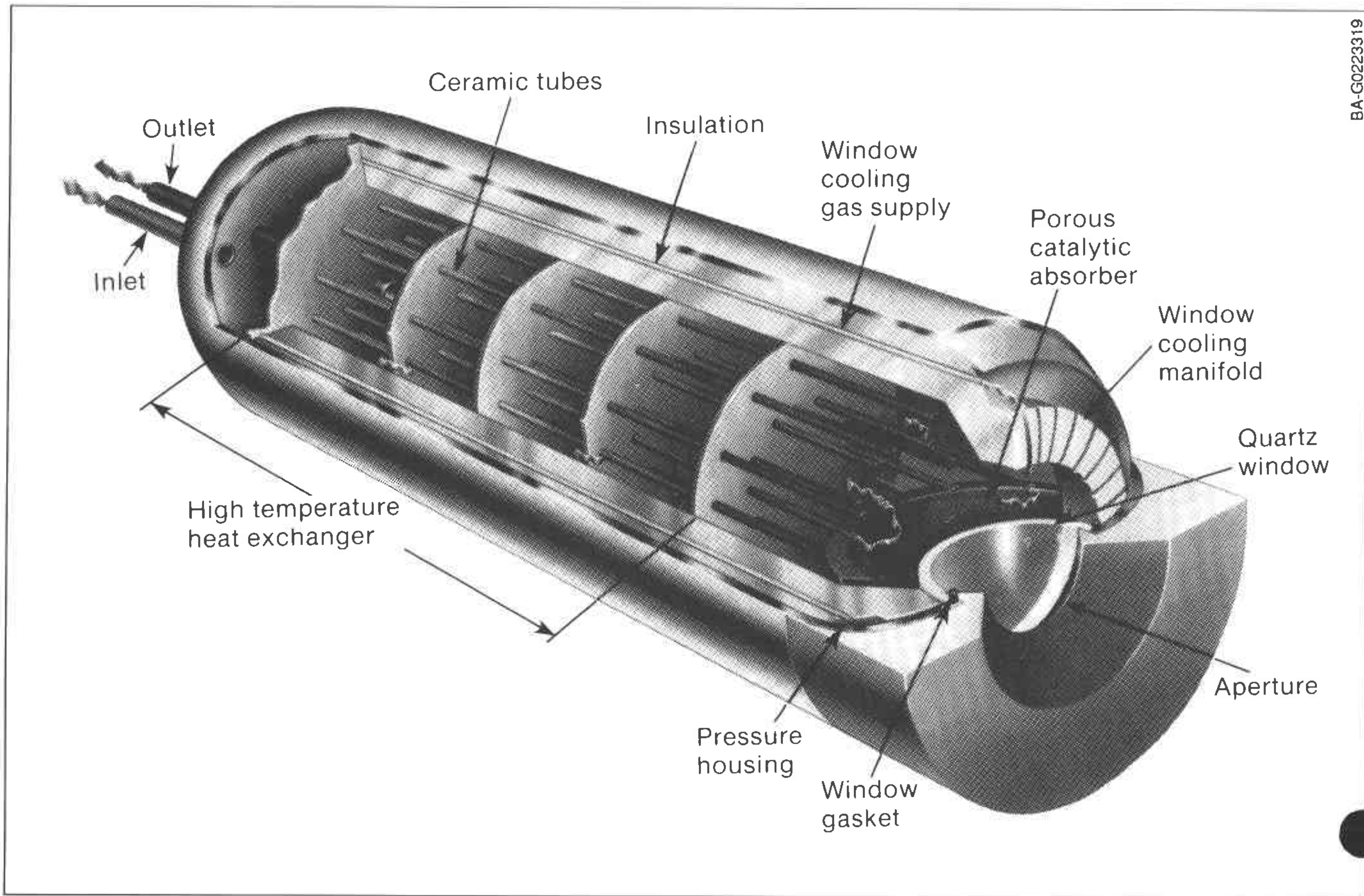

Figure 3.6 Direct Catalytic Absorption Receiver

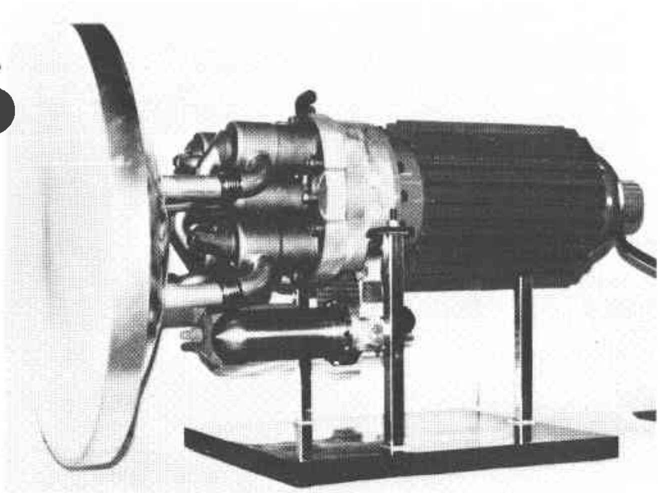

Figure 3.7 Mock-up of the STM4-120 and Reflux Heat-Pipe Solar Receiver

Engineering and Manufacturing Company to conduct an independent manufacturing cost assessment of their respective systems. Pioneer is scheduled to complete the evaluation of each system in early FY 1988.

The next phase of the ASCS program is scheduled to begin in FY 1988 when a contract will be awarded through competitive procurement for the detailed design and fabrication of a prototype ASCS. Testing of the prototype ASCS at the DRTF should begin in FY 1990.

Liquid Metal Thermal Electric Converter (LMTEC)

Since FY 1985, Sandia has been active in the evaluation and development of heat engine technologies applicable to dish-electric systems. This ongoing assessment of heat engine technologies identified the LMTEC concept as having the potential to meet the STT Program's long-term engine cost and performance goals but requiring significant engineering development. The LMTEC concept is appealing for the following reasons: its basic mechanical and electrical simplicity should yield engines with minimum maintenance and long life; as in the Stirling cycle, the ideal thermodynamic cycle efficiency approaches that of the Carnot cycle; and the efficiency appears to be relatively independent of scale to at least the 20-50 kW range for dish electric systems.

The following summarizes the progress made in the various LMTEC R&D areas in the past year:

- Construction and testing of the LMTEC bench test module (BTM) was completed. The test proved a number of concepts and design features, including the overall BTM envelope, the ceramic-to-metal seal, the location of electrical feed-throughs, the method of remote condenser cooling, the electromagnetic pump, the method of sodium insertion and BTM start-up, and the computer control system. Power output was achieved and valuable operating experience and data accrued. The major problem encountered was poor electrode permeability. This resulted in poor electrical performance and, in concert with a heater failure, breakage of the solid electrolyte. A positive result of this circumstance has been the development of a new electrode permeability testing technique that will enable screening of electrodes before actual BTM construction.

  Post-test analysis of the LMTEC BTM was completed. The analysis included visual and microscopic observations, x-ray photography, electrical and mechanical tests, and chemical analyses. The LMTEC computer model was extended to include the distributed-network character of the BTM. The model showed that the electrode permeability would have to be approximately three orders of magnitude less than that of a "good" electrode to explain the results. During electrical tests of the sort that the BTM underwent, such an electrode could also be expected to cause structural damage to the solid electrolyte as observed microscopically. Ultimate failure of the weakened electrolyte was caused by thermal shock, which occurred following failure of the main BTM heater.

- A new thin-film electrode permeability test has been developed that is based on the idea of electrically driving sodium through an electrode-electrolyte combination in the reverse direction from normal. Liquid sodium is used as the electrode on the uncoated side of the electrolyte. If the thin-film electrode is not readily wet by liquid sodium, then the current that is observed will be limited regardless of the applied voltage. The limit is determined by the combination of electrode permeability and the pressure available to drive the sodium vapor through the the electrode pores. This technique requires only very simple equipment, as illustrated in Figure 3.11. An evaluation of an electrode of the same type used in the first BTM showed it to have low enough permeability to explain the observed electrical performance.

- Contract work at the University of Pennsylvania and the University of Wisconsin has resulted in continued progress towards the successful production of single and polycrystalline samples of the mercury analog of sodium beta double prime alumina solid electrolyte. The synthesis is being accomplished by ion exchange techniques. Researchers have achieved approximately 85% exchange in single crystals and 20% in polycrystalline samples.

The LMTEC BTM work will be concluded with a report summarizing details of BTM design, construction, testing, and post-test analysis.

Transport and Storage

The economical transport and storage of thermal energy is critical to the development of solar thermal system technologies that use the point-focus distributed receiver (DR). Present sensible heat transport methods in the medium-to-low temperature range impose a penalty on collected energy delivered to the end use. Because of the very high temperature capability of parabolic dishes and the extensive piping required to deliver

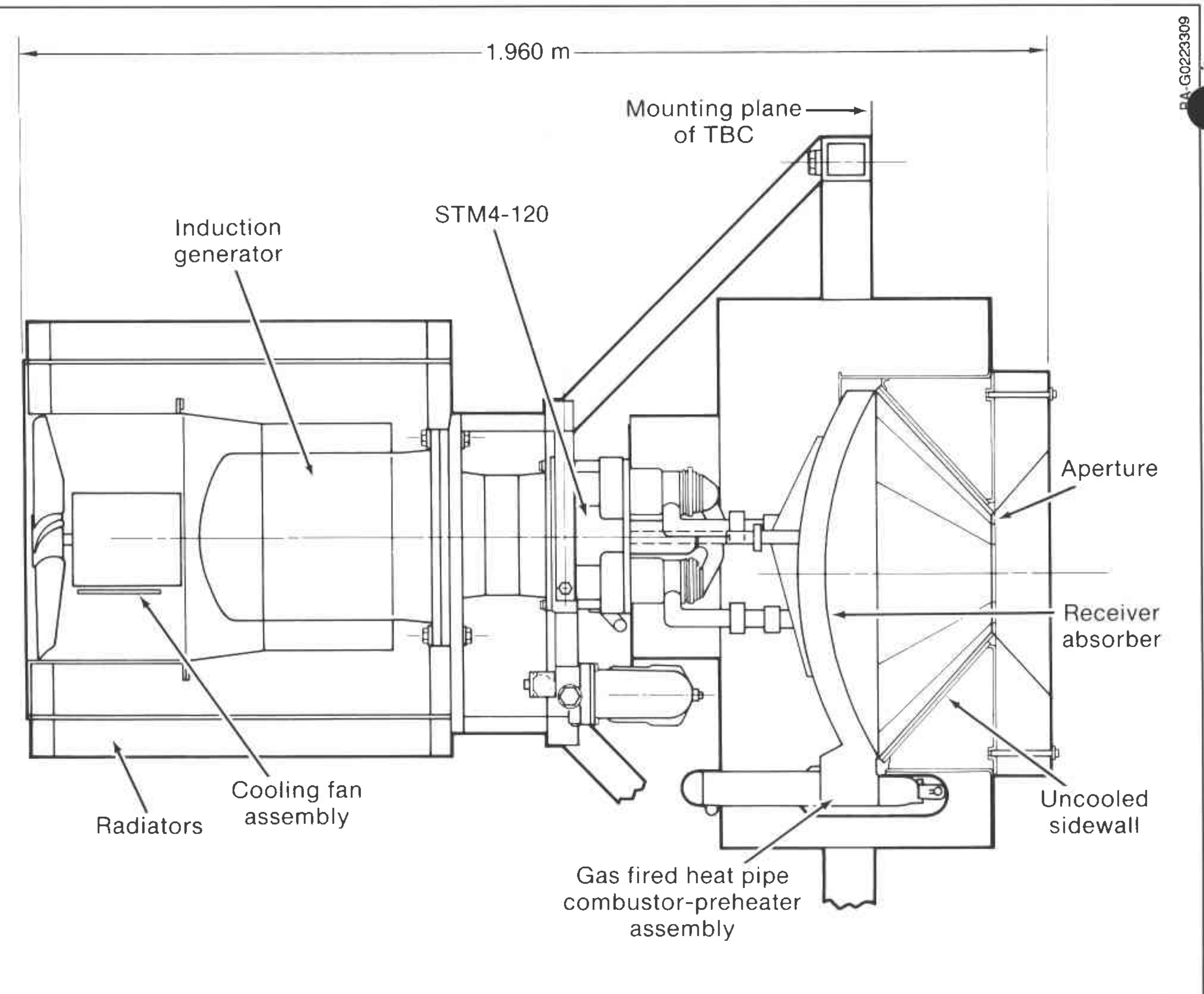

Figure 3.8 Schematic Diagram of the STM4-120 Stirling Engine Hybrid Solar Receiver Power Conversion Module

energy from a large collector field, increased losses and insulation costs make conventional sensible energy transport less attractive. Efforts are under way to identify more efficient methods of solar thermal energy transport capable of using higher receiver temperatures.

The objectives of this task are to identify, develop, evaluate, and demonstrate high efficiency, low cost energy transport and storage systems suitable for high temperature, solar thermal DR applications. A primary candidate for low-thermal-loss energy delivery is the concept of thermochemical (TC) energy transport. Products from an endothermic reaction in the solar receiver/reactor are transported to the end use where they are recombined in an exothermic reaction (releasing energy to the user), and the "feedstock" produced is recycled back to the collectors. Counterflow heat exchangers between the two streams at both ends of the loop allow transport at close to ambient temperatures, thereby significantly reducing piping heat loss and costs.

Present and near-term future activities stress energy transport concepts because they are currently considered much more critical to distributed receiver technology than energy storage development. The current emphasis is on developing and demonstrating the technology of TC transport for point-focus central engine applications. Early in FY 1986 the CO_2/CH_4 reforming/methanation system was selected as the TC energy transport system on which to base further development. Activities during the remainder of FY 1986 concentrated on (1) laboratory experiments to provide closed-loop TC transport system performance data and to address the major problem areas of the CO_2/CH_4 system (catalyst deactivation, carbon formation and high temperature mechanical properties of candidate structural materials) and (2) initial design of a field-scale Closed Loop Operations Experiment (CLOE) of the CO_2/CH_4 TC transport system.

Current activities include complementary modeling and experimental studies that build on the results of the earlier studies that will culminate in the field-scale experiment, and whose objective is to demonstrate the feasibility of TC energy transport for DR applications.

Model Development

Model development activity is aimed at obtaining the necessary computational tools for making performance/economics evaluations of sensible and TC energy transport systems for distributed receiver applications. Two approaches are under way: (1) development of a single-loop, steady-state TC energy transport performance model, also called the Closed Loop Efficiency Analysis (CLEA) model, and (2) development of a DR collector field transport system performance/economics optimization code SOLTES for both sensible and TC energy transport systems. Both models are important tools for extrapolating laboratory-scale results to the field-scale TC transport experiment, CLOE.

CLEA code activities in FY 1987 consisted of support for the central engine study being performed as part of the DR systems engineering and analysis effort (see below) and documentation of the initial version of the code, designated 86.1. This documentation will be completed in the first quarter of FY 1988.

The SOLTES steady-state sensible energy transport performance code was modified in FY 1987 by incorporating TC transport models obtained from the CLEA code. This TC version of SOLTES will be used to model the field-scale experiment, CLOE, and predict its performance for a range of anticipated operating conditions. The results of these calculations will aid in defining the experiments to be performed. Once experiments are under way, the results of additional SOLTES calculations will assist in analyzing the data and understanding the behavior of the CO_2/CH_4 TC transport system.

Model development activities are also part of a catalyst evaluation and development study being performed at the University of Houston. Two CO/H_2 methanation models and a closed-loop CO_2/CH_4 reforming/methanation model were completed during FY 1987. The two methanation models include reaction kinetics for the methanation and water gas shift reactions based on experimental reaction rate data for powdered 0.5% rhodium on alumina catalyst and no water added to the feed gas. The closed-loop model assumes equilibrium chemistry for both the reforming and methanation reactions and includes water recycled around the methanator.

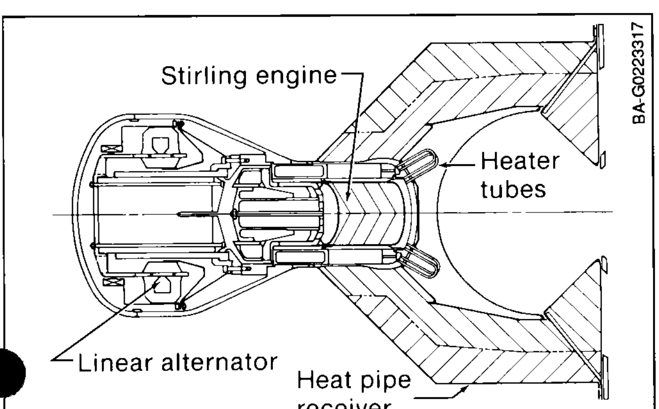

Figure 3.9 MTI Free-Piston Stirling Engine

Laboratory Experiments

Experiments continued during FY 1987 in the CLEA TC energy transport facility. This is a laboratory-scale (2.5 kW_t) facility based on the CO_2/CH_4 reforming/methanation chemical system. It is a single loop employing one reformer and one methanator that can be operated in open- and closed-loop configurations under steady-state or simulated solar conditions. A significant accomplishment was the completion of tests that provided critical data for the design of CLOE including information on catalyst selection, materials concerns, and operating procedures. In particular, experiments showed that the use of rhodium catalyst in the reformer and in the high temperature stages of the methanator, and copper coating of the exit piping and heat exchanger of the reformer, are necessary to prevent carbon deposition problems. Nickel catalyst, because of higher activity than rhodium below about 400°C, is preferred for the low temperature stage of the methanator.

To achieve higher conversion and better selectivity in the endothermic reaction and higher overall efficiencies, researchers designed and fabricated an endothermic reactor capable of reaction temperatures between 900° and 1000°C for the CLEA facility during FY 1987. Testing will emphasize obtaining data and operational experience pertinent to the field-scale TC energy transport experiment, CLOE phase I. The laboratory facility will also be available, if needed, to help troubleshoot problems encountered while testing in CLOE. These tests will be followed by tests involving advanced capability, high temperature reformers in support of CLOE phase II.

The University of Houston has continued catalyst evaluation and development studies in support of the CO_2/CH_4 TC transport system. Accomplishments in FY 1987 include: (1) preliminary determination of rate equations, heat transfer parameters, and deactivation rates and mechanisms for rhodium-based catalysts in pellet form, and (2) modification of existing computer models to incorporate information obtained in (1). These models aided in designing the reformers and methanator for the field-scale experiment, CLOE, and the 20 kW_t receiver/reformer to be tested at the Weizmann Institute of Science solar furnace in Rehovot, Israel (see Receivers section). Catalyst development and reactor modeling studies will continue at the University of Houston in FY 1988. Planned activities include refining the rate equations and heat transfer parameters and the model development activities, both described previously.

Coking experiments continued at the CLEA laboratory in FY 1987 to investigate carbon deposition on candidate reformer and methanator materials in representative gas environments (mixtures of CO, H_2, CO_2, and CH_4 at temperatures ranging from 400° to 900°C). Carbon deposition rates were barely discernible for quartz and copper. They were an order of magnitude higher for Inconel 625 and 405 and 316L stainless steels, and two orders of magnitude higher for plain carbon

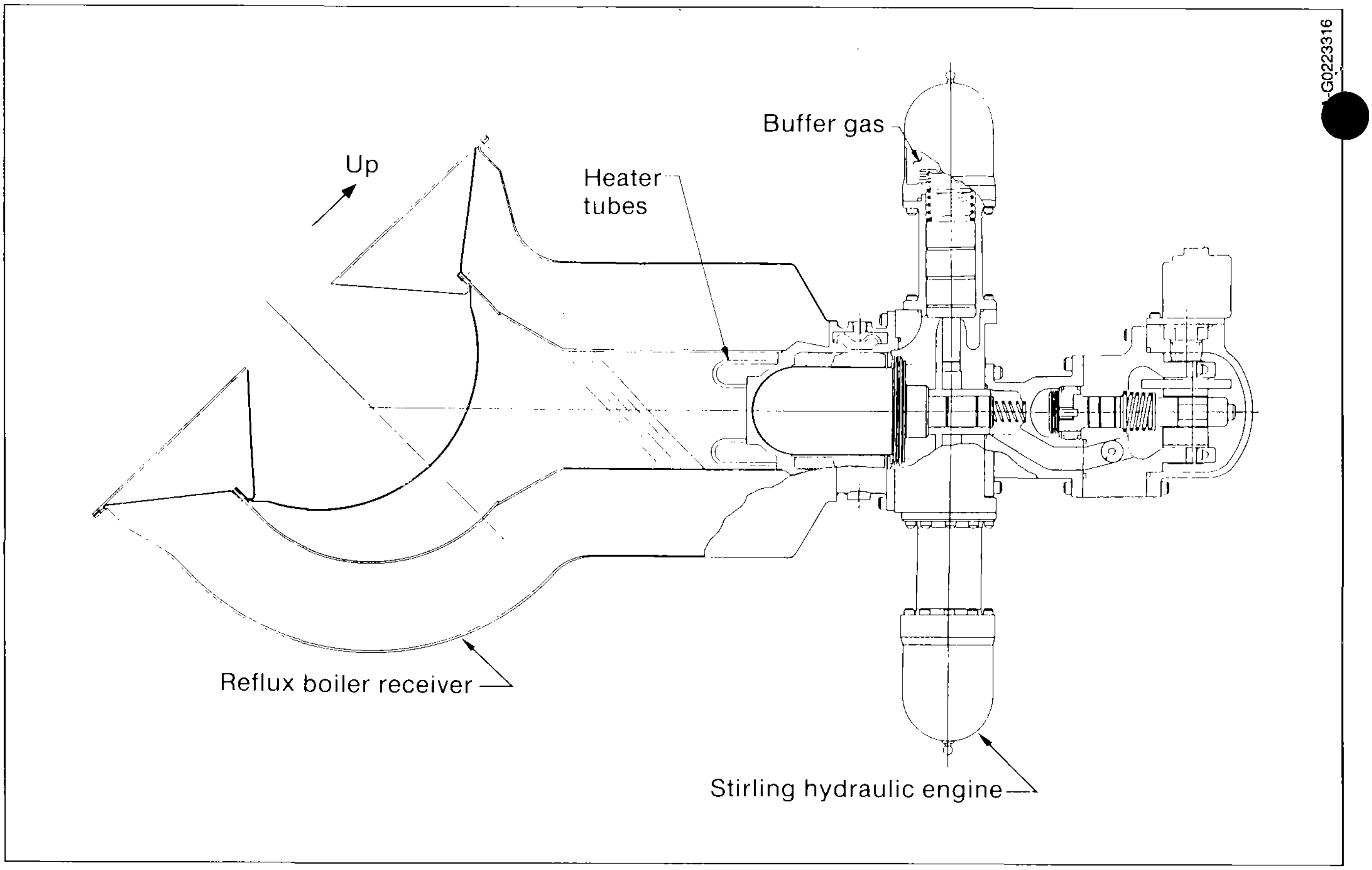

Figure 3.10 STC Free-Piston Stirling Engine

steel. Of particular significance was the inhibition of coking by copper in reformer environments. This was independently verified by tests in the CLEA laboratory facility in which the reforming reactor exit tube was lined with copper. Coking tests were also continued to investigate carbon deposition on typical reforming and methanation catalysts. Results from tests involving a rhodium catalyst and copper reveal that neither showed any catalytic effect over a wide temperature range (400°-1000°C) in either the Boudouard reaction or the decomposition of methane. In a gas mixture typical of the reforming environment (CO_2/CH_4 I 1:1), the results show rhodium to be a very effective, stable catalyst.

Sandia continued mechanical properties experiments in FY 1987 to evaluate the creep and weldability characteristics of candidate alloys in representative CO_2/CH_4 reforming environments. Based on the results obtained and on comparisons with the high temperature mechanical properties of other alloys (Incoloy 800H, Manaurite 36X, and Manaurite 900B), Inconel 617 was selected as the primary construction material for the CLOE reforming reactor tubes. It has significantly better tensile ductility and higher creep strength at 950°C — the maximum tube temperature anticipated in the CLOE reformers.

Field-Scale Experiment

As a follow-up to the modeling and laboratory experimental studies, the next logical step in developing TC transport technology is to proceed with testing at larger than laboratory scale and under more realistic conditions. A field-scale experiment, including multiple endothermic receiver/reactors (both conventionally and solar heated) and as many commercially available components as possible, will be a major step in demonstrating the practical feasibility of TC transport for solar applications.

The CLOE is based on the CO_2/CH_4 reforming/methanation chemical system and will be conducted in two phases. Phase I involves conservative, state-of-the-art receiver/reactor designs that will ensure successful operation of the system. Energy will be input using electric heaters to provide better control and more flexibility in performing the experiments. Phase II will involve advanced receiver/reactor design concepts capable of operating at higher temperatures, and at least one of these units will be mounted on a parabolic concentrator to demonstrate operation in a true solar environment.

A contract was placed early in FY 1987 with Resource Analysis International (RAI), Inc., Los Angeles, Calif., to perform a detailed design of the CLOE phase I system. The resulting design consists of two receiver/reformer/recuperator units, sized for 80-kW_t energy input (the heat rate for a 12-m dish) manifolded in parallel and connected through a piping network to a single 130-kW_t methanator unit. A significant accomplishment during the fourth quarter of FY 1987 was the completion by RAI of stage II (chemical engineering) of the CLOE phase I design.

Work was subsequently initiated on stage III (installation) of the CLOE phase I design. Black & Veatch Engineers-Architects (B&V), under contract to Sandia, will perform the necessary civil, architectural, mechanical, and electrical design and prepare a construction bid package. As a first step, however, the Pritchard Corporation, a subsidiary of B&V, initiated a review of the CLOE P&IDs, equipment and instrument specifications, and operating procedures. This review will be completed early in FY 1988 and will result in a set of updated P&IDs.

Controls Study

Based on experiences from previous solar collection systems, control failures are often a major cause of poor system performance. To address this issue, Sandia began a study in FY 1987 to identify control needs for distributed receiver systems. The controls study outlined development efforts that are needed to enhance the performance of solar thermal systems.

The conclusion of the controls study was that the program should emphasize developing intelligent tracking controls that aim the concentrator at a computed sun position. The tracking system should correct for alignment errors through software algorithms with information from sensors that measure the sun's position directly. This method of tracking control will eliminate the need for accurate field alignment of the concentrator and will provide self-diagnostic capabilities to the tracking system.

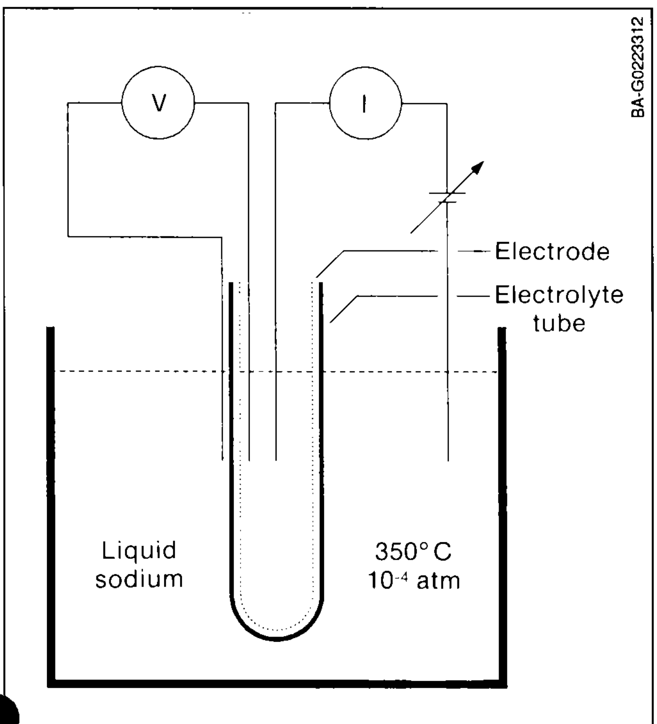

Figure 3.11 Electrode Screening by Pressure-Limited Current Measurement; Liquid-Liquid Cell

An intelligent tracking system has always been an attractive option but it has become a cost-effective option only with recent price reductions in microprocessors and position measuring devices. The development of improved tracking systems will be pursued in future concentrator development tasks.

System modeling efforts should also be increased to aid in the development of controls. Abrupt changes in power levels and daily variations in operating conditions require sophisticated controls that can accommodate a wide range of circumstances. Conventional control design techniques tend to focus on operation about a single point, and these design practices can lead to inappropriate system control procedures in solar power systems. Improved system models will lead to better control designs and aid in the assessment of system responses to component failures.

In addition to identifying the need for advanced tracking controls and improved system models, the controls study also identified a need for inexpensive flow regulating devices. Active flow control for individual receivers is seldom used in distributed receiver/central engine systems because of cost considerations. Without the use of active flow control, however, temperatures often vary throughout a field of collectors and the overall performance of a system is degraded. A study is currently under way to determine the extent to which performance is affected by various flow control practices. The use of thermostatically actuated valves such as the one illustrated in Figure 3.12 may be one method to improve system performance at a reasonable cost. Thermostatic valves tend to be inexpensive and are commonly used in automotive and domestic solar hot water systems.

Distributed Receiver Systems

Systems Engineering and Analysis

The effort of FY 1987 concentrated on completing phase II of the central engine study. This study investigated the viability of using current Rankine technology for conversion (thus avoiding expensive engine development) along with one of two types of heat transport methods: sensible and thermochemical. The study, involving daily simulations of each system, showed that for 50-MW_e plants the cost of electricity is \$0.07-\$0.1/kWh_e.

Each system was evaluated using near-term technology for the solar components and current technology as the baseline for the Rankine conversion equipment, assuming concentrators of near-term quality and cost. Two transport systems were considered: one sensible using NaK liquid metal and one thermochemical using the CO_2 reforming of methane. These two technologies represented the areas of greatest uncertainty both in performance and in cost at the study's beginning.

Through a contract with MTI, current engine technology in the 500-kW_e to 50-MW_e range of Rankine engines was evaluated.

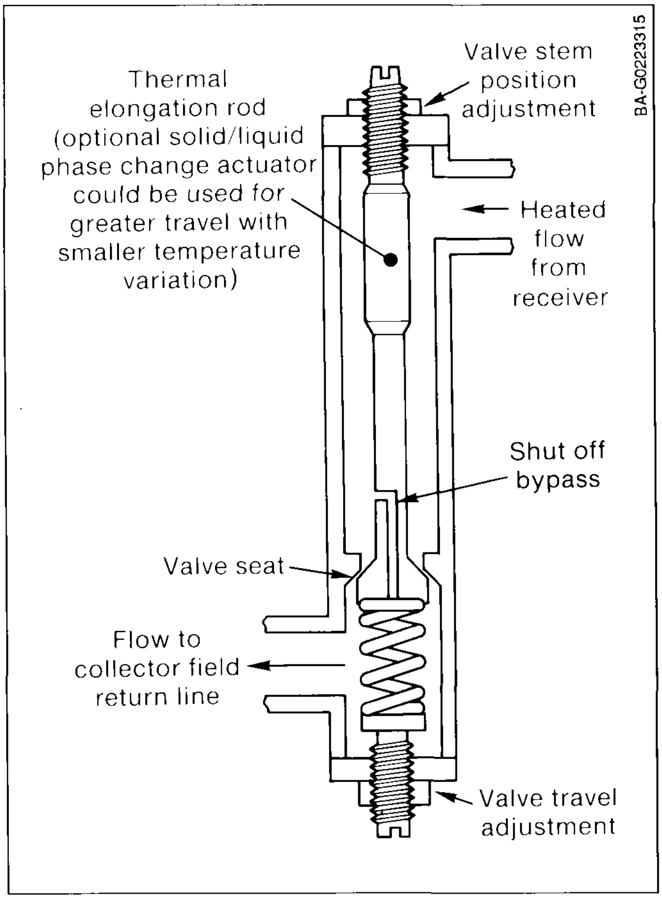

Figure 3.12 Conceptual Design for a Thermostatically Actuated Valve for Regulating Receiver Temperatures

MTI surveyed the industry on the available product line of turbo-machinery suitable for use with a field of parabolic dishes. Having identified potential turbine units, MTI designed complete conversion cycles and supplied performance and cost estimates where applicable.

The matrix of interest included turbine inlet temperature from 750° to 1200°F and sizes from 500 kW_e to 50 MW_e. MTI included both steam and organic turbine manufacturers in the survey; however, they found no organic Rankine engines in the range of interest. Actual turbine availability is shown in Table 3.1.

After identifying the turbines, MTI analyzed the design and off-design performance of the turbines and accompanying cycle components to be used with a simulation model of the solar collection system. They developed overall cycle performance as a function of steam flow by simulating the various components in a cycle configuration using SOLTES.

In addition to performance estimates of the Rankine systems in a solar application, MTI also developed cost information. They developed installed costs and O&M estimates for the power cycle from data obtained through various vendors and engineering judgment. This completed subtask represented a set of consistent performance and economic data on steam Rankine cycles of use to any renewable source not interested in the extensive and expensive route of engine development.

The next step was to model the entire system including concentrator, receiver, and transport supplying the Rankine conversion cycle. Six systems were modeled — two 500-kW_e plants with turbine inlet temperature of 750°F, two 50-MW_e plants with a turbine inlet temperature of 750°F, and two 50-MW_e plants with a turbine inlet temperature of 1000°F. Each plant was modeled with the two different transport systems designed to meet the cycle requirements.

The two transport systems exhibited different performance patterns, were physically quite different, yet performed similarly on an annual energy delivered basis in this study. The annual performance transport efficiency for the small plant ranged from 69% (for thermochemical, which is more dependent on pumping power and therefore conversion efficiency) to 85% (for the sensible system). For larger plants, the annual performance of the transport systems ranged from 74% (for thermochemical transport) to 80% (for the sensible system).

The larger plants produced energy at lower cost (7¢-10¢/kWh_e) than the small plants (25¢-35¢/kWh_e), primarily because of the high cost and low efficiency of the smaller turbines. It is important to note that the ability to improve the performance of these small turbines exists but has not been demanded by the market place. The large plants benefited greatly from the high conversion efficiencies of the turbines and were not significantly penalized by the increase in field size.

The results of phase II of the central engine study were encouraging for systems comprising a 50-MW_e steam Rankine turbine, a thermochemical transport system, and an appropriate number of near-term technology dishes. The study, in fact, indicated that the optimum size of such a plant might be larger than the 50-MW_e size studied.

Shenandoah Solar Total Energy Project (STEP)

The Solar Total Energy Project (STEP), located at Shenandoah, Ga., is the world's largest industrial application of the solar total energy (cogeneration) concept. The primary objective of the project is to evaluate a solar system that provides electrical power, process steam, and chilled water for air conditioning to a knitwear factory operated by Bleyle of America. In this application solar energy generates a large portion of Bleyle's electrical requirements and replaces part of the fossil fuels normally required to operate the factory.

The Shenandoah STEP plant became operational in 1982. Substantial facility upgrades were completed, and title to the project was turned over to the Georgia Power Company in 1985. Continuous operation testing was completed in FY 1986, as were tests of the turbine performance. Also, during FY 1986, Georgia Power began modifications to the collector field control system to simplify operation and reduce labor costs.

Table 3.1 Steam Rankine Engine Availability

Turbine Inlet Temperature (°F)	Size			
	500 kW_e	1 MW_e	10 MW_e	50 MW_e
750	Available	Available	Available	Available
900	N/A	Available	Available	Available
1050	N/A	N/A	N/A	(Available)[a]
1200	N/A	N/A	N/A	N/A

N/A = not available

[a]No turbines operating at 1050°F were located. There are several that operate above 900°F, however.

The revamped collector field control system was completed in FY 1987. Sandia also modified the STEP plant early in FY 1987 to improve the performance. The modifications consisted of installing a new fossil-fueled steam superheater to serve an energy topping function for the solar field, a new boiler tube bundle for improved personnel safety and a 40% increase in heat transfer area, and a buffer tank to increase the heat transfer fluid loop pressure and slow the evaporative loss of Syltherm heat transfer fluid. The modifications were completed by December 1986.

Georgia Power Co. has continued testing of the improved output of the STEP plant throughout FY 1987. The final reports of the results will be published in FY 1988. However, preliminary information shows that the solar field control modification has reduced the manpower required to operate the plant from about four people to two. The average electrical output of the plant, at normal solar insolation levels of 850-900 W/m^2, has been increased from 200 kW to 320 kW. The variability in electrical output, previously caused by variations in the solar insolation level, has been stabilized by adding the steam superheater to the cycle. Also, the Syltherm heat transfer fluid losses are currently low, because the low molecular weight thermal decomposition products, previously continuously removed, are now retained in the fluid. Consequently, the Shenandoah STEP plant is currently operating close to the original design conditions.

In FY 1988 Sandia will continue to work with Georgia Power to use the Shenandoah STEP facility to test systems and operational concepts useful to the overall solar thermal program. Examples include silver versus aluminum films for solar collectors and reverse return versus constant velocity tapered piping for fluid flow and temperature control in the collector field. Georgia Power plans an internally funded program to modify the balance-of-plant controls that will use the most advanced state-of-the-art hardware available to maximize the electrical output from the Shenandoah facility and also to evaluate control system upgrade options for their commercial power plants.

EC-460 Concentrator Wind-Load Tests

Sandia performed wind load testing of LaJet's LEC-460 concentrator at the DRTF to determine the strain induced in the concentrator's main support member under elevated wind conditions. The LEC-460 was selected because performance testing of it was completed and, therefore, the risk of damaging it by exposing it to winds beyond design levels was acceptable. Furthermore, the results could be compared to wind-load tests that were conducted in a wind tunnel on a scale-model of the similarly designed LaJet Innovative Concentrator. The test setup consisted of four strain gages positioned at 90° intervals around the diurnal drive beam, which carries the full concentrator load into the foundation. Data were collected automatically when winds exceeded 35 km/h (20 mph). Colorado State University has initiated analysis of the measurements collected to characterize the wind spectrum, predict stresses in the concentrator for design wind speeds, and determine the concentrator load coefficients, the natural frequency, and the aerodynamic admittance function of the structure.

Systems Experiments

Small Community Solar Experiment #1

Congress authorized the Small Community Solar Experiment #1 (SCSE #1) and appropriated $4 million in FY 1984 to design, construct, and test a competitively selected solar thermal dish-electric project connected to the utility grid at Osage City, Kans. The SCSE #1 solar power plant is designed to provide 100 kW_e using four 25-kW_e modules, each consisting of a dish comprising 95 aluminum-polymer film mirrors, with a total reflective area of 164 m^2. LEC is to provide the solar concentrator module. The organic Rankine cycle (ORC) engine will be provided by the Barber-Nichols (B-N) Company of Denver, Colo., who is the prime contractor with DOE. The system will be connected to the Osage City utility grid.

Because of the low performance of the originally selected collector, B-N proposed changing the subcontractor for the collector. B-N received proposals from Acurex, LaJet, McDonnell-Douglas, and PKI. After a technical evaluation and cost comparison, B-N recommended that LaJet's collector be used in the SCSE #1. In August 1987, a subcontract between B-N and LaJet was approved by DOE Albuquerque Operations Office. The B-N engine is to be tested on the LaJet concentrator after the testing is completed under the innovative point-focus concentrator program.

The B-N ORC engine has been installed on the 100-kW electric solar simulator at the DRTF for continued testing until the LaJet innovative concentrator has been qualified. The objective of testing with the electric heater will continue to qualify the B-N engine in the absence of a concentrator. Testing is under way of the second organic Rankine cycle engine for the Osage City verification module. The second engine differs slightly from the first in that it has two hot wells to operate with the tracking geometry of the LaJet concentrator. During the initial attempts to operate this engine with heat from Sandia's electric receiver heater, the engine was observed to reach nearly 80,000 rpm — well above the normal operating speed of 60,000 rpm. Post-test examinations revealed that the overspeed occurred when the wires connecting the alternator to the rectifier failed because they were smaller than specified. This failure disconnected the engine from both the normal load of the inverter and from the emergency electronic brake. No damage occurred to the turbine-alternator-pump except that a thrust bearing failed. The bearing was easily repaired and engine testing resumed. B-N has added an additional high speed shutdown function.

Small Community Solar Experiment #2

The SCSE #2 is a modular solar thermal plant to be installed on the Molokai Electric Company site, Molokai, Hawaii. PKI, the prime contractor, is designing five modules for the Molokai site. They will be fabricated and installed after the verification test module, presently under construction at the DRTF, has been successfully tested. Each module has a 306-m^2 parabolic dish concentrator that operates in series with a fossil heater to drive a 50-kW_e (net) piston steam engine/generator.

Progress on the verification test module, originally scheduled to be erected at Sandia in January and February 1987 and tested in March 1987, has been delayed for approximately 12 months while detailed design drawings were prepared and a complete structural analysis performed. Meanwhile, many improvements have been made in the design, including improvements to the structure, mirrors, receiver, boiler, engine, and controls.

The steam engine, furnished by Australia National University, a subcontractor to PKI, is a diesel engine that has been modified and adapted to use high pressure superheated steam. The engine, based on an earlier model that has operated in Australia, has been operated for over 200 h on steam from a fuel oil-fired boiler. At its rated operating conditions of 800 psi and 800°F for the inlet steam and 4-psia exhaust pressure, the engine operates with 19% thermal efficiency. The engine, operating in a fossil-fuel-only mode at the DRTF, has produced a maximum electrical output of 45 kW_e. The engine was limited in output by the boiler's capacity and is expected to achieve the full 50 kW_e in its hybrid solar operating mode.

Much of the collector structure and supports for the verification test module has been assembled at the DRTF. Main support bearings, receiver boom, and the main collector drive wheel (for one axis of the two-axis tracking system) are currently in fabrication.

Chapter 4
Solar Thermal Research Program

The Solar Thermal Technology Research Program comprises analysis, theoretical evaluation, computer modeling, laboratory and outdoor experimentation, and measurements that are performed for pursuing the definition and the development of all options for solar thermal technology. Specifically, this research is carried out to accomplish the following activities:

- Identify and verify the technical feasibility of new concepts, existing concepts that are not sufficiently advanced to require engineering development, and other ideas for converting solar thermal energy to useful end products. The intent of this research is to discover new ways to use solar thermal energy to produce useful end products. Such discoveries normally will be followed by research to gain proof of concepts and to define key issues for further research or engineering development.

- Obtain additional fundamental data on materials, mechanisms, operation, and performance of the concepts identified above so that systems and other analyses can be performed to determine the potential for future uses of the concepts.

- Characterize components, materials, and subsystems required for new or existing concepts that have not yet reached the engineering development stage.

- Develop general measurement technology, including evaluation and measurement of the basic solar resource and concentrated solar flux measurements.

The Solar Thermal Technology Research Program is implemented by the Solar Energy Research Institute (SERI) located at Golden, Colo. The research program uses the expertise and specialized R&D facilities of universities and industry. During FY 1987 SERI emphasized four specific areas described in detail in the following sections. The silver-polymer reflector research, membrane concentrator research, and direct absorption receiver (DAR) research have made remarkable progress during this fiscal year and are now becoming the baseline concepts for central receiver systems. The direct conversion research explored a number of options for direct use of photons in energizing chemical reactions and for use of highly concentrated solar flux in treating material surfaces. These concepts were carefully screened to arrive at one or two most promising concepts to be emphasized in future research.

Silver-Polymer Research

The goals of the silver-polymer research are: (1) to develop and verify the technical feasibility of at least one silver-polymer reflector material to construct low cost, lightweight concentrators; and (2) to develop durable, stable, ultraviolet-resistant polymer materials for application, especially optically transmitting polymers for use in fabricating silver-polymer reflectors. These materials should have a reflectance of at least 90% (into an acceptance angle of 4 mr) and maintain this optical performance for at least 5 years.

The principal objective of the research in FY 1987 was to improve the durability of the promising silver-polymer reflectors identified earlier. Another objective was to identify and characterize ultraviolet stabilizers for polymers so that they are protected in prolonged environmental exposure. Research is in progress to implement the long-term goal.

Because concentrators account for 35%-45% of the cost of a solar thermal system, durable, low cost, reflector materials are important for reducing concentrator cost. Using these materials would, in turn, reduce the solar thermal system cost, improve the expected useful lives of concentrators, and increase their optical efficiency.

Silver-Polymer Reflector Research

A multipronged approach to the research consists of the in-house effort at SERI on optical characterization of silvered polymers and on the chemical modification of polymer-stabilizer systems complemented by subcontracted work. The subcontract activities include:

- Industrial-scale fabrication and testing of flexible silvered acrylic mirrors by the 3M Company and studies on factors limiting the performance of laminated constructions.

- Laboratory-scale studies at the University of Akron on the effects of processing variables on the surface optical properties and durability of silvered polymers, and on the mechanical properties of polymer films for all-polymer membrane mirrors.

The experimental work consists of preparing in-house reflector films, securing silver-polymer reflector films from manufacturers, and characterizing their optical properties after preparation and at various stages of durability testing. Accelerated and real-time testing of durability (environmental exposure) was conducted in three ways: outdoor real-time exposure testing on racks located in Colorado, Arizona, Florida, and Minnesota; Weatherometer accelerated testing; and QUV accelerated testing. The experimental reflectors consisted of adhesive-substrate assemblies with silver-polymer reflectors (Figure 4.1).

During FY 1987, significant progress occurred in several areas. Researchers have shown that the initial optical performance of silver-polymer mirror films is regularly well within our long-range goals, and reflectance is maintained for more than 4 years outdoors in Colorado. It was demonstrated that the polymer films without silver maintain good specular transmittance in outdoor environments for more than 5 years at several locations. Data show that performance outdoors is site dependent and that at least one site causes reflectances to fall below our 5-year goal within a 2-year time interval. Finally, research showed that the silver/polymer interface is the major point of degradation, and the major causes of degradation are being verified through experiments.

One of the applications of polymer films is an ultralight free-standing membrane mirror. The silvered polymer membrane is clamped into a ring, and the desired focal length of the system is adjusted with a vacuum system. SERI demonstrated earlier that silvered polymers can attain specular reflectances in excess of the long-range goals. This result has been demonstrated for membrane configurations and for mirrors mounted on stiff substrates. For example, the excellent specularity data from the surface of an acrylic polymer sample is shown in Figure 4.2.

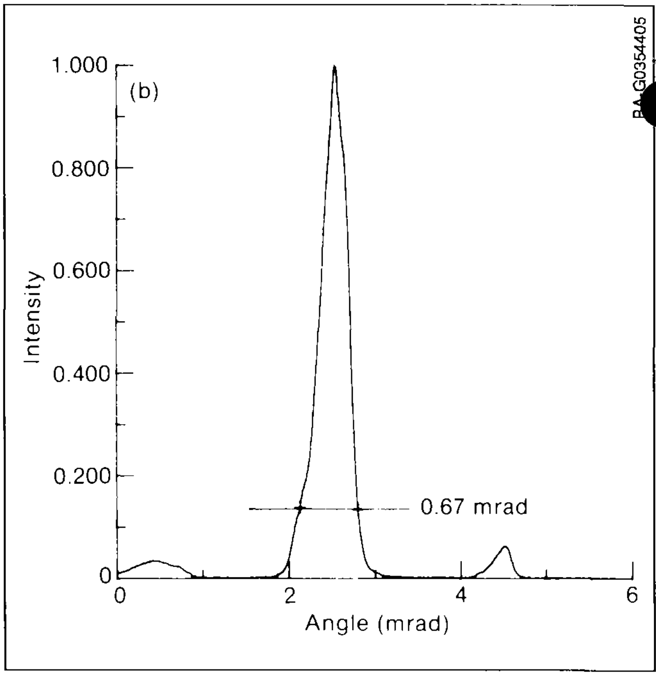

Figure 4.2 Specularly Reflected Beam, After Silvering, Measured as a Second Surface Mirror (wavelength 492 nm, angle of incidence 20°)

Ultraviolet-Resistant Polymer Materials Research

Polymers serve as a protective glazing over the silver. Such polymers must be stabilized against ultraviolet degradation and, at the same time, must be applied in ways that do not degrade the specularity of the underlying silver film.

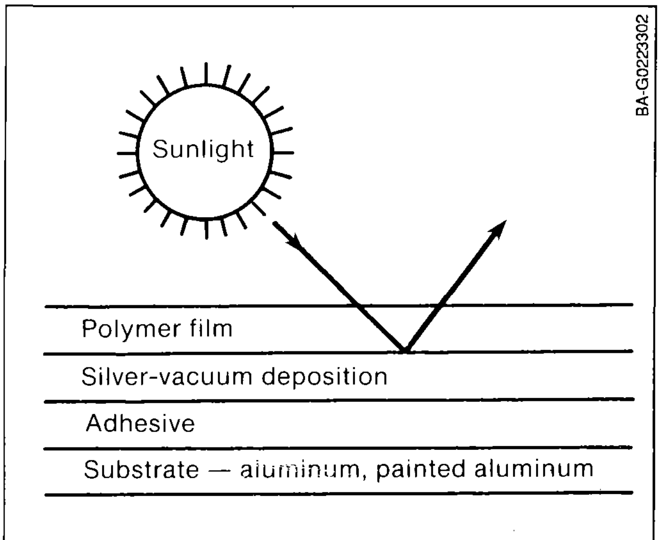

Figure 4.1 Schematic of the Cross Section of a Silver-Polymer Mirror

Ultraviolet stabilization of polymers was chosen for research because it appeared to be the most promising approach to achieve a long lifetime in the solar environment.

In FY 1987 the emphasis was on synthesizing and testing various polymeric stabilizers of the hydroxy-benzotriazole, hydroxy-benzophenone, and hindered amine classes to be included in the host polymer (polymethylmethacrylate) of interest. Because the stabilizer is bonded covalently to the host polymer, exudation and leaching are retarded, and the life of the stabilizer is increased. Scientists have used solvent-extraction tests to prove that the polymeric stabilizers are more permanent than low-molecular-weight forms of the same types of stabilizers. These researchers have also demonstrated the extra effectiveness of placing UV light absorbers near the polymer/air interface. Thus, polymeric stabilizers with UV protection are good candidates for further improvement in mirror durability.

Weathering tests demonstrated that both the optical performance of stabilized glazings and the photolytic stability of stabilizers are markedly dependent on the accelerated weathering mode selected. Photolytic deactivation of the stabilizers is slow enough not to limit outdoor lifetimes of mirrors for at least several years.

Weathering Tests

Extensive environmental tests were conducted in Colorado of novel systems. Through cooperation with industrial suppliers, outdoor weathering testing of samples continues at locations in Arizona, Florida, and Minnesota. Data suggest that weathering is harsher in Arizona or Florida as compared with Colorado or Minnesota. New stabilizer systems have improved polymer performance in Arizona and Florida. Researchers also observe that proper sealing of the mirror edges is necessary to avoid corrosion. Some of the results for the continuing tests are shown in Figure 4.3 in which the specular reflectance of several modifications of the ECP 300 film from the 3M Company are presented in relation to time outdoors. Some films have been in test for 3 1/2 years and continue to resist corrosion of the silver. Thus, the stability of the silver for an appreciable fraction of the long-term goal of 5 years has been established in environments like that of Golden, Colo. Phoenix, Ariz., is a much harsher environment and corrosion is obvious after 2 years of exposure (Figure 4.3).

For these tests, the silvered polymer is mounted on a firm substrate noted in Figure 4.3 as aluminum or glass. Researchers find that aluminum substrates can limit optical performance unless special precautions are taken to ensure that the aluminum is flat and smooth. Also in some tests, painted aluminum substrates enable the mirror to weather better than unpainted substrates. For test purposes, flat glass can significantly increase the specularity of the silvered polymer. Data in Figure 4.3 include weathering data at the limit for specularity corresponding to the long-range goal of 4 mr. Similar tests (not shown) are in progress for flat and polished stainless steel and aluminum substrates.

Studies are directed to identify those factors that cause the enhanced degradation in Arizona. Accelerated laboratory tests (approximately three times harsher than Arizona) show that blocking all the light from the mirror prevents any degradation for at least 13 months, while more controlled experiments that selectively filter the ultraviolet (UV) light have identified the relative importance of different wavelength regimes. The extent to which UV light is prevented from reaching the silver interface is shown to be important, and the reflectance loss is due to corrosion at the silver/polymer interface. The polymer is essentially intact, as shown by optical measurements on the polymer alone for various locations (Florida, Arizona, Texas), for up to 7 years.

Stabilizing the silver/polymer interface is the key durability problem at the 2-year timeframe in the harshest environments. Approaches being pursued include controlled screening of the UV light, better permeation barriers to slow ingress of atmospheric constituents, passivation of the silver interface, and control of additives and impurities in the polymer.

Membrane Concentrators

Background

Concentrator research in FY 1987 has focused almost entirely on stretched-membrane dishes. The major goal of the research is to define the cost/performance potential of using stretched-membrane technology for point-focus dish applications. The primary rationale for the research is that significant advantages, similar to those that have been shown for stretched-membrane heliostats, are also possible for point-focus dish applications. Research on heliostat reflectors for central receiver applications demonstrates that replacing the glass/metal reflector with a lightweight stretched membrane effectively lowers costs without losing performance. Because of the modularity (which allows a small initial plant size) and high efficiency possible with point-focus concentrators, these devices offer a promising alternative to central receivers for the use of solar thermal energy in electricity production. However, current parabolic dish designs using a silvered-glass reflector mounted on a rigid

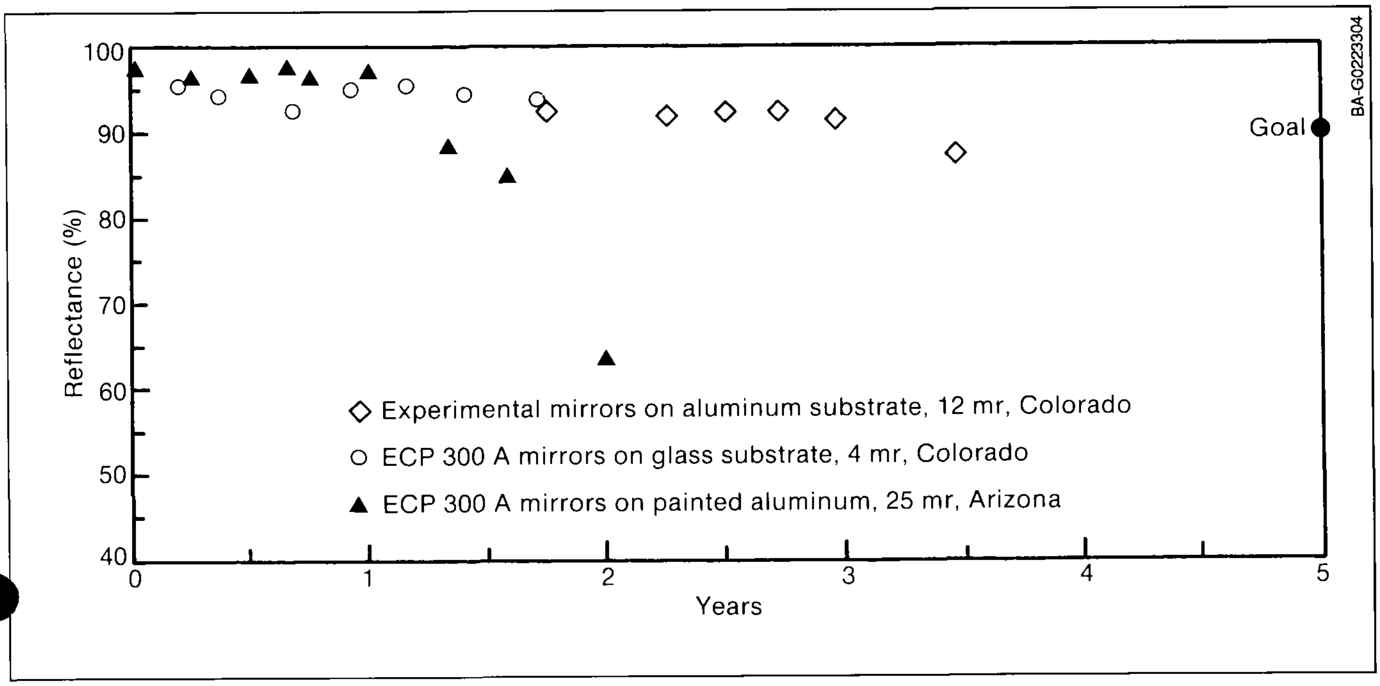

Figure 4.3 Reflectance versus Time Outdoors

support structure in excess of $200/m² still fall short of the DOE cost goal of $130/m².

The stretched-membrane dish research effort is aimed at determining how the benefits of stretched-membrane technology can best be applied to parabolic dishes. With their different geometry and much higher concentration ratios, dishes present new challenges compared with heliostats. The objectives of the research are to analyze the structural response and optical performance of membrane dish concepts, determine critical design parameters, and conduct experimental testing of prototypes. The research effort can be divided into three basic areas: structural analysis, optical and thermal analysis, and materials and fabrication. In the area of analysis, important tools for handling the unique problems of membrane dishes have been developed. These include detailed finite element models of membrane/ring systems, several simplified structural codes for modeling membrane deformation, and simplified optical/thermal analysis programs. In addition, SERI has performed a survey of candidate membrane materials, measured membrane properties, and directed the fabrication of a 2-m diameter prototype dish concentrator to be fabricated from composite materials.

Accomplishments and Major Findings

Structural Analysis. SERI has developed and used several structural models of axysymmetric membrane shape to determine the proper initial shape of a membrane prior to vacuum stabilization. When a stabilization vacuum is drawn, membrane dishes will deform in a fashion that can be optically significant. This is particularly critical for membrane materials with a low modulus of elasticity. This problem can be remedied by moving the edge attachment outward a small amount. The magnitude of this displacement is quite small, and may well be within typical manufacturing tolerances. More sophisticated analysis will be needed in order to completely characterize membrane response.

By making a conceptual comparison of alternative membrane support concepts, we have identified a central post, cable-supported design as highly promising. Currently, the cable-supported dish concept appears to be the most efficient structural membrane dish design. Finite element simulations indicate that 12 cables, front and rear, would give the largest margin of safety to prevent buckling of the ring. The optimum number of cables will be determined not only by buckling considerations, but also based on allowable ring deflections, specific ring design, and on cost of cables and attachments.

Optical/Thermal Analysis. Several simple computer models to determine optical figures of merit for membrane shapes have been developed. A computer model was also completed to determine overall dish thermal efficiency, which is used in conjunction with the CIRCE optical code. SERI has performed a detailed comparison of single-facet performance with the easier-to-fabricate multifacet designs both with and without secondary concentrators. Although it was known that a single facet would outperform the multi-facets, little quantitative data were available. The results indicate that for a sufficient number of facets the performance of a multifacet design with a secondary concentrator closely approaches the performance of a single facet.

Thermal performance of a parabolic dish appears to be less sensitive to reflector surface specularity than was previously believed. The results indicate that specularity error can be as high as 3 mr before performance degradation becomes unacceptable.

Materials and Fabrication. Researchers from industry and other organizations familiar with composite materials were brought together to discuss key issues and research needs. At this meeting, they agreed on the preferred matrix and fiber materials, determined ways to improve surface smoothness, and identified additional research needs. For example, surface smoothness can be improved by fillers, low-shrinkage resin, surface veils, and gelcoats.

SERI has demonstrated, with supporting data through subcontract with Science Applications International Corporation (SAIC), the capability to build a 2-m diameter prototype composite membrane dish from an inflated spherical steel mold. A hard parabolic mold was also built from epoxy. The shape of the mold will be determined in the next year, and the resulting dish shape and smoothness will also be evaluated.

DAR Research

The goal of the DAR research is to advance the state of theoretical and experimental knowledge of the phenomena involved in direct absorption of concentrated solar flux by a working fluid. This knowledge needs to be sufficient for an experienced designer to design a near commercial-scale DAR receiver, including the specification of feasible configurations, working fluids, and operating modes.

Research to date has provided the theoretical and experimental basis for the assessment that the DAR concept is both technically and economically feasible. Experimental results indicate the potential for a receiver thermal efficiency of 90%. Systems analysis studies by SERI, Sandia, and engineering organizations continue to show that a DAR will result in substantial reductions in the initial cost of the receiver and an increase in the total annual energy produced as compared with a tube-type receiver. These system analysis studies indicate that the ability of the DAR to absorb higher flux levels, and its potential for reducing the cost of the receiver by a factor of two as compared to a tube-type receiver, result in a corresponding reduction of 17% in the levelized cost of energy produced by a system using a DAR. Engineering evaluations assess the receiver to be simpler and more reliable and to have lower thermal inertia than tube-type receivers. These operational characteristics that cannot be fully quantified at this time should result in 20%-30% overall reduction in the cost of delivered electrical energy.

Direct Absorption Thermal Science Research

The objectives of DAR research in FY 1987 have been to study, both experimentally and analytically, the most significant heat transfer and fluid dynamics issues needed to understand the phenomena of direct absorption of concentrated solar flux in doped nitrate salt.

SERI has conducted small-scale experiments using the DAR Inconel test loop to understand the nitrate salt film behavior with and without a dopant. This included specific experiments designed to study film/wave stability under simulated variable solar flux. In addition, water-film experiments were conducted to study wave shape and convective heat transfer between the liquid and the solid surface.

Researchers also built an apparatus to observe the behavior of long films of water. The researchers are primarily interested in the development of roll waves after liquid films flow 1 or 2 m and the study of how these roll waves affect convective heat transfer and thermocapillary instabilities. The apparatus consists of a vertical, 7.5-cm o.d. lucite tube, 5 m in length. Water is pumped to the top of the tube where it is distributed uniformly over the circumference of the tube. Reynolds numbers in the range of 3000 to 40,000 can be achieved with the existing pump and piping. SERI designed and fabricated an instrument that allows researchers to measure a time series of the film thickness in any location on the lucite tube, thus providing information on the roll wave height, spacing, and other important parameters. This instrument enables the characterization of the wave pattern expected in a nitrate salt DAR.

Figure 4.4 shows a 1 sec record of film thickness taken 4.5 m from the top of the tube at three Reynolds numbers. Peaks in the figure correspond to the passage of the roll waves. Between those roll waves the film is quite thin, 1 mm or so, and on-going research is concerned with the possibility that those thin-film regions may dry out in the high flux. Similar data were taken for Reynolds numbers from 3100 to 39,000, and statistical analyses were performed to describe how the important wave parameters change with different flow regimes as described by different Reynolds numbers.

SERI researchers have also used this long-water film apparatus to study the ejection of droplets from the peak of the roll waves for liquids of various surface tension. Figure 4.5 shows droplets being ejected from a roll wave at a surface tension of 20-70 dyne/cm (nitrate salt has a surface tension of 110 dyne/cm) and a Reynolds number of 40,000. Many of the droplets are pulled back into the liquid film by aerodynamic forces. Figure 4.5 shows the fraction of roll waves that eject droplets as a function of Reynolds number. Using this configuration, namely a film falling on the outside of a long tube, a substantial number of waves eject droplets, but researchers feel that the actual mass of liquid lost from the film is small. This will be quantified with a long, flat salt film test in FY 1988.

Installation modifications of the DAR test loop at SERI's Field Test Laboratory Building (FTLB) were completed in FY 1987 (Figure 4.6). The purpose of the test loop is primarily to allow researchers to determine the behavior of clear and doped nitrate salts in the presence of high radiative flux.

Testing with the radiant heater began in FY 1987. Researchers developed a method for calibrating the flux produced by the heater in the plane of the DAR test panel. Results of the calibration showed that the heater produces peak flux as high as 700 kW/m^2 and that the flux distribution was quite uniform.

Researchers succeeded in containing molten nitrate salt at the edges of open channels in a no-flux environment. This problem was experienced during previous experiments. A number of different configurations were tested. A special C-shaped edge configuration succeeded in containing the salt. Tests showed that the molten salt was totally contained on the Inconel DAR test panel (15 cm wide by 60 cm long) at Reynolds numbers up to 20,000 (the maximum for the DAR flow loop). This edge containment configuration proved effective during flux tests as described below. Although a commercial DAR will operate most likely at higher salt flow rates, this method of salt containment seems to work well beyond Reynolds numbers of 40,000. If necessary, further refinements would allow the method to work at any flow rate.

Tests with the radiant heater were nearing completion at the end of FY 1987. The first flux-on-salt test involved flux at 520 suns peak (approximately 500 suns average) with high salt flow (Re = 21,000). The salt film was well behaved with no sign of dryout either on the panel or on the panel edges. A reduction in fluid flow rate to Re = 7000, at a flux of 490 kW/m^2, produced a dryout. These data duplicated the behavior of the carbonate salt tests at the ACTF in FY 1985. Although these Reynolds numbers are well below commercial operation (Re = 40,000) the results show that the behavior of very different salts can be correlated through the Reynolds number. Researchers also found that a nitrate salt film of Re = 9000 exposed to a flux of 490 kW/m^2 was quite stable when the film was disturbed mechanically in such a way as to simulate waves.

Northwestern University developed two hydrodynamic models to assess the likely possibility of flux-induced film dryout. The hope is that such models will provide guidance as to what DAR operating conditions may lead to salt film dryout. The first model considered a horizontal, quiescent salt film exposed to a lateral flux gradient (100 kW/m^2 per m) and a flux distribution meant to simulate the effect of waves on the salt film. Both clear and doped salt were considered. The lateral flux gradient resulted in a temperature gradient and attendant shear forces, but a negligible effect on the salt film. A disturbance simulating a ripple developed a depression of about 37% of the undisturbed film thickness. This depression was significant and suggested that the model should be extended to include the effect of film flow rather than a simple, quiescent film disturbed by a ripple. The reasoning here is that the depression may grow in the flow direction producing a vortex-like structure in the film. This model revision will begin in FY 1988.

Planning for the direct absorption panel research experiment proceeded during the year. This experiment will consist of a 4-m long by 1-m wide molten nitrate salt DAR panel to be mounted near the top of the CRTF tower in Albuquerque. This experiment will enable the experimentation with all the basic DAR phenomena in one experiment; namely, doped salt flow in dimensions enabling the development of full wavy flow of high Reynolds numbers, and a realistic, high solar flux density of various distributions.

DAR Materials Research

The goals of materials research are to identify materials (heat transfer fluids and containment materials, in particular) and collect materials' properties data for use in the design and development of effective, durable, and economically feasible DARs. Key issues are the optical performance, durability, and compatibility of the materials involved. Two categories of DAR materials were subjects of this research. The first category involved salts to be used as heat transfer fluids; the second involved containment materials. These materials are subjected to a rather severe environment in DAR use: working temperatures to 600°C with possible excursions to 700°C; in receiver hot spots solar fluxes to at least 500 suns with some design goals for peak fluxes above one thousand suns; uneven and cyclic heating; mechanical, hydraulic, and both static and dynamic thermal stresses; and chemical effects such as corrosion and decomposition because of environmental effects and material interactions.

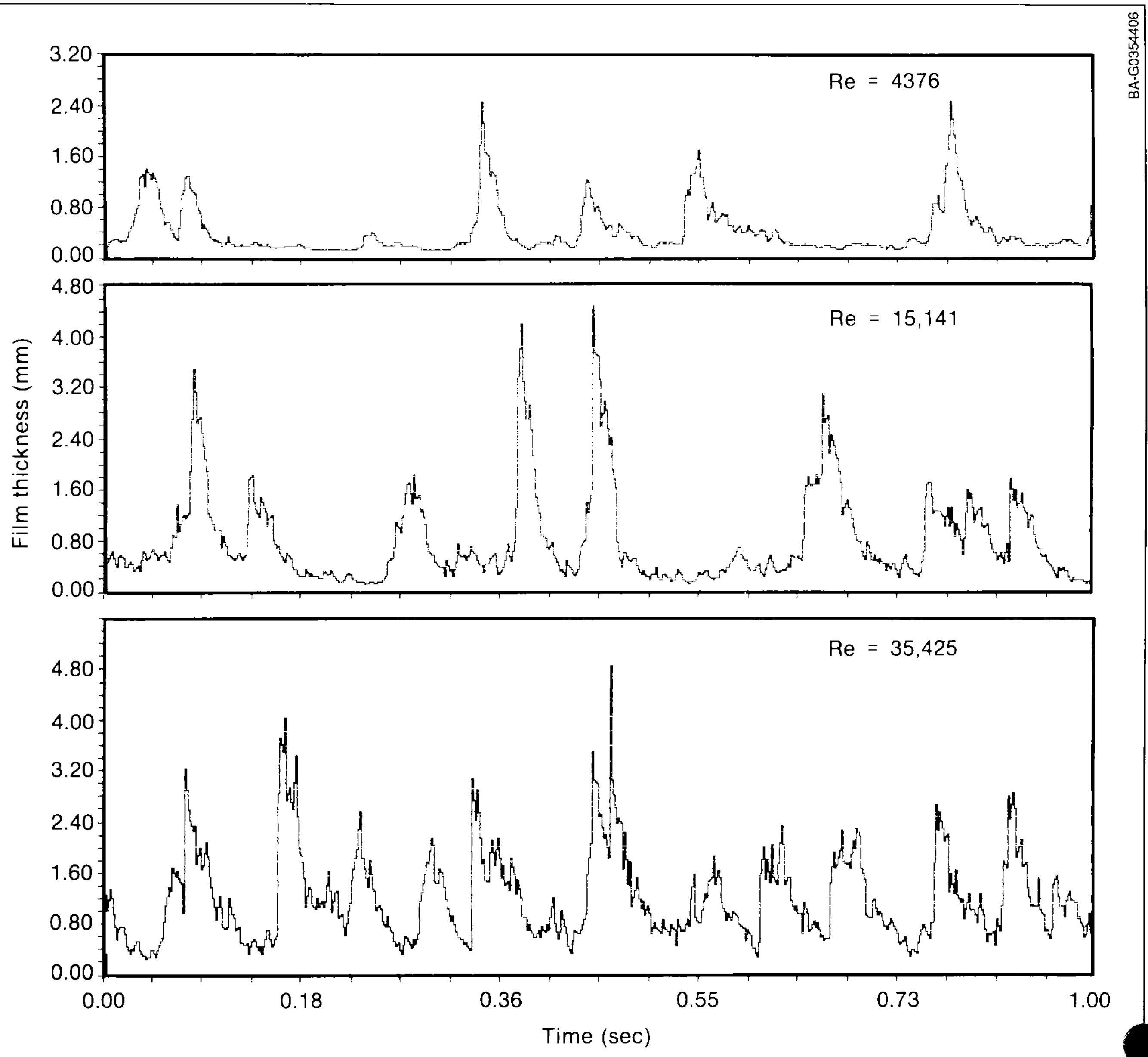

Figure 4.4 Film/Wave Characterization at Three Reynolds Numbers

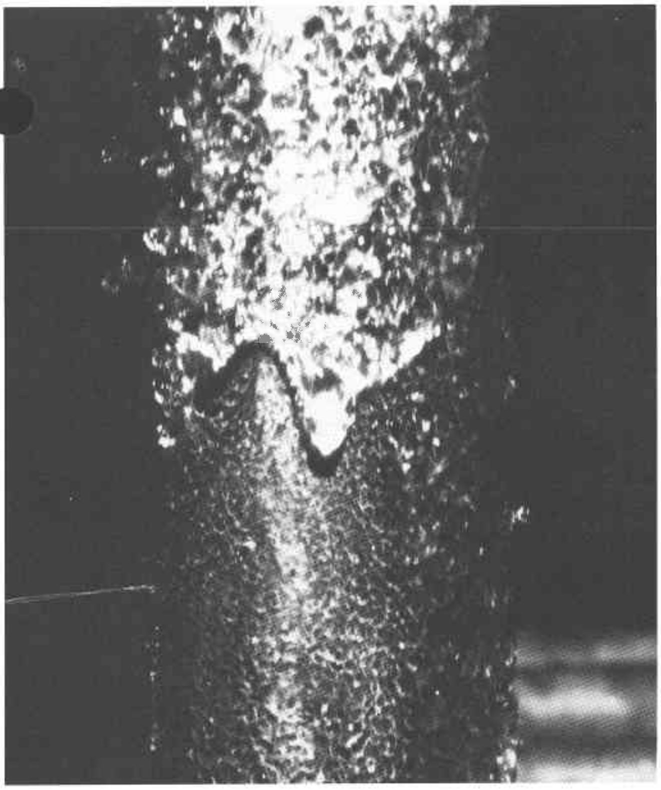

Figure 4.5 Droplet Ejection from the Crest of Falling Film/Wave

Work during 1987 addressed issues related to the properties of dopants for addition to the molten salt, and compilation of data on the physical and chemical properties of draw salt.

Because the chemical constituents of draw salt absorb only weakly in the solar spectrum, SERI is trying to identify materials that could be added to the molten salt to increase the absorbtance of solar energy. Theoretically, there are advantages for absorbing the incident radiant energy directly in the salt rather than absorbing it in the back plate of the receiver for subsequent transfer to the salt. The direct absorption reduces the temperature that the back plate must withstand. Previous work at Sandia identified various metal oxides that could be suspended in draw salt to serve this function. Researchers found that cobalt oxide remained in suspension more effectively than others that were tried.

Continuation of this work at SERI showed that low turbulence velocities of about 0.3 cm/sec will keep cobalt oxide in the 325-400 mesh size range in suspension. To reduce the settling rate of the absorber, a search was begun to find absorbing materials that would be less likely to agglomerate. Subcontracted work at the University of Nevada at Reno identified a number of metal oxides and minerals that exist in the form of submicron particles. These particles resist agglomeration and settling under some circumstances. Through screening work done this year, some particles were identified, including forms of iron, copper, and nickel oxides that had settling times that were about 10 times as long as that for the cobalt oxide used to date.

SERI researchers took a second approach. To avoid settling of the particles altogether, they made an effort to find absorbers that would be soluble in the molten draw salt. To this end they screened the properties of salts of oxyanions. Chromate anion, introduced as the potassium salt, is representative of the approach. It was soluble to about 5 wt % and produced highly colored and absorbing solutions. Unfortunately the color faded within a few hours so the effect could not be maintained.

A major review of the literature to collect data on the physical and chemical properties of molten nitrate salts was completed. This review includes properties important for system design, materials compatibility considerations, and coverage of the literature related to the chemical stability of molten nitrate salts. Application of draw salt in DAR configurations up to 600°C should be appropriate.

System Analysis Studies

DAR versus Salt-in-Tube Receiver. SERI updated an earlier comparison of the cost and performance of the DAR receiver with a salt-in-tube receiver in the context of a solar thermal system for electricity production to include an external receiver designed by the recent Utility Central Receiver Study. The Utility Study analyzed a state-of-the-art, salt-in-the-tube receiver that is smaller, more efficient, and less expensive than previous tube receiver designs.

The DAR tolerance for high flux levels allows the receiver to be smaller than the utility study salt-in-tube receiver by about 40%. This significantly reduces both the radiative and convective losses. Also, the parasitic power required by the salt pumps is reduced because of the decreased flow friction. The combination of these factors should improve the annual energy delivery

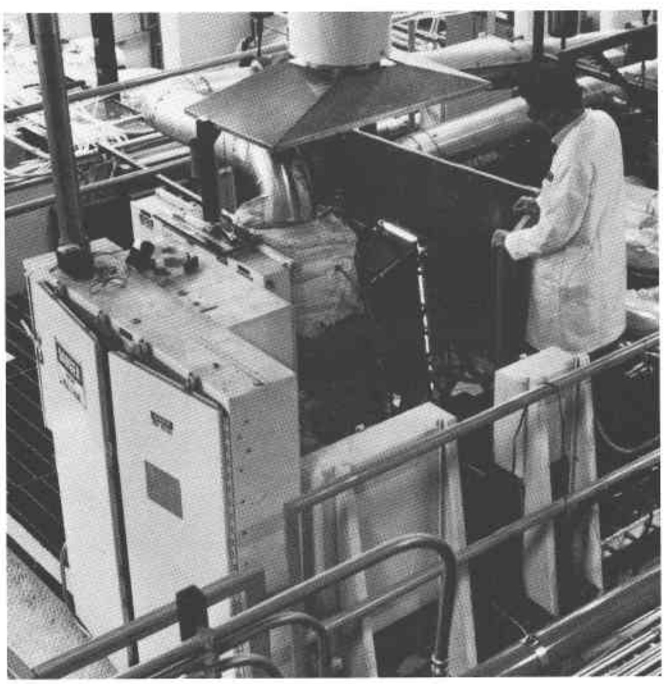

Figure 4.6 The DAR Test Loop at SERI's FTLP Showing the Radiant Solar Flux Simulator

by about 16%. Higher allowable flux levels result in a receiver of small area. The lowered cost of the DAR is attributed primarily to the smaller area of the receiver, and the relative simplicity of the concept. In comparison to the salt-in-tube receiver, the DAR should have significant advantages because of lower total material requirements (both for the absorber and the associated piping), assembly costs, and the number and complexity of required valves and controls. Overall, these advantages should allow the cost of the direct absorption receiver to be about 23% lower than the cost of the Utility Study salt-in-tube receiver. In addition to the improvements in receiver performance and cost, the absence of flow tubes in the DAR and the simplicity should increase the reliability of the receiver. Although it is difficult to quantify such effects without operational experience, some estimates place the improvement in availability at about 5%.

Internal Film Receiver versus Salt-in-Tube Receiver. SERI also performed a comparative evaluation on the internal film receiver (IFR) concept in which the working fluid (molten salt in the example here) flows in a film down the back side of the absorber plate, while the concentrated radiation is focused on the front. The IFR concept evolved as a variation of the general film receiver category that includes the DAR. However, whereas the working fluid in the DAR is exposed directly to the concentrated radiation, in the IFR the working fluid can be isolated from the ambient.

When compared to a conventional salt-in-tube receiver, the IFR has many of the advantages of the DAR, but of a lesser magnitude. For example, the flux limits for the IFR are expected to be well above those for a salt-in-tube receiver, but not nearly as high as those allowable in a DAR. As a consequence, the IFR will be larger than the DAR, but still smaller than the salt-in-tube receiver.

The comparison predicts about a 5% levelized energy cost (LEC) advantage for the IFR system over the salt-in-tube receiver system, compared with about a 16% advantage for the DAR system. Of the 5% advantage for the IFR system, roughly 3% can be attributed to improvements in performance, and 2% to decreases in capital cost. These results showed such a marginal improvement that the study of the IFR was concluded.

High Temperature Central Receivers. Another systems analysis effort focused on the potential for combining three advanced high temperature receiver concepts with a high efficiency steam-injected gas (STIG) turbine engine to generate electricity. The results of this study indicate that several of these combinations do offer the potential to improve on both the levelized energy cost for a comparable low temperature (550°C) DAR and the program cost goal of $0.05/kW.

The most promising high temperature system used a particle injection receiver (PIR) that achieves good efficiencies (90%) at high temperatures (1400°C) by absorbing the radiation in very small carbon particles which then oxidize to CO_2. Because of their small size (0.3 µm), these particles absorb a high fraction of the incident solar radiation, while emitting relatively little infrared radiation. The atmospheric pressure air within the receiver, which is heated by the particles to approximately 1400°C, transfers its heat to the high pressure air for the engine through two direct-contact heat exchangers (DCHX). The LEC predicted for this system was the best in the study, about 30% better than that predicted for the low temperature DAR and lower than the program goal.

The two other high temperature receivers examined included a DAR and a volumetric receiver. The high temperature DAR produced an LEC that was very similar to the low temperature DAR, and did not appear to offer any significant advantage over the lower temperature system. The volumetric receiver (VR) generally did not appear suitable for combination with the STIG turbine engine, particularly in comparison with the PIR. (Both receivers produce hot atmospheric-pressure air in this application, so the comparison is very direct.) Although performance analysis techniques and cost estimates for the VR are generally less mature than for the other systems, the results show that the VR cost and performance would have to improve substantially over the values used here before it would become competitive in the high temperature application studied.

The DCHX emerged as a major factor in improving the potential of all of the high temperature systems. The close approach temperatures possible with the DCHX kept receiver temperatures as low as possible, thereby minimizing thermal losses. The low estimated cost of the DCHX significantly reduced the overall system costs when compared to currently available air-to-air heat exchangers. Finally, although not investigated here, the DCHX offers the promise of liquid storage for an air receiver.

Generally, the results of this effort are more promising than almost any recent previous studies of high temperature central receivers. A major caveat on this work is that none of the high temperature systems analyzed here appeared likely to be viable in the near term, and several would require significant research and development efforts before they could be considered for commercialization. For example, the fluid required for the high temperature DAR system or for the high temperature DCHX has not been identified. Similarly, several aspects of the PIR also need better definition. The study produced a list of recommended activities that could, for a limited expenditure of resources, provide significant further definition of some of the major unknowns in these systems.

Overall, this effort has opened up several potentially promising avenues of research for increasing the cost effectiveness of electric power production with central receiver systems. Furthermore, both the PIR and VR concepts are expected to play a central role in new applications that make use of the direct concentrated solar flux. Thus, the overall payoff of these concepts may be larger than is immediately apparent in the context of electricity generation.

Solar Regenerative Thermoelectrochemical Conversion Systems

Researchers at the Hughes Aircraft Company have invented and are researching a regenerative thermoelectrochemical engine (RTEC) for efficiently converting concentrated solar thermal energy directly to electricity. RTEC appears to have significant potential for both dish and central receiver applications. Figure 4.7 depicts the cycle, with the working fluids shown in a generic fashion. The RTEC engine has the potential for high efficiency (up to 40%), good reliability (40,000-100,000 h lifetime) and good maintainability because simple pumps are its only moving parts. It also provides high-energy-density chemical storage. Only the regenerator of the working fluid and a small recuperative heat exchanger would be mounted at the focal point of a dish, with the balance of the system on the ground. All fluids in the ground portion of the system are liquids at 150°C or less, making energy transport to a central electrochemical cell possible; or, otherwise, modular cells may be used. The electrochemical cell and the regenerator can be decoupled by the use of storage, so that the potential exists for continuous electricity generation with fluid regeneration only when the sun shines. Projected cost of the engine is low at $200-$500/kW depending on scale. During this year a closer examination of the chemical process led to a research plan; researchers identified the critical areas of research and initiated appropriate activities. These activities include the electrode materials development, solar concentration and its interaction with the regenerator, and the properties of chemicals to be used.

SERI in-house research has centered on specifying the receiver/regenerator and materials of construction, and developing an analytical model of a dish-RTEC system. A subcontract has been placed with Hughes for electrochemical converter research during FY 1988 and 1989. The major focus of the FY 1989 research is assembly and operation of a 10-W prototype system for proof of concept. Hughes will provide the electrochemical converter and SERI will provide the regenerator module for the 10-W system. This experiment, coupled with systems assessments, should define the potential of RTEC to contribute to the practical application of solar thermal energy.

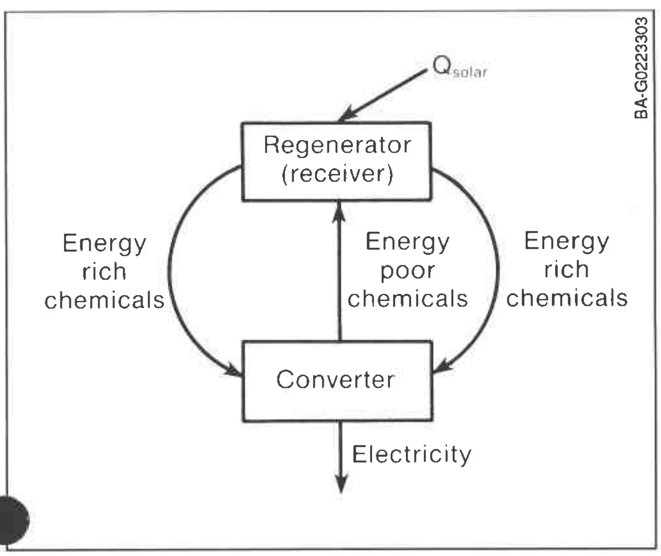

Figure 4.7 Thermoelectric Conversion Scheme Using Solar Thermal Energy

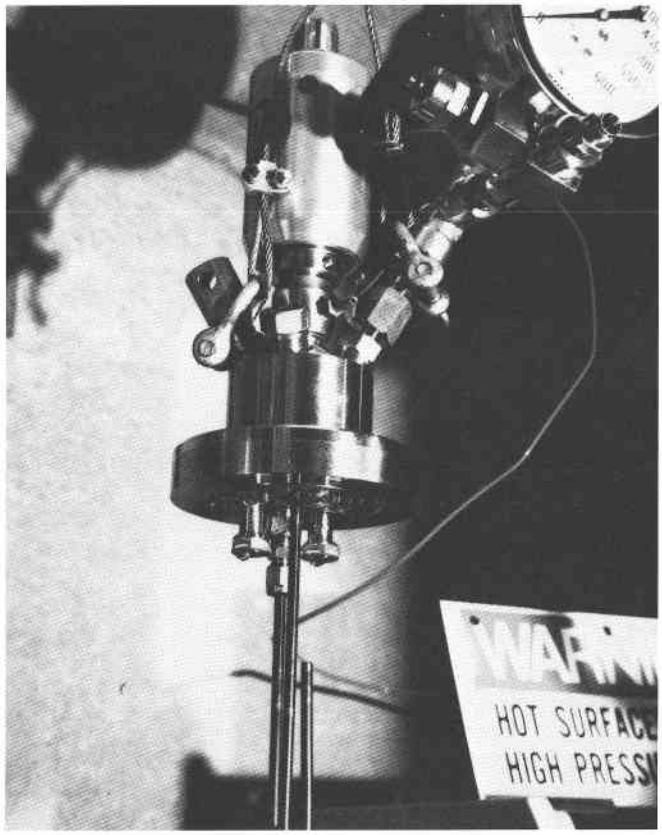

Figure 4.8 Opened-Up Autoclave Showing Stirring Mechanism

Receiver/Regenerator Research

A prerequisite to specifying a solar receiver/regenerator for an RTEC system is understanding the thermochemical process by which the depleted working fluid undergoes dissociation. Thus, the focal point of regenerator research in FY 1987 was the design and fabrication of the experimental apparatus for conducting thermochemical equilibrium dissociation experiments using a nominal composition of the working fluid, and the conduct of such experiments. Accomplishments included the design, fabrication, installation, and shakedown of the apparatus, and the performance of thermochemical dissociation experiments. Major equipment consists of an autoclave rated at 3500 psig at 600°C containing a molybdenum crucible, an autoclave heater, a gas chromatograph, and associated controls and instrumentation.

Figure 4.8 is a photograph of the opened-up autoclave, showing the stirring mechanism, thermocouple and some of the instrumentation. Experimental results during this year included the preparation of the working fluid from readily available chemicals, and the acquisition of data on the pressure/temperature relationship for the temperature range of 150°-600°C.

RTEC Materials Research

The goals of the materials research are to identify containment materials for the working fluids in the RTEC system and to obtain chemical and physical property data on the working fluids. SERI initiated this work in 1987. Work during this period focused on developing the test equipment and procedures for carrying out corrosion tests under operating conditions of up to 600°C and 600 psi. During this year SERI constructed a test system and developed an operating procedure. Samples of candidate materials to be tested, which included metals and ceramics, were obtained. Thermoanalytical work began on the properties of the working fluid. The working fluid shows rather complex chemical behavior over the temperature range from ambient to 600°C. Key physical parameters that influence the efficiency of the RTEC system include viscosity, density, heat capacity, and the temperatures at which various chemical and physical changes occur in the mixture.

Direct Conversion

The goal of the direct conversion research is to establish the feasibility of beneficially using direct concentrated sunlight energy for the production of transportable fuels and high value chemicals, and for the development of processes that use the unique nature of high flux, radiant energy. These goals are to establish the potential of using concentrated solar energy for increasing the supply of transportable fuels and for meeting important national energy needs.

Solar Detoxification of Hazardous Wastes

The objective of solar detoxification is to define the potential of direct concentrated sunlight to detoxify hazardous wastes. This effort includes gaining an understanding of the underlying phenomena. The hazardous wastes can be either liquids, solids, or solutions in water. Highly concentrated wastes will require high solar concentrations, while dilute aqueous solutions will require low solar concentrations.

Research at the University of Dayton on the solar detoxification of hazardous wastes such as polychlorinated biphenyls (PCBs), dioxin, trichlorobenzene, and others, has shown that shining concentrated sunlight directly on the reaction mass results in better destruction efficiency at lower temperatures than if the energy input were simple heat. Figure 4.9 shows the results of an experimental run using xanthone, for both thermal and photothermal reactions.

University of Dayton researchers have hypothesized a model that has parallel thermal and photothermal reaction paths for toxin destruction. For the normal incineration process, the photothermal destruction paths are not available. For solar detoxification with direct concentrated sunlight, the rate and destruction efficiency enhancements result directly from these extra reaction paths made available by the sunlight, as shown in Figure 4.9.

The University of Dayton researchers modified their apparatus to allow fluxes of up to 307 suns. Various compounds were experimentally examined to determine the extent of the photothermal enhancement of destruction efficiency, with benign isomers of toxic compounds such as polychlorinated biphenyls typically used. The experimental data validated the model, which makes it very useful for a priori prediction of the extent of photoenhancement for compounds that have not been tested.

Researchers are performing experiments to show the destruction of a dioxin isomer to 99.9999% for a thermal system and for a system with simulated sunlight in both oxidative and pyrolytic environments. Pyrolysis is partial destruction where the reaction is starved for air while the sunlight provides the energy for destruction. (This would result in a substantially reduced investment in the plant, reduced operating costs, and enhanced performance.)

Photoenhanced Conversion of Chemicals and Materials

The objective of this research is to show that direct use of concentrated solar flux will enhance the conversion of chemicals or materials to high value forms that are difficult or impossible to achieve using fossil fuels. Expected enhancements are improvements in yield and product selectivity, or a substantial

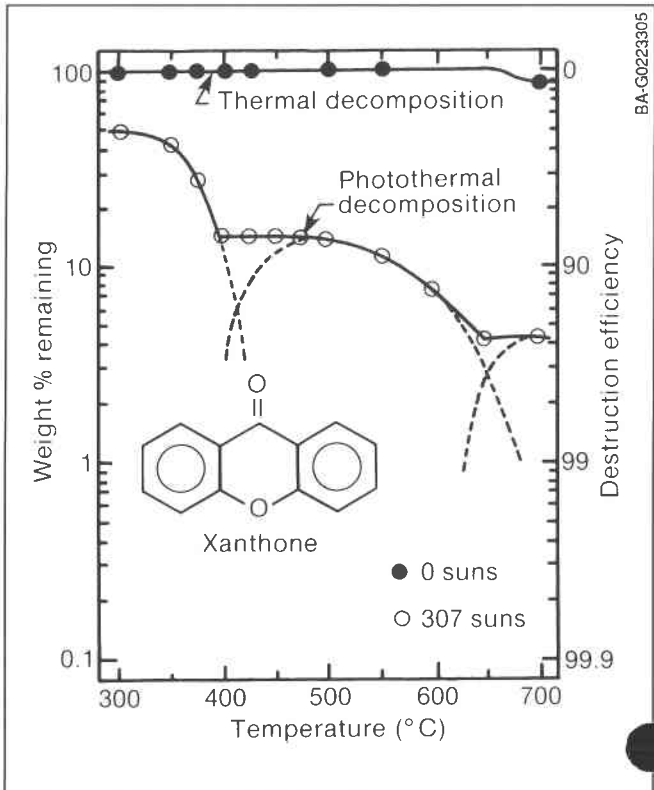

Figure 4.9 Solar Enhanced Decomposition of Xanthone

increase in the rate of conversion. The potential applications of the concentrated solar flux to enhance catalytic chemical reactions include the following conversion processes: high value aromatics from low value paraffins; gasoline octane enhancers from paraffins; and aldehydes, ketones, and ethers from alcohols.

Researchers at the University of Houston are experimentally investigating the photoenhancement of chemical reactions with emphasis on catalytic reactions. Their approach identifies photoenhancements (by experimental investigation) and the market opportunities. This combination will define the potential impacts of the research efforts and will establish the basic phenomena that may possibly be used for the bases of practical direct-conversion processes.

Researchers are emphasizing catalytic reactions that use solids to absorb the direct flux. This approach has the advantage of using the higher-energy photons to interact in a quantum fashion with chemical bonds, and using the balance of the solar spectrum to provide thermal energy to drive the chemical reaction. This process should be energy-efficient and should reduce the materials problems because the heat transfer through the walls is eliminated. Experiments at the University of Houston have looked at decomposition of alcohols and various hydrocarbon reactions to establish the existence of photoenhancements. Figure 4.10 shows a solar simulator with concentrated light directed onto a small fluidized bed catalytic reactor. University of Houston researchers have successfully addressed the difficult question of separating the photoenhancements from the thermal enhancements in a high temperature, high radiance environment. While the local absorption of radiation directly on the catalyst is thermally advantageous, the reaction rate acceleration due to the local temperature increase tends to mask the photoenhancements. One way of separating the effects is to measure directly the surface temperature, which is difficult because of the incident radiation, the reflected radiation, and the emitted radiation. Researchers used low energy electron diffraction to measure the actual surface temperature, which was correlated with a bulk catalyst temperature measured with a thermocouple welded to the shaded back of the catalyst sample. The results clearly indicate significant reaction rate enhancements well beyond those that can be accounted for by thermal enhancements for propanol decomposition and for the methanation of synthesis gases. The bulk temperature was less than the actual surface temperature for thin foil, ranging from about 20°C difference at a 300°C surface temperature to about 60°C difference at a 500°C surface temperature.

The University of Houston researchers independently confirmed the photoenhancement by the use of optical filters to selectively remove wavelength bands from the incoming radiation while increasing the radiation intensity to keep the reaction temperature approximately constant. The results show that as the higher energy photons were removed, the observed reaction rate decreased although the reaction temperature was maintained constant. This confirms there are two parallel reaction paths, a thermal reaction path (independent of wavelength) and a photo-reaction path (dependent upon wavelength). The researchers also performed experiments that confirmed the photocatalytic activity of vanadium pentoxide catalysts supported on silica and alumina substrates, as reported in Russian and Japanese journals.

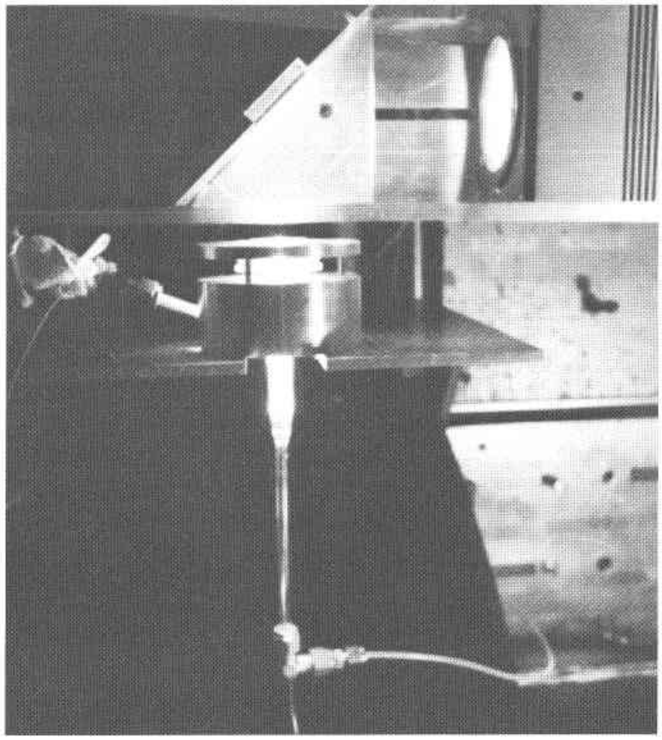

Figure 4.10 Apparatus for Investigating Solar-Assisted Chemical Reactions Using a Solar Simulator (University of Houston)

In addition to these experiments, researchers are building a data base of chemical reactions that are of industrial significance and are amenable to photoenhancement. This data base is especially aimed at chemical transformations that substantially increase the value of the products compared to the reactants. These activities will lead to a good definition of the potential of photoenhanced conversion of chemicals.

Solar Enhanced Material Processes

Researchers at Georgia Tech Research Institute have conducted experiments to compare the effects of solar irradiation of materials in a solar furnace with those of pure thermal effects obtained in an electric furnace. The goal of the work is to identify improvements in the properties of technologically important materials that may be induced by the exposure to high solar flux. Materials chosen for study include carbon fibers; advanced carbon-carbon composites; and a generation of zirconium and hafnium carbides in the form of powders, whiskers, or coatings.

Work in the carbon fiber task is progressing well. Researchers have set up a test matrix designed to identify variables important in determining fiber properties and have finished most of the experiments (Figure 4.11). Analytical evaluation of the

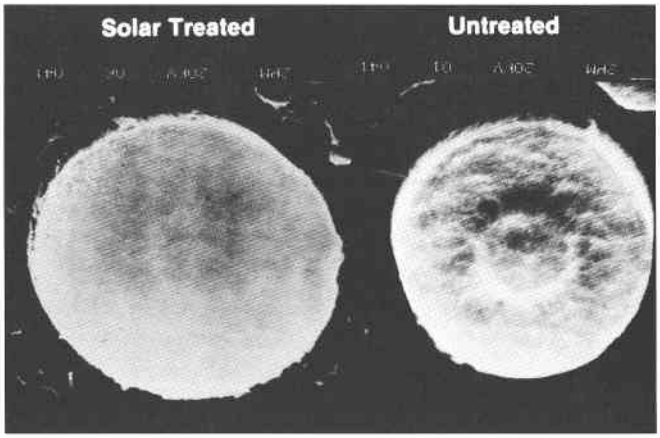

Figure 4.11 Carbon Fibers as Seen Through Scanning Electron Microscope

samples from the test is the slow step. The experimental plan is looking at the effect of four variables: fiber type (3 types), flux level (4 levels); residence time (3 times); and number of exposure cycles. The observables being measured to test for an effect are tensile strength and oxidation resistance. Researchers have developed and validated protocols for these tests and obtained some data on samples from the test matrix. The analytical work will provide a solid basis for determining the effect of solar processing on carbon fibers.

Recent work on the solar chemical vapor deposition process for producing hafnium carbide whiskers has been positive. Georgia Tech has produced whiskers in size ranges equal to or larger than commercially produced silicon carbide whiskers in the solar furnace. Lengths up to 200 microns have been achieved and are in the range of practical value. Ceramic whiskers are at the high value end of the product spectrum of ceramic raw materials. For ceramic powders, which are another potential product of the process, the current thinking in the industry is that the goal should be for materials in sub-micron size, mono sized, very pure, and spherical. It remains to be seen if a solar process can achieve this kind of result.

Researchers have successfully enhanced the oxidative resistance of commercial carbon fibers by direct flux processing in the solar furnace. Tests are under way to actually produce fibers and to test for beneficial changes in other properties. Experiments have resulted in production of hafnium carbide whiskers. Further experiments are under way to define the solar enhancement in this chemical vapor deposition process. The goal of these tasks is to use concentrated solar flux to increase the strength and abrasion resistance of strategic materials — materials that could lead to high efficiency, high temperature engines and turbines.

Another area of materials research emphasizes the use of highly concentrated solar radiation to produce high quality and high-value-added metallurgical coatings on materials. Materials used for substrates or for coatings were chosen on the basis of availability and relevance. Most material combinations represent areas of opportunities where solar furnace applications may be currently competitive with alternative processing, such as laser, arc lamp, induction, and flame. SERI made significant progress in research on systems that appear to be good candidates for this technology. A sample holder for tests at the solar furnace was designed and fabricated. Samples of various substrate materials were cut, lapped, and polished for the experiments. Seventy-six samples were exposed to the high solar flux in either air or flowing nitrogen gas. Numerous samples have been analyzed by metallurgical cross section, microscopic examination, microhardness testing, and by the methods of surface science and composition-in-depth profiling. The results of these experiments are encouraging.

Experiments with polished steel and pure material substrates painted with designs of phase-change temperature indicating paints showed that surface temperatures during high flux exposures could be measured to within ±50°C (Figure 4.12). The influence of the optical properties of the paint itself and communication from the melt zone of a paint strip to the unmelted zone cannot be ruled out as problem areas. However, believable results were obtained, compared to those obtained from the thermocouples welded to the back side of the target coupon and the known melting point of aluminum. Videotapes of exposure sequences show smooth propagation of temperature profiles from the region of peak flux outward in a time-resolved way. Analysis of these sequences may eventually provide a means of measuring the time evolution of the surface temperature during exposure to beams of known profile.

Two tool steels, A2 and 4240 tool steels, were used as substrates during the experiments because they are common, easily formed austenites that are easily hardened. In these experiments it was demonstrated that they can be phase-

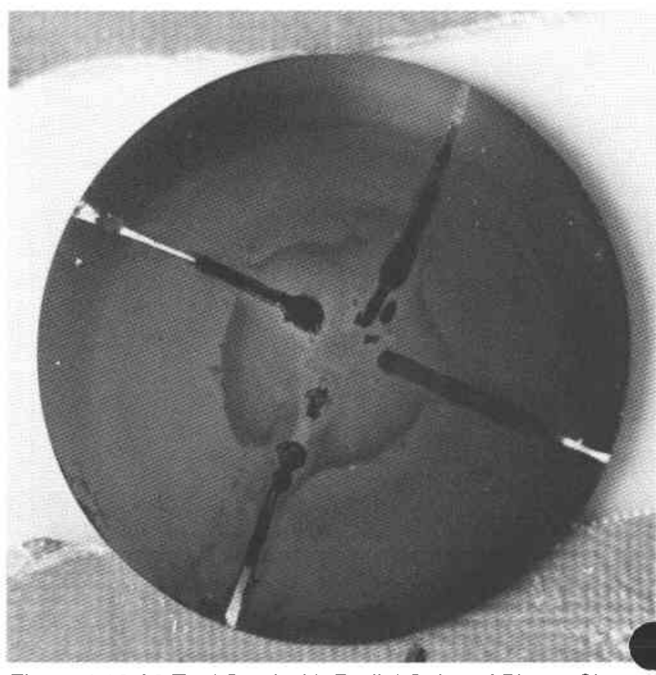

Figure 4.12 A2 Tool Steel with Radial Strips of Phase-Change Paints in the Range 538°C to 871°C

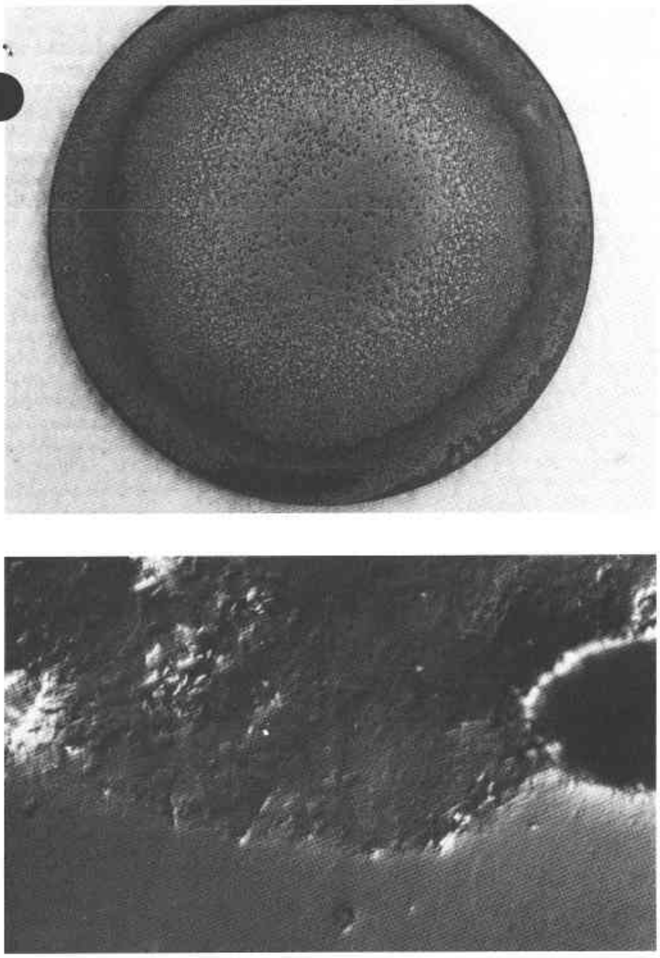

Figure 4.13 Top: Ni-Cr Powder Melt for Hard Facing Alloy on A2 Tool Steel; Bottom: Polished Cross Section Showing Alloy on Top and Steel on Bottom (1000X), Near Edge of Melt Zone

transformation-hardened by exposure to the solar beam. Microhardness of polished hardened samples was measured with the result that hardness values after exposure are in the same range as the best conventional methods. Furthermore, with pulsed application of the solar radiation, there is evidence of selective hardening of the surface region of the target materials.

In other experiments it was shown that powders of alloys and compounds can be adhered to the surface of a target material and melted to produce a desirable surface coating; for example, a coating with high temperature, corrosion- or wear-resistant properties. These coatings can be diffusion-bonded to the substrate material so that a coating having a desirable quality can be placed on a substrate having another desirable quality incompatible with the surface quality, while conserving the materials used for the surface coating (important for strategic or extremely expensive materials). An example of this type of coating is shown in Figure 4.13.

The coating material is a nickel-chromium alloy, applied to a steel substrate as a fine powder. A continuous melt has been formed and diffusion-bonded to the steel substrate, as shown during microscopic examination of the interfacial region after etching to expose the grain structure (Figure 4.14).

Other types of coatings were made using different preparatory procedures. High temperature, corrosion-resistant nickel aluminide coatings were made by exposing samples to high solar fluxes. In one series of experiments, researchers sputter-deposited thin nickel films onto various substrates, followed by thin aluminum films to produce nickel aluminide coatings of differing stoichiometry. Researchers accomplished alloying, bonding, and in some cases reaction with the substrate by exposure to solar fluxes in the neighborhood of 200 W/cm^2. An example of the formation of this type of coating on a steel substrate is shown in Figure 4.15. The coating has fully reacted with the substrate in the central region, where the flux was at peak levels, and to varying degrees toward the edge of the sample, where the flux was about 50% of peak.

Nickel aluminide coatings were also made by adhering mixtures of fine nickel and aluminum powders to the substrate and exposing the powders in the solar beam. Nickel aluminide coatings were chosen because they are being used commercially

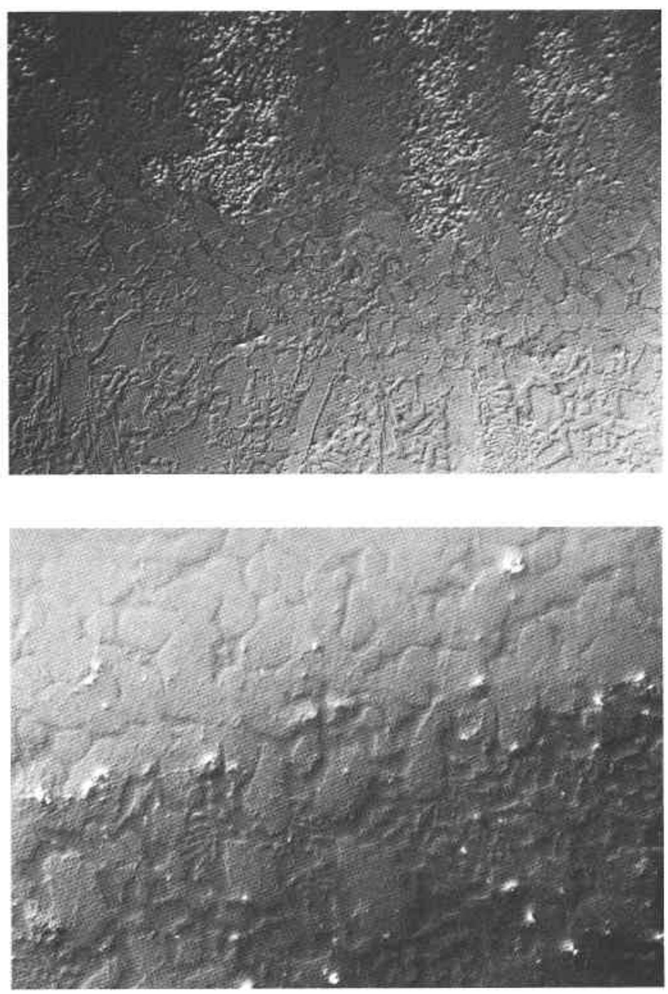

Figure 4.14 Top: Ni-Cr Alloy on A2 Tool Steel, as Polished (1000X) Near Center of Melt Zone; Bottom: Alloy Etched in 2% Nitol (500X), Showing Grain Transition Region, Near Center of Melt Zone

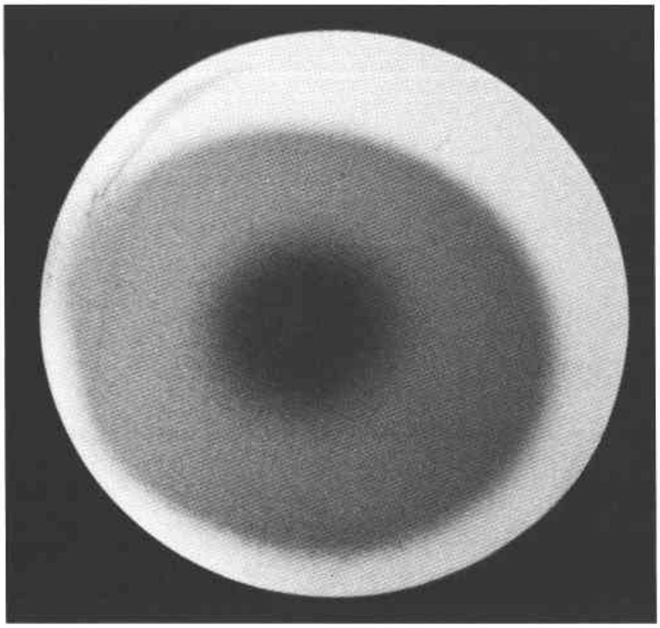

Figure 4.15 A1 Ni Coating Formed on 4340 Tool Steel Substrate with Vacuum-Deposited Thin Films (solar flux equals 200 W/cm²)

for high temperature, corrosion-resistant applications, and because alloying can be easily accomplished by pulsed heating. For mixtures of approximately equal mole percent, the reactions were highly exothermic and represented the initiation of self-propagating high temperature synthesis reactions. SERI used similar techniques to produce titanium carbide and titanium boride coatings. However, the quality of the films produced by the powder techniques was quite variable because the local conditions on the surface of the melt zone were not uniform. The techniques are interesting, because they represent an opportunity to apply high value coatings to large areas in an inexpensive manner.

Finally, surface reactions with nitrogen gas on titanium and steel substrates under high solar flux (Figure 4.16) were studied because of the possibility of inducing nitride growth on the surface. Nitride coatings on steel or titanium yield wear-resistant films which greatly extend the lifetime of some materials used in cutting, sliding, or bearing applications. Researchers found that a minor amount of nitrogen could be bonded in a major oxide. Oxygen was by far the most prevalent species on the surface, perhaps because of the inadequate purge by the gas flow in the sample holder or because of incorporated oxygen in the substrate material itself. A new reaction chamber is required for further investigation of these reactions at the Sandia solar furnace. Some collaborative work was done on titanium samples with GTRI using their reaction chamber; however, researchers have not yet analyzed these samples to determine the extent to which the nitrogen reacted with the surface.

Potential Impacts of Direct Conversion Research

Direct conversion research may result in new applications for solar thermal energy — both applications that extend the U.S. fossil fuel supply and those that assist in solving such national problems as detoxifying chemical wastes and developing materials that maintain high strength at high temperatures. These new applications, added to electricity and process heat, will result in a solar thermal technology that is able to address many of the nation's future energy needs.

SERI is emphasizing research to define and understand phenomena that could lead to processes to produce fuels and chemicals. The reason for this emphasis is that concentrated sunlight is a unique energy source capable of driving chemical reactions to use nonconventional natural resources in nonpolluting processes. Concentrated sunlight contains energetic photons, which are suitable for driving photoprocesses that can synergistically enhance thermal processes, such as catalysis. In addition, concentrated sunlight is capable of heating materials to a high temperature in a short time to produce materials with unique and desirable properties and to produce high value materials from inexpensive base materials. Concentrated sunlight is capable of performing transformations that are difficult or impossible to achieve using conventional energy sources.

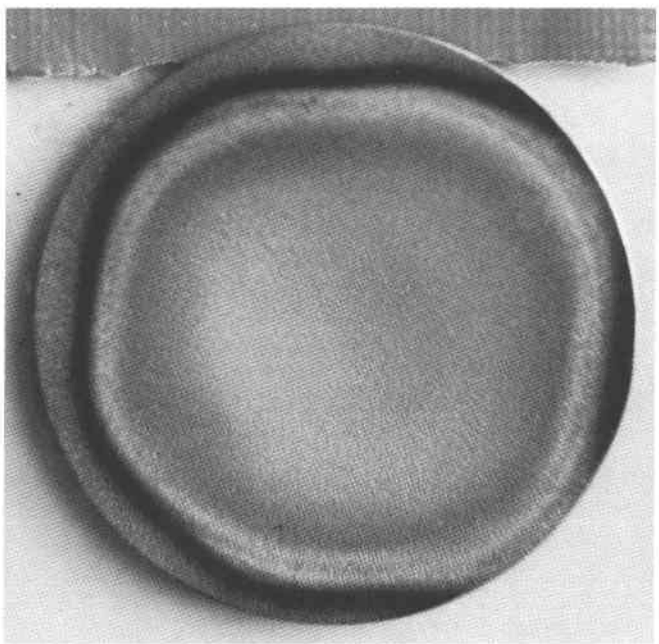

Figure 4.16 Titanium Substrate exposed to solar flux of 150 W/cm² in Nitrogen Purge

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Appendix B

Acronyms and Abbreviations

ACTF	Advanced Component Test Facility
APS	Arizona Public Service
ASCS	Advanced Stirling Conversion System
ATS	Advanced Thermal System, Co.
B-N	Barber-Nichols Company
B&V	Black & Veatch Engineers-Architects
BTM	Bench Test Module
Btu	British thermal unit
CLEA	Closed Loop Efficiency Analysis
CLOE	Closed Loop Operations Experiment
cm	centimeter
CR	central receiver
CRTF	Central Receiver Test Facility
DAR	direct absorption receiver
DCAR	direct catalytic absorption receiver/reactor
DCHX	direct-contact heat exchanger
DOE	Department of Energy
DR	distributed receiver
DRTF	Distributed Receiver Test Facility
f/D	focal-length-to-diameter
FPSE	free-piston Stirling engine
ft	foot
FTLB	Foothills Test Laboratory Building
FY	fiscal year
gpm	gallons per minute
h	hour
IFR	internal film receiver
kg	kilogram
km/h	kilometers per hour
kV	kilovolt
kW	kilowatt
kW_e	kilowatt electric
kWh	kilowatt hour
kWh_e	kilowatt hour electric
kW_t	kilowatt thermal
LEC	LaJet Energy Company; levelized energy cost
LeRC	NASA Lewis Research Center
LMTEC	liquid metal thermal electric converter
m	meter
M	million
mil	millimeter
mph	miles per hour
mr	milliradian
MSSCTE	Molten Salt Subsystem Component Test Experiment
MTI	Mechanical Technology Inc.
MW	megawatt
MW_e	megawatt electric
MWh_e	megawatt hour electric
MW_t	megawatt thermal
NMSU	New Mexico State University
O&M	operation and maintenance
ORC	organic Rankine cycle
P&ID	piping and instrument diagrams
PCB	polychlorinated biphenyls
PET	polyethylene terephthalate
PG&E	Pacific Gas and Electric
PIR	particle injection receiver
PKI	Power Kinetics, Inc.
R&D	research and development
RAI	Resource Analysis International, Inc.
RTEC	regenerative thermoelectric converters
SAIC	Science Applications International Corporation
SCE	Southern California Edison
SCSE	Small Community Solar Experiments
SERI	Solar Energy Research Institute
SKI	Solar Kinetics, Inc.
SNLA	Sandia National Laboratories Albuquerque
SPECO	Solar Power Engineering Co.
STC	Stirling Technology Co.
STEP	Shenandoah Solar Total Energy Project
STIG	steam-injected gas turbine engine
STM	Stirling Thermal Motors
STT	solar thermal technology
TBC	test bed concentrator
TC	thermochemical
UV	ultraviolet
VR	volumetric receiver
W	watt
WIS	Weizman Institute of Science

Appendix C
Glossary of Terms

alternator — an electric generator that produces alternating current.

absorber or receiver — a component of a solar collector that collects solar radiation in the form of heat. The heat is transported by a heat-transfer fluid through the receiver to its point of use.

absorptance — the ratio of absorbed to incident solar radiation. Absorptivity is the property of a material to absorb radiation.

baseline — reference against which a comparison is made.

baseload electric plant — an electrical generating facility that is designed primarily to satisfy a continuous demand.

Brayton-cycle engine — a heat engine that uses the thermodynamic cycle used in jet (combustion turbine) engines.

Btu — British thermal unit; the amount of heat required to raise the temperature of one pound of water (at 40°F) one degree Fahrenheit under a standard atmospheric pressure.

buffer storage — energy storage that is designed to allow a solar energy system to operate through transient solar conditions.

busbar energy cost — the cost of producing electricity, including plant capital and operating and maintenance expenses. Does not include cost of transmission or distribution.

cavity receiver — a receiver in the form of a cavity where the solar radiation enters through one or more openings (apertures) and is absorbed on the internal heat-absorbing surfaces.

central receiver system — a solar-powered system that uses an array of computer-controlled sun-tracking mirrors (heliostats) to concentrate the available solar radiation and focus it onto a nearby tower-mounted receiver. The energy absorbed by the receiver usually is removed as thermal energy.

closed-loop system — a system in which no part is vented to the atmosphere.

cogeneration — production of two or more types of energy by the same system; e.g., electricity and process heat.

collector efficiency — the ratio of the energy collection rate of a solar collector to the radiant power intercepted by it under steady-state conditions.

concentrator — a device that concentrates the sun's radiation onto a given area, thereby increasing the intensity of the collected energy.

concentration ratio — the radiant power impinging on a receiver surface divided by the radiant power incident upon the concentrating surface.

convection — heat transfer resulting from fluid motion in the presence of a temperature difference.

distributed receiver system — a solar-powered system in which each concentrating collector has its own attached receiver.

dual-axis tracking — capable of moving independently in two directions; e.g., in both north-south and east-west directions.

endothermic reaction — a chemical reaction that absorbs heat.

evaporator — a heat exchanger in which a fluid undergoes a liquid-to-vapor phase change.

external receiver — an exposed heat receiver, typically cylindrical in shape. In this type of receiver, tubes containing the heat-transfer fluid are on the outer surface of the receiver and directly absorb the radiant energy.

field experiment — the construction and testing of a solar energy system in an actual operating situation.

flat-plate collector — a nonconcentrating device that collects solar radiation, both diffuse and direct.

flux (radiant) — the time rate of flow of radiant energy.

flux density — the radiant flux incident per unit of area.

generator — a machine that converts mechanical energy into electrical energy.

heat exchanger — a device that transfers heat from one fluid to another.

heat pipe — a passive heat exchanger employing principles of evaporation and condensation to transfer heat effectively.

heat-transfer fluid — a fluid circulating through a receiver that absorbs the sun's heat.

heliostat — a device for reflecting light from the sun in a desired direction. A typical heliostat may consist of a number of flat (or slightly concave) mirror facets mounted to a drive mechanism capable of pointing the mirror array in any desired direction, usually onto a fixed receiver.

hemispherical bowl collector — a stationary, bowl-shaped, solar thermal collector that concentrates radiant energy onto a movable linear receiver.

hybrid system — an energy conversion system that can be operated from solar energy or fossil fuel either interchangeably or simultaneously.

insolation — the solar radiation available at the earth's surface. The maximum energy rate is about 1000 W/m^2 (100 W/ft^2).

levelized costs of energy — the charge for each unit of energy produced over the system life that will produce revenues equal to the life cycle cost when the time value of money is accounted for by the investor's discount rate.

linear (line)-focus receiver — a receiver that absorbs radiant energy along a line of focus.

module — (1) a unit consisting of a concentrator with support structure, receiver, and power conversion equipment. It can stand alone or be clustered with others to provide greater power capacity; (2) a self-contained unit that performs a specific task or class of tasks in support of the major function of the system.

molten salt solar thermal system — a solar thermal system that uses molten nitrate salt, a heat-transfer fluid, to store thermal energy.

organic Rankine-cycle engine — same as a Rankine-cycle engine (see Rankine-cycle engine) except that the working fluid in the cycle is an organic compound instead of water/steam.

parabolic dish collector — paraboloidal dish, dual-axis-tracking, solar thermal concentrator that focuses radiant energy onto an attached point-focus receiver or engine/receiver unit.

parabolic trough collector — a paraboloidal trough, usually single-axis-tracking solar thermal concentrator that focuses radiant energy onto an attached linear-focus receiver.

peak watt — unit used for the performance rating of solar-electric power systems. A system rated at one peak watt delivers one watt at a specified level of insolation.

point-focus receiver — a receiver that absorbs reflected radiant energy at a point of focus.

Rankine-cycle engine — a closed-loop heat-engine cycle using various components, including a working fluid pumped under pressure to a boiler where heat is added, a turbine where work is generated, and a condenser used to reject low-grade heat to the environment. The thermodynamic cycle upon which water/steam turbines are based.

receiver — see absorber.

repowering — the retrofitting of existing fossil-fueled utility or process-heat power plants with solar energy collection systems to provide the capability to displace a portion or all of the fossil fuel normally used.

retrofit — the installation of solar energy systems in already existing structures or facilities.

single-axis tracking — capable of moving in one direction; e.g., in an east-west direction.

solar energy — energy in the form of radiation emitted from the sun and generated by means of a fusion reaction within the sun.

solar furnace — a solar device used to obtain extremely high temperatures (over 2760°C; 5000°F) by focusing the sun's rays onto a receiver.

solar thermal electric conversion — the conversion of solar energy to thermal energy, which in turn powers a turbine/generator to produce electricity.

solar thermal energy system — a system that uses heat produced from the sun's rays to produce mechanical power, electric power, or process heat.

Stirling-cycle engine — an external-combustion engine using pistons driven by heated gas. The gas travels in a sealed system from a receiver to the cylinders. It is potentially more efficient than a steam engine or gas turbine.

storage-coupled — using an energy storage system to permit an end-use system to operate during periods when solar power from the receiver is inadequate (or not present) to satisfy the load.

sunfuels — transportable fluids produced from either nonrenewable or renewable resources, using energy from the sun in the synthesis process.

thermal energy storage system — any rechargeable unit capable of storing thermal energy for later use. Examples are storage as sensible heat in nitrate salt, oil, sodium, rock, water, or soil.

thermochemical conversion process — any process that transforms an initial set of chemical reagents into a different product set of chemicals involving the application or removal of heat energy.

thermocline storage — the storage of thermal energy where the hot and cold media are in the same container (tank) using the thermocline principle, which relies on a lower density hot fluid floating atop a higher density cooler fluid of the same type or which relies on hot solid material being separated from cooler solid material by a thermal gradient as in air/rock, air/ceramic brick applications.

total energy system — an energy system that uses waste heat from the generation of electricity to satisfy additional energy needs; e.g., electrical, heating, and cooling requirements.

tracking system — the motors, gears, and actuators instructed by computer command to maintain a proper orientation with regard to the sun and receiver positions.

turbine — an engine or machine driven by the pressure of steam, water, air, etc., against the curved vanes of a wheel or set of wheels fastened to a drive shaft.

working fluid — a pressurized fluid used to do work; e.g., drive a turbine. The pressurized working fluid in some systems is heated by passing through a heat exchanger from which it absorbs heat from a heat-transfer fluid.

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