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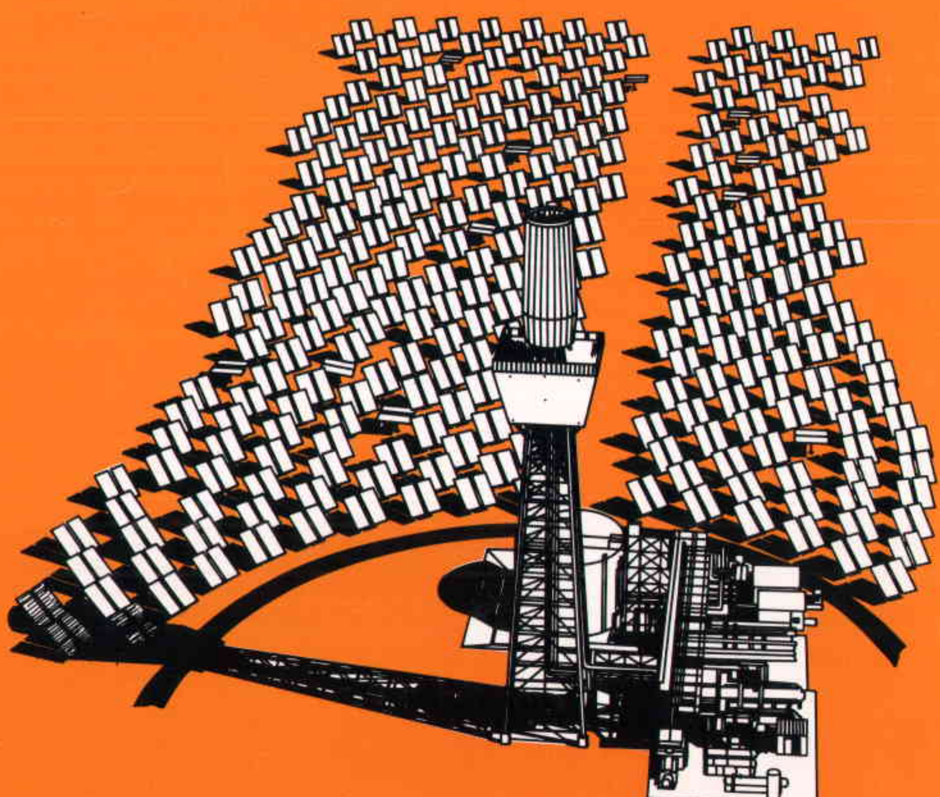
Solar Thermal

TECHNICAL INFORMATION GUIDE



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Solar Thermal

TECHNICAL INFORMATION GUIDE

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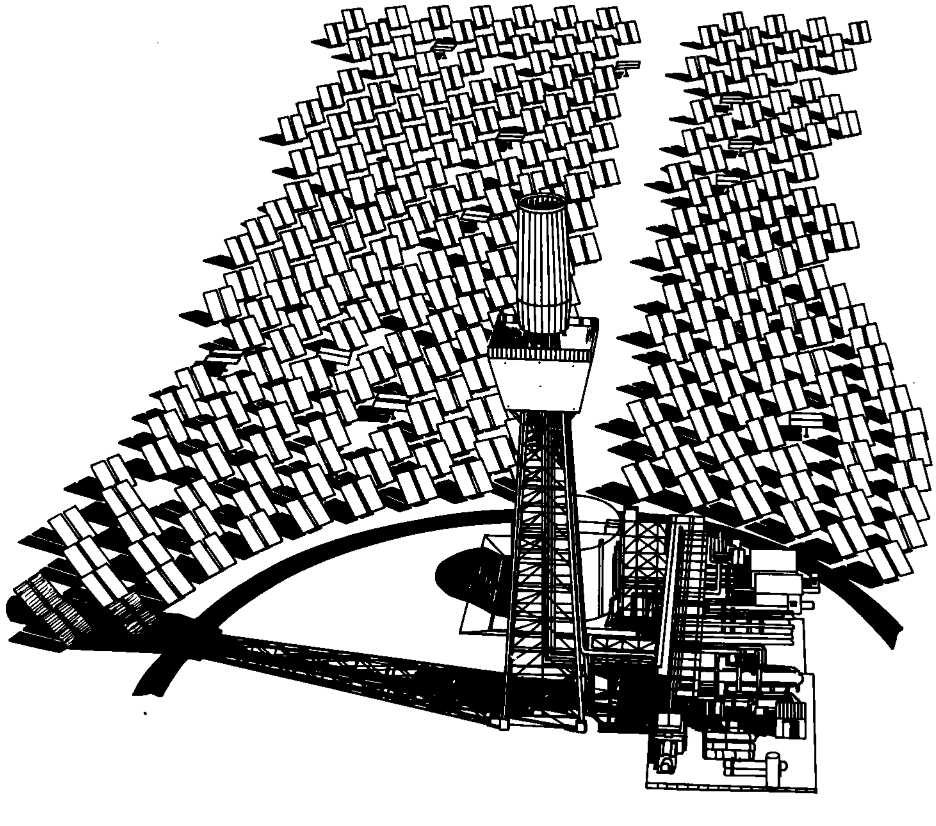

Preface

This guide is designed to help investigators search for information in the solar thermal technology field. The information ranges from history and technology basics to the latest in research and development. It is written to help several audiences, including engineers and scientists who may be unfamiliar with a particular aspect of solar thermal energy, university researchers who are interested in the field, manufacturers needing to learn more about specific topics, and librarians who provide information to their clientele.

Please note that the annotated references appearing throughout this guide do not represent all available material on a specific topic. The objective is to identify sources of basic information to help identify where to begin a search. The actual selection of references (and their placement in the guide) is based on several factors, including relevancy to the particular topic, frequency of citation in the professional literature, recommendations from solar thermal research engineers, currency, and availability.

Acknowledgements

This document was prepared under the auspices of the Solar Thermal Technology Division, Office of Renewable Technology, U.S. Department of Energy.

How to Use This Guide

This guide is divided into ten chapters, with Chapters 1-8 providing background on solar thermal energy development (including its history and current status) by topic. Within each topic, an overview is provided with references to relevant publications or information sources. Chapters 9 and 10 contain directories listing research centers and major technical information sources, respectively. Finally, two indexes are provided that list organizations (including research centers, associations, and major information sources) and research contacts, respectively.

The catalog of research centers (Chapter 9) is based primarily on those U.S. entries found in the *International Directory of New and Renewable Energy Information Sources and Research Centres* and from information contained in various technical reports and conference proceedings. During September and October 1983, individuals from each organization were contacted by SERI to provide a description of their solar thermal research activities along with a list of contacts.

The bibliographies, data bases, directories, associations, journals, and models listed under Information Sources and Design Tools (Chapter 10) are not intended to be exhaustive. Those publications or organizations most directly concerned with the subject area, who are available or accessible to the public, are included.

Many of the publications cited in this book are government reports. The *National Technical Information Service (NTIS)* is the central source for the public sale of government-funded research and development reports prepared by federal agencies, their contractors, or grantees. Requests for these publications should be sent to:[1]

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[1]Some of the more popular publications produced from federally funded work can be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402. Such publications, when cited in this guide, will contain specific ordering information within the annotated reference.

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Chapter 1
Introduction

History of Solar Thermal Technologies

The term solar thermal technologies, as used in this guide, refers to systems for making use of solar energy by first concentrating the incoming solar flux, and then converting this energy to heat, regardless of the final application. This distinguishes these technologies from, say, photovoltaic technologies which use the solar resource to produce electricity without this intermediate conversion. It also distinguishes it from (with the exception of solar ponds) those technologies which use the solar resource to produce heat without first concentrating it.

Solar power, as well as space and water heating technologies, has been evolving for thousands of years. The Greeks, Romans, and Chinese developed curved mirrors that concentrate the sun's rays onto an object with enough intensity to make it burst into flames in seconds. Legend has it that in 212 B.C. Archimedes had his soldiers use their polished shields as "burning mirrors" to set fire to the sails of the invading Roman ships at Syracuse.

Knowledge of "burning mirrors" disappeared from European culture during the Dark Ages, but resurfaced during the Renaissance when Leonardo de Vinci proposed to build a parabolic mirror four miles wide. It wasn't until the 1800s that extensive efforts were made to use solar energy for power production. Many of the first solar motors were developed by Augustin Mouchot, perhaps the most famous of which was his parabolic concentrating reflector that powered a printing press at the 1878 World's Fair in Paris.[1] Other inventors followed Mouchot.

One of the most successful leaders of the recent turn-of-the-century solar movement was Aubrey Eneas. In 1901 his 700-ft^2 focusing collector in the shape of a truncated cone received a great deal of public exposure when it was used to operate a 10-hp solar steam engine for a water pump at the Cawston Ostrich Farm in Pasadena, California.[2] Although Eneas' Solar Motor Company sold several of these solar pumps, their high price and susceptibility to damage from the environment deterred most potential buyers.

Frank Shuman, an American engineer, developed a more practical solar-driven hydraulic pump. In 1913 he successfully demonstrated the use of a 50-hp solar engine for pumping

Butti, Ken and Perlin, John. (1980). *A Golden Thread.* New York: Van Nostrand Reinhold Company; 289 pp.

This book describes the major advances in solar architecture and technology that have occurred since the time of the ancient Greeks. Its emphasis is on developments occurring in Western civilization, but it also includes some work from China and Japan. The technological developments are discussed within the economic, political, social, and cultural milieux of each period.

Daniels, Farrington and Duffie, John A. (1955). *Solar Energy Research.* Madison, WI: The University of Wisconsin Press; 290 pp.

This book is loosely based on a symposium on the utilization of solar energy held in Madison, Wisconsin, September 12-14, 1953. The contributions from the 31 authors illustrate the status of solar energy as of 1954. In addition, the appendix provides an historical survey of U.S. patents pertaining to the use of solar energy. An extensive bibliography is included.

Meinel, Aden B. and Meinel, Marjorie P. (1976). "Chapter 1. History of Applications." *Applied Solar Energy: An Introduction.* Reading, MA: Addison-Wesley Publishing Company; pp. 1-35.

This history of solar energy emphasizes the achievements made in the late Victorian era and during the period from 1945 to 1965. The technologies discussed center primarily on solar thermal power production but some of the early developments relating to solar hot water, solar residential heating, and photovoltaics are described also.

Halacy, D.S., Jr. (1973). *The Coming Age of Solar Energy.* Revised edition. New York: Harper and Row Publishers; 231 pp.

After presenting the need for solar energy, the book presents an historical overview of advances made in solar energy and then discusses some of the concepts and approaches which might be exploited in the future.

[1] *Mouchot, Augustin. (1879).* La Chaleur Solaire, *2nd. ed. Gauthier-Villars; 256 pp.*

[2] *Holder, C. (March 16, 1901). "Solar Motors."* Scientific American. *Vol. 84; pp. 169-170*

irrigation water from the Nile River at Meadi, Egypt. This device, which he designed with the aid of C.V. Boys, used long parabolic troughs that focused solar radiation onto a central pipe.[3] The outbreak of World War I disrupted plans to expand the use of the Shuman sun plant. With the increasing availability of low-cost oil and natural gas, there was minimal activity in the field of solar power until 1950. (It should be noted that there was a great deal of activity in the area of solar hot water, particularly in Florida, during the 1930s and 1940s.)

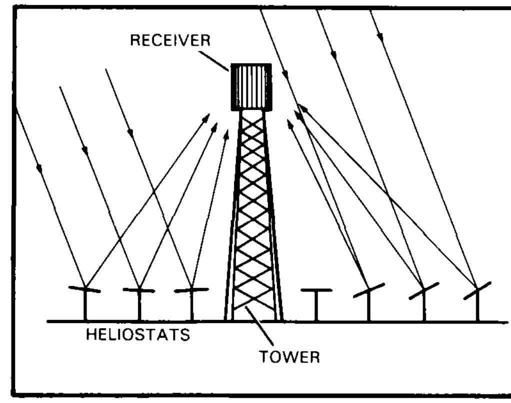
Interest in solar power revived in 1949 at a session of the centennial meeting of the American Association for the Advancement of Science (AAAS) which was devoted to future energy sources. At that time, the potential as well as the economic problems of solar energy utilization were presented by Farrington Daniels.[4] Some other conferences that considered solar power generation during that time were held by UNESCO in 1954, the Association for Applied Solar Energy in 1955 (presently known as the International Solar Energy Society), the U.S. National Academy of Sciences in 1961, and the United Nations in 1961.

Several solar furnaces were constructed in the 1950s and 1960s in France, Japan, and the U.S. The French and U.S. furnaces were developed to simulate the thermal radiation environment produced by a nuclear explosion. Widespread interest in solar thermal power systems developed only after research funds became available for the development of earth-bound solar electric power and process heat following the oil embargo in 1973.

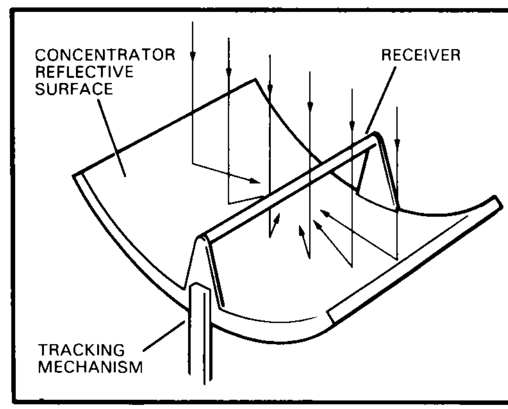
Overview of Solar Thermal Technology

Solar thermal technologies use the sun's concentrated radiant energy to produce heat that can be used directly in industrial and agricultural operations, be converted to mechanical or electrical power, or be applied directly in chemical reactions for production of fuels and chemicals. There are five basic types of solar thermal concepts which have been examined in recent years: (1) central receiver, (2) parabolic dish, (3) parabolic trough, (4) hemispherical bowl, and (5) salt-gradient solar pond. The first four concepts employ reflective-surface concentrating collectors that focus the sun's rays on a receiver where the radiant energy is converted to heat. The central receiver system employs several mirrors (called heliostats) and only one receiver; systems employing dishes, troughs, and bowls are referred to as distributed receiver systems since each mirrored collector has its own attached heat receiver, creating a distribution of receivers throughout a field of collectors.

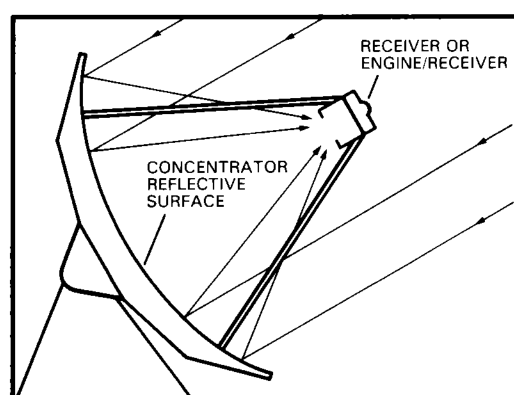
In order for these systems to concentrate the sun's rays effectively to obtain the high temperatures desired, some form



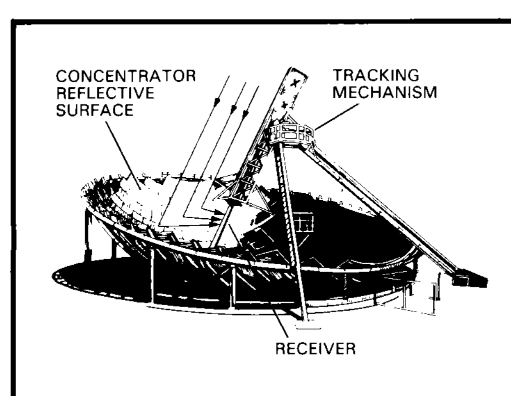
CENTRAL RECEIVER



PARABOLIC TROUGH



PARABOLIC DISH



HEMISPHERICAL BOWL

Collector Systems

[3]*Shuman, Frank. (February 18, 1914). "Feasibility of Utilizing Power from the Sun."* Scientific American. *Vol. 110; p. 179.*

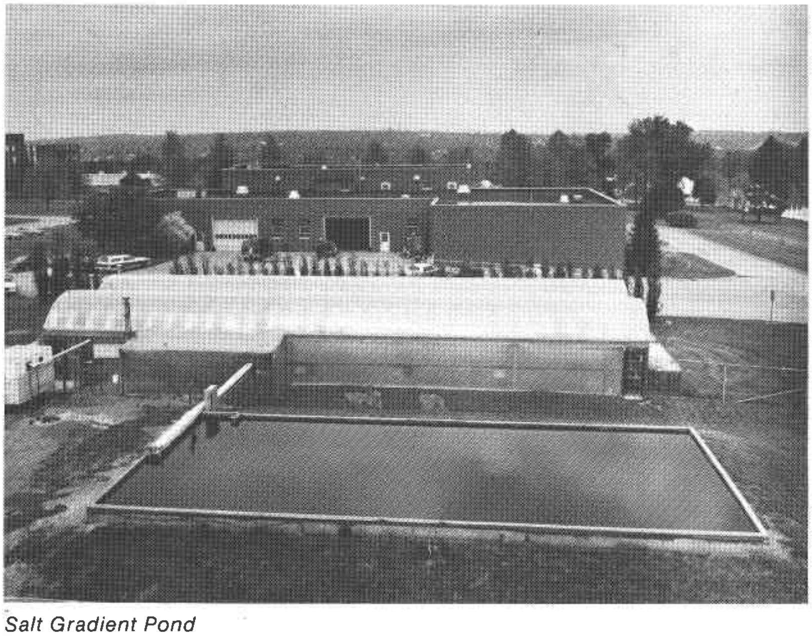
[4]*Daniels, F. (1949). "Solar Energy."* Science. *Vol. 109; pp. 51-57.*

of tracking is usually needed to make sure the concentrators are always exposed to direct sunlight. In central receiver systems, a field of tracking mirrors intercepts and redirects sunlight to a receiver mounted on top of a centrally located tower. Parabolic dishes track the sun along two axes and concentrate the sunlight on a receiver at the focal point of the paraboloid. Parabolic troughs, which usually track along one axis only, concentrate the sun's rays along an absorber tube at the optical focus of the trough. Finally, the hemispherical bowl concept uses a stationary, hemispherically shaped mirror to focus light along a moveable linear heat receiver that tracks with the sun.

The fifth solar thermal concept, the salt-gradient solar pond, maintains a high concentration of salt near the bottom of the shallow pond and a low concentration near its surface. The pond collects solar energy and stores it as thermal energy in the bottom, salt-rich layer where it can be piped out and used directly as heat or used to produce electrical power.

Currently, there are four general applications for solar thermal systems:

1. Electric power generation. The fluid heated in the receiver is vaporized or is used to vaporize a secondary fluid to run a turbine and generator.
2. Industrial process heat. The heat in the receiver is transferred via a working fluid to locations in a factory where process heat is required.
3. Total energy systems. The high-temperature fluid produced in the receiver is used to generate electricity. After running the turbine, the lower-temperature (but still hot) fluid is used for process heat, space heating, and/or hot water heating.
4. Fuels and chemicals. Many endothermic chemical processes (processes that require heat) can be performed by a solar thermal receiver serving as a chemical reactor.



Salt Gradient Pond

Kreider, Jan F. (1979). *Medium and High Temperature Solar Processes*. New York: Academic Press; 346 pp.

The purpose of this book is to describe, in an engineering context, many medium- and high-temperature solar processes (above 100° C) that are or will become technically viable during the remainder of this century. In addition, methods of assessing economic viability of elevated temperature solar processes are developed in detail and expected environmental impacts are summarized.

Kreider, Jan F. and Kreith, Frank. (1981). *Solar Energy Handbook*. New York: McGraw-Hill Book Company; 29 chapters and appendices.

The book collects into one volume all the archival data and procedures available for solar system assessment and design. For the most mature technologies, sufficient data is presented to permit technical and economic analysis and synthesis through the final system design stage. Three of the six sections are of particular interest to solar thermal: Perspective and Basic Principles, Solar-Thermal Collection and Conversion Methods, and Solar High Temperature and Process Heat Systems.

Wyman, Charles; Castle, James; and Kreith, Frank. (1980). "Review Paper: A Review of Collector and Energy Storage Technology for Intermediate Temperature Applications." *Solar Energy*. Vol. 24 (No. 6); pp. 517-540.

The technology and thermal performance of intermediate temperature solar collectors is summarized and the status of thermal and thermo-chemical storage methods is reviewed. It is concluded that collector technology is commercially available to achieve delivery temperatures up to 350° F at averaged yearly efficiences better than 30% in good solar climates and that linear parabolic, single-axis tracking troughs were the best type of collectors available at that time for intermediate temperature applications.

Leibowitz, L. and Hanseth, E. (January 1982). "Solar Thermal Technology — Outlook for the '80s." *Mechanical Engineering*. Vol. 104 (No. 1); pp. 30-35.

The development and application of advanced technology for improved solar thermal energy subsystems and components is described. Topics covered include approaches to improving performance, cost/performance targets, and a description of the advanced technology program.

State-of-the-Art Sources

The most difficult type of information to obtain in any technology is that which reports the latest developments in the field. Understandably, the publishing process takes time and creates gaps between the accomplishment and its documentation. The following suggestions offer alternatives to waiting for the latest information to appear in print. The most up-to-date information can be obtained by talking to those directly involved in particular aspects of the field. For example, Chapter 9 of this guide lists organizations performing solar thermal research (including government laboratories) and describes their areas of research.

Workshops and conferences provide a forum for researchers and others to present their latest findings and note industry trends. Information on recent conferences can be found in the conference section of this chapter as well as in other chapters (by specific topic).

Although less timely than personal contact, journal articles are the most up-to-date source of authoritative published information. For example, *Solar Energy Intelligence Report* provides news on current developments and activities in the solar field, and *Journal of Solar Energy Engineering* contains scholarly articles describing research findings and techniques. Chapter 10 in this book lists journals that are useful in the solar thermal field.

The publications cited here summarize recent developments in several solar thermal technologies. They discuss not only the technology, but also its potential and likely impacts.

Alvis, R.L.; Cameron, C.P.; and Lewandowski, A.A. (1983). "Solar IPH Systems Developed Under the Department of Energy MISR Project." *Solar Engineering — 1983: Proceedings of the ASME Solar Energy Division Fifth Annual Conference.* New York: The American Society of Mechanical Engineers; pp. 540-545.

The Modular Industrial Solar Retrofit (MISR) project competitively selected five companies to design, fabricate, and evaluate modular, mid-temperature, line-focus solar systems for industrial steam applications. This paper describes the system design requirements, the designs developed, and the results of the design evaluation test.

Bedard, R.; Overly, P.; and Bell, D. (1981). "Point-Focus Solar Concentrator Technology." *Proceedings of the 1981 Annual Meeting of the American Section of the International Solar Energy Society; Philadelphia, PA; 26-30 May 1981.* Edited by Barbara H. Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 324-328.

The paper summarizes the overall design of a point-focus concentrator and describes both state-of-the-art and advanced technology reflective panel design approaches. Test results of developmental panels are presented and the predicted thermal performance and production costs are provided.

Lawrence, C.L. and Hildebrandt, A.F. (1982). "Heliostat Systems: Technical and Economic Assessment." *Proceedings of the 1982 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Houston, TX; 1-5 June 1982.* Edited by Barbara H. Glenn and William A. Kolar. Vol. 5. Preprint edition. New York: ASES Publishing Office; pp. 305-310.

This report reviews and assesses the current status of heliostat system (usually known as power towers or central receivers) development. It examines recent design reports, describes expected economic and performance improvements, makes recommendations for the role that government can play in heliostat development, and recommends state and federal policies for development of solar commercialization and the formation of heating utilities.

Tabor, H. (1981). "Review Article: Solar Ponds." *Solar Energy.* Vol. 27 (No. 3); pp. 181-194.

This article provides the background to, and the current status of, solar ponds as proven, viable large-area collectors capable of providing both low-cost thermal energy and mechanical or electrical energy using state-of-the-art low-temperature turbo-generators. After a short background of the history and motivation for solar ponds, the article outlines the basic theory of salt-gradient solar ponds and provides practical details on how ponds are built and the heat is extracted. Finally, an account of solar pond experiences in several countries is presented.

Conferences and Other Educational Activities

Conferences, workshops, and other professional meetings often provide the latest developments in a field. Some organizations, including DOE and the national laboratories responsible for components of the Federal Solar Thermal Program, sponsor conferences and workshops. The Solar Energy Division of the American Society of Mechanical Engineers (ASME), the American Solar Energy Society (ASES), the Intersociety Energy Conversion Engineering Conference, and the International Solar Energy Society sponsor annual or semi-annual conferences that deal significantly with solar thermal topics.

Though most conference proceedings are listed under specific topic sections in this guide, the latest proceedings of these four organizations are listed here.

Specific solar thermal courses or programs offered through conventional post-secondary education institutions can be difficult to identify. The educational institutions listed under the Research Centers in Chapter 9 may allow special studies or projects in solar thermal if they have no official solar program. In addition, conferences and seminars provide good opportunities to learn about solar thermal whether or not they give official credit or degrees.

Glenn, Barbara H. and Kolar, William A., editors. (1982). *Proceedings of the 1982 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge. Houston, TX; 1-5 June 1982.* Volume 5. Preprint edition. New York: ASES Publishing Office; 2 V.

Murphy, Lawrence M., editor. (1983). *Solar Engineering — 1983: Proceedings of the ASME Solar Energy Division Fifth Annual Conference. Orlando, FL; 18-21 April 1983.* New York: The American Society of Mechanical Engineers; 632 pp.

Szokolay, S. V., editor. (1984). *Solar World Congress, Proceedings of the Eighth Biennial Congress of the International Solar Energy Society; Perth, Australia; 14-19 August 1983.* New York: Pergamon Press; 4 V.

Proceedings of the 18th Intersociety Energy Conversion Engineering Conference; Orlando, FL; 21-26 August 1983. (1983). New York: American Institute of Chemical Engineers; 5 V.

National Solar Energy Education Directory. 3rd ed. (May 1981). SERI/SP-751-1049. Golden, CO: Solar Energy Research Institute; 279 pp.

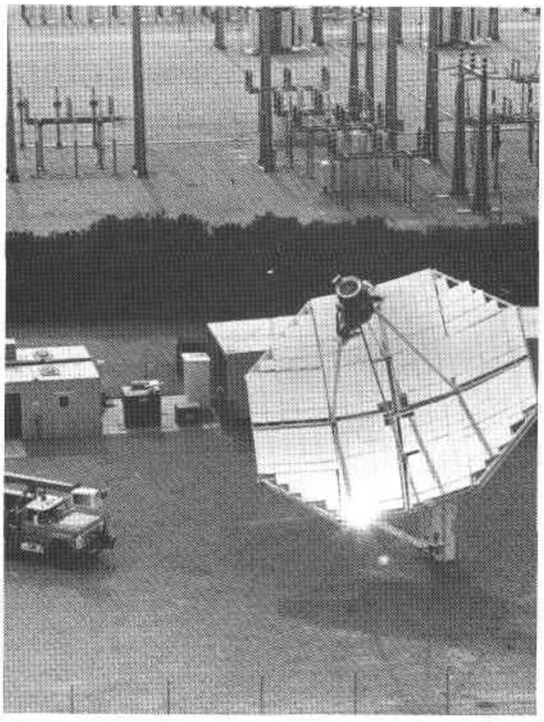
This directory lists solar energy or solar-related program and course opportunities offered at the post-secondary level. Twenty programs that deal with solar energy conversion are listed. Over 200 courses that relate to centralized solar power systems are identified.

Future Developments

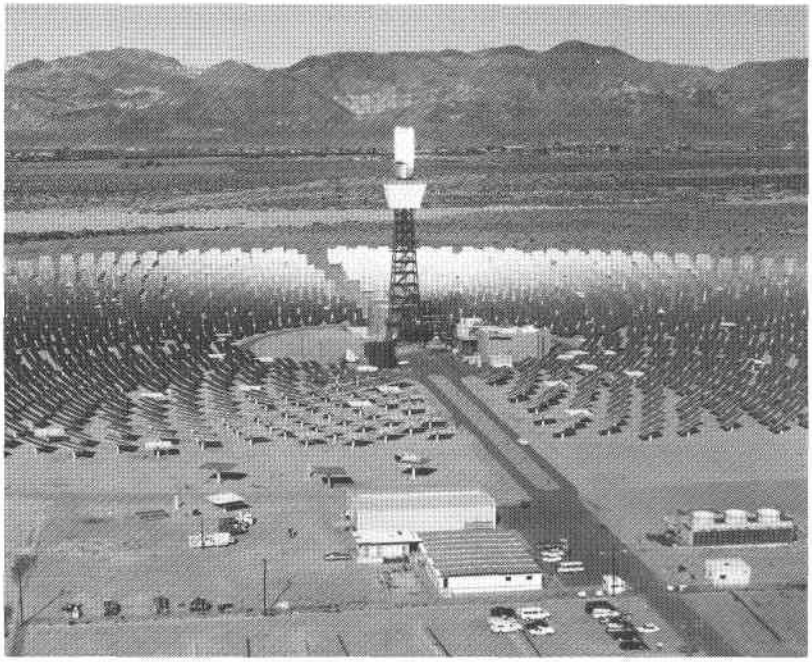
The industrial sector is the greatest consumer of energy in the U.S., accounting for almost 40% of the total amount of energy used in 1981. Electricity accounted for 31% of the energy usage of the industrial sector and almost 34% of the total primary energy used. Projections increase total energy usage of electricity to about 44% by the year 2000.

Solar thermal energy offers a significant potential for both electricity generation and industrial process heat applications. Estimates of potential impacts indicate that up to 3 quads (or about 520 million barrels of oil displaced) per year may be obtained from medium- and high-temperature solar thermal systems by the year 2000. About 0.4 quads per year of this total could be for electrical production which would account for about 2%-3% of all electrical production capability. The solar industrial process heat contribution (about 2.6 quads/year) might meet about 8% of the total industrial energy demand.

It appears that central receivers can become a technically and economically viable source of power by the late 1990s. Demonstrations of plants in the size range of interest to potential users and the development and demonstration of techniques needed for mass production of heliostats will be important for encouraging the use of central receivers.



Parabolic Dish On-Line with Southern California Edison



Solar One in Operation

Initial market penetration in the midterm (1985-1995) for distributed receiver systems will probably include mid-temperature industrial process heat, irrigation pumping, oil recovery, and solar cooling applications for parabolic troughs and remote electric utility applications for parabolic dishes. The post-1995 market for solar thermal technology is expected to expand the mid-term achievements, with increased mid-temperature IPH applications for troughs and additional dish applications in small community utilities and total energy systems.

"Chapter 3; Solar Collectors: Intermediate and High Temperature." (June 1981). *New and Renewable Energy in the United States of America.* DOE/S-0006. Washington, DC: Department of Energy; pp. 23-30.

As the United States' national paper for the 1981 United Nations Conference on New and Renewable Sources of Energy, this report describes the current technical and economic status of renewable energy in the U.S. and outlines the expectations for these energy sources. Chapter 3 examines four solar thermal techniques: (1) central receivers, (2) parabolic troughs, (3) parabolic dishes, and (4) hemispherical bowls. The chapter also covers current and potential applications, barriers, and development activities.

Fujita, T.; Manvi, R.; Roschke, E.J.; El Gabalawi, N.; Herrera, G.; Kuo, T.J.; and Chen, K.H. (November 1978). *Techno Economic Projections for Advanced Dispersed Solar Thermal Electric Power Plants to Years 1990-2000.* DOE/JPL-1060-78/4. Pasadena, CA: Jet Propulsion Laboratory; 157 pp.

Advanced technologies applicable to solar thermal electric power systems in the 1990-2000 time span are delineated for dispersed power applications that fulfill a wide spectrum of small power needs with primary emphasis on power ratings less than 10 MW. Techno-economic projections of power system characteristics are used as the basis for comparing technology development options to determine developmental directions offering the greatest potential for significant improvements.

Bennington, G.; Curto, P.; Miller, G.; Rebilo K.; and Spevak, P. (March 1978). *Solar Energy: A Comparative Analysis to the Year 2020.* HCP/T2322-01. McLean, VA: The MITRE Corporation; 64 pp.

The report describes a comparative analysis and potential market impact assessment of solar energy technologies, including mid- and high-temperature solar thermal applications. The analysis is then used to examine alternative recommendations for planning of the federal research, development, and demonstration program for solar technologies.

U.S. Federal Programs

The Division of Solar Thermal Technology (STT) within the U.S. Department of Energy (DOE) Office of Solar Heat Technologies sponsors research and development on advanced solar thermal energy conversion concepts; i.e., those systems that provide heat between about 90°C and approximately 1700°C (200°F to 3000°F). The federal-level decision to conduct solar thermal R&D was enacted into law in 1974 with the Solar Energy Research, Development and Demonstration Act (PL.93-473). The strategy of the Solar Thermal Technology Division has been to pursue a program of government-sponsored and cost-shared research, development and demonstration aimed at achieving a sufficient level of technical maturity for the various solar thermal technologies so that decision-makers within the private sector will find acceptable risks should they choose to manufacture, market, or use solar thermal systems.

Toward this end, the program has pursued improvement in the performance and reliability of systems through research and development of constituent materials, components, and subsystems. The technologies treated with the solar thermal program are central receivers, parabolic dishes, parabolic troughs and hemispherical bowls. Past research in the program also included salt-gradient ponds. Technical direction for these activities makes use of the technical expertise available to DOE through its network of national laboratories, with most of the work done by private industry under contract to, or in cost-shared partnership with, DOE and its field management organizations. The STT program is structured into three major elements: (1) Research and Technology, (2) Systems Test and Evaluation, and (3) Planning and Assessment.

To achieve the goal of generating a base of solar thermal technology for the private sector to develop, the STT program has set the following objectives:

Near-term (1980-1985) and mid-term (1985-1990) objectives:

1. Develop cost-competitive systems for electric and process-heat applications.
2. Develop high-performance and reliable systems and components.
3. Assure technology transfer and develop confidence in industrial users and suppliers.

Long-term (beyond 1990) objectives include technology development for fuels and chemicals production.

The research element of the Research and Technology program undertakes high-risk/high-payoff research for advanced materials, components, subsystems and processes; the technology element of the program develops reliable, durable, and cost-effective solar thermal components, subsystems, and systems. The major tasks are broken down into long-term research, central receiver research and technology, and parabolic dish research projects. The purpose of long-term research is to support the development of cost-effective advanced technology solar thermal systems through research in high-risk areas critical to those technologies: materials for high-temperature systems, polymeric materials for low-cost concentrators, durability studies for reflector materials, and advanced concept development with the emphasis on solar fuels and chemicals production concepts.

Other tasks in the Research and Technology program are concerned with the development of specific technologies. The Solar Central Receiver Technology Project encompasses R&D activities for central receiver systems that operate between 150°C and 1400°C (300°F and 2550°F). Tasks include development of high-temperature components, molten nitrate salts receiver systems, and advanced enclosed heliostats. The Central Receiver Test Facility (CRTF), managed under this task, plays an important role in these and other central receiver system, subsystem and component experiments. The mission of the Parabolic Dish Project is to develop technology of point-focusing parabolic dishes for the production of electricity. Research focuses on developing high-temperature, high-efficiency, energy conversion devices based on Brayton and Stirling cycles, development and optimization of the lower-temperature Organic Rankine cycle for the Small Community Experiment, and design of advanced concentrators.

The function of the Systems Test and Evaluation program is to test first-of-a-kind solar thermal systems and to evaluate their feasibility for further development by private industry. Systems that have been constructed or are in final development represent all the major solar thermal technologies, the 10 MWe Central Receiver Pilot Plant, IPH systems using parabolic trough collectors, the Crosbyton hemispherical bowl system, the Shenandoah thermal dish system, and the Small Community Experiment parabolic dish system. A major function of this element is to obtain system cost and performance evaluations, using operational data from these existing systems.

Primary activities in the Central Receiver Systems element of the Systems Test and Evaluation program include: testing, analysis and evaluation of operational data and performance of the 10 MWe Central Receiver Pilot Plant; conceptual design of high-temperature, high-efficiency advanced technology CR systems; technical support and co-funding of CR systems for repowering; and long-range central receiver planning. Activities of the Distributed Receiver Systems program element support the operation, analysis, and evaluation of parabolic trough and parabolic dish systems used to supply thermal energy to IPH or cogeneration applications.

Finally, the Planning and Assessment program, through the Technology Program Integrator (TPI) at Sandia, Livermore provides for planning, assessment, and documentation of solar thermal activities. The purpose of the activity is to maintain a cohesive program aimed at near- and long-term goals. This program is also responsible for international coordination, with the objective of aiding the development of solar thermal technology through the evaluation and exchange of information on international projects and related activities. This subtask includes support and funding of the International Energy Agency Small Solar Power Systems (SSPS) in Almeria, Spain.

Policy formulation, planning, and program assessment activities are performed by DOE headquarters with implementation of each program element delegated to the field. The solar thermal program's organizations include: Albuquerque Operations Office, Jet Propulsion Laboratory (JPL), San Francisco Operations Office, Solar Energy Research Institute (SERI), Sandia National Laboratories, Albuquerque (Sandia-Albuquerque), and Sandia National Laboratories, Livermore (Sandia-Livermore). It should be noted that JPL is transferring its solar thermal activities to Sandia-Albuquerque in fiscal year 1984, but it is listed here with the activities for which it was responsible before transition; this was done for both the sake of simplicity and to provide an historical understanding of the program structure since many of the reports currently available will refer to the JPL program.

The Albuquerque Operations Office has programmatic responsibility for distributed receiver systems. However, most of the technical management for these tasks is the reponsibility of JPL and Sandia-Albuquerque.

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The Jet Propulsion Laboratory has been responsible for the technical management of most parabolic dish research and it operated the Parabolic Dish Test Site. In addition, JPL has been responsible for producing the *Annual Technology Progress Report* as part of its Technical Information Dissemination work for the STT program. In 1984 this responsibility was shifted to Sandia National Laboratories, Albuquerque.

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The San Francisco Operations Office has had the responsiblity for managing several elements in the long-term research and central receiver system programs. The Office has programmatic technical responsibility for thermochemical and photochemical research components of the long-term research program. Sandia-Livermore provides technical management for the Office's central receiver projects, including the Barstow 10 MWe Central Receiver Pilot Plant.

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The Solar Energy Research Institute (SERI) manages the STT Research Program which has eight program elements including Innovative Concepts, University Research, Fuels and Chemicals Research, and Program Management. SERI has both field and technical management responsibility for elements of the long-term research program including thermal materials research, polymer materials research, and enclosed concentrator research. SERI is also providing support for parts of the trough/IPH evaluation and the distributed receiver high temperature concept development elements of the Distributed Receiver Systems program.

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Sandia National Laboratories, Albuquerque provides the technical management for the Distributed Receiver Systems program, including trough/IPH evaluation, Shenandoah total energy project evaluation, and distributed receiver high-temperature concept development. Sandia-Albuquerque has also taken over responsibility for parabolic dish research and projects from JPL.

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Sandia National Laboratories, Livermore activities are focused primarily on central receiver projects. Sandia-Livermore has both field and technical management responsibilities for all elements of the Central Receiver Research and Technology program. In addition, it provides technical management for all elements of the Central Receiver Systems field projects and also has field management responsibilities for the advanced systems for fuels concept design and thermal subsystems development elements of this project.

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Solar Thermal Technology: Annual Evaluation Report Fiscal Year 1982. (July 1983). DOE/JPL-1060-61. Pasadena, CA: Jet Propulsion Laboratory; 2 V.

This report documents the accomplishments and progress of the Department of Energy Solar Thermal Technology (STT) Program during fiscal year 1982. The focus of the STT Program is research and development leading to the commercial readiness of three primary solar thermal concepts: (1) central receiver, (2) parabolic dish, and (3) parabolic trough. To a lesser extent, the hemispherical bowl and the salt-gradient solar pond are being studied.

International Programs

Interest in solar thermal energy systems is not confined to the United States. It is being pursued actively in several industrialized nations. Work is currently under way on five major international central receiver projects located in Italy, France, Spain and Japan. Israel is pursuing the use of solar ponds to produce electricity. Saudi Arabia, in conjunction with the U.S., is using three solar thermal technologies (point-focus collectors, line-focus collectors, and central receiver) to demonstrate the use of solar energy for desalinating water.

International Energy Agency's SSPS Project

In order to strengthen cooperation in the area of energy policy, an agreement on an "International Energy Program" was formulated among several industrialized countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the the Organization for Economic Cooperation and Development (OECD) to administer the program. Twenty countries are currently members of the IEA, with the European Communities (EC) participating under a special arrangement.

In October 1977, ten IEA participating nations (Austria, Belgium, Federal Republic of Germany, Greece, Italy, Spain, Sweden, Switzerland, United Kingdom, and United States) initiated the Small Solar Power Systems (SSPS) project with the purpose of designing and constructing a Distributed Collector System (DCS) and a Central Receiver System (CRS). The two side-by-side SSPS solar thermal power plants, each capable of producing 500 kW, are located in the province of Almeria, Spain. The central receiver plant consists of a cavity receiver that uses sodium as the heat transfer medium, a thermal energy storage system, and 93 heliostats located north of the receiver. The distributed collector system has parabolic trough collectors of two types: one type tracks in two axes and one tracks in a single axis. Operation began in 1981 and the SSPS project test and operation phase is scheduled for completion in December 1984.

Baker, A.F. (May 1981). *International Energy Agency Small Solar Power Systems (SSPS) Project Review; (January 1981)*. SAND81-8216. Albuquerque, NM: Sandia National Laboratories; 68 pp.

A review of the International Energy Agency Small Solar Power System Project from its beginning to January 1981 is provided. The background of the project is summarized and a definition and technical description of the main subsystems for the Central Receiver System and Distributed Collector System are given.

European Communities' EURELIOS Project

Within the framework of its Solar Energy Research and Development Programme, European Communities (EC) decided in 1976 to build a solar power plant to be called EURELIOS. Design and construction of the central receiver power plant, located at Adrano, Sicily, was undertaken by an international consortium of Italian, French, and German companies. Construction was completed in 1980 and the 1 MW plant was first connected to the grid of the Italian National Electric Board (ENEL) in April 1981. EURELIOS has 182 heliostats (one half 52 m^2 in size and one half 23 m^2) configured in two

Gretz, Joachim. (1982). "Solar Thermal Electricity Generation; EURELIOS, the 1 MW (el) Helioelectric Power Plant of the European Communities." *International Journal of Solar Energy*. Vol. 1 (No. 1); pp. 3-19.

The article discusses the different solar thermal power electricity conversion technologies and summarizes the main solar power plants under construction or already in operation. EURELIOS, the world's first experimental solar power plant in the megawatt range, is described in detail and the first operational results are presented.

subfields to allow field demonstration of the performance, behavior, and economics of heliostats of considerably different size. The cavity type receiver uses water as the heat transfer fluid and has a thermal buffer system which allows 30 minutes of operation without solar input.

France's Themis and PERICLES Projects

The French National Center for Scientific Research (CNRS) has sponsored several projects in the area of solar energy. The most important for solar thermal applications are a central receiver (THEMIS), two types of concentrators (THEK and PERICLES), and a solar furnace. In the THEMIS project, a 2 MW central receiver solar power plant was completed in 1982 at Targasonne, France. The field of 201 dual-axis tracking heliostats concentrates the solar energy in a cavity receiver which uses molten salt as the transfer fluid. Molten salt is also used as the thermal storage material with up to 12 hr of stored electricity possible.

For medium-temperature applications, two types of concentrating collectors are being developed: (1) the THEK (Thermodynamic Energy Kilowatt) collectors, and (2) the PERICLES (Production of Energy in an Isolated Region by the Limited Concentration of Solar Energy) collectors. Eleven of the THEK collectors, which are of the parabolic dish type, are being used in the THEMIS project to provide auxiliary heat. The PERICLES collector design is a hemispheric bowl with an extra "visor" of concentrators that move on a track about the vertical axis of the bowl. A prototype PERICLES (10 m diameter) is operating in Marseilles, France. A full-scale PERICLES (30.8 m diameter) would produce about 85 kW, placing it between the THEK collectors and the THEMIS systems in power production.

The solar furnace, located near the village of Odeillo, has been in operation sice 1970. Considered the largest in the world, the Odeillo furnace uses 63 heliostats located on eight levels to horizontally reflect the sun's rays onto the corresponding eight floors of the paraboloid concentrator. The receiver intercepts a concentration ratio of about 20,000 from this huge reflector producing temperatures of up to 3825°C at the center of its focal plane.

Allard, J.P.; Genier, R.; and Smadja, M. (1983). "The French Solar Tower Plant, THEMIS." *Solar Engineering — 1983: Proceedings of the ASME Solar Energy Division Fifth Annual Conference. Orlando, FL; 18-21 April 1983.* Edited by Lawrence M. Murphy. New York: The American Society of Mechanical Engineers; pp. 294-300.

The paper describes the six main subsystems of the THEMIS central receiver power plant located in Targasonne, France. The main points of the test program are summarized also.

"Mini-Pericles Operates in France." (March 1981). *The Solar Thermal Report.* Vol. 2 (No. 2); p. 8.

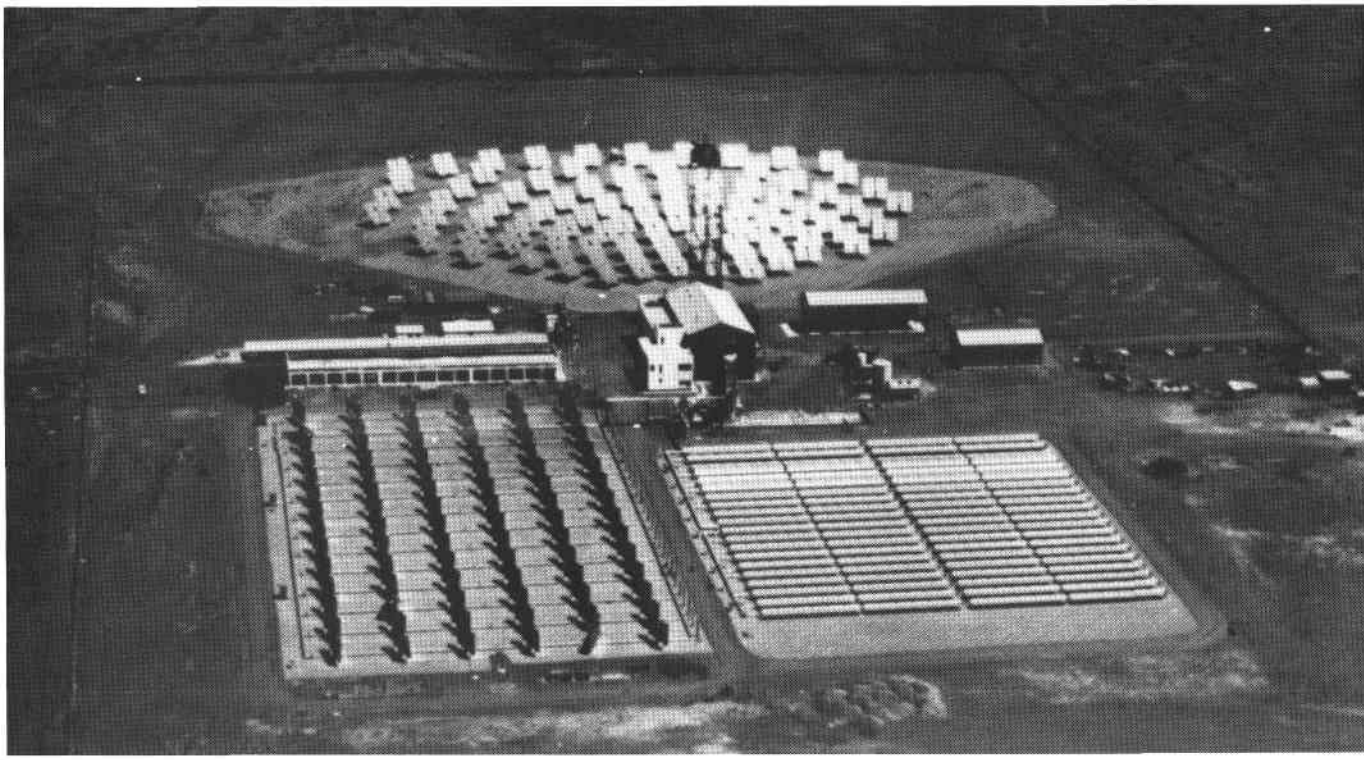
The article describes the small (10 m diameter) proof-of-concept version of the PERICLES collector system. A brief description of the full-scale PERICLES is provided also.

Spain's CESA-1

The CESA-1 (Central Electrica Solar de Almeria) Project, initiated early in 1979 under the sponsorhip of the Spanish Ministry of Industry and Energy, consists of the design, construction, and operation of a 12 MW pilot central receiver installation. Sandia National Laboratories-Livermore from the United States is providing technical assistance. The plant uses 300 heliostats, 39.6 m^2 each, which were designed and built by two companies in Spain. The receiver uses molten salt and water-steam as the heat transport fluid. Located in Almeria, Spain, near the IEA's Small Solar System Project, the plant is expected to become operational in 1983.

Munoz Torralbo, A. (1982). "A Spanish 'Power Tower' Solar System, the Project CESA-1." *Solar World Forum: Proceedings of the International Solar Energy Society Congress. Brighton, England; 23-28 August 1981.* Edited by David O. Hall and June Morton. New York: Pergamon Press; Vol. 4, pp. 2931-2935.

The paper describes the four major subsystems of the central receiver power plant CESA-1 including the collector subsystem, receiver subsystem, power subsystem, and energy storage subsystem. The background and objectives of the solar thermal project are described also.



Spain's CESA-1 Project

Japan's Sunshine Project

Begun in 1974, the Sunshine Project is the umbrella under which the Japanese goverment is developing alternative energy technologies. Research and development activities for solar thermal power generation systems have concentrated on the construction of two types of pilot plant at Nio, Japan, each with the electrical output of 1 MW. Completed in March 1981, the Central Receiver System was designed and manufactured by Mitsubishi Heavy Industries, Ltd. and the Plane Parabolic System by Hitachi, Ltd. Both pilot plants are designed to optimize land use and are best suited for small island and isolated community applications.

The central receiver plant consists of a field of 507 heliostats that focus sunlight on a cavity-type receiver. The receiver produces saturated steam for the turbine and a pressurized water storage subsystem with a capacity of 3 hr of power. The unique Plane Parabolic System design uses an array of dual-axis tracking heliostats to focus sunlight onto a series of elevated parabolic trough reflectors that further concentrate the light onto the linear receiver at their focal point.

Harigome, T.; Saishoji, T.; and Uto, T. (1982). "Solar Thermal Electric Power Generation System in Japan." *Solar World Forum: Proceedings of the International Solar Energy Society Congress. Brighton, England; 23-28 August 1981.* Edited by David O. Hall and June Morton. New York: Pergamon Press; Vol. 4, pp. 3277-3281.

The paper provides a general description of the Plane Parabolic System and the Central Receiver System pilot plants. The results of R&D on heliostats, solar heat collectors, and solar heat storage systems, and an outline of plant operational research plans are given.

Israel's Solar Ponds

Israel, having no indigenous fossil fuel supply, currently imports most of its energy. In an effort to achieve some degree of energy independence, the Israeli government has given strong support to the development of solar ponds to generate electricity. It is estimated that 27% of the country's electricity could be supplied by solar ponds by the year 2000.

Tabor, H. and Bronicki, Y.L. (1982). "The Next Twenty-Five Years — Solar Utilization in Israel." *Solar World Forum: Proceedings of the International Solar Energy Society Congress. Brighton, England; 23-28 August 1981.* Edited by David O. Hall and June Morton. New York: Pergamon Press; Vol. 4, pp. 3228-3236.

The first stage of a solar pond system, which is expected to produce up to 2000 megawatts of electricity by the year 2000, is in operation at Ein Bokek on the shores of Israel's Dead Sea. The 7000-m^2 pond inaugurated in December 1979 provides 150 kWe of peak power using an organic Rankine-cycle turbine/generator unit. Results have been encouraging enough to go on to the next stage — the construction of a 5 MW unit.

After discussing Israel's solar activities over the past 25 years, in particular the development of low-temperature turbines and of solar ponds as large-area collectors, the paper goes on to discuss the future electricity needs of the country. The plan to develop solar ponds so that they contribute 27% of the electricity needed by the year 2000 is sketched. Finally, other technologies and applications of solar energy are described and their potential contribution to Israel's energy needs are estimated.

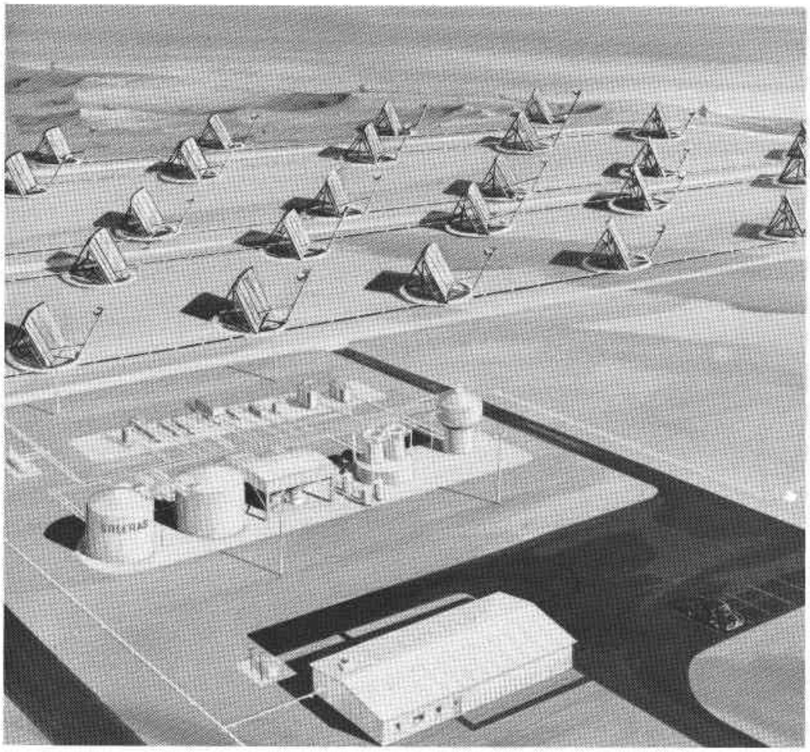
U.S.-Saudi Arabia Project

Saudi Arabia and the United States signed a Project Agreement for Cooperation in the Field of Solar Energy (SOLERAS) in October 1977 under the auspices of the United States - Saudi Arabian Joint Commission on Economic Cooperation. A specific objective of the Industrial Solar Applications program area is to demonstrate the use of solar energy in desalinating water and to advance the technical and economic feasibility of large-scale, solar-powered desalination of brackish water and seawater.

During Phase 1, Preliminary System Design and Cost Analysis, five solar energy water desalination systems were designed to deliver 6000 m^3 per day of desalted water from either seawater or brackish water. The five desalination system designs employed the following solar technologies: central receiver, wind generator and line- and point-focus collectors, point-focus collector, line-focus collector and photovoltaics, and another central receiver. During Phase 2, one of the systems designed for brackish water desalination and one for seawater desalination will be chosen for pilot plant construction. Finally, during Phase 3, the pilot plants will be operated, their performance measured, and local personnel will be trained in the operation and maintenance of the plant.

Luft, Werner. (1982). "Five Solar-Energy Desalination Systems." *International Journal of Solar Energy*. Vol. 1 (No. 1); pp. 21-32.

The article describes each of the solar desalination designs developed during Phase 1 of the SOLERAS program. Information on the performance and cost projections for each system are given also.



Artist's Conception of the SOLERAS Project in Yanbu, Saudi Arabia

Chapter 2
Theoretical Principles

Solar Radiation

The quantity of solar energy available for utilization depends upon a number of factors, including geographic location, site location of collector, collector orientation, time of day, time of year, atmospheric conditions, and collector design. Calculation of the performance and economics of medium- and high-temperature solar systems requires accurate analysis of these factors and many others.

The majority of high-temperature solar systems rely on the existence of **beam radiation** which may be concentrated to achieve high efficiency and high operating temperature. Beam radiation can be defined as the solar flux incident on a surface without significant direction change or scattering in the atmosphere. Beam radiation is also called direct radiation. Solar flux dispersed by various scattering mechanisms into the sky dome without a specific incidence angle on a terrestrial surface is referred to as **diffuse radiation**. Finally, the total of beam and diffuse radiation is called the total or **global radiation**. **Solar radiation**, itself, is the radiant energy issuing from the sun. Although solar radiation covers a wide band of wavelengths, the peak intensity occurs in the interval of visible light. Most solar radiation beyond the atmosphere is beam radiation. The annual mean solar flux at the "edge" of the atmosphere is called the **solar constant**.

As solar radiation travels through the atmosphere, a significant portion (25%-40%) is absorbed by such elements as water vapor and ozone in the atmosphere. This absorption is an effect apart from attenuation and blockage of sunlight by clouds, which may reduce incoming radiation by as much as 80%-90%. Also, because cloud distribution and cloud types are variable, their effects on incoming radiation are also variable. About one fourth of the remaining solar radiation is scattered so that it arrives at the earth's surface indirectly from the sun. Atmospheric scattering has an important consequence: It separates solar radiation into direct and diffuse components.

The amount of atmospheric absorption or scattering that affects incoming solar radiation depends upon the length of the atmospheric path, or the "thickness" of the atmosphere through which the radiation must travel. The measure of the atmospheric path is called **air mass**. An air mass value of 1.0 is assigned to an atmospheric path directly overhead at sea level. Because of numerous atmospheric variables, terrestrial sunlight in any one location varies greatly both in intensity and spectral composition. Also, diurnal and seasonal changes of the sun's angle and latitude to the earth affect the composition of solar radiation. The actual amount of sunlight falling on a specific geographic location is called **insolation**.

Boes, Eldon C. (1981). "Chapter 2. Fundamentals of Solar Radiation." *Solar Energy Handbook*. Edited by Jan F. Kreider and Frank Kreith. New York: McGraw-Hill Book Company; pp. 2-1 to 2-78.

The chapter gives a description of solar radiation as the energy source for solar energy systems. The basic topics covered are: basic geometric considerations; extraterrestrial solar radiation and atmospheric effects; summaries of solar radiation availabilities; and estimation and conversion formulas for solar radiation.

Kreider, Jan. F. (1974). "Chapter 2. Principles of Solar Radiation and Optics." *Medium and High Temperature Solar Processes*. New York: Academic Press; pp. 11-62.

The chapter includes information on terrestrial and extraterrestrial beam radiation, solar radiation geometry, beam radiation intercepted by surfaces, the solar energy resource, instantaneous and hourly solar radiation calculations, daily solar radiation calculations, monthly radiation calculations, and selected topics in optics.

Bendt, P. and Rabl, A. (April 1980). *Effect of Circumsolar Radiation on Performance of Focusing Collectors*. SERI/TR-34-093. Golden, CO: Solar Energy Research Institute; 50 pp.

Circumsolar data are used to calculate the effect of circumsolar radiation on both the instantaneous and the long-term average performance of focusing collectors. The sensitivity of a collector to circumsolar radiation depends on insolation conditions and collector parameters; it increases with geometric concentration ratio and decreases with threshold.

Frohlich, C. (1982). "Solar Radiation at the Earth's Surface." *Solar World Forum: Proceedings of the International Solar Energy Society Congress. Brighton, England; 23-28 August 1981*. Edited by David O. Hall and June Morton. New York: Pergamon Press; V. 3, pp. 2313-2321.

The paper presents methods and results of computation of direct solar radiation data taking into account different atmospheric conditions. Calculations are extended to include the effect of the center to limb variation of the solar disk — important for concentrating systems. A review of the spectral angular distribution of the sky radiance is presented also.

Boyd, David A. (1983). "The Stochastic Sun: Understanding the Intermittent Resource." *Alternative Energy Sources III*. Edited by T. Nejat Veziroglu. Washington, DC: Hemisphere Publishing Corporation; V. 1, pp. 3-15.

Many solar collectors do not face the sun directly at all times and hence cannot capture the full radiation amount since they suffer incident angle cosine loss. (The effective portion of beam radiation that can be intercepted is the direct-normal radiation times the cosine of the incidence angle.)

The "celestial sphere" is an imaginary sphere at an undefined distance from its center, the earth. It is a convenient device for locating celestial objects when their distance from earth is not important. Since the sun moving on the sphere has two degrees of freedom, only two angles are needed to specify the instantaneous position of the sun. The solar altitude and azimuth angles are used for this purpose. The solar azimuth angle is measured in the horizontal plane between the north/south line and the projection of the sun's rays onto the horizontal plane. The solar altitude angle is measured from the local horizontal plane upward to the center of the sun. The solar declination is the angle at noon on the equator between the overhead (zenith) direction and a line co-linear with the sun's rays.

The intensity of solar radiation on a surface depends upon the angle at which the sun's rays strike the surface. Concentrating collectors are particularly sensitive to the incidence angle, cosine optical effect. The **solar incidence** angle is the angle between the solar rays and the surface normal. Most concentrating collectors require some form of tracking to maintain the sun within their field of view and to minimize the incidence angle. Either one- or two-degree-of-freedom modes are used. Two-degree-of-freedom tracking maintains the collector aperture normal to the sun's rays so that the minimum incidence angle is zero. Single-axis tracking can involve either a horizontal, east/west axis or a horizontal, north/south axis of rotation. Also, a polar mount, which employs a north/south axis tilted up at an angle equal to the local latitude, can be used.

Finally, it is important to determine the availability of solar radiation at a potential solar thermal application site in order to determine the site's suitability and the ideal collector design. Often it is preferable to use historical radiation data, but this is not available for many sites. There are dozens of different types of instruments for measuring either solar radiation intensity or integrated solar energy over a given time interval. Beam or direct radiation is measured by a normal incidence pyrheliometer. Such measurements are directly applicable for focusing collectors that can use only the direct component of solar radiation. Diffuse radiation is measured in several ways, the most common of which uses a horizontal pyranometer.

Obtaining historical solar radiation data for many regions is difficult. Even though there are hundreds of locations in the United States with records of solar radiation measurements, many of these data records are brief — dating back only to the mid-1970s. There are about 100 U.S. sites that have more complete radiation measurement records. These records are more valuable because they permit compilation of long-term average amounts of solar energy available at that location.

This paper introduces the concept of the "ideal system" as a device for separating resource limits from system effects. It examines the limitations on ideal system performance arising from intermittency and discusses the relationship between real systems and ideal systems. Finally, it illustrates the general nature of the results of such an approach and of their implications for solar utilization.

Solar Radiation Energy Resources Atlas of the United States. (October 1981). SERI/SP-632-1037. Golden, CO: Solar Energy Research Institute; 174 pp. Oversized book plus microfiche insert.

The Atlas presents the geographical, seasonal (monthly), and diurnal (hourly, daily) distribution of the available solar radiation energy resources in the U.S., together with relevant meteorological data. The information is presented in the form of contour maps, graphical plots, and tables. The two data bases used to produce the Atlas are the SOLMET and ERSATZ solar radiation energy and meteorological data bases.

Knapp, Connie L.; Stoffel, Thomas L.; and Whitaker, Stephen D. (October 1980). *Insolation Data Manual*. SERI/SP-755-788. Golden, CO: Solar Energy Research Institute; 281 pp.

Long-term monthly averages of solar radiation, temperature, degree-days, and global R_T (the ratio of average global radiation to average daily extraterrestrial radiation on a horizontal surface) for 248 National Weather Service stations is presented. The information is based on both SOLMET and ERSATZ station data.

Solar energy availability based upon only a few years of data can be misleading since year-to-year variation can be great.

The National Weather Service (NWS) has been responsible for measuring and collecting most of the radiation data for the U.S. The records include data measured in many locations for widely varying periods of time and are archived by the National Climatic Data Center in Asheville, North Carolina. Many of the data are of questionable accuracy since pyranometer calibrations were not made frequently and the sensor response showed a loss of accuracy with time. The Center has rehabilitated some hourly and daily time-scale data for 55 sites for the period 1950-1975. In addition to historical data, synthetic data have been generated for approximately 220 sites using meteorological regression models. Both the historical and the generated data are available from the SOLMET data base, as well as data from ongoing collection efforts. The information from the SOLMET data base is available in several publications and from the National Climatic Data Center.

Optics of Solar Collection

Geometrical optics is used as the basic tool in designing almost any solar optical system. Optics can be thought of as the descriptive method that quantitatively predicts the interaction of a surface and a beam of incident solar energy. Radiation may either be reflected from, transmitted through, or absorbed by a substance. In solar conversion, special optical phenomena of interest are: (1) transmission through a transparent material; (2) reflection from a mirror-like surface; and (3) absorption of radiation by an absorbing medium.

The **transmission** of light through a smooth, homogeneous transparent medium, usually glass or plastic, with no internal scattering is the goal of transmissive optical materials. A material with good transmitting properties should have: (1) high transmittance of sunlight; (2) durability under lengthy exposure to sunlight and possible high temperatures; and (3) dimensional stability. The optical behavior of a substance can be characterized by two wavelength-dependent physical properties: (1) the index of refraction, and (2) the extinction coefficient. The index of refraction determines the amount of light reflected from a single interface; the extinction coefficient is the amount absorbed and scattered in a substance in the course of a single pass of radiation through the material.

The **reflection** of radiation from a surface may be specular or diffuse. In specular reflection the angle of incidence of a ray is equal to the angle of reflectance and is in the same plane. Specular reflection is the type encountered in focusing or concentrating solar collectors. In order for reflection from a surface to be totally specular, all surface microcharacteristics must be smaller than the wavelength of the radiation undergoing reflection. In the case of focusing solar collectors, this is usually ensured by using highly polished surfaces and vacuum-deposited metals.

Welford, W.T. and Winston, R. (1979). "Chapter 3. Principles of Optics Applied to Solar Energy Concentrators." *Solar Energy Handbook*. Edited by Jan F. Kreider and Frank Kreith. New York: McGraw-Hill Book Company; pp. 3-1 to 3-24.

After a discussion of the use of ray-tracing in optical design and analysis of solar devices, the basic designs and geometric optics of image-forming solar concentrators are reviewed. Some concepts of physical optics are introduced.

Meinel, Aden B. and Meinel, Marjorie P. (1977). "Part 2. The Optics of Solar Collection." *Applied Solar Energy; An Introduction*. Reading, MA: Addison-Wesley Publishing Company; pp. 117-260.

The five chapters in this section cover luminance of collector optics, refractive collector optics, mirror collector optics, fixed-mirror collectors, and optical surfaces.

Winston, Roland and Mlavsky, A.I., editors. (1977). *Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 114 Optics Applied to Solar Energy Conversion; San Diego, CA: 23-24 August 1977*. Bellingham, WA: Society of Photo-Optical Instrumentation Engineers; 96 pp.

Two of the four sessions deal with thermal solar energy utilization. The six papers presented in these sessions cover such topics as optical evaluation techniques, comparison of solar concentrating properties, and descriptions of several different types of collectors.

Wen, L.; Huang, L.; Poon, P.; and Carley, W. (November 1980). "Comparative Study of Solar Optics for Paraboloidal Concentrators." *Journal of Solar Energy Engineering*. Vol. 102 (No. 4); pp. 305-315.

A device that increases the flux at the absorber of a solar collector above ambient levels is called a concentrator. The concentration effect is accomplished by use of either reflecting or refracting elements which are located so that the solar flux is focused or funneled onto the receiver component. Line-focusing, single-axis collector types achieve a concentration multiplication in the range of 50. Point-focusing or dual-axis tracking solar collectors can concentrate the solar flux by about 4,000. Both line- and point-focusing collectors require relatively precise optical elements to maintain a sharp focus. Continuous tracking of the sun is required to maintain the focus.

Several terms encountered in the analysis of concentrators should be defined. The **concentration ratio** (CR) is the ratio of the aperture area to the absorber area. The **aperture area** is the area intercepting the radiation. The **absorber area** is the area receiving concentrated solar radiation. For the optically ideal concentrator with no losses, all radiation from the aperture enters the receiver zone. The **acceptance angle** is the angle over which solar radiation is to be collected during a period in which no collector tracking need be done.

The **absorption** of radiation to produce heat is accomplished by the receiver component of the collector system. The principal heat loss mode from high-temperature solar collectors is radiation, or radiative transfer, which occurs by the emission and absorption of photons in the infrared (IR) wavelength spectrum. In order to improve the solar thermal system's performance, it is important to lower the thermal emittance of the receiver surface while maintaining a high solar absorptance. When absorption is complete, there is no reflection. Such a body is called a perfect "black body." Total black body conditions are approached but never attained by experiment.

Absorption and emission generally increase with temperature. Since ability of a receiver to absorb the solar flux with little reflectance is greatly improved when a selective absorber coating is applied to the surface, higher temperatures can be a problem. Most selective absorber films, such as black chrome, are best used at temperatures below 300°C (570°F). Although research has been undertaken to develop high-temperature selective coatings, few selective absorber materials are available commercially.

Different analytical methods for computing the flux distribtion on the focal plane of a paraboloidal solar concentrator are reviewed. The effects resulting from using different assumptions in the definition of optical parameters used in these methodologies are compared and discussed in detail. The parameters include solar irradiance distribution, reflector surface specular spreading, suface slope error, and concentrator pointing accuracy.

Bendt, P.; Rabl, A.; and Gaul, H.W. (July 1981). *Optical Analysis and Optimization of Parabolic Trough Collectors; A User's Guide*. SERI/TR-631-602. Golden, CO: Solar Energy Research Institute; 24 pp.

The results of a detailed optical analysis of parabolic troughs are summarized by some universal graphs and curve fits. The graphs enable the designer to calculate the performance and optimize the trough's design with a simple hand calculator. The sensitivity of the optimization to changes in collector parameters and operating conditions is evaluated.

Look, D.C. and Sundvold, P.D. (1983). "Analysis of Concentrating Collectors of Energy from a Distant Point Source." *Solar Energy*. Vol. 31, (No. 6); pp. 545-555.

A procedure to analyze the energy leaving a point source, being reflected from one surface, and striking another was applied to focusing collectors. Specifically, it was applied to parabolic and circular cylindrical reflector surfaces for three different materials when the source was a function of wavelength. Besides finding the overall collector efficiency, the flux striking the receiver, the monochromatic collector efficiency as a function of wavelength, and the spatial collector efficiency as a function of the reflector position are presented also.

Sakurai, Takemaro and Shibata, Yukio. (1983). "Theoretical Concentration of Solar Radiation by Central Receiver Systems." *Solar Energy*. Vol. 31 (No. 3); pp. 261-270.

The purpose of the article is to present a general theory of solar concentration by central receiver systems in order to be able to compare the performance characteristics of ideal and practical cases. The solar concentrators have been calculated for various values of obliquity of the incident radiation, assuming that plane heliostat-mirrors sufficiently small in dimension, cover a circular field without clearance. Through this calculation, the performance characteristics of this system such as the availability of the radiant energy incident on the heliostat-field, the distribution of interruption by an adjacent mirror, the optimum rim-angle for the mean area- and mean volume-concentration, and the attainable temperatures were revealed.

Call, P.J.; Jorgensen, G.T.; and Pitts, J.R. (August 1981). "The Effect of Receiver Optical Properties on Solar Thermal Electric Systems." *Journal of Solar Energy Engineering*. Vol. 103 (No. 3); pp. 207-212.

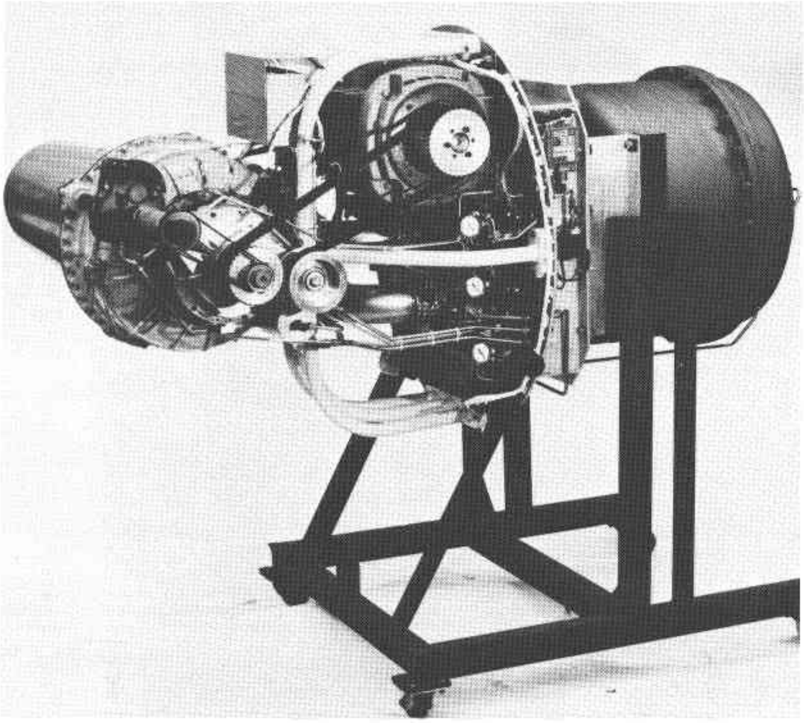
The importance of reducing the thermal emittance of the receiver surface on the cost-effective operation of intermediate and high-temperature (greater than 400°C) solar thermal electric power plants is discussed. Computer codes for seven systems (point- and line-focus) are used to independently determine optimum operating conditions for selective and nonselective receiver surfaces.

Thermodynamics

The design and analysis of all solar thermal systems requires familiarity with the fundamentals of thermodynamics and heat transfer. Whenever a temperature difference exists, energy may be transferred from the region of higher temperature to the region of lower temperature. According to thermodynamic concepts, the energy which is transferred as a result of a temperature difference is called "heat." Thermodynamic laws can predict the amount of energy required to change a system from one equilibrium state to another, but they cannot predict how fast these changes will occur. The engineering science of heat transfer supplements the first and second laws of thermodynamics by providing methods of analysis that can be used to predict rates of energy transfer as well as temperature distribution.

One of the unique and technically most attractive feature of solar energy from a thermodynamic viewpoint is the feasibility of matching different means of collection to applications requiring a broad range of temperatures. The laws of thermodynamics are able to quantitatively describe this feature of solar energy and provide the means of solar energy collection to the task to be performed.

A common measure of the efficiency with which energy is used is so-called first law efficiency. The first law efficiency is defined as the ratio of useful energy output to the quantity of energy input into a device.



Brayton Cycle Engine; Garrett Turbine Engine Co.

Kreider, Jan F. (1979). "Chapter 3. Selected Topics in Thermodynamics and Heat Transfer for Elevated-Temperature Solar Processes." *Medium and High Temperature Solar Processes.* New York: Academic Press; pp. 63-99.

The first section of this chapter is concerned with discussing the basic principles of engineering thermodynamics. The first and second law efficiencies are defined, the thermodynamic availability of sunlight is described, second law efficiencies of common thermal processes are outlined, and thermodynamics of heat engines is summarized.

Meinel, Aden B. and Meinel, Marjorie P. (1977). "Chapter 14. Thermodynamic Utilization Cycles." *Applied Solar Energy; an Introduction.* Reading, MA: Addison Wesley Publishing Company; pp. 489-525.

The chapter discusses the conversion of solar heat into work by means of three thermodynamic cycles: (1) the Rankine cycle, (2) the Brayton cycle, and (3) the Stirling cycle.

Adler, Carl G.; Coulter, Byron L.; and Byrd, J. William. (1981). "Thermodynamic Limits of Solar Thermal Power." *Proceedings of the 1981 Annual Meeting of the American Section of the International Solar Energy Society; Philadelphia, PA; 26-30 May 1981.* Edited by Barbara H. Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 386-390.

A method to analyze central receiver power plant operation under both steady-state and cyclic conditions is presented. The approach used does not assume a simple Carnot efficiency, but addresses the question as to what penalties accrue for deviation from the ideal. The independent impact of the thermodynamic properties of the working fluid on predicted efficiencies is analyzed also.

The second law of thermodynamics provides a means of assigning a quality index to energy. The concept of available energy (i.e., energy available to do work) provides a useful measure of energy quality. Using this concept, it is possible to analyze means to minimize the consumption of available energy to perform a given process, thereby ensuring the most efficient possible conversion of energy for the required task.

Using the concept of availability, it is possible to define a second law *efficiency* of a process as the ratio of the minimum available energy which must be consumed to do a task divided by the actual amount of available energy consumed. It is more useful in identifying optimal energy conversion processes than the first law efficiency since it focuses attention on device interactions that transform radiant energy into work and heat.

Heat engines are used in solar electricity production, solar pumping, solar cooling, and other applications requiring shaft drive. Three thermodynamic cycles often considered for solar applications are the Brayton cycle, Stirling cycle, and the Rankine cycle. The Carnot cycle operates at the maximum efficiency permitted by the second law of thermodynamics and is the ideal by which the other cycles are compared.

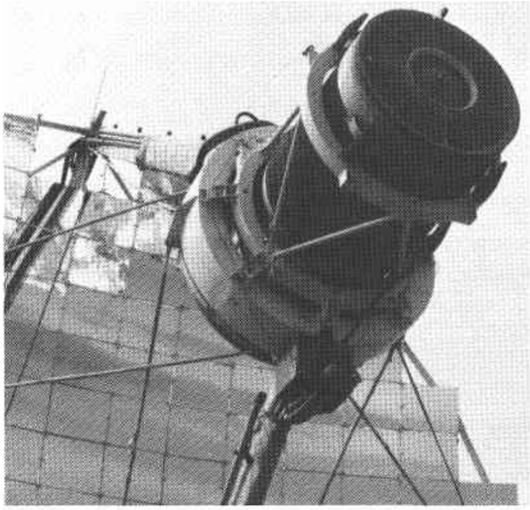
The Rankine cycle is familiar as the cycle on which most steam turbines operate, and the Brayton cycle is familiar as the cycle of an aircraft jet engine. The fundamental difference between the two is that the Rankine cycle accomplishes the compression stage with the working medium in the liquid state, the heat causing the fluid to go through a phase change before or as it enters the expansion stage of a turbine. The Brayton cycle always works with a gaseous medium, compressing it, adding heat, and expanding it through the turbine. The Stirling cycle, unlike the others, is not widely used, but its efficiency makes it desirable for use in solar applications.

The Brayton or gas turbine cycle uses two constant pressure steps. The working fluid is compressed isentropically to the point where heat addition at constant pressure occurs. Work is produced by an isentropic expansion to lower pressure followed by constant pressure heat rejection. The gas turbine cycle is usually operated as an open cycle where gas is exhausted to the atmosphere and fresh air is inducted into the turbine. Heat addition occurs by means of solar heat addition (via a heat exchange) or fuel combustion in the burner after compression.

The Stirling cycle engine utilizes *isothermal* heat addition expansion followed by a constant volume regenerative cooling process. Heat is then rejected in an isothermal compression followed by regenerative heating. Heat transfer to and from the regenerator is completely within the heat engine. Since heat exchange within the generator is slow, Stirling cycle engine speed is slow unless substantial heat transfer areas are used.

Steam turbines used for power of electricity production operate in the Rankine cycle. The Rankine cycle can be considered as a modified, vapor-phase Carnot cycle with the

Testing Stirling Engine on Parabolic Dish



Organic Rankine Cycle Engine Under Test at Parabolic Dish Test Site substitution of a liquid-phase pump for the Carnot cycle vapor compressor. For practical reasons, the cycle is rarely operated solely in the vapor phase.

Two counteracting phenomena are present in solar-powered engine systems. The efficiency of a heat engine increases as the input fluid temperature increases, whereas the efficiency of a solar collector decreases with outlet temperature. A system first law efficiency can be defined as the product of collector and engine efficiency such that the efficiency first increases with collector temperature, then decreases as collector heat losses overwhelm thermodynamic gains owing to progressively higher engine inlet temperature. Real engines have lower efficiency values than the theoretical limit for several reasons: (1) real fluids must be used with associated thermodynamic penalties, (2) turbines and pumps are not perfect, and (3) thermal and mechanical losses occur in piping and all components of the system.

Heat Transfer

Heat transfer occurs by three basic mechanisms: (1) radiation, (2) conduction, and (3) convection. Conduction is the only heat transfer mode in opaque solid media. When a temperature gradient exists in such a body, heat will be transferred from the higher to the lower temperature region. The rate at which heat is transferred by conduction is proportional to the temperature gradient times the area through which heat is transferred.

When a fluid comes in contact with a solid surface at a different temperature, the resulting thermal energy exchange process is called convective heat transfer. There are two kinds of convection processes: (1) natural or free convection, and (2) forced convection. In the first type, the motive force is the density differences in the fluid which result from its contact with a surface at a different temperature and gives rise to buoyant forces (when the surface is at a higher temperature than the ambient fluid). An example of free convection is the heat transfer between the wall or roof of a house and the surrounding air. Forced convection occurs when an external force moves a fluid past a surface at a different temperature than the fluid's. Since the fluid velocity in forced convection is usually higher than in free convection, more heat can be transferred at a given temperature difference.

Thermal radiation is a form of electromagnetic energy, and all bodies emit thermal radiation by virtue of their temperature. Radiation transfer occurs by the emission and absorption of photons. Photon energy is related to the frequency of radiation, and the radiation emitted by a body usually encompasses a range of wavelengths. Radiation transfer increases in proportion to the difference between the fourth power of the body temperature and the fourth power of the background temperature. Therefore, the principal heat loss mode from very high-temperature solar receivers is radiation (in the infrared wavelength spectrum).

Kreider, Jan F. (1979). "Chapter 3. Selected Topics in Thermodynamics and Heat Transfer for Elevated-Temperature Solar Processes." *Medium and High Temperature Solar Processes*. New York: Academic Press; pp. 63-99.

The majority of this chapter is devoted to principles of heat transfer. Conduction, convection, radiation, and combined heat transfer modes are examined. The emphasis is on topics of special concern to high-temperature solar collectors. (It is assumed that the reader is familiar with the basic principles of heat transfer.)

Meinel, Aden B. and Meinel, Marjorie P. (1977). "Chapter 10. Basic Elements of Heat Transfer," and "Chapter 11. Heat Transfer in Solar Collectors." *Applied Solar Energy; an Introduction*. Reading, MA: Addison-Wesley Publishing Company; pp. 316-412.

Chapter 10 reviews the aspects of thermodynamics and heat transfer that impact solar applications in general. Chapter 11 analyzes the thermal behavior of several types of solar collector systems.

Falcone, P.K. (October 1981). *Convection Losses from Solar Central Receivers; Proceedings of a DOE/SERI/SNLL Workshop*. SAND81-8014. Albuquerque, NM: Sandia National Laboratories; 190 pp.

Fifteen papers cover research into convection losses as an important part of the energy lost from solar central receivers.

The three modes of heat transfer described above rarely exist independently. In most solar thermal systems all three modes are present. For example, hot fluid in a pipe loses heat to its environment by convection and conduction to the pipe wall, conduction through the insulation, and radiation and convection from the external surface of the pipe. Methods used to calculate the magnitude of these heat losses for various conditions can also be used to predict the performance of the concentrator system. Parameters specific to a given collector must also be included in measuring system performance. These other parameters include optical efficiency, collector aperture area, absorber and envelope infrared emittances, fluid flow rate and inlet temperature, mirror reflectance, envelope absorptance and outside diameter, absorber outside diameter, convection coefficient, and local insolation and temperature.

Energy Storage

Energy storage is present in most solar systems to provide a means for meeting typically steady energy demands required by most applications. Although the cost and added system complexity arising from the addition of storage may be completely eliminated if solar is used only in a "fuel-saver" mode, the use of at least short-term storage to bridge brief periods of inadequate insolation caused by cloud passage is usually desired.

There are four basic types of energy storage: (1) thermal, (2) electrical, (3) mechanical, and (4) chemical. Thermal energy can be stored as sensible heat, latent heat or phase change, or in reversible chemical reactions. Electrical energy is usually stored electrochemically in batteries. Mechanical energy can be stored inertially as kinetic energy in flywheels or as potential energy in compressed air or elevated liquids. Hydrogen, perhaps the chemical storage form of most interest for solar applications, may be stored as a compressed gas, a cryogenic liquid, a hydride, or with fixed nitrogen as liquid ammonia or urea. These four modes of storage can be integrated into solar energy systems in various ways to produce heat, cold, electrical and mechanical power, and hydrogen fuel or feedstock.

Since the initial form of energy produced by thermal energy systems is heat, thermal energy storage is the type most often considered for use with concentrating systems. Thermal storage materials must meet several basic criteria, including high storage energy density; good durability under many thermal cycles; high longevity of stored energy; second law match of storage to application; appropriate storage configuration for efficient heat input and extraction; low cost; low toxicity, flammability; vapor pressure, and chemical reactivity; and low-volume expansivity.

Sensible heat storage in solid media can be an effective method of storage for high-temperature processes. Most solids have desirable energy density values. However, since many solids that are economically viable for thermal storage have relatively small conductivity values, a large surface-to-volume

Bruckner, A.P. and Hertzberg, A. (December 1982). *High Temperature Integrated Thermal Energy Storage System for Solar Thermal Applications; Final Subcontract Report*. SERI/STR-231-1812. Golden, CO: Solar Energy Research Institute; 116 pp.

A novel, high-temperature (1400° C) solar thermal energy storage system that uses molten slag as the storage medium is analyzed and the conceptual design and experimental work is described.

Copeland, R.J. (April 1980). *Preliminary Requirements for Thermal Storage Subsystems in Solar Thermal Applications*. SERI/RR-731-364. Golden, CO: Solar Energy Research Institute; 209 pp.

Methodologies for the analysis of value and comparing thermal storage concepts are presented. Buffer, diurnal, and baseload storage values are analyzed. Necessary data to use the methodology are included.

Kriz, Thomas A. and Swet, C.J. (August 1982). *Solar Storage for Process Heat and Building Application: A Review of Prior Assessments*. SERI/TR-231-1595. Golden, CO: Solar Energy Research Institute; 113 pp.

The technical and economic viability of energy storage is assessed in this critique of 80 reports on storage for building and water heating and cooling, and 13 reports on storage for process heat applications. The essential findings and types of systems studied are examined for each report.

Swet, Charles J. (1981). "Chapter 6. Energy Storage for Solar Applications." *Solar Energy Handbook*. Jan F. Kreider and Frank Kreith, editors. New York: McGraw-Hill Book Company; pp. 6-1 - 6-35.

The chapter describes and analyzes the various forms of energy storage including thermal storage as sensible and latent heat; storage in reversible chemical reactions; mechanical energy storage; electrochemical storage; and hydrogen storage.

"Thermal Energy Storage," and "Energy Storage with Phase Change Materials." (1983). *Alternative*

ratio is needed for efficient heat transfer. In most cases a packed bed of uniformly sized particles is used for this reason. Particle beds also have a desirable property in that significant temperature stratification can be achieved which allows energy to be extracted at high temperature and high thermodynamic availability.

Phase-change, or latent-heat, media are compact, high energy density materials. The principle behind this type of storage is that a material can gain or lose heat by isothermal phase change between solid and liquid (heat of fusion), liquid and vapor (heat of vaporization), or solid crystalline phases (heat of solid-solid transition). Phase-change media have considerable promise for solar thermal storage at elevated temperature if several criteria are met: (1) high latent heat of fusion, (2) appropriate melting point, (3) high thermal diffusivity and conductivity, (4) low volume expansivity, (5) low cost, (6) negligible chemical reactivity, (7) low vapor pressure and toxicity, and (8) minimal maintenance.

Metallic fluorides are a promising material. Not only do they have high energy densities at a range of temperatures ideally suited for high-temperature thermal storage, but metallic fluorides are also excellent storage media from a thermodynamic viewpoint. The availability of heat stored at 400°C-800°C (750°F-1500°F) is high and is well matched to high performance solar collector requirements and heat-engine conversion to shaft work. Several salt hydrates can be used at moderate temperatures as storage media. However, some experience a fundamental problem — the deterioration of the freeze-thaw cycle repeatibility. Even if the cycle repeatibility problem can be solved, economic costs may negate the energy-density advantage of phase-change materials.

The required match between the solar energy source and the task, or load, is an important criterion in the selection of storage size and type. If large excursions in storage temperature are permitted, then sensible-heat storage may be used. If delivery to load must be in a narrow temperature range, then isothermal phase-change storage or a secondary heat exchanger with flow control may be required.

Energy Sources III. Edited by T. Nejat Veziroglu. Washington, DC: Hemisphere Publishing Corporation; V. 1, pp. 175-413.

The 14 papers presented in these two sections are from the Third Miami International Conference on Alternative Energy Sources held December 15-17, 1980 in Miami Beach, Florida.

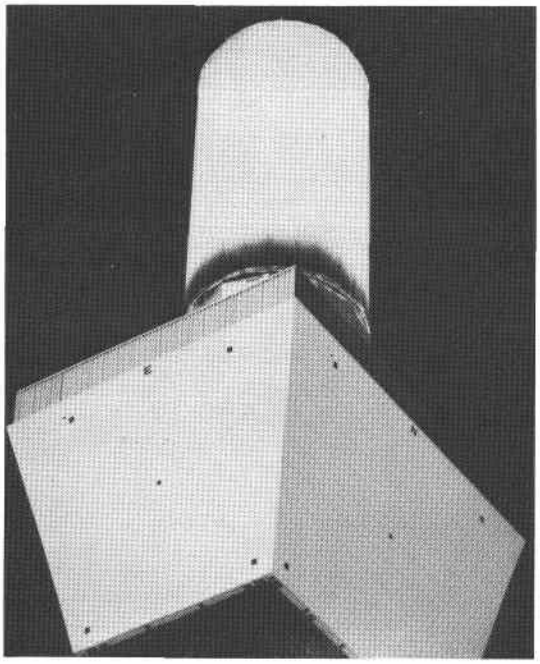
Chapter 3
Central Receiver Technology

Central Receiver Systems

One of several solar thermal concentrating collector technologies under development by the U.S. Department of Energy, solar central receiver power systems, is a promising way to harness solar thermal energy for large-scale applications. In a central receiver system, a field array of sun-tracking mirrors (heliostats) reflect sunlight onto a receiver located on a tower, heating a fluid that circulates within the receiver. The resulting thermal energy, often at temperatures above 500°C (930°F) can be used directly or indirectly for process heat in industrial or agricultural applications, or for driving a turbine to produce electrical power.

The principal advantage of central receiver systems over other solar systems is their ability to produce energy at high temperatures and favorable costs in large centralized installations. In particular, central receivers have the ability to transport energy optically, at low loss to a common point. However, since the amount of solar energy incident on the collector area varies with weather and time of day, the energy output of the central receiver system also varies. Central receivers are able to store energy inexpensively as sensible heat to extend plant operation, which can be an advantage over other solar electric technologies.

The basic configurations of solar central receiver systems are solar stand-alone and hybrid solar-fossil. Operation of a solar



Solar Central Receiver Power Tower

Battleson, K.W. (April 1981). *Solar Power Tower Design Guide: Solar Thermal Central Receiver Power Systems, a Source of Electricity and/or Process Heat.* SAND81-8005. Albuquerque, NM: Sandia National Laboratories; 170 pp.

The information necessary to perform preliminary evaluations of whether a solar thermal central receiver plant is technically and economically feasible, as well as desirable, for the potential user's application is provided. The cost elements, performance, and operation of solar central receiver systems are described.

Hildebrandt, A.F. and Dasgupta, S. (May 1980). "Survey of Power Tower Technology." *Journal of Solar Energy Engineering.* Vol. 102, (No. 2); pp. 91-104.

The article reviews (1) the history of the power tower program, (2) state-of-the-art in heliostat, receiver, and storage design, (3) system economics, (4) simulation studies and implications, (5) alternate applications for the power tower, and (6) some financing and energy aspects of solar electric conversion.

Hildebrandt, A.F. and Laurence, C.L. (April 1981). *Solar Technology Assesment Project Volume IX: Heliostat Systems: Technical and Economic Assessment.* Cape Canaveral, FL: Florida Solar Energy Center; 88 pp. Work performed by University of Houston, Houston, TX.

This report provides a review of the literature on heliostat systems including subsystem design and research experiments; full-scale system designs; assessments, evaluations, rankings, application and marketing studies; and heliostat manufacturing studies. The report also reviews and assesses the current status of heliostat system development, examines recent design reports, reports expected economic and performance improvements, and recommends state and federal policies for solar commercialization.

Fallerico, L.N. (April 1980). *A Description and Assessment of Large Solar Power Systems Technology.* SAND79-8015. Livermore, CA: Sandia Laboratories; 158 pp.

An overview of present large solar thermal central receiver power system technology is provided with emphasis on systems using thermal storage. Included are the technical concepts upon which the systems are based and estimated cost, performance, and assessment of typical systems. Sandia Laboratories assessments of the strengths and weaknesses of each technology are included also.

stand-alone system is dependent entirely on solar input. The addition of a fossil heat source in a hybrid plant increases the plant's operational flexibility. Both configurations can be coupled with thermal storage which buffers weather-caused interruptions and can extend plant operations beyond sunset.

Solar thermal central receiver energy conversion systems are comprised of several subsystems, two of which — heliostats and receivers — are unique to solar power plants. These subsystems, as well as others concerned with heat transport, thermal energy storage, engines and power converters, and controls, are discussed in more detail in the following sections.

Department of Energy Solar Central Receiver Annual Meeting; Claremont, CA; 13-15 October 1981. (February 1982). SAND82-8002. Albuquerque, NM: Sandia National Laboratories; 320 pp.

Thirty-five papers were presented at the annual meeting and organized into two sessions: (1) Systems, and (2) Component Development. Some of the following topics were covered: overview of the federal program; descriptions of Solar One, Themis, Small Solar Power Systems Project (SSPS); repowering and cogeneration projects; financing of central receivers; and reports on new developments in receiver and second-generation heliostat technology.

Kreith, Frank and Meyer, Richard T. (November-December 1983). "Solar Thermal Central Receiver Energy Conversion." *American Scientist.* Vol. 71 (No. 6); pp. 598-605.

The basic principles of central receiver technology are described and its potential as a source of high-temperature heat for electric energy and industrial processes is discussed. In addition, the environmental impacts and siting requirements of central receivers are summarized.

Components and Subsystems

Heliostats

The collector or heliostat subsystem consists of a large array of individual heliostats focused onto a tower-mounted receiver while tracking the sun to achieve a solar concentration of 500 or more. Several optical factors have to be evaluated in the design of a heliostat field, including the geometric shape of the field, the distribution of heliostats within the field, the shadowing and blocking of heliostats by other heliostats, the irradiance from each mirror, the irradiance from the entire array, and the effects of mirror waviness, surface specularity, curvature, and tracking errors. The various geometric, optical, and redirected energy intensity factors typically may limit the radius of the heliostat field to about 5-7 times the tower height. Typical electrical power design applications have concentration ratios of 200:1 to 1000:1, and tower heights of 65-150m (213-492 ft).

The main element of this subsystem is the heliostat itself. A heliostat is comprised of the following elements: a reflective surface or mirror, mirror support structure, drive mechanism, pedestal, foundation, and heliostat controller. The balance of the collector subsystem also includes the wiring and system controls.

The reflecting element of a typical glass heliostat is a mirror similar to a household mirror. Current designs have reflective areas of 430-650 ft^2. For ease of manufacture and transportation, the reflecting surface has several panels rather than a single large mirror. The glass is relatively thin and has a low iron content in order to minimize the absorption loss of the light in passing through the glass. The thin glass must be supported to form a flat or slightly concave mirror surface. The panels, when assembled into a heliostat, are canted

Bammerot, R.B. and Lawrence, C.L. (November 1980). "A Design Method for Optimizing Collector Systems for Small Solar Central Receivers." *Journal of Solar Engineering.* Vol. 102 (No. 4); pp. 240-247.

The design methodology for the determination of the optimal heliostat field layout or placement is presented in detail for a small solar central receiver. The optimization process is reviewed and cost and performance models discussed.

Second Generation Heliostat Evaluation: Summary Report. (January 1982). SAND81-8034. Albuquerque, NM: Sandia National Laboratories; 54 pp.

The Second Generation Heliostat Development Program is the second major heliostat development cycle in DOE's Solar Thermal Central Receiver Program. Five heliostat designs were evaluated and four were found to be viable with unique approaches to the same generic design. The report briefly describes the designs, summarizes test results and cost estimates, and discusses designcomparisions. A complete listing of all the individual second generation heliostat reports is supplied.

Murphy, L.M. (May 1983). *Technical and Cost Benefits of Lightweight, Stretched-Membrane Heliostats.* SERI/TR-253-1818. Golden, CO: Solar Energy Research Institute; 41 pp.

The report contains a description of a novel, lightweight, heliostat reflective module and support structure called the stretched-membrane concept. Anticipated engineering and system benefits of the stretched-membrane concept and analytical and testing rationale supporting these anticipated benefits are reviewed.

slightly with regard to each other to focus the sun's light. Canting of the panels varies throughout the field and depends on the heliostat-to-receiver distance.

Several designs have been used to support the mirror panels. These supports typically are attached to a torque tube or box beam that is bolted to a gearbox or similar mechanical actuator. The gearbox provides rotation of the mirror panel assembly about vertical and horizontal axes. The gearbox is supported by a pedestal rising 10-16 ft above the ground. The choice of foundation/pedestal design may be determined by site soil conditions and installation economics. The field wiring for control signals and power to the heliostat is trenched into the ground.

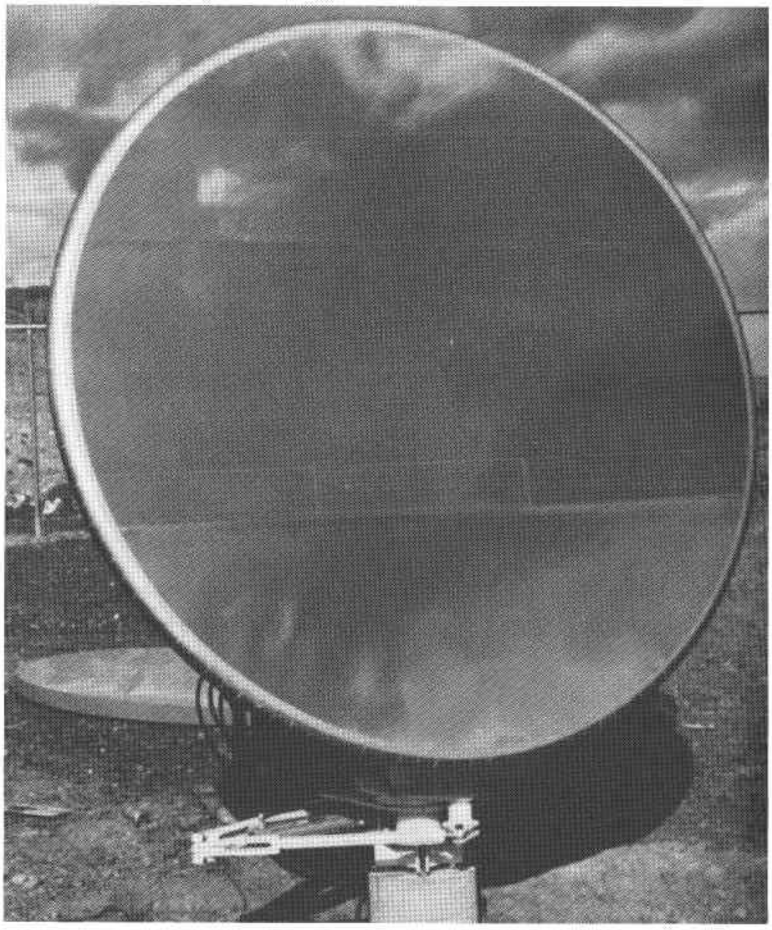
Heliostats are arranged typically in a radial staggered array which reduces land usage and minimizes blocking of reflected light. The heliostats are tightly packed near the tower with just enough separation to prevent mechanical interference. For heliostats located farther from the tower, the spacing increases in order to minimize blocking of the reflected beams. The shape of the optimum heliostat field is a function of the power level of the plant. In the continental U.S. the noontime sun is always south of the tower; thus, for small plants, a field of heliostats north of the tower is usually the most cost-effective. As plant size increases, the attenuation of the atmosphere becomes sufficiently large for the most distant north-field

King, D.L. and Arvizu, D.E. (May 1981). "Heliostat Characterization at the Central Receiver Test Facility." *Journal of Solar Energy Engineering*. Vol. 103 (No. 2); pp. 82-88.

This paper summarizes the work that led to the current state of heliostat evaluation capability. It includes a description of the CRTF heliostat, measurements of environmental degradation of mirror reflectance, heliostat beam measurements with an instrumented sweeping bar, beam quality and tracking accuracy data, and comparisons of measured beam data with the heliostat computer model HELIOS.

Brandt, L.D. (November 1980). *A Strategy for Heliostat Commercialization*. SAND80-8239. Albuquerque, NM: Sandia National Laboratories; 47 pp.

Commercial viability of the solar central receiver technology depends, in part, on the availability of low-cost, mass produced heliostats. This study recommends a path for developing an industry capable of producing such heliostats. Conclusions are drawn mainly from discussions with firms involved in the heliostat research and development program.



Stretched Membrane Collector Concept

heliostats that the performance of the plant can be improved by locating heliostats first to the east and west of the tower and then eventually to the south.

The heliostats represent the most expensive subsystem in a central receiver plant. Research and development has emphasized designs and materials that will increase durability and reflectivity while reducing costs. Alternatives to silver-backed glass, such as metallized polymers, are also under investigation. Four second-generation heliostat designs have recently been developed and tested. The goal for these heliostats is to improve the cost/performance ratio of the first-generation heliostats through technical advances and mass production techniques.

Receivers

Although the heliostat subsystem represents the greatest cost factor in central receiver applications, the receiver subsystem introduces the greatest technical challenge. The purpose of the receiver subsystem is to intercept and absorb the concentrated solar radiation reflected from the collector subsystem and to transfer most of it to the heat transport fluid. The solar receiver's efficiency and operating temperature directly affect the performance of the entire system. Since the receiver comes between the concentrator and the power conversion or thermal process subsystem, its design requirements cannot be separated from the specific application and system configuration. The required characteristics of a particular solar receiver are determined by the temperature and pressure needed by the power conversion or thermal process subsystem, the heat transfer characteristics defined by the working fluid, the mechanical configuration of the solar system, the optical characteristics of the concentrator, and by the available materials. In general, the requirements would be to maximize efficiency, provide a lifetime of about 20-30 years with minimum maintenance, and design for acceptable cost of mass production.

Many designs have been developed for different configurations and heat transport fluids. There are two basic types of receivers: (1) external, and (2) cavity. The most suitable configuration is selected for a given application on the basis of system level trade-off studies that include considerations of the working fluid and its desired inlet and outlet temperatures, the incident solar flux, the field layout, the thermal efficiency of the design, and the cost and weight of the receivers. In addition, the thermal performance of a receiver depends on design trade-offs among the following energy loss mechanisms: spillage, reflection, and heat loss through convection or radiation.

Mounted atop a tower, the receiver heat-absorbing surfaces are generally similar to those of a fossil-fueled boiler; panels are made up of tubes arranged in parallel and welded to headers at each end. External receivers have heat-absorbing panels that are flat or convex toward the heliostat field for smaller plants or cylindrical in shape for large plants. In general, external receivers are smaller, lighter, less expensive,

Boese, F.K.; Merkel, A.; Stahl, D.; and Stehle, H. (1981). "A Consideration of Possible Receiver Designs for Solar Tower Plants." *Solar Energy*. Vol. 26, (No. 1); pp. 1-7.

The goal of this paper is to discuss some of the main receiver properties to be considered in designing a central receiver system. The 500 kW IEA central receiver plant in Almeria, Spain serves as an example. Considerations concerning the optimum geometry as well as thermodynamic behavior are described.

Kudirka, A.A. (February 1983). "Ceramic Technology for Solar Thermal Receivers." *Journal of Solar Energy Engineering*. Vol. 105 (No. 1); pp. 73-79.

Candidate ceramic materials for solar receivers and characteristics are described, potentially applicable fabrication and processing methods are discussed, and their applicability and promise for solar receivers is assessed. Current ceramic receiver development status and plans are described, including one receiver that has been tested successfully at gas exit temperatures of up to 1415°C.

Durrant, O.W.; Capozzi, T.J.; and Best, R.H. (August 1982). "The Development and Design of Steam/Water Central Solar Receivers for Commercial Application." *Journal of Solar Energy Engineering*. Vol. 104 (No. 3); pp. 173-181.

A receiver design that can be assembled in various sizes, capacities, and geometrics is described. Special design features to overcome the unbalance of north-to-south field flux ratios, effect of partial and transient cloud patterns, and many thermal cycles are also described.

Pomeroy, B.D.; Roberts, J.M.; and Narayanan, T.V. (February 1981). "High-Flux Solar Absorber Concept for Central Receiver Power Plants." *Journal of Solar Energy Engineering*. Vol. 103 (No. 1); pp. 52-55.

An external absorber concept that uses liquid sodium coolant and a three-header configuration is described. The mechanical design of this absorber is discussed and thermal performance estimates are presented showing the solar-capture efficiency over a range of solar intensities.

and require less accurate steering and less optical precision for the heliostat systems since their interception area is larger. However, thermal losses are greater for external receivers, and they become less efficient as the operating temperature increases.

In a cavity receiver, the solar radiation reflected from the heliostat passes through an aperture in the receiver before it strikes the heat transfer surfaces, which are tubular panels similar to those of external receivers. The internal heat transfer area of a cavity receiver can be two or three times as great as that for an external receiver.

Minimizing the energy loss from the receiver is important. Cavity receivers have less thermal loss because each beam that enters the cavity is reflected internally many times before it can escape and the area for convection loss is small. Because of the small aperture size, cavity receivers require greater mirror accuracy and spillage is usually more significant than for external receivers. The choice of external or cavity receiver design is based ultimately on minimizing the total system cost per unit of energy delivered to the working fluid.

One concern for further research and development is heat loss mechanisms that are not well characterized for objects as large as receivers. The effects of intermittent sunlight, single-side heating of receiver tubes, and creep fatigue need further investigation also. Finally, materials and fabrication processes will need to be selected to yield more cost-effective designs.

Thermal Storage

An energy storage subsystem is necessary to maintain plant output at a constant level despite insolation variations. Storage can also be used to extend plant operation into non-solar hours, although fossil-fuel back-up systems are presently considered a more cost-effective method. Energy storage concepts that first require electrical generation (e.g., pumped water, compressed air, flywheel, or battery storage) do not fulfill the basic requirement of buffering the turbine from solar insolation variations; therefore, thermal energy storage (TES) is preferred for this purpose.

Thermal storage concepts can be classified into three categories: (1) sensible-heat, (2) latent-heat (phase change), and (3) thermochemical (reversible chemical reactions). Of these, sensible heat storage presently is the most practical method. Both latent-heat and thermochemical storage systems require additional development before they can be evaluated in detail and considered for implementation on a large scale.

Two basic types of sensible heat storage are commonly used with central receiver systems: (1) separate hot and cold storage tanks, or (2) a single tank with a thermocline temperature gradient. Both systems store the energy absorbed by the heat transport fluid as it passes through the receiver. The stored energy is then extracted when needed by pumping the hot fluid from storage either directly to the electrical generation system or industrial process, or to an intermediate heat exchanger.

Bruckner, A.P. and Hertzberg, A. (December 1982). *High Temperature Integrated Thermal Energy Storage System for Solar Thermal Applications*. SERI/STR-231-1812. Golden, CO: Solar Energy Research Institute; 116 pp. Work performed by Aerospace and Energetics Research Program, University of Washington, Seattle, WA.

Analysis, conceptual design, and experimental work for a high-temperature solar thermal storage system that uses molten slag as the storage medium are described. Sensible heat is extracted from the molten slag in a direct-contact droplet heat exchanger. Capital cost and present worth revenue requirement data are developed from a 10-MWe central receiver electric power system for 1, 6, 15, and 48-hr storage.

Copeland, R.J. (April 1980). *Preliminary Requirements for Thermal Storage Subsystems in Solar Thermal Applications*. SERI/RR-731-364. Golden, CO: Solar Energy Research Institute; 209 pp.

Methodologies for the analysis of value and comparing thermal storage concepts are presented in this report. Value data for thermal storage in large solar thermal electric power applications are described and a ranking index to compare thermal storage concepts performing the same mission is derived.

Faas, S.E. and Peila, W.C. (1983). "Thermal Storage Experience at Solar One and the Molten Salt Thermal Energy Storage Subsystem Research

Hot tank/cold tank storage uses two (or more) tanks in which the fluid in each is at a uniform temperature and the fluid level changes as thermal energy is added or withdrawn from storage. The storage medium flows from the hot tank through a heat exchanger, where the energy is transferred to the turbine working fluid, and then into the cold tank. Hot tank/cold tank systems are applicable to sodium, nitrate salt, or oil storage fluids. This approach is less sensitive to instabilities, but is more expensive than a single tank.

A thermocline storage system relies on temperature stratification within a single tank to provide containment for both the hot and cold storage fluid. The operation of the system depends on the relatively poor thermal conductivity of the storage medium to maintain the stability of the thermal gradient. For thermoclines using only liquid, the density difference between the hot and cold fluid allows the hot liquid to float atop the cold liquid. The use of a solid material in the tank, such as rock, can provide for increased volumetric storage energy density in two ways: (1) reducing the amount of costly liquid needed, and (2) impeding the mixture of the hot and cold fluid.

The storage system selected for the Barstow pilot plant is a rock/oil thermocline system. If air is used as the heat transport fluid, then thermocline energy storage may be established in a porous solid medium, such as brick or rock. During operation, energy is stored by removing cold fluid from the bottom of the tank, heating it either directly in the receiver or through an intermediate heat exchanger, and returning the hot fluid to the top of the tank. For heat extraction the direction of the storage fluid flow is reversed and sent to the load.

Studies on latent-heat storage systems have focused on liquid-solid phase changes, making use of the heat of fusion. In particular, several technology development and system studies have been conducted on latent-heat storage using inorganic salt phase-change materials (e.g., carbonates, chlorides, fluorides, hydroxides, and nitrates). In general, results have shown the advantages of latent-heat systems in providing high energy storage densities and availability of stored latent-heat at nearly constant temperatures. However, three of the major problem areas in such systems are: (1) designing to accommodate the volume change upon phase transition, (2) ensuring that the system will maintain a clean transition between solid and liquid without long-term changes in the structure and composition, and (3) preventing solid-buildup on heat-transfer surfaces.

Chemical storage systems also have been the subject of extensive research and development. Their theoretical energy densities and amenability to ambient temperature storage make chemicals an attractive storage medium. However, the high power-related costs, due to system complexity and efficiencies, (significantly lower than those expected for sensible-heat systems) make thermochemical-storage systems less competitive than sensible-heat systems.

Experiment." *Proceedings of the 18th Intersociety Energy Conversion Engineering Conference (IECEC); Orlando, FL: 21-26 August 1983.* New York: American Institute of Chemical Engineers; V. 4, pp. 1762-1768.

Preliminary information concerning construction and performance of two thermal storage systems is discussed in this paper. One system is the dual-media (oil/rock) thermocline storage system, a first-generation storage technology, constructed in 1982 at Barstow, California. The other system, also constructed in 1982, is an engineering prototype molten nitrate salt, single-medium, dual-tank storage unit. This latter system, located in Albuquerque, New Mexico, represents a second-generation storage technology.

Heat Transport and Exchange

A major distinguishing characteristic between central receiver systems is the type of heat transport fluid used to deliver the thermal energy from the receiver to the electrical power generation, industrial process, or storage subsystem. In fact, receivers are commonly identified according to their working fluids; e.g., molten salt receiver. The type of working fluid is also an important factor in thermal storage subsystems. At present, six heat transport fluids have been studied in detail: (1) water/steam, (2) molten nitrate salt, (3) liquid sodium, (4) oil, (5) gas (air or helium), and (6) carbonate salts.

An ideal working fluid is one that has high heat transfer rates and heat capacity, is stable and non-corrosive at operating temperature, has a low vapor pressure, is easily pumped, does not freeze or boil, and is safe and inexpensive. Since no fluid which satisfies all of these requirements exists, the choice of transport fluid is a subject for detailed study and optimization.

The piping in a central receiver solar plant is a significant cost item. The type of working fluid used is a major factor in the cost of piping. The highest temperature fluids frequently require the use of special compatible alloys. At higher temperatures the piping may also be required to withstand high pressure. For heat-transport fluids that freeze at ambient temperatures (e.g., salt, sodium, and some oils), provision must be made for heat tracing on the pipes and for draining the pipes during periods of extended shutdown. Finally, the pipes must be designed to accept the differential expansion from their maximum temperature to ambient.

In a central receiver system the heat-transport fluid must be moved up the tower (riser) to the receiver in a relatively cool state and down the tower (downcomer) in a hot state. Additional horizontal piping is required to reach the load. Pumps for moving the heat-transport fluid up the tower (high head) and through the heat exchangers (low head) are available for all fluids presently under study, although molten salt pumps for large, high head applications still require development.

Heat exchangers are used in some solar power plant designs to transfer thermal energy from the heat transport or storage fluid to the final working fluid. Heat exchangers may also be required for charging or discharging thermal storage. Water/steam and air systems do not necessarily require exchangers if the heat transport and working fluids are the same.

Battleson, K.W. (April 1981). "Heat Transport and Exchange Subsystem." *Solar Power Tower Design Guide*. SAND81-8005. Albuquerque, NM: Sandia National Laboratories; pp. 37-40.

This section of the Guide describes the heat-transport fluid, piping, and heat exchanger characteristics that are important to consider in central power systems. A table on the properties of heat-transport fluids is included.

Schneider, G.R. and Morgan, G.R. (December 1980). *Thermal Stability Tests of Heat Transfer Fluids for Transfer and Storage of Thermal Energy*. DOE/ET/20417-4. Huntington Beach, CA: McDonnell Douglas Astronautics Company; 133 pp.

The report evaluates the high-temperature (290-345°C; 550-650°F) thermal stability, material compatibility, and surface fouling of selected commercial heat-transfer fluids. Of particular interest is the suitability of these fluids for use as a heat transfer or sensible heat storage medium for solar thermal electric power generation plants.

Wright, John D. and d'Agincourt, Carolyn. (1982). "Direct-Contact Air/Molten Salt Heat Exchange for Solar Thermal Systems." *Energy — the Spark and Lifeline of Civilization: Proceedings of the 17th Intersociety Energy Conversion Engineering Conference; Los Angeles, CA; 8-12 August 1982*. 82CH1789-7. Piscataway, NJ: IEEE Service Center; Vol. 3, pp. 1492-1497.

This paper presents a technical and economic analysis of direct-contact heat exchangers. A system in which salt is heated in a conventional fin-tube heat exchanger is compared to a system that uses a combination of conventional and direct-contact heat exchange. The technical problems and potential of each system are examined, the costs compared, and other possible applications suggested.

Preliminary Heat Pipe Testing Program; Final Technical Report. (March 1981). DOE/SF/10756-1. San Francisco, CA: Bechtel National, Inc.; 261 pp. Work also performed by Dynatherm Corporation, Cockeysville, MD and Foster Wheeler Development Corporation, Livingston, NJ.

The objective of the Preliminary Heat Pipe Testing Program is to accumulate data on the ability of high-temperature metallic heat pipes to perform under the type of cyclic service conditions that could be encountered in receivers of certain solar thermal power systems or high-temperature process-heat supply systems. A central receiver combined-cycle solar hybrid power system was selected as the reference design. The appendices contain the complete text of the two subcontractors' final reports.

Power Conversion

This subsystem converts the energy produced by the solar thermal central receiver into its final end-use form. A separate control system controls the integration and operation of the plant and its various subsystems. Both types of subsystems are already employed in most large modern power generation

Hiller, C.C. (July 1978). *An Introductory Comparison of Brayton and Rankine Power Cycles for Central Solar Power Generation*. SAND78-8010. Albuquerque, NM: Sandia National Laboratories; 50 pp.

plants and industrial processes, although the degree of sophistication varies from plant to plant. Electric power generation systems, in particular, are well developed for conventional utility power plants and represent a mature technology that needs minimal research and development for use with solar applications.

The power conversion subsystem interfaces with the heat transport and exchange subsystem and may be a turbine-generator for electricity generation or an industrial process, or both. Both Rankine and Brayton cycle turbine generators can be used in solar electric power systems; however, the Rankine turbine tends to be more easily adapted to solar applications. Steam conditions can be readily achieved in solar thermal central receivers that match the throttle conditions for a wide range of Rankine steam turbines by either using water/steam as the working fluid or producing steam through a heat exchanger that uses another working fluid.

If the working fluid is air or some other suitable gas, a Brayton cycle turbine may be used to generate power. Typical Brayton-cycle plant-operating temperatures are higher than those proposed for solar Brayton systems; therefore, gas turbines obtained for application to solar plants may not be as efficient as conventional Brayton cycle machines.

The end-use of an IPH central receiver is to produce the steam, hot air, or other hot fluid needed to perform the industrial process by either interfacing the receiver working fluid with the process working fluid through the use of a heat exchanger or by using the same fluid or both. There is a greater variety of energy requirements in the process heat industries than in the utility industry. A major consideration in selecting the end-use subsystem is the type of final process fluid to be used, its temperature, and whether it can be the same as, or can be easily coupled to, the heat-transport fluid.

Many industrial processes use air or steam as the working fluid. Although an air central receiver is probably not cost-effective for large-scale electricity generation, it may be the best system for an industrial process requiring hot air. In addition, such a hot air system might have a topping (Brayton) or bottoming (Rankine) cycle to form a cogeneration system producing both electricity and process heat. If a process requires steam, then a salt, sodium, water- or oil-coupled central receiver might be a cost-effective option.

Usually the master control system consists of three primary subsystems, each with its own compiler: (1) the operational control system, (2) the data acquisition system, and (3) the peripheral control system. Central receiver power plants use control systems that are more complex than those used in existing fossil power plants in order to integrate the independent controls of the subsystems (collector, receiver, storage, and electrical power generation or industrial process heat operation). The need for the greater sophistication is also caused by the more dynamic nature of the solar power source, in particular, the need to respond to cloud transients.

The report presents both a detailed discussion of the characteristics of Brayton and Rankine power cycles, and an examination of their advantages and disadvantages as applied to central receiver power generation. The characteristics of each cycle are discussed for a variety of configurations and are highlighted with numerous examples.

1-MW(th) Solar-Thermal Conversion Full-System Experiment. (August 1982). EPRI-AP-2435-SY. Palo Alto, CA: Electric Power Research Institute; 63 pp. Work performed by Boeing Engineering and Construction Company, Seattle, WA.

This summary report describes the planning and design of a complete Brayton-cycle solar central receiver experimental system that would include all components of a commercial size electric utility solar power plant. Descriptions of the electric power generation subsystem and the control subsystem are included.

Project Descriptions

10 MWe Central Receiver Pilot Plant (Solar One)

Solar One is presently the world's largest solar electric generating station. This pilot scale research and development plant is a cooperative effort between the federal government and private industry to demonstrate the technical feasibility, economics, and environmental acceptability of the solar thermal central receiver concept. Located in the Mojave Desert near Barstow, California, Solar One is a joint project of the Department of Energy (DOE), Southern California Edison (SCE), the Los Angeles Department of Water and Power (LADWP), and the California Energy Commission (CEC). The solar portion of the facility was designed and constructed under the direction of DOE and the turbine/generator facilities were designed and constructed by SCE.

Solar One began providing power for the Southern California Edison grid on April 12, 1982 and has been undergoing checkout and testing since that time. The plant is designed to produce at least 10 MW of electric power for the utility grid (after supplying the plant's parasitic power requirement) for 7.8 hr on the plant's "best design day" (summer solstice) and for 4 hr on the plant's "worst design day" (winter solstice).

The collector subsystem for Solar One is a 360-degree field array of 1815 sun-tracking heliostats produced by Martin Marietta. Each heliostat is made of 12 slightly concave mirror panels, totaling 39.9 m^2 of mirror surface, mounted on a geared drive unit for azimuth and elevation control. A sophisticated microprocessor and computer control subsystem is used to store annual and daily sun position data and to aim the heliostats individually and by group. In addition, a beam characterization subsystem calibrates each heliostat beam with regard to its focus on the receiver, its beam shape, and the beam power density.

Designed to produce 510°C (950°F) steam, the receiver subsystem is an external type, based upon a single-pass-to-superheat steam boiler. It consists of 24 panels arranged in a vertical cylindrical configuration 7 m (23 ft) in diameter with a total surface area of 300 m^2 (3250 ft^2). A lattice steel tower supports the receiver at a height of 60 m (200 ft) from the desert floor to the center point of the vertical receiver.

The thermal storage subsystem extends the plant's electrical power generating capability into nighttime or during periods of cloud cover and also helps maintain portions of the plant in a warm status during non-operating hours and for plant start-up the following day. The storage subsystem is a single-tank thermocline type consisting of 6.4×10^6 kg (6300 tons) of rock and sand, and 908 m^3 (240,000 gal) of thermal oil. Steam at 275°C (525°F) can be produced from storage with a rated electric-power capacity of the solar plant operating from thermal storage of 7 MWe for 4 hr.

The turbine generator is rated at 12.5 MWe and is a single-case design for cyclic duty. It is the same general machine used for marine drives. The rated turbine thermal-to-electric efficiency

Bartel, James J. and Skvarna, Paul E. (June 1983). *Overview of the Construction and Start-Up of the 10-MWe Solar Thermal Central Receiver Pilot Plant; April 1983.* SAND83-8021. Albuquerque, NM: Sandia National Laboratories; 36 pp. Work also performed by Southern California Edision Company, Rosemead, CA.

This report presents an overview of the construction and start-up of the 10 MWe Solar Thermal Central Receiver Pilot Plant near Barstow, California. The costs and schedule of the project are discussed, the planned test program is outlined, and significant experiences to date are presented.

Vant-Hull, Lorin L. and Hildebrandt, Alvin F. (1982). "Solar One — The 10 MWe Central Receiver Pilot Plant at Barstow, CA." *Proceedings of the 1982 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Houston, TX; 1-5 June 1982.* Edited by Barbara Glenn and Gregory E. Franta. Vol 5.1. Preprint edition. New York: ASES Publishing Office; pp. 361-366.

The research steps leading to the selection of the design for Solar One are summarized. Photographs taken during various phases of the construction program are presented with a description of present operational status.

10-MWe Solar Thermal Central Receiver Pilot Plant: Solar Facilities Design Integration. Plant Operating/Training Manual. (July 1982). DOE/SF/10499-83 Rev. Huntington Beach, CA: McDonnell Douglas Astronautics Company; 301 pp.

This document provides plant- and system-level operating instructions for the Solar One generating station. It is intended that these instructions be supplemented by collector system operating instructions and information from individual equipment suppliers. The manual contains three sections: (1) Status, (2) Transition, and (3) Collector Field Operating Instructions. The Status section instructions identify plant conditions, process controller responsibilities, process conditions and control accuracies, operating envelopes, and operator cautions. The Transition operating instructions identify the sequence of activities to be carried out to accomplish such transitions as start-up or shutdown of an individual flow path. The third section of the manual provides background information on central receiver field operations and defines heliostat groupings and specific commands to be used in support receiver startup.

is 35% from receiver steam and 35% from thermal storage steam.

Solar One is operated with a computerized master control system. Each subsystem has its own distributed process controller connected to the master control system. The process controllers are digital computers that operate the system's valves, motors, pumps, relays, and other equipment. Ultimately, the plant will be fully automated with only operator override, making it possible for one person to operate the entire plant.

A five-year test program is now under way at Solar One. The first two years of the test program will be devoted to design verification of the individual components and systems and to demonstration of the various modes of operation. During the last three years of the test program, electric output will be maximized and plant reliability will be demonstrated.

Additional solar thermal central receiver electric power plants are located in Europe and Japan and are discussed in the International Program section of the introduction.

ARCO's Solar Thermal Enhanced Oil Recovery (STEOR) System

ARCO Oil and Gas Company has designed and constructed a solar thermal enhanced oil recovery (STEOR) pilot plant at ARCO's Fairfield Lease in Kern County, California. The solar thermal central receiver system is being used to augment the injection of steam, which is produced mainly by a natural gas-fired steam generator on the site, into oil wells.

Designed by ARCO Power Systems, the system consists of 30 heliostats (1585 m^2; 17,050 ft^2 total reflector area) arranged in five circular arcs in a north field. The site is 12,000-16,000 m^2 (3-4 acres). The receiver unit is a natural circulation steam generator, configured as a flat surface array (approximately 3 m^2; 10 ft^2) of steam-generation tubes. It is mounted 20 m (66 ft) above ground on a tower. No thermal storage is provided since the system is designed to operate primarily from 9:00 a.m. to 6:00 p.m. each day. Expected output is 1 MW on clear days, with the steam produced at a rate of 0.433 kg/s (3440 lb/hr). The injection steam is produced at a pressure of 6.9 MPa (1000 psia) and a temperature of 285°C (545°F).

The major objective of the project is attainment of operational and maintenance experience with the STEOR concept in an actual field environment. Upon completion of the system, a 6-month engineering test program will be performed to check out the system, define performance over the full operational range, and establish and refine operation and maintenance procedures. This will be followed by a full-year operational test period during which the annual performance of the plant will be monitored. After the test period, plans call for integrating the plant into the normal field operation.

Blake, F.A. and Anderson, A.J. (1983). "Solar Enhanced Oil Recovery Project Using Heliostats." *Transactions of the Third Circum Pacific Energy and Mineral Resources Conference; Honolulu, HI; 23-28 August 1982*. Edited by Stuart Watson. Tulsa, OK: American Association of Petroleum Geologists; pp.529-535.

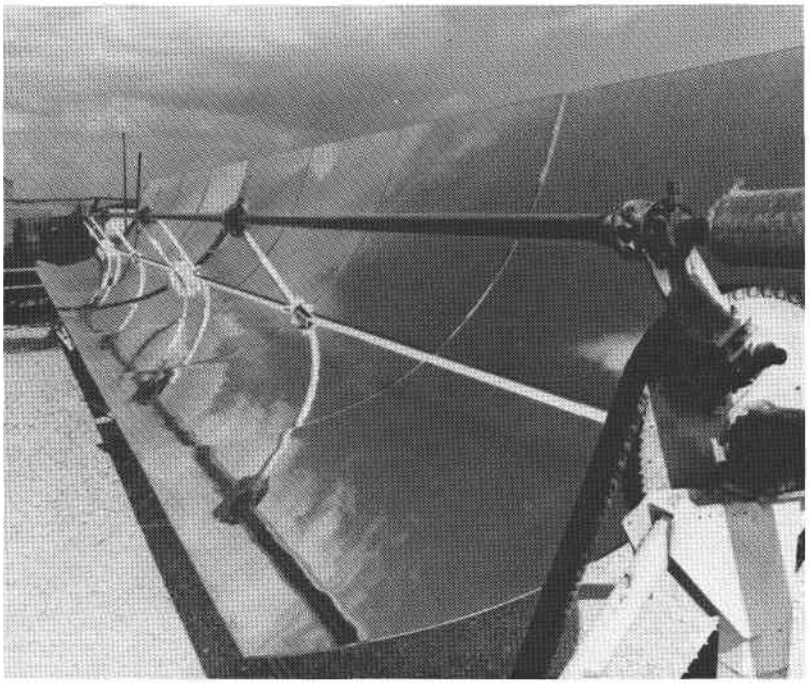
The description of the pilot module Solar Thermal Enhanced Oil Recovery (STEOR) system, located at ARCO's Fairfield Lease in Kern County, California, examines the central receiver's major subsystems and summarizes the construction process. Several illustrations are included.

Chapter 4
Distributed Receiver Technology

Parabolic Trough

Parabolic troughs are U-shaped collectors lined with a highly reflective material, such as mirrored glass, that concentrates the sun's rays along a linear absorber/receiver tube placed at the focal line of the trough. A fluid in the receiver is heated by the radiant energy and then transported to the point of use by means of a piping network. Collector efficiency is increased by designing the trough to track the daily movement of the sun; concentration ratios of up to 50:1 can be achieved. The collector, thermal transport, and control subsystems are discussed in more detail in the following sections. (The storage and energy conversion or end-use subsystems are not described here since they are similar to the ones already described in the preceeding chapter on Central Receivers.)

Typically, a parabolic trough system consists of a field of trough-shaped collectors, each coupled with its own heat receiver. Since this arrangement creates a distribution of receivers throughout a field of collectors, parabolic troughs are referred to as distributed receiver systems. These systems offer the advantage of modularity. The minimum useful unit is called a collector loop, which is the number of collector modules needed to give the required temperature rise between the inlet and outlet manifolds in the field. Generally, systems consist of several collector loops installed in parallel lines either on roof tops or on prepared foundations. The size of the



Parabolic Trough

Leonard, James A. (1978). *Linear Concentrating Solar Collectors — Current Technology and Applications*. SAND78-0949C. Albuquerque, NM: Sandia National Laboratories; 29 pp. Presented at the Solar Thermal Concentrating Collector Technology Symposium; Denver, CO; 14-15 June 1979.

This report surveys linear concentrating collector technology. Included are fundamentals of the technology, descriptions of collectors with particular emphasis on the types tested at the DOE/Sandia Midtemperature Solar Systems Test Facility (MSSTF), performance test results, problems identified through operating experience, cost projections, and a discussion of applications of linear concentrating and mid-temperature solar collectors.

Champion, Roscoe L., editor. (February 1981). *Proceedings of the Line-Focus Solar Thermal Technology Development Conference; Albuquerque, NM; 9-11 September 1980*. SAND80-1666. Albuquerque, NM: Sandia National Laboratories; 482 pp.

Intended as a seminar for people in industry as well as the federal government who are interested in line-focus solar technologies, the conference included the following sessions: overview of the federal line-focus program, line-focus system development, line-focus subsystem development, line-focus component development, materials development, and instrumentation development.

Evaluation of Line Focus Solar Central Power Systems. (March 1980). ATR-80(7773-03)-1. El Segundo, CA: The Aerospace Corporation; 2 V.

Three line-focus concepts for central utility power generation are analyzed and evaluated and their potential compared with that of the central receiver point-focus concept. Specifically, the report includes summaries of the systems and subsystem designs; performance and cost evaluations; and descriptions of line-focus applications, growth potential, and development issues.

Kutscher, Charles F.; Davenport, Roger L.; Dougherty, Douglas R.; Gee, Randy C.; Masterson, P. Michael; and May, E. Kenneth. (August 1982). *Design Approaches for Solar Industrial Process Heat Systems: Nontracking and Line Focus Collector Technologies*. SERI/TR-253-1356. Golden, CO: Solar Energy Research Institute; 452 pp.

This document is meant to serve as a handbook for the design of solar industrial process heat systems. Choosing appropriate components such as collectors, storage, piping, insulation, pumps, valves, heat exchangers, and heat-transfer fluids is covered in detail. System integration, controls, field is given in terms of the total area of collector surface in all the troughs.

Parabolic trough concentrating collectors usually track the sun along one axis only; either a horizontal east/west or a horizontal north/south axis of rotation. More rarely, a polar mount can be used which employs a north/south axis tilted at an angle equal to the local latitude. In mid-latitudes, a parabolic trough aperture tracking about the horizontal north/south axis receives approximately 10% more energy than one tracking about the east/west axis. Polar axis tracking approaches within 4% the radiation availability of a dual-axis tracker, making about 30% more energy available than is possible using an east/west axis. However, the polar-axis mount is generally believed to be impractical for large installations because of problems with plumbing and wind loading. The use of a horizontal north/south axis also presents difficulties in that there are substantial seasonal variations in output, resulting from variations not only of insolation but also of optical efficiency at low incidence angles.

As with central receivers, the hot fluid from the trough receiver tubes can be used directly in process heat applications or converted to mechanical or electrical power. Parabolic troughs are also capable of cogeneration of both thermal and electric energy when linked with steam or organic Rankine-cycle engine-generators. However, since they operate at lower temperatures (up to 400°C; 750°F) than central receivers and dishes (up to 1000°C-1500°C; 1830°F-2730°F, respectively), parabolic troughs are used principally for process heat applications. Because of their modularity and conversion efficiencies of over 60% at low to medium temperatures, troughs are often considered to be the solar technology of choice for such temperature applications.

Although presently not considered as viable as the point-focus central receiver power systems described in the previous chapter, line-focus central receiver concepts have also been proposed for electrical power applications. Analogous to the individual line-focus, parabolic trough collector/receiver, the line-focus central power system focuses several rows of trough collectors upon a single linear receiver mounted on a row of towers in front of the collectors. By retaining the simplicity of the single-axis parabolic trough collector and requiring less piping than a distributed system, the central receiver line-focus system reduces piping parasitics such as heat loss, cost, and absorber-fluid pressure drop.

Components and Subsystems

Collector Subsystems

The concentrator and receiver of a trough system create a closely integrated unit called a collector. The receiver is that element of the system where the radiation is absorbed and converted to thermal energy, and includes the absorber, associated covers and insulation. The concentrator, or optical system, is the part of the collector that directs radiation onto the receiver.

economics, start-up procedures and safety and environmental issues are also addressed, and a new method for predicting energy delivery is included. The handbook is designed to be used by readers with experience in basic mechanical engineering. Previous solar energy experience is not required.

Eicker, P.J.; Eason, E.D; Hankins, J.D.; Hosteller, L.D.; Iannucci, J.J.; and Woodard, J.B. (March 1981). *Design, Cost and Performance Comparisons of Several Solar Thermal Systems for Process Heat.* SAND79-8279 to 8282. Albuquerque, NM: Sandia National Laboratories; 4 V.

Conceptual designs of central receiver, parabolic dish, and parabolic trough systems are obtained for several process heat applications. Cost and performance estimates for each design are used to calculate levelized delivered process heat costs. The four volumes of the report are titled respectively: *Executive Summary, Concentrators, Receivers*, and *Energy Centralization*.

Harrigan, Raymond W. (April 1983). *Handbook for the Conceptual Design of Parabolic Trough Solar Energy Systems Process Heat Applications.* SAND81-0763. Albuquerque, NM: Sandia National Laboratories; 320 pp.

Presented are the techniques needed to execute conceptual designs of process heat systems employing parabolic trough solar collectors. The design tools are presented in a graph format and each of 26 SOLMET sites is represented. The conceptual design resulting from the use of these design charts approximates the collector area needed to displace a constant thermal demand, the land area needed for collector deployment, the appropriate quantity of sensible heat storage, the fraction of fossil fuel displaced by solar, and the capital cost of the collector-storage subsystem.

Alvis, Robert L.; editor. (March 1983). *Proceedings of the Distributed Solar Collector Summary Conference — Technology and Applications; Albuquerque, NM; 15-17 March 1983.* SAND83-0137C. Albuquerque, NM: Sandia National Laboratories; 358 pp.

With a primary emphasis on line-focus collectors, the proceedings cover research on development of components and subsystems, and systems engineering and analysis. The results of the MISR project are reported, including system design descriptions and test results, and operating experience and performance data from distributed collector experimental field projects are described.

Gee, R. and Murphy, L.M. (August 1981). *Near-Term Improvements in Parabolic Troughs: An Economic and Performance Assessment.* SERI/TR-632-870. Golden, CO: Solar Energy Research Institute; 59 pp.

This analysis quantifies the performance potential of various component improvements from a systems viewpoint. The performance data are used to

The basic principle used in the design of parabolic trough collectors is to concentrate the solar energy incident upon a large area onto a smaller receiver area. By reducing the area (size) of the hot receiver, thermal losses are reduced, allowing operation at high temperatures with high efficiency. Typically, parabolic trough collectors have concentration ratios (i.e., aperture area/receiver area) between 20 and 50.

The efficiency of the collector subsystem makes a significant impact on the performance of the entire parabolic trough system. The optical efficiency of the collector is the fraction of sunlight intercepted by an ideal collector aperture facing the sun directly, compared to that which is eventually absorbed by the absorber component of an actual collector which may or may not face the sun directly. Variables affecting parabolic trough collector efficiency fall into several groups:

1. Operating conditions (insolation, tracking mode, operating temperature, flow rate).
2. Properties of materials (reflectance, absorptance).
3. Receiver type (absorber shape, evacuated or non-evacuated).
4. Concentrator geometry (concentration ratio and rim angle).

determine the value of each improvement on an economic basis. The improvements considered are evacuated receivers, silvered-glass reflectors, improved receiver selective coatings, higher optical accuracy concentrators, and higher transmittance receiver glazings.

Youmans, D.; Bell, D.; and Carlton, R. (1981). "State-of-the-Art Solar Trough Collector." *Proceedings of the 1981 Annual Meeting of the American Section of the International Solar Energy Society; Philadelphia, PA; 26-30 May 1981.* Edited by Barbara H. Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 300-303.

This paper summarizes the design of Acurex Corporation's second generation line-focus collector and presents the rationale for the major subsystem design decisions. The predicted annual thermal performance and estimated production costs are also provided.

Concentrators

The parabolic concentrator component reflects direct solar radiation to an absorber tube located at the focus of the parabola. The concentrator is covered with a reflective material having a high specular reflectance. Three major types of reflectors have been used: (1) polished aluminum sheets, (2) aluminized plastics, and (3) silvered glass. Polished aluminum has a specular reflectance of 0.75 to 0.80 when new, but it suffers from gradual reflectance loss as the aluminum degrades in weather. The specular reflectance of plastic film is usually from 0.80 to 0.86 when new. However, scratching of the surface by airborne particles results in loss of the film's specularity. Although it is the most expensive of the three, silver-backed glass offers the advantages of higher performance (0.90 to 0.95 reflectance) and ease of maintenance.

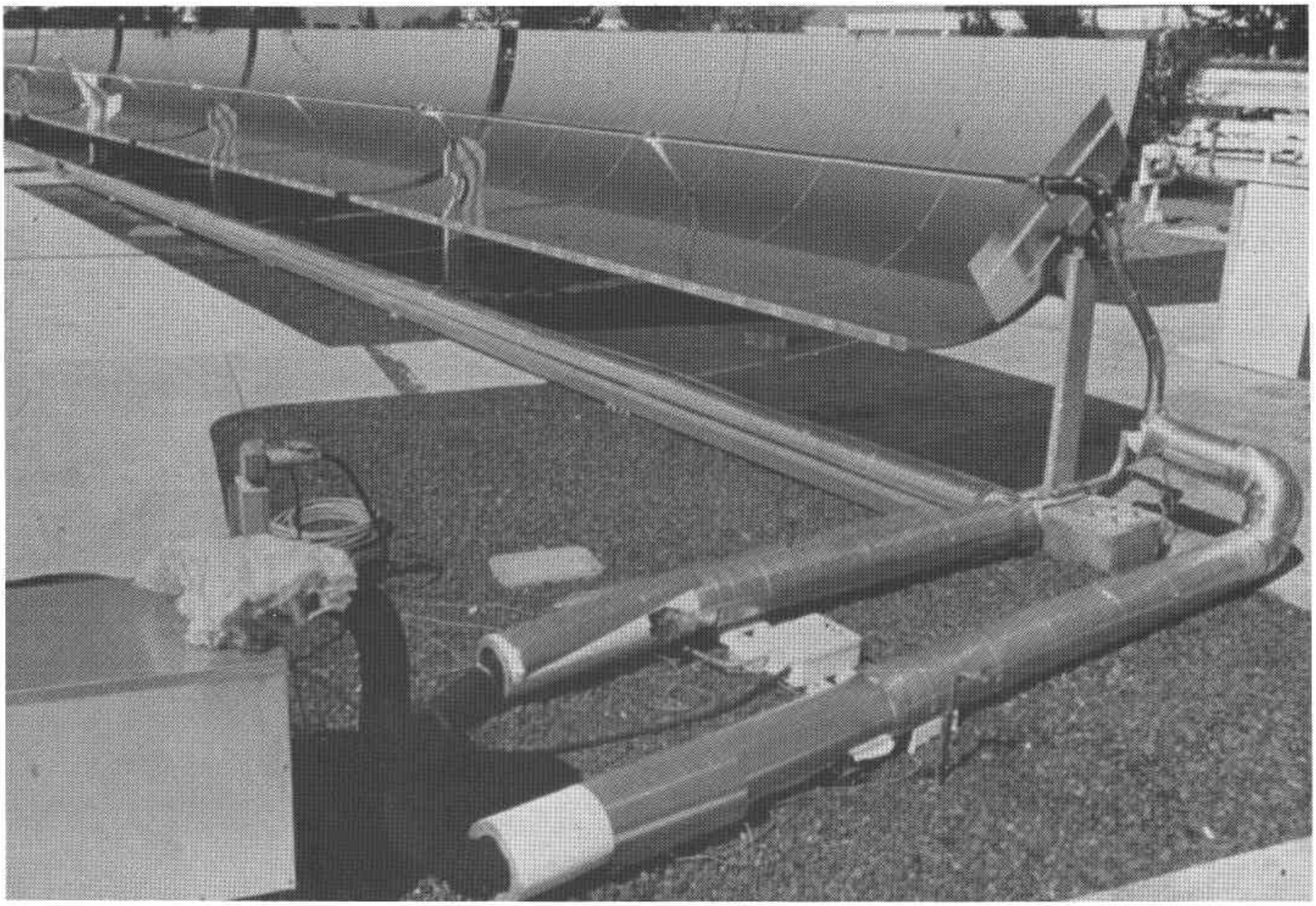
The actual trough portion of a parabolic concentrator provides the correct optical shape for the reflective surface, maintains this shape to within acceptable tolerances during operation, and protects the reflective surface during non-operating periods. Determination of construction methods and materials to be used for the trough are based on preliminary guidelines such as shape (parabola definition), aperture, deflection allowance under moderate wind, and no structural failure up to a specified wind speed. At present, lightweight trough designs appear to be more desirable than heavy design concepts.

The tracking support structure for multiple reflectors and their common drive requires foundations, pylons, and bearing support mechanisms. The foundation design for a line-focusing collector system must take into account the unique aerodynamic and mechanical forces experienced by such a

The following papers from the *Proceedings of the Line-Focus Solar Thermal Energy Technology Development Conference*, cited at the beginning of this chapter, contain information on the concentrator, including tracking and support structures subsystems for parabolic troughs: Auld, Harry E., "Foundations for Line-Focusing Solar Collectors," pp. 247-254; Biester, Albert W., "Sheet Metal Trough Reflector/Structure," pp. 281-290; Champion, Roscoe L., "Sheet Metal Reflector Structures," pp. 273-280; Champion, Roscoe L., "Sheet Molding Compound (SMC) Reflector/Structures," pp. 291-096; Kirsch, Paul A., "Development Effort of Sheet Molding Compound (SMC) Parabolic Trough Panels," pp. 297-306; Lewis, Brett A., "Analytical and Experimental Studies of Some Parabolic Line Concentrator Design Concepts," pp. 327-336; Lewis, I. Earl, "Thermally Formed Parabolic Glass Panels," pp. 323-326; McDowell, Joseph W., "Honeycomb Reflector/Structure," pp. 307-314; Martin, Samuel B., "Glass Laminate Reflector/Structure," pp. 315-322; Randall, Robert A., "Drive System for Line-Focus Collectors," pp. 351-357; Reed, Theodore H., "Pylons," pp. 255-264; and Reuter, Robert C., "Initial Parabolic Trough Design and Parametric Evaluation," pp. 265-272.

Bendt, P.; Rabl, A.; and Gaul, H.W. (July 1981). *Optical Analysis and Optimization of Parabolic Trough Collectors; A User's Guide.* SERI/TR-631-602. Golden, CO: Solar Energy Research Institute; 24 pp.

The results of a detailed optical analysis of parabolic trough solar collectors are summarized by a few universal graphs and curve fits. The graphs enable the designer of parabolic trough collectors to calculate the performance and optimize the design with a hand calculator. The method is illustrated by specific examples that are typical of practical applications.



Collector Drive String

system. The pylons that mount the reflector structure, secure them to a suitable foundation, and contain the bearings used for rotating the reflectors by the tracking device system, must be able to also withstand these stresses. When multiple collectors are combined end-to-end into a drive-string row, the pylons at different positions provide different functions and are subject to different loads resulting in the need for varying designs. Design goals are to reduce the amount of materials used and devise lower-cost designs.

The driver for trough collectors is the mechanism that rotates a string of collectors to track the sun, and stows the collectors in a particular orientation. Stowage is required to preclude inadvertent focusing and to minimize mirror soiling and damage. A drive system must provide enough force, or torque, to operate the system under all expected wind conditions, have sufficient precision of operation for accurate tracking, and have sufficient speed to provide stowage in a reasonably short time.

Receivers

The receiver is that component of the parabolic trough collector system that converts the radiant solar energy into thermal energy. In accomplishing this function, consideration must be given to major factors influencing performance and

The following papers from the *Proceedings of the Line-Focus Solar Thermal Energy Technology Development Conference*, cited at the beginning of this chapter, contain information on the receiver subsystem: Torkelson, Leroy E., "Passively cost such as effective heat transfer to the working fluid, accommodation of expansion, mechanical deflection, thermo-optical design, durability, reliability, and cost of construction and replacement.

Although parabolic trough receivers may be of either a planar or tubular configuration, flat plate absorbers have the disadvantage of shading the reflector without regaining the lost radiation. Hence, most receivers use an absorber consisting of a metal tube coated with a selective coating that has a high absorptance for the solar spectrum and a low emittance for infrared radiation. Since the absorber is very hot, the tube is usually enclosed in a glass envelope (often containing a vacuum) to reduce convective/radiative heat loss. A heat-transfer fluid is circulated through the receiver tube to absorb the thermal energy and then transport it through the piping network to storage or the end-use system.

The size and position of a receiver are important factors in the performance of a parabolic trough collector system. It must be large enough to capture most of the energy reflected by the parabola and also compensate for tracking and slope errors; too large a receiver may have unnecessary heat loss.

The portion of the receiver within the focal area of the reflector can be more critical than the receiver size for troughs in the concentration ratio range above 20. Computer studies on some of the earlier parabolic troughs determined that if the receiver tube were moved ±3% of the focal length (or 60% of the receiver diameter) out of the focal plane, the efficiency would be reduced by one half. Since it is difficult to locate a receiver precisely along the focal line when mechanical deformations and fabrication tolerances are considered, it was suggested that receivers be oversized to compensate for focal length variations.

Thermal Transport Subsystems

The thermal transport piping is one of the main components of a parabolic trough collector field. Used to transport the heated working fluid from the collectors to the end-use system or to storage, the energy transport subsystem consists of pipes, pumps, expansion tanks, valves of various types, and heat exchangers. In designing the collector field piping, one must consider the effects of the layout on collector performance, thermal losses within the field, electrical energy for pumping, and the capital and installation cost of the piping network. In most solar thermal systems, standard circular pipes of steel, copper, aluminum, or special alloys are used to transport heat, in the form of internal energy within the pumped fluid.

Heat-transport fluids commonly used in parabolic trough piping systems include water and organic fluids such as Therminol 66 and Caloria HT-43. Heat exchangers are used when it is necessary to transfer heat from one fluid stream to another if the two fluid streams cannot be mixed. For example, although many process heat applications can make direct use of the heat-transport fluid, which circulates through the solar thermal receivers, most food manufacturers prefer to use an exchanger to transfer the heat to a process fluid which is deemed safer in case of accidental contamination.

Evacuated Receivers," pp. 369-376; and Treadwell, George W., "Non-Evacuated Receivers," pp. 358-368.

Gerich, Jerry W.; Reitler, Thomas A.; and Merriam, Marshall F. (March 1980). "Measuring Overall Emittance of Concentrator Receiver Pipes." *Solar Engineering Magazine*. Vol. 5 (No. 3); pp. 33-34.

This paper describes a method for measuring overall emittance of receiver pipes and gives some experimental results obtained on steel pipes with black chrome covering a nickel selective surface. The research attempted to provide a more reliable measure of emittance when it was determined that the use of room temperature emittance data provided by many manufacturers might result in an overestimate of collector efficiency.

Eriksson, D.J. (1983). "Development of a Sealed Receiver." *Solar Engineering — 1983: Proceedings of the ASME Solar Energy Division Fifth Annual Conference; Orlando, FL; 18-21 April 1983*. Edited by Lawrence M. Murphy. New York: The American Society of Mechanical Engineers; pp. 554-559.

The development of a new receiver for parabolic troughs is described. It uses a soldered glass-to-metal seal, and incorporates a stainless steel expansion bellows to connect glass and steel tubes. Advantages of the seal include excellent resistance to thermal shock and an airtight glass-to-metal seal that maintains a clean annulus between the glass and steel tubes.

The following papers from the *Proceedings of the Line-Focus Solar Thermal Energy Technology Development Conference*, cited at the beginning of this chapter, contain information on the thermal transport subsystems: Morton, Robert E., "Design of Collector Subsystem Piping Layouts," pp. 137-144; Sharp, John, "Design of Collector Subsystem Piping Layouts II," pp. 145-158; and Harrigan, Raymond W., "Subsystem Collector Piping Heat Losses," pp. 159-168.

Meyer, Robert D. (March 1983). *Energy Transmission System Heat Losses*. SAND82-1138. Albuquerque, NM: Sandia National Laboratories; 77 pp.

This report describes a series of heat loss experiments performed to determine the relative contribution of various components in thermal energy and transport storage systems. The items evaluated include pipe insulation, control and hand valves, flex hoses, various pipe geometries, and storage tanks. The data were collected in conjunction with thermal solar energy experiments but are applicable to many other types of heat transport systems.

Parabolic trough collectors are usually laid out horizontally to the ground to take advantage of their linear geometry and to reduce interconnecting plumbing and complex collector support structures. A field can consist of one collector loop, or many, depending upon the energy required for a particular application. Field designs attempt to minimize the impact of electrical and thermal parasitics on the operational costs.

Electrical parasitics include the energy needed to pump the heat transfer fluid through the manifold piping and the parabolic trough receiver tubes. It is important that the pumps do not allow the pressure to drop below the boiling point pressure in order to avoid vapor lock, boiling, or pump cavitation. Also, it is desirable to maintain a constant fluid temperature rise across the collector loop which requires that the fluid flow vary in proportion to the changing solar energy input. Although increasing the size of the manifold piping will decrease some of the electrical parasitic, increasing the pipe size also increases thermal loss.

Thermal parasitics can be divided into two general types: (1) actual, and (2) potential. Actual thermal parasitics are the heat losses from the collector field, the principal parasitic factor that decreases the overall thermal efficiency of parabolic trough collector fields. Although there is significant heat loss during operation, in distributed solar thermal systems a considerable amount of energy is also lost during the cool-down of hot pipes and fluid when the system is shut down. Piping heat loss can be reduced by using smaller pipe sizes or thicker pipe insulation, but smaller pipes require greater pumping power and capital costs increase with thicker insulation.

Potential thermal energy parasitics is that energy lost when the collectors shade each other at different times during the day. The shading penalty for collectors with a north/south tracking axis is great enough to considerably reduce the performance advantage that a north/south field would ordinarily have over an east/west field. To reduce shading, the collectors can be spaced farther apart, but doing so will increase the actual thermal losses, the electrical parasitics, and the capital costs.

Control Subsystem

Safe, high-performance operation of a concentrating trough, solar collector field requires that several control functions be accomplished; in particular, collector tracking, fluid control, and status display. However, communication between the master field controller and individual collector controllers is difficult and expensive since solar fields usually cover a large area. It is considered desirable to integrate all control functions into one control unit that could then use a microprocessor to reduce the size, cost, and complexity of the circuitry while increasing its flexibility and capability.

Of the major control functions, suntrackers that drive the troughs to stay in focus throughout the day have probably received the most attention. The majority of trackers that are presently in the field are variations on the conceptually

Sharp, J.K. and Chaing, C.J. (March 1983). "Siting Trade Offs for Parabolic Trough Fields." *Proceedings of the Distributed Solar Collector Summary Conference — Technology and Applications*. Edited by Robert L. Alvis, Albuquerque, NM; 15-17 March 1983. SAND83-0137C. Albuquerque, NM: Sandia National Laboratories; pp. 33-42.

This study describes the effect of spacing, location, and orientation on net energy collected for both daily and annual operation. Descriptions of the generic system and the computer model used to simulate the performance of the system are given.

The following papers from the *Proceedings of the Line-Focus Solar Thermal Energy Technology Development Conference*, cited at the beginning of this chapter, contain information on the control subsystem for parabolic troughs: Ahrens, Brandon, "Integrated Solar Field Control Systems," pp. 337-344; Shindwolf, Rudolph, "Fluid Control for Parabolic Trough Collectors: Simulation Studies and Test Results," pp. 169-180; and Williams, Jim and Steen, Rodger, "Sandia Solar Collector Field Control System Detailed Design Review," pp. 345-350.

Wright, J. and Masterson, M. (1983). "Temperature Control of Line-Focus Solar Collectors." *Solar Engineering — 1983: Proceedings of the ASME Solar Energy Division Fifth Annual Conference; Orlando, FL; 18-21 April 1983*. Edited by Lawrence M. Murphy. New York: The American Society of Mechanical Engineers; pp. 568-574.

simple, shadow band tracker. A shadow band tracker has a bar or plate that shades a pair of optical or thermal sensors. Since it must be pointed directly at the sun to keep the sensors equally shaded, any change in shading causes the tracker to signal the trough to move to stay in focus with the sun. Shadow band trackers have a fundamental problem in that they must be aligned with the trough. This is difficult and often requires excessive maintenance. However, other types of trackers that meet the stringent precision and accuracy requirements of concentrating troughs are often expensive, erratic, or both.

Fluid temperature control is required to prevent overheating and to maintain relatively constant output temperature for varying solar input conditions. The complexity of the control system is highly dependent on the requirements of the process using the thermal energy. Simple fluid control systems can be used for industrial process heat systems operating at temperatures well below the collector capability. The other extreme of fluid control system complexity is required in systems that generate electric power. In order to maximize heat engine performance, it is necessary to operate at as high a temperature as possible with minimal variability.

Since parabolic trough collectors are capable of achieving temperatures far in excess of those the receiver can tolerate, the fluid temperature control system must also provide safeguards to ensure that the system is not damaged in the event of low fluid flow. Receiver tubes will over-expand, buckle and can break the glass envelopes around them, and the selective surface on the receivers will be ruined if overheated. In addition, the heat-transfer fluid in systems that do not use water will deteriorate rapidly above a certain temperature. To prevent damage, the collector controllers are configured so that the collectors will remain in focus only if everything is functioning within prescribed bounds. If sensors detect a loss of flow, over-temperature, loss of power, or over-travel of the receiver, the absence of a signal from the controller causes the collectors to be in the stow position.

Finally, providing information about the status of the field to an operator or field technician is an important function of the field controller, though not technically a control operation. One suggested approach is to provide access to the display of system functions into levels. A field operator would be able to access basic information but would not have any control input beyond simple manual overrides to handle unusual situations. Unrestricted control access could be made available to a service technician, allowing him to extract detailed diagnostic information and to input commands to the system.

Project Descriptions

Irrigation Demonstration Systems

The U.S. Department of Energy sponsored three projects in the late 1970s to demonstrate the feasibility of using solar thermal energy to power irrigation plants in the arid Southwest.

The problem of maintaining a fixed collector field outlet temperature is addressed. In particular, frequency response techniques are used to develop simple relations that relate controller tuning constants to collector construction and field layout. The rules of thumb are tested by performing dynamic numerical simulations of a collector row with flow rate control.

Gee, R. (1980). "Line-Focus Sun Trackers." *Proceedings of the 1980 Annual Meeting of the American Section of the International Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Phoenix, AZ; 2-5 June 1980.* Edited by Barbara Glenn and Gregory E. Franta. Newark, DE: AS/ISES Publishing Office; V.3.1. pp. 501-504.

This paper defines the three major types of trackers, describes some recent sun tracker developments, and outlines the testing program underway at SERI. The three major types of sun trackers covered are (1) computer trackers, (2) shadow band trackers, and (3) flux line trackers.

Baultinghouse, Karlan D. (March 1983). "Integrated Solar Tracker Development and Test." *Proceedings of the Distributed Solar Collector Summary Conference — Technology and Applications; Albuquerque, NM; 15-17 March 1983.* Edited by Robert L. Alvis. SAND83-0137C. Albuquerque, NM: Sandia National Laboratories; pp. 89-106.

The paper describes the development and testing of an integrating direct-view optical-resistance wire solar flux sensor. The hybrid tracking control system has advantages over both indirect computer sun-angle and shadow-band tracking.

The following papers presented in the *Proceedings of the Line-Focus Solar Thermal Energy Technology Development Conference* discussed irrigation projects using parabolic trough systems:

Parabolic trough solar collectors and Rankine-cycle turbine engines were the principal components of all three plants.

The Shallow Well Irrigation Project located near Willard, New Mexico was dedicated in July 1977. The system was designed to pump approximately 0.04 m^3/s (700 gal/min) of water into a ground level reservoir from a depth of 30 m (100 ft) using 1200 m^2 (13,000 ft^2) of line-focus parabolic troughs to drive the 25-hp irrigation pump. The system also generated 18 kW of electricity for a potato warehouse. A dual-tank thermocline storage system was tested as part of the project. Since the objectives of the experiment were achieved, DOE terminated its support of the system on July 31, 1980 and ownership of the system was transferred to New Mexico State University.

The Gila Bend Solar-Powered Irrigation Pumping System was dedicated in 1977. Located on the Gila River Ranch southwest of Phoenix, Arizona, the irrigation system was designed to pump 38 m^3/min (10,000 gal/min) at peak operation. Nine rows of concentrating collectors equaling 540 m^2 (5800 ft^2) of collecting area, supplies 150°C (300°F) water to power the 50-hp (37-kW) Rankine cycle turbine. Unlike the Willard installation, the Gila Bend irrigation system does not incorporate any storage capacity into the design.

The 150-kW Solar Irrigation Project is a parabolic trough installation near Coolidge, Arizona that supplies electrical energy produced by the installation to the local utility grid in exchange for power to run three 50-hp irrigation pumps. At the time of its dedication in November 1979, the facility was the world's largest operating solar thermal power plant. The collector field is made up of 2140 m^2 (23,040 ft^2) of line-focus parabolic trough collectors arranged in eight loops oriented north/south. Energy storage is a 114 m^3 (30,000 gal) tank of hot oil, sufficient for approximately 6 hr of turbine generator operation. Solar energy is converted to electrical energy by means of an organic Rankine cycle power conversion module that uses toluene as the working fluid.

Fenton, Don, Abernathy, G.H. and Krivokapich, G.A, "Operation of Willard Solar Irrigation Project," pp. 51-58; and Larson, Dennis L., "Coolidge 150 kWe Solar Irrigation Project," pp. 59-66.

Alexander, G.; Busch, D.F.; Fischer, R.D.; and Smith, W.A. (March 1979). *Final Report on the Modification and 1978 Operation of the Gila-Bend Solar-Powered Irrigation Pumping System.* SAND79-7009. Albuquerque, NM: Sandia National Laboratories; 85 pp.

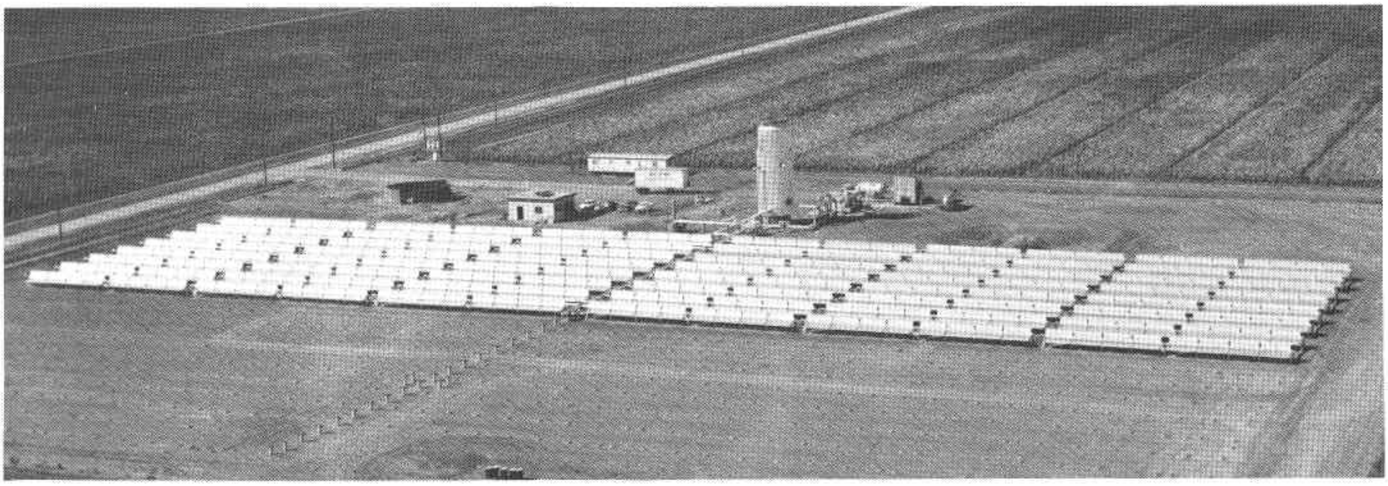
The report includes information on the following topics: project background, description of the system at the beginning of the program, modifications made during 1978, operation and maintenance during the 1978 irrigation season, and observations of and recommendations for the Gila Bend irrigation system.

Larson, Dennis L. (October 1983). *Final Report of the Coolidge Solar Irrigation Project.* SAND83-7125. Albuquerque, NM: Sandia National Laboratories; 73 pp.

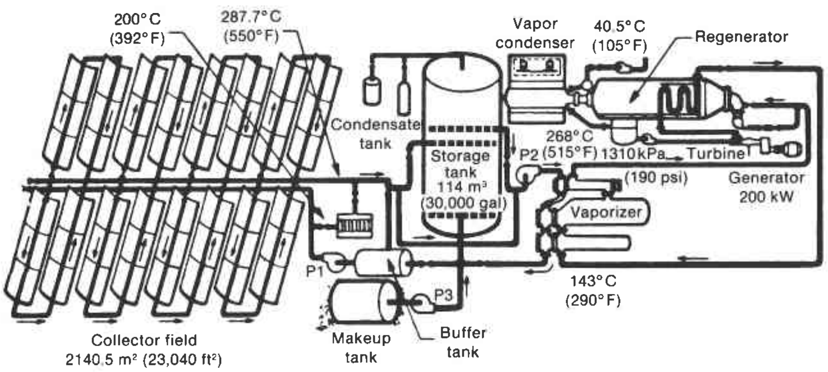
This document summarizes information from the three annual reports on the operation of the Coolidge Solar Irrigation Facility from October 1979 through September 1982. The performance of the facility and its operational and maintenance requirements during the project's duration are examined.

Krivokapich, G.A.; Fenton, D.L.; Abernathy, G.H.; and Otis, J.V. (August 1983). *Journal of Solar Energy Engineering.* Vol. 105 (No. 3) pp. 268-276.

The article describes the Willard irrigation system and presents the operational results. A discussion of the operational results examined major maintenance activities, important operational achievements and problems, and ways of reducing capital costs in future systems.



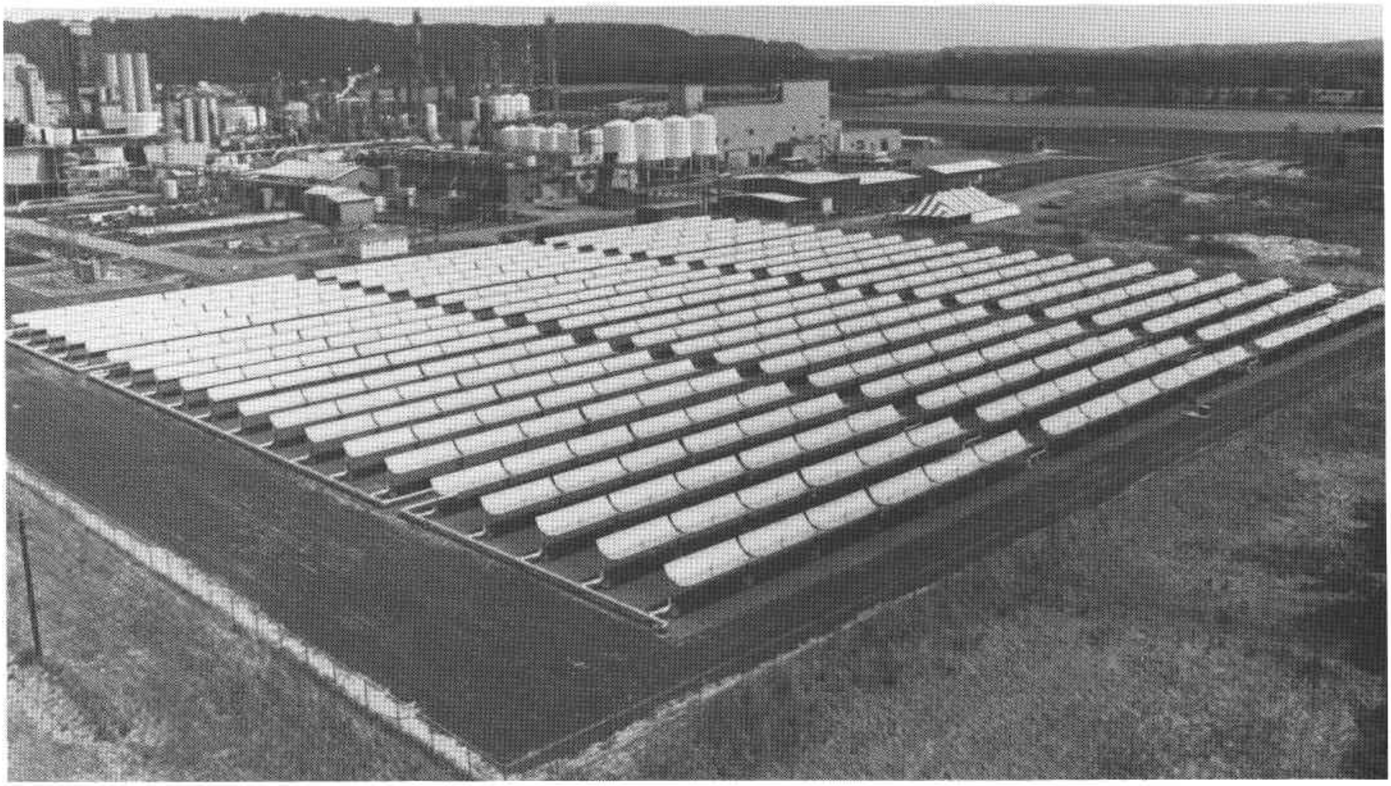
150-kWe Solar-Powered Irrigation Project at Coolidge, Arizona



Flow Diagram of 150-kWe Solar-Powered Irrigation Project

IPH Field Test Systems

The Industrial Process Heat (IPH) Field Test program was initiated in 1976 to evaluate the technical feasibility of solar thermal energy for industrial process heat applications. Since that time there have been 17 solar energy systems installed in four phases at industrial plants throughout the U.S. The systems have used a variety of collectors including flat plates, evacuated tubes, and parabolic troughs. Several of the earlier experiments have been transferred to their respective hosts, others have been upgraded or are in the process of upgrade, and two have been terminated. Construction of seven trough experiments was completed during fiscal year 1982 and all



Trough IPH Experiment at the USS Chemical Company in Havervill, Ohio

Table 4-1. IPH Projects: Location and Prime Contractor

Project	Location	Contractor	Status	Collector Area (m^2)
Home Laundry Co.	Pasadena, California	Jacob Engineering Co.	Operational (Oct. 1982)	604
Southern Union Refining Co.	Lovington, New Mexico	Energetics Corporation	Operational (Jan. 1982)	937
Lone Star Brewery	San Antonio, Texas	Southwest Research Inst.	Operational (June 1982)	878
Ore-Ida Foods	Ontario, Oregon	TRW	Operational (Feb. 1982)	884
Dow Chemical Co.	Dalton, Georgia	Foster-Wheeler Development Corp.	Operational (Nov. 1981)	923
USS Chemical Co.	Haverhill, Ohio	Columbia Gas	Operational (June 1981)	4683
Caterpillar Tractor Co.	San Leandro, California	Southwest Research Inst.	Operational (Feb. 1983)	4682

systems were operating by the end of the fiscal year (September 30, 1982). The seven parabolic trough projects, their locations, and prime contractors are listed in Table 4-1.

The trough IPH systems are designed and installed at industrial sites where the energy produced can be supplied directly to the plant's energy distribution line. Upon completion of installation, the systems, which are instrumented for detailed data collection, will be operated for a period of at least one year (although two experiments will take at least two years) under DOE funding to obtain experimental operational data on performance, reliability, operation and maintenance costs. After the operational period, the systems will be transferred to the industrial hosts for continued operation. The systems are planned as continuing sources of energy for the industrial plants as well as examples of solar energy applications for other prospective users.

Bergeron, Kenneth D. (1981). "An Overview of Solar Industrial Process Heat." *Proceedings of the Line-Focus Solar Thermal Energy Technology Development Conference; Albuquerque, NM; 9-11 September 1980.* Edited by Roscoe L. Champion. SAND80-1666. Albuquerque, NM: Sandia National Laboratories; pp. 79-86.

The article discusses DOE's Solar IPH Field Test Program as well as evaluating IPH as an energy market sector and reviewing the On-Site Materials Exposure Program.

Harley, E. L. and Stine, W. B. (October 1983). *Solar Industrial Process Heat (IPH) Project; Technical Report, October 1981 - September 1982.* SAND83-2074. Albuquerque, NM: Sandia National Laboratories; 136 pp.

A report of the work performed in the Solar Industrial Process Heat Project during FY1982 is presented. The work consisted of solar energy experiments at eight industrial sites, performed under separate DOE contracts by seven different prime contractors. A description is given of each of the experiments along with a discussion of system performance, operation and maintenance experience.

"Session III - Solar Field Projects." (March 1983). *Proceedings of the Distributed Solar Collector Summary Conference — Technology and Applications; Albuquerque, NM; 15-17 March 1983.* Edited by Robert L. Alvis. SAND83-0137C. Albuquerque, NM: Sandia National Laboratories; pp. 247-357.

Of the 18 papers, 12 deal with solar IPH projects including the seven parabolic trough projects sponsored in the 4th cycle of DOE's Industrial Process Heat Field Test Program.

MISR Projects

The Modular Industrial Solar Retrofit (MISR) Project is a DOE effort to bring together the technology developed in line-focus (trough) solar systems and to assist solar system suppliers in incorporating this integrated technology into modular system designs. The modular design has the potential of reducing design and manufacturing costs of follow-on systems, reducing first-of-a-kind design problems, and increasing operational reliability. Managed by Sandia-Albuquerque National Laboratory, the objectives of the project are to detect design problems and allow the designers to correct them, and to obtain operational and performance experience for designers and potential system buyers. The first unit produced by each of the participants was purchased by DOE for design evaluation purposes and to remove the one-of-a-kind design problems.

Five contracts were awarded in 1981 on a competitive basis to design, manufacture, and install a test system to qualify the design. The companies receiving contracts included Acurex Corporation; BDM, Inc.; Custom Engineering, Inc.; Foster-Wheeler Development Corporation; and Solar Kinetics, Inc. The systems were to be nominally 2300 m^2 (24,750 ft^2) in size and produce 6.9 to 17.2 MPa saturated steam. They were to be capable of operating in an unattended mode and have sufficient fail-safe controls. In addition, ten MISR system/industry interface designs were conducted with selected companies to determine the cost and possible installation problems associated with installing an MISR system at an industrial plant.

Alvis, R.L. and Lewandowski, A.A. (1983). "Solar IPH Systems Developed under the Department of Energy MISR Project." *Solar Engineering — 1983: Proceedings of the ASME Solar Energy Division Fifth Annual Conference; Orlando, FL; 18-21 April 1983.* Edited by Lawrence M. Murphy. New York: The American Society of Mechanical Engineers; pp. 540-545.

This paper describes the system design requirements, the designs developed, and the results of the design evaluation tests for the MISR project.

"Session II - MISR System and Plant Interface Designs and Qualification Results." (March 1983). *Proceedings of the Distributed Solar Collector Summary Conference — Technology and Applications; Albuquerque, NM; 15-17 March 1983.* SAND83-0137C. Edited by Robert L. Alvis. Albuquerque, NM: Sandia National Laboratories; pp. 135-246.

The 12 papers presented in this session present the results of the MISR project, including system design descriptions and test results.

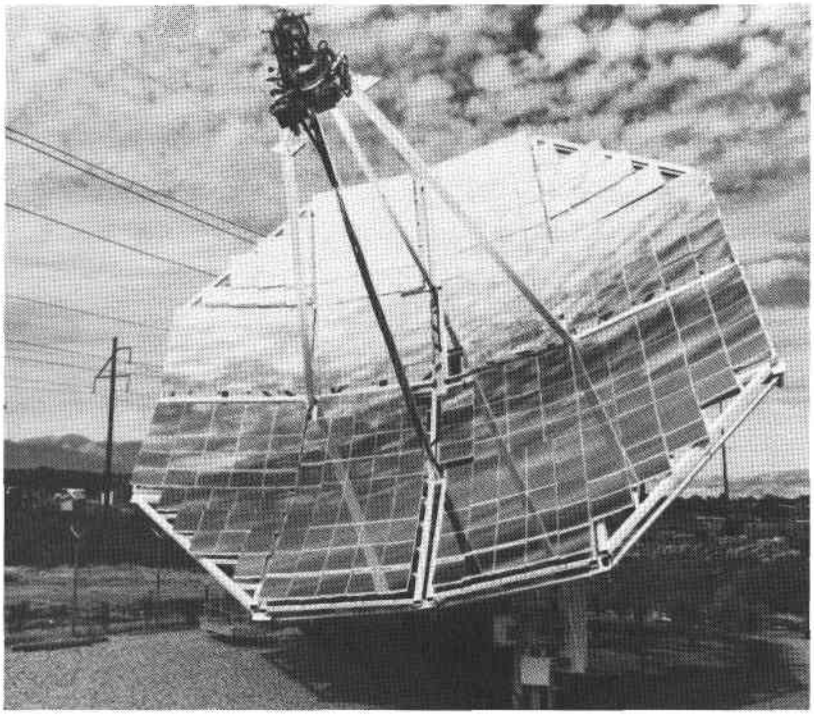
MISR Qualification Test Facility at SNLA

During fiscal year 1982, test facilities were designed and constructed at the Solar Energy Research Institute (SERI), in Golden, Colorado and at Sandia National Laboratories in Albuquerque, New Mexico. The evaluation process involved installation of one qualification test system (QTS) of each design, with the respective test facility supplying the necessary support equipment. The evaluation of the five designs was completed mid fiscal year 1983 and preliminary results for each system were reported at the *Distributed Solar Collector Summary Conference* held in March 1983.

Parabolic Dish

Parabolic dish systems consist of a dish-shaped parabolic concentrator that focuses the sun's rays on a receiver mounted in front of the dish at its focal point (making it a point-focus solar thermal technology). The sunlight focuses on an opening in the receiver, heating a fluid circulating within the receiver's coils. The hot fluid can be transported to the ground for a variety of thermal uses, or direct electrical generation can be accomplished by integrating an engine/alternator with the receiver at the focal point. For maximum effectiveness, the parabolic dish is arranged for dual-axis tracking of the sun.

The parabolic dish is not a new concept; similar devices were used to power a printing press in Paris (1878) and an irrigation pump in California (1910). However, research on these early machines was deemed impractical and discontinued when major fossil fuel discoveries reduced the price of conventional fuels significantly. Recent prices have been lower than any time since 1978. However, the use of parabolic dishes, as well as the other solar technologies, are now viable options in some situations.



Parabolic Dish

Truscello, Vincent C. and Williams, A. Nash. (April 1980). "Heat and Electricity from the Sun Using Parabolic Dish Collector Systems." *Proceedings of the First Semi-Annual Distributed Receiver Systems Program Review; Lubbock, TX; 22-24 January 1980.* DOE/JPL - 1060-33. Pasadena, CA: Jet Propulsion Laboratory; pp. 19-26.

This paper addresses point-focus distributed receiver (PFDR) solar thermal technology for the production of electric power and industrial process heat. The thermal power systems project conducted by JPL is described also. The characteristics of PFDR systems and the cost targets for major subsystems hardware are identified.

Parabolic Dish Solar Thermal Power Annual Program Review Proceedings; Atlanta, GA; 8-10 December 1981. DOE/JPL - 1060-52. Pasadena, CA: Jet Propulsion Laboratory; 353 pp.

The primary objective of the review is to present the results of activities of the Parabolic Dish Technology and Applications Development element of DOE's Solar Thermal Energy Systems Program. Twenty-four papers are presented on the subject of development and testing of concentrators, receivers, and power conversion units; system design and development for engineering experiments; economic analysis and marketing assessments; and advanced development activities.

Schmidt, G.; Schmid, P.; Zewen, H.; and Moustafa, S. (1983). "Development of a Point Focusing Collector Farm System." *Solar Energy*. Vol. 31, (No. 3); pp. 299-311.

The Space Division of Messerschmitt-Balkow-Balohm (MBB), in conjuction with the Kuwait Institute for Scientific Research (KISR), is engaged in designing and building a 100-kW solar power station near the city of Kuwait. Point-focusing paraboloidal collectors were chosen for the farm system. Some of the experiences gained during a general analysis and design of solar farm systems, as well as the component testing phase of the KISR/MBB project, are summarized and used to outline possible future development trends of such farm systems.

Krepchin, Ira P. (September 1983). "Feast or Famine for Solar Dishes." *Solar Age*. Vol. 8, (No. 9); pp. 60-65.

An overview of the development of parabolic dishes is provided from a commercial viability standpoint. Government efforts in developing dishes are

Each dish is a complete power-producing unit (module) that can function either as an independent system or as part of a group of modules linked together forming a larger system. A single parabolic dish module can achieve fluid temperatures from 300°C to 1600°C (570°F-2910°F) and can generate 20-30 kW of electricity. Dish systems can also be readily designed to provide for hybrid operation in which conventional fuels provide heat on a transient or steady-state basis to compensate for variations in insolation.

Since a parabolic dish system consists of individual modules, it can accommodate both incremented growth in system requirements and the need for low capital investment. The distributed nature of the modules also provides flexibility in siting since they may be located at a distance from the point of use or dispersed in areas surrounding it.

Perhaps the distinctive advantage offered by dish solar concentrators is their ability to achieve the high concentration ratios (500:1-3000:1) needed to produce high temperatures. These high temperatures allow greater conversion efficiencies to be obtained from heat engine power converters and provide the wide range of temperatures needed for a variety of thermal outputs. Together, the high temperatures and modularity available from parabolic dishes allow them to be considered for a wide range of applications, including both small and large utilities, power for remote sites, water pumping, industrial process heat, and production of fuels and chemicals.

Parabolic dish collectors do have some disadvantages. The dual-axis tracking, which allows dishes to obtain such high concentration ratios, requires the addition of tracking equipment and controls that add to the system's complexity and cost. Dishes do not use land space as efficiently as other kinds of collectors, and the field piping layouts can cause great thermal losses. This is less of a problem when the heat is converted directly to electricity at each dish since the electrical wiring needed to transport the energy to a central location is not as subject to losses.

reviewed and major types of dish concentrators are described, including the Fresnel reflector, radio-telescope reflectors, geodesic-frame based reflectors, and reflectors using snap-on surfaces.

Pons, R.L. (November 1980). "Optimization of a Point-Focusing, Distributed Receiver Solar Thermal Electric System." *Journal of Solar Energy Engineering*. Vol. 102, (No. 4), pp. 272-280.

This paper presents an approach to optimization of a solar concept employing solar-to-electric power conversion at the focus of parabolic dish concentrators. The optimization procedure is presented through a series of trade studies that include the results of optical/thermal analyses and individual subsystem trades.

Components and Subsystems

Concentrator

The largest subsystem of a parabolic dish module is the concentrator, typically a shallow dish with a reflective surface, that tracks the sun to focus sunlight on a receiver. The conventional optical configuration for a dish concentrator is a paraboloidal mirror. The mirror's compound curvature, in which a cross section of the dish in any direction conforms to the same parabola, causes the focus to occur at a point instead of along a line. Instead of one large curved mirror, the paraboloidal shape may be segmented into several individual reflecting facets which may be curved or flat.

The ability to reflect and focus sunlight is a principal consideration when selecting materials and designs for dish concentrators. The optical material used mostly is silvered glass. Reflective materials must be curved, the exact shape of

Jaffe, L.D. (January 1982). *Dish Concentrators for Solar Thermal Energy: Status and Technology Development*. DOE/JPL-1060-48. Pasadena, CA: Jet Propulsion Laboratory; 62 pp.

A wide variety of point-focusing concentrators presently under consideration for solar thermal energy use are reviewed in this paper. Basic examinations of the following concentrator characteristics are given: optical configuration, optical materials, structure for support of the optical elements and of the receiver, mount, foundation, drive, and controls.

Beveridge, Brian. (December 1980). *Parabolic Dish Concentrator Designs and Concepts*. Pasadena, CA: Jet Propulsion Laboratory; 29 pp.

the facets dependent upon the design of the concentrator. Forming glass mirrors into a dish contour is difficult to accomplish. Some of the approaches employed have included attachment of sagged (thermally formed) glass; bonding of flat, chemically strengthened glass that is elastically formed to dish contour; use of small mirrors, as in a mosaic; and use of laminated glass and steel. Materials other than glass, (e.g., aluminum or aluminized Mylar), can be shaped more easily, but have lower reflectivity than back-silvered glass and may degrade faster.

The thermal losses from a paraboloid are small and primarily radiative. Therefore, the performance of high-concentration paraboloids is more sensitive to optical properties than to thermal losses. The optical efficiency of a paraboloid depends on the following factors: mirror reflectance, the receiver cover (if any) transmittance, the receiver absorptance, the fraction of the aperture not shaded by supports and absorber, the intercept factor depending on mirror slope error and solar beam spread, and the amount of tracking error.

A secondary optical element or terminal concentrator may be added to a parbolic dish receiver to increase the geometric concentration ratio attainable at a given intercept factor. The increased geometric concentration may be used to reduce receiver losses, to permit higher receiver temperatures and so increase engine efficiency, or to reduce concentrator cost by permitting use of a primary of lower optical quality. This terminal concentrator may be a Fresnel lens or a mirror, such as a compound elliptic concentrator or a hyperbolic trumpet. A secondary concentrator, called a cassegrainian reflector, may also be used to fold the optical path and thus reduce costs by permitting shorter ducts to the receiver and power conversion equipment, by locating these components closer to the ground and so reducing maintenance costs, and by eliminating the relatively heavy support structures.

The three basic components of a conventional dish are: (1) the main structural framework of the dish that supports the reflector panels, (2) the reflector panels to which the reflector material is applied, and (3) the reflector material and its method of application. The three components are interrelated and their affect on the weight of large dish structures must be minimized for several reasons, including cost, weight, drive power, materials limitations, and support requirements.

The dish framework must support the reflector panels while resisting gravity, wind, and snow loads. To minimize the framework, the reflector panels should contribute to the overall structural capability of the full dish assembly. If the reflector panel can bridge adjacent frame members, the panel can increase the overall strength of the dish by becoming an integral part of the structure while decreasing the framework requirements.

Dish concentrators require rotation about two axes to follow the sun. For rotation in elevation, the mirror is often supported by bearings at the end of a diameter. Such elevation bearings are usually placed on wheeled pedestals that rotate in azimuth

The first section of this summary describes ten dish system designs in production or under detailed development as of 1980 (some of the designs have since been dropped). The second section includes descriptions of five advanced concepts under consideration in 1980. Drawings or photographs accompany each description. The detailed descriptions in the first section emphasize the concentrator subsystem but information is also provided on the receiver and thermal transport subsystem.

Bouquet, F. (1982). "Evaluation of Solar Reflective Surfaces for Dish Concentrators." *Proceedings IECEC '82; 17th Intersociety Energy Conversion Engineering Conference; Los Angeles, CA; 8-12 August 1982*. 82CH1789-7. Piscataway, NJ: IEEE Service Center; pp. 1511-1516.

The technology for evaluating solar reflective surfaces is presented in this paper with special application to parabolic dishes. Commercial second-surface glass mirrors are emphasized but aluminum and metallized polymeric films are included also. Criteria for metallization of solar mirrors to prevent environmental degradation are presented. Important factors concerning the performance of the mirrors are summarized and typical costs are treated.

Jaffe, L.D. (May 1982). *Optimization of Dish Solar Collectors With and Without Secondary Concentrators*. DOE/JPL - 1060-57. Pasadena, CA: Jet Propulsion Laboratory; 123 pp.

Methods for optimizing parabolic dish solar collectors and the consequent effects of various optical, thermal, mechanical, and cost variables are examined in this report. In particular, the problems of optimization of the optical characteristics of dish concentrators is examined.

on a track. Concrete piers, often with a concrete ring, are the foundation. A less expensive approach may be to support the mirror with elevation and azimuth bearings near its center, mounted on a single post or tripod resting on a concrete pier. Edge-mounting of the mirror is possible also.

Drive mechanisms can use electric or hydraulic drives through gears, chains, cables, linear actuators, or jacks. Although performance, cost, reliability, and maintenance of each remain to be determined, hydraulic drive may facilitate emergency stow.

Analog or digital controls may be used to point the concentrator at the sun. Most common is tracking by using sun sensors, together with stored information on the sun's location for use during cloudy intervals.

Receivers

A key element of parabolic dish collectors is the receiver. The concentrated incident solar flux is distributed on the interior walls and heat transfer surfaces of the receiver, which is located at the focal plane of the dish. Most of the energy is absorbed by the heat-transfer fluid circulating within the receiver's walls. A portion of the energy escapes back through the aperture or is lost from the outer surfaces of the receiver.

Receivers differ in design and power output depending on their function. They can be used to supply heat to a power-conversion unit (Brayton, Rankine, or Stirling) for the production of mechanical power or electricity, or they can be used in the production of process heat. Since the receiver absorbs concentrated solar radiation at temperatures up to 1500°C (2730°F), receiver materials need to be able to withstand high operating temperatures.

It is desirable to minimize receiver size and weight since small size improves fabricability and enhances the probability of survival under stressful conditions. In addition, small size aids in mounting and packaging of the receiver. A secondary consideration is to maximize the receiver cavity efficiency. The cavity efficiency takes into account the receiver thermal losses, primarily radiation and convection losses out the aerture opening, and losses from the receiver outer surface.

Although point-focusing systems are designed occasionally with open flat or spherical receivers, most use cavity receivers. The two primary advantages of cavity receivers are (1) the exposed area (or aperture) for outgoing radiation and convection is no greater than the exposed area for incoming solar radiation, and (2) the effective energy absorptance of a cavity is greater than that of an open receiver, thereby improving performance. Typical cavity receiver efficiencies in dish collectors range from a low of about 0.60 to a high of 0.95 or greater.

The size of the receiver aperture affects both the solar power delivered to the receiver by the concentrator and the thermal power lost via the aperture by the receiver. A large aperture permits more of the concentrated sunlight to enter the receiver but also increases radiative and convective losses via the

Strumpf, Hal J.; Kotchick, David M.; and Coombs, Murray G. (July 1982). "High-Temperature Ceramic Heat Exchanger Element for a Solar Thermal Receiver." *Parabolic Dish Solar Thermal Power Annual Program Review Proceedings; Atlanta, GA; 8-10 December 1981*. DOE/JPL - 1060-52. Pasadena, CA: Jet Propulsion Laboratory; pp. 233-247.

The results of a study on the development of a high-temperature ceramic heat exchanger element to be integrated into a solar receiver producing heated air are given in this paper. Several conceptual designs for the heat exchanger elements were evaluated with regard to thermal performance, pressure drop, structural integrity, and fabricability.

"Session II: Receiver Development." (April 1980). *Proceedings of the First Semi-Annual Distributed Receiver Systems Program Review; Lubbock, TX; 22-24 January 1980*. DOE/JPL - 1060-33. Pasadena, CA: Jet Propulsion Laboratory; pp. 75-98.

The three papers presented in this session of the conference describe several different parabolic dish receiver concepts. Two of the receivers were designed for Rankine energy conversion systems; one for a Stirling engine and one for a Brayton system.

Manvi, R.; Fujita, T.; Gajanana, B.C.; and Marcus, C.J. (November-December 1981). "Thermal Buffering of Receivers for Parabolic Dish Solar Thermal Power Plants." *Journal of Energy*. Vol. 5, (No. 6); pp. 381-386.

The article explains the need for buffering in dish systems. A computer analysis performed to assess thermal buffering characteristics of receivers containing sensible and latent heat thermal energy storage is described.

aperture. Receiver aperture size optimization interacts with the optimization of the concentrator itself and is dependent on the level of concentrator performance desired. Since insolation varies with the diurnal and seasonal cycles, as well as local cloud cover, the thermal energy entering the receiver is subject to corresponding time-dependent fluctuation.

The impact of these fluctuations on dish systems, which mount a power converter adjacent to the receiver, can be reduced by incorporating sensible and/or latent heat storage inside the receiver. The addition of thermal storage to receivers is referred to as thermal buffering since it provides a buffer between the variations in solar flux and the heat delivered to the heat engine. Buffering reduces engine part-load operation, improves efficiency, and alleviates control requirements. Additionally, buffer storage reduces engine start/stop cycles resulting from cloud cover. The use of buffer storage can, therefore, improve system operational characteristics during periods of rapidly fluctuating insolation and extend engine life.

Energy Conversion

When the energy collected by the parabolic dish is transported as a heated working fluid to a central location to be converted to electricity or used as a process fluid, the energy conversion equipment needed is similar to that described under Central Receiver. However, dishes can alternatively convert the heat collected directly to electricity by using a power converter located at the site of each dish.

Locating a power converter or heat engine at each collector minimizes the problem of heat loss from high-temperature ducting. The engine can be mounted on the ground near the collector with flexible ducts carrying the working fluid from the absorber cavity to the engine. Another method uses a secondary reflector at the dish focused to reflect energy to the heat engine suspended at the counterweight position of the collector. Both of these methods carry certain performance penalties. The most desirable approach, and the one most commonly in practice, involves suspending the engine itself, along with the receiver, above the concentrator, such that the aperture of the receiver is in the focal plane of the concentrator.

The combination of heat engine and receiver, when coupled with tracking and control subsystems, constitutes a power module. The effect of engine size on engine efficiency is an important influence on dish diameter. As engine size and power increase, so does the dish area required to provide the required solar flux. Power converters in the 20-25 kilowatt class work well with concentrator diameters of about 11 meters. As engine size is increased above this class, the manufacturing, transportation, and maintenance costs required for the correspondingly larger dish size increase and tend to overcome the small gain made in engine efficiency.

Since both the concentrator and the receiver tend to have efficiencies two or three times as high as power converters, the power converter plays a key role in the overall efficiency and

Truscello, Vincent C. (1981). "Power Converters for Parabolic Dishes." *Proceedings of the 1981 Annual Meeting of the American Section of the International Solar Energy Society; Philadelphia, PA; 26-30 May 1981*. Edited by Barbara H. Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 319-323.

This paper presents the development status of receivers and power conversion units to be used with parabolic dish concentrators. Applications are identified, and the key role played by the power converter element of the collector module is emphasized. Organic Rankine, air Brayton, and Stirling power conversion units are covered.

Nelving, Hans-Goran and Percival, Worth. (1983). "Design and Testing of A Second Generation Solar Stirling Engine Power Conversion System." *Proceedings of the 18th Intersociety Energy Conversion Engineering Conference (IECEC); Orlando, FL; 21-26 August 1983*. New York: American Institute of Chemical Engineers; V. 1, pp. 339-344.

The design and testing of the improved, second generation 4-95 solar Stirling engine power conversion system is discussed. Design rationale and performance results are presented for the improved receiver design, improved concentrator alignment, integrated cooling unit, and improved control system. Test results including maximum and average module performance are shown.

"Session III: Power Conversion Development." (April 1980). *Proceedings of the First Semi-Annual Distributed Receiver Systems Program Review; Lubbock, TX; 22-24 January 1980*. DOE/JPL-1060-33. Pasadena, CA: Jet Propulsion Laboratory; pp. 99-118.

Three papers were presented in the power conversion session of the conference. They examine the organic Rankine engine developed by Ford Aerospace and Communications Corporation, a Brayton engine developed by AiResearch cost-effectiveness of the solar collector. The power converter is also a major factor in the design integration of the collector module. Its weight is borne by the concentrator, and together with its large moment arm, has a strong effect on both system weight and on the dynamics of tracking control. Thus, the power converter is involved in both the cost and the performance of dish systems and in determining its service life and operation and maintenance costs.

Three types of heat engines are being tested for use with parabolic dishes: (1) Brayton, (2) Rankine, and (3) Stirling. Key development issues are the achievement of high engine performance and reliability and identification of operating requirements at the interface of the engine and receiver. An Organic Rankine Cycle (ORC) engine/generator unit has been selected as the power converter to be used in the first dish system for the small community series of engineering experiments because of its low life-cycle energy cost. The ORC working fluid is toluene, which is heated to about 371°C (700°F) in the receiver and then expanded through a single-stage axial flow turbine. The exhaust vapor passes through a regenerator and into a forced-air cooled condenser which constitutes the outer ring of the converter assembly. A high-speed alternator of the permanent magnet type is directly coupled to the turbine; its output is solid-state rectified for transmission to a central collection point.

Open-cycle air Brayton engines for parabolic dishes offer higher efficencies than the ORC, and cost benefits accrue from their current development as automotive gas turbine engines. One of the first-generation dish Brayton engines, developed by Garrett AiResearch, is designed to operate at a turbine inlet temperature of 815°C (1500°F). The engine is a recuperated, open-cycle machine in the 20-kilowatt size. When coupled with a high efficiency generator, it has an expected efficiency of 30%. Higher-temperature engines are being developed so that even higher efficiencies can be expected in second-generation Brayton engines.

Of the heat engine types considered for dish electric systems, the Stirling cycle offers the highest potential efficiency with a practical upper limit of about 45%. Although the technological complexity and limited life of Stirling engines currently make them impractical to use, research is underway, particularly in the automotive industry, to improve their performance and, in the case of solar energy applications, their ability to operate in all attitudes. The Stirling engine has many similarities to the technology used in conventional internal combustion engines, but heat is supplied externally and continuously to heat a gas which is contained in a completely closed system. The system developed by United Stirling of Sweden can produce 25 kWe at temperatures up to 700°C (1290°F).

A final consideration in designing the energy conversion subsystem is to determine the type of generator to connect to the heat engine: (1) synchronous alternating current; (2) induction alternating current; or (3) direct current. Direct current shunt generation is well suited to operation of a parallel field since start-up is simple and voltage control is

Manufacturing Company, and the Stirling P40 engine from United Stirling of Sweden.

Ramakumar, R. and Bahrami, K. (1980). "Dispersed Solar Thermal Generation Employing Parabolic Dish-Electric Transport with Field Modulated Generator Systems." *Proceedings of the 1980 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Phoenix, AZ; 2-6 June 1980.* Edited by Barbara Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 539-543.

This paper discusses the application of field-modulated generator systems (FMGS) to dispersed solar thermal electric generation from a parabolic dish field with electric transport. Electric conversion options, application of FMGS to dispersed solar thermal electric generation, and control interface and monitoring requirements are described.

accomplished easily by excitation control. However, direct current generators are about 50% more costly than alternating current generators and conversion to alternating current is required for most applications at extra cost and parasitic loss.

A more common machine is the synchronous ac generator. Establishing and maintaining synchronization is the main difficulty. Induction ac generators are also compatible with solar heat engine pairing and are particularly easy to control. This generator can be used as a motor to spin the heat engine rotor at synchronous speed. As solar power is applied, the engine rotor will operate slightly above synchronous speed and generate power. Efficiency of the induction generator is slightly less than for the synchronous generator but reliability is good.

Energy Transport Subsystem

Two types of energy transport subsystems can be used with parabolic dishes: thermal or electrical. Heat produced by the dishes can be transported as a thermal transport fluid in a piping network to a central location where it can be converted to electricity, used as a process fluid, or used to heat another working fluid. On the other hand, electricity can be produced at each collector and then transferred via cable to a central power system. A thermal transport system for dishes begins directly at the outlet of the receiver unit proper and entails all the piping, valves, pumps, etc. necessary to connect each receiver to the end-use point and then back again to the receiver inlet port (the cole leg). The design is broken into two elements: (1) receiver to ground (and return), and (2) base of dish to end-use point and return. The former is called the riser and downcomer segment and is assumed to be identical for every dish in the field. The latter element is the thermal transport network.

A typical riser/downcomer piping travels from the inlet/outlet ports of the receiver along separate support struts to the edge of the dish, curves along the back of the dish to the vicinity of the pedestal, attaches to a pedestal pipe with a short segment of flexible hosing (to accommodate dish movement) and ends near ground level. Depending on system temperature, the risers may or may not require insulation. The combined length of the combined riser and downcomer assembly can be about 42 m (140 ft) for a 100 m^2 (1075 ft^2) dish, making the piping a significant cost consideration.

The parabolic dish system's thermal transport network, less straightforward to design than the riser/downcomer segment, shares many of the characteristics, problems and potential solutions found in parabolic trough transport systems. However, even when dish piping systems are made to look as similiar to the trough's as is possible, their field piping lengths (and hence costs) differ significantly. After the trough receiver tube has been included in calculating the piping layout, dish pipe lengths are roughly 1 1/2 times greater than that required for troughs, and the costs are roughly twice that of the trough.

Iannucci, J.J. and Hostetler, L.D. (March 1981). *Design, Cost, and Performance Comparisons of Several Solar Thermal Systems for Process Heat, Volume IV: Energy Centralization.* SAND79-8282. Albuquerque, NM: Sandia National Laboratories; 91 pp.

A large matrix of self-consistent piping systems for dishes, troughs, and central receivers are designed, cost-estimated, and analyzed for performance. First order design differences and similarities are highlighted, with special emphasis on the comparison of dish and trough piping.

Fujita, T.; Revere, W.; Biddle, J.; Awaya, H.; and DeFranco, D. (1981). "Design Options for Low Cost Thermal Transport Piping Networks for Point Focusing Parabolic Dish Solar Thermal Systems." *Proceedings of the 1981 Annual Meeting of the American Section of the International Solar Energy Society; Philadelphia, PA; 26-30 May 1981.* Edited by Barbara H. Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 339-343.

Three design options for use in design tradeoff studies are investigated: (1) working fluids of steam, Therminol, and draw salt; (2) dish packing factors ranging from 0.3 to 0.5; and (3) supply and return temperatures ranging from 38°C (100°F) to 510°C (950°F). In addition, design variations involving the incorporation of flexible hoses to reduce installation costs are discussed, and transient heat soak losses associated wth cloud passage and evening shutdown are evaluated.

Pons, R.L. and Dugan, A.F. (1983). "Power System Optimization for a Point-Focus Solar Thermal Power Plant." *Solar Engineering — 1983: Proceedings of the ASME Solar Energy Division Fifth Annual Conference; Orlando, FL; 18-21 April 1983.* Edited by Lawrence M. Murphy. New York: The American Society of Mechanical Engineers; pp. 283-287.

The paper addresses the cost/performance optimization of the electrical subsystem for a distributed parabolic dish power plant with the energy conversion units mounted at the focus of each dish. Detailed cost estimates are prepared for the electrical components and the effect of dish size, dish field layout and spacing, and power cable size are examined.

The piping design process for parabolic dish systems (and troughs) consists of several tasks: (1) layout of collector and end-use point locations; (2) selection of piping scheme to connect collectors to the end-use point; and (3) determination of diameter and insulation thickness of each pipe segment as influenced by pipe and insulation capital costs, pumping power, and thermal losses. The primary influence on pipe length is the location or packing of the collectors. When dishes are closely packed, reduced field piping requirements result in smaller thermal transport losses and lower direct costs. However, these lower costs for closer packing must be traded off at a system optimization level with higher losses caused by shading of dishes by adjacent dishes. Systems that minimize shading without an increase in overall pipe length and resemble fluid flow designs in nature (i.e., trees or river basins) come closest to providing the optimum piping layout.

The transport of collector-produced electricity instead of heated fluid to a central site eliminates the high parasitic thermal losses suffered by high-temperature pipe networks. Some electrical power is lost, however, because of current thermal resistance heating. Standard components of the electrical energy transport system include the electrical cable, a central transformer, circuit breakers, capacitors for power factor control, motor/generator starters, and miscellaneous parts.

The actual transport of power from dish generators to the central site can be accomplished by buried cable that uses a routine construction method. Aluminum is less expensive than copper for cable material but has a higher resistivity; hence, more material is required. This is not altogether undersirable since the large aluminum wires lose heat to the ground more rapidly than smaller copper wires, therefore reducing the electrical resistance that rises with wire temperature. The overall efficiency of the elecrical transport system is estimated to be about 93%.

Project Descriptions

Solar Total Energy Project

The Solar Total Energy Project (STEP) at Shenandoah, Georgia uses parabolic dishes to generate electricity, process steam, and chill water for air conditioning. The energy is supplied to the Georgia Power Company grid and to a nearby knitwear factory owned by Bleyle of America, Inc. Objectives of this program include: (1) assessment of the interactions of solar total energy technology in an industrial application with an electric utility grid interface; (2) acquiring data for comparing cost and performance predictions; (3) promotion of industry engineering and development experience with complete solar total energy systems; and (4) dissemination of technical data.

When the solar system is fully operational, the solar total energy system will supply approximately 3 MW of thermal power that will, in turn, produce 400 kilowatts of electricity. In addition, the system will provide 610 kg/hr (1380 lb/hr) of

Hunke, Robert W. and Leonard, James A. (March 1983). *Solar Total Energy Project Summary Description*. SAND82-2249. Albuquerque, NM: Sandia National Laboratories; 20 pp.

A summary description of the energy system, its location, and the project site are presented for the Solar Total Energy Project (STEP) at Shenandoah, Georgia.

Saydah, A.R.; Kownig, A.A.; Lambert, R.H.; and Kugath, D.A. (April 1983). *Final Report on Test of STEP Shenandoah Parabolic Dish Solar Collector Quadrant Facility*. SAND82-7153. Albuquerque, NM: Sandia National Laboratories; 129 pp.

The report describes the "Quadrant Facility," an array of four 7-m diameter parabolic dishes, installed at Sandia Laboratories in Albuquerque, New Mexico, whose purpose is to support the design and development requirements for the Shenandoah project. The tests performed provided

process steam at a temperature of 170°C (335°F), and a major portion of the factory's air conditioning (up to 257 tons). Any excess electricity generated will be supplied to the Georgia Power Grid. Energy needs required by the Bleyle Plant beyond what can be supplied by the solar energy system is supplied by conventional sources.

The solar collector field consists of 114 parabolic dish collectors 7 m (23 ft) in diameter, making up a total aperture area of about 4400 m^2 (47,200 ft^2). The collectors are arrayed in a repeating diamond pattern. Using computer tracking, together with fiber optics, each collector tracks the sun and reflects a solar flux of over 235 suns to its receiver. The silicon transfer fluid circulating within the receiver is heated to 400°C (750°F) and then pumped to a heat exchanger where it boils water and superheats steam.

The superheated steam, over 370°C (700°F), drives a turbine generator, producing electricity. Medium-pressure steam is extracted from the turbine for knitwear pressing, and low-pressure steam is exhausted from the turbine and processed further to produce chilled water for air conditioning. A thermocline tank is used as a buffer storage supply for transient solar conditions.

useful information on the adequacy of the mechanical and structural design of the collector, the insulating quality of the various materials investigated, the pipe field design, the receiver design, the tracking system, and the reflector surface.

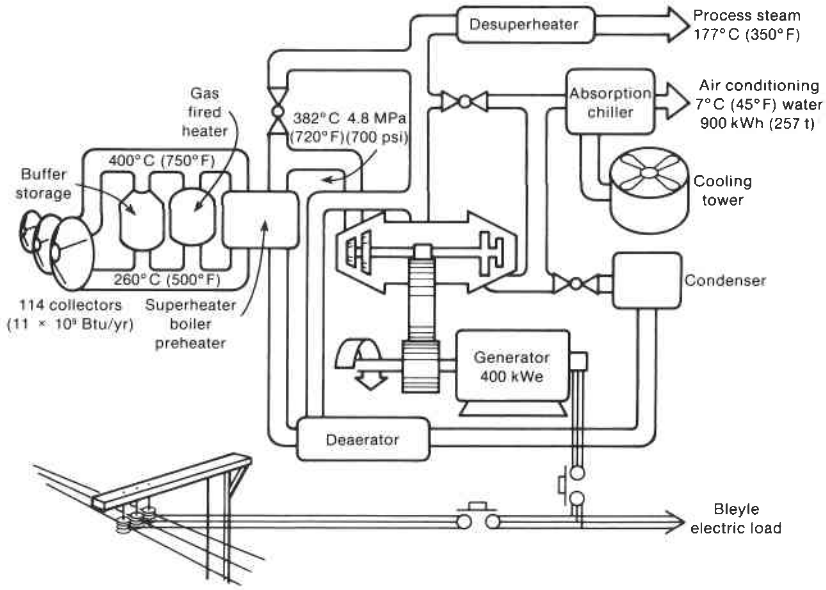
King, J. Willard and Geurts, Gary F. (1983). "Solar Total Energy Project — Shenandoah, Georgia." *Proceedings of the 1983 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy; Volume 6; Minneapolis, MN; 1-3 June 1983.* Edited by Barbara H. Glenn and Teresa Jankovic. New York: ASES Publishing Office; pp. 513-518.

The paper describes the Solar Total Energy Project located at Shenandoah, Georgia. In particular, plant activities and performance characteristics during 1982 and the beginning of 1983 are documented.

Solar Total Energy Project; Shenandoah, Georgia Site. Annual Technical Progress Report for the Period July 1, 1980 through June 30, 1982. (1982). ALO/3994-83/1. Atlanta, GA: 79 pp.

Summary information for the period July 1, 1977 through June 1980 is included as well as the detailed data reflecting the more recent progress of the Shenandoah Solar Total Energy Project (STEP). Information is provided on the STEP project participants, site preparation and construction, meteorology station, information dissemination efforts, and costs.

STEP in Operation at Shenandoah, Georgia



Schematic Diagram of STEP

The construction of the solar project was completed early in 1982. During the remainder of the year, start-up operations and acceptance tests were conducted by a joint operational team of Sandia National Laboratories and Georgia Power Company. Various electrical and mechanical problems became apparent during this phase and have mostly been resolved. The program has now moved into the experimental operations test phase which will take two years, after which an additional two years of independent operation by Georgia Power Company is scheduled.

Capitol Concrete Industrial Process Heat Experiment

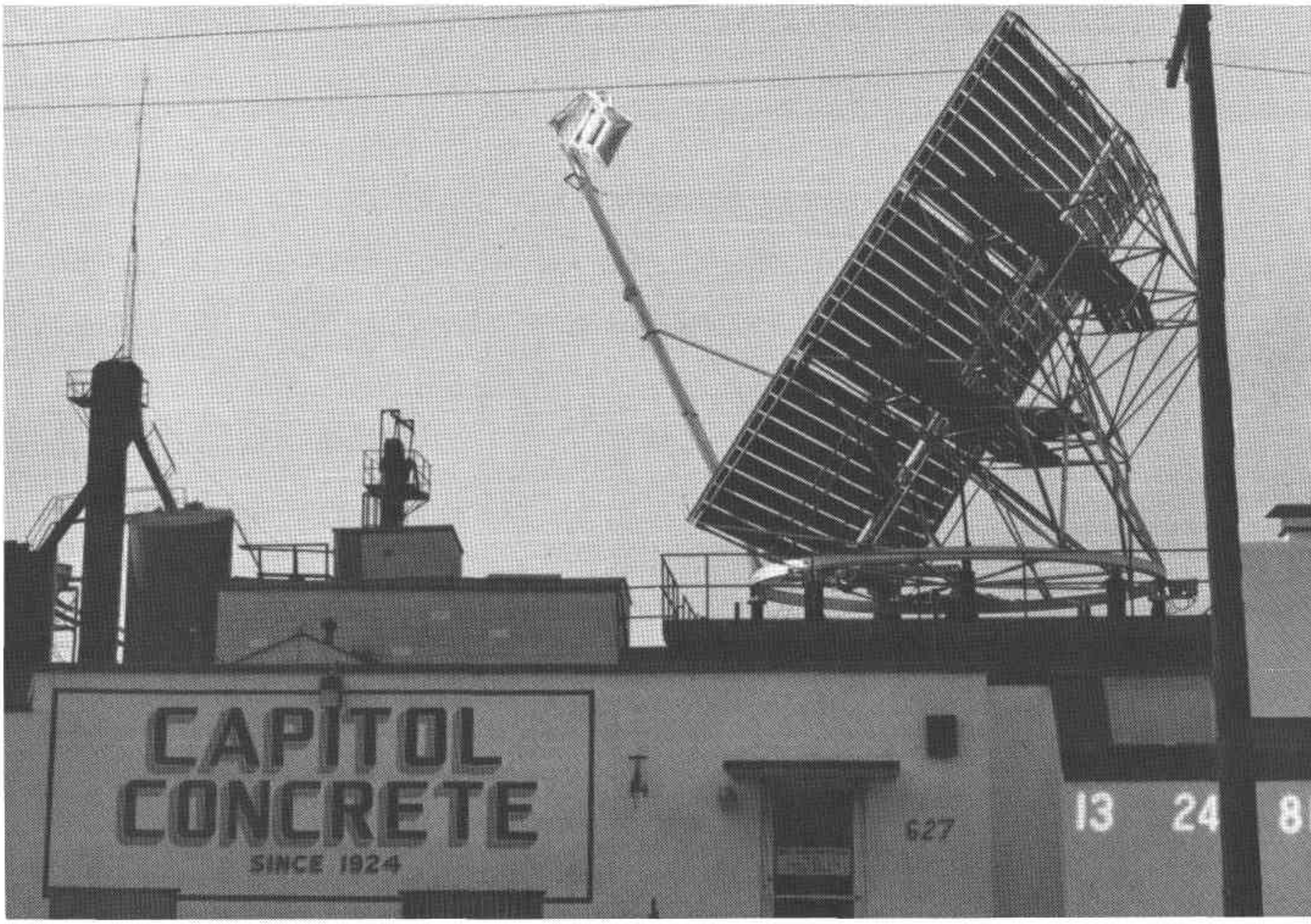
The Capitol Concrete Industrial Process Heat Experiment was initiated in 1980 by JPL to determine the technical feasibility of using a Fresnel point-focusing collector to provide process steam in an industrial environment. The concentrator, which was designed and fabricated by Power Kinetics, Inc. (PKI), consists of 864 square mirrors mounted on 198 identically curved modular support assemblies attached to a lightweight space-frame structure. The 80 m^2 (864 ft^2) array is mounted on a 7.3 m (24 ft) diameter steel track which, in turn, rests on eight casters mounted on the foundation. Tracking is accomplished by rotating the collector track on its casters for azimuth and simultaneously rotating each mirror support assembly for elevation.

The concentrator focuses sunlight on a cavity receiver. The 11 m (36 ft) boom supporting the receiver at the focal plane is hinged at the concentrator base for easy access and is stabilized with guy wires. A piston pump supplies boiler water from a feed tank to the receiver where it is converted to steam.

The solar collector was incorporated into the plant to provide steam for curing blocks in an autoclave at pressures of 15-16 psig. Installation of the system at Capitol Concrete Products was completed in fiscal year 1982 and DOE's

Auger, J. Scott and Browning, Ray. (1983). "Capitol Concrete Solar Industrial Process Heat Experiment." *Proceedings of the Distributed Solar Collector Summary Conference —Technology and Applications; Albuquerque, NM; 15-17 March 1983.* Edited by Robert L. Alvis. SAND83-0137C. Albuquerque, NM: Sandia National Laboratories; pp. 293-296.

An overview of the Capitol Concrete Industrial Process Heat Experiment is presented. The experimental results are given for the system failure analysis, system operability testing, and performance testing.



Capitol Concrete IPH Experiment in Topeka, Kansas

participation in the operational responsibility was assumed by Capitol Concrete at that time.

The experience gained during the Capitol Concrete project has led to similar Fresnel point-focusing collectors being built at Hill Air Force Base in Utah and in Yanbu, Saudi Arabia.

Chapter 5

Other Solar Thermal Technologies

Hemispheric Bowls

Unlike the other concentrating collectors discussed in previous sections, hemispheric bowls consist of a stationary reflector that directs sunlight onto a tracking linear absorber or receiver which is suspended above the bowl cavity. Bowls can be larger than other concentrating devices because the reflecting surface does not move to track the sun. Bowls are installed at an angle to the horizon corresponding to the latitude of a given location and the receiver is moved to maintain a position at the focal line of the bowl's reflecting surface.

Hemispheric bowls, which are also known as Stationary Reflector/Tracking Absorbers (SRTA) and Fixed Mirror Distributed Focus (FMDF) devices, are constructed from a matrix of accurately aligned spherically contoured glass mirror panels attached to a rigid support structure. Because of the spherical symmetry of the collector assembly, the optical behavior of this concentrator is independent of solar incidence angle, unlike any other concentrator. Solar rays entering the collector aperture are reflected to form a focus distributed along a line that extends from the reflective mirror surface to one half the radius of curvature of the concentrator mirror surface. The solar ray that passes through the center of curvature of the concentrator forms the axis of the roughly linear focus. The linear focus maintains essentially the same characteristics and position with regard to the center of curvature and the sun throughout the day.

Consequently, a receiver is placed in the linear focus and pivoted, via a support structure, about the center of curvature to intercept essentially all direct light rays entering the concentrator aperture while following the motion of the sun. The receiver is a hollow tube surrounded by a spiraling coil. Water is piped up one of the receiver supports, fed into the tube, and allowed to flow to the lower end of the receiver. The heat absorbed by the receiver converts the water to steam which rises up through the spiral coil. Accurate controls are required to optically align the receiver with the linear focus of the bowl concentrator to provide maximum heat collection.

The main advantage of the hemispherical bowl is that it uses a fixed reflector which makes possible the construction of large units at reasonable cost. Other advantages of the spherical bowl shape is that the focal zone is well shaped for concentration and heat transfer, and the power on the receiver remains constant throughout the day.

The major disadvantage of hemispherical bowl systems is the incidence angle loss. This angle depends on the latitude and the orientation of the reflector and varies with the time of day

Fruchter, E.; Grossman, G.; and Kreith, F. (November 1982). "An Experimental Investigation of a Stationary Reflector/Tracking Absorber Solar Collector at Intermediate Temperatures." *Journal of Solar Energy Engineering*. Vol. 104 (No. 4) pp. 340-344.

The design, construction, and testing of a concentrating solar collector based on the Stationary Reflector/Tracking Absorber (SRTA) principle is described. The system consists of a fixed, 2.5-m diameter, spherical mirror that focuses solar radiation on a movable cylindrical absorber tracking the sun.

O'Hair, Edgar A. (1983). "Present Solar Bowl Technology Status," and Walters, Robert R. "E-Systems Fixed Mirror Distributed Focus (Bowl) Collector Technology Summary." *Proceedings of the Distributed Solar Collector Summary Conference — Technology and Applications; Albuquerque, NM; 15-17 March 1983.* Edited by Robert L. Alvis. SAND83-0137C. Albuquerque, NM: Sandia National Laboratories; pp. 342-357.

These two papers summarize the work performed since 1975 on the hemispheric bowl concept and describe its present technology status. The Crosbyton bowl is discussed and the estimated performance and economics for a prototype collector field design comprised of a large number of 61-m (200-ft) bowls is described.

and time of year. Degradation in the collector's performance occurs during times of the day that are appreciably removed from solar noon and during times of year at which the aperture is not at a favorble inclination. Since the convection and radiation losses from the absorber are constant at a given collector temperature, the thermal efficiency of the collector system also decreases with increasing incidence angle and at a rate faster than the rate of decrease of the cosine of the angle of incidence.

Optical and view factor losses account for about a 50% performance penalty. Thermal losses are relatively smaller and account for a loss of from 2% to 15% of the total incident radiation over a day. The remaining 35%-50% of the incident radiation can be converted ultimately to heat for operation of a power plant or other thermal conversion device. Bowls, such as the PERICLES in France and the SOLAR GRIDIRON in Texas, can produce temperatures up to 550°C (1020°F). Other smaller bowls intended for mid-temperatrue applications produce temperatures in the range of 300°C (570°F).

Crosbyton Solar Power Project

A 20-m diameter (65-ft) hemispheric bowl has been in operation near Crosbyton, Texas since January 23, 1980. The Crosbyton bowl, also known as the Solar Gridiron and the Analog Design Verification System, was designed and built for DOE by a team of researchers from Texas Tech University and E-Systems, Inc. The concept uses a spherical segment mirror to concentrate incident solar radiation and a once-through, high-pressure steam boiler to capture the concentrated light energy for use in process heating or for electrical power generation. The Crosbyton bowl is capable of producing steam at temperatures of about 550°C (1020°F) and 7 MPa pressure.

Reichert, John D. and Watson, Karan L. (1982). "The Crosbyton System." *Proceedings of the 1982 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Houston, TX; 1-5 June 1982*. Preprint edition. Edited by Barbara Glenn and Gregory E. Franta. New York: ASES Publishing Office; V. 5.1, pp. 343-348.

System and performance descriptions of the Crosbyton bowl are given. In addition, a method is provided to evaluate the optical/thermal properties of a solar gridiron collector before the system is built.

The Crosbyton bowl is constructed of a mosaic of 438 silvered glass facets, each about 1 m² in size, that are stressed to a spherical shape and bonded to paper honeycomb backing structures. The collector is tilted 15 degrees to the south,

20-m Hemispherical Bowl in Operation near Crosbyton, Texas which obtains 85% of the annual maximum benefit available from tilting the bowl (the costs involved outweigh the performance advantages of tilting the bowl to its optimum 33-degree angle). The receiver consists of a cylindrical structure 15.25 cm (6 in.) in diameter around which tubing is helically wrapped. The receiver tubes are made of Inconel 617 and painted black with Pyromark paint to provide an average absorptivity of about 90%.

The most significant technical problem identified during operation has been the so-called "mirror hot-spot." The mirror facets at the base of the focal line have been found to absorb enough energy to heat and crack from thermal stress. This problem occurs only when the receiver is not in tracking position to absorb reflected energy; so, it is not a daily problem. Preventive measures, such as shading devices or active cooling systems, are being examined, but major emphasis has been on developing a mirror panel capable of withstanding the condition without active protection.

Other significant investigations have involved the development of lower-cost components. These have included larger individual facets and a concept called the "super panel" which consists of large multi-faceted, factory-assembled panels. The super panel would reduce the amount of field labor at a bowl construction site by permitting the installation crew to install a larger area of reflective surface in a single operation.

Receiver Assembly of Hemispherical Bowl near Crosbyton, Texas. The water inlet and steam output lines are visible in the foreground.

Salt-Gradient Ponds

Solar thermal energy systems based on the solar pond concept differ considerably from the other solar thermal technologies examined in previous sections. The solar pond is simultaneously a collector of solar radiation and a large body of thermal storage.

Any pond converts insolation to heat, but, in most natural ponds, the temperature gradient sets up convection currents that mix the pond's water. Surface evaporation and convection create rapid heat loss. The solar pond minimizes vertical convection or surface evaporation and convection.

Solar pond concepts may be classified into two categories: (1) those that reduce heat loss by covering the pond's surface, and (2) those that reduce heat loss by preventing convection within the water storage medium. This latter category contains the nonconvecting salt-gradient pond. Since the salt-gradient pond also appears to be the most promising concept for solar thermal applications, it is the only type of solar pond to be discussed here.

Salt-gradient solar ponds are shallow bodies of water in which salt has been dissolved in high concentrations near the bottom and in decreasing concentrations approaching the surface. The main feature of the salt-gradient pond is that the high concentrations of dissolved salt near the pond's bottom is sufficient to maintain a density so that the heated brine

Tabor, H. (1981). "Review Article: Solar Ponds." *Solar Energy*. Vol. 27 (No. 3); pp. 181-194.

This report provides the background and the current status of solar ponds as proven viable large-area collectors capable of providing both low-cost thermal energy and mechanical or electrical energy using state-of-the-art low-temperature turbo-generators. The following topics are covered: history and motivation for using solar ponds; basic concepts and theory of the solar pond; problems and limitations of ponds; practical details, costs and experiences in solar ponds to date; and applications and the future potential of solar ponds.

Nielsen, Carl E. (1980). "Chapter 11: Nonconvective Salt-Gradient SolarPonds." *Solar Energy Technology Handbook. Part A: Engineering Fundamentals*. Edited by William C. Dickinson and Paul N. Cheremisinoff. New York: Marcel Dekker, Inc.; pp. 345-376.

The chapter briefly reviews solar pond research performed to date; summarizes the theory and operating procedures so far as they are established; discusses the problems remaining to be solved; presents simple calculations of pond performance; and concludes with characterization of some possible applications and estimates of cost of heat in each case.

remains heavier than the colder, but lighter, upper layers. Thus, the hottest part of the pond remains at the bottom. The high salt concentration is maintained in the lower portion of the pond by pumping in concentrated brine near the pond's floor. At the same time, the low salt concentration is maintained near the surface by continuously feeding cool, fresh water into the top layer. Salts most commonly used are sodium-chloride (NaCl) and magnesium chloride ($MgCl_2$), although there are numerous other possibilities. Total depth may range from a fraction of a meter to several meters.

Normally, ponds consist of three zones: (1) a relatively thin homogeneous and convective surface layer, (2) a nonconvective gradient zone in which there are gradients in salinity and temperature, and (3) a homogeneous and convective bottom zone. The top layer is affected by wind and evaporation. This layer serves no independently useful purpose and is kept as thin as possible. The nonconvective gradient zone transfers heat by conduction only, water being opaque to thermal radiation at the temperature of operation. Thus, it acts as a partially transparent window of low thermal conductivity that allows some of the solar radiation to penetrate into the bottom zone to heat it, while at the same time, the middle layer insulates the bottom against heat loss. The bottom gradient zone remains gravitationally stable because of its salinity, and it is this layer that provides useful thermal storage.

Tabor, Harry and Weinberger, Zvi. (1981). "Chapter 10: Nonconvecting Solar Ponds." *Solar Energy Handbook*. Edited by Jan F. Kreider and Frank Kreith. New York: McGraw-Hill Book Company; pp. 10-1 to 10-29.

The purpose of this chapter is to define the potential of solar ponds and to describe their problems. Sections are included on establishing and maintaining the nonconvective pond, the available solar irradiation and its absorption in the pond, temperatures and efficiencies of solar ponds, energy extraction methods, geophysical and ecological factors, and specific applications.

Solar Ponds: A Selected Bibliography. (November 1981). SERI/TR-752-711. Golden, CO: Solar Energy Research Institute; 24 pp.

The bibliography is divided into three sections: (1) solar ponds, (2) shallow solar ponds, and (3) patents. Two hundred sixty-eight citations are listed.

Kamal, Jyoti and Nielsen, Carl E. (1982). "Convective Zone Structure and Zone Boundaries in Solar Ponds." *Proceedings of the 1982 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Houston, TX; 1-5 June 1982*. Vol. 5.1. Preprint edition. Edited by Barbara Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 191-196.

The paper reports results of a study of the temperature structure in convective zones and in the transition region between convective and gradient zones. The paper describes observations made in ponds and laboratory tanks; a model for convective heat transfer is presented; and the implications for pond operation are discussed.

Natural Solar Ponds

Salt-gradient ponds or lakes have existed in nature for a long time although the phenomenon was observed and recorded only relatively recently. In the limnological (the study of fresh water conditions) literature, the lakes are called meromictic lakes and the salt-concentration gradient is called the halocline. In addition to their salt-gradient characteristics, all of the naturally occurring solar lakes are protected by surrounding geographic features from wind-caused mixing. Natural nonconvective, salinity-gradient solar ponds can be found throughout the world including Hungary, Israel, the United States, Venezuela, and the Antarctic.

The first recorded reference to a natural solar lake was published by Kalecsinsky in 1902, in which he describes the Medve Lake in what was then Transylvania. The lake displayed temperatures increasing up to 70°C (160°F) at a depth of 1.2 m (4 ft) at the end of summer. A near-saturation salinity of 25% solium chloride has been recorded at the bottom.

Several other naturally occurring solar-heated lakes have been discovered since that time. A natural solar lake near Eilet, Israel has apparently been in existence for 3000 years but was not identified and recognized as a solar pond until 1976. A lake

Kalecsinsky, A. (1902). "Ueber die ungarischen warmen und heissen Kochsalzseen als naturliche Warmeaccumulatoren, sowie uber die Herstellung von warmen Salzseen und Warmeaccumulatoren." *Annalen der Physik*. Vol. 7 (No. 4); pp. 408-416.

Anderson, G.C. (1958). "Some Limnological Features of a Shallow Saline Meromictic Lake." *Limnology and Oceanography*. Vol. 3 (No. 259); pp. 259-270.

Seasonal variations of physical, chemical, and biological features of Hot Lake, a shallow saline body of water occupying a former epsom salt excavation in north central Washington, were studied for almost two years.

Wilson, A.T. and Wellman, H.W. (22 December 1962). "Lake Vanda, An Antarctic Lake." *Nature*. Vol. 196 (No. 4860); pp. 1171-1173.

The article describes a study of the physics and chemistry of Lake Vanda and reports the heat balance of the lake.

Hudec, P.P. and Sonnenfeld, P. (1974). "Hot Brines on Los Rocques, Venezuela." *Science*. Vol. 185; pp. 440-442.

near Oroville, Washington has displayed temperatures of 50°C (122°F) in midsummer at a depth of 2 m. Although under a permanent ice cover, Lake Vanda in the Antarctic has displayed bottom temperatures at a depth of 66.4 m (218 ft) of 25°C (77°F) while the ambient temperature was -20°C (-5°F).

The natural hot brines found in a restricted shallow island lagoon in Venezuelan Antilles are described.

Cohen, Y.; Krumbein, W.; Goldberg, M.; and Shilo, M. (July 1977). "Solar Lake (Sinai). 1. Physical and Chemical Limnology." *Limnology and Oceanography*. Vol. 22, (No. 4); pp. 597-608.

A detailed study of the limnology of Solar Lake during 1969-1974 is presented. It is described as a mesothermic, hypersaline desert lake with extremely high solar heat accumulation and an unusual type of holomixis with summer overturn.

Artificial Solar Ponds

The idea of building artificial solar ponds and using the resulting thermal energy for practical purposes was suggested by Israeli scientists in the 1950s. Later, the concept was expanded to include conversion of parts of naturally occurring large bodies of salt water, such as the Dead Sea, to solar ponds. In 1960 an experimental solar pond covering 625 m^2 (6725 ft^2) was constructed at the Dead Sea, thus proving the technical feasibility of the artificial solar pond concept. Since 1974 Israel has been one of the leading countries in solar pond research. Descriptions of Israeli solar ponds can be found in the International Programs section of Chapter 1.

Solar pond research in the United States began in 1974 at Ohio State University as the outgrowth of a search for a long-term, heat-storage system. A 200-m^2 pond was built in 1975 and has been in operation since that time. Subsequently, a 400-m^2 pond has been built in Columbus, Ohio. Some of the objectives for the two experimental ponds are to test boundary migrations and stability, measure perimeter heat loss, test reflectors, and conduct heat extraction experiments.

Work on solar ponds has been reported also from other U.S. universities and research centers. The University of New Mexico has constructed a sodium chloride pond 170 m^2 (1830 ft^2) in size and 2.5 m (8 ft) deep. Temperatures in excess of 100°C (212°F) have been reported. The largest research-only, salt-gradient pond was built by Argonne National Laboratory (ANL) in 1980; 1010 m^2 (1/4 acre) in size and 4.27 m (14 ft) deep, the pond is considered to be a regional facility and is available to researchers other than ANL for conducting solar pond experiments.

Several large-scale solar pond projects that would be located near natural salt-water lakes have been proposed. In particular, Truscott Brine Lake, Great Salt Lake and the Salton Sea have been studied as possible locations. Although none of the projects has actually been built, conceptual designs have been completed for each.

Finally, several solar ponds have been built to provide heat for actual applications, as well as experimental purposes. The two largest of these "working" ponds are located in Miamisburg, Ohio and Chattanooga, Tennessee. The Miamisburg pond is 2000 m^2 (21,500 ft^2) in size and 3 m (10 ft) deep. One of the first solar ponds built with the specific intention of providing

Nielsen, Çarl E. and Kamal, Jyoti. (1981). "The 400 m^2 Solar Pond: One Year of Operation." *Proceedings of the 1981 Annual Meeting of the American Section of the International Solar Energy Society; Philadelphia, PA; 26-30 May 1981.* Edited by Barbara H. Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 758-762.

Data on solar input, heat gain by the pond, heat loss to the earth, and heat conducted upward through the gradient zone have been analyzed and an energy balance for the year was calculated.

Weeks, D.D. and Bryant, H.C. (1981). "What Happens When a Solar Pond Boils?" *Proceedings of the 1981 Annual Meeting of the American Section of the International Solar Energy Society; Philadelphia, PA; 26-30 May 1981.* Edited by Barbara H. Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 768-771.

A description of the thermal history of the University of New Mexico salt-gradient solar pond is given, followed by an account of boiling that the pond experienced during July 1980.

Hull, J.R.; Cha, Y.S.; Sha, W.T.; and Schertz, W.W. (1982). "Construction and First Year's Operational Results of the ANL Research Salt Gradient Pond." *Proceedings of the 1982 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Houston, TX; 1-5 June 1982.* Vol. 5.1. Preprint edition. Edited by Barbara Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 197-202.

The paper describes features of the construction and initial results of the Argonne National Laboratory Research Salt Gradient Solar Pond (ANL-RSGSP) that may be of interest to future users of either the pond facility or experimental data derived from the pond.

Chinery, G.T. and Siegel, G.R. (1983). "Design, Construction, and Cost of TVA's 4000 m^2 (1-Acre) Nonconvecting Salt Gradient Solar Pond." *Solar Engineering — 1983: Proceedings of the ASME Solar Energy Division Fifth Annual Conference; Orlando, FL; 18-21 April 1983.* Edited by Lawrence M. Murphy. New York: The American Society of Mechanical Engineers; pp. 150-156.

Design criteria, construction specifications, and a detailed breakdown of actual costs incurred in the construction of TVA's solar pond are documented.

useful heat, the Miamisburg pond provides heat to the city's recreational building and swimming pool.

The 4000-m² (1-acre) nonconvecting, salt-gradient solar pond constructed by the Tennessee Valley Authority (TVA) in 1981-82, was built to demonstrate the technical and economic feasibility of the solar pond concept for producing direct heat for agricultural purposes, buildings, and industrial process applications in the TVA region. More of an experimental pond than the Miamisburg pond, the TVA pond will also be used to determine if the nonconvecting solar pond concept could provide heat at sufficiently high temperatures to permit practical electrical power generation by low-temperature power cycles. In addition, this pond is considered a national "test bed" for solar pond experiments by groups other than TVA.

Wittenberg, L.J. and Harris, M.J. (February 1981). "Construction and Startup Performance of the Miamisburg Salt-Gradient Solar Pond." *Journal of Solar Energy Engineering*. Vol. 103 (No. 1); pp. 11-16.

In addition to descriptions of the design and construction of the Miamisburg, Ohio solar pond, information is given on maintenance, performance, thermal energy balance, and cost evaluation of the pond.

Solar Pond Construction and Operation

Constructing a solar pond involves building a suitable container, filling it with brine in such a way as to create the desired gradient, and providing a system for heat removal. Mechanical components can include a piping network and pumping system, turbine/generator, condensor, and evaporator. The container, in its simplest form, is merely an area surrounded by an earth embankment. In order to prevent possible leakage, it may be necessary to use a liner. Ponds can also be built within an existing body of salt water, such as the Great Salt Lake and the Dead Sea, using a dike for separation.

When filling a pond, all that is necessary, in principle, is to add two layers. The bottom part is filled with water to which the salt is then added and dissolved by stirring the water with a pump. After the salt is dissolved, the remaining depth of the pond is filled with fresh water. The transition between the brine and fresh water will eventually grow to produce a gradient zone. However, with this approach, it can take a considerable amount of time to reach equilibrium. The final desired state can be reached more rapidly by filling the pond with several layers of graded salinity.

In order to maintain the pond's solar heating attributes, the effects of wind and fouling need to be minimized and the salinity gradient needs to be renewed continually. Wind control is needed for ponds of any appreciable size in order to avoid mixing of the top surface water with the nonconvecting zone. The thicker the top convecting zone is, the more solar radiation it absorbs, reducing the temperature and efficiency of the pond. Fouling of the water by either inorganic dirt or organisms reduces the transparency of the pond, particularly if the particles are suspended under the surface where they cannot be rinsed off. Biological growth can be suppressed by chemical means. The maintenance of the salinity gradient is accomplished by a combination of surface washing and adding salt to the bottom.

Solar ponds are readily applicable to such low-temperature uses as residential or commercial district heating and hot water, low-temperature industrial or agricultural process heat,

Fynn, R. Peter and Short, Ted H. (February 1983). *The Salt Stabilized Solar Pond for Space Heating: A Practical Manual*. Special Circular 106. Wooster, OH: Ohio Agricultural Research and Development Center, Ohio State University; 40 pp.

The manual is designed to inform potential users of the existence of solar ponds, and to provide information on the applications and operation of solar ponds. Although not intended to be a complete design guide, information is given on the primary elements of solar pond construction and operation.

Jaluria, Yogesh. (February 1982). *Heat Rejection and Energy Extraction within Solar Ponds*. SERI/RR-252-1393. Golden, CO: Solar Energy Research Institute; 57 pp.

The report studies the thermal and fluid flow processes underlying heat rejection to the surface layer in the top half and energy extraction from the storage zone in the bottom half of a pond. The study concludes that the gradient layer can be maintained, with a negligible effect from the two recirculating flows, if the flows are spread over the width of the pond, a suitable diffuser height is used to reduce the flow velocities, and the diffusers are located as far as possible from the interface with the gradient zone.

Lin, E.I.H.; French, R.L.; Singer, M.J.; Wu, Y.C.; McMurrin, J.C.; Barbieri, R.H.; Walton, A.L.; Jones, S.C.; Hurick, M.G.; Levine, N.; and Richter, P.H. (March 1982). *Regional Applicability and Potential of Salt-Gradient Solar Ponds in the United States*. DOE/JPL-1060-50. Pasadena, CA: Jet Propulsion Laboratory; 2 V.

The study was conducted from August 1980 through November 1981 to assess solar pond resources, applicability, and potential use in the U.S. The study focused on the general characteristics of twelve geographic regions that included: a survey of natural resources essential to solar ponds; an examination of meteorological and hydrogeological conditions affecting pond performance; the identification of potentially favorable pond sites; calculation of regional thermal and electrical energy output; a study of selected pond design cases; an or preheating for higher-temperature industrial process heat applications. Combined with organic Rankine cycle engines, solar ponds can be used for electric power generation. By using the heat to operate an absorption chiller, solar ponds can be used for cooling, also.

In order for the energy generated by a solar pond to be used for any of these applications, the heat must first be extracted from the pond. So far, two heat removal methods have been used with solar ponds. In the first method, hot brine pumped from the bottom of the pond is circulated through an external heat exchanger or evaporator and returned to the pond. The use of appropriate diffusers prevent excessive velocities of motion within the pond and thereby minimize the erosion of the gradient zone. The second tested method for heat removal is the use of heat-exchange pipes in the pond. Heat-exchange fluid, normally water, passed through these pipes is heated and transfers the heat to radiators or other systems where the heat is to be used. If the heat exchanger is located a short distance below the lower boundary of the gradient zone, the heat removal can stimulate convection through the lower convective zone and remove heat from its entire volume.

Solar ponds differ markedly from other collectors in performance characteristics. One reason for this is that the optimum gradient-zone depth, that is, the system configuration, is different for each set of values of radiation input, heat output, and working temperature. Also, solar ponds are constantly open to the environment and are, thus, constantly operating, collecting all available solar radiation. Considerations in siting a solar pond include: (1) availability of an inexpensive source of salt and water for pond maintenance; (2) absence of geophysical structures such as stresses, strains, and fissures; (3) lack of close proximity to underground fresh water or underground aquifers; and (4) availability of flat land to reduce earth-moving.

evaluation of five major potential market sectors; a detailed economic analysis; and a comparison of solar pond energy costs with conventional energy costs.

Moshref, A. and Crevier, D. (1982). "Electric Power Generation by Solar Ponds: Modelling and Optimization." *Proceedings of the 1982 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Houston, TX; 1-5 June 1982.* Vol. 5.1. Preprint edition. Edited by Barbara Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 203-208.

This paper presents a basis for the systematic optimization of a solar pond power plant. The procedure consists of (1) the examination of the system components and the formulation of their mathematical models and governing equations in terms of thermodynamic and economic parameters, and (2) the solution of the mathematical model using an optimization program.

Edesess, Michael; Henderson, Jon; and Jayadev, T.S. (December 1979). *A Simple Design Tool for Sizing Solar Ponds.* SERI/RR-351-347. Golden, CO: Solar Energy Research Institute; 32 pp.

The report provides simple formulas in "cookbook" format to calculate the required pond surface area and depth. These formulas will enable a potential user to determine the approximate size of solar pond needed for the proposed application and location. In addition, examples of solar pond sizes at various locations in the United States are given.

Chapter 6
Applications

Solar Thermal Electricity Production

Potential and Technologies

Approximately 25% of end-use energy in the U.S. is electrical. This creates a large potential market for solar thermal electric technology. Electrical applications considered for development include peaking, intermediate, and baseload utility plants; cogeneration; irrigation; remote villages; and small community and industrial parks. With the active development of solar thermal electric systems about ten years ago, their technical feasibility has been demonstrated using a variety of approaches. The selection of which conversion approach is best for a particular application depends upon several variables of which the most important are the performance and cost characteristics of the system.

Solar thermal electric power is generated by absorbing the sun's radiant energy and converting it to thermal energy. Usually the thermal energy is converted to mechanical energy by one of several procedures, and then the mechanical energy is used to drive a conventional generator to produce electricity. A storage subsystem may or may not be interposed between the collector and heat engine subsystems. The major considerations used in determining which system is best for a particular application are system performance, component and system cost, the size of the plant needed, nature of the load and availability, the amount and type of insolation available, reliability, and institutional issues. Usually the most important single decision factor is the cost of energy produced by the system.

Murphy, Lawrence M. (July 1981). *The Use of Solar Thermal Energy to Generate Electricity*. SERI/TP-632-1287. Golden, CO: Solar Energy Research Institute; 2 pp.

The status of the various solar thermal electric concepts is discussed along with the principal areas of research for each respective concept. Cost issues and prospects for the economic competitiveness of solar thermal electric systems with conventional systems are outlined.

Rosenburg, L. S. and Revere, W. R. (June 1981). *A Comparative Assessment of Solar Thermal Electric Power Plants in the 1-10MWe Range*. DOE/JPL-1060-21. Pasadena, CA: Jet Propulsion Laboratory; 79 pp.

The objective of this study is to rank a number of candidate thermal power systems in terms of the cost of electric energy each system produces. The study focused on small (l - 10 MWe) thermal power systems for the small community electric power market.

Solar Thermal Plant Impact Analysis and Requirements Definition Study; Final Report. (February 1982). NASA-CR-169310. Pasadena, CA: Jet Propulsion Laboratory; 522 pp. Work performed by Science Applications, Inc., McLean, VA.

The objectives of this study are to select case studies from potential solar electric system types, site locations, and applications and to evaluate these cases with regard to system performance, system impacts and economic analysis, conceptual design, and requirements of definition. The system concepts evaluated included a range of design alternatives: central versus dispersed generation; Rankine, Brayton, and Stirling thermodynamic cycles; different energy transport modes (electric, oil, sodium, steam); and storage, no storage, and hybrid fossil configurations.

Baccelli, Elizabeth and Gordon, Karen. (July 1982). *Electric Utility Solar Energy Activities: 1981 Survey.* AP-2516-SR. Palo Alto, CA: Electric Power Research Institute; 310 pp.

The report contains brief descriptions of 943 solar energy projects being conducted by 236 utility companies. In the area of solar thermal electric power, the EPRI survey discovered that 64 projects had been undertaken by 53 utilities during 1981.

Nonconcentrating collector systems that can be used to provide thermal energy for electric generation include flat plate collectors, evacuated tube collectors, and solar ponds. However, most of these collector systems are best suited for applications other than power generation because of their poor performance/cost characteristics in this application. A possible exception to this is the salt-gradient solar pond which appears to be an attractive means of electricity generation because of the low cost of the pond collector and the pond's inherent storage system. The development of solar ponds is still in the preliminary stages with many issues such as hydrodynamic stability, salt contamination, liner durability, and effective heat-transfer methods still being investigated to determine realistic performance/cost measures for ponds relative to other concepts.

Both point-focusing and line-focusing concentrating collector systems have been proposed for solar thermal electric applications. Line-focus collector concepts are either of the distributed receiver type or the central receiver type. The most developed line-focus technology is the distributed single-axis tracking parabolic trough. Although the bulk of parabolic trough development has been carried out with industrial process heat in mind, electricity generation can be cost-effective relative to other line-focus technologies. A potentially attractive use of trough technology is the combined generation of thermal and electrical energy; this method cascades the energy use so that the energy produced at each point is matched with the most appropriate use. Called a cogeneration total energy system, this type of application is discussed in more detail later.

The two point-focusing technologies of particular interest for electricity generation are parabolic dishes and central receivers. Parabolic dishes with small heat engines located at each concentrator appear to have potential as a cost-effective method for generating electricity. This power generation modularity makes parabolic dish systems ideal for producing electricity for small communities and other self generators. Distributed parabolic dish systems have inherent advantages over central receiver systems in other ways, including low visual impact, flexible land use, modular-incremental capacity buildup, relatively quick start-up, and low initial energy investment.

For electricity generation above about 10 MWe, central receiver systems begin to become cost competitive. Central receivers, like parabolic dishes with individual heat engines, do not need the extensive field piping and the associated pumping power and thermal losses required by most line-focus systems. Also, they are capable of achieving the high temperatures needed for generating electricity at traditional efficiencies of about 30%-40%. Central receiver systems can produce supersaturated steam at 480°C-535°C (900°F-1000°F); these temperatures are comparable with those in modern coal-fired plants and nuclear plants. For these reasons, central receivers are regarded as having good potential as a large-scale source of solar thermal power for electric utility grids.

Moshref, A. and Crevier, D. (1982). "Electric Power Generation by Solar Ponds: Modelling and Optimization." *Proceedings of the 1982 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Houston, TX; 1-5 June 1982.* Vol. 5.1. Preprint edition. Edited by Barbara Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 203-208.

A mathematical model for the steady-state analysis of the economic performance of a solar pond electric power system using a heat engine is presented. The analysis indicates that solar ponds can probably generate electric power economically at latitudes higher that 45 degrees if certain conditions are met.

Pons, R. L. (November 1980). "Optimization of a Point-Focusing Distributed Receiver Solar Thermal Electric System." *Journal of Solar Energy Engineering.* Vol. 102 (No. 2); pp. 272-280.

An approach to optimize solar-to-electric power conversion at the focus of parabolic dish concentrators is presented. The key parameters used in optimization and system selection consist of those relating to the optical/thermal performance of the concentrator/receiver combination, those relating to overall system performance, and the system's life-cycle energy cost.

Slemmons, Arthur J. (April 1980). *Line-Focus Solar Central Power System—Phase 1.* DOE/ET 20550-2. Menlo Park, CA: SRI International; 3V.

This report contains a summary of the systems analysis, parametric analysis, selection and conceptual design of the optimized system, and determination of the commercial market for solar line-focus central power plants. The system is analogous to the line-focus, parabolic cylinder "trough" collector/receiver, but much larger. Several rows of single-axis heliostats are focused on a horizontal cylindrical cavity receiver mounted on a tower.

Hildebrandt, A.F. and Dasgupta, S. (May 1980). "Survey of Power Tower Technology." *Journal of Solar Energy Engineering.* Vol. 102 (No. 2); pp. 91-104.

The article reviews (1) the history of power towers, (2) state of the art in heliostat, receiver, and storage design, (3) system economics, (4) simulation studies, (5) alternative applications for the power tower, and (6) some financing and energy aspects of solar electric conversion.

Muffezzoni, C. and Parigi, F. (1982). "Dynamic Analysis and Control of a Solar Power Plant-I. Dynamic Analysis and Operation Criteria." And "Dynamic Analysis and Control of a Solar Power Plant-II. Controls System Design and Simulation." *Solar Energy.* Vol. 28 (No. 2); pp. 105-116 and pp. 117-128.

Based on experiences with the EURELIOS 1 MWe solar power plant located in Italy, the first article shows how a careful dynamic analysis of the power generation process is necessary for the verification and assessment of the receiver design, the precise formulation of the plant operations procedures and

Presently, most research on central receiver systems is directed toward improving their performance in electricity production; the majority of prototype plants built to date have been designed to generate electricity. Solar thermal electric systems are presently cost-competitive with conventional alternatives in some remote applications, but not generally competitive with electricity generation by conventional utilities. For the most part, solar thermal central receiver plants are being designed to supply intermediate load requirements in electrical utility plants where they can displace expensive and short-supply fuels such as oil and gas. The introduction of solar thermal power into utility systems is expected to use the following operating modes:

1. The repowering and/or hybrid mode, in which the solar is combined with conventional fossil fuels.
2. The fuel-saving mode, in which the capacity of a conventional fossil fuel plant is increased by adding solar.
3. Stand-alone operation, in which the solar plant has sufficient internal storage capacity to allow for operation during adverse weather and at night. This will likely be the last type to be introduced since the storage system increases its cost substantially.

safety conditions, and the specification of the control system requirements. The second paper evaluates the design and performance of the steam generator control system for the solar power plant described in the first paper.

Solar Thermal Repowering or Hybrid Systems

A hybrid system is an energy conversion system that can be operated from a solar energy subsystem or a conventional energy subsystem, located at a common site, either interchangeably or simultaneously. Repowering refers to 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. Generally, the terms hybrid and repowering are used interchangeably and refer to the addition of a solar system, usually without storage, to a conventional power plant. The term "retrofit" is often used when referring to such repowering of an industrial operation.

Solar repowering projects for large oil/gas-fired electrical generating plants are being viewed as the stepping-stone to commercial stand-alone solar plants. Repowering offers a relatively low-risk technical path to large-scale test and demonstration of central receiver technology. The confinement of risk to the solar portion of the plant makes utility involvement more attractive and facilitates cost-sharing arrangements between the public and private sectors. Solar repowering also has significant potential in the industrial sector for such process heat applications as enhanced oil recovery and petroleum processing, both of which are suited for solar central receiver technology.

The U.S. Department of Energy has developed 13 site-specific conceptual repowering and retrofit designs for electric utility and industrial process heat (IPH) applications. Designs for utility applications cover oil- and natural-gas-powered plants varying in size from 25 MWe to 111 MWe. The IPH studies considered such diverse applications as oil refining, enhanced oil recovery, natural gas processing, uranium ore processing,

Gibson, J. C. (June 1982). *Solar Repowering Assessment*. SAND81-8015. Livermore, CA: Sandia National Laboratories; 65 pp.

This report provides an assessment of solar repowering studies that were completed by 1980. The possibility of interfacing with existing plants, the interest expressed by plant managers in the central receiver concept, and the awareness on the part of industry of the need to develop alternative energy sources all point to near-term high potential for solar central receiver technology. A major barrier to private investment appears to be the need for larger experimental projects to establish actual costs and develop initial operating experiences. Detailed summaries of the 13 conceptual design studies are provided.

Dubberly, L.J.; Gormely, J.E.; and McKenzie, A.W. (August 1979). *Solar Thermal Repowering Systems Integration*. SERI/TR-8037-1. Golden, CO: Solar Energy Research Institute; 156 pp. Work performed by Stearns-Roger Services, Inc., Denver, CO.

A solar repowering integration analysis that defines the balance-of-plant characteristics and costs associated with the solar thermal repowering of existing gas/oil-fired electric generating plants is presented. Solar repowering interface requirements for water/steam and sodium-cooled central receivers are defined for unit size ranging from 50 MWe to 350 MWe. Balance-of-plant cost estimates are presented for each of six combinations of plant types, receiver types, and percentage solar repowering. The appendix contains several cost-estimate worksheets.

Hansen, F.R.; Lindner, D.L.; and Vitko, J. (March 1983). *Economics of Scale in the Production of Steam with Solar Thermal — Fossil Boiler Hybrid Systems*. SAND82-8202. Albuquerque, NM: Sandia National Laboratories; 99 pp.

gypsum board drying, and ammonia production. Smaller than utility repowering plants, the IPH plants range in size from 11.8 MWt to 43.5 MWt.

Levelized energy costs for steam plants in the size range 15 MMBtu/hr to 400 MMBtu/hr have been estimated for steam produced by several different technologies, including stand-alone oil- and coal-burning plants as well as solar central receiver fossil boiler hybrid plants. Models for the costs of plant subsystems used in these calculations are presented and discussed. Designs of the solar-fossil hybrids examined were optimized with regard to solar fraction and amount of thermal storage used by simulation of plant operation.

Kuo, S. C. (March 1983). *Large Gas Turbine Modifications for Solar-Fossil Hybrid Operation.* EPRI AP-2852. Palo Alto, CA: Electric Power Research Institute; 154 pp. Work performed by United Technologies Research Center, East Hartford, CT.

Representative gas turbine designs presently available or possibly available by the late 1980s were examined in order to determine the scope of modifications required for solar-fossil hybrid operation in a utility environment. The results highlight the feasibility of modifying existing commercial gas turbines for solar-fossil hybrid operation rather than the more costly development of new gas turbines for this application.

Small Community Power Systems

One of the more promising early applications of small solar thermal power systems is small municipal and rural electric utilities. Influencing the potential for solar thermal power systems in this small community market are the following factors:

1. Electrical energy is typically provided to small communities by diesels, old oil- or gas-fired power plants, or by a non-resident utility transmitting power over an appreciable distance. Frequently, these small community markets are best served by dispersed energy sources that meet the specific needs of the user.
2. Island communities, rural areas, mines and other remote industries, and developing countries all tend to be isolated; i.e., not part of the national grid, distant from fuel supplies, or in an area for which an energy supply has not yet been provided.

Although several of the solar thermal technologies can be adopted for small community applications, the Small Community Solar Experiment (SCSE) sponsored by DOE and managed by the Jet Propulsion Laboratory (and more recently Sandia National Laboratories/Albuquerque) has selected the parabolic dish as the solar technology to be applied first. As an energy source, which can perform well at small-scale, parabolic dish power systems offer several advantages to small communities. They perform well at both low- and high-latitude sites, resulting in wide geographic applicability. The modular nature of parabolic dishes makes them especially suitable for decentralized applications. Finally, the high optical concentration ratio of the dish enables high temperatures to be achieved, leading to high conversion

Marriott, A.T. and Kiceniuk, T. (1980). "The Small Community Solar Thermal Power Experiment." *Proceedings of the 1980 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Phoenix, AZ; 2-5 June 1980.* Edited by Barbara Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 524-528.

This paper describes the small community electricity market and details the Small Community Solar Thermal Power Experiment. In particular, the suitability of parabolic dish systems for this application is discussed.

Steitz, P.; Mayo, L.G.; and Perkins, S.P., Jr. (November 1978). *Assessment of the Potential of Solar Thermal Small Power Systems in Small Utilities.* N79-16377. Pasadena, CA: Jet Propulsion Laboratory; 208 pp. Work performed by Burns & McDonnell, Kansas City, MO.

The study assessed the potential for solar thermal small power systems by comparing the economics of the power supply expansion plans for seven hypothetical utilities through the year 2000, both with and without solar systems. In addition, non-economic factors that could influence the potential role of solar thermal power systems in small utilities are discussed.

Pons, R.L. (July 1982). "Development Status of the Small Community Solar Power Systems." *Parabolic Dish Solar Thermal Power Annual Program Review Proceedings; Atlanta, GA; 8-10 December 1981.* DOE/JPL-1060-52. Pasadena, CA: Jet Propulsion Laboratory; pp. 53-99.

The paper presents the development status and test results for the Small Community Solar Thermal Power Experiment. Current activities on the Phase II efficiencies and the potential for low-cost power if these systems are produced in large quantities.

The type of parabolic dish system chosen for the Small Community Solar Experiment uses a distributed engine design in which a small heat engine (Rankine, Brayton, or Stirling) is located at or near the receiver of each concentrator. The electricity generated is then transported via power cables to a substation of the local power grid. Osage City, Kansas was selected as the prime site for the Small Community Solar Experiment in 1982 and money was approved by Congress to proceed with plans to build a 100-kWe plant.

power module development effort are presented with emphasis on the receiver, the plant control subsystem, and the energy transport subsystem. Numerous charts and pictures are included.

Industrial Process Heat

Industrial process heat (IPH) is the thermal energy used directly in the preparation or treatment of materials and goods manufactured by industry. The industrial sector consumes about 39% of the total energy demand in the U.S. Presently, most of this energy is supplied by oil, coal, or natural gas. Process heat energy, which represents approximately 45% of industry's energy consumption, can be supplied through a transfer fluid, primarily hot water, steam or hot air, or by direct heating.

The technical and economical feasibility of supplying industrial process heat from a solar collector depends upon four factors. First, there must be an adequate quantity of heat, which is highly dependent on available land area and local climate. Second, the heat must be of adequate quality for the intended purpose. Heat quality depends mainly on the type of solar collector; for example, heat available from a flat plate collector at 90°C (200°F) cannot be used directly as steam. Third, the heat must be transferred with as little heat loss as possible from the fluid stream to the process or material where it is to be used. Finally, the solar energy IPH system must be economically competitive with conventional energy systems.

Approximately 50% of the total industrial process heat demand is for temperatures below 300°C (570°F). These low- to medium-low temperature applications can use line-focusing collectors, evacuated tube collectors, and even conventional flat plate collectors and solar ponds for the lowest temperature applications. Most higher temperature applications require a concentrating solar IPH system with dual-axis tracking such as parabolic dishes and central receivers.

The following are factors which make solar energy suitable for industrial process heat applications.

- IPH systems can be used all year round.
- Many processes are in temperature ranges well-suited for solar technologies.
- Many end-uses are possible without thermal storage requirement.
- Expert field maintenance is usually available within industry.

Brown, Kenneth C.; Hooker, Douglas W.; Rabl, Ari; Stadjuhar, Shirley A.; and West, Ronald E. (January 1980). *End-Use Matching for Solar Industrial Process Heat*. SERI/TR-34-091. Golden, CO: Solar Energy Research Institute; 225 pp.

In order to identify the proper matches of solar collector technology and industrial process needs, various combinations of collectors, processes, and locations are evaluated using the method of "end-use matching." Data for industrial process requirements and plant locations, meteorological conditions, solar equipment, and economic factors are assembled in the data bases PROSYS and ECONMAT. Viable near-term solar applications are identified by comparing solar system costs with local fuel costs.

Solar Industrial Process Heat Conference Proceedings, Houston, TX; 16-19 December 1980. (1980). SERI/CP-632-952. Golden, CO: Solar Energy Research Institute; 316 pp.

Forty-six papers were presented concerning the use of solar thermal energy to supply industrial process heat. The topics covered include hot water, hot air, low-temperature steam, intermediate-temperature steam, central receiver retrofit projects, current projects, components and systems designed for particular applications, and marketing and financing of solar IPH systems.

Eicker, P. J.; Eason, E. D.; Hankins, J. D.; Hostetler, L. D.; Iannucci, J. J.; and Woodard, J. B. (March 1981). *Design, Cost and Performance Comparisons of Several Solar Thermal Systems for Process Heat; Volume 1 — Executive Summary*. SAND79-8279. Albuquerque, NM: Sandia Laboratories, 28 pp.

Conceptual designs of central receiver, parabolic dish, and parabolic trough systems are examined for several process heat applications. Cost and performance estimates are made for each of these designs and are used to calculate levelized delivered process heat costs. The other four volumes of this report provide more detailed information: *Volume II — Concentrators* (SAND79-8280); *Volume III — Receivers* (SAND79-8281); *Volume IV — Energy Centralization* (SAND79-8282); and *Volume V — Systems* (SAND79-8283).

- They can displace scarce fossil fuels.
- Operation is environmentally clean.

The following are potential disadvantages to solar industrial process heat.

- Variable nature of insolation requires solar systems to have full backup, or adequate storage.
- Process requirements, such as temperature control, may make integration with a solar system difficult.
- The large land areas required for many industrial size solar applications may be unavailable or expensive.
- Solar IPH is a new technology and long-range equipment reliability has yet to be proven.
- Such systems must often compete against less expensive fuels, such as coal, and favorable utility rates.
- In some industrial locations, pollution affects the surface of collectors and may cause rapid degradation of materials.
- The system cannot meet industry expectations for a rapid payback (usually 3-5 years) on equipment.

Low- and Medium-Temperature Applications

There are four basic categories of IPH applications: (1) hot water, (2) drying, (3) steam, and (4) direct process heat. The first three are usually considered to be low- to medium-temperature applications that can use systems such as solar ponds, evacuated tube collectors, and line-focusing collectors. However, some steam systems have been designed to use point-focusing collectors; one example is the use of a central receiver to generate steam for enhancing oil recovery. Direct process heat is generally treated as a high-temperature application requiring the use of concentrating collectors (especially point-focusing devices).

Great amounts of heated water, about 0.2 quad, at temperatures between 50°C (120°F) and 100°C (212°F), are required in several industries for cooking, washing, bleaching, anodizing, refining, and related uses. Preheating boiler feed-water accounts for another 3 quads. Water can be heated either directly in a collector loop or by means of a separate heat-transfer fluid used in conjuction with a heat exchanger. Solar ponds can also be used to heat a substantial volume of water for low-temperature applications.

Nearly 1.4 quads of energy is required in the United States for the production of hot, dry air in industrial processes below 200°C (390°F). This air is required in a large variety of drying and dehydration operations involving food processing, crop drying, and other industrial drying operations. The two most common ways to supply solar-heated air are (1) to heat the air directly in the collectors, and (2) to heat a liquid in the collectors and then use a liquid-to-air heat exchanger.

Steam is the most common heat-transfer medium for low-temperature (usually less than 200°C) indirect process heat. Generally, steam is delivered in a saturated state and is

Fraser, M.D. and Hiers, H. S. (1981). "Solar Process Heat Systems." *Solar Energy Handbook.* New York: McGraw-Hill Book Company; pp. 21-1 to 21-41.

The purpose of this chapter is to show how available solar technology can be used in an industrial environment. It is intended that a system designer can use the material presented to select a system conceptual design, including collector type, and storage type and size, to estimate the amount of energy provided by a solar process heat system, and to perform an approximate cost estimate. Conceptualized solar process heat system designs are shown to illustrate some design principles and to emphasize important considerations.

Kutscher, Charles F.; Davenport, Rodger L.; Dougherty, Douglas A.; Gee, Randy C.; Masterson, P. Michael; and May, E. Kenneth. (August 1982). *Design Approaches for Solar Industrial Process Heat Systems; Nontracking and Line-Focus Collector Technologies.* SERI/TR-253-1356. Golden, CO: Solar Energy Research Institute; 423 pp.

This handbook is intended to assist in the preliminary design of solar industrial process heat systems for the production of hot water, drying, and steam. The first part describes the design methodology and gives an overview of solar energy in industry. The second part, "Conceptual Design," describes how to choose the proper application and system configuration and how to estimate the amount of energy the solar system can be expected to supply. The third part, "Preliminary Design," describes how to select and optimize system components and explains control systems, installation and start-up details, economics, and safety and environmental issues. Several appendices supply supplementary data and explain how results in the text were derived.

Hooker, Douglas W.; May, E. Kenneth; and West, Ronald E. (May 1980). *Industrial Process Heat Case Studies.* SERI/TR-733-323. Golden, CO: Solar Energy Research Institute; 123 pp.

The results of seven IPH case studies are presented for the following industries: crude oil production (dewatering), aluminum container manufacturing, corn wet milling, polymeric resin manufacture (paint production), fluid milk processing, baking, and meat processing. For each process that was examined, the PROSYS software was used to simulate the average annual performance of the solar system most suited for the application. The ECONMAT software then determined the cost-effectiveness of the solar system compared to the conventional fuel source currently being used in the process.

typically used to heat a vessel to drive a chemical reaction but it may also be employed for evaporation, crystallization, etc. About 6 quads of energy is consumed in the United States for process heat, 80% at temperatures below 200°C (390°F). Because of the higher temperatures required, industrial steam applications normally require concentrating collectors such as parabolic troughs. Three ways to supply process steam with solar collectors are (1) to use a high-temperature fluid in the collector and transfer the heat to an unfired boiler, (2) to circulate pressurized water in the collector and flash it to steam, and (3) to boil water in the collector.

Kreith, F. and Davenport, R.L. (1982). "Overview of Solar Industrial Process Heat (SIPH) Applications Below 120°C." *Solar World Forum: Proceedings of the International Solar Energy Society Congress; Brighton, England; 23-28 August 1981.* Edited by David O. Hall and June Morton. New York: Pergamon Press; pp. 1596-1616.

This paper gives an overview of solar IPH technologies and economics for applications below 120°C and outlines a procedure for optimally matching solar systems to energy requirements. Cost and system performance of operational solar IPH installations are summarized, and steps required to reduce the cost of the energy delivered by future systems are presented.

Feustel, J. E. (1982). "Application of Solar Process Heat Above 120C in Industrial Processes." *Solar World Forum: Proceedings of the International Solar Energy Society Congress; Brighton, England; 23-28 August 1981.* Edited by David O. Hall and June Morton. New York: Pergaman Press; pp. 1617-1632.

The report describes the overall configurations and major components of solar IPH systems in the temperature range of 120°C to 350°C. Some application examples and an outlook on the market potential and the economic efficiency of solar IPH systems are also presented.

High-Temperature Applications

High-temperature, direct process heat accounts for a large fraction of industrial process heat. It is estimated that 50% of all industrial process heat in the U.S. is required at temperatures over 400°C (750°F). The major portion of this requirement is supplied as direct refractory heat in industries such as primary metals, glass, and Portland cement.

Although there seems to be minimal near-term potential for solar in the primary metals industry, a potential market does appear to exist for high-temperature solar IPH in the glass container, brick and clay, and lime and cement industries. If the technology is tailored for the application and the cost of solar systems is reduced, then there is a potential for fuel savings of over 0.5 quad annually.

Some of DOE's repowering program projects have developed conceptual designs for high-temperature solar thermal IPH retrofit systems. However, little work has been done to build actual high-temperature direct process heat systems except in the area of fuels and chemicals where some small-scale solar furnace systems exist. This application is discussed in the following section.

"Mid and High-Temperature Industrial Process Heat." (June 1980). *Solar Thermal Power-Systems.* DOE/CS/21036-01. El Segundo, CA: The Aerospace Corporation; pp. 79-93.

This section of the report examines medium- and high-temperature (175-1100°C; 350-2000°F) IPH applications appropriate for use with solar energy with emphasis on those applications that might be served by solar thermal technology developed for large-scale power production. The results of a study that sized the market potential, identified promising applications, and determined future program needs for solar IPH systems are summarized. In particular, the following industry groups were examined: paper and allied products, chemicals, petroleum products, stone, clay and glass, and primary metals.

Fish, J.D. (April 1980). *Solar Industrial Process Heat Markets for Central Receiver Technology.* SAND80-8214. Livermore, CA: Sandia National Laboratories; 18 pp.

The report synthesizes available information concerning industrial process heat markets and concludes that only two types of central receiver systems need to be developed to have a significant impact on industry: (1) systems producing saturated steam up to 550°F, and (2) systems delivering air up to 1200-1500°F. Applications amenable to near-term penetration are identified for both types of systems.

DeLaquil, P.,III; Yang, C. L.; and Moring, J. E. (February 1983). *Solar Central Receiver High Temperature Process Air Systems.* SAND82-8254. Livermore, CA: Sandia National Laboratories; 68 pp.

The cost-effectiveness of solar central receiver high-temperature industrial process air delivery systems is evaluated. Seven solar air-heating receiver concepts are compared at outlet temperatures of 1000° F, 1500° F, and 2000° F and at operating pressures of 1, 5, and 10 atmospheres. Piping and compressor machinery costs are also reported.

May, Kenneth E. (March 1980). *Solar Energy and the Oil Refining Industry*. SERI/TR-733-562. Golden, CO: Solar Energy Research Institute; 33 pp.

The paper surveys process heat requirements of the major petroleum refinery processes. Alternatives to natural gas and residuum as refinery fuel sources are discussed.

Fuels and Chemical Production

Since solar thermal energy can generate temperatures high enough to promote the endothermic chemical reactions needed to produce fuels and industrial chemical feedstocks, these industries have been targeted as potentially important solar thermal applications. Although generation of fuels and chemicals by direct solar technologies is in its infancy, the potential benefits make it worthwhile to pursue. For example, solar thermal heat can substitute for the combustion of a fuel (e.g., petroleum, natural gas, or coal) thereby conserving supplies and limiting environmental impacts caused by mining. Also, unlike other solar technologies, solar-made fuels can utilize the existing nationwide distribution network of pipelines. Finally, processes exist in the laboratory, which, if coupled with solar thermal heat and developed, would provide unlimited quantities of a renewable fuel/feedstock, notably hydrogen.

In order to produce the temperatures required in fuel and chemical processing, a solar furnace is used. A solar furnace can be either a central receiver design (already described in Chapter 3) or a double-reflector system (to achieve the highest temperatures). The double-reflector type of solar furnace uses one or more heliostats to reflect the sun's rays onto a parabolic mirror that concentrates the light and then redirects it to the actual receiver. The largest solar furnace of this type, located in Odeillo, France, has achieved a temperature as high as 3800°C (6900°F) at the center of its focus.

The heat generated by a solar furnace can be used for chemical processing in three ways. The first approach is to use solar

Horizontal Solar Furnace

Suresh, D.; Rohatgi, P.K.; and Coutures, J.P. (1981). "Review Paper: Use of Solar Furnaces-I; Materials Research." *Solar Energy*. Vol. 26 (No. 5); pp. 377-390.

Suresh, D.; Charters, W.W.S.; and Rohatgi, P.K. (1981). "Review Paper: Use of Solar Furnaces-II; Thermophysical Properties" *Solar Energy*. Vol. 28 (No. 4); pp. 273-280.

Both papers summarize the possible applications of solar furnaces. The first paper is concerned with the use of solar furnaces to study high temperature properties of materials such as phase studies, crystal growth, vaporization studies, purification and stabilization of refractories, and in testing materials at high temperatures. The second paper reviews the use of solar furnaces to measure high-temperature thermophysical properties of materials including thermal expansion, thermal conductivity and diffusivity, thermal energy absorption, mechanical properties, optical characteristics, and electrical properties of materials.

Edgar, R.M.; Richards, E.H.; and Mulholland, G.P. (1982). "Solar Furnace for Flux Gauge Calibration and Thermal Effects Testing." *Proceedings of the 1982 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge; Houston, TX; 1-5 June 1982.* Vol. 5.1. Preprint edition. Edited by Barbara Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 331-335.

The solar furnace constructed at the Central Receiver Test Facility of Sandia National Laboratories, although primarily designed to evaluate and calibrate flux gauges, can be used for such purposes as materials evaluation, chemical processes and production, and aerodynamic heating tests. The paper describes the furnace's components, including the heliostat, concentrator, attenuator, test table, data acquisition system, system control, and data station.

Assessment of Fuels and Chemicals Production Using Solar Thermal Energy; Final Report. (January 1982). DOE/SF/aa496-1. Kansas City, MO: Black and Veatch Consulting Engineers; 413 pp.

The current market-dominating fuels and chemical processes are reviewed to identify those appearing to have the greatest potential for successful integration with a solar thermal heat source. In addition, such advanced concepts as coal gasification and oil shale are examined. Based upon the initial screening, a case-study type of examination was made to estimate plant costs, thermal process heat systems, as described in the previous section, to bring heat into the chemical plant in the form of steam, hot air, etc. The second method has the chemical reaction take place in the receiver and requires that existing process hardware and designs be adapted to the solar system's heat receiver and that methods to extend production capacity levels (i.e., storage of intermediate products, etc.) be developed. Finally, a third way to use the concentrated solar energy of a furnace is to directly irradiate the reactants. Although this approach requires the most research of all, it offers several advantages. High heating rates can be achieved. Removal of the reactants from the concentrated beam can result in rapid quenching of the reaction and the formation of new chemical species. The feedstock inventory behind the surfaces exposed to the solar flux can remain relatively cool and serve as containment to the reaction.

Solar furnaces have been used for high-temperature chemistry, high-temperature property measurement, thermal shock research, and solar power plant receiver testing. Exploratory studies demonstrate that the solar thermal energy from some of the fuels and chemicals which these furnaces produce can be used to drive all major fuel and chemical processes, including reduction, gasification, pyrolysis, and liquefaction. Solar furnaces are candidates for processing synthetic gas from coal, shale oil processing, ammonia production, styrene manufacture, metal oxide decomposition, and preparation of elemental phosphorus.

Two materials of particular interest are the production of hydrogen from water by electrolysis and flash pyrolysis of biomass materials to produce liquid and gaseous hydrocarbons. Some economic analyses suggest that the use of solar thermal energy for the production of fuels and feedstocks from such raw materials as natural gas and coal could become economical before the turn of the century. Elimination of toxic waste (e.g., PCBs) by dissociating them through the application of high temperature and UV light is also a possible application.

operational performance, technical difficulties, and financial characteristics for several of the most representative systems.

New Applications of High-Temperature Solar Energy for the Production of Transportable Fuels and Chemicals and for Energy Storage. (January 1979). ATR-78 (7691-04)-1. Los Angeles, CA: The Aerospace Corporation; 89 pp.

This study identifies new industrial processes for the production of transportable fuels and essential chemicals that could capitalize on the high temperatures achievable through solar thermal power technology. In particular, the report describes a conceptual configuration for a closed-loop carbon recovery concept that can take advantage of the high temperatures achievable with solar thermal power technology to produce carbon monoxide and hydrogen.

Shaft-Powered Applications

For several applications, conversion of solar energy to shaft or mechanical power through the use of a heat engine is more efficient than converting to electricity, particularly for water pumping and air-conditioning. Solar air-conditioning has an advantage in that the cooling load is almost in phase with high solar input periods in the summer. Solar irrigation systems are of interest since the locale requiring irrigation is often an area that has high solar availability.

McNelis, Bernard, editor. (January 1982). *Conference Proceedings: Solar Energy for Developing Countries — Refrigeration and Water Pumping; London, England; 27 January 1982*. London, UK Section of the International Solar Energy Society; 109 pp.

Of the 14 papers presented at the conference, six deal with solar cooling and seven address solar water pumps. The papers review applications for solar refrigeration and water pumping and describe specific system designs and evaluations.

Solar Cooling

Solar cooling can be used to provide refrigeration for food preservation or air-conditioning for buildings. Of the three basic types of cooling systems (vapor compression,

Copeland, Robert J. and Parsons, J. Roger. (1982). "Use of Parabolic Trough Collectors for Residential/Light Commercial Solar Cooling Systems."*Proceedings IECEC '82: 17th Intersociety* absorption, and desiccant), the vapor compression cycle, frequently called Rankine-cycle solar air-conditioning, appears to be the most promising system for use with high-temperature solar thermal power sources. In a simple Rankine-cycle cooling system, energy from the solar collector is sent to a storage tank that can then transfer the energy through a heat exchanger to a heat engine. The heat engine powers a mechanical compressor that compresses the refrigerant vapor. At the present time solar cooling is not economically competitive with existing cooling technologies, but it is expected to become a viable cooling power source as collector designs become more cost-effective and techniques for generating mechanical energy from solar energy are perfected.

Energy Conversion Engineering Conference; Los Angeles, CA; 8-12 August 1982. 82CH1789-7. New York: Institute of Electrical and Electronic Engineers; V. 3, pp. 1562-1567.

The potential for using parabolic trough rather than flat plate collectors for residential/light commercial solar cooling systems is considered. An overview of the effects of high source temperature on absorption cycle, desiccant cycle, and heat-engine-driven vapor compression cycle cooling systems is given.

Bilgen, E. (1979). "Chapter 46 — Solar Powered Refrigeration." *Solar Energy Conversion; An Introductory Course.* Edited by A. E. Dixon and J. D. Leslie. New York: Pergamon Press; pp. 1223-1243.

The utilization of solar-powered refrigeration units in cooling and food preservation is reviewed. In addition, solar cooling methods to use with intermittent and continuous cycles are discussed.

Irrigation Pumping

Early attention to solar thermal mechanical systems was directed toward water-pumping applications with outputs ranging up 100 kW. Both Eneas' and Shuman's solar thermal devices, built in the early 1900s, were designed to power irrigation systems. Solar-powered irrigation pumping has several advantages: periods of maximum insolation usually coincide with periods of maximum pumping demand, power required is usually less than 300 kW and can be met by low- to medium-temperature collectors, and irrigation schedules can be adjusted often to match insolation availability or pumped water storage can be used to meet nighttime or cloudy-day demands. The seasonal nature of irrigation pumping requirements can also be exploited by designing multiple-use systems that use heat collected from the collector field for drying, auxiliary electric power, or greenhouse heating during non-irrigating seasons.

At present most solar irrigation system designs use a dual-loop system to drive Rankine-cycle turbines for pumping power. Water under pressure or an organic fluid is circulated in a field of concentrating collectors and heated to 200°C or more. The hot fluid flows through a heat exchanger to vaporize a working fluid which then expands through the turbine to provide shaft power. Although single-loop systems that heat the working fluid directly in the collector have been proposed, the handling of low-vapor pressure fluids in collector receivers can present problems.

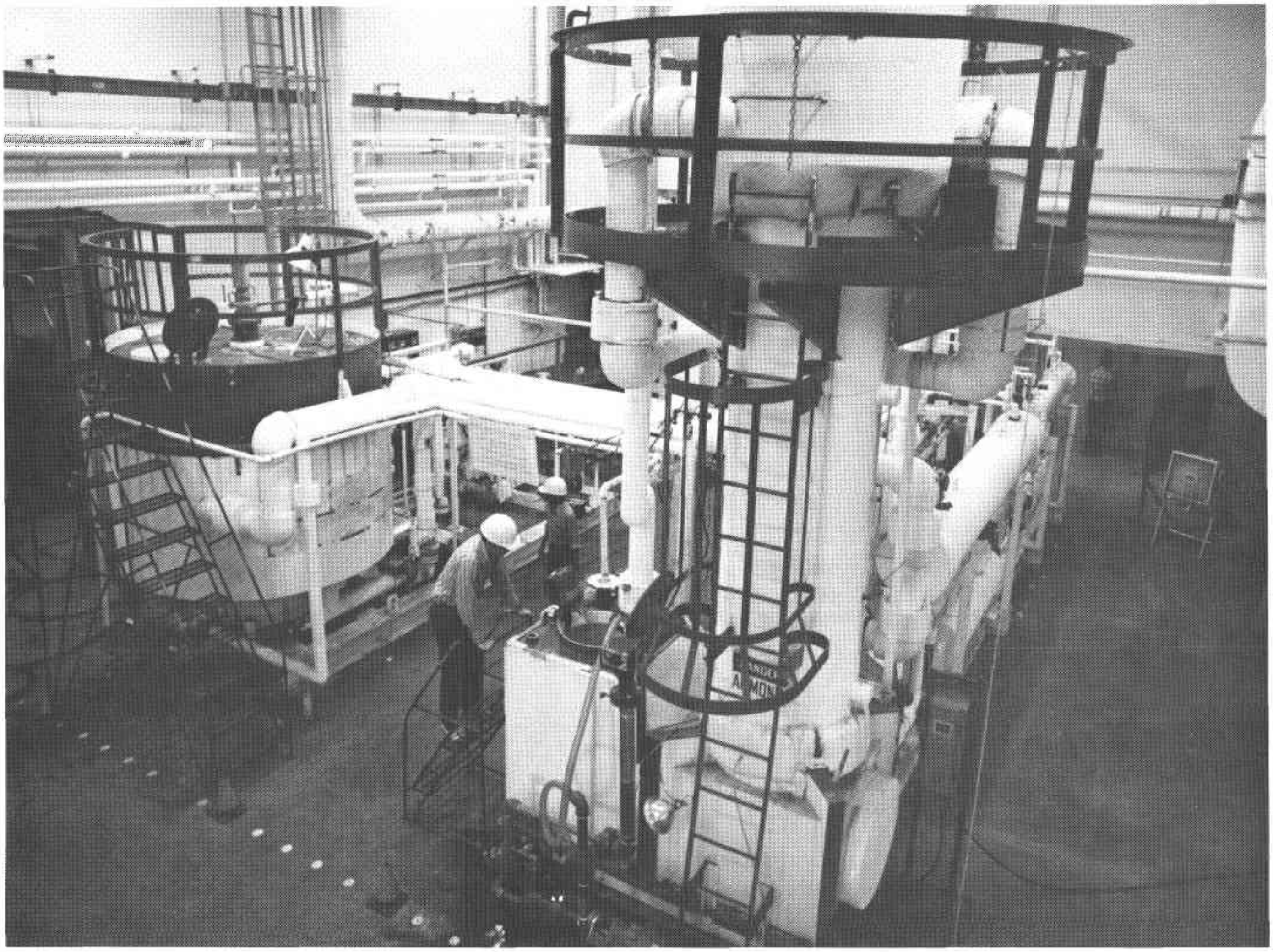
It appears that thermal systems using linear focusing collectors rather than flat plate collectors are the most cost-effective because of the small receiver area required. However, for small-scale pumping in developing countries, the simpler technology of flat-plate collector systems may be more desirable. Three irrigation pumping projects using parabolic trough systems are described in Chapter 4.

Karmeli, David; Atkinson, Joseph F.; and Todes, Mark. (1981). "Economic Feasibility of Solar Pumping." *Solar Energy.* Vol. 27 (No. 30); pp. 251-260.

Two major questions concerning the economic feasibility of solar pumping are addressed. The first of these is concerned with finding a least-cost solar system by considering alternative types of energy storage. The second involves determining locations where solar energy would be economically competitive with electricity or fuel as a power source for pumping installations.

Fischer, Robert D. and Talbert, Sherwood G. (1980). "Chapter 34-Irrigation Pumping." *Solar Energy Technology Handbook. Part B; Applications, Systems Design, and Economics.* Edited by William C. Dickinson and Paul N. Cheremisinoff. New York: Marcel Dekker, Inc.; pp. 239-275.

The article examines the need for solar pumping in the U.S. and then reviews the history of solar pumps. The requirements, design options, and operational considerations for solar pump systems are discussed. Finally, an overview is given of major solar pump systems and the economics and future prospects of solar-powered irrigation pumps.



6000-gpd Indirect Freeze Desalination Pilot Plant at Chicago Bridge and Iron Research Center in Plainfield, Illinois

Solar Thermal Desalination Process

Providing adequate water is becoming a serious problem in arid areas of the world. Even if water is available, it is often saline or brackish — requiring desalination to make it potable or useful for irrigation. At present most of these desalination plants are powered by conventional fossil fuels directly or through the electric grid system. However, since most arid regions possess a large solar resource, there is a significant potential for the use of renewable solar resources to supply the energy required for desalination.

Separation of water from salts in an aqueous salt solution can be accomplished by several different processes including distillation, freezing or crystallization, and membrane selective transport techniques. **Distillation** involves separating the more volatile component (H_2O) through evaporation from the less volatile salts either by raising the temperature of the solution at constant pressure or by lowering the pressure at constant temperature. The most common commercial distillation processes using direct heat are multi-stage flash evaporation (MSF), multi-effect distillation, and single-effect evaporation.

Proceedings Solar Desalination Workshop; Denver, CO; 23-28 March 1981. SERI/CP-761-1077. Golden, CO: Solar Energy Research Institute; 2 V.

Although jointly sponsored by the Saudi Arabian National Center for Science and Technology and the United States Department of Energy, the conference also included papers on desalination processes and projects outside the SOLERAS program. The 29 papers presented include overviews of desalination and solar technologies, descriptions of water resources (particularly in the western United States and Saudi Arabia), descriptions of individual desalination projects, and explanations of various solar desalination approaches.

Luft, Werner. (1982). "Five Solar-Energy Desalination Systems." *International Journal of Solar Energy.* Vol. 1 (No. 1); pp. 21-32.

The article describes the five solar desalination systems selected for pilot-plant design and construction as a part of the SOLERAS program. In addition,information is given on the performance parameters and cost projections for the five systems.

In **freezing**, the solution is cooled until water separates itself by crystallizing within the saline solution — the crystals are then washed from the salt. Finally, there are two desalination processes that utilize the selective transport properties of membranes: (1) **reverse osmosis** and (2) **electrodialysis**. In both, a membrane that has a high rejection to the passage of one of the components (either water or salts) separates the highly saline salt solution from a more dilute one.

Large-scale solar-powered desalination systems do not differ greatly from conventionally powered desalination systems. In general, the subsystems consist of feedwater pretreatment, solar collectors, an electric power generator, a distillation or membrane unit, an energy storage subsystem, a brine disposal subsystem, and product water storage and delivery subsystems. The United States-Saudi Arabian SOLERAS program is the sponsor of several solar-powered desalination demonstration projects. These projects will employ five different solar power production methods, including three solar thermal technologies (central receiver, line-focus collectors, and point-focus collectors), photovoltaics, and wind generators in various combinations with six desalination technologies.

"Working Papers Volume II: First World Congress on Desalination and Water Re-use; Florence, Italy; 23-27 May 1983." (May 1983). *Desalination*. Vol. 45; 406 pp.

Volumes 44-47 of the *Desalination* journal are devoted to the working papers from the First World Congress on Desalination and Water Re-use. Volume II of these working papers (Volume 45 of *Desalination*) contains an entire section on solar and freezing processes. The six papers in this section describe various solar desalination projects located throughout the world and include information on the desalination processes involved.

Total Energy Systems

A solar total energy system (STES) uses waste heat from the generation of electricity to satisfy additional energy needs such as electrical, heating, or cooling requirements. The concept of total energy is related closely to that of cogeneration which involves the production of two or more types of energy (for example, electricity and process heat) by the same system. The main advantage of cogeneration over separate generation of electricity and industrial process heat is the increase in thermodynamic efficiency. A total energy or cogeneration system uses the energy present in the solar heat efficiently by ensuring a close match. If the matching is done properly, productive use of the available energy can be increased over that which could be achieved if the processes were not cascaded but operated in parallel from the same heat source.

A solar total energy system may be envisioned as a process that cascades energy of high quality to lower quality in discrete increments. At each step, characterized by temperature, energy is withdrawn from the stream and utilized to meet requirements particular to that given temperature. Thus, low-temperature, low-quality energy is used to meet building heating and cooling requirements, whereas high-temperature energy is used for conversion to high-quality electrical energy.

Existing between the two application limits — electric power plants whose sole output is electricity and a thermal plant whose sole output is heat — the solar total energy system is characteristically small (in terms of utility power plants) and located close to the demand for thermal energy. The design and

Harrigan, Raymond W. (1980). "Chapter 32: Total Energy Systems Design." *Solar Energy Technology Handbook. Part B — Applications, Systems Design, and Economics*. Edited by William C. Dickinson and Paul N. Cheremisinoff. New York: Marcel Dekker, Inc.; pp. 166-204.

This chapter deals primarily with the development of solar total energy system (STES) designs to the degree useful in evaluating concept feasibility. The intention is to give the reader enough information to determine if a concept is promising enough to execute a detailed design of an STES facility for the particular application. A hypothetical application is used to illustrate design considerations such as load definition, load compatibility with STES, collector field sizing, baseline design evaluation and economics, and selected design references.

Rose, Keith A. (February 1982). "Solar Central Receiver Cogeneration Program." *Department of Energy Central Receiver Annual Meeting; Claremont, CA; 13-15 October 1981*. SAND82-8002. Albuquerque, NM: Sandia National Laboratories; pp. 89-94.

The objectives and accomplishments of the Solar Central Receiver Cogeneration Program are described and overviews of four of the seven projects are provided.

Anderson, John S. (April 1982). *Solar-Cogeneration Assessment Report of Solar Central-Receiver Cogeneration Conceptual-Design Study Projects*. SAND82-8005. Livermore, CA: Sandia National Laboratories; 54 pp.

This document contains a brief description of the conceptual design, a summary of the prime construction of the world's first solar total energy plant in the private sector was completed in 1982 in Shenandoah, Georgia. Sponsored by the U.S. Department of Energy in conjunction with the Georgia Power Company, the 3-MWt Solar Total Energy Project furnishes electrical power, process steam, and other thermal energy to a nearby knitwear factory. The solar system consists of a collector field of 114 parabolic dish collectors that supply thermal energy at 400°C to drive a 400-kWe multi-stage Rankine-cycle turbine generator.

Studies were also undertaken by the Solar Central Receiver Cogeneration Program to investigate the potential for a solar cogeneration facility based on the central receiver project. Seven projects were selected for the program. Each involved developing a conceptual design based on a specific plant to represent a typical site. Work on the projects was completed by September 1981 and the results indicated that central receiver cogeneration systems could become viable given a favorable economic and regulatory climate.

contractor's economic analysis, and the site owner's assessment for each of seven proposed central-receiver-based cogeneration facilities. In spite of variables that make absolute comparisons impossible, the report concludes that the projects indicate that central receiver cogeneration has several promising applications and should be studied further.

Kearney, D.W; Davis, R.B; Kostrzerva, L.; and Davidson, K. (1983). "A Comparison of Solar/Gas Industrial Process Heat and Cogeneration Systems." *Proceedings IECEC '83; 18th Intersociety Energy Conversion Engineering Conference; Orlando, FL; 21-26 August 1983.* New York: American Institute of Chemical Engineers; V. 5, pp. 2072-2077.

Solar systems integrated with conventional gas-fired systems are considered to offer the possibility of an attractive and economic process heat or cogeneration option. This report describes research that examined candidate systems to assess potential technical barriers to the interfacing of these technologies. A detailed economic evaluation was conducted also to compare such systems with conventional gas-fired equipment and with a gas-only cogeneration system. The results showed that gas/solar cogeneration (particularly gas-fired cogeneration systems) is economically attractive.

Chapter 7
Performance and Reliability

Performance of Solar Thermal Systems

Determination of the overall performance of a concentrating collector depends on several parameters. Changing these parameters in an effort to improve performance usually involves changes in cost. Economic analyses, discussed in the next chapter, are necessary to assess the value of any proposed design change. The best system is one that meets all the performance objectives required by a given application while doing so at the lowest cost for delivered energy, over a period of time, for that particular application. Although the performance features discussed in this section are not the only factors to be considered when selecting the optimal system for an application, they do provide a better understanding of a particular concentrator and the effect of various trade-offs on its performance.

The performance parameter of prime importance is the useful energy available from the collector. The useful energy gain is maximized if all loss mechanisms are minimized. These loss mechanisms can be separated into two categories: (1) optical and (2) thermal.

Several factors affect the ability of an optical system to direct the incoming beam radiation to the absorber or target and add its energy to the heat-transfer fluid. These include absorption of radiation in the reflecting or refracting elements, surface irregularities of these elements, and size and positioning of the absorber. Also considered are optical properties of the receiver itself, including transmittance losses through receiver envelopes and receiver absorptance. An assessment of the collector's optical efficiency is usually based on solar ray-tracing techniques that use as inputs the collector geometry, solar disk size, irradiance, and material properties (transmittance, reflectance, and absorptance). Convection and radiation losses are the thermal losses also of concern in a concentrating system.

A thermal analysis of a collector's efficiency would determine the portion of radiation heat input that is transferred to the working fluid by calculating the heat loss by conduction, re-radiation, and convection to the atmosphere. Some of the more significant thermal losses occur in the collector field piping and storage tank — particularly for distributed-receiver solar thermal technologies. These thermal losses occur during both operation of the solar system and cool down (such as when the system is shut down overnight).

In addition to the optical and thermal losses already discussed, the performance of the solar thermal system depends on the efficiency of its various subsystems. The field efficiency includes the collector-field-averaged effects of receiver/tower

Kreider, Jan F. (1979). "Chapter 5: Medium-Temperature Solar Processes." *Medium and High Temperature Solar Processes*. New York: Academic Press; pp. 161-222.

Section V of this chapter deals with the long-term performance of medium-temperature solar processes. Most of the information provided in this section is also applicable to high-temperature solar thermal processes.

Proceedings of the STTF Testing for Long-Term Systems — Performance Workshop; Albuquerque, NM; 7-9 January 1981. (July 1981). STTFUA-81/11. Albuquerque, NM: Solar Thermal Test Facilities Users Association (STTFUA); 341 pp.

The purpose of the workshop was to review baseline solar thermal energy system (STES) data and to identify areas where additional STES testing is needed to upgrade their reliability or consistency. The session topics include: user's requirements for commercial solar thermal systems; direct-beam insolation: diurnal, annual, seasonal, and geographical variations; mirrors and heliostats; long-term reflectivities, maintenance, design and operational problems; experience in testing central receivers; STTF testing of storage systems; solar fuels and chemicals; and a panel discussion on STTF experiments for establishing durability, maintenance, and lifetime specifications.

Rabl, Ari. (1981). "Yearly Average Performance of the Principle Solar Collector Types." *Solar Energy*. Vol. 27, (No. 3); pp. 215-223.

The results of hour-by-hour simulations for 26 meteorological stations are used to derive universal correlations for the yearly total energy that can be delivered by the principal solar collector types: flat plate, evacuated tubes, CPC, collectors that track about one axis, collectors that track about two axes, and central receivers. The method used to derive this information is described.

Evans, D.L. (1981). "Chapter 9: High-Concentration Solar Thermal Collectors." *Solar Energy Handbook*. Edited by Jan F. Kreider and Frank Kreith. New York: McGraw-Hill Book Company; pp. 9-1 to 9-37.

The majority of this chapter is devoted to performance of high-concentration collectors. The first section deals with specific performance parameters and covers optical and thermal performance in particular. The other section deals with system performance topics, especially receiver size, receiver position, collector tracking, and shadowing by adjacent collectors.

Gordon, J.M. and Zarmi, Y. (1983). "The Utilizability Function - I; Theoretical Development of a New Approach " and "The Utilizability Function - II;

shading of field/concentrators, mirror reflectivity; cosine losses; mutual shading and blocking; atmospheric attenuation, and receiver misses. The receiver efficiency includes the effects of reflectivity, radiation, and convection. Since the solar thermal technologies discussed here can concentrate only the direct insolation received from the sun, accuracy of collector tracking and shading by adjacent collectors also become important factors in determining system performance.

The data obtained from determining the efficiency of the various performance parameters can be combined with site-specific, long-term irradiation conditions to predict average collector-field performance on a yearly basis. It is this long-term performance data that is vital for assessing the economic viability of a particular solar thermal system. The utilizability method is a technique for making such detailed long-term average performance calculations for systems that operate at constant or nearly constant temperature. Utilizability describes the fraction of the total solar radiation incident upon a collector during a specified period (e.g., month or year) that is above a specific threshold and is hence "useful" energy; that is, delivered to the working fluid.

Energy availability depends on many system and climatic parameters, but especially important are insolation statistics, collector parameters and operating conditions, and collector tracking and solar geometry. The result is a plot of collector yearly average energy delivery vs. operating temperature.

Validations of Theory Against Data-Based Correlations." *Solar Energy*. Vol. 31 (No. 6); pp. 529-543.

These two articles discuss a new theoretical approach to the calculation of the utilizability function and apply it to the case of the annual performance of solar collectors of high concentration ratio. The first paper presents details of the theory and derivation; the following paper gives the solved numerical examples and the comparisons with results based on detailed meteorological data.

Kutscher, Charles F.; Davenport, Roger L.; Dougherty, Douglas A.; Gee, Randy C.; Masterson, P. Michael; and May, E. Kenneth. (August 1982). "Section 6.0: Annual Performance of a Solar Energy System." *Design Approaches for Solar Industrial Process Heat Systems; Nontracking and Line-Focus Collector Technologies*. SERI/TR-253-1356. Golden, CO: Solar Energy Research Institute, pp. 83-138.

This section presents some performance analysis design tools that do not require the use of a computer, although many were generated with the help of the SOLIPH computer model. Each subsection addresses one aspect of IPH system performance and presents design tools for predicting its impact on the annual performance of the entire IPH system. The six subsections cover the following topics: (1) annual energy collection for several IPH system configurations; (2) incident-angle effects; (3) row-to-row shading effects; (4) annual thermal losses of collector field piping and storage; (5) utilization and availablilty of the solar system; and (6) outline of the step-by-step procedure.

Materials and System Performance

The materials used in solar thermal technologies play an important role in the principal issues of acceptable performance, adequate life, and low cost, which must be addressed in order for widespread use of concentrating collectors to occur. Elements exposed to the atmosphere, such as mirrors, will be subject to degradation mechanisms; e.g., deposition of dust, corrosion by water vapor and chemicals in the atmosphere, and photochemical degradation. Because of the daily variation of solar insolation and of short-term fluctuations caused by cloud passage, some elements of the system will be subject to cyclic fatigue. Materials problems such as these must be resolved in advance so that potential buyers can have confidence in the expected lifetimes of their solar devices. Cost reduction is also an essential element in developing a commercially viable solar thermal technology. Materials research will provide a basis for improving the elements of life-cycle costs by providing an understanding of material properties and their interactions with each other in the system environment.

Murr, Lawrence, E., editor. (1980). *Solar Materials Science*. New York: Academic Press; 788 pp.

The book is based on a lecture series designed for a graduate student level and is intended to provide an overview of the materials aspects of solar energy development. The subject matter is divided into three categories: (1) solar collector (photothermal) materials; (2) solar storage and photochemical materials; and (3) solar conversion (photovoltaic) materials. The book can also serve as an introduction to solar materials sciences, particularly the first chapter by Richard S. Classen and Barry L. Butler.

Reisfeld, Sherry K. (January 1983). *A Solar Materials Annotated Bibliography*. LA-9581-MS. Los Alamos, NM: Los Alamos National Laboratory; 112 pp.

Projects in solar materials research, funded for the most part by DOE, are described. Each project description includes contractor information, contract number, duration of the project, objectives of the work, and important publications resulting from the investigation. In many cases, methodology and results are included also.

Optical Materials

The optical components of a concentrating collector are critical elements in determining a system's efficiency. The reflectance, transmittance, and absorptance are the most important attributes of the materials used in the reflector, receiver, and cover (if any) components of the system.

Reflector or **mirror materials** are used in concentrators in order to redirect and intensify the incident sunlight onto a receiver surface. Diffuse reflection does not contribute significantly, so it is the specular reflectance that must be maximized. In addition to the reflectance properties, other important properties of mirrors used in solar concentrators must be considered, including the environmental stability of the material, resistance to hail impact, mechanical properties, manufacturing tolerances, and cost.

Of all the metals that could be used for solar reflectors, only silver and aluminum have solar reflectance values greater than 0.90; respectively, 0.98 and 0.92. In most solar applications, the metal-reflecting layer is protected by a transparent coating such as glass or plastic film. The index of refraction of most coating materials, typically 1.5, reduces the solar average reflectance by 0.01 for silver and 0.04 for aluminum. The construction of the reflector (front-surface or second-surface) also affects the specularity and the reflected beam intensity of various mirror materials. In a front-surface mirror, the reflecting layer is applied to the substrate and then overcoated with a protective coating. In a second-surface mirror, the reflecting layer is applied to a transparent superstrate which is then bonded to a support structure.

The different types of reflector materials can be divided conveniently into three classes: (1) silvered glass, (2) metallized plastic films, and (3) polished aluminum sheet. The optical performance of any reflector is dependent on the performance of both the coating and the reflective material. The solar reflectance values obtained for typical silvered glass mirrors are usually less than the theoretical value of 0.97, often closer to 0.83, primarily from absorption within the glass caused by impurities, mainly iron. These solar reflectance properties can be improved by (1) reducing the amount of iron in the glass, (2) controlling the oxidation state of the iron, (3) adding chemicals to the glass which will form a compound with the iron and thereby modify the optical absorptance, and (4) reducing the thickness of the glass.

There are several metallized plastic mirrors available for solar applications. The reflecting aluminum or silver layer is usually vacuum-deposited. Hemispherical reflectance values for silver materials are typically near 0.95 while materials that use aluminum are typically near 0.85-0.87. Absorption of insolation within the plastic film can reduce the solar reflectance below these values, although usually by not more than a few percent since the films are very thin. The specularity of the reflected beam is primarily controlled by both the surface roughness of the metallized side of the plastic film and the lamination procedure used to bond the film to the substrate. Polished aluminum mirror materials are generally

Pettit, R.B. and Roth, E.P. (1980). "Chapter 5; Solar Mirror Materials: Their Properties and Uses in Solar Concentrating Collectors." *Solar Materials Science.* Edited by Lawrence E. Murr. New York: Academic Press; pp. 171-197.

The chapter reviews the state of the art of mirror materials with application to solar concentrators. After specular reflectance is defined, the optical measurement techniques developed specifically for these materials are discussed. Next, the solar reflectance properties of mirror materials (glass, metallized plastics, polished aluminum, and protective coatings) are summarized. Finally, current problem areas and future areas of research are discussed.

Butler, B.L.; Call, P.J.; Jorgensen, G.L.; and Pettit, R.B. (October 1979). *Solar Reflectance, Transmittance and Absorptance of Common Materials.* SERI/TP-334-457. Golden, CO: Solar Energy Research Institute, 8 pp.

The solar reflectance, transmittance, and absorption of common materials used for solar glazing, reflector, and absorber fabrication are compiled for easy reference.

Bouquet, F. (July 1980). *Cost/Performance of Solar Reflective Surfaces for Parabolic Dish Concentrators.* DOE/JPL-1060-40. Pasadena, CA: Jet Propulsion Laboratory; 55 pp.

The purpose of this report is to provide information on the selection and evaluation of materials for mirror components of parabolic dish concentrators. Cost/performance ratios for various operating conditions are discussed for double curvature parabolic concentrators. Some important factors concerning performance of the mirrors are summarized and typical costs are treated briefly.

Buhrman, R.A. and Craighead, H.G. (1980). "Chapter 9; Composite Film Selective-Absorbers." *Solar Materials Science.* Edited by Lawrence E. Murr. New York: Academic Press; pp. 277-317.

The chapter discusses the general physical and optical properties of composite films. The emphasis is on vacuum-deposited films.

Pettit, R.B. and Sowell, R.R. (March 1983). "Status of Black Chrome Coating Research." *Proceedings of the Distributed Solar Collector Summary Conference — Technology and Applications; Albuquerque, NM; 15-17 March 1983.* SAND83-0137C. Edited by Robert L. Alvis. Albuquerque, NM: Sandia National Laboratories; pp. 81-88.

Recent results regarding the optimization of electro-deposited black-chrome, solar selective coatings for operation in solar collectors at temperatures up to 300° C are summarized. An accelerated temperature aging test is described and the use of sol-gel protective films is discussed also.

Ignatiev, Alex. (1980). "Chapter 4; The Optical Properties - Microstructure Relationship in Particulate Media: Optical Tailoring of Solar Absorbers." *Solar Materials Science.* Edited by Lawrence E. Murr. New York: Academic Press; pp. 151-170.

protected by the application of an anodized film several microns thick. Solar average hemispherical reflectance values of 0.85 to 0.87 for these materials are typical of aluminum reflectors. Although most of these materials are mechanically and chemically polished to increase their specularity, the soft nature of aluminum makes it difficult to eliminate all surface defects. Therefore, the specular reflectance is usually from 5% to 15% below the hemispherical reflectance values.

Protective coatings are being developed to improve the abrasion resistance of metallized plastic mirrors. These coatings offer the advantages of low cost, light weight, and improved optical performance. Protective coatings are also being considered for front-surface mirrors, but these are still in an exploratory stage of development.

Receivers, that part of the solar thermal system on which the reflector focuses the sun's rays, consist of an absorber, which may have a selective **coating** on the outside, and often a glass cover or envelope that partially or totally encloses the absorber. A receiver with desirable optical properties absorbs all the incident light with a minimum of the energy being re-radiated. The optical response of solar absorbers is strongly dependent on the microscopic structure of the absorber material.

Although it is thought that optical tailoring of a material can be accomplished through the manipulation of its microscopic structure, modification of the optical response of absorber materials is presently achieved only through interference effects caused by the application of anti-reflection coatings. The improvement that can be achieved by selective absorber coatings is strongly dependent on specific collector design, but most concentrating collectors benefit from their use. For example, the efficiency of a linear concentrating collector operating at 300°C (570°F) can be improved from 16% to 42% by the use of a selective coating.

Dielectric rich composites (cermets), which most coatings use, are generally strongly absorbing over much of the solar spectrum. When such a composite coating is formed on a highly reflecting metal surface, the resulting absorber-mirror tandem can be a strongly absorbing, yet selective, photothermal collector. The most intensively studied and widely employed low-temperature (less than 300°C; 570°F) selective absorber is a black chrome coating. However, black chrome coating is electroplated onto the metallic substrate and hence, along with other electroplated coatings, tends to fail when used for high-temperature applications (greater than 350°C; 660°F). Coatings that are either vacuum or sputter deposited have superior integrity and tend to be considerably more stable in hostile high-temperature environments.

The properties of **cover materials** are of less interest for concentrating collectors, which make little use of covers, than for low-temperature flat-plate and evacuated-tube collectors. The exception to this is the glass envelope that may be used to enclose the absorber tube — particularly in parabolic trough systems. The cover material is required to transmit as much of the solar spectrum as possible while blocking re-radiation of

The optical response of absorbers has been attributed to the particulate nature of the material. The relationship between optical response and microscopic structure is examined after the basic principles of electromagnetic radiation absorption by a medium are reviewed.

long wavelength thermal energy. Performance problems that need to be addressed for cover materials are reflection losses from the front and back surfaces of the cover and absorption into the cover of part of the solar spectrum (a particular problem of glass with lead impurities).

Heat-Transfer and Structural Materials

Once the solar optical materials needs are identified, the energy storage and transfer functions of the materials must be evaluated. Virtually all solar systems for direct conversion to heat require materials to absorb the solar flux and to contain the working fluid. At the high-temperatures achieved by concentrating collectors, these materials must be able to withstand the stresses imposed by both the operating temperature and the intermittent nature of solar energy. For example, at the 10 MW Central Receiver Pilot Plant, problems experienced with the heat-transfer material, Incoloy 800, included creep at the 550°C (1020°F) operating temperature and low-cycle fatigue induced by the diurnal cycle and random clouds. In addition, working fluids used at high internal pressure, such as water/steam, require that the receiver tubes have thick walls.

The solar collector **support structure materials** must not only provide strength and stiffness, but they must be as low in cost as possible in order to help bring the cost of energy produced by the system down to levels competitive with conventional energy. It is desirable to have a lightweight structure fabricated from low-cost raw materials. The performance requirements for a parabolic trough support structure are (1) to provide the correct optical shape to the reflective surface, (2) to maintain this shape within specified tolerances during operation, (3) to service and protect the reflective surface under extreme weather conditions, (4) to align the reflective surface with the sun, and (5) to withstand long-term exposure to the environment.

Materials and System Reliability and Maintenance

Although solar energy systems require no fuel, they are characterized by high initial cost. A service life measured in decades is required to amortize that initial cost at acceptable rates. For solar energy to have a great impact, not only must acceptable cost be achieved, but the public must have confidence in the product and its performance over the design lifetime. Confidence in reliable performance and system-life projections is based on a thorough knowledge of the materials and their properties for use in the intended environment.

Material degradation appears to be a common problem challenging the development of solar thermal power. Material failure can include chemical, mechanical, or combined modes of degradation. Some of the major material issues of interest to solar thermal technologies are (1) creep, creep-fatigue, thermal and corrosion fatigue, and their interaction in high-

Preliminary Heat Pipe Testing Program; Final Technical Report. (March 1981). DOE/SF/10756-1. San Francisco, CA: Bechtel National, Inc.; 226 pp.

The purpose of this program was to accumulate data on the ability of high-temperature metallic heat pipes to perform under the type of cyclic service conditions that would be encountered in receivers of certain solar thermal power systems or high-temperature process heat supply systems. The reports, *Heat Pipe Receiver Development*, by Foster Wheeler Development Corporation and, *Final Report for Heat Pipe Testing Program*, by Dynatherm Corporation are included in their entirety in the appendix.

Reuter, Robert C. (February 1981). "Initial Parabolic Trough Design and Parametric Evaluation." *Proceedings of the Line-Focus Solar Thermal Energy Technology Development; A Seminar for Industry; Albuquerque, NM; 9-11 September 1980.* SAND80-1666. Edited by Roscoe L. Champion. Albuquerque, NM: Sandia National Laboratories; pp. 265-272.

The paper discusses both promising and unsuccessful materials and designs for use with parabolic troughs. Construction concepts and materials for troughs must be able to fulfill basic guidelines such as shape (parabola definition), aperture, deflective allowance under moderate wind, and no structural failure up to a specified wind speed.

temperature thermal conversion systems; (2) degradation of reflectors by chemical corrosion and adverse mechanical or thermal conditions; and (3) corrosion and degradation of thermal storage system materials. Although some conditions in solar-thermal power systems are similar to those in conventional nuclear and fossil-fired systems, the thermal fluctuations caused by diurnal cycling and intermittent cloud cover represent a thermal and cyclic stress environment that is unique to solar energy systems.

Receiver and Storage Materials

The major receiver material issues are influenced by the heat-transfer fluids and operating conditions of the individual solar thermal system. The central receiver prototypes being investigated presently include gas, sodium, salt, organic, and water-cooled systems. The receiver material needs for each of these systems is described below.

In gas-cooled systems, the characterization of both metallic and ceramic receiver materials under creep, fatigue, and creep-fatigue conditions that result from steady-state loads, mechanical vibrations, and thermal cycling is required. The structural stability of super alloys and silicon carbide as solar receiver materials under oxidizing conditions at high temperatures (above 600°C; 1110°F) is necessary. Some considerations of gas-cooled systems may include the following: slow crack propagation in ceramic receivers; fretting and wearing of ceramic and alloy components; microstructural instability of alloys in high-temperature systems; carburization/decarburization of high-temperature alloys; and degradation of ceramic insulation and changes of emissivity.

Research is underway to expand the use of liquid-metal and molten-salt systems for high-temperature applications. Topics under study to increase performance and reliability are sodium corrosion and mass transport; development of high-strength ferritic alloy; thermal stripping and thermal fatigue damage; use of molten nitrate salt as the primary heat-transfer medium in both receiver and storage subsystems; development and/or modification of coolant containment alloys for receiver operation up to 700°C (1290°F); caustic cracking of steam generator tubes; and stress corrosion cracking of alloys by molten salts.

The mechanical reliability of the receiver, particularly as a function of the thermal and environmental variables encountered, is of primary importance for water/steam cooled systems. The two major materials issues in this area are (1) the applicability of the existing ASME high-temperature design codes, and (2) more high-temperature design data on potential alloys for receivers. Other concerns include the maintenance of coolant chemistry and the interaction of the working fluid with container materials.

In general, for both aqueous and oil systems, the choice of coolant and the selection of container materials should be integrated decisions. For example, organic coolants that produce low operating pressures allow the use of thinner wall

Pohlman, Steven L. (1980). "Chapter 10; *Corrosion Science and Its Application to Solar Thermal Energy Material Problems*." *Solar Materials Science*. Edited by Lawrence E. Murr. New York: Academic Press; pp. 319-373.

This chapter concentrates on problems that may limit the development of solar thermal systems because of material failure, including chemical, mechanical, or combined modes of degradation. The first section reviews each solar thermal technology, especially concentrator receivers, and discusses anticipated material problems. The second section presents the basic theories used in corrosion and electrochemical research.

Basic Research Needs and Opportunities on Interfaces in Solar Materials. (April 1981). CONF-8006156. Washington, DC: Department of Energy; 248 pp.

The proceedings of this workshop present the generic problems at materials interfaces in solar energy systems and ideas on interfacial materials research needed to provide a scientific foundation for these technologies. Included in the proceedings is an executive summary that provides an overview of solar technologies and interfacial phenomena, several reviews and the status of important topics related to solar technologies, and summaries of the needs and opportunities for research on interfaces in solar materials.

Morris, V.L. (January 1982). *Final Report; Solar Collector Materials Exposure to the IPH Site Environment*. SAND81-7028/1 and 2. Livermore, CA: Sandia National Laboratories; 2 V. Work performed by McDonnell Douglas Astronautics Company, Huntington Beach, CA.

In situ environmental exposure tests, conducted at nine proposed intermediate-temperature industrial process heat (IPH) sites, are documented. Three types of reflector materials were evaluated: (1) second-surface silvered glass, (2) aluminized acrylic film on aluminum substrate, and (3) black chrome absorber material and low-iron float glass were evaluated for thermal, photochemical, and environmental degradation. The effect of soiling of the reflector, absorber, and glass materials was evaluated also.

Ewing, J. and Zwissler, J. (June 1979). *Performance Prediction Evaluation of Ceramic Materials in Point-Focusing Solar Receivers*. DOE/JPL-1060-23. Pasadena, CA: Jet Propulsion Laboratory; 48 pp.

The objective of this study is to evaluate the use of ceramics in high-temperature solar thermal sections than that required for an aqueous coolant, and may also reduce the necessity for corrosion control. The thermal properties and thermal-mechanical stability of selective coatings are also important considerations in the design of thermal systems, as is the thermal and corrosion fatigue of the receiver tubes and primary heat-transfer systems. Success of solar thermal designs depends on awareness of the critical parameters, experience of existing technology, and careful and continual control of variables.

Compatability of the dual media with each other and with the containment vessel is the main research topic area for sensible heat storage materials. The main reason for designing storage systems to use a second material other than the working fluid is economic (i.e., to reduce the needed amount of the expensive working fluid). A secondary issue is that a steep thermocline cannot be maintained in a single medium. Typical dual-phase storage concepts include hydrocarbon oils with granite, molten salts with taconite (iron ore), air or gas with refractories, and air with rock.

The cyclic-elevated temperatures found in storage systems will degrade the solids and may promote detrimental interactions between the two media. For example, hydrocarbon oils will readily crack at high temperatures in the presence of oxygen, react with the granite, and form organic acids that could then corrode the storage vessel. Also, the liquid or gas may cause fragmentation of the rock by combined action of chemical attack and thermal stress.

Establishing compatibilities of the inorganic hydrates, organics (waxes), eutectics, and nitrate compounds identified for storage use with potential containment materials, such as stainless, ferritic, and carbon steels is a major area of study in latent-heat thermal storage systems. For example, molten salts are a leading candidate for high-temperature thermal storage in large-scale solar systems. However, containment is the single most important concern since the normally corrosive characteristics of molten salts are aggravated by the cyclic temperature conditions encountered in solar systems.

Thermochemical energy storage utilizing reversible chemical reactions has several advantages over sensible and latent heat processes, including higher energy density, long-term and ambient temperature storage capabilities, and lower energy capacity cost. Cost considerations and material selection appear to be the major unresolved issues. Material issues affecting the reliability of several promising processes vary according to system type. In thermal decomposition reactions there is a lack of understanding of the long-term dynamic behavior of reactant/product particles. For catalyzed type of reactions there is a lack of long-term data on catalyst performance under temperature cycling conditions. Processes involving sulfur and oxygen species at elevated temperatures are considered to provide the most severe conditions for material containment.

applications. A performance prediction model was adapted to evaluate the use of ceramic materials in solar receivers for point-focusing distributed applications. The system performance requirements considered included the receiver operating environment and system operating parameters for various types of engines.

Murr, Lawrence E., editor. (1980). "Section 2: Solar Storage and Thermochemical Materials." *Solar Materials Science*. New York: Academic Press; pp. 376-485.

The four chapters in this section focus on the materials issues of phase-change and thermochemical storage. The first two chapters discuss salt-hydrate storage systems and the last two provide an overview of thermochemical reaction applications to solar energy storage.

Schneider, G.R. and Morgan, G.R. (December 1980). *Thermal Stability Tests of Heat Transfer Fluids for Transfer and Storage of Thermal Energy*. DOE/ET/20417-4. Huntington Beach, CA: McDonnell Douglas Astronautics Company; 133 pp.

The results of laboratory tests conducted to evaluate the high-temperature (290-345° C; 550-650° F) thermal stability, material compatibility, and surface fouling of selected commercial heat-transfer fluids are given. The tests provided information on the rate of fluid replenishment required, the change of viscosity, the composition of lost products, and the rate of fouling of heat-transfer surfaces as a function of temperature and time. Determinations were made on the effect of the presence of materials likely to be used in the energy storage subsystem (rocks, stainless steel, and carbon steel) on these properties.

Mirror Materials

Perhaps the primary area of interest in materials research for concentrating collectors is the reliability and lifetime characteristics of the solar thermal system's optical-materials, especially mirror materials. In most applications, the total mirror surface area deployed is large and, thus, has a significant impact on the system's cost. Also, the reflective properties of the mirrors are a major factor in the performance of the entire system. Any degradation in the mirror's optical properties interferes with the solar thermal system's ability to collect energy, thus decreasing the power level and increasing the cost of the remaining energy available from the system. The environmental stability of the mirror, the resistance of the mirror and support structure to impact and mechanical stresses, and the effect of soiling on the mirror combine to determine the durability of the mirror for concentrator applications.

Since, historically, mirrors have been produced for use as mostly indoor applications, stability or resistance of mirror materials exposed to degradation mechanisms in the environment, such as ultraviolet radiation, moisture, temperature cycling and abrasion, is an important factor in determining the mirror's suitability for use in solar thermal applications. The reflector is the most crucial component to the mirror's performance and, unfortunately, is most susceptible to corrosion when exposed to the atmosphere. Chemical degradation of the reflector's metallic surface is thought to be caused by corrosion resulting from the combination of water and at least one other chemical entity.

Degradation of the silver, which appears as black spots or streaks, has been detected after approximately 6 months of outdoor exposure in some locations. Both edge protection and back surface protection of the silver layer using edge sealants and improved paints are being investigated to minimize degradation for silvered glass mirrors. The glass surface of this type of mirror is considered to be less of a problem. Glass samples exposed outdoors for over 10 years exhibit transmittance values that are typically within 2%-3% of the original values. In addition, glass has good abrasion resistance. New kinds of glass, lighter and cheaper than conventional glass, are being formulated for solar applications.

Unless special UV stabilizers are added, the plastics commonly used for metallized plastic solar mirrors can suffer from ultraviolet degradation which causes increased absorption of radiation and crazing or embrittlement. In addition, plastics have less abrasion resistance than glass. Polished aluminum mirror materials avoid many of these problems. Environmentally, these materials have good abrasion resistance and ultraviolet stability and have maintained their reflectance properties after extended outdoor exposure. However, because aluminum is a soft metal, it is difficult to remove all scratches and pits from the surface during mechanical polishing and the protective anodized film may introduce small scattering centers. These surface defects greatly reduce the mirror's specular reflectance.

Durability of Reflecting Surfaces Used in Solar Heliostats: Washington, DC; 29-30 July 1981. (January 1982). DOE/AL/16306-T1. Atlanta, GA; Georgia Institute of Technology; 94 pp.

The goal of this workshop was to present a base of information and develop industry positions on several key topics related to solar mirror durability. A summary of the workshop and the discussion paper that served as the basis of the workshop's deliberations are included as well as the proceedings of the workshop. Topics include mirror manufacturing, coatings and backings, experience with mirror glass in heliostats, and mirror testing.

Roth, E.P. and Pettit, R.B. (1980). "Chapter 6; The Effect of Soiling on Solar Mirrors and Techniques Used to Maintain High Reflectivity." *Solar Materials Science.* Edited by Lawrence E. Murr. New York: Academic Press; pp. 199-227.

This chapter covers the effect of natural soiling on mirror reflectance, effect of accumulated dust on specular reflectance, scattering theory, deposition and adhesion, accelerated deposition studies, and cleaning strategies.

Morris, V.L. (November 1982). *Environmental Degradation of Solar Optical Materials; Volume 1. Literature Survey.* SAND82-7068/1. Albuquerque, NM: Sandia National Laboratories; 118 pp. Work performed by McDonnell Douglas Astronautics Company, Huntington Beach, CA.

A review of available literature on the environmental degradation of solar optical materials, both transmitting and reflecting, is summarized in detail. The summary is followed by a bibliography of 164 references published from 1960 to present. Emphasis is placed on the physical and chemical degradation effects of the exposure environment on the optical materials proposed for solar energy systems. The extensive appendix includes a listing of organizations contacted in a telephone survey, a listing of standards and specifications developed for solar energy systems, and tables describing *in situ* field tests performed to measure degradation of transmitting and reflecting solar concentrator materials.

Bouquet, F. (July 1980). *Criteria for Evaluation of Reflective Surfaces for Parabolic Dish Concentrators.* DOE/JPL-1060-39. Pasadena, CA: Jet Propulsion Laboratory; 67 pp.

A summary of the technology for evaluating reflective surfaces for parabolic solar dishes is presented in this report. Commercial, second-surface glass mirrors are emphasized, but aluminum and metalized polymeric films are included also. Criteria for sealing solar mirrors in order to prevent environmental degradation and criteria for bonding sagged or bent mirrors to substrate materials are described. A glossary and major references concerning optical criteria are included.

Kerstein, A. (April 1981). *Comparison of Alternative Washing Systems for Heliostats.* SAND81-8207. Albuquerque, NM: Sandia National Laboratories; 26 pp.

The effect of freeze/thaw thermal cycling, impact by objects such as hail, and long-term environmental exposure can create bond degradation at the interfaces of the various mirror materials. Good interfacial adhesion between material (i.e., metal/glass, metal/polymer, and metal/metal) is of primary importance to long-term reliability of solar concentrator systems. Reflective metals on glass or polymers must maintain good adhesion. Poorly bonded silver, for example, will flake or peel away from the glass resulting not only in a loss in reflectance but also in further reactive sites for moisture and other aggressive contaminants. Protective organic coatings over metallized surfaces must adhere to them in order to provide protection from moisture, atmospheric pollutants, etc. Structural adhesives that join the structural back-up panel to the reflective surface must adhere in order to maintain the structural integrity and dimensional stability of the subsystem. Sealants must adhere tightly to panel edges to stop moisture or airborne pollutants from inward migration and eventual attack of the metallized reflective surface.

Another major degradation mechanism for mirrors is the accumulation of dust and foreign particles on surfaces exposed to the environment. The effect of the deposited particles is to reduce the reflected energy by both absorbing and scattering the light. Specular reflectance losses as great as 25% have been observed for mirrors exposed for only a few weeks. The degree to which the particles reduce the collection of reflected energy depends on their composition, number, and size distribution. An additional factor is the optics of the collection systems; scattering caused by dust accumulation at the concentrator surface can result in severe energy losses. Thus, from an economic point of view, periodic cleaning or reduction of soil accumulation is a practical necessity.

An understanding of the mechanisms of dust deposition and adhesion can lead to the development of techniques to maintain high reflectivity under outdoor exposure conditions. Present cleaning strategies can be categorized as follows:

1. Keep dirt from settling and adhering to the surfaces (includes stowing the mirror in an inverted or vertical position).
2. Modify the surface so that strong bonding cannot develop.
3. Wash off dirt with water or low-surface energy detergent-type solutions before strong chemical or mechanical bonding can develop.
4. Wash off dirt with chemically or mechanically active cleaning techniques capable of breaking the chemical and mechanical bonds that have developed.

The first two strategies involve such techniques as ultrasonic vibration, electrostatic biasing, and anti-static, anti-soiling surface coatings. Basically passive, these strategies are primarily capital-intensive but can possibly result in lower long-range cleaning costs. The last two cleaning strategies are labor-intensive techniques that can place economic restrictions on the operation of a solar thermal system. Research has shown that glass mirrors can be cleaned to within 2% and acrylic mirrors to within 8% of their initial reflectance using a

Two methods proposed for washing heliostat mirrors (one is track-mounted and the other affixed to each heliostat) are described. A cost-benefit evaluation, which takes into account the random nature of rainfall patterns and soiling processes, compares the two systems.

Steele, Charles R.; Stephanou, Nicholas; Steele, Marielouise; and Nelson, Drew. (June 1981). *Stress Analysis for Spherically Curved Glass Reflectors.* SAND81-7015. Livermore, CA: Sandia National Laboratories; 95 pp. Work performed by Shelltech Associates, Stanford, CA.

The report contains an analysis of the stresses that occur in elastically deformed spherically curved glass mirrors (i.e., hemispheric curve reflectors) for solar energy applications. Forming stresses, residual stresses, spring-back deformation, and thermal stresses are analyzed. In addition, fracture mechanics and stress corrosion are discussed. Results are presented in generalized form to allow for use in new designs.

high-pressure tap-water spray, possibly followed by a final rinse of deionized water. Mechanically or chemically active cleaning is required to restore 100% of the initial mirror reflectance. However, it is not clear if there may be some long-term buildup of non-removable soil or degradation of the mirror surface when this type of cleaning is used.

Field Test Sites

Test facilities have been designed to test, characterize, and provide operating experience for each of the major solar thermal technologies. Various prototypes or scale models of the important subsystems can be tested before final design of these facilities. The testing program allows parallel development and comparison of alternate concepts and increases the probability for successful operation of pilot plants. Reports concerning activities and results from these test facilities are a major source of performance data on concentrating collectors. In addition to the articles cited after each test facility, current information on activities at most of these sites can be found in the most recent *Solar Thermal Technology Annual Technical Progress Report*. (The complete citation can be found under Federal Programs in Chapter 1.)

There are several test facilities designed to evaluate central receiver systems, which are located at Sandia-Albuquerque, Georgia Tech, and White Sands Air Force Base. The 5 MW **Central Receiver Test Facility** (CRTF), located in Albuquerque, New Mexico is managed by Sandia National Laboratories for DOE. The facility consists of a 61-m (200-ft) tower, 222 heliostats (each 37 m^2) positioned in a north field, a computerized control and data acquisition system, and a video-based system for evaluating heliostat performance.

Moeller, C. Eugene; Brumleve, Thomas D.; Grosskreutz, Charles; and Seamons, Larry O. (1980). "Review Paper: Central Receiver Test Facility — Albuquerque, New Mexico." *Solar Energy*. Vol. 25 (No. 4); pp. 29-302.

The basic philosophy is outlined for the facility and the capabilities of the CRTF are defined. A general description of the facility is followed by details of all support systems: the tower, the heliostat array, the control building with its computer control and data acquisition systems, and the meteorology station and tower. Finally, present and future tests are outlined with a listing of proposed high-temperature experiments by university and industrial investigators.

As the main central receiver test site, the primary goal of the CRTF is to provide experimental engineering data for the design, construction, and operation of receivers and other components for proposed large-scale, solar-powered, electrical generation or process heat plants. A secondary goal is to provide a solar test facility for evaluating concepts and processes in high-temperature technology.

The primary purpose of the Georgia Tech 400 KWe **Advanced Components Test Facility** (ACTF), located in Atlanta, Georgia, is to encourage research and development in high-temperature solar thermal technology. The ACTF is particularly concerned with the use of concentrated solar energy for the production of high temperatures to increase conversion efficiencies of thermodynamic cycles and to produce fuels and chemicals. Major elements of the facility include a field of 550 round mirrors, a 20-m test tower located at the geometric center of the mirror field, an experimental support platform mounted on top of the tower, an instrument and control building, a computerized data collection system, and a heat-rejection system. Equilibrium temperatures of about 1827°C (3320°F) are possible.

Brown, C.T. and Lefferdo, J.M. (1981). "Applied Research in the Solar Thermal Energy Systems Program." *Proceedings of the 1981 Annual Meeting of the American Section of the International Solar Energy Society. Philadelphia, PA; 26-30 May 1981.* Edited by Barbara H. Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 405-409.

The three program elements within the Solar Thermal Research and Advanced Development (RAD) program (materials research, fuels and chemicals research, and applied research) are described in this paper with particular attention given to the applied research activity and the Advanced Components Test Facility (ACTF). The ACTF facilities are outlined and descriptions of some of the experiments performed at the test site are included.

The White Sands facility is actually a solar furnace. Operated by the U.S. Army, the 30-kW **White Sands Solar Furnace** (WSSF) uses a double reflector system. A single, large heliostat made up of 356 flat reflectors, tracks the sun and reflects its energy to a secondary concentrator, consisting of 180 spherical mirrors, which in turn reflects the energy to a 5-cm target area, achieving temperatures up to 2725°C. The facility also incorporates a shutter system to provide thermal pulses of variable intensity and duration.

Hagen, T.L. (1980). "JPL's Parabolic Dish Test Site." *Proceedings of the First Semi-Annual Distributed Receiver Systems Program Review; Lubbock, TX; 22-24 January 1980*. DOE/JPL-1060-33. Pasadena, CA: Jet Propulsion Laboratory; pp. 119-123.

A description of the Parabolic Dish Test Site (PDTS) objectives and capabilities is given. In addition, the various facilities and equipment at the PDTS, and the concentrator experiments being performed are described.

The JPL **Parabolic Dish Test Site** (PDTS), located at Edwards Air Force Base in the California Mojave Desert, has been established to conduct DOE-sponsored work in testing solar point-focusing concentrator systems and at temperatures ranging from 315°C (600°F) to 1650°C (3000°F). The flexible nature of the facility will allow the following related hardware to be tested: (1) complete concentrator-receiver-power conversion systems, (2) concentrators, (3) high-flux density receivers, (4) thermal transport, (5) power conversion systems, and (6) hybrid systems using point-focusing solar concentrators and fossil fuels.

Additional objectives of the PDTS are to perform acceptance testing of prototype solar thermal power systems before full-scale production and to test industry-developed point-focusing systems as time and funding permit. The facilities at the PDTS include several types of concentrators, test equipment such as calorimeters and a flux mapper, a computerized data acquisition system, and a weather station. The concentrators constructed at the PDTS are a precursor concentrator, an Omnium-G electric generating plant, two test bed concentrators, and a prototype concentrator — the Parabolic Dish Concentrator No. 1.

The **Midtemperature Solar Systems Test Facility** (MSSTF), operated by Sandia National Laboratories in Albuquerque, New Mexico, was established to serve as a national engineering evaluation center for mid-temperature-range component and subsystem development. Both line- and point-focus collectors can be tested. The MSSTF consists of (1) a Collector Module Test Facility (CMTF) to obtain thermal and optical performance data for prototype collectors of up to about 45 m^2 in aperture, (2) a Systems Test Facility (STF) for evaluating larger collector fields, and (3) other subsystems and components under development for use in the collection and utilization of solar energy in the mid-temperature range. The test facilities at Sandia and SERI used for testing MISR prototype systems are discussed in the chapter on Parabolic Troughs.

McCulloch, W.H. (1980). "Test Experience at the DOE/Sandia Mid-temperature Solar Systems Test Facility." *Proceedings of the 1980 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge. Phoenix, AZ; 2-6 June 1980*. Edited by Barbara Glenn and Gregory E. Franta. New York: ASES Publishing Office; pp. 488-490.

Dudley, Vernon E. and Workhoven, Robert M. (1980). "Concentrating Solar Collector Test Results." *Proceedings of the 1980 Annual Meeting of the American Solar Energy Society: Progress in Solar Energy — The Renewable Challenge. Phoenix, AZ; 2-6 June 1980*. Edited by Barbara Glenn and Gregory E. Franta. New York, NY: ASES Publishing Office; pp. 491-495.

The Mid-temperature Solar Systems Test Facility (MSSTF) is described in these two papers. The first paper presents some of the insights and experiences acquired during the years the MSSTF has been in operation. The second paper summarizes some of the results obtained from testing concentrating solar collectors at the Collector Module Test Facility, which is part of the MSSTF.

The **Solar Thermal Test Facilities Users Association** (STTFUA) was organized in 1977 at the request of DOE to inform researchers, particularly those in universities and industrial R&D laboratories, of the availability of federally funded solar test facilities and to interest them in helping advance solar thermal technology, particularly high-temperature solar research. STTFUA performed the following functions: disseminating information, stimulating participation in solar thermal programs, handling research proposals, encouraging use of private-sector resources, evaluating capabilities of test facilities, and acting as the primary access link between users and solar thermal test facilities. Test facilities participating in STTFUA include the Georgia Tech Advanced Components Test Facility, Sandia's Central Receiver Test Facility, the White Sands Solar Furnace, JPL's Parabolic Dish Test Site, and two French solar furnaces operated by CNRS and located near Odeillo, and Font-Romeu, France. Proceedings of conferences sponsored by STTFUA and papers by STTFUA participants presented at other conferences are good sources of information about high-temperature solar research projects.

Smith, F.B. (May 1982). *Solar Thermal Test Facilities Users Association Final Report, October 1, 1980 through April 30, 1982*. STTFUA-81-19. Houston, TX: University of Texas; 43 pp.

After a summary of the user association's activities, information is provided on the experiment program. Also included is an information exchange and dissemination activities including conference outlines, a publications list and a copy of the newsletter, administrative details including lists of 1981 and 1982 associates, and a budget summary.

Standards

Solar thermal system developers in industry need to know how materials and systems will perform when subjected to combinations of environmental and system operating conditions. Any limitations in the application of materials and systems should be understood and quantified, and such information made readily available to the designer. An efficient way of developing and maintaining this information, which may be updated as new information becomes available, is through the preparation, use, and maintenance of standards.

Additional potential benefits to be derived from standards development include

- Improved safety, reliability, and interchangeability.
- Development of a strong industrial technology base.
- Definition of the engineering aspects of systems and components to facilitate value engineering analysis.
- Aid in accelerating the commercialization process.
- Assistance in demonstrating the technical rationale and economics of systems.
- Providing part of the basis for assuring utilities, institutional lenders, and local authorities of the engineering practicalities of proposed systems.

In the United States, most national standards are generated through a voluntary committee system made up of various branches of government (e.g., National Bureau of Standards); professional and technical societies (e.g., American Society of Mechanical Engineers); manufacturing and non-manufacturing trade associations (e.g., National Electrical Manufacturers Association); and testing and inspection bodies (e.g., National Fire Protection Association). The voluntary standards-writing

Blackman, J.B. and Linskens, M.C. (1983). *Solar Engineering — 1983: Proceedings of the ASME Solar Energy Division Fifth Annual Conference; Orlando, FL; 18-21 April 1983*. Edited by Lawrence M. Murphy. New York: The American Society of Mechanical Engineers; pp. 314-318.

A description is presented of a consensus standard test method, developed by the ASTM Solar Energy Committee, for determining the thermal performance of concentrating solar collectors. The procedures determine the optical response of the collector for various angles of incidence of solar radiation, and the thermal performance of the collector at various operating temperatures for the condition of maximum optical response.

Cobb, H.R.W. (July 1981). *A Standards Application and Development Plan for Solar Thermal Technologies*. SERI/TR-742-885. Golden, CO: Solar Energy Research Institute; 232 pp.

As part of DOE's effort to develop a quality assurance and standards plan for solar thermal technologies, this document presents data obtained from appropriate sections of industry. The function of solar thermal systems, subsystems, and components are defined, and a list of applicable existing industry codes and standards are presented in matrix form. The need to modify existing standards or develop new ones for solar thermal technologies is discussed.

Rao, M.S.M. (February 1982). *An Interim Structural Design Standard for Solar Energy Applications (Evaluation of ANL Tests)*. SAND80-8193. Albuquerque, NM: Sandia National Laboratories; 62 pp. Work performed by Foster Wheeler Development Corporation, Livingston, NJ.

program is, in large part, administered by the American National Standards Institute (ANSI), which is a voluntary federation of more than 400 standards-writing bodies in the U.S.

Although many of the existing standards developed by these various organizations can be applied to components and materials used in solar thermal systems, there is a need to modify existing standards or develop new ones to adequately represent the unique aspects of solar thermal technologies. The two organizations currently involved in developing solar thermal standards are the American Society for Testing and Materials (ASTM) and the American Society of Mechanical Engineers (ASME).

The lead ASTM committee responsible for solar standards writing is Committee E-44 on Solar Energy Conversion. The subdivisions of Committee E-44, specifically responsible for development of standards for evaluating the thermal performance of concentrating collectors, are Subcommittee E44.07 (Active Solar Energy Process Heating Systems) and Subcommittee E44.08 (Solar Thermal Conversion Power Systems). A standard for determining thermal performance of concentrating collectors has been developed by subcommittees E44.07/08. Future efforts will be directed at developing calculation procedures for determining heat loss for various irradiance levels and use of the calorimetric ratio technique for determining the product of mass and specific heat. For further information on ASTM solar thermal standard development, contact

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The ASME Solar Standards Committee has also been working on developing codes and standards for solar thermal technologies that will eventually be submitted to ANSI. Efforts so far have focused on developing a solar receiver code and modifying existing ASME boiler codes to more accurately reflect solar thermal needs. For further information on ASME solar thermal standard development, contact

Michael Hogan
ASME
United Engineering Center
345 East 47th Street
New York, NY 10017
(212) 705-7722

The development of a set of interim design rules and standards applicable to central receiver solar power system components that generally fall under the scope of the ASME Boiler and Pressure Vessel Code is presented. The results of the following four tasks are included: (1) analytical studies of zero-hold-time tests, (2) study of mean stress shift, (3) analytical studies of hold-time tests, and, (4) creep fatigue life evaluation. The materials used in the tests were type 316 H stainless steel and Incoloy 800.

Chapter 8
Economics and General Issues

Economic Analysis of Solar Thermal Systems

A primary challenge for solar energy technologies is the same challenge as that existing for all other energy technologies, namely, that of reducing the cost of delivered energy to competitive levels.

The methods used to calculate the cost of delivered energy are well-established in the energy industry, and can be applied to provide comparative evaluations of the competitiveness of energy systems and technologies regardless of the nature of the resource used. Typically, the initial cost of the plant and the cost of operation and maintenance are the main factors influencing the cost of delivered energy. Criteria other than the cost of delivered energy have been and are occasionally used to measure the economic performance of an energy technology.

Many of the costs occur at various points in time through the life of a solar system. Therefore, these costs must be reduced to an equivalent set of costs based on uniform currency values at one specific point in time to make valid comparisons possible with competing energy sources. The discipline of engineering economics provides a method of cost comparison using the principles of discounted cash flow. The method is based on the idea that cash flows have both a monetary value and a time value. In order to reduce cash flow at various times to equivalent flows at a fixed time, the value of future cash flow must be reduced (or discounted) to the present by the time value of money.

The various cash flow factors, once derived, can be used to reduce the various costs associated with the purchase and operation of a solar system into a series of uniform yearly payments — called the annual worth, the annualized cost, or the levelized cost — over the expected economic or mechanical life of the system. Two generic cost types may be identified in solar economic analyses: first, capital cost that includes such items as mechanical components of the collector; storage vessels, materials, supports, and insulation; labor and construction; design fees, testing and shakedown; and profit and overhead. The second type of cost recurs through the system's life and may include interest on loans; maintenance; operating costs; replacements and repairs; insurance; and taxes. All of these costs can be combined into a single equation representing the yearly or levelized cost.

Kreider, Jan F. (1979). "Chapter 7. Economic Analysis of Solar-Thermal Systems." *Medium and High Temperature Solar Processes*. New York: Academic Press; pp. 272-303.

The economics of medium- and high-temperature systems are considered, with emphasis on methods and principles of analysis. The following topics are covered: engineering economics — particularly discounted cash flow, solar system cost equations, production functions, and optimal system selection.

Latta, A.F.; Bowyer, J.M.; Funita, T.; and Richter, P.H. (February 1980). *The Effects of Regional Insolation Differences Upon Advanced Solar Thermal Electric Power Plant Performance and Energy Costs*. DOE/JPL-1060-17, Rev. 1. Pasadena, CA: Jet Propulsion Laboratory; 109 pp.

The study determines the performance and cost of four 10-MWe advanced solar thermal electric power plants (central receiver, paraboloidal dish, parabolic trough, and compound parabolic concentrators) sited in various regions of the continental United States. Each region has different insolation characteristics which result in varying collector field areas, plant performance, capital costs, and energy costs. The informative appendices include insolation data for thermal power systems design and economic studies, performance and cost characteristics of advanced solar thermal power plants, and parametric tradeoff and sensitivity analyses of advanced solar thermal power plants.

The Analysis of Construction Costs of Ten Solar Industrial Process Heat Systems. (December 1981). SERI/TR-09144-1. Golden, CO: Solar Energy Research Institute; 263 pp. Work performed by Mueller Associates, Inc., Baltimore, MD.

Analyses of the construction costs of ten DOE-funded solar industrial process heat (IPH) systems were performed in a uniform manner to allow the identification of significant trends and areas for potential cost reductions. Cost data were collected for each system in the following breakdown structure: collector/array, support structure, piping/ductwork,insulation, heating and cooling equipment, storage, controls, and electrical and general construction.

Norris, H.F. and White, S.S. (December 1982). *Manufacturing and Cost Analyses of Heliostats Based on the Second Generation Heliostat Development Study*. SAND82-8007. Albuquerque, NM: Sandia National Laboratories; 326 pp.

The manufacturing processes and users' costs are analyzed for the Second Generation Heliostats. Mass production scenarios are examined by comparison and manufacturing analyses. Different transportation scenarios are compared, as are the

The benefit from owning a system must be known as well as the discounted annual cost in order to assess the costs-to-benefits ratio. The primary benefit from owning a solar system is the displacement of fuel and the associated cost savings. It is usually assumed that a solar system does not replace a conventional backup system but only displaces part of its fuel (i.e., it acts as a fuel saver). This is because most solar energy systems are constrained by the law of diminishing returns which prohibits the economical existence of a full-load solar system that can provide 100% of the demand at all times. A convenient way of quantifying solar system performance, useful in the optimization of solar systems, is by means of a technical production function that relates the magnitude of all system inputs — collector and storage sizes, fluid flow rates, etc. — to useful energy delivery.

Many types of solar systems can be designed to displace the majority of fuel required to provide energy for a given process. In order to select the optimal system, the costs and benefits mentioned above must be analyzed to determine which system provides the maximum benefit for the least cost. The minimum annual cost (MAC) method is used to find the solar system configuration with the minimum cost of accomplishing a given task by using a mix of solar- and fuel-based energy. The minimum value of the annual worth of solar energy plus fuel energy is the optimization criterion, with constraints imposed by physical or economic limits.

Another method of optimization is to select the solar plus fuel mix which assures the maximum internal rate of return on investment (IRR). The IRR method is more difficult to use than the MAC method. One common economic index is the payback period which is defined as the time required to recoup an initial investment in net savings. Although the method is popular, it is inadequate for careful economic studies since it ignores the time value of money and cash flow occurring after the payback period, penalizes long lifetime projects, and cannot rank competing systems.

site assembly and installation procedures. Users' costs are allocated to the central manufacturing facility, to transportation from the central manufacturing facility to the field, and to the field sites. Costs are compared also for these major components: reflective assembly, drive mechanism, controls and field wiring, foundation/pedestal, and support structure. Breakdowns are given for direct materials, direct labor and other expenses including an estimate of the gross profit. A contractor-estimated capital price to the utility is shown for each heliostat design as well as estimated operations and maintenance expenses.

Krawiec, Frank. (November 1983). "Concepts of Learning and Experience in Developing Solar Thermal Technologies." *Technological Forecasting and Social Change*. Vol 24 (No. 3); pp. 207-246.

The economic and technological aspects of solar thermal technology development, including a brief discussion of the U.S. heliostat research and development program, are presented. The cost scenario influencing the prospects of solar thermal technology, including the factors determining cost for a prototype heliostat, are discussed along with production cost scenario and cost variation. Finally, the concepts of learning and experience to predict heliostat cost reduction are examined.

Market Penetration

For successful market penetration, a new technology must meet the technical needs of potential users and offer a competitive advantage over existing equipment in terms of either performance or price. In order to realistically assess the market penetration for solar thermal systems, in either process heat or power generation industries, the energy use and technical requirements of present industrial process or power technology must be cataloged to provide an understanding of the existing industrial network. In addition, it is necessary to determine geographical location of industry and the investment decision criteria employed by industry for the purpose of establishing cost goals for solar thermal that are realistic and comparable to accepted industrial financial practice.

The two market sectors that solar thermal is expected to penetrate in the near future are the industrial and electric

Solar Central Receivers: The Technology, Industry, Markets, and Economics. (September, 1981). DOE/SF/11436-2. Bethesda, MD: Booz-Allen & Hamilton, Inc.; 145 pp.

The purpose of the study is to examine the potential of central receiver systems to provide energy for specific market segments in the southwest U.S. The study focuses on technology development status, candidate manufacturers and suppliers, markets and economic factors.

Turner, A. Keith; Weber, Joseph C.; and DeAngelis, Michael. (December 1981). *A Geographic Market Suitability Analysis for Low- and Intermediate-Temperature Solar IPH Systems*. SERI/TR-733-1194. Golden, CO: Solar Energy Research Institute; 2 V. Work also performed by Colorado School of Mines, Golden, CO.

utility sectors. Industry accounts for about 40% of the gross U.S. energy demand, a large portion of which is utilized as process heat at temperatures from 60°C (140°F) to over 1650°C (3000°F). Of the 29.1 quads of energy that industry consumed in 1979, 12.5 quads were for industrial process heat (IPH). Solar thermal energy conversion technologies have a great potential to satisfy industrial energy demand at nearly every temperature required. The solar thermal technology presently available is capable of supplying energy for process heat requirements at temperatures up to about 300°C (570°F). Approximately 50% of total industrial process heat requirements fall in this temperature range.

The second sector with significant potential for solar thermal energy systems is the electric utility industry. Uncertainties of economics, fuels, utilization, and regulations associated with many of the conventional electricity generation options have led several utilities to explore opportunities in unconventional technologies. Solar thermal systems are expected to penetrate the utility market in a repowering mode initially. Repowering is the concept of adding a solar-thermal conversion front-end to an existing conventional fossil fuel power plant and, thus, replacing some of the expensive oil and gas now being consumed.

Several criteria need to be considered when determining the competitive advantage of solar IPH systems (many of the same criteria can also be used for determining utility solar thermal system competitiveness) over conventional IPH systems in certain geographical areas of the United States. The first criterion is the ability of the solar thermal system to supply the required energy. This criterion is dependent on the insolation available at a site and the local climate. Another consideration is the local air quality regulation in force. For example, non-attainment areas require that no further adverse changes in the air quality occur. In such an area, the non-polluting nature of a solar thermal system would be a significant factor in favor of its use.

A second geographical consideration is the status of competitive fuel. Areas where fuel prices are high or there is a prospect of energy curtailments make the inherent self-sufficiency of a solar energy system more desirable. Finally, the location of industrial demand indicates promising target areas for solar thermal market development. Factors to consider are industry plant locations, industry energy consumption locations, and industrial growth patterns.

To achieve actual market acceptance, solar thermal systems must meet the investment criteria of prospective users which may differ between industrial and utility markets. The basic elements to be evaluated in making such an investment decision include

- Amount of capital available for investment.
- Expected return from investment in a solar thermal system.
- Expected return from an alternative investment.
- Non-financial factors or biases.

This study is an assessment of geographic markets for solar thermal industrial process heat based on market suitability analysis methods that have been refined over the past 20 years by land-use planners. The criteria used include output of different types of low- and intermediate-temperature solar thermal collectors, air quality constraints for competitive fuels, state solar tax incentives, fuel costs, low industrial use of coal, high industrial growth areas, and industry energy consumption in different parts of the U.S.

International Solar-Thermal Market Assessments: An Evaluation. (December 1982). DOE/AL/19929-T6. Washington, DC: Solar Energy Industries Association; 18 pp. plus appendices.

The report lists, describes, and evaluates literature that may contain information on the international market for solar thermal technologies. The extensive appendices include a bibliography of international solar assessments, samples of the contents of various assessments, and a brief by the International Trade Administration on electric power systems and energy conservation equipment.

Perwin, E.; Levine, A.; Mikasa, G.; Noun, R.; and Schaller, D. (December 1981). *Decision Criteria of Potential Solar IPH Adapters*. SERI/TR-663-1032. Golden, CO: Solar Energy Research Institute; 50 pp.

The study examines the factors that enter into some executives' decisions regarding new or replacement energy sources, with attention to purchasing solar thermal energy equipment for generating industrial process heat. Detailed interviews with decision-makers from ten manufacturing firms were conducted.

Habib-agahi, Hamid and Jones, Sue Campbell. (September 1981). *Irrigation Market for Solar Thermal Parabolic Dish Systems*. DOE/JPL-1060-49. Pasadena, CA: Jet Propulsion Laboratory; 33 pp.

The potential size of the on-farm pumped, irrigation market for solar thermal parabolic dish systems in seven high-insolation states is estimated. The study is restricted to the displacement of three specific fuels: (1) gasoline, (2) diesel, and (3) natural gas.

Krawiec, Frank; Thomas, Tom; Jackson, Frederick; Limaye, Dilip R.; Isser, Steve; Karnofsky, Ken; and Davis, Todd D. (October 1980). *Current and Future Industrial Energy Service Characterizations*. SERI/TR-733-790. Golden, CO: Solar Energy Research Institute; 3 V.

The study examines present and future energy demands, end-uses, and cost data to characterize typical energy applications and resultant services in the industrial sector for the U.S. It also projects state industrial energy demand and prices for 15 selected states.

When assessing investments, industrial customers seem willing to accept longer payback periods, or a lower rate of return, for projects offering energy savings. Generally, a minimum return level is set which varies by type of industry. Projects assessed as high risk have higher required returns. In addition, market growth prospects and the amount of capital available for investment will influence the investment decision. Non-financial factors that tend to affect investment selection by industrial users include a reluctance to be the "first purchaser" of a new technology, a preference for "off-the-shelf" equipment, and a preference to purchase supplies rather than fully integrate a production process into their business to produce energy.

Electric utilities, although sensitive to capital costs, also screen investments on the basis of operating characteristics. The evaluation technique, levelized busbar cost yields required cost of electricity needed to recover capital and operating costs over the life of the system, discounted to present dollar values. Given their mandate to provide assured power at reasonable but not necessarily the lowest rates, utilities must balance the often conflicting goals of low capital-intensive equipment, low operating costs, and dependable and adequate generation. In addition to meeting internal criteria, utility capital investments must meet criteria imposed by regulatory bodies. These might include limitations of recovery of interest expense during construction, requirements for selection of least-cost technology, and disallowance of cost items considered to be inappropriate or excessive.

Financing

Incentives and regulatory legislation having significant bearing on the potential for solar technology commercialization have been enacted. In addition to the federal incentives, which are summarized in the section on federal legislation, individual states have enacted legislation which includes provisions for income tax credit deductions, accelerated depreciation, property tax exemptions, and sales tax exemptions. The specific incentives vary from state to state. Most of the tax incentives, both state and federal, have an expiration date — for many, this is December 1985.

Most of the literature on financing large-scale solar projects is concerned with solar power plants, specifically central receiver plants. As a direct result of the various tax incentives and regulatory legislation in existence, the financing alternatives for solar facilities have been enhanced, although most of the federal legislation makes non-utility or third party ownership of solar plants significantly more attractive than utility ownership.

Although direct financing of solar technologies by utilities is unlikely during early commercialization, use of a purchase-lease option, in which the utility would lease the solar facility from an intermediary purchaser, makes utility participation more desirable. However, even with indirect financing,

Bos, Peter B. (June 1982). *Financing Alternatives and Incentives for Solar Thermal Central Receiver Sytems.* DOE/SF/11587-1. Menlo Park, CA: Polydyne Inc.; 79 pp.

As a result of various recently enacted incentive and regulatory legislation (both state and federal), the commercialization of solar thermal central receiver systems will involve financing alternatives other than conventional utility financing. This study identifies the potential financing alternatives and the associated requirements and impacts on the DOE program.

Munjel, P.K.; Walter, J.; and Mathur, P.N. (December 1981). *Third-Party Financing of Central-Receiver Repowering Projects.* ATR — 2-7981-02-1. El Segundo, CA: The Aerospace Corporation; 21 pp.

This study investigates an innovative third-party financing approach for the first solar thermal repowering plant that may reduce the need for direct DOE cost-sharing during the early application stage of central receiver technology by industry.

White, Sharon Stanton. (December 1979). *Municipal Bond Financing of Solar Energy Facilities.* SERI/TR-434-191. Golden, CO: Solar Energy Research Institute; 83 pp.

utilities are barred from many of the tax advantages of owning a solar thermal system. Therefore, many of the financial options which are considered most desirable during the time period that these tax incentives are available lend themselves to intermediary or third-party financing.

Some of these intermediary options include R&D limited partnerships, manufacturer financing (sale-leaseback), and intermediary financing. The Energy Research Tax Act (ERTA) of 1981 provides for a 25% tax credit for R&D expenses incurred during a given tax year if they are more than the average expenses during the base period. An R&D limited partnership takes advantage of this legislation by the limited partner providing financing to the general partner in order to conduct research and development in return for the tax benefits and potential profits. Because of the direct economic interest of the manufacturers of solar technologies, there is an interest on their part to arrange for the required financing, either directly or indirectly, and sell the power under a long-term contract to the end-user. In a sale-leaseback arrangement, the manufacturer enters into a long-term energy purchase agreement with the local electric utility company but arranges for the financing of the solar facility with an intermediary or third-party by selling the solar facility to the intermediary and then leasing back the facility.

Because of the high technological and financial risks associated with the commercialization of new, as yet unproven, solar technologies, manufacturers frequently cannot take all the risks themselves. The various incentives provided in tax and regulatory legislation often make it attractive for intermediaries or third parties to assume the associated risks. The most common structure for intermediary financing is a general or limited partnership, where the tax credits and/or losses from its activities can be passed on to the partners. Most of the alternative financing options described use some form of limited partnership.

The application of the laws of municipal bond financing to solar facilities is examined. The type of facilities considered include solar thermal IPH and power production facilities. The report covers general legal principles of municipal securities financing followed by specific bond laws in California, Florida, Illinois, New Mexico, and New York. Several hypothetical cases are given but none uses solar thermal systems as an example.

Bergeron, Kenneth D. (May 1981). *Incentives for Solar Energy in Industry*. SAND81-0048. Albuquerque, NM: Sandia National Laboratories; 34 pp.

The study analyzes the effects of government subsidies and other incentives on the use of solar energy in industry. Topics include the effects of tax equity, direct subsidies, and government-guaranteed loans.

Solar Thermal Industry

The solar thermal industry includes companies developing parabolic dish, parabolic trough, and central receiver systems. Many firms are developing more than one of these technologies. In surveys conducted by the Jet Propulsion Laboratory (JPL) and the Solar Energy Industries Association (SEIA) it was discovered that most solar thermal companies received at least some, if not all, of their funding from the government (most were providing research and development to the government, as well as architectural and engineering services).

During the summer of 1981, JPL surveyed 54 solar thermal firms. Fifty-two percent of these firms were already marketing their products and the remainder had plans to do so in the near future. About half of the firms in the survey were manufacturing subsystems or components and about 25% were producing "turnkey" systems. The types of products most

Levine, Ned and Slonski, Marie. (August 1982). *A Survey of Manufacturers of Solar Thermal Energy Systems*. DOE/JPL-1060-56. Pasadena, CA: Jet Propulsion Laboratory; 92 pp.

Sixty-seven firms that had received DOE funding for the development of solar thermal energy systems were surveyed in the summer of 1981. The report describes the activities of the 54 firms that were still involved in solar thermal and analyzes the role of the federal government in the industry.

La Porta, Carlo and Markov, Nina. (December 1982). *Status of the Solar Thermal Industry: An Assessment*. DOE/AL/19929-T4. Washington, DC: Solar Energy Industries Association; 22 pp. plus appendices.

The results of interviews conducted with 16 solar thermal companies and 5 utility companies in August 1982 are reported. The topics covered include industry-government relations;

commonly planned for future production were items related to distributed systems such as troughs, dishes, industrial process heat systems, and collectors. The few firms that mentioned central receivers were mostly interested in supplying components and subsystems such as control systems, Rankine engines, power conditioners, and thermal storage.

technological and commercial readiness, barriers and needs; and status of relations with the utility sector. The appendices include documents on private-sector investment in centralized solar thermal technologies and the solar thermal industry opinion on the Business Energy Tax Credit.

The SEIA survey was conducted in August 1982 and interviewed 16 solar thermal companies and 5 utilities. Twelve of the 16 companies were dependent on direct government support with half of these receiving 25%-50% of their R&D funds from the government; the other half received 80%-100%. The four remaining companies do not presently receive federal support, although they did until recently.

According to most industry representatives in the central receiver area, basic receiver technology and cost of hardware is no longer considered to be a fundamental problem. (The price of heliostats, for example, is expected to come down to a competitive level with mass production). Of the three solar thermal technologies, the central receiver industry is considered to be at a particularly critical point in its development. Whether or not prospective projects materialize is uncertain primarily because of their large scale and attending high cost and risk which creates unique financing problems.

The parabolic trough industry is more advanced commercially but at present they rely on the existence of the solar tax credits. Trough companies tend to be 100% solar; without any other product to fall back on they are vulnerable to cut-backs in federal support. Technological problems with troughs appear to be insignificant. Trough technology is now in its fourth generation and appears to be able to meet basic reliability and maintainablility standards. Parabolic dish companies are farthest behind in terms of technological and commercial development. Dish companies, however, do not believe that technological problems will be a major barrier to commercialization. The modular nature of dishes will make financing less of a problem, which is another advantage.

Environmental and Safety Issues

Potential environmental, health, and safety impacts associated with the production and use of solar thermal energy systems appear in most cases to be negligible, easily mitigated, or site-specific. Pollutants arising during routine operation are relatively minor and can be controlled by methods that are used routinely in industry. Impacts on land-use, local ecology, and water use during construction and operation of a solar thermal system may be more significant, although still less than that for most conventional power generation technologies.

Lindberg, R.G.; Daniels, J.I.; Hastings, J.; and Phinney, S.; editors. (June 1982). *Environmental Assessment of the U.S. Department of Energy's Solar Thermal Technology Program.* UCLA 12/1372. Los Angeles, CA: University of California; 215 pp.

This document identifies general environmental, health, and safety concerns associated with deployment of solar thermal systems. In addition, the document is intended to aid in planning future research in the area of environmental controls and in preparing site-specific environmental assessments and impact statements.

Mining of raw materials such as bauxite, copper ore, and iron ore for solar collectors will be increased, thus increasing the amount of airborne particulates and exhaust gases from machinery. However, the majority of materials used in solar

Lindberg, R.G. and Turner, F.B. (1982). "Environmental Considerations in Siting Solar Thermal Power Systems in Deserts of the Southwestern U.S.A." *Solar World Forum:*

systems can be recycled making the mining emissions a one-time event.

Large expanses of land are needed for solar thermal systems — approximately 2.6 km^2 (1 mi^2) to capture 100 megawatts of electricity. In addition to the difficulty of finding and purchasing such large tracts of land, the construction of any large facility such as a power plant will impact the local ecosystem. For example, in the arid regions of the southwest U.S., where it is expected that many of the first systems will be built, the construction of a central receiver solar thermal plant can be expected to destroy parts of the ecosystem within the power plant site, displace windblown dust and sand into adjacent downwind sites, and possibly affect plant and animal life around the site.

Unlike central receivers, distributed solar thermal power systems are modular in nature, diminishing the need for contiguous land parcels and perhaps modifying the impacts of plant construction and operation on the local ecosystem. The operation of a solar thermal power system is not likely to cause any pollution, with the possible exception of an accidental release or spillage of some working fluids that may be used for heat transport or storage. Several of these fluids are quite toxic and others may be a fire hazard.

A more likely hazard during the operation of a solar thermal system exists at the focus of the system's heliostats or other concentrators which may cause burns, eye injuries, and fires. The very high solar flux created at the focus of a central receiver could blind aircraft pilots or even damage the aircraft. However, there are relatively simple precautions that can be taken to prevent most of these problems.

Finally, the use of solar power systems will actually help to reduce the environmental impacts caused by conventional power plants. For example, the replacement of fossil fuel combustion with solar heat would reduce the emission of pollutants such as CO, CO_2, NO_x, SO_x, particulates, acid rain, and unburned hydrocarbons. The environmental benefits of a solar thermal system could be substantial on a regional level.

Proceedings of the International Solar Energy Society Congress; Brighton, England; 23-28 August 1981. Edited by David O. Hall and June Morton. New York: Pergamon Press; pp. 1510-1514.

This paper provides an environmental perspective to siting large-scale solar thermal power systems (STPS) in the arid southwestern U.S., and describes on-going environmental studies in the environs of small 10-WMe STPS pilot plants located in the Mojave Desert near Barstow, California. Particular environmental concerns in the areas of land-use, ecological effects, and water supply are addressed.

Holbeck, H. J. and Ireland, S. J. (February 1979). *Siting Issues for Solar Thermal Power Plants with Small Community Applications*. DOE/JPL-1060-78/2 Rev. 1. Pasadena, CA: Jet Propulsion Laboratory; 41 pp.

Siting issues associated with small dispersed solar thermal power plants for utility/small community applications of less than 10 MWe are discussed for three categories: (1) system resource requirements, (2) environmental effects of the system, and (3) potential impact of the plant on the environment.

Hurt, P.R. and Lindberg, R.G. (September 1982). *A Preliminary Safety Analysis of Conceptual Hybrid, Repowering and Retrofit Applications of Solar Thermal Central Receiver Technology*. UCLA 12/1380. Los Angeles, CA: University of California; 107 pp.

A preliminary safety analysis of 15 conceptual designs of hybrid, repowering/retrofit applications of solar thermal central receiver technology is described in this report. The approach is generic in nature and focuses on safety concerns associated with the physical interfaces between solar thermal and fossil fuel technologies used in tandem to produce either electricity or industrial process heat. Health and safety concerns are associated primarily with fluid leaks including molten salt, molten sodium, hydrocarbons, and steam; fire or explosion; and increased maintenance repair necessitated by some failure modes.

Federal Legislation

In the past few years, the U.S. Congress has enacted a wide range of energy legislation with the common goal of reducing the nation's dependence on imported oil and encouraging the development of domestically abundant or renewable energy technologies. Those laws that have a direct or indirect impact on the development and use of solar thermal energy systems are described below.

The Solar Energy Research, Development and Demonstration Act of 1974 (P.L. 93-473) authorizes a vigorous federal solar program in three areas: (1) resources determination and assessment; (2) research and development; and (3) demonstration. Its goal is to provide the nation with the option of using solar energy to meet future energy requirements. Planning for the Solar Thermal Power Systems Program

Bottaro, Drew J. (April 1982). *Summary of State Activities under PURPA Section 210*. MIT-EL 82-020 Cambridge, MA: MIT Energy Laboratory, 31 pp.

Bottaro, Drew J. and Radcliffe, Robert R. (April 1982). *Summary of State Activities Under PURPA 210 — Appendix*. MIT-EL 82-019. Cambridge, MA: MIT Energy Laboratory; 130 pp.

This study examines the actions of the 50 state public utility commissions under PURPA section 210, a federal statute designed to encourage cogeneration and small power production. The actions of the commissions affect both the variable benefits (i.e., the rate paid) and fixed costs (e.g., interconnection requirements) to which new and renewable energy technologies, particularly photovoltaics, will be subject. The appendix summarizes the activities of each state public utility continues to follow the guidelines established by this act. In addition, P.L. 93-473 established the Solar Energy Research Institute, authorized U.S. participation in international research projects, and provided for the development of incentives for rapid commercialization of solar technologies.

The Public Utility Regulatory Policies Act (PURPA) became federal law as part of the *National Energy Act* on November 9, 1978 (P.L. 95-617; 16 U.S.C. 2601 *et seq*). The law's broad purpose is to encourage conservation and the efficient use of energy resources by public utilities; this can be done, in part, by encouraging cogeneration and small power production.

Sections 201 and 210 of PURPA encourage these two forms of electricity production by mandating that electric utilities purchase from and sell to cogeneration and small power-producing facilities, and exempting these facilities from certain regulations. In February and March 1980, the Federal Energy Regulatory Commission (FERC) issued final regulations implementing sections 201 and 210. According to these regulations, by March 20, 1981, state utility commissions and unregulated utilities must have begun implementing these regulations.

However, implementation of this law has been slowed as a result of two recent court challenges to PURPA. In February 1981, a Mississippi federal court declared Titles I, II, and Section 210 of the act unconstitutional; however, this ruling was, in turn, struck down by the U.S. Supreme Court in June 1982. In another case, a Washington, D.C. district court invalidated two provisions of Section 210 relating to the full avoided cost and interconnection rules. FERC appealed this ruling and, again, the Supreme Court upheld the existing provisions.

The *Crude Oil Windfall Profits Tax Act* of 1980 (P.L. 96-223; 26 U.S.C. 1, *et seq.*) provides a 40% tax credit on the first $10,000 of expenditure for persons installing solar, wind, or geothermal energy systems in or on their principal residences. For businessess, the "business energy investment tax credit" permitted for solar and wind energy investments was raised to 15%, which, with the addition of the normal 10% investment tax credit, results in a total tax credit of 25%. (Note: *The Tax Equity and Fiscal Responsibility Act* of 1982 reduces the depreciation basis for property eligible for the federal investment tax credit and energy tax credit.) Both the personal and business tax credits will expire in December 1985.

The Economic Recovery Tax Act of 1981 (P.L. 97-34) amends the Internal Revenue Code; it is not aimed specifically at encouraging acquisition of renewable energy equipment. The major tax code change with implications for the economic performance of new energy installations is the new Accelerated Cost Recovery System (ACRS). Under this system, new property is classified into one of three categories, each allowing more rapid depreciation by shortening previous allowable depreciation periods and by allowing more rapid depreciation rates within this new period. Another change is to the investment tax credit (ITC) rules, which were modified

commission on several aspects of the implementation of PURPA. *The Powerplant and Industrial Fuel Use Act* (PIFUA) also became federal law as part of the *National Energy Act* in November 1978 as P.L. 95-620. This act severely restricts the use of petroleum or natural gas by electric utilities and major fuel-burning installations. Instead, the use of coal, other indigenous energy resources, synthetic gases, and alternative fuels are promoted. Research and use of large capacity solar energy systems are especially encouraged by some of the exceptions that continue to allow the burning of natural gas or oil by utilities. For example, utilities and major fuel-burning installations may burn some gas if they combine it with an "alternate fuel."

Howard, Judy. (February 1980). *The National Energy Act Statutes and Solar Energy.* SERI/TR-434-424. Golden, CO: Solar Energy Research Institute; 62 pp.

Four of the five statutes that make up the National Energy Act of 1978 are examined in regard to their effect on solar technology commercialization and solar energy users. The statutes include the National Energy Conservation Policy Act (NECPA), the Energy Tax Act (ETA), the Public Utilities Regulatory Policies Act (PURPA), and the Powerplant and Industrial Fuel Use Act (PIFUA). Federal regulations issued pursuant to the various provisions are identified and discussed also.

Section 210 of PURPA and Solar-Thermal-Energy Development: The Current Regulatory Environment and Suggestions for Future Action. (January 1983). DOE/AL/19929-T7. Washington, DC: Solar Energy Industries Association; 19 pp.

This paper explores the present and future PURPA, section 210 regulatory implications for solar thermal qualifying facilities. After outlining the present PURPA, section 210 regulatory environment and its consequences for solar thermal energy development, the paper described legislation pending before Congress to amend PURPA S210. Finally, possible amendments to PURPA S210 that might further stimulate construction and operation of economically sound solar thermal facilities are explored. Attachments to the paper include copies of section 210 of PURPA, the FERC regulations for this section, the American Electric Power Service Corporation's challenges of the FERC regulations, three studies addressing the status of state regulatory authority implementation of FERC's rules, and four bills introduced in the 97th Congress to amend PURPA S210.

to conform to the new ACRS. The full ITC now applies to property with an ACRS lifetime of only five years (which appears to include solar equipment). However, *only those* amounts invested in energy equipment, which the investor has at-risk, are eligible for the credit. The ITC rules also apply to the Energy Tax Credits.

Chapter 9
Solar Thermal Research Centers

ARCO Power Systems

Heliostat design, development, manufacturing, and solar thermal system engineering, development, and marketing. The ARCO Power Systems Program of ARCO Solar conducts research and development on the design and performance of heliostat systems and central-receiver solar thermal power systems. The dual-axis trackers in ARCO Solar's one-megawatt and six-megawatt photovoltaic power systems are of ARCO Power Systems design, modified for direct rather than reflecting tracking. ARCO Power Systems is field-testing a one-megawatt (thermal) steam generator system designed for enhanced oil recovery; this system has been in daily operation since November 1982.

ARCO Power Systems
Suite 307
7061 S. University Boulevard
Littleton, CO 80122
(303) 798-1317

Key Personnel: F.A. Blake, ARCO Power Systems Program Manager (central receiver systems); J.A. Kaehler, Manager of Engineering (electronic controls); D.N. Gorman, Master Mechanical Engineer (receivers, thermal systems); R.J. Thomas, Structural Engineer (tracker, receiver, tower structures).

Acurex Solar Corporation

An industrial systems commercial IPH group and a systems development group performing R&D on point-focus and line-focus solar collectors as well as design and implementation of PV systems. Holographic Solar Concentrator Development is employed for both line focus and point focus. It also provides complete engineering services in the design, construction, and operation for any solar thermal or power generation system. Solar thermal research programs are performed primarily to support overall commercialization of solar systems, concentrating on product development of trough collectors and components, dish concentrators, and low-cost, plastic flat-panel collectors. Involved in thin-film materials research for low-cost solar collectors, research on evacuated tube receivers, and research on front-surface mirrors. Specific effort is in progress on glass reflectors, drive-and-tracking control systems, absorber materials, and improving the manufacturing process to increase reliability and reduce cost.

Acurex Solar Corporation
555 Clyde Avenue
P.O. Box 7555
Mountain View, CA 94039
(415) 964-3200

Key Personnel: Timothy K. Muller, Project Manager (IPH systems, low-cost collector development); Donald R. Duffy, Engineering Manager (IPH systems, trough and other collector development, system computer modeling, basic materials, and system R&D); Hans Dehne, Project Manager (mechanical engineering); Winston Lowe, Section Leader (stress analysis); Jacques Hull, Materials Engineer (materials science).

Advanco Corporation

Specializes in solar parabolic-dish Stirling engine systems for electric power generation, and in solar-augmented, modular gas-fired cogeneration systems. Advanco has developed tools for optical, thermal, control and heat transfer analysis of high-concentration ratio point-focus dish-receiver systems. Advanco is the prime contractor for the design, fabrication, and testing of a commercial prototype 20-kW dish Stirling system, designed for application in small communities, remote installations, or to augment utility grids. This work is being

Advanco Corporation
999 N. Sepulveda Blvd., Suite 314
El Segundo, CA 90245
(213) 640-2429

Key Personnel: Byron J. Washom, President (dish Stirling systems); Terry Hagen, Chief Engineer (dish Stirling systems).

performed under a cooperative agreement with DOE. Advanco operates a fully instrumented solar thermal test facility at Rancho Mirage, California.

AiResearch Manufacturing Company

A broad-based company with advanced technical and manufacturing capabilities in turbo machinery, heat transfer, and electronic controls. AiResearch manufactures solar receivers for point-focusing distributed power systems for both steam- and Brayton-cycle power conversion systems. The company also developed a ceramic receiver for producing 2200°F air for an advanced gas turbine power system and is currently developing a ceramic receiver for a solar-driven hydrogen fuel production system.

AiResearch Manufacturing Company
2525 W. 190th Street
Torrance, CA 90509
(213) 323-9500

Key Personnel: Robert Hunt, Manager (heat transfer; cryogenic systems sales); Oscar Buchmann, Project Engineer (solar receivers, steam, Brayton cycle); Murray Coombs, Program Manager (ceramic solar receivers); John Turnquist, Sales Manager (small size Rankine and Brayton cycle power systems).

Altas Corporation

Concentrates on the development of technology and hardware in the energy field. Most of the work, to date, has been in solar thermal energy, with some work in conservation and in the energy-efficient use of gas. Altas Corporation does R&D in solar energy and conservation technology as applied to heating and cooling systems in buildings. Work is underway in the development of gas-fired equipment for heating domestic hot water and for space heating. Previous studies have developed an advanced solar/gas water heater, defined the potential damage to flat-plate collectors from hailstorms, and helped to define the potential and limitations of heat pump systems. The heat exchanger factor concept in solar collection systems was originated at Altas Corporation.

Altas Corporation
308 Encinal Street
Santa Cruz, CA 95060
(408) 425-1211

Key Personnel: Francis de Winter, President (system analysis, application of physics to thermal processes, equipment design); Howard Grunes, Project Management (equipment development, parametric studies using laboratory experiments and computer simulations); Elizabeth Clark, Conference Coordinator (meetings coordination, preparation and editing of reports and proceedings).

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (AHSRAE)

An international technical society founded in 1894 to advance the art and science of heating, refrigeration, air-conditioning and ventilation, and the related arts and sciences for the benefit of the general public. The Society supports its own research program and cooperates with other organizations on joint projects. The Society also sponsors research projects at various colleges, universities and research firms in all phases of heating, refrigeration, air-conditioning, and ventilation. Some recent solar-related projects include the effect of solar energy on heat gain, the effect of daylighting on energy savings, the use of solar-assisted heat pumps, and the development of solar design manuals.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
1791 Tullie Circle, NE
Atlanta, GA 30329
(404) 636-8400

Key Personnel: J. Richard Wright, Director of Technology; William W. Seaton, Manager of Research; Stanley A. Mumma, Chairman of Technical Committee on Solar Energy Utilization.

Ar-Lite Panelcraft, Inc.

Produces minimum-cost structures (of polymer concrete) to support photovoltaic and other solar collectors. The company fabricates practical collector structures of progressively increasing cost-effectiveness.

Ar-Lite Panelcraft, Inc.
13030 Wayne Road
Livonia, MI 48150
(313) 525-9400

Key Personnel: Marcel Fermani, General Manager; Peter Bertelson, R&D.

Argonne National Laboratory (ANL)

Operated by the University of Chicago as a multi-purpose energy R&D laboratory. R&D programs include nuclear energy research, high energy physics, physical and life sciences, engineering technology, and environmental research. ANL has performed basic and applied research in the area of solar collector development, thermal energy storage, salt gradient solar ponds, ocean thermal energy conversion (OTEC), and active and passive heating and cooling of houses. ANL has been the lead center of OTEC heat exchanger development and testing and biofouling of heat exchanger surfaces. ANL is the U.S. representative on the IEA Task VII activities in large-scale thermal energy storage.

Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
(312) 972-6230

Key Personnel: William Schertz, Manager, Solar Applications (collector development, heating and cooling); Roger Cole, Staff Engineer (thermal energy storage); John Hull, Staff Engineer (solar ponds); Norm Sather, Manager, Solar Technology (OTEC, biomass); Anthony Thomas, Staff Engineer (OTEC).

Arizona Public Service Company (APS)

Focuses on R&D efforts on developing technologies and methods that will provide the resources and equipment needed in the future to minimize costs, assure adequate energy supplies, and meet changing regulations. Much of the R&D in which APS is involved is performed jointly with industry organizations such as the Electric Power Research Institute, the Gas Research Institute, WEST Associates, the Gas-Cooled Reactor Associates, and the Electric Vehicle Council. Research involvement encompasses the areas of energy production through the utilization of resources in the following categories: coal and other fossil fuels, nuclear, fusion, solar, wind, and geothermal. To these are added the areas of energy transport, storage, and utilization. Applications of solar thermal technologies have been directed specifically to develop large-scale central-station and small on-site solar energy resources as a supply of electricity or fuel. Solar repowering of the APS Saguaro plant, for which a preliminary design has been completed, is a solar central receiver system using a molten-salt heat-transfer fluid. In support of this activity, APS has been involved in receiver and storage system tests, using molten salt. Present involvement, as a participant, is with the Molten Salt Electric Experiment at the Central Receiver Test Facility in Albuquerque, New Mexico.

Arizona Public Service Company
Research Programs Department
P.O. Box 21666
Phoenix, AZ 85036
(602) 271-2194

Key Personnel: Joseph McGuirk, Manager, Research Programs; Eric R. Weber, Senior Research Engineer.

Arthur D. Little, Inc.

Provides broad-based technical and management consulting services to industry and government. Technical activities include development of specialized prototype hardware in high

Arthur D. Little, Inc.
Acorn Park
Cambridge, MA 02140
(617) 864-5770

technology fields. The company has undertaken detailed technical and economic assessments of a wide range of solar thermal power options including (1) parabolic dish/Brayton-cycle engines, (2) parabolic troughs/organic Rankine engines, and (3) low-level concentrates/organic Rankine engines. Computer programs were developed in support of these programs to allow estimates of daily, seasonal, and annual performance levels in different regions of the U.S.

Key Personnel: W. Peter Teagan, Manager, Alternative Power Systems Unit.

The BDM Corporation

Turnkey system analysis, design R&D construction, extensive work in parabolic trough and dish systems, including instrumentation. BDM performs component development including collectors, working fluids, storage, valves, controls, and skid mounting.

The BDM Corporation
1801 Randolph Road, SE
Albuquerque, NM 87106
(505) 848-5341

Key Personnel: W. E. Schwinkendorf, ASC Manager/Senior Staff Member (design, modeling); W. R. Kauffman, Director (design, testing).

Babcock & Wilcox (B&W)

Performs both in-house and contract R&D in various advanced energy concept areas. In the area of solar technology, B&W is involved in solar thermal central receiver systems: design, fabrication, erection, and operation. In addition, basic and applied research is conducted in solar support areas such as ceramics, insulating materials, thermal/hydraulic analysis, fracture mechanics, water treatment/chemistry, corrosion, fluid dynamics, shock and vibration analysis, elevated temperature creep/fatigue, seismic analysis, failure analysis, dynamic analysis, and simulation/instrumentation and controls. B&W's solar experience has centered around the solar thermal central receiver technology. This experience includes many projects from feasibility studies and conceptual designs in receivers and thermal energy storage systems to fabrication and testing of receiver- and steam-generator subsystems. In addition, B&W has designed and fabricated a steam generator subsystem for the Molten Salt Electric Experiment.

Babcock & Wilcox
1562 Beeson Street
Alliance, OH 44601
(216) 821-9110

Key Personnel: Floyd N. Anderson, Manager, Marketing (contract research); William F. Clancey, Principal Engineer (new products engineering); Cynthia L. Dalton, Marketing Specialist (contract research); George Grant, Manager (new products engineering); Michael L. Seale, Marketing Representative (commercial components).

Barber-Nichols Engineering Co.

Specializes in Rankine engines and turbo machinery. The company has the personnel to provide analytical engineering and mechanical design as well as a machine shop with special equipment for turbo machinery fabrication. The company also has a complete test facility capable of simulating solar fields up to 10×10^6 Btu/hr and testing solar engines and air-conditioners of up to 200 kW and 100 tons of cooling. Solar Rankine engine design and fabrication includes 15 units presently operating at various locations around the U.S. and in Saudi Arabia. Solar air-conditioning units include 3-ton, 25-ton, 77-ton, and 100-ton units. Power units include 3-kW, 16-kW, 25-hp, and 50-hp units. These units were designed to operate on flat plate collectors, plus or minus 200°F; evacuated

Barber-Nichols Engineering Co.
6325 W. 55th Avenue
Arvada, CO 80002
(303) 421-8111

Key Personnel: R. E. Barber, Vice President (solar project manager); W. D. Batton, Senior Project Engineer (solar project engineer).

tube collectors plus or minus 275°F; concentrating troughs, plus or minus 350°F; and point focusing, plus or minus 750°F.

Bartlesville Energy Technology Center

A government research operation of the U.S. Department of Energy dedicated to research on natural gas and petroleum in its various phases. Two systems have been built as demonstration projects: (1) one completed 600-ft^2 flat-plate solar system; and (2) a 1300-ft^2 parabolic solar system presently being completed.

Bartlesville Energy Technology Center
P.O. Box 1398
Bartlesville, OK 74005
(918) 336-2400

Key Personnel: Jerry A. Tipton, Chief of Facilities Branch (technical project officer for the construction of the above projects); Kenneth J. Hughes, Director, Division of Operations (writes and lectures on solar energy); J.M. (Jack) Beaudry, Chief of Engineering Branch (engineering aspects of solar systems).

Battelle Columbus Laboratories

Pursues sponsored research programs for both government and private agencies. Programs of research and development include those in the physical, social, and life sciences; engineering technology; energy, and environmental research. Researchers at Battelle have worked on a wide variety of solar research including solar parabolic cylinders for multistage desalination, solar heating and cooling, industrial process heat, solar-powered engines, wind generators, solar (PV) cells, thermal energy storage, solar production of hydrogen, advanced solar greenhouses, bioconversion of crops for fuel, solar materials, water pumping, encapsulation materials, optical coatings, total solar systems, and solar economics. Complete facilities and instrumentation are available for basic research projects as well as construction of demonstration systems.

Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201
(614) 424-6424

Key Personnel: D. Karl Landstrom, Projects Manager (solar systems, greenhouse technology); G. Stickford, Principal Research Scientist (solar modeling, systems, passive); S. Talbert, Principal Research Scientist (solar thermal, demonstration projects, desalination); V. McGinnis, Senior Research Scientist (materials, plastics); J. Broehl, Senior Research Scientist (solar economics); R. Fischer, Principal Research Scientist (solar modeling, solar systems).

Battelle Pacific Northwest Laboratory

See: Pacific Northwest Laboratory (PNL)

Bechtel Group, Inc.

The Research and Engineering organization within Bechtel provides technical support to the Bechtel companies and performs contract research for clients in new technological fields of significance to major engineering and construction projects. Bechtel has participated in major solar thermal research and development programs since 1972. Bechtel's experience covers the range of technologies from central receiver, parabolic dish, and parabolic trough technologies to solar ponds. Activities and interests include conceptual and preliminary design and economic assessment studies and final design, engineering, and construction. Major recent projects include a 100 MWe Solar Hybrid Brayton-cycle plant, the Pioneer Mill Solar Cogeneration Facility, the Solar 100 Molten Salt Central Receiver conceptual design, the final design of the 30 MWe Carrisa Plains Solar Power Plant, and a central receiver cost and performance assessment.

Bechtel Group, Inc.
50 Beale Street
San Francisco, CA 94105
(415) 768-1234

Key Personnel: Jack Darnell, Manager, Power Technology Group (solar thermal project development and technology assessment); Gerry Braun, Supervisor, Solar Technology Section (solar thermal project development and technology assessment); Pat DeLaquil, Solar Technology Section (central receiver design optimization and economic analysis); Bob Lessley, Solar Technology Section (heat transport and thermal storage system design; central receiver and parabolic trough power plant design); Bruce Kelly, Solar Technology Section (distributed and central receiver heat transport system design; design optimization and system integration).

Black & Veatch, Engineers-Architects

Offers engineering design and construction management services to the electric power generation, transmission, and distribution industry. The company carries out engineering R&D in advanced energy conversion systems, including solar thermal central receivers. Major emphasis is on electric power generation by means of central receiver technology, utilizing both water/steam and molten-salt heat-transfer fluids. Testing and test facility design for component/subsystem verification continues to be an area of expertise. Application of this technology to water desalination, cogeneration, and production of fuels and chemicals is included in past and current projects. The company performs system analysis, conceptual, preliminary and detailed design of solar plants. Evaluation and economic assessment of altenative energy sources are an ongoing project activity.

Black & Veatch, Engineers-Architects
P. O. Box 8405
Kansas City, MO 64114
(913) 967-2000

Key Personnel: J.C. Grosskreutz, Manager, Advanced Technology Projects (central receiver power plant design, solar test facility design, fuels and chemicals R&D, research planning/policy); John E. Harder, Project Manager (central receiver power plant design, solar thermal desalination of water, cogeneration).

Boeing Engineering Company

An R&D oriented organization with capabilities in design, analysis, testing and evaluation. The Solar Thermal Group is currently involved in DOE and EPRI sponsored programs. Goals include the advancement of promising solar thermal energy conversion and storage systems to the point of economic commercial value and establishment of a product line. Boeing's emphasis is on solar central receiver systems that use the Brayton cycle for power conversion. Industrial process heat applications are also of interest. Energy storage, including chemical, phase-change and sensible heat concepts are subjects of continuing research. Plastic dome enclosure heliostats and silvered glass heliostats, with emphasis on cost reduction, are the subjects of ongoing research. Technical assessment services are provided also. Current activities are directed to economic evaluation of solar central receiver concepts for small, stand-alone power- and process-heat plants.

Boeing Engineering Company
Solar Energy Systems
P. O. Box 3707, Mail Stop 9A-42
Seattle, WA 98124
(206) 575-5588

Key Personnel: Donald H. Bartlett, Manager, Central Receiver Systems (cavity receiver systems, controls, plastic and glass heliostats system design and economics, energy storage); William D. Beverly, Senior Specialist Engineer (thermal design/analysis, system analysis and economics of central receiver, heliostat field and energy storage concepts, development, test and evaluation of components and systems).

Booz-Allen & Hamilton, Inc.

Management and technical consulting firm for many of the largest U.S. industrial firms, major utilities, financial institutions, and many other corporations. Work is performed also for many federal agencies as well as numerous state and local governments. The research program has involved industry assessments (technology, markets, industry status and economics) for solar central receivers, technology R&D planning for advanced solar/gas technologies, program office support for DOE offices, market analysis and projections (including impacts of government incentives) for solar central receivers, industrial process heat systems, and dual-axis tracking-dish systems, and utility impact analyses for industrial process heat systems.

Booz-Allen & Hamilton, Inc.
4330 East West Highway
Bethesda, MD 20814
(301) 951-2000

Key Personnel: Alan S. Hirshberg, Officer (policy, strategic planning, technical and economic assessments); Steven A. Haas, Senior Associate (technical assessment, economic analysis); William H. Babcock, Senior Associate (planning, economics, market analysis).

Brown University

University research team (under negotiation). The research program is concerned with the application of second-law analysis to solar thermal installations with special emphasis on chemical processes.

Brown University
Center for Energy Studies
Providence, RI 02912
(401) 863-2685

Key Personnel: Joseph Kestin, Research Professor of Engineering (thermodynamic analysis of energy conversion and second-law applications).

Burns & McDonnell Engineering Co.

Design and consulting engineering of electric generating systems. Performs economic and technical evaluations of solar technologies for electric power generation. Experience includes technology assessments for a wide range of alternative energy systems including solar thermal. Also performs documentation and cataloging support for solar research and development programs.

Burns & McDonnell Engineering Co.
P.O. Box 173
Kansas City, MO 64141
(816) 333-4375

Key Personnel: Peter Steitz (technology assessment); Douglas Criner (technology assessment and system design); Mary Soderstrum (research documentation).

Burt Hill Kosar Rittelmann Associates

An architectural/engineering firm offering complete architectural/engineering design services, as well as energy management, and research and analysis services. The firm emphasizes an integrated systems approach to the design of energy-efficient buildings, including residential, commercial, institutional, and industrial applications. The company has been involved in all aspects of solar thermal energy utilization (including research, analysis and feasibility studies, design tool development, and applications) for over a decade. Research activities include technology assessment, product development, system design/integration, and system feasibility/optimization studies. Past projects have included both active and passive systems, solar ponds, and daylighting research/applications.

Burt Hill Kosar Rittelmann Associates
400 Morgan Center
Butler, PA 16001
(412) 285-4761

Key Personnel: Paul W. Scanlon, Management of Energy Division; S. Faruq Ahmed, Mechanical Engineer, Solar System Research/Applications Specialist.

California Polytechnic State University

Primarily an undergraduate university with strong emphasis on technical programs in agriculture, architecture, and engineering. Applied solar research has been conducted in the areas of application to agricultural dehydration, passive home heating and cooling, industrial solar dehydration, solar heating of commercial greenhouses, and solar heated brooder house. Demonstration projects have been constructed and placed in operation, the most significant being the Fresno Solar Dehydrator with 27,000 ft^2 of solar collectors, 700 tons of rock storage, and an industrial size heat-recovery wheel. Computer thermal simulation models have been developed and tested against the actual operating demonstration projects.

California Polytechnic State University
Agricultural Engineering Department
San Luis Obispo, CA 93407
(805) 546-2378
(805) 546-2814

Key Personnel: Edgar J. Carnegie, Professor and Department Head, Agricultural Engineering Department (application of solar energy to agriculture); Phil Niles, Professor, Aero/Mechanical Department (passive solar design, computer thermal modeling); Ken Haggard, Professor, Architecture Department (passive solar design); Jens Pohl, Professor, Architecture Department (air-inflated structures, solar thermal processes).

Carrier Corporation

Contracts work in all areas of heat-operated cooling equipment including absorption, Rankine, adsorption, and heat pumps. Carrier also manufactures and distributes air-conditioning and heating equipment. Major effort is in absorption technology operated at relatively low temperatures entering a generator that can utilize all types of solar collectors. Both water-cooled and air-cooled versions are available. Heat-operated heat pumps are under development.

Carrier Corporation
Energy Systems Division (ESD)
Carrier Parkway
P.O. Box 4808
Syracuse, NY 13221
(315) 433-4621

Key Personnel: W.J. Biermann (absorption systems, refrigeration, absorption pairs); R.C. Riemann (absorption chiller designs); H.H. Hopkinson (refrigeration); G.B. Orbesen (applications).

Cherne, Jack

Research, design, development, and construction of solar thermal systems for commercial and industrial process-heating applications. Systems include cogeneration applications. Solar systems include flat plate, linear parabolic, and point-focusing concentrators. Development and implementation of energy conservation and energy management systems are part of the total packages offered. Research is continuing in the economic application of these solar thermal systems.

Cherne, Jack
Professional Engineer
339 20th Street
Santa Monica, CA 90402
(213) 393-4759

Key Personnel: Jack Cherne, Principal (solar heating and cooling of buildings; solar total energy systems; low-temperature solar industrial process heat; high-temperature solar industrial process heat; energy storage; geothermal energy systems; heat transfer fluids, including air, water, and thermal oils; cogeneration; solar thermal system marketing; solar education; solar economics).

Colorado School of Mines

Conducts research in solar thermal resource assessment, insolation measurement, ocean thermal energy conversion, thermo-electrics, and photovoltaics.

Colorado School of Mines
Department of Physics
Golden, CO 80401
(303) 273-3830

Key Personnel: R.B. Bowersox, Professor Emeritus (insolation measurement); F.S. Mathews, Professor (resource assessment, ocean thermal energy conversion); J.U. Trefny (thin film thermoelectrics, amorphous materials); D.L. Williamson (photovoltaics, amorphous materials).

Colorado State University

Involves study of reversible thermochemical reactions for energy conversion, transport, and storage. This concept permits potential high efficiency transport and storage of solar energy in chemical-bond form. Research has been involved with identifying liquid-phase chemistry for such applications and also has studied the reversible ammonia reaction. A second area of interest in research is the development of an open-cycle cooling system employing solar-heated air; this system utilizes flat plate collectors, and a chiller/packed tower combination having aqueous lithium chloride as the working fluid.

Colorado State University
Department of Agricultural and Chemical Engineering
Fort Collins, CO 80523
(303) 491-7871

Key Personnel: Terry G. Lenz, Professor of Chemical Engineering.

Colorado State University

A research center that concentrates on development of cost-effective active and passive solar heating and cooling systems. Major efforts are in testing, improving, and evaluating heating and cooling systems, developing thermal modules of systems and buildings, and analyzing component performance. CSU has five active and passive solar houses that have been utilized since 1973 to develop and improve solar-space and hot-water systems. Basic studies in heat transfer, computer models, and component interactions are conducted, much of it in the form of student theses.

Colorado State University
Solar Energy Applications Laboratory (SEAL)
Fort Collins, CO 80523
(303) 491-8618

Key Personnel: S. Karaki, Director (SEAL) (solar heating and cooling of buildings, modeling, analysis); G.O.G. Lof, Professor of Engineering (solar heating and cooling of buildings); W. S. Duff, Professor of Mechanical Engineering (solar heating and cooling, modeling, analysis); C. B. Winn, Professor of Mechanical Engineering (solar heating and cooling controls, modeling, passive, analysis); P. Burns, Assistant Professor of Mechanical Engineering (solar heating and cooling, passive, heat transfer); T. Lenz, Associate Professor of Chemical Engineering (solar heating and cooling, solar reactors, chemical-energy storage); A. Kirkpatrick, Assistant Professor of Mechanical Engineering (solar heating and cooling, passive, heat transfer).

Columbia Gas System Service Corporation

An integrated natural gas utility company involved in exploration, production, transmission, storage, and the distribution of natural gas. Columbia's Research Department has been involved in solar energy research since 1973. Present projects seek to identify where further engineering studies are needed on solar equipment and to evaluate the feasibility of public utility effort in the solar energy field. Columbia has completed the design, installation, and operation of a 3000 ft^2 solar system in a commercial office building. The solar system provides a portion of the heating, cooling, and domestic hot-water energy needs of the building. The Columbia Gas System Service Corporation and USS Chemicals Division of U.S. Steel Corporation have also completed the design and installation of a solar energy system to produce 160 psig, 375°F process steam for use in the production of chemicals at the USS Chemicals plant in Haverhill, Ohio. The 50,400 ft^2 solar collector array delivers 6 billion Btu/year of solar-generated process steam to the facility.

Columbia Gas System Service Corporation
Research Department
1600 Dublin Road
Columbus, OH 43215
(614) 481-1000

Key Personnel: J.P. Dechow, Principal Investigator (solar thermal energy systems); E.A. Reid, Jr., Program Manager (solar thermal energy systems).

Cornell University

A research center at Cornell University specializing in experimental and theoretical condensed matter physics. Efforts in the past have concentrated on selective surfaces for photothermal conversion, and especially on heterogeneous or mixed media conforming to the cermet geometry. The research carried out, to date, has involved both experimental and theoretical approaches and is directed toward a fundamental understanding of multicomponents in homogeneous systems.

Cornell University
Laboratory of Atomic and Solid State Physics
Clark Hall
Ithaca, NY 14853
(607) 256-5061

Key Personnel: A. J. Sievers, Professor (selective surfaces/experiment); N. W. Ashcroft, Professor (selective surfaces/theory).

Corning Glass Works

A manufacturer of specialty glasses and glass-ceramics whose applications cover many disciplines. More than 30,000 different glasses are melted annually in the company's 43 domestic production plants. Present activity in the solar thermal field relates to anti-reflection surfaces having up to 99% transmission across the solar spectrum 0.35 to 2.5 microns. This is a glass-processing feature, not a coating.

Corning Glass Works
Advanced Products Department
MP 8-05-5
Corning, NY 14831
(607) 974-7630

Key Personnel: Herbert A. Miska, Supervisor, Product Engineering (aerospace/solar); Arthur F. Shoemaker, Senior Marketing Development Specialist (aerospace/solar).

Crosbyton Solar Power Project (CSPP)

See: Texas Tech University

DSET Laboratories, Inc.

A private sector laboratory and a member of the American Council of Independent Laboratories. Major endeavors are in materials weathering, solar device testing, optical properties measurements and spectrophotometry of materials, surfaces and devices (lamps, services, etc.). Capabilities include many standard test services and specialized product R&D test services. DSET Laboratories has been engaged in product R&D testing for private sector companies as well as various governmental agencies since 1974. DSET has been involved in testing standard flat-plate technology for water and space heating. DSET is a DOE-approved laboratory for testing solar thermal concentrators in support of Sandia Laboratories' Industrial Process Heat (IPH) Program. Experimental test work had been conducted in support of solar thermal test standards (ASHRAE 93-77, 96-80, 96-1981). Research has explored the area of diffuse sky modifiers for thermal performance and the development of spectra for continuous solar simulators.

DSET Laboratories, Inc.
Box 1850
Black Canyon Stage I
Phoenix, AZ 85029
(602) 465-7356

Key Personnel: G.A. Zerlaut, President (sky models/radiation measurement); W.J. Putman, Manager Solar Conversion (test facilities, test methodology, instrumentation & measurements); J.S. Robbins, III, Chief Engineer (climatological measurements & instrumentation, thermal performance testing); L.A. Bard, Supervisor, Solar System Test Laboratory (test methodology & test facilities solar thermal systems).

DSMA Engineering Corporation

Consulting engineers specializing in low-loss, high-flow quality air circuits for the international aerospace and automotive industries. This resulted from a proposed design for a solar generating plant based on the Ericsson Cycle. The collector system and air circuitry are extensions of existing practice, but the design is based on combined heat absorption, storage, and heat transfer in a refractory tower using basic materials suitable for use in third world countries. The development of this portion of the design has evolved into theoretical heat transfer studies, including latent heat concepts.

DSMA Engineering Corporation
6220 S. Orange Blossom Trail
Suite 186
Orlando, FL 32809
(305) 851-7442

Key Personnel: A.V. Logie; M.A. Griffin.

Design Evolution 4, Inc.

A design and engineering firm specializing in fiberglass composite structures and production systems using the advanced RTM (Resin Transfer Molding) process. During the past several years the company has done extensive research in the production feasibility of large, low-cost, point-focus solar collectors and also satellite antenna receivers. Because of the instability of large fiberglass reinforced plastic (FRP) panels, research efforts emphasized composite core materials. During the prototype test program two series of RTM prototype molds were fabricated to get an actual hands-on feel for the large, low curvature, parabolic shapes. Variations of test panels were core materials; core thickness 1/2 in. to 1 1/2 in.; skin material (resins) polyester type; skin thickness 0.060 in. to 0.200 in.; resin fillers; mold temperatures; cure rates; shrink; and contour variations. For optical testing, JPL mounted the panels in their 25-ft space simulator that provides a high quality collimated beam of light over a circular area nearly 19.7 ft in diameter. This beam was used to directly measure optical image-forming characteristics of the concentrator panels. For the design aperture diameter of 15 in., approximately 98.5% of the energy from point source was intercepted. The goal is to design and engineer advanced RTM systems and turnkey operations for the FRP industry.

Design Evolution 4, Inc.
P.O. Box 143
1004 W. Main Street
Lebanon, OH 45036
(513) 932-3100

Key Personnel: John Plessinger, President; Jerry Myers, Vice President.

Deutsche Spezialglas A.G. (Desag)

See: Schott America Glass and Scientific Products, Inc.

Dow Corning Corporation

Conducts research and development in silicone technology areas. Syltherm 444 was developed and tested over a five-year period; its advantages include non-corrosiveness, chemical resistance, high flash point, and stability at high temperatures. Present activities include improving the thermal stability of silicone fluids for their use in heat transfer systems. Both lower temperature solar thermal applications, such as flat-plate solar collectors, as well as higher temperature solar projects, such as parabolic collectors, utilize silicone fluids. Dow Corning's involvement is primarily from a material standpoint, with some overlap into the area of the application itself.

Dow Corning Corporation
2200 W. Salzburg Road
Midland, MI 48640
(517) 496-4000

Key Personnel: Scott Andre, Group Leader, Heat Transfer Fluids (heat transfer systems for high temperature solar); Fred Honerkamp, Senior Market Supervisor (heat transfer fluids for lower temperature solar, such as flat plate solar collectors); David Romenesko, Technical Service and Development Specialist (silicone fluid technology specialist); Richard F. Smith, Technical Specialist (silicone fluids; lead role in the development of Syltherm 444).

Dynamics Technology, Inc.

Engaged in theoretical, numerical, and experimental research through contracts with the U.S. Department of Defense and the U.S. Department of Energy. The company is involved primarily with fluid mechanics but includes branches of physics and engineering as well as computer numerical-control machine sales. Explores research pertaining to solar central receivers, solar pond hydrodynamics, and total energy systems analysis.

Dynamics Technology, Inc.
22939 Hawthorne Boulevard
Suite 200
Torrance, CA 90505
(213) 373-0666

Key Personnel: Robert L. Gran, Chief Scientist (central solar receivers — fluid dynamics and heat transfer); Toshi Kubota, Consultant (central solar receivers); Don Jacobson, Senior Scientist (total energy systems, solar ponds).

Dynatherm Corporation

Involved in the development and fabrication of low- and high-temperature heat pipes. Typical applications for low-temperature heat pipes are space craft radiators and electronic equipment. High-temperature liquid-metal heat pipes are used primarily in the semiconductor industry. Under several DOE-sponsored projects, concepts for high-temperature (800°C) gas heaters for central solar receivers were studied. The required heat pipe technology was developed in the laboratory. Long-life performance under simulated solar cycling conditions was demonstrated. A prototype of a small receiver module consisting of a seven-pipe heat exchanger was successfully tested at a solar facility (Georgia Tech).

Dynatherm Corporation
Marble Court Off Industry Lane
Cockeysville, MD 21030
(301) 666-9151

Key Personnel: Walter B. Bienart, President (physics, heat transfer); David A. Wolf, Vice President, Engineering (high-temperature heat transfer/liquid-metal heat pipe technology).

EG&G Idaho, Inc.

Prime contractor at the Idaho National Engineering Laboratory. Technical support and R&D in DOE programs in solar and other renewable energy areas. Specific solar activities include design and monitoring of hybrid residences, performance monitoring of passive residence, technical monitoring of industrial process heat systems, proposal evaluation, and general program support.

EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415
(208) 526-0111

Key Personnel: Kenneth Liebelt (thermal and process anaysis).

EG&G Washington Analytical Services Center, Inc.

A high-technology company interested in advancing the goals of alternative energy. EG&G is involved with testing and test-results analysis of solar thermal systems evaluated at Sandia National Laboratories. EG&G has developed test procedures and test items to evaluate all components of solar thermal including drive-stand test fixtures, flex-hose test systems, fluid loops and many electronic test components. EG&G has operated the mid-temperature solar system test facility, the collector module test facility, and the modular industrial solar retrofit test facility, all at Sandia. EG&G has also been involved in the central receiver test facility development.

EG&G Washington Analytical Services Center, Inc.
2450 Alamo Avenue, SE
P. O. Box 9100
Albuquerque, NM 87119
(505) 243-2233

Key Personnel: Karl D. McAllister, Project Manager (component and system test and test evaluation, operation and installation of systems); Vernon Dudley, Research Scientist (development of hardware and software, conducting and evaluating experiments, development of test procedures); George Morin, Engineer (installation of solar systems, operation and data collection of components and systems).

El Paso Electric Company

An investor-owned electric utility serving west Texas and south-central New Mexico. Present solar thermal research activities include participation in DOE's Solar Repowering program for the repowering of the company's Newman Unit 1 with solar central receiver technology; participation in the University of Texas at El Paso solar pond project; membership on the ASME Solar Codes Committee, and membership on the utility advisory board of DOE's Vanguard Project, Southern California Edison's 100 MW Solar Power Plant, and EPRI 1990 Hybrid Solar Study.

El Paso Electric Company
303 North Oregon
El Paso, TX 79960
(915) 543-5711

Key Personnel: James E. Brown, Supervisor - Resource & Analysis (solar central receiver/project management, ASME Solar Codes); Richard Gambino, Research & Development Engineer (solar ponds/project management); Ed Hernandez, Special Projects Engineer (solar central receiver parabolic dish/project management).

Electric Power Research Institute (EPRI)

Coordinates a national electric power R&D program. Through planning, selection, funding, and management of research projects conducted by contracting organizatons, EPRI promotes the development of new and improved technologies to help the utility industry meet present and future electric energy needs in environmentally and economically acceptable ways. EPRI-sponsored solar thermal research is aimed at understanding the status of and enhancing the prospects for solar thermal electric power systems. Current activities involve documentation and evaluation of field test performance and experience for major, existing experimental installations such as the Solar One central receiver pilot plant; and participation in government/industry cost-shared system experiments aimed at reducing technical risks associated with advanced central receiver concepts.

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303
(415) 855-2000

Key Personnel: Edgar A. DeMeo, Manager, Solar Power Systems Program; John E. Cummings, Director, Renewable Resource Systems.

Electrospace Systems, Inc.

Designs and manufactures a microprocessor-based controller for solar concentrators. This sophisticated system may be expanded easily in a modular manner to achieve centralized control of an array of 1 to 32 concentrators via a master control unit. Extensive error and status reporting is available in both digital and analog form. A four-quadrant, photovoltaic-based solar sensor provides continuous dual-axis error signals for tracking the sun. Elaborate software for ephemeral calculations, memory tracking, and various other custom routines are available to the customer.

Electrospace Systems, Inc.
P. O. Box 1359
Richardson, TX 75080
(214) 231-9303

Key Personnel: D. E. Heitzman, Vice President, Marketing; Charles Huey, Controls Systems Department Head; Tom Scanio, Control Systems Group Head; Kevin Keough, Control Systems Program Engineer.

Energy Engineering, Inc. (EEI)

Performs R&D and manufacturing of solar heating equipment and other energy products. Presently the primary product is the efficient heatpipe(tm) Passive Solar Water Heater that uses boiling-and-condensing freon heat transfer in a flat plate collector to transfer heat to an insulated integral storage tank. Solar thermal research conducted by EEI deals primarily with the use of boiling-and-condensing heat transfer in solar systems. In addition to the development and commercialization of the heatpipe(tm) Passive Solar Water heater, EEI has development in progress on photovoltaic total energy systems, air collector systems, heat recovery power generation systems, and manufacturing techniques for heat pipes.

Energy Engineering, Inc.
4616 McLeod NE
Albuquerque, NM 98109
(505) 884-1610

Key Personnel: Karl Thomas Feldman, Jr. (boiling and condensing heat transfer, heat pipes, passive solar DHW and space heating systems); Richard Hindmarsh, Manufacturing Specialist (solar system manufacturing).

Energy Research & Generation, Inc. (ERG)

Specializes in research, development and engineering involving energy-related technologies, and development and production of energy-related products. The objective of ERG is to invent, develop, patent, manufacture, and commercialize energy-related products that represent the leading edge of

Energy Research & Generation, Inc.
Lowell & 57th Street
Oakland, CA 94608
(415) 658-9785

Key Personnel: G. M. Benson, Director of RD&E (Stirling engines, linear alternators, heat technology. ERG is developing free-piston, Stirling-engine-driven linear alternators, composite ceramic receivers and hot end of Stirling engine; developing high temperature electrolyzer integral with ceramic receiver, and ceramic biomass/fossil fuel combustors for solar augmentation.

exchangers, composite ceramic materials, solar receivers, high-temperature electrolysis); R. V. Vincent, Senior Engineer (free-piston Stirling engine dynamics, gas bearings, heat pipe); W. D. Rifkin, Senior Engineer (Stirling cycle thermodynamics, heat exchangers, composite materials); G. Schmidt, Senior Engineer (Stirling engine and linear alternator design).

Engelhard Corporation

Precious metal fabricators: precious metal catalysts for chemical, petroleum, energy and pollution abatement; metallurgical and electronic materials containing precious metals; and refining reclamation of precious metals from spent materials. Performs solar thermal research in solar absorbers, the development of materials capable of operating as solar absorbers in the 300°C-500°C temperature range. Work sponsored by SERI was initiated in 1976 and completed in 1980. Also develops silver-containing materials for general use as solar reflectors.

Engelhard Corporation
Engelhard Industries Division
Menlo Park
Edison, NJ 08818
(201) 321-5000

Key Personnel: Robert J. Farrauto, Research Manager, Chemistry and Auto Exhaust Emissions Systems (absorbers/reflectors); Frank Russo, Research Chemist (reflectors); M. Novotny, Technical Director, Electronics (absorbers/reflectors).

Enrico Fermi Institute

See: University of Chicago

Entech, Inc.

Manufacturer of Linear Fresnel Lens Solar Collector Systems, including heat collectors, photovoltaic collectors, and hybrid heat/photovoltaic collectors. System Integrator for Solar Power Systems. Performer of Research & Development on Line-Focus, Point-Focus, and Distributed-Focus concentrators. Entech has developed line-focus Fresnel lens heat collectors with about 70% efficiency at 200°F and about 60% efficiency at 400°F. Also built fixed-mirror bowl concentrators which operate at 1000°F and parabolic dish concentrators which operate at 2000°F. Currently developing improved line-focus and point-focus Fresnel lens heat collectors. The hybrid heat/photovoltaic Fresnel collector system at DFW Airport has provided 47% total efficiency for the past 17 months, meeting performance predictions.

Entech, Inc.
1015 Royal Lane
P.O. Box 612246
DFW Airport, TX 75261
(214) 456-0900

Key Personnel: Mark J. O'Neill, Executive V.P. Engineering & Operations (concentrator optics, thermodynamics, heat transfer, systems engineering); Robert R. Walters, V.P. Marketing (system design, economics, & marketing); A.J. McDanal, Manager, Systems Engineering (concentrator optics, thermodynamics, heat transfer); David B. Muzzy, Manager & Systems Engineering (collector testing, system installation); Jeffrey L. Perry (collector manufacturing, materials science).

Ford Aerospace & Communications Corporation

Responsible for the development of the sodium-sulfur battery system as well as the Small Community Solar Power Experiment (SCSE) program, both under the sponsorship of DOE. The SCSE program is aimed at the development of a solar thermal system based upon the point-focus distributed receiver (PFDR) concept. Multiple, dual-axis parabolic dish concentrators are used with an integrated power conversion assembly (PCA) mounted at the focus of each dish. The PCA is a cavity receiver and an organic Rankine engine-generator

Ford Aerospace & Communications Corporation
Aeronutronic Division
Ford Road
Newport Beach, CA 92660
(714) 720-6063

Key Personnel: R.L. Pons, Manager Mechanical Engineering Department (systems analysis, thermo-dynamics, heat transfer, fluid mechanics, design); K.R. Nelson, Program Manager (program management, test operations); T.B. Clark, Principal Engineer (program engineering, unit; the output of each dish is collected in a conventional direct current electrical system with central point inversion to alternating current and utility grid interfacing. Plant control is entirely automatic; i.e., without the need for human operators. Ford Aerospace is responsible for the receiver and the control subsystems as well as the overall system; Barber-Nichols Engineering provides the engine-generator unit and Acurex Corporation provides the parabolic dish concentrator. Upon completion of the present R&D effort, a four-dish, 100-kWe demonstration plant will be installed at Osage City, Kansas.

systems analysis, thermo-dynamics, heat transfer, fluid mechanics, design); W.A. Conway, Senior Engineering Specialist (systems test/integration, instrumentation, field operations); F.P. Boda, Senior Engineering Specialist (power conversion); D.G. Fulton, Senior Engineering Specialist (controls).

Foster-Miller, Inc.

Consulting firm with both government and commercial clients, specializing in thermal and mechanical systems. The company has engaged in both component and systems development projects including design and testing of a solar-powered steam engine for use with parabolic dish collectors, design and testing of an organic Rankine-cycle pump for use with low-cost solar collectors, and design of a solar power plant for a sea water desalination system. The latter includes parabolic dish collectors, molten salt for thermal storage, and a steam-powered prime mover. The company also recently developed and delivered a mobile heliostat cleaning system for the Solar One project in Barstow, California.

Foster-Miller, Inc.
350 Second Avenue
Waltham, MA 02154
(617) 890-3200

Key Personnel: Roger Demler, Division Manager (steam power systems); Ira P. Krepchin, Project Engineer (point-focusing collectors, heat transfer fluids, systems integration, steam power systems); Elizabeth C. Powlin, Project Engineer (heliostat maintenance systems, steam power systems).

Foster Wheeler Solar Development Corporation

Engaged in the development and design of components and systems for solar thermal energy applications. Conceptual design studies of external surface and cavity-type receivers for water/steam, molten salt, and sodium service is another company endeavor. Applications include power generation, process heat, and enhanced oil recovery. Detailed preliminary design and development of fabrication methods for molten-salt central receiver and associated steam generator; design, construction, and testing of water/steam cavity receiver; system design, installation, testing, and field modification of parabolic trough systems for process heat are other areas of exploration.

Foster Wheeler Solar Development Corporation
12 Peach Tree Hill Road
Livingston, NJ 07039
(201) 533-3637

Key Personnel: Robert J. Zoschak, President (central receivers and systems); A.C. Gangadharan (high-temperature structural analysis and materials); D.J. Allen (systems analysis and optimization); S.F. Wu, Program Manager (thermal/hydraulic analysis and design).

GA Technologies, Inc.

An energy technology and contract research organization owned by Gulf Oil Company. GA is active in the development of advanced technologies to help meet the nation's continuing energy needs and in the conduct of related product businesses. GA is developing the High Temperature Gas-Cooled reactor (HTGR). Among long-range company activities, GA conducts a broad-based fusion R&D effort. The company also has active programs in the application of solar energy and in thermochemical water-splitting as a non-fossil renewable source of hydrogen. GA is developing the sulfur iodine

GA Technologies, Inc.
P.O. Box 85608
San Diego, CA 92137
(714) 455-3000

Key Personnel: Gottfried Besenbruch, Senior Principal Engineer (project management of solar research); Lloyd Brown, Hydrogen Project Manager (chemical engineering, solar fuels and chemicals); John Norman, Senior Staff Scientist (chemistry, solar hydrogen).

thermochemical water-splitting cycle for the production of hydrogen using solar energy. Chemical processing systems, including the thermal decomposition of H_2SO_4 are being studied. Solar tests of this process have been carried out and advanced tests are planned. The company is also developing a thermochemical sulfur-based thermal energy storage system that promises seasonal storage capability. In addition, GA has developed a fixed-mirror linear solar collection system and has conducted solar research on power tower (ACTF) heat exchanger/catalytic reactor development.

The Garrett Corporation

Produces high technology equipment with primary emphasis on gas turbines, environmental control systems, heat transfer, electronics power conversion, and pneumatics. Garrett manufactures industrial gas turbines in the 500 kW range; the company is also developing ceramic solar gas turbines in the 20 kW to 100 kW range and subatmosphere solar gas turbines in the 8 kW to 15 kW range. Garrett is developing both a ceramic Brayton-cycle and a metal Rankine-cycle solar receiver. Inverters in a full range of sizes up to several megawatts are manufactured.

The Garrett Corporation
9851 Sepulveda Boulevard
Los Angeles, CA 90009
(213) 417-6836

Key Personnel: Robin Mackay, Market Development.

Garrett Energy Research and Engineering, Inc.

Contract research, development, and engineering company operating in the field of alternate energy technology. Extensive studies on solar storage systems, including low temperature (refrigeration), room temperature (building air-conditioning) and high temperature. Also involved with solar thermal storage and utilization in pond collection systems.

Garrett Energy Research and Engineering, Inc.
911 Bryant Place
Ojai, CA 93023
(805) 646-0159

Key Personnel: Donald E. Garrett, President (solar thermal storage systems, pond collection systems); Charles R. Russell, Senior Engineer (solar thermal storage systems, pond collection systems).

Gas Research Institute (GRI)

Chartered in 1976 to provide a centralized national organization to formulate, present, and manage a comprehensive natural gas R&D program on behalf of member pipeline and utility companies and the gas consumer to enhance the supply, distribution, and utilization of gaseous fuels. GRI plans, selects, funds, and manages contractor-performed R&D which maximizes the value of gas energy services while minimizing the cost of supplying and delivering gaseous fuels. Part of GRI's development of more efficient gas-using equipment, which meets environmental standards while offering lower projected consumer costs and reduced energy consumption, involves solar-augmented, gas-fired energy systems. As a result of initial technology assessments, R&D activities are directed at integrating gas and solar energy equipment in passively heated and cooled structures, domestic water heating appliances, and cogeneration systems. The use of gas-fired space and zoned central heating systems in

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 60631
(312) 399-8100

Key Personnel: Keith Davidson, Program Manager, Advanced Energy Systems; Doug Kosar, Project Engineer, Solar/Gas Systems.

passively heated structures and the potential use of gas-fired dehumidification in passively cooled structures is being thermally and economically characterized by experimentation and analysis to identify optimal combined systems to be developed further. Various solar/gas DHW system configurations have been characterized, including system design improvements, with prototype development of an integrated single-tank solar/gas water heater now planned. A prototype of a gas/solar cogenerator, employing a heat engine/parabolic dish solar concentrator, for commercial cogeneration is also planned for development. A present assessment is evaluating the potential future impacts of gas/solar systems on gas load profiles and consumer and utility/pipeline economics.

Georgia Institute of Technology

Education and research. The objectives of the research are (1) develop materials for high temperature solar thermal energy processes, (2) develop solar reactors for high-temperature conversion of solar energy to storable chemicals and fuels, and (3) develop diagnostic techniques for surface temperatures in a concentrated solar beam. Samples of ceramics and transparent windows are being exposed to solar flux up to 230 w/cm^2 in chemical and gaseous atmospheres. A direct flux reactor and a solar blind pyrometer are being developed.

Georgia Institute of Technology
Engineering Experiment Station
Energy and Materials Sciences Laboratory
Atlanta, GA 30332
(404) 894-3589

Key Personnel: Robert A. Cassanova, Program Director (high-temperature solar thermal systems); S.H. Bomar, Jr., Principal Research Engineer (high-temperature materials); C.T. Brown, Facility Director (high-temperature diagnostics, central receiver component testing); D.H. Neale (direct flux reactors); P.E. Mackie (data acquisition, solar blind pyrometry); J.M. Lefferdo (systems analysis, thermal analysis); T.B. Elfe (thermal, structural and optical modeling).

Georgia Institute of Technology

Conducts applied research programs in areas such as energy, agriculture, robotics, and automation. Research supports local, national, and international clients in both government and private sectors. Research activities involve analysis of advanced concepts for production of synthetic fuels. Systems to supply industrial process heat have been analyzed for use at many industries in the southeastern U.S. Passive monitoring has been conducted at residential sites in the region. Solar pond research is also being conducted.

Georgia Institute of Technology
Engineering Experiment Station
Technology Applications Laboratory (TAL)
Atlanta, GA 30332
(404) 894-3636

Key Personnel: James L. Clark, Senior Research Engineer (industrial process heat, solar ponds); James L. Walsh, Senior Research Engineer (synthetic fuels industrial process heat); Thomas F. McGowan, Senior Research Engineer (residential solar energy systems, industrial process heat); Douglas Moore, Research Engineer (industrial process heat).

Georgia Power's Shenandoah Solar Center

An investor-owned electric utility that evaluates solar energy and its use as a solution to the national energy dilemma. GPC is operating three major solar facilities in Georgia and others are in planning stages. The Solar Total Energy Project in Shenandoah is the world's largest industrial application of solar cogeneration. The solar collector field consists of 114 parabolic dish collectors 23 ft in diameter and track the sun in two-axes. The corporate headquarters of GPC in Atlanta has one of the largest commercial applications in the U.S. of solar

Georgia Power's Shenandoah Solar Center
7 Solar Circle
Shenandoah, GA 30265
(404) 253-0218

Key Personnel: E.J. Ney, Manager, Solar Operations (all systems); J. Willard King, Solar Engineering Manager (solar IPH systems).

energy for building heating, cooling, and domestic hot water. The solar system includes 23,712 ft^2 of parabolic trough collectors that track east to west. A privately funded photovoltaic residence in Roswell has 4.1 kW of solar cells; there are many passive solar and conservation features incorporated into the home.

Gibbs & Hill, Inc.

Involved in the design and construction of fossil, hydroelectric and nuclear power plants and in the development of advanced energy conversion technologies. Gibbs & Hill has been actively involved in the development of solar central receiver technology. One project G&H developed is an air-based cogeneration facility for a copper smelter. Another project entailed repowering of an oil-fired power plant using molten salts. Both projects relied upon a solar central receiver to generate transport/working fluid temperatures in excess of 1000°F.

Gibbs & Hill, Inc.
Eleven Penn Plaza
New York, NY 10001
(212) 760-4000

Key Personnel: Paul P. DeRienzo, Vice President Consulting Engineering; Shashank S. Nadgauda, Director of New Technology Department and Special Projects; Vincent P. Buscemi, Chief Consulting Engineer; Rathbun B. Squires, Assistant Director New Technology Department and Special Projects; Lloyd Winsor, Assistant Chief Consulting Engineer; Norman W. Hinsey, Engineer.

Grumman Energy Systems Company

Manufacturers of solar thermal components including solar collectors and heat exchanger modules. Applications include residential and commercial/industrial domestic water and space heating, swimming pool heating, and process heat. Performs R&D of medium-temperature evacuated tube collectors, and the design and analysis of concentrating equipment.

Grumman Energy Systems Company
445 Broad Hollow Road
Melville, NY 11747
(516) 454-8673

Key Personnel: Joseph A. Ciocca, Director, Engineering; Burt Swerdling, Project Engineer.

Hawaii Natural Energy Institute (HNEI)

See: University of Hawaii at Manoa, Hawaii Natural Energy Institute (HNEI)

Heery Energy Consultants, Inc.

Provides energy-related services in the following areas: new buildings, existing buildings, alternate energy sources, and controls technology. Heery Energy solar thermal research is primarily in the area of monitoring and data analysis. The company is presently involved in parabolic trough tracking systems, solar ponds, photovoltaics, and parabolic dish high-temperature systems.

Heery Energy Consultants, Inc.
880 West Peachtree Street, NW
Atlanta, GA 30367
(404) 881-0497

Key Personnel: Glenn Bellamy, Project Manager (tracking systems, data collection, monitoring data analysis); Glenn Jardine, Project Manager (photovoltaics).

Honeywell, Inc.

Specializes in applied R&D for industry and government, as well as for other Honeywell Divisions. Technological disciplines include controls, advanced sensors, human factors, robotics, simulation, communication, and energy management. TSC does not commercialize, but catalyzes appropriate

Honeywell, Inc.
Technology Strategy Center (TSC)
1700 West Highway 36
Roseville, MN 55113
(612) 378-4178

product commercialization. Honeywell has been involved in the development of solar systems since 1940. Its solar expertise ranges from residential to industrial systems, from simple domestic hot water to complex cooling and power generating systems, from flat-plate to dual-axis tracking collectors, and from differential temperature sensors to tailorable microprocessor controllers. Honeywell continues its investigation of solar controls and systems for residential, commercial, and industrial applications and participates in development programs. Honeywell products have been, and continue to be used in solar controls, but the company does not market solar-specific equipment.

Key Personnel: Dennis Mool, TSC Director of Marketing; Bob Aasen, Principal Engineer.

Illinois State University

Solar research projects involved in (1) grain drying using both liquid and air systems, (2) solar hay drying, (3) solar heating for livestock buildings, (4) solar water heating for farm homes, and (5) solar heating of farm homes. The last two projects were sponsored by NASA, General Electric, the U.S. Department of Energy, and Illinois State University.

Illinois State University
Department of Agriculture
Normal, IL 61761
(309) 438-5654

Key Personnel: R.D. Henry, Professor and Chairman, Department of Agriculture (agricultural applications of solar energy).

Insights West, Inc.

An energy consulting firm specializing in state-of-the-art technology reviews, applications evaluations, market assessments, and market penetration analysis. The company is most active in those areas involving technology transfer from a research status to a field development and commercialization stage. Major studies have been completed on the thermal application by end-users of all solar technologies, fuel cells, and industrial heat pumps. Technical evaluations comparing competing solar thermal technologies and the use of solar for cogeneration have been completed. Strong points of expertise include the understanding of end-use industrial and commercial (air-conditioning) uses by temperature and volume, electrical and thermal use hourly profiles, the impacts of thermal storage, the commercialization opportunities and barriers to solar thermal systems, utility regulatory factors and practices, and cogeneration technologies.

Insights West, Inc.
900 Wilshire Boulevard
Suite 1100
Los Angeles, CA 90017
(213) 680-3273

Key Personnel: John H. Williams, President (end-use industrial applications, technology transfer, cogeneration technologies, utility practices and market assessments); David W. Kearney, Vice President, Technical Applications (solar thermal, ocean and wind technologies, industrial heat pumps, thermal storage, and heat transfer).

Institute of Gas Technology (IGT)

A not-for-profit contract research organization specializing in non-nuclear energy research including both basic and development programs. Presently, IGT has programs in the design of solar thermal reactors for the production of fuels and chemicals and the design and construction of a solar desalination unit. There are also programs in the design of a solar thermal storage unit and the production of elemental phosphorous in a fused-salt reactor using a solar simulator. Much of the solar thermal work originates from the use of solar energy to power thermochemical hydrogen production cycles and previous programs in solar fuels and chemicals.

Institute of Gas Technology
3424 South State Street
Chicago, IL 60616
(312) 567-3650

Key Personnel: Ronald H. Carty, Senior Chemical Engineer (solar fuels and chemicals); Bernard Yudow, Chemical Engineer (solar reactors); Thomas Whaley, Senior Advisor (solar fuels and chemicals); Robert Remick, Research Supervisor (solar reactors, solar fuels and chemicals); James Schrieber, Engineering Supervisor (solar reactors, solar fuels and chemicals); Randy Petri, Chemical Engineer (solar thermal storage, solar fuels and chemicals).

Jacobs Engineering Group Inc.

A full-service engineering and consultation organization specializing in providing engineering, design and construction services for process plants in the petroleum refining, petrochemical, mineral extraction and refining, chemical, plastics, detergent, fertilizer, energy, environmental, pharmaceutical, cosmetics, and food industries. Jacobs' Advanced Systems Division conducts resesearch into the feasibility, design, performance, and optimization of solar thermal systems. Projects in solar thermal research include (1) optimization studies for the design of 50,000 ft^2 of solar collector field-piping layouts; (2) design of production prototype trough-field layout; (3) solar production of industrial process steam — design, construction, O&M of 6496 ft^2 trough solar collector system; (4) design and construction of 23,040 ft^2 parabolic trough solar collector system for a commercial office building; (5) detailed design and construction of 400-acre solar evaporation pond system; (6) detailed site evaluation, conceptual and final design for 35 mi^2 of solar evaporation ponds on the Dead Sea; and (7) conceptual design and life-cycle cost analysis of solar energy system to provide space heating and hot water.

Jacobs Engineering Group Inc.
251 South Lake Avenue
Pasadena, CA 91101
(213) 449-2171

Key Personnel: Mayer Schwartz, Project Manager (program management); Robert E. Morton, Senior Project Engineer (conceptual design, optimization studies); John R. Hoopes III, Project Engineer (feasibility studies, solar system performance evaluation); William F. Smith, Instrumentation Engineer (solar system control system design); Andrew O. Clark, Project Engineer (solar system operation and maintenance).

Jet Propulsion Laboratory (JPL)

A NASA laboratory concerned primarily with unmanned space exploration. JPL has conducted various economic analyses for DOE's Solar Thermal Technology Program. The primary emphasis has been to estimate the market potential and quantify the expected future energy cost-savings associated with developing cost-competitive solar thermal technologies. The analysis was conducted under alternative scenarios for future fuel prices and solar thermal system costs. Using the results of this analysis, solar thermal technology's impact on environmental quality and oil imports was discussed also. The results could be used to examine employment impacts, tax revenue impacts, export market potential, and implications for the allocation of R&D funds within technology areas.

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91103
(213) 354-4321

Key Personnel: Katsuaki L. Terasawa, Senior Economist, Supervisor Economics Group (economic analysis for conventional and alternative energy systems); Hamid Habib-Agahi, Senior Economist (economic analysis for conventional and alternative energy systems); William R. Gates, Senior Economist (economic analysis for conventional and alternative energy systems).

Jet Propulsion Laboratory (JPL)

Conducts unmanned space flight planetary missions and other space flight science missions for NASA. It also conducts associated R&D. In addition, JPL performs R&D in selected areas of its expertise for federal agencies such as DOE. Beginning in 1977, JPL has managed the Solar Parabolic Dish Electron project. Three different modules based on organic Rankine, Stirling, and Brayton-cycle are being developed via system contracts to industry. Advanced concentrators are being developed separately.

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
(213) 354-4321

Key Personnel: Alan T. Marriott, Manager, Thermal Power Systems (TPS) Project; John W. Lucas, Assistant TPS Manager for Parabolic Dish Project.

Joe North, Inc.

Commercial and industrial insulation. Installed insulation on the Solar Total Energy Project at Shenandoah in Newnan, GA.

Joe North, Inc.
P. O. Box 95
Scottdale, GA 30079
(404) 659-0342

Key Personnel: John North, Project Supervisor (insulation of systems).

Lennox Industries Inc.

Manufactures flat-plate solar collectors and solar water heating systems in addition to a full line of air-conditioning and heating products. Lennox conducts applied, product-related research on liquid-heating flat-plate solar collectors and domestic hot water systems. Previous research has been performed on solar Rankine/Rankine cooling and solar-assisted heat pumps. Present efforts center around improving the efficiency and reliability of DHW systems while reducing initial cost.

Lennox Industries Inc.
Research and Development Lab
1600 Metro Drive
Carrollton, TX 75006
(214) 245-2525

Key Personnel: Hal Rhea, Vice President, R&D; Dick Cawley, Manager, Heat Pump, Compressor and Solar Development; Roger Hundt, Chief Engineer, Solar and Advanced Systems.

Lockheed Missiles & Space Company, Inc.

Basic and applied research and development. Lockheed is presently involved with innovative concepts for solar energy collection, storage, and use. Programs include SERI, DOE-sponsored research for open-cycle liquid desiccant cooling, ORNL-sponsored energy storage program using PCA-filled wall panels, and Lockheed-funded passive humidity control devices for long-term storage in outside containers.

Lockheed Missiles & Space Company, Inc.
Huntsville Research & Engieering Center
4800 Bradford Drive
Huntsville, AL 35807
(205) 837-1800

Key Personnel: Paul McCormick (desiccant cooling); Philomena Grodzka (energy storage); Jim Fletcher (energy storage).

Lockwood Greene Engineers, Inc.

Full service architectural/engineering firm. Lockwood Greene provided all architectural/engineering services for the Solar Total Energy Project at Shenandoah, Georgia.

Lockwood Greene Engineers, Inc.
P.O. Box 491
Spartanburg, SC 29304
(803) 578-2000

Key Personnel: Robert Bercik, Sr. Project Manager (Solar Total Energy Project); C.W. Minch, Project Manager (solar studies).

Mann-Russell Electronics, Inc.

Original equipment manufacturer combining custom design and manufacture of electronics and machinery for dielectric heating of material, process control, and quality control with primary market in forest products industry. Specific work includes electronic tracking systems (dual-axis) to guide solar collectors, heat-pipe research, and collector platform development.

Mann-Russell Electronics, Inc.
1401 Thorne Road
Tacoma, WA 98421
(206) 383-1591

Key Personnel: George F. Russell, Inventor.

Martin Marietta Corporation

Goals are to commercialize solar thermal central receiver and concentrating photovoltaic systems. Martin Marietta's activities in solar thermal research include integration of the

Martin Marietta Corporation
P. O. Box 179
Denver, CO 80201
(303) 977-3000

Molten Salt Electric Experiment, a large-scale test, along with other research supporting both heliostat and central receiver areas. In regard to molten salt central receivers, the company is conducting research on molten salt freezing, salt-compatible valve stem packings, innovative approaches for measuring receiver tube temperatures, and master controls. Martin-Marietta is also conducting research on advanced high-temperature receivers. Research in the heliostat area includes (1) the producibility and cost of these components with large production quantities, (2) development of mirrors capable of a 30-year service life, (3) reduction of wind loads on the structure and drive mechanism, and (4) improvements in the control system techniques, hardware, and software.

Key Personnel: H.C. Wroton, Director, Solar Energy Systems (management); C.N. Bolton, Manager, Solar Thermal Applications (management); T.R. Tracey, Program Manager, Molten Salt Electric Experiment (solar thermal receiver systems, thermal control and system integration); R.K. McMordie, Department Staff Engineer (solar thermal receiver systems research; thermal control, fluid flow, materials); M.W. Frohardt, Systems Engineer (heliostat research and development, systems engineering and heliostat manufacturing).

Mathematical Sciences Northwest, Inc. (MSNW)

A subsidiary of the Spectra-Physics Corporation specializing in research and development with federal support in the areas of advanced lasers, controlled fusion, energy and flow technology. Its goals are to seek innovative solutions to contemporary key technical problems. The energy and flow technology groups at MSNW are engaged in solar thermal research on aeroflows used to reduce convective losses from thermal receivers, to cool and clean receiver windows and, in some cases, to replace the window with an inert gas barrier when corrosion or erosion becomes too severe. Related work includes a droplet heat exchanger test facility to characterize low-to-high temperature direct-contact heat exchangers suitable for various solar thermal applications. Previous work includes a novel photovoltaic solar thermal heat engine concept having an overall efficiency of 50%, a high-temperature solar thermal energy-storage scheme involving molten slags of various types, and droplet heat-exchanger research.

Mathematical Sciences Northwest, Inc.
2755 Northup Way
Bellevue, WA 98004
(206) 827-0460

Key Personnel: Robert T. Taussig, Director of Energy Technology (program manager for aerowindows for solar receivers, direct-flux solar receivers, combined photovoltaic/thermal heat engines, and high-temperature thermal storage systems); William J. Thayer III, Director of Flow Technology (program manager to high-temperature direct-contact heat exchangers, heat transfer and flow systems).

McDonnell Douglas Corporation

Conducts aerospace-related RD&D for missile, space and energy sytems. The company conducts systems design, design integration for dual-axis tracking heliostat hardware and turnkey solar thermal central receiver power plant with a broad range of power generation levels (1 MWe-100 MWe) for a variety of bulk electricity and process heat applications. It is responsible for the design and subsystem integration of the 10 MWe Central Receiver Pilot Plant (Solar I) being tested in Barstow, California and is designing a project with Southern California Edison for a 100 MWe commercial central receiver plant called Solar 100 to be located in the Mojave Desert in California.

McDonnell Douglas Corporation
5301 Bolsa Avenue
Huntington Beach, CA 92647
(714) 896-4323

Key Personnel: Ray W. Hallet, Director, Energy Programs (solar thermal central receiver and parabolic dish technology); Lynn W. Glover, Program Manager, Large Utility Systems (solar thermal central receiver technology); Richard J. Faller, Program Manager, Dish Stirling (dish Stirling technology); Frank Duquette, Manager; Energy Program Development and Energy Program Business Development.

Mechanical Technology Inc. (MTI)

A technology-intense company specializing in advanced energy systems and conversion equipment development; these include organic Rankine cycles, Brayton systems, and Stirling engine systems. Component development is focused in the area of high-speed turbomachinery and Stirling engines (both kinematic and free piston). High-speed turbomachinery examples include radial inflow steam turbines, gas expanders, air compressors, and process-fluid lubricated machinery. Emphasis is placed on the manufacture of components and systems by developing a proprietary position to achieve a commercial marketplace share. Contract R&D is featured also. High-performance energy-conversion equipment has been developed for various solar thermal projects. These include (1) 400-kWe steam turbine generator to provide total energy at a knitting mill in Shenandoah, Georgia, (2) freon turbomachinery for a 25-ton solar chiller (a radial-inflow R-113 compressor and an R-113 turbine using process-fluid lubricated bearings in a hermetically sealed enclosure were developed as a subcontractor to the Carrier Corporation for a DOE-sponsored solar chiller project), and (3) a 3-kWe free-piston Stirling engine (FPSE) was developed as part of the JPL Point-Focusing Solar Thermal Program. An engine was delivered to JPL for testing on their parabolic dish collector.

Mechanical Technology Inc.
968 Albany-Shaker Road
Latham, NY 12110
(518) 785-2211

Key Personnel: H.M. Leibowitz, Manager, Cogeneration Systems (turbomachinery development); T. Marusak, Manager, Stirling Systems Projects (free-piston Stirling development).

Minnesota Mining and Manufacturing Co. (3M)

Develops and markets sun-control films for windows, highly reflective weatherable films for concentrating trough and dish solar collectors, and non-selective and selective solar-absorbing paint and films. The 3M energy control group is engaged in the development of abrasion-resistant PMMA/aluminum reflecting films (FecP-244), weatherable silver-reflective films with 97% reflectance, high-temperature non-selective solar-absorbing paint, and selective solar-absorbing films and foils.

Minnesota Mining and Manufacturing Co.
Energy Control Products Project
3M Center, Bldg. 207-1W
St. Paul, MN 55144
(612) 733-1031

Key Personnel: B.A. Benson, Sr. Product Development Specialist (development/reflecting films; absorber coatings); J.L. Roche, Product Development Specialist (development/reflecting films); R.B. Lowenberg (marketing/solar products).

Mississippi State University

University department with research laboratory and facilities for conducting solar research. MSU is conducting research in a variety of solar thermal applications. These include design, development, analysis, and testing of solar-passive water walls, Trombe walls for prefabricated metal buildings, active and passive air collectors, crop- and lumber-drying applications, thermal storage systems (with phase change materials), and cooling and dehumidification systems.

Mississippi State University
Mechanical and Nuclear Engineering Department
P. O. Drawer ME
Mississippi State, MS 39762
(601) 325-3260

Key Personnel: Lynn D. Russell, Professor (passive/active collectors, storage, cooling and dehumidification systems); Richard Forbes, Professor (passive/active collectors, storage, cooling and dehumidification systems); Charles W. Bouchillon, Professor (heating and cooling prefabricated metal buildings).

Mueller Associates, Inc.

A consulting engineering firm specializing in the technology transfer of renewable energy concepts from a conceptual stage to an actual working system. Services include analysis, simulation model development, system design (e.g., plans and specifications), construction services, solar technology tracking, project management, and program planning. The primary focus of the firm's solar thermal research activities is to advance the state of the art in system design and analysis; this includes identifying and analyzing promising concepts for their technical, economic, and marketing viability, performing feasibility studies for specific applications, and preparing construction documents. This effort has involved a significant amount of simulation model development and data base development/manipulation.

Mueller Associates, Inc.
1401 S. Edgewood Street
Baltimore, MD 21227
(301) 646-4500

Key Personnel: J.S. Moore, Department Manager (technology tracking/alternative energy option evaluation); T.D. Swanson, Project Manager (system analysis/simulation model development); A.R. Flesher, Project Engineer (design of state-of-the-art solar systems); L.M. Mapes, Senior Designer-Lighting (daylighting analysis and design).

Naval Civil Engineering Laboratory (NCEL)

See: U.S. Department of the Navy

New Mexico Solar Energy Institute

A state-supported organization pursuing R&D and informational and educational activities in the field of energy conservation including solar thermal, wind, bioenergy and photovoltaic systems. Solar thermal R&D includes industrial process heat applications, solar ponds, commercial and residential space heating-and-cooling systems and hot water systems, agricultural applications, cogeneration systems and energy conservation, desalination, and earth-sheltering techniques. Specific activities in these areas include conceptual system design, system analysis, performance monitoring and evaluation, production of technical and non-technical publications and reports, design and conduction of workshops and seminars.

New Mexico Solar Energy Institute
New Mexico State University
P.O. Box 3 SOL
Las Cruces, NM 88003
(505) 646-1846

Key Personnel: Roger Farrer, Head, Heating & Cooling Division; Martin Selinfreund, Research Engineer (space heating and cooling, hot water, earth shelter); Ronald Polka, Technician (performance monitoring, solar ponds).

New Mexico State University (NMSU)

The NMSU/PSL horizontal solar furnace, owned and operated by the Mechanical Engineering Department and the Physical Science Laboratory of New Mexico State University, is available for small-scale, high-intensity solar testing. The furnace has been used by the Central Receiver Test Facility at Sandia National Laboratory to recalibrate circular-foil flux-gauges and to screen low-cost materials for use in protecting against beam spillage. Los Alamos National Laboratory conducted experiments involving small-scale coal gasification and molybdenite ore roasting in air. New Mexico State University personnel have conducted a variety of experiments including a study of the effect of high flux levels on the performance of photovoltaic cells.

New Mexico State University
Physical Science Laboratory (PSL)
P.O. Box 3548
Las Cruces, NM 88003
(505) 646-2118
(505) 522-9262

Key Peronnel: George P. Mulholland, Professor of Mechanical Engineering(materials testing); William C. Stevens, Chief, Energy Research & Development Section, Physical Science Laboratory (solar furnace operation).

Nielsen Engineering & Research, Inc.

Pursues R&D in fluid mechanics and heat transfer. Reducing thermal losses in solar central receivers is a main goal of the company.

Nielsen Engineering & Research, Inc.
510 Clyde Avenue
Mountain View, CA 94043
(415) 968-9457

Key Personnel: J.J. McMillan, Principal Engineer (heat transfer and fluid mechanics).

North, Joe, Inc.

See: Joe North, Inc.

Northwestern University

Educational institution. Primary emphasis of the Technological Institute of the University is technical education with a strong emphasis on research and development. Masters and Doctoral thesis work is directed toward the design and construction of nontracking solar trough facilities. Cusp designs of the CPC type are being investigated with special emphasis placed on their nontracking capability and an evacuated receiver provided with a selective surface for maximum heat recovery.

Northwestern University
Chemical Engineering Department
Evanston, IL 60201
(312) 492-3452

Key Personnel: George Thodos, Professor.

Oak Ridge National Laboratory (ORNL)

A federally owned, contractor-operated laboratory. Activities include engineering research in various aspects of energy including production, conservation, and environmental effects. The laboratory is not presently engaged in solar thermal research, development, or evaluation activities. The Laboratory performed work previously for DOE involving the evaluation of solar thermal energy systems. This included work on (1) economics of solar applications for district heating, (2) capacity credit for solar thermal electric-generating stations on utility grids, and (3) supplying participants for system design reviews of the Shenandoah Solar Thermal Project in Georgia.

Oak Ridge National Laboratory
P.O. Box Y, Bldg. 9102-2
Oak Ridge, TN 37830
(615) 574-5819

Key Personnel: Stephen I. Kaplan, Group Leader, Chemical Heat Pumps and Renewable Energies (laboratory contact for engineering/economic evaluation of solar thermal systems).

Ohio State University

Conducts basic and applied research in agriculture, home economics, and natural resources. Solar thermal research is directed toward the eventual practical use of solar energy for crop drying and space heating of rural residences and greenhouses. Work on plastic collectors for grain drying has been done and one of the oldest operating solar ponds in the U.S. in use since 1975 is being used to heat a greenhouse. A solar pond laboratory has been established to study the influence of heating rate, maximum temperatures, and salt concentration on salt diffusion and gradient zone stability. Tanks in the laboratory contain brine that can be heated by overhead radiation or electric heaters from below. In February 1983, the Center published a basic manual on solar ponds as Special Circular No. 106.

Ohio State University
Ohio Agricultural Research and Development Center
Wooster, OH 44691
(216) 263-3700

Key Personnel: David L. Elwell, Research Scientist (solar ponds); R. Peter Fynn, Research Associate (solar ponds); Harold M. Keener, Associate Professor (solar collectors/drying grain); Ted H. Short, Professor (solar ponds).

use distributed applications, and (2) large utility-scale systems. In large systems, PNM has contributed to development of central receiver technology for solar hybrid repowering applications by performing economic and technical evaluations under a DOE contract; PNM has participated in central receiver and heliostat development studies. Currently, PNM is involved in the Molten Salt Electric Experiment which is funded jointly by DOE, EPRI, and other electric utilities.

Key Personnel: Steve Pyde, Group Leader, Energy Management (end-use applications); Abbas Akhil, Senior Energy Conversion Engineer (utility scale applications).

Raymond Kaiser Engineers, Inc. (RKE)

Architect-engineering services; construction management and construction. Applied R&D in solar power cogeneration systems for DOE engineering-design of solar (water) heating systems for hospitals and various processes. RKE is an international engineering and construction organization that recently developed and standardized cost and technical data on solar power cogeneration plants in a computerized-based data management system. The company has provided clients with construction cost estimates on large solar power generation systems for the past four years, including the DOE-sponsored studies of the 10-MW and 100-MWe solar central receiver plants. RKE assisted Pacific Gas and Electric in development of their solar photovoltaic program using silicon dendritic web technology. It also performed major power planning study for Bonneville Power Administration Company solar thermal, solar photovoltaic, and wind power plants.

Raymond Kaiser Engineers, Inc.
300 Lakeside Drive
P. O. Box 23210
Oakland, CA 94623
(415) 271-4194

Key Personnel: P.J. Selak, Marketing Manager (power systems); J.F. Doyle, Project Engineer (design of solar systems); F.L. Harris, Project Manager (management of solar R&D and design); R.N. Stark, Project Estimator (development of standardized computer data management system); I. Kornyey, Project Estimator (estimating all types of large solar generation plants); R.K. Reynolds, Mechanical Engineer (R&D of solar systems and heat storage vessels); R.L. Lang, Project Economist (wind and solar studies).

Research Engineering Associates

A consulting firm specializing in thermal analysis of energy systems and devices. Capabilities include computer simulation, on-site data logging and analysis, and component design and testing. Company interests are primarily directed at developing parabolic trough systems, especially experimental study of in-situ steam generation. Areas of continuing interest include environmental degradation of optical surfaces, system controls, and instrumentation.

Research Engineering Associates
299 California Avenue
Palo Alto, CA 94306
(415) 322-0488

Key Personnel: Michael Kast, President (in-situ steam generation,thermosciences); Patricia Hurtado, Associate (instrumentation, thermosciences).

Rocket Research Company

Develops and manufactures energy conversion reactors for rocket propulsion and pneumatic/hydraulic power. Designs catalytic reactors for solar energy conversion and storage. Conducts systems analysis for energy conversion efficiency and cost analysis for return on investment. Conducts solar thermal conversion using reversible chemical reactions for energy transport and storage. Energy transport occurs with "chemical heat pipes" that are proposed for distributed parabolic dish collectors. Diurnal and seasonal fluctuations of insolation can be leveled by storage of dissociated chemicals, allowing exothermic recombination or direct chemical-to-electric conversion to occur during night hours to maintain

Rocket Research Company
11441 Willows Road, N.E.
Redmond, WA 98052
(205) 885-5000

Key Personnel: Eckart W. Schmidt, Senior Staff Scientist (reversible chemical reactions, high-temperature catalysts, high-temperature materials); Donald R. Poole, Senior Staff Scientist (reversible chemical reactions, high-temperature thermodynamics).

constant electrical output of power plant or match the load profile of the utility.

Rockwell International

A designer, fabricator, and systems integrator for solar thermal power systems. The Energy Systems Group (ESG) has designed systems and equipment for solar central receiver and parabolic dish systems. The R&D focus for central receivers has been on high-temperature solar components, including the solar receiver, steam generator, and thermal storage. Proprietary or patented technology has been developed in each of these areas. Parabolic dish development activities have centered on the design and fabrication of low-cost concentrators. ESG is systems integrator for the DOE/Advanco parabolic dish/Stirling engine system module program. Research is being conducted on advanced liquid-metal components applicable to solar use, and innovative solar technologies including receivers and thermal storage.

Rockwell International
Energy Systems Group
8900 De Soto Avenue
Canoga Park, CA 91304
(213) 700-8200

Key Personnel: George J. Hallinan, Director, Advanced Programs; Thomas H. Springer, Program Manager, Solar Electric Systems; Alan Z. Ullman, Project Manager, Carrisa Plains Solar Plant; William W. Willcox, Project Engineer, Solar Parabolic Dish Projects.

Rockwell International

A DOE field laboratory operated by the Energy Systems Group of Rockwell International. The Energy Technology Engineering Center (ETEC) is a multipurpose engineering and test laboratory that specializes in the management of technical projects and development test programs for a variety of energy disciplines. Experience in solar thermal includes the following types of projects: flat plate, evacuated tube, concentrators, passive cooling, solar ponds, space heating, industrial process heat, drainback systems, closed loop systems, solar thermal power, and ocean thermal energy conversion. ETEC is qualified to provide technical support in program planning and management; technical and economic evaluation of solar thermal design concepts; research, development, computer analysis, and testing services; and instrumentation controls, and performance monitoring.

Rockwell International
Energy Technology Engineering Center
P.O. Box 1449
Canoga Park, CA 91304
(213) 700-5519

Key Personnel: J.O. Bates, Programs Manager, Energy Programs; F.W. Poucher, Programs Manager, Solar Energy Programs.

SRI International

A nonprofit research institute working for U.S. and foreign industries and governments. SRI has been doing research on Line Focus Central Receiver (LFCR) solar thermal electric power plants, glass-reinforced concrete (GRC) parabolic troughs, and large wind turbine blades.

SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025
(415) 859-3162

Key Personnel: Arthur J. Slemmons, Senior Research Engineer.

Salt River Project (SRP)

Supplies both water and electric power to approximately 360,000 customers in the Phoenix valley area. It is a public utility with municipal status that tests and evaluates solar systems and components. Major solar thermal projects include the testing of one 50-ton and one 3-ton solar-powered Rankine

Salt River Project
P.O. Box 1980
Phoenix, AZ 85001
(602) 273-5394

Key Personnel: Richard F. Durning, Staff Consulting Engineer (research programs management with air-conditioning, power generation, and heating system. SRP supports a residential solar water-heating system test program conducted by Arizona State University to evaluate seven types of systems. Salt River Project is program coordinator for the development of an all-Arizona network of solar monitoring stations and is participating in the tests of a photovoltaic-powered deep-well pump installation. It is cooperating with the Arizona Solar Energy Commission in various solar activities and projects.

background in power plant engineering and construction); Graydon Peoples, Senior Consulting Solar Engineer (solar programs management with past experience in HVAC and solar R&D management, marketing and education); William James, Energy Management Engineer (customer energy management engineer responsible for energy product and systems evaluation and manager of 3-ton solar Rankine project).

Sanders Associates, Inc.

Involved in the development of selected components for use in solar-thermal electric and fuels and chemicals systems. The current major undertaking, which is sponsored by DOE, is the development and testing of a small (8 kWe) parabolic dish solar Brayton electric module capable of hybrid or solar-only operation. Sanders Associates has the role of system integrator and also provides the high-temperature solar receiver. Numerous solar receivers have been designed, built, and tested providing output gas temperatures up to 2600°F using ceramic technology originally developed for military infrared countermeasure applications. Systems integration work on an 8-m^2, 8-kWe solar electric dish system is underway.

Sanders Associates, Inc.
95 Canal Sreet
Nashua, NH 03061
(603) 885-5069

Key Personnel: Daniel J. Shine, Jr., Manager, Program Development; Don H. Ross, Director, Energy Systems Center; S. Bear Davis, Chief Engineer, Solar Thermal Systems.

Sandia National Laboratories/Albuquerque (SNLA)

A DOE national laboratory. Sandia has lead-lab responsibility for parabolic dish R&D, line-focus R&D, and concentrator development. The program at Sandia consists of parabolic dish technology development which contains the following subtasks: systems engineering, energy transport, receiver development, concentrator development, controls development, engine and module development, and field experiments; and distributed receiver long-term evaluation consisting of Shenandoah evaluation, IPH projects, MISR, and technology transfer.

Sandia National Laboratories/Albuquerque
P.O. Box 5800
Albuquerque, NM 87185
(505) 844-8508

Key Personnel: J.V. Otts, Manager, Solar Thermal Test Facility; J.A. Leonard, Manager, Distributed Receiver Research Division.

Sandia National Laboratories/Livermore (SNLL)

The Field Technical Manager for the Department of Energy, Division of Solar Thermal Technology Central Receiver Program, responsible for technical direction of all aspects of the central receiver program. Current activities include test and evaluation of Solar One, the 10-MWe Solar Thermal Central Receiver Pilot Plant at Barstow, California; Part A and Part B of the repowering final design program; the Molten Salt Electric Experiment; the central receiver fuels and chemicals program; and development of new concepts for receivers, heliostats, storage, and other central receiver unique components. Other central receiver responsibilities include the

Sandia National Laboratories/Livermore
P.O. Box 969
Livermore, CA 94550
(415) 422-2447

Key Personnel: Leo Gutierrez, Director of Engineering, Chairman and U.S. Representative, IEA/SSPS Executive Committee; Clif Selvage, Department Manager, Chairman, IEA/SSPS International Test and Evaluation Team; James B. Wright, Manager, Solar Central Receiver Department; Alan C. Skinrood, Supervisor, Central Receiver Systems Evaluation Division; William G. Wilson, Supervisor, Central Receiver

Central Receiver Test Facility in Albuquerque, New Mexico and coordination of central receiver international activities, including DOE's involvement in the International Energy Agency/Small Solar Power Systems Project (IEA/SSPS). In addition to the central receiver activities, Sandia Livermore provides a Technology Program Integration (TPI) function for the DOE Division of Solar Thermal Technologies. The TPI function includes development of long-range SST program plans including coordination with field organization planning, and conducts technical and economic analysis to support the planned program.

Components Division; Joan B. Woodard, Division Supervisor, Solar Thermal Technology Program Integrator.

Schott America Glass and Scientific Products, Inc.

Involved in the research, development, and production of specialty glasses and glass components. Deutsche Spezialglas A.G. (Desag) produces thin borosilicate substrates suitable for photovoltaic application and high-transmission low-iron glass. Desag also produces precision-bent mirror panels of high reflective efficiency for parabolic line focus and parabolic dish collector systems. The pieces are custom made to exact specifications.

Schott America Glass and Scientific Products, Inc.
Deutsche Spezialglas A.G. (Desag)
3 O'Dell Plaza
Yonkers, NY 10701
(914) 968-8900

Key Personnel: Anthony Smith, Technical Sales, Schott America (thin substrates and mirror panels); Manfred Krause, Sales, Desag (glass for solar energy systems).

Science Applications, Inc. (SAI)

A high technology and development firm that provides technical services that encompass scientific research, analysis, concept development, design planning, and management. SAI provides multi-disciplinary capabilities in the development and implementation of solar energy systems for governmental and industrial experimental and commercial applications. SAI's solar thermal experience includes system design, system implementation, component and system testing, financial and economic feasibility assessment, and operator training. Specific R&D activities include the design, testing, and implementation of solar thermal electric plants (concentrators, receivers, storage controls, utility integration and maintenance); development of solar electric power generation expansion plans for utility and non-utility customers; design of industrial process heat systems; and design work on optical concentrators for a variety of solar thermal applications.

Science Applications, Inc.
1710 Goodridge Drive
McLean, VA 22102
(703) 821-4300

Key Personnel: Henry Leirs, Senior Scientist (array and system design, system integration, program management); Orin Merrill, Division Manager (system planning, computer simulation, economic analysis); Jeffrey Morehouse, Senior Scientist (heating and cooling system analysis, computer simulation, R&D program planning); Stephen K. Young, Senior Scientist (integrated system design and optimization); Richard J. King, Scientist (planning and analysis, marketing and educational advancement).

Science Applications, Inc. (SAI)

Areas of work interest include computer technology, management systems, high technology development, and defense contracting. SAI consults in the area of process and plant design and project management. Providing basic technical and economic evaluations, the company is interested in comparison of processes applicable to the energy industry. Through the Mining/Geotechnical, Chemical Engineering, and Economic Analysis Divisions, the company has analyzed projects for methanol production, solar ponds, and cogeneration for infrastructure development.

Science Applications, Inc.
1726 Cole Blvd.
Golden, CO 80401
(303) 279-0701

Key Personnel: Robert D. Knecht, Project Manager (process and plant design, evaluation and comparison).

Sierra Pacific Power Company

Electric, gas & water, investor-owned utility research and development department. Projects include solar repowering conceptual design study, solar central receiver advanced conceptual designs for repowering applications, Sandia Molten Salt Steam Generator Subsystem Research Experiment, Sandia Molten Salt Receiver Subsystem Research Experiment, Solar 100 Conceptual Study, and parabolic dish-Sterling.

Sierra Pacific Power Company
P.O. Box 10100
Reno, NV 89520
(702) 789-4011

Key Personnel: R.G. Richards, Supervisor, R&D (solar processes); W.K. Branch (central tower/thermal systems, resource planning); W.E. Blockley (Parabolic Dish-Stirling Power Systems).

Solar Energy Research Institute (SERI)

Serves as the nation's primary federal laboratory for solar energy research and performs functions assigned by the Department of Energy in research, development, and testing. SERI carries out its mission by conducting and coordinating long-term, high-risk research and development on solar technologies that private industry cannot reasonably be expected to undertake. This work advances scientific understanding and establishes a sound technological base enabling the private sector to make well-informed choices among technology options. SERI explores new ideas and focuses its research and development efforts on promising technologies. SERI is the lead center for the planning, management, and implementation of the Solar Thermal Research Program within the DOE Solar Thermal Technology (STT) Program. SERI conducts basic and applied research in thermal materials, optical materials, the thermal sciences, concentrators, solar fuels and chemical processes and other areas, as applicable, in order to (1) support distributed receiver and central receiver technology development within the STT Program, and (2) identify advanced and innovative concepts that can be the basis for future technology development to meet long-term cost and performance targets. Examples of specific activities in the SERI program are (1) development of innovative low-cost, lightweight durable heliostats and dish concepts; (2) development of low-cost, UV-resistant silver/polymer films that have specular reflectances of at least 90% and a service life of at least 5 years; (3) development of a high-temperature/high-flux direct absorption receiver concept integrated with thermal storage; and (4) development of at least one compatible thermal fluid/containment material pair for use in solar thermal systems operating at temperatures in the range of 600°C to 900°C.

Solar Energy Research Institute
Solar Thermal and Materials Research Division
1617 Cole Boulevard
Golden, CO 80401
(303) 231-1000

Key Personnel: Larry Shannon, Director, Solar Heat Research Division; Ken Olsen, Deputy Director, Solar Heat Research Division; Bimleshwar P. Gupta, Manager, Solar Thermal Research Program; Gordon Gross, Branch Chief, Materials Research Branch; Dave Johnson, Branch Chief, Thermal Research Branch; John Thornton, Branch Chief, Thermal Systems and Engineering Branch.

Solar Kinetics, Inc.

Manufactures parabolic trough collectors for solar thermal applications. The primary field addressed by the company's product is the industrial process heat market. The company's products have also been used to drive absorption chillers for the refrigeration process. The company offers its systems with solar thermal storage, utilizing heat-transfer oil, and has successfully built a solar thermal system with 24-hr heat

Solar Kinetics, Inc.
3300 Century Circle
Irving, TX 75060
(214) 721-1070

Key Personnel: Carroll Reed, Technical Director; John Witt, Project Engineer; David White, Project Engineer; Jeff Johnston, Project Engineer; Ken Cook, Project Engineer; Michael Bernard, Supervisor, Technical Services.

delivery. The company also builds 7-meter parabolic dish collectors for solar thermal application, although this segment of the company's business receives less emphasis.

Solar One Visitor Center

Disseminates information to the general public on the testing and operation of Solar One (10 MWe Solar Thermal Central Receiver Pilot Plant). The site is not open to the public except to the media and research personnel, but the Center has displays, literature, and films to explain not only Solar One but all other energy sources including information on conservation, load management, and home use of solar power. Solar One, being the first of its kind in the United States and the largest central receiver solar plant in the world, is the testing ground for solar power. A five-year test program began on August 1, 1982 with two years designated for design verification testing and completion of plant automation and three years for optimizing the generation of electricity. Two major reports published by Sandia Laboratories are as follows: *Overview of the Construction and Start-up of the 10 MWe Solar Thermal Central Receiver Pilot Plant April 1983* (SAND83-8021 6-83) and *10 MWe Solar Thermal Central Receiver Pilot Plant 1982 Operational Test Report* (SAND83-8027 11-83).

Solar One Visitor Center
P.O. Box 325
37502 National Trails Highway
Daggett, CA 92327
(619) 254-2810

Key Personnel: Joseph N. Reeves, Solar One Program Director, Southern California Edison Company; Duncan Tanner, Technical Manager, Sandia Laboratories; Doug Elliott, Project Director, U.S. Department of Energy; Patricia E. Tong-Snyder, Supervisor, Solar One Visitor Center.

Solar Steam Inc.

Currently completing research and development work leading toward mass production of large, geodesic point-focus parabolic dishes.

Solar Steam Inc.
#400 Old City Hall
625 Commerce Street
Tacoma, WA 98402
(206) 627-1627

Key Personnel: Douglas E. Wood, Chairman of Board, Innovator of Program; Tom Hammond, Principal Engineer, Mechanics & Structural; Dave Richards, Staff Engineer from Boeing, Shareholder.

Southern California Edison (SCE)

Provides electricity to 9 million inhabitants in a 50,000 square mile service area. SCE's power generation mix includes oil, gas, coal, nuclear, hydro, and alternative and renewable energy resources. SCE's Research and Development Organization is dedicated to the development of alternative and renewable energy resources, including solar, wind, hydro, geothermal, cogeneration, and fuel cells to offset the use of fossil fuels. SCE's goal is to have 2150 MW installed by 1992, based on alternative and renewable energy resources; 350 MW to be derived from solar energy. The Research and Development Organization is investigating several solar thermal technologies including central receivers, parabolic dishes, parabolic troughs, and solar salt ponds. In particular, it is evaluating the capital, operating, and maintenance costs of solar thermal for power generation and comparing the

Southern California Edison
Advanced Engineering, Research and Development Organization
P.O. Box 800
2244 Walnut Grove
Rosemead, CA 91770
(213) 572-1212

Key Personnel: Charles B. McCarthy, Vice-President, Advanced Engineering; Ian R. Straughan, Manager, Research and Development; Joe N. Reeves, Project Manager (central receivers); William H. von KleinSmid, Supervising Research Engineer (parabolic troughs); Igal Meitlis, Project Director (parabolic troughs); John Stolpe, Supervising Research Engineer (parabolic dish); Raymond Cedillo, Project Manager (parabolic dish).

performances of the technologies in order to eventually select the most promising solar thermal system(s) for long-term commercial development. The Research and Development Organization's central receiver program is responsible for SCE's participation in the 10-MW Solar Unit One operating near Barstow, California. SCE has also developed a conceptual design for a 100-MW central receiver. Parabolic trough activities are focused on the construction of a 49-MW demonstration facility which will commence with the installation of a 15-MW system in 1984. The parabolic dish project is currently installing a 25-kW prototype concentrator near Palm Springs, California for a two-year test starting December 1983. Solar salt pond efforts involve "participant" siting and design efforts to build four 5-MWe ponds on a dry lake bed in the California desert.

Southwest Research Institute (SwRI)

A not-for-profit institution dedicated to serving the research needs of industry and government. A major portion of the solar thermal research program at SwRI deals with design and installation of solar industrial process heat systems utilizing parabolic trough and flat plate collectors. Other projects include monitoring a passive solar retrofit on a local government building, demonstrating the application of solar energy to the distillation of ethanol, and the production of ammonia with a solar-energy-driven catalytic chemical reaction.

Southwest Research Institute
P.O. Box 28510
6220 Culebra Road
San Antonio, TX 78284
(512) 684-5111

Key Personnel: D. M. Deffenbaugh, Manager (solar industrial process heat, ammonia production); S.T. Green, Research Engineer (solar industrial process heat, alcohol production, residential systems); S.J. Svedeman, Research Engineer (solar industrial process heat, passive solar, solar ponds).

Springborn Laboratories, Inc.

An organization devoted to contract research and development in plastics, coatings, adhesives, elastomers, and sealants. Research has been carried out on the development of long-life, weather-resistant, low-cost plastic glazing materials and UV-protective coatings as well as thin-film solar collectors. Protective coatings and films were also designed for heliostat components such as thin-film solar collectors. Protective coatings and films were also designed for heliostat components such as the polyester dome, the metallized heliostat mirror surface, and the back surface of the silver mirror to prevent spotting. Materials and processes have been developed for the encapsulation of solar cells including EVA pottant, acrylic outer covers, and adhesives-coupling agent systems. UV absorbers have been reacted with the pottant and outer covers to provide long-life materials. Studies have been carried out to predict lifetime under weathering conditions. Methods of bonding acrylic Fresnel lenses to low-iron glass and manufacturing processes are under investigation for parquet lamination.

Springborn Laboratories, Inc.
Springborn Center
Enfield, CT 06082
(203) 749-8371

Key Personnel: Bernard Baum, Manager, Materials Science & Technology (solar collectors, heliostats, photovoltaic flat-plate and concentrator modules); Paul Willis, Project Manager, Materials Science & Technology (materials, lifetime studies, design of photovoltaic systems and synthesis of non-extractible UV stabilizers); W.W. Holley, Project Manager, Materials Science & Technology (acrylic Fresnel lenses for concentrators); R.A. White, Project Manager, Materials Science & Technology (thin-film solar collectors); W.R. Diehl, Manager, Engineering (manufacturing processes for Fresnel lens parquets).

Stanford University

Development of a code for simulating heat transfer from an orthogonal-mixed convection layer. The major purpose is the production of heat losses from a solar central-station power plant.

Stanford University
Department of Mechanical Engineering
Stanford, CA 94305
(415) 497-3148

Key Personnel: Joel Ferziger, Professor of Mechanical Engineering (heat transfer computation); Bahram Afshari, Research Assistant (heat transfer computation).

Stearns Roger Engineering Corporation

A full-line architectural and engineering construction company with experience in energy development projects encompassing all of the standard fuels, such as the fossil fuels to the latest in renewables such as solar central receivers. Stearns-Roger, while not performing laboratory research directly, is involved with the economics study, process development, equipment requirements, and all the engineering studies required for the development of innovative solar thermal process designs.

Stearns Roger Engineering Corporation
4500 Cherry Creek Drive, South
P. O. Box 5888
Denver, CO 80217
(303) 758-1122

Key Personnel: W. R. Lang, Project Manager (A/E Const. Solar Thermal Systems).

Stone & Webster Engineering Corporation

Provides project management and engineering support to evaluate and develop solar thermal system design for government, utility, and industrial clients. The company's support of solar thermal central receiver technology is evidenced through its recently completed preliminary design for repowering an 82-MW gas-fired unit with a 42-MW solar thermal central receiver steam supply system. In addition, SWEC prepared the conceptual design of a 100-MWe solar central receiver closed Brayton-cycle power plant. SWEC's experience with distributed receiver designs includes an analysis and conceptual design for solar heating of feedwater as a means of regaining generating capability lost in gas-to-oil conversions. SWEC has evaluated the feasibility of and prepared conceptual designs for a desalination unit powered by distributed solar thermal collectors. The company has completed the detailed design of a modular solar thermal system using linear-focusing collectors capable of producing 250-psig saturated steam for industrial process use. SWEC has studied potential applications and commercialization of solar electric central stations and distributed smaller facilities in both the southeast and southwest regions of the U.S. Technical, financial, regulatory, institutional and resource requirements needed for demonstration and commercial deployment of solar electric generating systems have been evaluated in detail.

Stone & Webster Engineering Corporation
P.O. Box 2325
Boston, MA 02107
(617) 589-5111

Key Personnel: Reiner W/ Kuhr, Project Engineer (Central Receiver system design and analysis); Duncan M. Moodie, Manager (Advanced Power Technologies Section); Conrad M. D'Esopo, Engineering Manager.

Sundstrand Corporation

A large multi-product corporation involved in development and manufacture of advanced technology equipment for commercial and aerospace applications. Sundstrand has done considerable work in the area of energy conversion systems to convert solar thermal energy into mechanical power or electricity.

Sundstrand Corporation
4747 Harrison Avenue
P.O. Box 7002
Rockford, IL 61125
(815) 226-6000

Key Personnel: Warren Adam, Manager, Technology Development; Dick Niggemann, Chief, Thermo Dynamic Research Engineer; Doug Lacey, Product Line Manager.

Sunmaster Corporation

Manufactures evacuated-tube solar collection equipment and systems. Conducts research on fluid flow, construction materials, reflective materials, and selective absorber materials.

Sunmaster Corporation
35 West William Street
P.O. Box 1077
Corning, NY 14830
(607) 937-5441

Key Personnel: D. Michael Platt, Vice-President, Engineering.

Sunpower Inc.

Stirling engine development and contract research with emphasis on free piston-linear alternators and hot-air crank machines burning solid fuel or biomass; duplex Stirling heat pumps and biomass or solar-powered free-cylinder water pumps. Sunpower has reached the fifth generation of its free-piston solar machines, the latest being a 10-kW machine, with all up weight of 150 kg, 0.8-m length, 0.4-m diameter, linear alternator directly coupled to free-piston engine in the same 20-bar enclosure. A 4-kW biomass-burning crank engine is ready for commercial production. Simple Stirling free-cylinder water pumps operating on solar or biomass power have been demonstrated.

Sunpower Inc.
6 Byard Street
Athens, OH 45701
(614) 594-2221

Key Personnel: William Beale, Director of Research (thermal systems, Stirling engines); David Gedeon, Chief Analyst (simulation and analysis of Stirling engines); David Berchowitz, Senior Design Engineer (design and analysis of Stirling engines); J. Gary Wood, Senior Design Engineer (design of hot-air kinematic Stirling engines for biomass utilization).

Suntec Systems, Inc.

Manufactures parabolic trough concentrators. The current model, Mark IV, is 10 ft by 120 ft per row. Applications are electric power generation, space heating/cooling, and industrial process heat. No specific R&D activity other than product development in normal business.

Suntec Systems, Inc.
6901 West 110 Street
Minneapolis, MN 55438
(612) 831-0446

Key Personnel: Jon Davison, President.

Tennessee Valley Authority (TVA)

Plans, develops, coordinates, and manages TVA's energy research, development, and demonstration activities. It ensures that the conduct and implementation of energy technology assessment and demonstration activities will yield the lowest long-term cost for providing electric power consistent with reliability for service, energy conservation, and environmental considerations. As appropriate, it participates in the development of energy technologies and demonstrations to help solve the nation's energy problems. It

Tennessee Valley Authority
Division of Energy Demonstrations and Technology
Electrical Systems and Utilization Branch
1850 Commerce Union Bank Building
Chattanooga, TN 37401
(615) 751-0011

Key Personnel: Graham R. Siegel, Program Manager (solar ponds, PV, desiccant cooling); William C. Irwin, Project Engineer (solar ponds, PV, desiccant cooling).

recommends participation with other organizations where significant benefits are likely to accrue to the TVA power program and the national energy effort. Demonstration of the technical and economic feasibility of nonconvecting solar ponds (NCSP) in the TVA region and as a research laboratory for such facilities. The NCSP is 1 acre in size, 10 ft deep, double-lined, containing 2000 tons of salt which should achieve trapped/stored heat levels of 180°F-190°F minimum with the ability to produce energy at the average yearly power level of 140 kWt (or enough to heat 70 houses). Also involved in advanced studies and model simulation analysis of dry desiccant cooling system as compared with heat pumps and central resistance heating and vapor compression air-conditioning.

Tennessee Valley Authority (TVA)

Conducts studies and investigations to identify solar and renewable energy resource applications that are cost-effective for the conservation of non-renewable energy resources; develops programs and demonstrations to promote the use of these applications in the Valley; and provides technical evaluation and coordination assistance to those organizations responsible for implementing such programs. Solar thermal research activities of the Solar Applications Branch (SAB) include laboratory performance testing of residential solar water heaters and wood heaters, and commercial biomass boilers and shallow solar ponds. SAB is conducting extensive field monitoring of installed residential solar water heating, wood heater backup systems, and passive design features; and commercial water heating and biomass boilers to validate laboratory results and predicted performance from solar thermal energy models. SAB is also evaluating the performance of alternative configurations of a breadbox batch water heater.

Tennessee Valley Authority
Solar Applications Branch
300 Credit Union Building
715 Market Street
Chattanooga, TN 37401
(615) 751-6741

Key Personnel: Patricia H. Harris, Branch Chief, Solar Applications Branch.

Texas Tech University

A solar thermal research project under the Engineering and Electrical Engineering Department of Texas Tech University. Investigates and advances the knowledge of and component state of the art of the specific and unique features of the fluid mechanics of (solar bowl) technology. Previous efforts have focused on solar thermal steam electrical power generation. The presently funded research is to investigate other potential uses and associated costs and the impact these will have on the critical unique components. After analysis, certain designated components will be designed, fabricated, and tested at the CSPP site.

Texas Tech University
Crosbyton Solar Power Project
Lubbock, TX 79409
(806) 742-3441

Key Personnel: Edgar A. O'Hair, Project Director (control, mechanical fluids); Travis L. Simpson, Project Manager (facility operation); L. David Clements, Researcher, Associate Professor (solar receiver); James E. Jonish, Researcher, Professor (system economics); C.V.G. Vallabhan, Researcher, Associate Professor (mechanical and thermal stress); R.M. Anderson, Researcher, Associate Professor (analytical models); Jerry R. Dunn, Researcher, Associate Professor (fluid mechanics).

Townsend and Bottum, Inc.

Provided complete construction management services for the solar portion of DOE's 10 MWe Solar Thermal Control Receiver in Dagget, California. Also provided overall project scheduling, cost analysis, and budget following. Townsend and Bottum provided complete construction services for the ARCO 1 MWe Photovoltaic Plant in Hesperia, California. Townsend and Bottum continually provides consulting services for the planning of various types of solar power plant projects. Services include feasibility studies, cost analysis, budget development, project schedule development, constructibility studies, and construction planning.

Townsend and Bottum, Inc.
1919 W. North Temple
P.O. Box 22156 A.M.F.
Salt Lake City, UT 84122
(801) 531-8444

Key Personnel: Roger J. Schwing, Area Manager (construction and management); John M. Abram, Project Superintendent (field construction management).

Trident Engineering Associates, Inc.

Basic and applied R&D in the application of solar energy to process heating and drying applications for commercial markets. Developed solar systems for the food-drying industry and the drying of bagasse for the sugar cane industry for use as fuel in the production of electricity. Evaluated the capabilities of the current generation of evacuated-tube solar collectors.

Trident Engineering Associates, Inc.
48 Maryland Avenue
Annapolis, MD 21401
(301) 267-2128
(301) 269-0340
(301) 261-2483

Key Personnel: Mitchell A. Kapland, Chairman (project development); B.J. Graham, Senior Engineer (physics, solar capabilities, applications, and materials); Maido Saarlas, Senior Engineer (mechanical design of solar systems and applications).

UMC Industries, Inc.

A manufacturer of standard and/or custom engineering drives used for azimuth and/or elevation positioning of solar collectors of various types (trough, dish, photovoltaic arrays, heliostats for central receivers). Winsmith has conducted research and development on special slow-speed, high-torque, minimum backlash drives for solar collectors. Many of the drives support the solar collector as well as provide precise positioning. A major contract was successfully completed for DOE on the design for a mass-producible drive for trough collectors.

UMC Industries, Inc.
Winsmith Division
172 Eaton Street
Springville, NY 14141
(716) 592-9311

Key Personnel: Werner H. Heller, Vice President Engineering (solar collector drives); Ron Bhise, Project Manager (solar collector drives); John L. Heinz, Vice President Sales & Marketing (solar collector drives).

U.S. Department of Energy (DOE)

The Department of Energy's Division of Solar Thermal Technology is responsible for developing the Program's objectives and funding the research needed to achieve them. Assistance to DOE/Headquarters is supplied by the DOE's Albuquerque and San Francisco Operations Offices. Thus, DOE is responsible for the disbursal of funds, and the management of the research and development contained in this document. It coordinates the activities at the Sandia National Laboratories (Albuquerque and Livermore), the Solar Energy Research Institute, and the Jet Propulsion Laboratory.

U.S. Department of Energy
Division of Solar Thermal Technology
Forrestal Building
1000 Independence Avenue, S.W.
Washington, DC 20585

Howard S. Coleman, Director
(202) 252-1535
Clifton Carwile, Deputy Director
(202) 252-5584

Key Personnel: Clifton Carwile, Chief, Systems Test and Evaluation Branch; Martin Scheve, Chief, Research and Technology Branch; Robert Hughey, Director, San Francisco Operations Office; Dean Graves, Program Manager, Albuquerque Operations Office.

U.S. Department of the Army

Performs research to assist the Army in fielding cost-effective and reliable solar energy systems. Solar energy research falls into two major areas: (1) Project Planning, and (2) Solar System Design. Information collected will be used to define optimal "standard" systems that will be incorporated into the Corps' *Solar Technical Manual and Guide Specification.* Also developed an instrumentation package and test procedures for verifying that an installed system is performing as specified at the time of the system acceptance.

U.S. Department of the Army
Construction Engineering Research Laboratory
ATTN: CERL-ES
P.O. Box 4005
Champaign, IL 61820
(217) 373-7281

Key Personnel: David M. Joncich, Team Leader (active system feasibility/design).

U.S. Department of the Interior

Performs engineering studies and verification testing of advanced energy projects including solar and wind power systems as they apply to the Bureau's specific needs. This is done to assist Bureau planners and designers in evaluating alternative energy systems and in preparing appropriate designs and specifications for these systems. The Bureau's research activities in the area of solar thermal presently deal with (1) integration of solar thermoelectric power plants with the federal hydroelectric power system, (2) monitoring the performance of the solar DHW heating systems that have been installed in visitor centers and other Bureau facilities, and (3) assessment of the technical and economic feasibility of solar total energy systems, including salt-gradient solar ponds and dish and trough collectors, in Bureau applications requiring project power.

U.S. Department of the Interior
Bureau of Reclamation
Engineering & Research Center
Advanced Energy Applications Office, Code D-1500E
P.O. Box 25007
Denver, CO 80225
(303) 234-6305

Key Personnel: Harry E. Remmers, Assistant Coordinator, Solar Applications (solar system design and analysis of solar central receivers, solar DHW, solar ponds, and solar photovoltaic systems).

U.S. Department of the Navy

The principal RDT&E center for Navy shore facilities, fixed-surface and subsurface ocean facilities, and for the Navy and Marine Corps construction forces. NCEL has evaluated the potential for solar thermal in providing both domestic hot water and space heating. It has provided an easy-to-use handbook for Navy field personnel to determine the feasibility of using solar for a particular application. Presently, NCEL is contracting with Los Alamos National Laboratory for a similar handbook to cover passive solar heating experiments. Efforts in this area are directed toward 2-story, wood-frame dwellings and multi-story, concrete-block buildings. NCEL is investigating the potential of concentrator technology for supplying some of the Navy's steam load. Through an interagency agreement with DOE, NCEL is providing field requirements to the Jet Propulsion Laboratory for developing an electricity-producing parabolic dish, receiver, and engine. NCEL has contracted with JPL for a feasibility study of a salt-gradient solar pond for heating and cooling at a specific Navy site.

U.S. Department of the Navy
Naval Civil Engineering Laboratory
Energy Program Office, Code L03AE
Port Hueneme, CA 93043
(805) 982-5468

Key Personnel: Louis Huang, Principal Investigator (concentrator technologies); Ed Durlak, Principal Investigator (flat plate technologies); Charles Miles, Principal Investigator (passive solar designs); John Stephenson, Mechanical Systems Division Director; David Holmes, Program Manager (renewable sources).

United Stirling, Inc. (USI)

A subsidiary of United Stirling AB of Sweden; a high technology company dedicated to the commercial development of the Stirling external heat engine for solar electric power. USI was formed in 1979 to aid the transfer of Stirling technology and to accomplish engine production in the U.S. United Stirling has been studying applications and developing hardware for Stirling solar thermal power since 1978. It first demonstrated a Stirling solar thermal power plant at Georgia Tech University in 1981, and has been cooperating with JPL during 1982-83, producing power for the SCE grid by means of a 25-kW Stirling engine at the focal point of each of the two JPL Test Bed Concentrators at Edwards, California. Total operating time exceeds 700 hr; continuous runs up to 13.5 hr have been achieved. Overall efficiency of 27% from solar input, to the dish, to power in the grid has been measured. United Stirling is installing a new model of their solar engine at Palm Springs, California in late 1983 under a DOE cost-sharing program involving 30 major contractors.

United Stirling, Inc.
211 The Strand
Alexandria, VA 22314
(703) 549-7174

Key Personnel: Bengt Hallare, President; Worth H. Percival, Technical Director; David Wells, System Integrator.

United Technologies Research Center (UTRC)

The central research laboratory for United Technologies Corporation. UTRC has been engaged since the early 1970s in research and development on solar-powered heat pumps and air-conditioning systems. This work has been performed under Corporate, DOE, and SERI (MRI) sponsorship. The systems employ Rankine power cycles in which the expansion turbine drives the compressor of a conventional (Rankine) cooling system. A variety of heat pump and cooling-only systems have been developed in the laboratory and tested. This effort has culminated in the successful 3-year field test of a 20-ton cooling-only version of the Rankine/Rankine system in an office building in Phoenix, Arizona.

United Technologies Research Center
Silver Lane
East Hartford, CT 06108
(203) 727-7294

Key Personnel: F.R. Biancardi, Manager of Advanced Systems (solar power systems); G. Melikian, Manager, Energy Conversion Systems (solar power systems).

University of Alabama in Huntsville

Conducts solar energy research and development which includes providing solar information, technical advice and assistance, developing engineering analysis, and improving the use of solar energy and related energy sources. General research and development of solar thermal systems. The Alabama Solar Energy Center (ASEC) is involved in the design, installation, test evaluation and analysis of solar water and space heating systems; photovoltaics; preparation of codes, standards and specifications for solar design; solar economics computer program preparation; and storage tank and heat exchanger performance evaluation.

University of Alabama in Huntsville
Kenneth E. Johnson Environmental and Energy Center
Alabama Solar Energy Center
Huntsville, AL 35899
(205) 895-6707

Key Personnel: Leonard Adcock, II, Test Engineer (photovoltaics); Jerome C. Brainerd, Associate Professor (solar-assisted heat pumps); Gerald R. Guinn, Director, ASEC (agricultural, industrial process heat, conservation, DHW, heating, cooling, active design, HVAC, cogeneration, biomass, photovoltaics); Leigh Lloyd Hummer, Director, Solar Test Facility (test engineering, instrumentation analysis, evaluation); Bernard M. Levine, Senior Research Associate (energy conservation, active and passive solar energy systems, marketing and economics); Bruce J.

Novell, Research Associate (active and passive solar heating and cooling, solar performance and economic analysis, instrumentation-testing, solar industrial and agricultural process, solar greenhouses, earth-sheltered houses); Bernard J. Schroer, Director, JEEC (solar research and development, analysis, evaluation); Kenneth T. Spain, Research Associate (design and analysis of solar space and water heating systems, active solar systems, solar applications in commercial and industrial process heating); Donald B. Wallace, Associate Professor (solar heating and cooling, solar collector design, solar energy systems analysis, photovoltaics); Carl Ziemke, Senior Research Associate (solar consultant, biomass fuels).

University of Arizona

Conducts research on water and energy use in irrigated agriculture and energy use on dairy farms. Solar energy research investigations have included solar thermal generation of electricity for irrigation pumping, especially the evaluation of facility performance in the field. Direct solar pumping of water is also under investigation.

University of Arizona
Department of Soils, Water and Engineering
429 Agricultural Sciences Bldg., No.38
Tucson, AZ 85721
(602) 621-1646

Key Personnel: Dennis L. Larson, Professor (solar generator plant performance and maintenance).

University of Arizona

A graduate department of the University of Arizona, and a research center for applied and theoretical optical technology. The Solid-State Optics Group and the Thin-Film Laboratory conduct advanced research in the preparation and characterization of optical materials, particularly in the form of thin films, and the development of spectrally selective coatings withstanding long-term operation at temperatures in excess of 500°C. Other areas include the use of chemical vapor deposition (CVD) for the study of the correlation between process parameters on the one hand, and the composition, microstructure, and optical properties of thin films on the other; and synthesis of simple, two-phase cermet films of good spectral selectivity, such as Black Molybdenum and Black Tungsten, surviving long-term exposure to 500°C. The Center also studies the deposition of CVD molybdenum reflector films of high infrared reflectance ($R_{absolute}$ = 98.7% at 10 micrometers) and bulk electrical conductance; the development of amorphous silicon-carbon alloys of good solar absorptance resisting crystallization up to 1000°C; and synoptic studies of groups of materials such as the transition-metal carbides and nitrides for the design of novel optical materials on the basis of band structure aspects.

University of Arizona
Optical Sciences Center
Tucson, AZ 85721
(602) 621-2263

Key Personnel: Bernhard O. Seraphin, Professor, Optical Sciences (physics of the optical properties of materials, material sciences aspects of solar energy conversion).

University of California at Berkeley (UCB)

Conducts research in the areas of (1) thermal storage in thermoclines and phase change media, (2) evaluation of heat losses from solar cavities and external receivers, and (3) turbulence modeling and experiments in flows subject to large buoyant forces.

University of California at Berkeley
Department of Mechanical Engineering
Berkeley, CA 94720
(415) 642-6460

Key Personnel: C.L. Tien, Vice Chancelor for Research; Joseph A.C. Humphrey, Professor (measurement and numerical modeling of thermal-driven flows with large buoyant forces); R. Greif, Professor.

University of California at Berkeley (UCB)

Formerly the Sea Water Conversion Laboratory, the Water Thermal and Chemical Technology Center (WTC) conducts basic research on energy-intensive thermal and chemical processes, especially in water desalting and reclamation, and on related aspects of energy production and conservation. Solar-related studies include experimental salt-gradient solar pond; high-yield evaporator for use with solar-generated low-pressure steam; organic-vapor two-component Rankine cycles to produce electric power from solar and waste-heat energy; flat-plate solar collector; and self-standing solar stills to produce potable water.

University of California at Berkeley
Water Thermal and Chemical Technology Center
47th Street and Hoffman Boulevard
Richmond, CA 94804
(415) 231-9535

Key Personnel: Everett Howe, Professor Emeritus, Mechanical Engineering (solar and solar-assisted distillation, solar ponds, flat-plate solar collectors); Marshal Merriam, Associate Professor, Engineering Science (solar pond construction and operation; wind energy, solar energy collectors, reflectors and absorbers, and materials; tides, waves, currents, and ocean thermal energy; economic and geographic *interfacing of solar energy utilization*); Badawi Tleimat, Principal Development Engineer (solar and solar-assisted distillation, Rankine cycle, solar ponds, flat-plate solar collectors); Cal Herrmann, Research Specialist (solar ponds); Theodore Vermeulen, Professor, Chemical Engineering (solar ponds, Rankine cycle).

University of California at Los Angeles (UCLA)

A dedicated laboratory of the U.S. Department of Energy operated by the Regents of the University of California. It is organized into three divisions. The Nuclear Medicine Division is a multidisciplinary program utilizing radioisotopes for study of physiological and biochemical processes *in situ*. The Biomolecular and Cellular Sciences Division focuses on fundamental cellular processes. The Environmental Biology Division focuses on an integrated study of arid region ecosystems. All three divisions conduct a mix of basic research and research applied to the biomedical and environmental consequences of energy technologies. The Solar Project, administered through the Environmental Biology Division, has had primary responsibility for assessing the environmental effects of DOE Solar Thermal Power System projects. Initially, this included occupational health and safety, public health, socio-economic factors, institutional constraints, ecology, alternatives, and mitigations. Current activities involve ecological monitoring in the vicinity of the 10 MWe STPS pilot plant near Barstow, California.

University of California at Los Angeles
Laboratory of Biomedical and Environmental Sciences
900 Veteran Avenue
Los Angeles, CA 90024
(213) 825-8729

Key Personnel: Robert G. Lindberg, Project Manager (solar thermal technology and environmental effects); Frederick B. Turner, Research Biologist (ecological effects of STPS development); Philip Rundel, Associate Director for Environmental Biology (physiological ecology of desert plants).

University of Chicago

Major effort is in the application of principles of the recently developed field of non-imaging optics and experimental testing of non-tracking solar concentrators usually referred to as compound parabolic concentrators (CPCs). In the past three years the research group has built an experimental panel of evacuated solar thermal concentrating collector tubes that requires no tracking or tilting adjustments and is still competitive in efficiency and annual energy delivery with tracking line-focus parabolic troughs. Other research is directed toward the development of secondary concentrators

University of Chicago
Enrico Fermi Institute
5640 South Ellis Avenue
Chicago, IL 60637
(312) 962-7756

Key Personnel: Roland Winston, Professor of Physics, (theory and applications of non-imaging optical techniques, solar concentrator design); Joseph J. O'Gallagher, Senior Research Associate (design, development and testing of prototype solar concentrators).

that can double or triple the concentrations achievable with point-focus primaries or relax the optical and tracking tolerances required for a given concentration.

University of Florida

A research and educational facility involved in developing energy conversion practices that have primary application in the residential sector. Lab personnel are also responsible for organizing and operating a training in alternative energy technologies program for developing countries. Solar thermal research ranges from application of solar-heated water to the design, development, and testing of high-temperature storage systems. Various conversion devices have also been developed that allow the research group to convert solar energy into high temperatures via concentration.

University of Florida
Department of Mechanical Engineering
Solar Energy Laboratory
Gainesville, FL 32611
(904) 392-0812

Key Personnel: E.A. Farber, Distinguished Service Professor (heat transfer and storage); H.A. Ingley, Assistant Professor (thermal conversion systems); R.W. Dixon, Assistant in Engineering (testing of commercial solar thermal devices).

University of Hawaii at Manoa

Provides leadership, focus, and support for energy-related research at the University which will lead to the development of the state's indigenous natural energy resources — geothermal, direct solar radiation, biomass, wind, and ocean energy systems. It engages in research, development, and demonstration projects covering the entire range of renewable energy technologies. The Institute is engaged in fundamental studies of the use of concentrated solar radiation (greater than 1000 suns) to effect chemical processes within chemical reactors. To date, emphasis has been on the radiant flash pyrolysis of biomass materials as a source of high value fuels and chemicals. Other solid-phase decomposition processes are also being studied.

University of Hawaii at Manoa
Hawaii Natural Energy Institute
2540 Dole Street
Honolulu, HI 96822
(808) 948-8890

Key Personnel: Michael J. Antal, Coral Industries Professor of Renewable Energy Resources (solar thermal engineering, chemical reactor design); Ali Tabatabaie-Raissi, Research Associate (solar thermal engineering, chemical reactor design); William S. Mok, Research Associate (solar thermal engineering, chemical reactor design); Paul C. Ekern, Professor (solar insolation data).

University of Houston

An interdisciplinary energy research organization that reports at a college level to the Provost's office. Funding is from a University State line Item, Department of Energy through a Solar Thermal Advanced Research Center and contracts from various agencies. Overall goal of the Laboratory is to develop and support energy-related research and to maintain support from a number of sources. Power tower research has been supported at the University since 1970. Emphasis has been on modeling of heliostat fields and evaluating flux densities at the central receiver for various conditions. Systems scaling and economic factors have been modeled. A great number of heliostat field layouts have resulted from extensive computer modeling. The present STARC program is concerned mainly with chemicals and fuels and their storage problems. These involve surface physics under solar irradiation, chemical heat-pipe systems involving receiver reactors, the ammonium hydrogen sulphate cycle, and high-flux capability receivers. The discipline of physics heat transfer and chemical engineering are applied to research in solar problems of interest.

University of Houston
Energy Laboratory, 112 SPA
4800 Calhoun
Houston, TX 77004
(713) 749-4861

Key Personnel: Alvin F. Hildebrandt, Director (central receivers, heat pumps); Lorin L. Vant-Hull, Head, Solar Thermal (central receiver optical and system analysis; insolation modeling); James T. Richardson, Professor (solar heat-pipe-driven catalytic receiver/reactors, solar methane reforming); H. William Prengle, Associate Dean/Professor (engineering design of solar reactors heat transfer and reaction rate effects); Nagaraja Shamsundar, Assistant Professor (design equations for passive latent heat-storage heat exchangers); Wayne E. Wentworth, Professor (chemical evaluation of reactions suitable for chemical storage); Alex Ignatiev, Associate Professor (photo-activated processes at the surface of solar-related materials); John Lienhard (high-flux heat transfer - to 20 MW/m^2 - via jet impingement cooling).

University of Illinois at Champaign-Urbana (UICU)

The solar energy program is a research and teaching program which is part of the Department of Mechanical and Industrial Engineering. Its goal is to provide courses and to do research in order to promote the cost-effective utilization of solar energy. Conducts research on convective losses from solar receivers, modeling and simulation of passive and active solar heating systems including both space and water heating, research of heat and mass diffusion in solar ponds, and monitoring of solar systems.

University of Illinois at Champaign-Urbana
Department of Mechanical and Industrial Engineering
1206 West Green Street
Urbana, IL 61801
(217) 333-1176

Key Personnel: A. M. Clausing, Professor of Mechanical Engineering (convective losses, modeling and simulation); T. A. Newell, Assistant Professor of Mechanical Engineering (solar ponds modelling and simulation).

University of Minnesota

The 4.2-m Solar Research Furnace at the University of Minnesota, which shares many of the features of the large furnaces in Odeillo, France and White Sands, New Mexico, was designed to handle bench-top and micro-pilot-plant experiments. The purpose of the Solar Research Furnace is to investigate the use of sunlight as a source of process heat in the range of 1000°K to 3000°K and the fabrication and testing of reactors and associated equipment for such process. Research projects have included production of hydrogen and oxygen from water; production of hydrogen and sulfur from hydrogen-sulfide; and high-temperature electrolysis using sunlight as a source of process heat.

University of Minnesota
Department of Mechanical Engineering
111 Church Street, SE
Minneapolis, MN 55455
(612) 373-2851

Key Personnel: Edward A. Fletcher, Professor; Richard B. Diver, Research Associate (solar thermochemical); Dennis Kunnerth, Research Associate (electrolysis).

University of Minnesota

State university with teaching, research, and extension activities. Present research considers new design concepts for line- and point-focus solar collector thermal receivers. Simulation studies include transient thermal and fluid flow performance for use in design of a liquid heating prototype. Use of the receivers for steam generation is also being investigated with the porous absorber operating in a two-phase flow condition.

University of Minnesota
Thermal Environmental Engineering Laboratory
Minneapolis, MN 55455-0111
(612) 373-3038
(612) 373-3043

Key Personnel: Benjamin Y.H. Liu, Professor (radiation measurement and estimation); Thomas H. Kuehn, Associate Professor (thermal modeling, system design); James W. Ramsey, Associate Professor (thermal modeling, testing).

University of Oregon

Research and development in the area of solar radiation and its immediate applications. The Laboratory maintains an 11-station solar radiation monitoring network. Both direct and global measurements are made. Primary goal is to evaluate the solar electric potential of the region. Specific projects include a study of diffuse-global empirical correlation, direct-global variations, seasonal effects, and the amount and deviation of short-term fluctuations.

University of Oregon
Solar Monitoring Laboratory
Eugene, OR 97403
(503) 686-4765

Key Personnel: David K. McDaniels, Director; Frank Vignola, Assistant Director.

University of Pennsylvania

Research in a broad area of heat transfer, fluid mechanics, thermodynamics and thermal engineering as applied to solar thermal processes: heating, process heat, cooling, power, and ocean thermal energy conversion. Specific projects undertaken are the application of solar heating in the urban environment (and the University of Pennsylvania SolaRow house), analysis and testing of solar collectors, flow distribution in dual-manifolds, thermal and flow design of solar collector arrays, wind effects on thermal performance of collector arrays, thermodynamics of absorption heat pumps, analysis and design of passive solar heating of courthouses, Rankine-cycle solar cooling, development of the solar-powered/fuel-assisted Rankine power cycle (SSPRE), research on wind effects and thermal performance of salt-gradient solar ponds, instrumentation for performance monitoring of solar systems, and second low (energy) analysis of solar processes.

University of Pennsylvania
Department of Mechanical Engineering and Applied Mechanics
220 S. 33rd Street
Philadelphia, PA 19104
(215) 898-7244

Key Personnel: Noam Lior, Associate Professor of Mechanical Engineering.

University of Utah

Engaged in heat exchanger development and thermal-fluid modeling. Major emphasis in the study of direct-contact heat exchangers has taken place for the past decade. Additional work in solar ponds and collector systems continues to be conducted.

University of Utah
Mechanical & Industrial Engineering Department
Salt Lake City, UT 84112
(801) 581-6441

Key Personnel: R.F. Boehm, Professor of Mechanical Engineering (fluid modeling, collector development, solar pond analysis, direct-contact heat exchanger studies and design).

University of Washington

Educational research institution. The major objective is to explore the physics of conversion of concentrated sunlight into laser light without the need for an intermediate step of energy conversion. High efficiency and power are desired. This is to be accomplished using a solar-heated black-body cavity as the indirect source of light for optically pumping infrared lasers such as CO_2.

University of Washington
Department of Aeronautics & Astronautics, FS-10
Seattle, WA 98195
(206) 543-1950

Key Personnel: Walter H. Christiansen, Professor of Aeronautics & Astronautics (solar lasers, non-equilibrium gas physics, gas dynamics).

University of Wisconsin-Madison

Engaged in research in solar thermal processes aimed at developing methods for predicting the performance of solar thermal processes and designing those processes. Simulation methods have been developed to numerically solve the sets of equations describing the performance of components of systems. The solar process simulation program, TRNSYS, developed at the Laboratory is widely used in studies of new processes and components. Design methods such as f-Chart and phi bar have been developed for sizing a wide range of active and passive systems.

University of Wisconsin-Madison
Solar Energy Laboratory
1500 Johnson Drive
Madison, WI 53706
(608) 263-1586

Key Personnel: John A. Duffie, Director (thermal processes); William A. Beckman (simulation and design methods, utilization); Sanford A. Klein (simulation and design methods, absorption cooling); John W. Mitchell (buildings loads, controls).

Utah State University

Conducts water-related research and development programs. The solar-related water research programs include solar salt ponds and solar-powered water pumps. The pump design objective is to develop a small economical pump that can be used on small acreages in developing countries. Another area of research invoves methylene-blue-enhanced photo degradation of herbicides, pesticides, and industrial wastes.

Utah State University
Utah Water Research Laboratory
Logan, Utah 84322
(801) 750-1000

Key Personnel: Clair Batty, Associate Director of UWRL (solar ponds); Duane Chadwick, Associate Professor of Electrical Engineering (solar pump); Dean Adams (methylene-blue-enhanced photo degradation).

Veda, Inc.

A professional services company engaged primarily in research and development activities related to military weapon systems and to solar energy applications for a variety of industrial processes. Veda has been involved in developing systems conceptual designs for highly concentrated solar energy applications to chemical processing. Desalination-brine concentration, production of elemental phosphorous, fractional distillation of metals, isotope separation, production of silicon carbide, precalcining and production of Portland cement are some of the processes investigated. Many of these involve the use of a direct-flux reactor followed by cogeneration of electricity. Deficiencies of existing approaches have been identified, resulting in the awarding of two patents with another patent pending. These devices have been demonstrated for proof of principle, and real-time simulations of systems utilizing them have been performed. The patented devices are available for licensing. Veda does not manufacture hardware.

Veda, Inc.
1225 South Jefferson Davis Highway
Suite 300
Arlington, VA 22202
(703) 486-0505

Key Personnel: E.N. Hunter, Vice President, Business Development (program management); W.T. Moore, Senior Engineer/Scientist II (systems analysis and design, patent holder, #4137897, #4338922); Alan Conwell, Senior Engineer II (math analysis and simulation development); L.E. Ehrhardt, Project Engineer (project management).

Washington Analytical Services Center, Inc.

See: EG&G Washington Analytical Services Center, Inc.

Westinghouse Electric Corporation

Involved with many areas of solar energy. Emphasis has been in the fields of conceptual design of photovoltaic power systems, wind energy systems, energy storage for photovoltaic conversion systems, photovoltaic utility/customer interface studies, solar thermal system studies, and performance analysis of reformed alcohol fuels for combustion turbines. Westinghouse AST has performed work for DOE, EPRI, and SERI including Impact Analysis of Solar-Thermal Power Plants, Design Study and Economic Assessment of Multi-Unit Offshore Wind Energy Conversion Systems, Economic Study of Solar-Thermal Power Systems, and Analysis of Dissociated Alcohol Fuels in Combustion Turbines. Expertise within AST includes mechanical, electrical, and structural engineering disciplines.

Westinghouse Electric Corporation
Advanced Systems Technology
14142 Denver West Parkway
Golden, Colorado 80401
(303) 279-8082

Key Personnel: N. H. Woodley, Manager, AST Western Operations (utility applications of solar thermal systems); D. J. Keys, Systems Engineer (solar thermal system design and analysis); J. T. Day, Manager, Energy Resource Planning (economic analysis of solar thermal systems); M. J. Malone, Energy Resource Engineer (economic analysis of solar thermal systems).

Westinghouse Electric Corporation

Involved in power systems planning and analysis studies. It provides power systems consulting services to electric utilities, large industrial companies, and government agencies. Previous solar thermal studies include utility impact and value analysis for DOE, EPRI, SERI, and individual utilities. This division of Westinghouse also developed a solar thermal plant model and surrounding procedures to model the coordinated operation with conventional generating units. Design impact analysis has also been provided.

Westinghouse Electric Corporation
Advanced Systems Technology
777 Penn Center Boulevard
Pittsburgh, PA 15235
(412) 824-9100

Key Personnel: John T. Day, Manager, Generation and Economics (impact, value analysis and optimum operating strategies).

Winsmith Division

See: UMC Industries, Inc.

Chapter 10
Information Sources and Design Tools

Included on the following pages are many of the major sources of technical information on solar thermal energy that are accessible to the public. This list is not intended to be exhaustive, but concentrates solely on those organizations or publications that are most directly concerned with solar thermal energy.

This chapter is organized alphabetically by the following types of information sources:

- Bibliographies
- Data Bases
- Directories
- Associations
- Journals
- Models

Although specialized solar thermal energy bibliographies (such as those cited on the following pages) can provide a comprehensive listing of publications, many books and reports contain extensive bibliographies or reference lists that may also be quite useful. On the other hand, because published bibliographies can become quickly outdated, computerized data bases will often be the best way to find recent publications. Additionally, data bases can also make it easier to locate specific types of publications, or publications from specific types of sources.

Directories and associations have also been listed because of their potentially valuable ability to direct an inquirer to persons or organizations currently involved in the solar thermal energy field. Finally, journals (often published by trade/professional associations involved in the renewable energy field) are frequently valuable sources of up-to-date developments regarding the state of the art.

Bibliographies

Solar Concentrators - A Bibliography

This is an international compilation of over 1400 annotated references categorized under the following headings: Cylindrical Parabolic Trough Concentrator; Fresnel Lens and Reflector Systems; Russell's Fixed Mirror Solar Concentrator; Hemispherical Bowl/SRTA System; Tabor-Zeimer Circular Cylinder; Mirror Boosters, V-Trough and Polygonal Troughs; Compound Parabolic Concentrator/Non-imaging

Mathur, S.S.; Kandpal, T.C.; Singh, R.N. (1982). *Solar Concentrators — A Bibliography*. Energy Series: SB 01. Greenbelt, MD: Innovative Informations Incorporated; 186 pp.

Concentrators; Paraboloid of Revolution/Solar Furnaces; Central Tower Receiver Systems; Two-Stage Solar Concentrators; Photovoltaic Concentrator Systems; Tracking of Solar Concentrators; Materials Problems in Solar Concentrators. Each entry is number coded and keyed to the alphabetical author index following the bibliographic entries. An alphabetical listing of publication sources is also included.

Environmental Degradation of Solar Optical Materials; Volume 1. Literature Survey

The bibliography in this document contains a list of 164 references, most obtained from a survey of the literature published from 1960 to the present, with the emphasis on the physical and chemical degradative effects of the exposure environment on optical material proposed for solar energy systems. In addition, references obtained from a telephone survey of organizations conducting research in this area were also included, so that a few of the references in the bibliography refer to unpublished reports and conversations. The majority of this document is devoted to a summarization of the information contained in the citations and to various appendices.

Morris, V.L. (November 1982). *Environmental Degradation of Solar Optical Materials; Volume 1. Literature Survey*. SAND82-7068/1. Albuquerque, NM: Sandia National Laboratories; 118 pp. Work performed by McDonnell Douglas Astronautics Company, Huntington Beach, CA.

Bibliography of the Seasonal Thermal Energy Storage Library

This bibliography is an instrumental tool for the Seasonal Thermal Energy Storage (STES) Library, developed under the direction of V.E. Hampel of the Lawrence Livermore Laboratory. It contains over 1700 references on topics related to thermal energy storage including non-aquifier storage methods, economic feasibility, aquifier characterization, thermal fatigue of aquifer and well materials, corrosion, heat transfer equipment, and industrial applications. The STES Library is continually updated and accessible via the STES Technology Information System, a computer-based data file. The main emphasis of the bibliography is on the storage of energy in aquifers through articles pertaining to many types of thermal energy storage.

Prater, L.S.; Casper, G.; Kawain, R.A. (August 1981). *Bibliography of the Seasonal Thermal Energy Storage Library*. PNL-3645, Pacific Northwest Laboratory, Richland, WA; 296 pp.

A Solar Materials Annotated Bibliography

This bibliography is a compilation of the projects related to solar material and/or significant materials tasks of the Department of Energy's "National Plan for Solar Heating and Cooling Research and Development" program. It is broken into two major sections. The first lists various projects by contractor, reference number, (to the second section) and material/activity under the headings: absorbers; glazings; insulation; heat-transfer fluids; corrosion; and other. The second major section provides an alphabetical listing of contractors followed by an annotated project description that includes important reports on publications for each project.

Reisfeld, S.K., compiler. (January 1983). *A Solar Materials Annotated Bibliography*. LA-9581-MS. Los Alamos National Laboratory. Available from: NTIS; 112 pp.

A Bibliography of Sources of Experimental Data Leading to Thermal Properties of Binary Aqueous Electrolyte Solutions

This is a bibliography of sources of experimental data that can be used to calculate either relative apparent molal enthalpies or apparent molal heat capacities for aqueous electrolyte solutions. The data types included are calorimetric heat capacity measurements, enthalpies of solution as a function of molality, enthalpy of dilution measurements, electromotive force measurements as a function of temperature, and vapor pressure measurements as a function of temperature. Approximately 900 references to the primary literature are included.

Smith-Magowan, D.; Goldberg, R.N. (March 1979). *A Bibliography of Sources of Experimental Data Leading to Thermal Properties of Binary Aqueous Electrolyte Solutions*. National Bureau of Standards Special Publication 537. Washington, DC: U.S. Government Printing Office; 85 pp.

Solar Ponds - A Selected Bibliography

The entries include citations to solar pond research at the Solar Energy Research Institute as well as research performed throughout the U.S. and internationally. The bibliography is divided into three sections: I. Solar Ponds; II. Shallow Solar Ponds; and III. Patents. Selected references on fluid mechanics are included in Section I. The citations in each section are alphabetical by first author and include title and complete bibliographic information.

Solar Ponds — A Selected Bibliography. (November 1981). SERI/TR-752-711. Golden, CO: Solar Energy Research Institute. 24 pp.

Data Bases

Chemical Abstracts

Updated twice monthly; began in 1967. Contains over 5,000,000 records and covers chemical science literature from more than 12,000 journals, patents from 26 countries, new books, conference proceedings, and government research reports. Main subject sections include biochemistry, organic chemistry, macromolecular chemistry, applied chemistry and chemical engineering, and physical and analytical chemistry. Corresponds to printed *Chemical Abstracts Indexes*.

Supplier: Chemical Abstracts Service
P.O. Box 3012
Columbus, OH 43210
Tel: (614) 421-6940

Compendex

Updated monthly; began in 1970. Contains over 1,000,000 records and corresponds to the printed *Engineering Index*. Worldwide coverage of approximately 2000 serials and over 900 monographic publications. Areas covered include aerospace engineering, bio-engineering, chemical engineering, civil engineering, construction materials, control engineering, electrical engineering, electronics and communications engineering, engineering geology, marine engineering, mining engineering, nuclear technology, and petroleum engineering.

Supplier: Engineering Information, Inc.
United Engineering Center
345 East 47th St.
New York, NY 10017
Tel: (212) 644-7600

EDB (Energy Data Base)

Updated biweekly; began in 1974. Over 640,000 citations. Data base coverage is retroactive to late 1800s. The bibliographic data base covers all energy topics and references to books and journal articles, report literature, conference papers, patents, dissertations, and translations. Citations include the following types of fields: title, author, complete bibliographic

Contact: David E. Bost
DOE Technical Information Center
Science and Technology Branch
P.O. Box 62
Oak Ridge, TN 37830
Tel: (615) 574-1000

information, abstract, and subject descriptors. It includes information announced in *Solar Energy Update* and *Energy Research Abstracts*. EDB is available from DOE/RECON, a retrieval system whose access is limited to DOE-approved organizations and several commercial data base vendors.

Energyline

Updated monthly; began in 1971. Comprehensive coverage includes economics; U.S. policy and planning; international political and economic issues; research and development; resources and reserves; environmental impact; electric power transmission and storage; fuel production; fuel transport; nuclear power; and industrial, transportation, and residential consumption. Includes data for government agencies and both profit and non-profit organizations. Each record contains basic organization information; names, addresses and phone numbers of key energy contacts; and, when applicable, a brief description of the organization's goals and activities, including the names and addresses of branch offices and personnel. The printed publication is Energy *Information Abstracts*

Supplier: Environment Information Center, Inc. (EIC)
Document Room
292 Madison Ave.
New York, NY 10017
Tel: (212) 949-9494

NTIS

Updated biweekly; began in 1970. A bibliographic data base, NTIS contains over 834,000 citations consisting of government-sponsored research, development, and engineering reports, along with analyses and journal articles prepared by federal agencies, their contractors, or grantees. It is the means through which federal reports (that are unclassified and authorized for unlimited distribution) are made available for sale to the public. NTIS reports are available in either paper or microfiche. Citations include the following fields: title, author, report numbers, conference proceeding information, availablity source, abstract, and subject descriptors. NTIS is available on-line through a number of commercial data base vendors; custom searches can be requested directly from the National Technical Information Service (NTIS). Magnetic tapes of the data base are also available for purchase or lease. *Government Reports Announcements and Index*, the printed version of the NTIS data base, is published semi-monthly.

Contact: National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Tel: (703) 557-4660

Directories

Desalination Directory

This is an international directory of companies, institutions and research organizations involved in desalination and water purification technologies. The directory is divided into two major sections listing organizations and individual researchers and professionals in the field. The organization section gives a full address and general description of the particular entry's specific areas of interest and/or production. A general alphabetical index and a geographic index are appended to the organizational section. Each individual involved in the technology is listed alphabetically with his/her affiliate address.

Balaban, Miriam, editor. (December 1982). *Desalination Directory*. New York, NY: Elsevier Science Publishers; 364 pp.

1984 Energy Products Specifications Guide: Conservation, Solar, Wind & Photovoltaics

This directory lists more than 1000 energy products available in the United States. Published annually, the directory focuses on two areas: (1) renewable energy, including solar, wind, and photovoltaic products, and (2) conservation, including insulation products, high-efficiency glazing, primary heating and cooling systems, and low-energy mechanical systems. Each entry includes the product name; manufacturer's name, address, contact person, and telephone number; product description, including features, options, installation requirements, maintenance requirements, guarantee/warranty information, and suggested list price; and technical specifications. Many entries are accompanied by a drawing, photograph, graph, or chart. A manufacturer index and a product index complete the directory.

1984 Energy Products Specifications Guide: Conservation, Solar, Wind & Photovoltaics. (1984). Harrisville, NH: SolarVision, Inc.; 757 pp.

The Solar Energy Directory

This directory lists U.S. organizations working with the direct use of solar energy including the fields of solar heating and cooling, solar thermal energy and photovoltaics. The directory contains eleven categories of listings, some of which are professional and trade organizations, government concerns, utilities, manufacturers and research institutions. Entries are alphabetical within categories and include addresses, phone numbers, organizational descriptions, key personnel and other important factors.

Oddo, S.; McPhillips, M.; Gottlieb, R., editors. (1983). *The Solar Energy Directory*. New York: Grey House Publishing, Inc.; 312 pp.

Solar and Alternate Energy Buyers Guide — 1983-1984

The Guide provides categorized product listings under such headings as: Process Heat Systems, Thermal Storage Devices, Chemical Storage Concentrating Collectors, Instrumentation, etc. Entries are listed alphabetically by company name within each category. A manufacturer's alphabetical listing provides company addresses and a brief description of their products. A short related associations listing is also provided as are Reader Action Cards for obtaining additional information on manufacturers and products.

"Solar and Alternate Energy Buyers Guide — 1983-1984." (July/August 1983). *Solar Engineering and Contracting*; Vol. 2 (No. 5); pp. 35-65.

Associations

Association of Energy Engineers (AEE)

Founded in 1977, the Association of Energy Engineers is an organization composed of engineers, architects and other professionals interested in energy conservation. Annual conventions are held by the organization and papers presented are assigned to divisions such as plant and building energy management, solar, wind power, and education. The Association publishes a newsletter as well as *Energy Engineering Journal* and *Energy Economics Policy and Management Journal*.

Contact: Albert Thumann, Executive Director
Association of Energy Engineers
4025 Pleasantdale Road
Suite 340
Atlanta, GA 30340
Tel: (404) 447-5083

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)

Founded in 1894. The American Society of Heating, Refrigerating and Air-Conditioning Engineers is a professional organization that conducts a number of research programs in cooperation with universities, research laboratories, and government agencies. Research areas include effects of air-conditioning, inside air quality, heat transfer, flow processes and cooling processes.

Contact: A.T. Boggs, Executive Vice-President
ASHRAE
1791 Tullie Circle, N.E.
Atlanta, GA 30329
Tel: (404) 636-8400

American Solar Energy Society (ASES)

Founded 1970. The American Solar Energy Society (ASES), formerly known as the American Section of the International Solar Energy Society (AS/ISES), is one of the oldest and largest national sections of ISES. The professional association's basic purpose is to provide leadership and education in all aspects of solar technology, applications, and research in order to speed the transition to widespread use of solar energy. Ten topical divisions encourage activity in specific technical disciplines. Two divisions, Engineering and Solar Radiation, may be of interest in the solar thermal area. The Engineering Division includes the areas of solar thermal applications, heating and cooling, process heat, solar thermal power and ocean thermal power. The Solar Radiation Division includes the areas of solar energy data, atmospheric physics and meteorological optics, instrumentation and radiometry, and radiation transfer. ASES has over 7000 members and 29 regional chapters. Publications include the Society's official magazine, *Solar Age* (monthly), and its quarterly newsletter, *SolSource*.

Contact: Donald W. Aitken, Chariman of the Board of Directors
American Solar Energy Society
2030 17th St.
Boulder, CO 80302
Tel: (303) 443-3130

Gershon Meckler, Head of the Engineering Division
Gershon Meckler Associates
1101 Connecticut Avenue, N.W.
Washington, DC 20036
Tel: (202) 296-5131

Dr. Paul Berdahl, Head of the Solar Radiation Division
Lawrence Berkeley Laboratories
Energy and Environment Division
Building 90, Room 2024K
Berkeley, CA 94720
Tel: (415) 486-5278

American Society of Mechanical Engineers (ASME), Solar Energy Division, Solar Thermal Power Committee, Industrial Process Heat Committee, Heating and Cooling Committee, Testing and Measurements Committee

The Solar Energy Division of the American Society of Mechanical Engineers (ASME) was founded in 1978. Eight technical committees have been formed under the Division's heading. Four of these committees are of importance to professionals in the solar thermal field: (1) the Solar Thermal Power Committee deals with solar thermal power systems including both distributed and centralized systems and high temperature collectors; (2) the Industrial Process Heat Committee covers solar thermal applications for process heat, emphasizing operational results and system design; (3) the Heating and Cooling Committee deals with medium-temperature solar thermal applications including collector development, ponds, system operational results, water and space heating and space cooling systems; and (4) the Testing and Measurements Committee's scope covers basic measurement techniques and instrumentation as applied to the testing and evaluation of solar hardware.

Contact: M. Kudret Selcuk, Chairman
Solar Thermal Power Committee
Jet Propulsion Laboratory
MS 507-228
4800 Oak Grove Boulevard
Pasadena, CA 91109
Tel: (213) 577-9300

James Rogan, Chairman
Industrial Process Heat Committee
McDonnell Douglas Astronautics
5381 Bolsa Avenue
Huntington Beach, CA 92647

S.M. Rossi, Chairman
Heating and Cooling Committee
Vitro Labs
14000 Georgia Avenue
Silver Springs, MD 20910
Tel: (301) 871-7200

D.Y. Goswani, Chairman
Testing and Measurements Committee
Department of Mechanical Engineering
North Carolina A&T State University
Greensboro, NC 27411
Tel: (919) 379-7799

Solar Energy Industries Association (SEIA), Solar Thermal Energy Division

Founded in 1974. SEIA is an independent trade association whose membership consists primarily of manufacturers of solar equipment, contractors, and professionals in related areas. Principal activities include government affairs programs, publications, information collection, and sponsoring conferences and workshops. The Annual Conference and Trade Show is held during the spring. The official publication is *SEIA News*. SEIA has 13 state chapters and 8 technology-specific divisions. The Solar Thermal Division has initiated a study to develop a 5-year industry/government technology development plan for central receivers and parabolic dish and trough collector systems with commercial applications.

Contact: David Gorin, Executive Vice President
Solar Energy Industries Association
1156 15th Street, NW
Suite 520
Washington, DC 20005
Tel: (202) 293-2981

Frank Duquette, Chairman of SEIA Solar Thermal Divison
McDonnell Douglas
5301 Bolsa Avenue
Huntington Beach, CA 92647
Tel: (714) 896-4323

Journals

Advanced Solar Energy Technology Newsletter

Monthly; began in 1974. Written in a letter format, this publicaton gives short descriptions of new government (emphasis) and industrial programs in all of the solar energy technologies as well as reviews of related books. New developments and contracts are highlighted. Selected recent and upcoming conferences in the solar technology fields are reported. Each issue has a "Bonus Insert" of recent U.S. Solar Energy Patents.

Advanced Solar Energy Technology Newsletter
Advanced Solar Energy Technology
Carl M. Landon, editor
1609 West Windrose
Phoenix, AZ 85029

ASHRAE Journal

Monthly; began in 1959. This periodical is the professional journal of the American Society of Heating, Refrigerating and Air-Conditioning Engineers. Each issue contains informational columns of relevance on current governmental appropriations, industrial innovations, a calendar of events, professional services directory and advertiser's index. Features cover topics related to heating, ventilation, and cooling of primarily industrial institutions and buildings. Energy conservation and renewable energy systems are sometimes highlighted. Articles are accompanied by photographs, graphs, and tables. Indexed in *Chemical Abstracts* and *Engineering Index*.

ASHRAE Journal
American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
1791 Tullie Circle NE
Atlanta, GA 30329

ASHRAE Transactions

Yearly; began in 1895. Subject areas include thermal performance, thermal models, HVAC design, solar heat pump systems, solar pond systems, indoor air quality and retrofitting capabilities for various systems and installations. Published as a two-volume set; one of technical papers and one of symposium papers. Includes alphabetical author and title indexes, graphs, tables, charts, and blueprints. Indexed in *Chemical Abstracts* and *Engineering Index*.

ASHRAE Transactions
American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
1791 Tullie Circle
Atlanta, GA 30329

Applied Solar Energy

Bimonthly; began in 1965. This is an English translation of the Russian Akademiya Nauk Uzbekskoi S.S.R. journal "Geliotekhnika," composed primarily of technical papers and reviews by Russian scientists. Subject areas include solar converters, solar power plant heating systems, characteristics of collector coatings, mirror aging, insolator models, polyheliostat development, temperature differentials in solar ponds, as well as several photovoltaic technology studies. Technical paper compilation including charts, figures, tables and graphs. Indexed in *Chemical Abstracts* and *Engineering Index*.

Applied Solar Energy
(English translation of Geliotekhnika)
Allerton Press, Inc.
150 Fifth Avenue
New York, NY 10011

Desalination

Random; began in 1966. Includes original research, review and technical papers on desalting and water purification, desalination methods (present and proposed), design of desalination plants and operational systems studies. An international journal, it includes an author index with country association. Papers include all figures and tables. Indexed in *Chemical Abstracts*, *Engineering Index*, *Ocean Abstracts*, and *Excerpta Medica*.

Desalination
Elsevier Scientific Publishing Co.
Box 211
1000 AE Amsterdam
Netherlands

International Journal of Solar Energy

Quarterly; began in 1982. Publishes experimental, theoretical, and applied results in both the science and engineering of solar energy. Provides current information from Europe, North America, Japan, and the developing nations. Includes review articles, articles on development achievements and original research, and "new items and technical notes." Book reviews, future conferences, and forthcoming papers are included irregularly.

International Journal of Solar Energy
Harwood Academic Publishers
Cooper Station, P.O. Box 786
New York, NY 10017

International Solar Pond Letters

Irregular; began in 1979 under the title "Solar Pond Newsletter," published by the Los Alamos National Laboratory. Since 1982 it has been sponsored by the Solar Pond Technical Committee of the Engineering Division of ASES, Inc. Contents are short, newsworthy articles on current developments in the solar pond field. Information on worldwide solar pond experiences, discoveries, theories and projects is included.

International Solar Pond Letters
American Solar Energy Society, Inc.
1230 Grandview Avenue
Boulder, CO 80302

Journal of Solar Energy Engineering

Quarterly; began in 1980. Publishes peer-reviewed papers dealing with basic research, design, and engineering applications of solar energy technologies. Articles are abstracted and average 5-8 pages in length. Includes book reviews and events calendar. Indexed in *Engineering Index*.

Journal of Solar Energy Engineering
The American Society of Mechanical Engineers
United Engineering Center
345 East 47th Street
New York, NY 10017

Renewable Energy News

Monthly; in February 1982, *Canadian Renewable Energy News* purchased *Solar Times* and a new publication, *Renewable Energy News*, resulted. Covers worldwide renewable energy and appropriate technology news. Each issue also includes longer articles providing in-depth information on a particular technology or program.

Renewable Energy News
P.O. Box 32226
Washington, DC 20007

Solar Energy

Monthly; began in 1957. Devoted to the science and technology of solar energy applications, this journal provides a medium for the exchange of solar energy knowledge on an international basis. Articles cover the following solar technologies: heating and cooling, wind, OTEC, photovoltaics, photochemistry, solar thermal, biomass, and radiation and measurement. In addition to full length articles, the journal includes technical notes, letters, and book reviews.

Solar Energy
Pergamon Press
Maxwell House, Fairview Park
Elmsford, NY 10523

Models

Solar thermal models cover fluids, polymers, receivers, collectors, systems analysis, solar ponds, and economics. Because there are so many performance models, each has been listed in the specific subcategory into which it falls.

Design

Cavity/CREAM Code

Generates cavity geometry from design parameter inputs. Allows development and implementation of aim strategies, including aperture obstruction effects. Generates view factors and redistributes incident solar band radiation. Implements adiabatic and active heat exchange surfaces. Computes wall temperature and iterates infrared radiation interchange to a convergent solution. Provides output of wall temperatures, heat removal per heat exchange element, and aperture losses in both solar and infrared bands.

Availability: Model available to the public for a nominal fee
Used by: Mechanical engineers
Language: Fortran
Machine: Mainframe
Documentation: Lipps, F.W. (1981). *Theory of Cellwise Option for Solar Central Receiver Systems*. SAN/1637-1. Livermore, CA: Sandia National Laboratories. Work performed by University of Houston, Houston, TX.
Developed by: Lorin Vant-Hull and Fred Lipps, University of Houston
Contact: Lorin Vant-Hull
University of Houston
Energy Laboratory, SPA 4800 Calhoun
Houston, TX 77004
(713) 749-1154

PADLL (Pier Analysis and Design for Lateral Loads)

PADLL employs the so-called four-spring model in conjunction with a finite beam element model to predict the load-deflection response of drilled pier foundations that are subjected to lateral loads. The program offers the designer the capability of analyzing and designing both near-rigid and flexible piers embedded in multilayered soil profiles. PADLL has two analysis options: (1) ultimate capacity analysis, and (2) nonlinear load-deflection analysis. It also has the capability of designing a pier (selecting diameter and depth) to satisfy one to four performance criteria. The final design solution is based on a minimum pier diameter criterion or a minimum concrete volume criterion, at the designer's discretion. Each PADLL run

Availability: Model available to EPRI members for free; to others for a fee
Used by: Utilities, structural and mechanical engineers
Language: Fortran IV
Machine: Mainframe
Documentation: *Laterally Loaded Drilled Pier Research*. (1982). EPRI Report EL-2197. Palo Alto, CA: Electric Power Research Institute. Work performed by GAI Consultants, Inc., Monroeville, PA.
Developed by: GAI Consultants, Inc.
Contact: Electric Power Software Center
1930 HiLine Drive
Dallas, TX 75201
(214) 655-8883

requires run options, soil parameters, pier parameters, and load/criteria. Outputs include a load deflection diagram and table of displacements.

SYNOPSYS (Synthesis of Optical Systems)

Provides methodology to evaluate optical systems. The optimization program allows the user to specify a cost function which may include several criteria or mechanical goals and enables the definition of an optical design that best accomplishes those goals consistent with the laws of optics. A multiple configuration capability is available which allows optimizaton of several different systems simultaneously. Analysis features are available which provide geometrical or diffraction-theoretic imaging. Mechanical properties of lenses, clear aperture and beam profiles, etc. can be investigated or the user can obtain a mechanical drawing of the entire system as seen from any direction. The program is interactive in nature and has free formatted reading capability and the capability of storing intermediate data or parameters for later access and re-evaluation. User input information varies widely with application but basically the user must declare what type of analysis is to be performed and then define cost functions and supply parametric data for both optical and mechanical systems.

Availability: Model available; fees vary
Used by: Optical engineers, designers
Language: Fortran
Machine: Mainframe
Documentation: Dilworth, D. (1983). *SYNOPSYS User's Manual.* Medford, MA: Optical Systems Design, Inc.; 200 pp.

Dilworth, D. (1983). *SYNOPSYS Tutorial Manual.* Medford, MA: Optical Systems Design, Inc.; 200 pp.
Developed by: Donald Dilworth, Optical Systems and Design, Inc.
Contact: Donald Dilworth
Optical Sytems Design, Inc.
3 Johnson Avenue
Medford, MA 02155
(617) 488-3099

Economics

BUCKS — Economic Analysis Model of Solar Electric Power Plants

Developed for the economic analysis of solar thermal central receiver technology in utility networks and for comparative evaluation of alternate plant designs. The model calculates power production costs for a single solar thermal central receiver power plant. Specifically, it calculates levelized busbar energy costs (the constant revenue per unit output required over the plant lifetime to compensate for its fixed and variable costs, to pay interest to stockholders, and to provide return to shareholders). It does not include transmission and distribution costs or other indirect utility costs.

The data required for BUCKS are of two types: (1) plant performance and size information, and (2) cost and economic data. Data are supplied for a reference plant where detailed costs are known. A plant similar in design but different in size is then described with input variables that include net electrical generation from the plant; collector, receiver, turbine, and storage capacities; parasitics required; storage charging/discharging rates; and operational hours during the year. The cost and economic information is provided by FORTRAN data statements as follows: escalation rates, years of escalation, tax rate, construction years, capital form and rates, year of commercial operation, and indicator to use or charge the referenced plant parameters. The referenced design cost and economics data, which are contained in the subroutines for as many as three designs of six subsystems, include cost estimates of each of 33 solar-related items; cost estimates of each of 27 nonsolar-related items; costs of each of

Availability: Model available to the public
Used by: Planners, economic analysts
Language: Fortran
Machine: Mainframe
Documentation: Brune, J.M. (1978). *BUCKS — Economic Analysis Model of Solar Electric Power Plants.* SAND77-8279. Livermore, CA: Sandia National Laboratories.
Developed by: Joan Brune, Sandia National Laboratories, Livermore
Contact: Gordon Miller
Sandia National Laboratories
Livermore, CA 94550

seven operating and maintenance (O&M) tasks; estimated plant lifetime; contingency, insurance, and property tax; O&M escalation rate; and storage media replacement.

HELCAT (Heliostat Cost Analysis Tool)

A heliostat cost analysis tool that processes manufacturing, transportation, and intallation cost data to provide a consistent structure for cost analyses. HELCAT calculates a representative product price based on direct input data including purchased and raw materials; consumables; direct labor hours per heliostat; land size; building size; equipment and tooling cost; quantity and other costs such as subcontracts, site-retained capital, and direct transportation charges; and various economic, financial, and accounting assumptions. A set of nominal economic and financial parameters that can be changed to describe a specific manufacturer's business practice is included for the user.

Availability: Model available to the public
Used by: Utilities, economists, engineers
Language: Fortran
Machine: Mainframe
Documentation: Brandt, L.D. and Chang, R.E. (1981). *Heliostat Cost Analysis Tool.* SAND81-8031. Livermore, CA: Sandia National Laboratories.
Developed by: Sandia National Laboratories, Livermore
Contact: Larry Brandt
Sandia National Laboratories
Livermore, CA 94550

Levelized Energy Cost Model

An indicator of average cost of energy (standardized to a levelized busbar equation) over the life of a system that enables the user to compare energy systems on a cost basis. Inputs are five separate capital costs, operations and maintenance costs on an annual basis, capital replacement costs, tax rate for the state in question, insurance rate, discount rate, and general inflation rate. Final output is the levelized cost of energy in dollars per kilowatt hour.

Availability: Model available to the public
Used by: Utilities, solar system contractors, economists, solar researchers
Language: Fortran (with BASIC and PI versions)
Machine: Mainframe, microcomputer (microsoft BASIC), and programmable calculator (HP and TI)
Documentation: Doane, J.W. and O'Toole, R.P. (1976). *The Cost of Energy from Utility-Owned Solar Electric Systems.* JPL 5040-29. Pasadena, CA: Jet Propulsion Laboratory; 75 pp.
Developed by: J.W. Doane and R.P. O'Toole, Jet Propulsion Laboratory
Contact: Henry Awaya
Jet Propulsion Laboratory
4800 Oak Grove Drive
MS 506-432
Pasadena, CA 91109

The Model

Equally applicable to large and small systems, this model is designed to assess the economic attractiveness of investing in solar thermal power plants. It has the capacity to analyze a variety of alternative financing methods. Inputs include capital costs, loan interest and amount, lease payments, federal and state tax rates and credits, and a depreciation schedule for solar and non-solar equipment. Output is a year-by-year statement of net cash flow from the project and a yearly and total calculation of the effective net present value.

Availability: Model available to the public
Used by: Researchers, utilities, entrepreneurs
Language: Visicalc, SuperCalc
Machine: IBM PC
Documentation: Williams, T.A.; Cole, R.J.; Brown, D.R.; Dirks, J.A.; Edelhertz, H.; Holmlund, I.; Malhotra, S.; Smith, S.A.; Sommers, P.; Willke, T.L. (1983) *Solar Thermal Financing Guidebook* PNL-4745. Richland, WA: Pacific Northwest Laboratories; 175 pp.
Developed by: Tom Williams, Pacific Northwest Laboratories
Contact: Tom Williams
Pacific Northwest Laboratories
P.O. Box 999
Richland, WA 99352

Performance

CYCLE3

Models and analyzes various Rankine-cycle energy conversion systems including supercritical cycles with or without regeneration and subcritical cycles with or without regeneration and/or superheat. The program will accommodate a variety of working fluids, generating the required

Availability: Model available to the public
Used by: Energy conversion engineers; mechanical, chemical, thermodynamic engineers
Language: Fortran
Machine: Mainframe
Documentation: Abbin, J.P. and Leuenberger, W.R. (1977). *Program CYCLE: A Rankine Cycle*

thermodynamic properties internally. Properties of 15 power-conversion working fluids are presently included in the program. CYCLE3 is an extension of an earlier program and has the additional capability to model cycles that include expansions in the two-phase ("wet-vapor") region. CYCLE3 is interactive and predicts cycle efficiency. Required input includes upper and lower cycle temperatures, upper cycle pressure, and efficiencies of system components.

Analysis Routine. SAND74-0099 (Revised). Albuquerque, NM: Sandia National Laboratories; 90 pp.
Developed by: J.P. Abbin and W.R. Leuenberger, Sandia National Laboratories, Albuquerque
Contact: Joe Abbin
Sandia National Laboratories
Division 2541
Albuquerque, NM 87185
(505) 844-8590

TAP2 (Thermal Analysis Program)

Provides the capability to use finite element models for the steady-state and transient thermal analysis of a structure with conductive and convective heat transfer. Provides an efficient interface between independent thermal and structural analyses, and can be used in the development of an integrated analysis system. TAP2 is suited for the thermal analysis of a wide range of structures such as solar panel heating systems, nuclear reactors, and other environmental applications. The program includes a finite element library of six elements: two conduction/convection elements to model heat transfer in a solid, two convection elements to model heat transfer in a fluid, and two integrated conduction/convection elements to represent combined heat transfer in tubular and plate/fin fluid passages. Input is a nodal geometry of the model, element nodal connection, and thermal material properties. Output includes nodal temperatures and element heat fluxes.

Availability: Model available
Used by: Mechanical, aerospace, and structural engineers
Language: Fortran IV
Machine: Mainframe
Documentation: Thornton, E.A. (1981). *Integrated Transient Thermal Structural Finite Element Analysis.* NASA-TM-83125. Hampton, VA: NASA Langley Research Center; 19 pp. Work performed by Old Dominion University, Department of Mechanical Engineering and Mechanics, Norfolk, VA.
Developed by: Earl Thornton, Old Dominion University, Department of Mechanical Engineering and Mechanics
Contact: COSMIC (to obtain model)
University of Georgia
112 Barrow Hall
Athens, GA 30602
(404) 542-3265

Earl Thornton (for technical questions)
Old Dominion University
Department of Mechanical Engineering and Mechanics
Norfolk, VA 23508
(804) 440-3720

Performance — Collectors

DELSOL2

A performance and design optimization code that uses an analytical Hermite polynomial expansion/convolution-of-moments method for predicting images from heliostats. It typically requires less computer time for performance calculations than either MIRVAL or HELIOS, the two Sandia codes that preceded it. Performance is evaluated on the basis of zones that are formed by sectioning the heliostat field radially and azimuthally or on the basis of individual heliostats. Time-varying effects of insolation, cosine, shadowing and blocking, and spillage are calculated, as are the time-independent effects attributable to atmospheric attenuation, mirror reflectivity, receiver reflectivity, receiver radiation and convection, and piping losses. Optimization runs use a data base created by a performance run in order to determine field layouts and a system configuration that is based on the lowest levelized energy cost for the total system. Many system sizes can be optimized in a single run.

Input data includes such parameters as site location, insolation, sunshape; heliostat field information; heliostat information; receiver-related information; flux-related information; efficiency reference values for power, radiation and convection, hot and cold piping losses; optimization-

Availability: Model available to the public
Used by: Mechanical engineers
Language: Fortran IV
Machine: Mainframe
Documentation: Dellin, T.A., Fisk, M.J., and Yang, C.L. (1981). *A User's Manual for DELSOL2: A Computer Code for Calculating the Optical Performance and Optical System Design for Solar Thermal Central Receiver Plants.* SAND81-8237. Livermore, CA: Sandia National Laboratories.
Developed by: Sandia National Laboratories, Livermore
Contact: C.L. Yang
Sandia National Laboratories
Livermore, CA 94550

related input on heliostat density, receiver width and height; cost data; and economic analysis information.

HELIOS

Evaluates the performance of central receiver heliostats, parabolic dish, and other reflecting solar energy collector systems. Calculations are made with respect to fields of individual solar concentrators and a single target surface. Uses cone optics to evaluate flux density. Safety considerations with respect to abnormal heliostat tracking can be evaluated. Effects included in detail in HELIOS are declination of the sun, earth orbit eccentricity, molecular and aerosol scattering in several standard clear atmospheres, atmospheric refraction, angular distribution of sunlight, reflectivity of the facet surface, shapes of focused facets, and distribution of errors in the surface curvature, aiming, facet orientation, and shadowing and blocking.

HELIOS is used where a detailed description of the heliostat is available and an extremely accurate evaluation of flux density is desired. It has been used to evaluate heliostat compliance to design criteria, as well as the characteristics of the Barstow heliostats, IEA heliostats, second generation heliostats, and CRTF heliostats. It is also used for personnel safety calculations.

Input includes problem and output data, sun parameters, receiver parameters, facet parameters, heliostat parameters, time parameters, and atmospheric parameters.

Availability: Model available to the public
Used by: Mechanical engineers
Language: Fortran
Machine: Mainframe
Documentation: Vittitoe, C.N.; Biggs, F.; and Lighthill, R.E., (1978). *HELIOS: A Computer Code for Modeling the Solar Thermal Test Facility; A User's Guide.* SAND76-0346, Albuquerque, NM: Sandia National Laboratories.

Vittitoe, C.N. and Biggs, F. (1981). *A User's Guide to HELIOS: A Computer Program for Modeling the Optical Behavior of Reflecting Solar Concentrators, Part III: Appendices Concerning HELIOS — Code Details.* SAND81-1562 and Part I, SAND81-1180. Albuquerque, NM: Sandia National Laboratories.
Developed by: Sandia National Laboratories, Albuquerque
Contact: C.N. Vittitoe or F. Biggs
Sandia National Laboratories
Albuquerque, NM 87185

IH (Individual Heliostat Code)

Generates layout of heliostat field (radio-stagger configuration similar to Solar-One). Also allows instant, diurnal, and annual computation of shading, blocking, and other performance factors for each heliostat. Receiver flux maps and individual heliostat aim strategies are also available. This optics model is designed so that input is entered through a main program and three data modules: (1) heliostat, (2) collector field, and (3) receiver data modules. Default values based on Solar-One are provided for many of the input requirements.

Availability: Model available to the public for a nominal fee
Used by: Mechanical engineers
Language: Fortran
Machine: Mainframe
Documentation: Lipps, F.W., and Vant-Hull, L.L. (1982). *Generalized Layout for Collector Field with Broken Planes including Modifications to the RC Optimization Cellay and IH Performance Codes.* SAND PROC 84-1637. Livermore, CA: Sandia National Laboratories. Work performed by University of Houston, Houston, TX.

Lipps, F.W. (1981). *Theory of Cellwise Option for Solar Central Receiver Systems.* SAN/1637-1. Livermore, CA: Sandia National Laboratories. Work performed by University of Houston, Houston, TX.
Developed by: Lorin Vant-Hull and Fred Lipps, University of Houston
Contact: Lorin Vant-Hull
University of Houston
Energy Laboratory, SPA
4800 Calhoun
Houston, TX 77004
(713) 749-1154

Optical Analysis and Optimization of Parabolic Trough Collectors

The results of a detailed optical analysis of parabolic trough solar collectors are summarized by universal graphs and curve fits. The graphs enable the designer of parabolic trough collectors to calculate the performance and optimize the design with a hand calculator. The method is illustrated by specific examples that are typical of practical applications. The sensitivity of the optimization to changes in collector parameters and operating conditions is evaluated. The variables affecting collector efficiency fall into several groups: (1) operating conditions (insolation, tracking mode, operating temperature, flow rate), (2) properties of materials (reflectance, absorptance), (3) receiver type (absorber shape, evacuated or non-evacuated), and (4) concentrator geometry (concentration ratio C and rim angle O).

Availability: Model available to the public
Used by: Parabolic trough designers
Machine: Programmable calculator
Documentation: Bendt, P.; Rabl, A.; and Gaul, H.W. (1981). *Optical Analysis and Optimization of Parabolic Trough Collectors.* SERI/TR-631-602. Golden, CO: Solar Energy Research Institute; 24 pp. Available also as "Optimization of Parabolic Trough Solar Collectors." (1982) *Solar Energy* Vol. 29 (No. 5); pp. 407-417.
Developed by: P. Bendt, A. Rabl, and H.W. Gaul, Solar Energy Research Institute
Contact: NTIS
5285 Port Royal Road
Springfield, VA 22161

Yearly Average Performance of the Principal Solar Collector Types

Calculates the yearly total energy deliverable by the principal collector types: flat plate, evacuated tubes, CPC, collectors that track about one axis, collectors that track about two axes, and central receivers. The method is recommended for rating collectors of different types or different manufacturers on the basis of yearly average performance. The method is also useful for evaluating the effects of collector degradation, the benefits of collector cleaning, and the gains from collector improvements (due to enhanced optical efficiency or decreased heat loss per absorber surface). Only three variables are needed: (1) the operating threshold (for thermal collectors this is the average heat loss divided by the optical efficiency), (2) the geographical latitude, and (3) the yearly average direct normal insolation. The rms deviation between the correlation and the exact results is about 2% for flat plates and 2% to 4% for concentrators.

Availability: Document available from NTIS
Used by: Engineers, consultants, utilities, policy analysts
Machine: Programmable calculator
Documentation: Rabl, A. (1981). *Yearly Average Performance of the Principal Solar Collector Types.* SERI/TR-631-716. Golden, CO: Solar Energy Research Institute. Also available under the same title in *Solar Energy.* (1981). Vol. 27 (No. 3); pp. 215-233.
Developed by: A. Rabl, Solar Energy Research Institute
Contact: NTIS
5285 Port Royal Road
Springfield, VA 22161

Performance — Cooling

DESSIM (Desiccant Simulation)

Simulates the adiabatic adsorption/desorption process in dehumidifiers; developed to predict the performance of desiccant cooling systems. The model uses pseudo-steady-state heat and mass transfer relationships to predict the behavior of desiccants in finite elements of a dehumidifier. Although the sorption process is a transient one, these mass transfer and heat transfer calculations are done using equations for steady-state, counterflow mass exchangers and heat exchangers; hence, the name pseudo-steady state. Inputs to the model are properties of the desiccant material, details of the dehumidifier design, and design conditions of the air to be dehumidified. Outputs are the outlet state of air being dehumidified (relative humidity, temperature), efficiency of the dehumidifier, and the amount of energy required to regenerate the dehumidifier.

Availability: Documentation available through National Technical Information Service (NTIS)
Used by: Mechanical engineers, architects, HVAC system designers
Language: Fortran IV
Machine: Mainframe
Documentation: Barlow, R.S. (1982). *Analysis of the Adsorption Process and of Desiccant Cooling Systems — A Pseudo-Steady-State Model For Coupled Heat and Mass Transfer.* SERI/TR-631-1330. Golden, CO: Solar Energy Research Institute; 138 pp.
Developed by: Robert Barlow, Solar Energy Research Institute
Contact: Dennis Schlepp
Solar Energy Research Institute
Solar Thermal and Materials Research Division
1617 Cole Boulevard
Golden, CO 80401
(303) 231-7309

NTIS
5285 Port Royal Road
Springfield, VA 22161

Performance — Materials

FILTHI (Film Thickness)

Analyzes the reflectance of multilayer stacks of absorbing and/or reflective materials; predicts reflection-absorbance values for radiation polarized parallel, perpendicularly, or elliptically to the plane of incidence for a wide range of polycarbonate film thicknesses. Inputs are the refractive indices of air, polymer film, and metal; incidence angle of radiation from the perpendicular to the surface; polarization state of the incident radiation; and thickness of the polymer film. Reflection absorbance (RA) is calculated according to the equation $RA = \log_{10} (R/R_0)$ where R is the reflectance at a given wavelength of the polymer-coated metal and R_0 is the reflectance at a given wavelength of the bare metal. Therefore, the model predicts the reflection-absorbance of the polymer film on the metal at the given wavelength.

Availability: Model available to the public
Used by: Spectroscopists
Language: Fortran
Machine: Mainframe
Documentation: Webb, J.D. (1982). *An Experimental Approach to Evaluating Environmental Degradation Mechanisms in Bisphenol-A Polycarbonate Films on Metallic Substrates*. SERI/TR-255-1602. Golden, CO: Solar Energy Research Institute; 140 pp.
Developed by: John Webb, Solar Energy Research Institute
Contact: John Webb or Gary Jorgenson
Solar Energy Research Institute
Solar Thermal and Materials Research Division
1617 Cole Boulevard
Golden, CO 80401
(303) 231-1480 (Webb)
(303) 231-7283 (Jorgenson)

Performance — Receivers

DRAC (Dynamic Receiver Analysis Code)

First in a series of driver programs for the more general code TOPAZ (Transient One-Dimensional Pipe Flow Analyzer). DRAC is a relatively easy-to-use code that permits the user to model both transient and steady-state thermohydraulic phenomena in solar receiver tubing. Users may specify arbitrary time-dependent incident heat flux profiles and flow rate changes and DRAC will calculate the transient excursions in tube wall temperature and fluid properties. Radiative and convective losses are accounted for, and the user can model any receiver fluid (compressible or incompressible) for which thermodynamic data exist.

DRAC models a fluid-flow/heat transfer configuration that is frequently encountered in the design and use of solar central receivers; that is, the absorption of redirected solar heat flux from the heliostat field into a moving receiver fluid. DRAC is capable of determining transient as well as steady-state tube wall and fluid temperatures during operation. The user specifies arbitrary incident heat flux and flow rate disturbances for a single tube. DRAC then calculates the resulting tube wall cross-temperature profiles and fluid properties as a function of axial position and time.

The fluid flow/heat transfer configuration to be analyzed by DRAC is input in a single namelist. A heat-transfer fluid enters a single receiver tube where it is heated by incident solar flux. The user specifies a constant inlet temperature, a time-dependent inlet mass flow rate, an exit pressure, and a time-dependent peak solar flux. The code then calculates the one-dimensional-transient fluid temperature, pressure, and mass flow profiles. The two-dimensional-transient tube wall temperature distribution is also calculated with axial

Availability: Model available to the public
Used by: Mechanical engineers
Language: Fortran
Machine: Mainframe
Documentation: Winters, W.S. (1981). *Dynamic Modeling of Solar Central Receivers*. SAND81-8213. Livermore, CA: Sandia National Laboratories
Developed by: Sandia National Laboratories, Livermore
Contact: W.S. Winters
Sandia Laboratories
Livermore, CA 94550

conduction effects neglected. Not a self-contained code, DRAC is a user-friendly interface to TOPAZ and DASSL, two general purpose codes developed at Sandia. TOPAZ was written for the purpose of modeling a highly general class of transient problems encountered in the design and evaluation of solar central receiver components and systems.

HEAP (Heat Energy Analysis Program)

HEAP has the basic capability to solve any general heat transfer problem but also has some specific features that are "custom-made" for analyzing solar receivers. HEAP can be utilized in the detailed analysis of solar receivers not only to predict their performance under varying solar flux, ambient temperature, and local heat transfer rates, but also to detect the location of hot spots and metallurgical difficulties, and to predict performance sensitivity of neighboring component parameters.

The basic methodology utilized by HEAP is based on a nodal, finite-difference approach to the heat transfer calculations. The receiver is characterized in space by nodes or zones and in time by time increments. Between any two arbitrary nodes, the differential heat transfer rate equations are expressed with all modes of heat transfer included. The net energy stored in each node is calculated using the first law of thermodynamics including the energy exchange to and from neighboring nodes. For steady-state solutions, a Newton-Raphson iteration solution is used to solve for the temperature distribution of the equilibrium nodes and the net energy stored at the source/sink nodes. For transient solutions, a forward-marching finite difference numerical technique is used to solve for the nodal temperature histories.

Input to the HEAP program consists of solar flux distributions, optical and physical properties, fluid flow rates, and boundary conditions. The radiation view factors are supplied by the user in terms of a subroutine. Output generated by HEAP includes temperature distribution, fluid outlet conditions, accumulated energy extracted, receiver efficiency, and heat losses.

Availability: Model available through COSMIC
Used by: Engineers
Language: MBASIC, Fortran
Machine: Mainframe
Documentation: Lansing, S.L. (1979). *HEAP: Heat Energy Analysis Program — A Computer Model Simulating Solar Receivers*. JPL Publication 79-3 prepared for DOE (DOE/JPL-1060-13) JPL Report Number 5102-106. Pasadena, CA: Jet Propulsion Laboratory.
Developed by: S.L. Lansing, Jet Propulsion Laboratory
Contact: COSMIC
University of Georgia
112 Barrow Hall
Athens, GA 30602
(404) 542-3265

RADSOLVER

Calculates the radiation energy transport in arbitrarily shaped solar cavity receivers. In contrast to the common assumption of gray surfaces used in the modeling of radiation transport, RADSOLVER accounts for the wavelength-dependence of emission and reflection with a band model of the radiative properties. The phenomena included in RADSOLVER are thermal emission, reflection and absorption of thermally emitted and solar energies, and multiple reflections of both types of radiant energy among the zones of the cavity. The basis of RADSOLVER is the radiosity method of radiation heat transport analysis which has been modified to account for the wavelength-dependence of the surface optical properties. Energy that would be transported within and from the cavity by convection (natural or forced) is not taken into account; therefore, RADSOLVER is strictly applicable to cavities whose

Availability: Model available to the public
Used by: Heat transfer engineers, mechanical engineers, utilities
Language: Fortran
Machine: Mainframe
Documentation: Abrams, M. (1981). *RADSOLVER — A Computer Radiative Heat Transfer in Solar Cavity Receivers*. SANDI81-8248. Livermore, CA: Sandia National Laboratories.
Developed by: Sandia National Laboratories, Livermore
Contact: M. Abrams
Sandia National Laboratories
Livermore, CA 94550

interior air mass is stably stratified in a windless environment.

For a solar cavity whose interior surface is subdivided into an arbitrary number of zones, RADSOLVER determines

1. The heat transfer (the net energy flux into a zone that would be available; for example, for input to a working fluid), and
2. The irradiation and radiosity (the fluxes of incoming and exiting solar and thermal radiation at each zone).

RADSOLVER also calculates the temperature of any adiabatic zone present in the cavity.

REBUFFS

The numerical procedure solves rigorous forms of continuity and momentum equations but filters out high frequency pressure fluctuations through a special treatment of the energy equation. The Boussinesq approximation is not made, meaning that density is allowed to vary with temperature according to an equation of state. Initial input required is the configuration dimensions and boundary conditions of interest and physical property formulations. Finite difference approximations to the conservation equations are derived by volume integration of the latter over a grid covering the calculation domain. Time-dependent and/or steady-state solutions of the two-dimensional, laminar flow heat-transfer fields are computed to a user-determined level of accuracy.

Availability: Model available for a fee
Used by: Mechanical, electrical, chemical engineers
Language: Fortran
Machine: Mainframe
Documentation: Gosman, A.D.; Ideriah, F.J.K. with revisions by Arnal, M.P. (1983). *Teach-2E: A General Computer Program for Two-Dimensional, Turbulent, Recirculating Flows*. FM-83-2. Berkeley, CA: University of California, Department of Mechanical Engineering, Berkeley, CA. Work also performed by the Department of Mechanical Engineering, Imperial College of Science and Technology, London University, London, England.
Developed by: Joseph Humphrey, Patrick LeQuere, and Frederick Sherman, University of California, Berkeley
Contact: Joseph Humphrey
University of California
Department of Mechanical Engineering
Berkeley, CA 94720

RELAP

Originally developed to model the transient response of steam/water systems in nuclear power plants, RELAP has been modified to model solar thermal central receiver systems. The modified RELAP model can be used to analyze the dynamic response of the pilot plant receiver to cloud or control system-induced transients. Simulation of the entire plant, including storage and turbine-generator, can be used to investigate master control system functioning and possible transients resulting from operating mode changes. The model predicts (1) steady-state operating conditions from a zero-power, cold-water start-up for a given incident heat flux, (2) the effect of the changes in the axial flux profile on the calculated temperature profile, and (3) the pressure and frequency of thermal-hydraulic oscillations due to changes in the panel flow resistance. A thermal storage subsystem module of Barstow's dual-media thermocline storage subsystem is included. The final RELAP modification, which is not yet complete, is the modeling of the control subsystem. This module will simulate actions of the plant's master control system and subsystem controllers. Many levels of input are required for RELAP: hydrodynamic inputs define the subdivision of physical space (i.e., components, pumps, valves, pipes, junctions, and volumes); heat structure inputs define the

Availability: Model available to the public
Used by: Mechanical engineers
Language: Fortran
Machine: Mainframe
Documentation: Kmetyk, L.N. and Byers, R.K. (1981). *Analysis of 5-Tube Solar Receiver Panel Test Data*. SAND81-0402. Albuquerque, NM: Sandia National Laboratories.

Kmetyk, L.N. and Byers, R.K. (1981). *Analysis of 70-Tube Pilot Plant Solar Receiver Panel Test Data*. SAND81-1220. Albuquerque, NM: Sandia National Laboratories.

Byers, R.K. and Kmetyk, L.N. (1981). *Development of a RELAP Model for the Barstow Thermal Storage Subsystem*. SAND81-8181. Albuquerque, NM: Sandia National Laboratories.
Developed by: Sandia National Laboratories, Livermore and Albuquerque
Contact: Pat De Laquil
Sandia National Laboratories
Livermore, CA 94550

Lubo Myra Kmetyk
Sandia National Laboratories
Albuquerque, NM 87185

boundaries and intensity of volumes where heat is added to the system; equipment performance inputs define the operating characteristics of pumps, valves, and other components in the system; control system inputs determine the logical operation of the control components modeled into the system; physical property data must be input for each of the hydrodynamic control volumes and heat structures; and time step parameters and option switches must be set to ensure proper operation of the model.

SCRAM (Sandia Central Receiver Approximation Model)

A mathematical approximation procedure developed for quick evaluation of the optical performance of solar thermal central receiver systems. A stepwise regression procedure is used to construct a polynomial fit to a set of data points. These data points are local field efficiences for a matrix of radial and azimuthal locations and a particular set of sun angles. The data points are generated by other codes that evaluate central receiver field performance in detail. The SCRAM model is specific for the particular heliostats and field layout pattern and includes shadowing, blocking, cosine losses, and atmospheric attenuation. Tower height, mirror reflectivity, atmospheric attenuation model, ratio of mirror area to heliostat area, and receiver losses may be varied. Optical field performance is calculated for any sun angle by evaluating a polynomial that has coefficients based on user-defined heliostat field boundaries and tower height. The field model can be coupled to models for the receiver or load.

Availability: Model available to the public
Used by: Mechanical engineers
Language: Fortran
Machine: Mainframe, minicomputer, microcomputer
Documentation: Bergeron, K.D. and Chiang, C.J. (1980). *SCRAM: A Fast Computational Model for the Optical Performance of Point Focus Solar Central Receiver Systems*. SAND80-0433. Albuquerque, NM: Sandia National Laboratories.
Developed by: Sandia National Laboratories, Albuquerque
Contact: K.D. Bergeron or C.J. Chiang
Sandia National Laboratories
Albuquerque, NM 87185

Performance — Solar Ponds

LASL Solar Pond

The model is used to determine pond performance under various operating conditions. From such variables as initial salinity and temperature profiles, time steps, thermal physical properties, wind velocity, and insolation instantaneous temperature and salinity profiles can be predicted as well as interface locations and energy balance quantities (i.e., heat losses and associated measurements).

Availability: Model available to the public
Used by: Research engineers, scientists
Language: Fortran
Machine: Mainframe
Documentation: Meyer, K.A. (Nov. 1983). "A Numerical Model to Describe the Layer Behavior in Salt-Gradient Solar Ponds". *Journal of Solar Energy Engineering*. Vol. 105 (No. 4); pp. 341-347.
Developed by: Kenneth A. Meyer, Los Alamos National Laboratory
Contact: G.F. Jones
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545
(505) 667-6847

PON

This model is a simple algorithm for comparing the effects of light absorption by candidate solar pond solutes on the optical performance of an idealized pond. To obtain the total solar energy available at various depth increments the following input is required: depth increments, optical properties of the saline solution and concentration of solution, as a function of the depth.

Availability: Model available to the public
Used by: Solar pond designers and researchers
Language: Fortran
Machine: Mainframe
Documentation: Webb, J.D. (1981). *Optical Transparency of Inexpensive Salt Solutions for Construction of Density-Gradient Solar Ponds*. SERI/RR-641-615. Golden, CO: Solar Energy Research Institute; 46 pp.
Developed by: John Webb, Solar Energy Research Institute

shadowing, blocking, heliostat tracking, and random errors in tracking and in the conformation of the reflective surface, insolation, angular distribution of incoming solar rays to account for limb darkening and scattering, attenuation between the heliostats and the receiver, reflectivity of the mirror surface, and aiming strategy.

Three receiver types are included in the code. MIRVAL can be modified to evaluate other heliostats or receivers by changing a small number of subroutines. Information needed includes a file that groups the heliostats in the heliostat field in a regular way; sunshape information (describing the angular dependence of power from the sun); heliostat type, configuration, dimensions, and performance; receiver type and dimensions; zoning options; insolation; attenuation; and start/stop times for a calculation.

Receiver Optics for Central Receiver Solar Power Plants. SAND77-8280, Livermore, CA: Sandia National Laboratories.
Developed by: Sandia National Laboratories, Livermore
Contact: P.L. Leary
Sandia National Laboratories
Livermore, CA 94550

NS Cellwise Performance Code

Generates flux maps, receiver intercept data, diurnal and annual performance data, start-up, and cloud passage transience. This optics model is designed so that input is entered through a main program and three data modules: (1) heliostat, (2) collector field, and (3) receiver data modules. Default values based on Solar One are provided for many of the input requirements.

Availability: Model available to the public for a nominal fee
Used by: Mechanical engineers
Language: Fortran
Machine: Mainframe
Documentation: Lipps, F.W. and Vant-Hull, L.L. (1980). *A User's Manual for the University of Houston Solar Central Receiver System — Cellwise Performance Model: N.S.* (Volumes 1 and 2). SAN/0763-4-1/2-2/2. Livermore, CA: Sandia National Laboratories. Work performed at University of Houston, Houston, TX.
Developed by: Lorin Vant-Hull and Fred Lipps, University of Houston
Contact: Lorin Vant-Hull
University of Houston
Energy Laboratory, SPA
4800 Calhoun
Houston, TX 77004
(713) 749-1154

RC Cellwise Optimization Code

Defines heliostat spacings and field boundaries for cost-optimal performance of a central receiver system. Provides data for "waterfall" charts, receiver flux maps, annual energy design point power, and capital cost data for optimized systems. This optics model is designed so that input is entered through a main program and three data modules: (1) heliostat, (2) collector field, and (3) receiver data modules. Default values based on Solar One are provided for many of the input requirements.

Availability: Model available to the public for a nominal fee
Used by: Mechanical engineers
Language: Fortran
Machine: Mainframe
Documentation: Laurence, C.L. and Lipps, F.W. (1980). *A User's Manual for the University of Houston Computer Code — RC: Cellwise Option for the Central Receiver Project.* SAN/0763-3. Livermore, CA: Sandia National Laboratories. Work performed by University of Houston, Houston, TX.
Developed by: Lorin Vant-Hull and Fred Lipps, University of Houston
Contact: Lorin Vant-Hull
University of Houston
Energy Laboratory, SPA
4800 Calhoun
Houston, TX 77004
(713) 749-1154

ROSET (Representation of Solar Electric-Thermal)

A set of five computer programs designed to provide an estimate of the probable energy output of a solar thermal power system. The first four programs use hourly weather data for a year to calculate hourly electric energy output for a solar thermal system. The last program uses one or more electric energy output files created by the first four programs to provide an energy distribution for each hour of a typical day (one typical day per month).

Several types of collector systems can be simulated: point-focus central receiver, line-focus central receiver, point-focus distributed receiver, fixed-mirror distributed focus, line-focus distributed receiver-tracking collector, line-focus distributed receiver-tracking receiver, low-concentration nontracking collector, Fresnel lens, and shallow solar ponds.

ROSET was designed to function as part of a larger program package that can be used to determine the value of solar energy power systems (SEPS) to electric utilities. The results from ROSET, estimates of the electricity production derived from the solar thermal power system, are provided so that the utility load forecast can be modified to incorporate the SEPS generation. The final program determines the break-even cost of each SEPS penetration ($/rated kW) and the SEPS marginal value ($/rated kW), where value is the utility's present worth savings of reduced operating costs and modified capital additions. These values can be combined with total SEPS cost to determine the maximum amount of SEPS capacity that can be economically justified as an addition to a utility system.

Availability: Documentation available from the National Technical Information Service (NTIS); software available from the National Energy Software Center. Fees vary. See Contact information for addresses.
Used by: Utilities, small energy cooperatives
Language: Fortran IV
Machine: Mainframe
Documentation: O'Doherty, R. (1982). *ROSET: A Solar Thermal Electric Power Simulation User's Guide*. SERI/TR-214-1449. Golden, CO: Solar Energy Research Institute; 69 pp.
Developed by: Joe Finegold, Ann Herlevich, and Bob O'Doherty, Solar Energy Research Institute
Contact: National Energy Software Center
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

NTIS
5285 Port Royal Road
Springfield, VA 22161.

Solar Thermal Plant Model

Model is based on one developed by Aerospace Corporation which simulates, on an hourly basis, the energy flow within a solar thermal electric generating plant. The program is constructed in a modular fashion to represent the major subsystems of such a plant. The model takes as input the hourly incident normal insolation, and through a series of conversion efficiency and loss calculations, develops the electrical output of the turbine-generator. It accounts for the operation of thermal storage and is capable of simulating several of different solar plant concepts. The basic approach of the model is to account for energy flows by use of device efficiencies, some of which are directly input; others are calculated through mathematical relationships in the program.

The alterations to the basic model fall into four categories: (1) solar plant dispatch logic, (2) solar plant availability, (3) turbine-generator efficiency representation, and (4) model output formats. The altered model works on a daily basis. The solar plant dispatch logic is basically a process of four steps, the objective of which is to minimize the operating costs of the balance of the utility system within the insolation availability and plant parameter constraints. Solar plant availability was addressed by implementation of a table of solar plant output multipliers to add some flexibility in the use of the solar plant model. To adequately represent the operation of a solar plant with a dry cooling tower, an additional turbine-generator

Availability: Model available by special arrangement with EPRI
Used by: Utility planners and operators, solar power plant manufacturing industry and engineers
Language: Fortran IV
Machine: Mainframe
Documentation: Westinghouse Electric Corporation. (1978). *A Methodology for Solar Thermal Power Plant Evaluation*. EPRI ER-869. Palo Alto, CA: Electric Power Research Institute; 120 pp. Work performed by Westinghouse Electric Corporation.
Developed by: John Day, Westinghouse Electric Corporation
Contact: Edgar DeMeo
Electric Power Research Institute (EPRI)
Solar Power Systems Program
3412 Hillview Avenue
Palo Alto, CA 94303
(415) 855-2159

efficiency factor is required. Modifications were made to the output to facilitate use by other models. Two of these include the addition of a net residual system load and the cumulative electrical energy generated.

SOLSTEP (Simulation of Localized Solar Thermal Electricity Production)

A tool for evaluating the thermodynamic and economic performance of alternative solar thermal power plants. Inputs include meteorological tapes and insolation data (ranging from daily to every 15 minutes), thermodynamic performance parameters (optical efficiency, heat transport efficiency, energy conversion efficiency, and energy storage efficiency), and solar system costs (capital, operating, and maintenance). Output is annual power production estimates, levelized energy cost for point estimates, and a variety of capacity factors for optimized systems.

Availability: Model available to the public
Used by: Large electric utilities, researchers
Language: Fortran
Machine: Mainframe
Documentation: Bird, S.P. (1980). *Assessment of Solar Operations for Small Power Systems Applications. Volume 5; SOLSTEP: A Computer Model for Solar Plant System Situations.* PNL-4000, Vol. 5. Richland, WA: Pacific Northwest Laboratories.
Developed by: S.P. Bird, Pacific Northwest Laboratories
Contact: Walter Laity
Pacific Northwest Laboratories
P.O. Box 999
Richland, WA 99352

SOLTES (Simulator of Large Thermal Energy Systems)

A modular, heat-and-mass balance code that simulates the quasi-transient or steady-state response of thermal energy systems to time-varying data such as weather and loads. The modular form of SOLTES allows complex systems to be modeled. Component performance is described by thermodynamic models. A pre-processor is used to construct and edit system models and to generate the main SOLTES program. It is possible to realistically simulate a wide variety of thermal energy systems such as solar, fossil, or nuclear power plants; solar heating and cooling; geothermal energy; and solar hot water.

Four categories of input data are required to run SOLTES: (1) component/information routine data, (2) executive routine control data, (3) fluid loop definition data, and (4) fluid property data. Weather data and load data are optional categories.

Availability: Model available to the public
Used by: Mechanical engineers
Language: Fortran
Machine: Mainframe
Documentation: Fewell, M.E. and Grandjean, N.R. (1980). *User's Manual for Computer Code SOLTES-1B (Simulator of Large Thermal Energy Systems).* SAND78-1315, Albuquerque, NM: Sandia National Laboratories.
Developed by: Sandia National Laboratories, Albuquerque
Contact: M.E. Fewell or N.R. Grandjean
Sandia National Laboratories
Albuquerque, NM 87185

STEAEC (Solar Thermal Electric Annual Energy Calculator)

A computer model that estimates the annual performance of a solar thermal electric power plant. STEAEC is a quasi-steady-state model with a constant (but user-variable) time step. Factors such as energy losses and delays incurred in start-up, effects of ambient weather conditions on plant operation and efficiency, effects of hold time and charge and discharge rates on deliverable energy in storage, subsystem maximum and minimum power limits, and auxiliary power requirements are taken into account in the computation of the annual electrical output of the plant. Default parameters can be modified easily through the use of NAMELIST inputs. STEAEC does not model thermodynamics. Input to STEAEC is through namelists which include descriptions of collector field efficiency, collector field parameters, receiver parameters, piping losses, turbine operating parameters from the receiver and from storage, and storage charging and discharging parameters.

Availability: Model available to the public
Used by: Utilities, engineers, economists
Language: Fortran
Machine: Mainframe
Documentation: Woodard, J. and Miller, G.J. (1978) *STEAEC — Solar Thermal Electric Annual Energy Calculator Documentation.* SAND77-8278. Livermore, CA: Sandia National Laboratories.
Developed by: J. Woodard, Sandia National Laboratories, Livermore
Contact: Gordon Miller
Sandia National Laboratories
Livermore, CA 94550

Systems Analysis

STESEP (Solar Total Energy System Evaluation Program)

Provides tradeoff evaluations relating to cascading thermal power conversion systems, determination of optimal collector sizes and operating conditions, and comparison of solar total energy concepts in various types of commercial buildings in different parts of the country. The program can use either a deterministic approximation of weather conditions or hourly weather data. It determines component demand loads based on steady-state energy balances to meet the load requirements for electrical, heating, ventilation and air-conditioning, and process heat demand loads for average day conditions. Component sizes and use are estimated to determine yearly energy use. System capital and return costs are evaluated to determine the life-cycle cost. The program provides yearly energy use and life-cycle cost of the system. The user must provide electrical, heating, ventilation and air-conditioning, and process heat demand loads; system capital and recurring costs; component parametric data; and some meteorological information.

Availability: Limited to members of the National Energy Software Center. Fees vary.
Used by: Systems designers, engineers
Language: Fortran IV
Machine: Mainframe
Documentation: McFarland, B.L. (1979). *Manual for the Solar Total Energy System Evaluation Program.* SAND 78-7045. Albuquerque, NM: Sandia National Laboratories; 153 pp. Work performed by Rockwell International Energy Systems Group, Canoga Park, CA.
Developed by: Rockwell International Energy Systems Group
Contact: National Energy Software Center
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439
(312) 972-7250

STPP (Solar Thermal Power Plant)

A modularized computer simulation program for solar thermal power plants. The program assumes a continuous utility demand with the solar element providing input to the grid when the system power output exceeds a specific minimum level. The excess energy is stored. When the load cannot be met by the solar components, the available storage is assumed to supply the load demand. Costing is based on the bus-bus energy cost concept. Program execution requires user-supplied weather data. The program is modular in nature; consequently, the user must supply specific module connection information and the corresponding parametric data.

Availability: Model available from COSMIC
Used by: Utilities, mechanical engineers, economists
Language: Fortran
Machine: Mainframe
Documentation: El-Gabalawi, N.; Hill, J.; Bowyer, J.M.; and Slonski, M.L. (1978). *A Modularized Computer Simulation Program for Solar Thermal Power Plants.* Prepared by Jet Propulsion Laboratory for the U.S. Department of Energy. Pasadena, CA: Jet Propulsion Laboratory.

Latta, A.F.; Bowyer, J.M.; Fujita, T.; and Richter, P.H. (1980). *The Effects of Regional Insolation Differences Upon Advanced Solar Thermal Electric Power Plant Performance and Energy Costs.* DOE/JPL-1060-17 Rev. 1. Pasadena, CA: Jet Propulsion Laboratory.

Rosenberg, L.S. and Revere, W.R. (1981). *A Computer Assessment of Solar Thermal Electric Power Plants in the 1-10 MWe Range.* DOE/JPL-1060-21. Pasadena, CA: Jet Propulsion Laboratory.
Developed by: N. El-Gabalawi, G.M. Hill, M. Slonski, J. Bowyer, Jet Propulsion Laboratory.
Contact: COSMIC
University of Georgia
112 Barrow Hall
Athens, GA 30602
(404) 542-3265

The following models are complete but have not been documented. Most are available on a limited basis. If one should appear to meet a particular modeling need, the contact person will provide further information on use and availability.

HTES (High Temperature Energy Storage)

Solves general heat transfer problems; can model storage materials and phase change materials. Similar to HEAP.

Contact: C. Yung
Jet Propulsion Laboratory
MS 511-203
4800 Oak Grove Drive
Pasadena, CA 91109

OPTIK

Determines solar flux patterns on the receiver surfaces of large, point-focus concentrator systems (11-12 m dishes).

Contact: Tom Elfe
Georgia Institute of Technology
EES/EMSL
Atlanta, GA 30332

PIPE

Optimizes the piping network that carries heat from a solar dish collector to industrial facilities.

Contact: J. Shredder
Jet Propulsion Laboratory
MS 511-203
4800 Oak Grove Drive
Pasadena, CA 91109

SOLTOT

Provides a methodology for estimating cylindrical parabolic trough collectors with single-axis tracking.

Contact: Bob Morton
Jacobs Engineering Group, Inc.
251 South Lake Avenue
Pasadena, CA 91101

TRANS

Estimates thermal losses through insulated pipes for a 24-hour simulation.

Contact: Bob Morton
Jacobs Engineering Group, Inc.
251 South Lake Avenue
Pasadena, CA 91101

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