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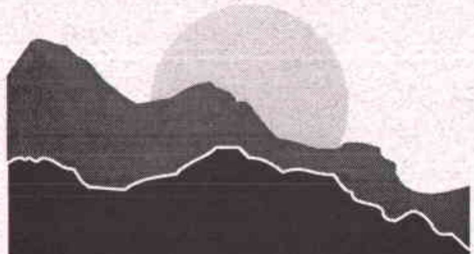

ANNUAL SUMMARY
FISCAL YEAR 1995

October 1995

FY95

Sandia National Laboratories

Sandia National Laboratories
Albuquerque, New Mexico

NREL

National Renewable Energy Laboratory
Golden, Colorado

SUMMARY OF ACCOMPLISHMENTS: FY95

Significant progress toward program goals and objectives was made during FY95. Following are selected highlights. Details can be found in the main body of the report.

Solar Two

- Solar Two construction was completed on time and within budget. Operation begins in FY96.

Dish/Engine Joint Venture Programs

- SAIC/STM operated their dish/Stirling system for more than 150 hours on-sun. During steady operation, the system produced about 17.8 kW_e. They completed Phase 1 of their USJVP.
- Cummins initiated on-sun testing of the CFIC free-piston Stirling engine in its DSJVP program.
- Cummins completed construction of its first USJVP concentrator.

System Operation and Maintenance Cost Reduction

- An *in situ* method of repairing broken heat-collection elements was developed.
- Replacement mirrors that can withstand higher wind forces were developed.
- Improved information transfer helped plants achieve 110% of design on-peak performance.
- Improvements to the part-load behavior of the SEGS plants will help to optimize plant performance.
- The O&M cost reduction program is projected to save KJCOC between $42 and $100 million. New solar thermal projects are projected to have O&M costs reduced by 15% to 30%.

Solar Manufacturing Technology

- Two contracts were placed to develop manufacturing technologies for heliostats and to reduce their cost.
- One contract was placed to develop improved manufacturing methods for power tower receiver components.
- Several Design for Manufacturing and Assembly workshops were held for industry partners.

Concentrator Technology

- An industry advisory panel completed its first annual review of DOE's optical materials research activities with the goal of soliciting directions for future work.
- A systems analysis study was initiated to evaluate advanced optical materials.
- Two subcontracts were initiated with SAIC for developing processes for dense alumina-coated and diamond-like-coated reflector materials.
- Two new outdoor test sites were activated, completing the network of six outdoor sites that are representative of environmental conditions of prospective sites for solar system installation. The two new sites are located near Daggett, California, and Miami, Florida.
- We released a request for quotation for advanced concentrator concepts and received 14 proposals in response.
- Sun♦Lab started an effort to develop a Video SHOT system to ray-trace solar concentrators.
- A contract was placed with Solar Kinetics, Inc. and Allied Signal for preliminary evaluation of a dish/Brayton system.

Power Conversion Technology

- A CRADA with Rockwell International to develop an advanced central receiver was initiated in May.
- We supported the Solar Two Project during construction and startup.
- Nitrate salt freeze/thaw tests were completed to quantify damage to receiver materials.
- We conducted a study to investigate the feasibility of converting Solar Two to a commercial plant.
- A joint study with SMUD was conducted to evaluate a 30-MW_e Kokhala hybrid power tower plant to be located in Sacramento, California.
- We demonstrated the felt/metal-wick heat-pipe concept with two full-scale dish receivers. One receiver was tested on-sun for 500 hours with no degradation in performance. Two joint venture program partners are considering our receiver design.
- We tested a Cummins 75-kW_t heat-pipe receiver on Sandia's power tower to 115-kW_t throughput, a record for a heat-pipe receiver.
- The Cummins hybrid receiver accumulated more than 260 hours of operation.

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INTRODUCTION

A need for new electric generating capacity, a heightened awareness of the environmental impacts associated with energy generation and use, and increased attention to energy efficiency will lead to a greater demand for solar thermal electric and other alternative energy technologies in the years ahead.

To date, over 350 MW_e of solar thermal electric systems have been installed in the United States, representing over 90% of the world's installed solar capacity. This power meets the needs of over 350,000 people and annually displaces the energy equivalent of 2.3 million barrels of oil. In addition, key cooperative joint ventures representing 50/50 cost share between the federal government and the private sector have been established for power tower, parabolic dish/engine, and parabolic trough technologies. These joint ventures, valued at over $150 million, strengthen the partnership among industry, utilities, and users. They are some of the current steps being taken to reduce levelized energy costs from solar thermal electric plants to between 6 and 10 cents per kilowatt-hour, thus leading to direct competition with conventional technologies.

OUR VISION

Our vision for solar thermal electric technology is the large-scale acceptance and installation of U.S.-designed and U.S.-manufactured solar thermal electric systems operating worldwide by the year 2000. We expect to realize this vision through a coordinated program of joint venture projects, technology development and validation, and market conditioning.

OUR MISSION

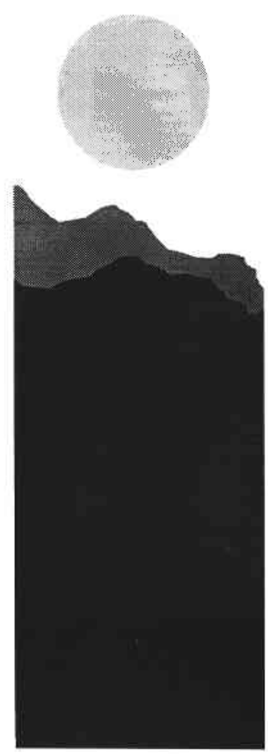
The mission of the Solar Thermal Electric Program is to work with current and potential manufacturers and users of solar thermal electric technology and to

- Develop reliable and efficient solar thermal electric systems for generating economically competitive power that can contribute significantly to the national energy mix and thereby reduce dependence on imported energy sources;
- Increase acceptance of this technology as a candidate for cost-competitive modular power generation by utilities, industry, and manufacturer/user groups, both in the United States and abroad; and
- Aggressively support developing the industrial base required for this technology to penetrate the various energy applications and markets, thereby creating new jobs and business opportunities for U.S. industry.

OUR STRATEGY

The Solar Thermal Electric Program strategy is consistent with the objectives set forth by the Office of Solar Energy Conversion in *Solar 2000—A Collaborative Strategy.*[1] The Department of Energy (DOE) and its field laboratories (Sandia National Laboratories and the National Renewable Energy Laboratory) will

- Increase, through cooperative ventures, industrial participation in both the planning and execution of program elements. Specifically,
  - *The Solar Two molten-salt power tower project led by Southern California Edison will provide the technical base for Solar 100, the first 100-MW power tower plant.*
  - *The Cummins Power Generation, Inc. 7-kW_e dish/Stirling system, designed for both remote and grid-connected applications, will be operated at utility and industrial sites.*
  - *The Utility Scale Joint Venture Program for 25-kW_e dish/Stirling systems will field initial hardware, with the last phase of this program resulting in at least one megawatt of dish/engine system capacity installed by utilities.*



[1] *SOLAR 2000—A Collaborative Strategy*, Office of Solar Energy Conversion, United States Department of Energy, Washington, D.C., February 1992.

— *The operations and maintenance cost reduction study with the Kramer Junction Company Operating Company will provide for lower levelized energy costs for power tower and dish/engine solar systems as well as trough plants.*

- Utilize the analytical and experimental capabilities of the program to support and enlarge the solar thermal technology base and the user, supplier, and decision-making constituencies. Specifically,

  — *Industry/laboratory teams will extend the performance and reliability of critical system components (concentrators, receivers, optical materials, etc.) through focused research and development.*

  — *Industry and user requests for assistance will be addressed by the Solar Thermal Design Assistance Center and other program resources.*

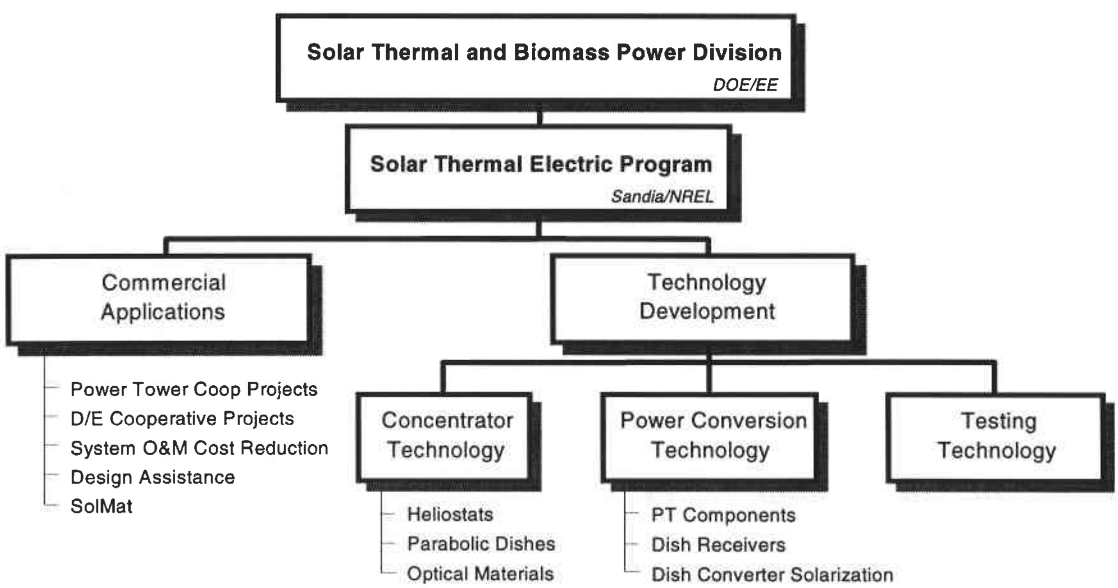
  — *Information exchange through conferences, road shows, and publications will be used to bring the technology to the attention of regulators, potential users, and the public.*

The DOE's role in implementing the program strategy centers on developing improved cost effectiveness and reliability of solar thermal electric components and developing additional energy markets with high strategic or economic value to U.S. industry. This balanced approach to technology development and validation, coupled with joint-venture projects and market conditioning, will introduce essential technological improvements while allowing industry to acquire the production experience to further lower cost. Implementing this strategy relies on the following: (1) opportunities for research to identify and prove solar electric generation concepts for trough, power tower, and dish components and processes; (2) technology development to translate research into useful prototypical hardware; and (3) industry interaction through technical assistance and joint-venture projects to validate and commercialize the technology.

This report describes the progress made during FY95 toward acceptance of solar thermal electric technology as a serious candidate for cost-competitive electric power generating options by utilities, industry, and other manufacturer/user groups.

OUR MANAGEMENT STRUCTURE

Specific implementation of the Solar Thermal Electric Technology Program is assigned to two field laboratories, Sandia National Laboratories in Albuquerque, New Mexico, and the National Renewable Energy Laboratory in Golden, Colorado. Sandia National Laboratories is the program's lead laboratory. Together, these two field laboratories are responsible for implementing the research and development plans that have been formulated to meet the objectives of the program. Activities are conducted both in-house at the laboratories and through subcontracts placed with private industry, other research organizations, and universities.



I. COMMERCIAL APPLICATIONS

The Solar Thermal Electric Program emphasizes two major categories of modular solar thermal technology: power towers (central receiver systems) and parabolic dish/engine systems. These two types of systems can satisfy utility needs for capacities ranging from a few kilowatts up to 200 MW. The program also supports existing parabolic trough collector systems for the purpose of operation and maintenance cost reduction. The 354 MW of installed solar electric generating systems trough capacity represents $1.2 billion of capital equipment and an invaluable source of information regarding solar electric power plant operating experience. Much of this experience is appropriate for power tower and dish/engine system operations.

The program emphasizes cost-shared activities where there is significant industrial involvement in the planning and execution of the activities. These government/industry partnerships represent teams that are uniquely qualified to rapidly advance each technology. The partnerships combine the manufacturing, marketing, and management skills of industry with the solar-specific experience base and analytical and experimental capabilities of the government laboratories. Presently, five major 50/50 cost-shared cooperative activities are underway within the program with a total value of nearly $150 million. The following organizations are the private sector leaders of these joint activities:

A. Southern California Edison and a consortium of other utilities and industry (power towers).

B. Cummins Power Generation, Inc. and Science Applications International Corporation (dish/engine systems).

C. Kramer Junction Company Operating Company (system operation and maintenance cost reduction).

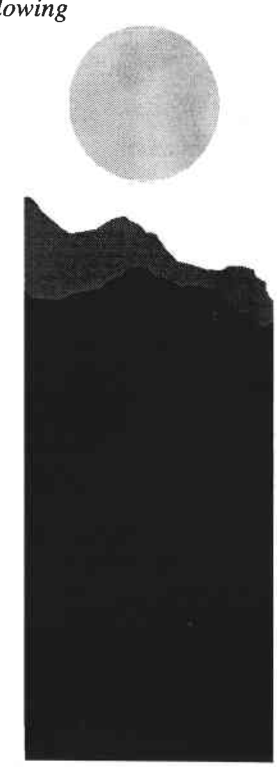
A. POWER TOWER COOPERATIVE PROJECTS

The goal of this project is to advance the near-term commercialization of solar power tower electricity generating facilities. The components for a power tower plant have been proven through testing and analysis. The next step in commercializing the technology is to design, construct, and operate a demonstration plant of a size that is large enough to reduce to acceptable levels the risks (technological and economic) of building the first commercial plant.

A consortium of U.S. utility concerns led by Southern California Edison Company (SCE) is conducting a cooperative project with the U.S. DOE and industry to convert the 10-MW_e Solar One Central Receiver Pilot Plant to utilize molten-nitrate-salt technology. Successful design, construction, and operation of the converted plant, called Solar Two, will reduce the economic risks of building the initial commercial power tower projects and accelerate their commercial acceptance. Joining SCE and the DOE in sponsoring this project are the following organizations: Los Angeles Department of Water and Power, Idaho Power Company, PacifiCorp, Sacramento Municipal Utility District, Arizona Public Service Company, Salt River Project, California Energy Commission, Electric Power Research Institute, South Coast Air Quality Management District, Bechtel Corporation, Rockwell International Corporation, and Nevada Power Corporation. Sandia chairs the project's Technical Advisory Committee and supports the DOE in technically monitoring the project. The Solar Two Project will convert the Solar One heat transfer system from water/steam to molten nitrate salt by replacing the water/steam receiver and oil/rock thermal storage systems with nitrate-salt receiver, thermal storage, and steam generator. The estimated cost of Solar Two, including its three-year test period, is $48.5 million. The plant is expected to be on-line in late 1995.

Rationale

Utilities, utility commissions, governments, and investors want clean, renewable energy sources that can provide centralized electrical power in the western United States. In addition, American companies are very interested in providing solar thermal technology to fulfill some of the new generating capacity anticipated abroad. Molten-salt central receiver (power tower) technology can meet these needs and is on the brink of commercialization. The technical feasibility of power towers has been proven; cost, performance, and reliability can be accurately predicted. However, large-scale validation of the technology is still needed to



overcome the perceived risk associated with the large capital investment required for constructing solar power plants. Capital costs are high because all of the fuel needed for the life of the plant is purchased up front in the form of hardware that is necessary for capturing the sun's energy.

The Solar Two Project will provide the large-scale validation of power tower technology needed to commercialize the technology. Solar Two is a utility/industry-led, cost-shared project to retrofit the 10-MW_e Solar One Pilot Plant with a molten-salt receiver and thermal energy storage system. The cost of Solar Two ($49 million) is being shared by the DOE and a consortium of utilities, industries, and agencies. The participants and contributors include the following: *Utilities:* Southern California Edison (Project manager), Los Angeles Department of Water and Power, Idaho Power, PacifiCorp, Sacramento Municipal Utility District, Arizona Public Service Company, Salt River Project, and Nevada Power; *Industries:* Bechtel Corporation (engineering and construction), Rockwell International (receiver), and Chilean Nitrate Corporation (salt); *Agencies:* California Energy Commission, Electric Power Research Institute, and South Coast Air Quality Management District.

To support power tower commercialization, efforts are needed in three key areas: (1) increasing awareness of power tower technology and its benefits by utilities, regulatory agencies, and industry; (2) supporting the utility-consortium's effort to implement the Solar Two Project; (3) transferring DOE-developed technology to industry and the utilities for use in Solar Two and in their commercialization efforts. Supporting the assessment and development of the first commercial power tower plants is another important area that will be addressed in our power tower and systems analyses activities.

FY95 Accomplishments

This year, Engineering (Phase 3) and Construction (Phase 4) of Solar Two were completed (see Figure 1). Also, Startup, Checkout and Acceptance (Phase 5) and Operation (Phase 6) were initiated. At the end of the fiscal year, the project was one month behind schedule and on budget, with approximately $1.6 million remaining in contingency, given the project's $46.9 million in firm commitments.

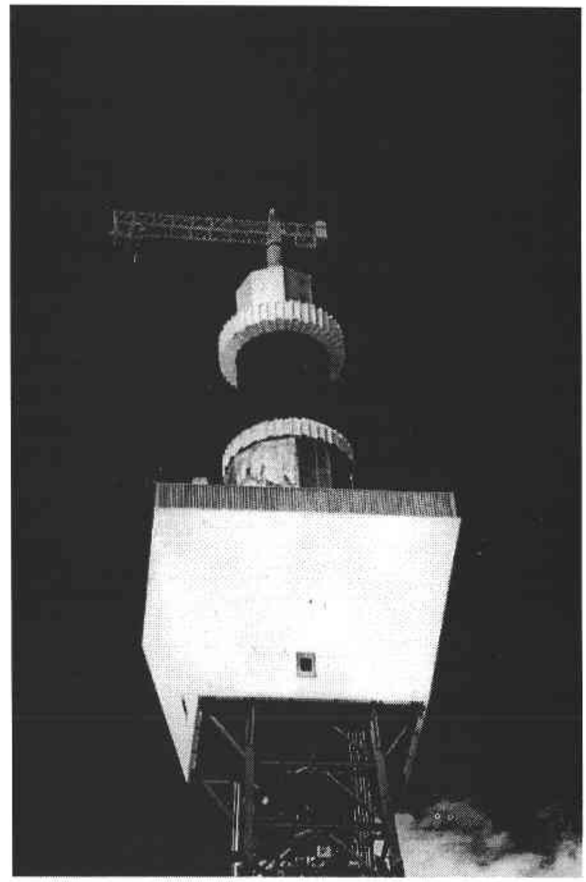


Figure 1. The new Solar Two receiver, constructed and installed this year.

In FY95, we witnessed the materialization of the design work that was performed in FY94. Bechtel oversaw construction and installation of (1) the Rockwell receiver (see Figure 2); (2) the Pitt-Des Moines salt storage tanks; (3) the three ABB Lummis steam generator heat exchangers; (4) the refurbished General Electric turbine and power generation system; (5) salt piping, heat tracing, and insulation; (6) the salt pump sumps and pumps (see Figure 3); (7) the Queue Systems master control system; and (8) 108 new (LUGO) heliostats (see Figure 4) as well as relocation of a number of existing Solar One heliostats. In addition, 3.3 million pounds of nitrate salt were delivered to the site by Chilean Nitrate Corporation. This salt is on loan to the project at no cost in exchange for a limited partnership in the project.

Another major accomplishment this year was the preparation of Bechtel's *Design Guide for Commercial Central Receiver Projects.* This document is meant to convey to future designers of solar power plants the basis for Bechtel's design

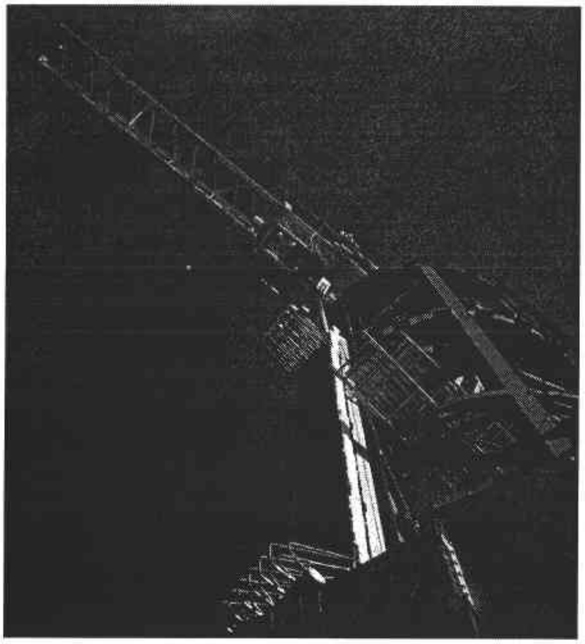


Figure 2. Installation of the first Rockwell receiver panel.

Figure 3. Installation of the pump sump for hot salt. Salt will be pumped from this vessel to the steam generator system.

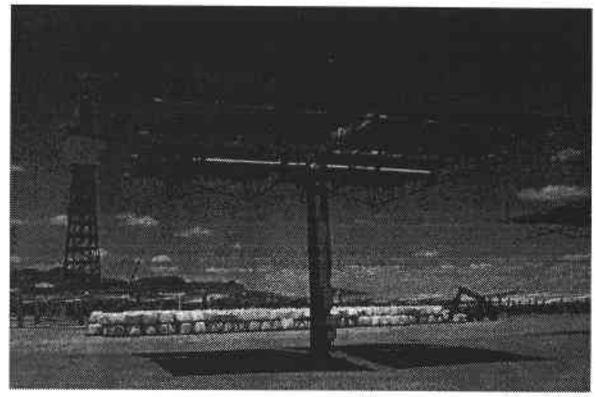


Figure 4. Solar Two under construction. Pictured are one of the new LUGO heliostats, the tower before the new receiver is installed, and 3.3 million pounds of nitrate salt for the energy storage system.

decisions, many of which were influenced by the Solar Two Technical Advisory Committee (TAC). In addition, the Test and Evaluation (T&E) Plan was delivered by the T&E team that consisted of scientists, engineers, and planners from Bechtel; the utility, industry, and agency participants (listed in this section under Rationale); and Sandia.

SCE assigned a full-time manager to ensure that the T&E Plan is carried out successfully. The T&E Plan describes 21 tests that will be performed in three years of plant operation. These tests were designed to ensure that the technical objectives of Solar Two are met. The objectives are to (1) validate the technical characteristics of the nitrate-salt systems; (2) improve the accuracy of economic projections for commercial projects by increasing the database of capital, operating, and maintenance costs; and (3) gain the ability to accurately model larger plants.

The last major player to enter the Solar Two Project will be the operation and maintenance (O&M) contractor, who is expected to be on board by late November 1995. In FY95, Bechtel and SCE drafted the O&M statement of work and issued it for bid.

Sandia continued to chair the Solar Two TAC. This year, the TAC focused on the T&E Plan, review of system startup and checkout plans, and keeping abreast of the technical issues related to construction.

Sandia also continued to support the maintenance and assessment of the collector field at Solar Two by providing training on various canting and tilt measurement techniques, refurbishing and installing the beam characterization system, and assisting with troubleshooting in the field. Sandia also hosted a meeting at the National Solar Thermal Test Facility (NSTTF) to acquaint startup and T&E personnel with lessons learned through years of construction, installation, and operation of molten-salt systems. Sandia and now NREL (through Sun♦Lab) will continue to work closely with SCE and Bechtel to ensure the success of the project.

To improve technology transfer and accelerate communications, Sandia assigned an engineer to the site full time. The engineer attends all status meetings, keeps a photographic record of project progress, and helps to coordinate a variety of activities. This individual also keeps the DOE current on all plant issues and activities.

FY96 Task Description

In 1996, the Solar Two Project will consist of Phase 5, Startup, Checkout and Acceptance, and the first six months of Phase 6, Operation. Phase 5 will encompass all of the activities necessary for verifying that the plant performs up to specification and can be turned over to the O&M personnel for routine operation. A key acceptance test will be 100 hours of successful cumulative operation of the entire plant. Acceptance of the plant is anticipated in February 1996, and formal dedication of Solar Two is expected in May or June of that year.

Operation in FY96 will be limited to fulfilling segments of Phases I through III of the T&E Plan (see Figure 5). Overall, T&E is expected to last three years, involving 21 tests that examine everything from determining tank stresses to identifying parasitic energy consumption. These tests will also identify optimal operating conditions during a two-year period of normal plant operation.

Sun♦Lab support of Solar Two will consist of five primary tasks: (1) coordination of Sun♦Lab activities and on-site support, (2) T&E support, (3) chairmanship of the Solar Two TAC, (4) technical support (i.e., technology transfer), and (5) evaluation of plant performance. This support will help enable successful plant startup and operation through technology transfer, ensure that the T&E activities obtain the information

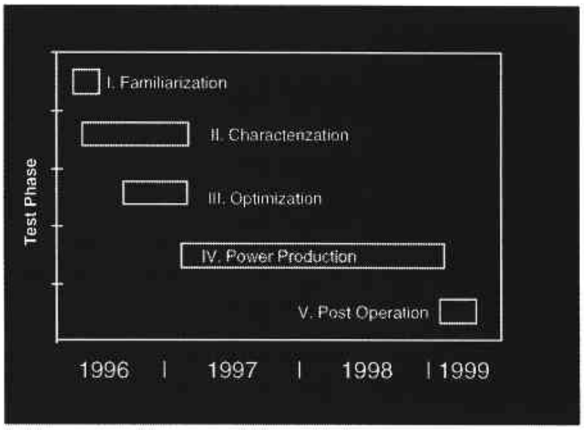


Figure 5. Schedule for the Test and Evaluation Phase of Solar Two, including 21 tests ranging in scope from validating individual component designs to operating the plant under normal conditions for a period of two years.

necessary to guarantee that Solar Two meets its stated objectives, and provide stewardship for the investment by the American taxpayer. A key new activity for Sun♦Lab will be to direct the teams that will perform the eight plant evaluations described in the T&E Plan.

In 1996, the TAC will review all of the individual test procedures, the test reports as needed, and the O&M procedures written by the O&M contractor.

B. DISH/ENGINE COOPERATIVE PROJECTS

The objective of the dish/engine cooperative projects is to commercialize economically competitive dish/engine solar thermal electric systems for remote and utility markets. The approach is to form joint ventures with industry, utilities, and other users. Although good technical progress continued on the Dish/Stirling Joint Venture Program (DSJVP) with Cummins Power Generation, Inc. (Cummins), the DSJVP suffered delays caused by problems with the Stirling engine/linear alternator. Science Applications International Corporation's (SAIC) Utility-Scale Joint Venture Program (USJVP) completed Phase 1 and is preparing a Phase 2 workplan for submission in November of 1995. Cummins continued work on Phase 1 of its USJVP, which is scheduled for completion in February 1996. Hardware for all of the subsystems is being worked on; some subsystems are complete.

Rationale

U.S. industry and electric utilities have concluded that solar thermal electric generating systems based on a parabolic dish concentrator and a Stirling engine can be economically competitive in several markets by the late 1990s. The Dish/Stirling Joint Venture and the Utility Scale Joint Venture programs offer industry the opportunity to realize this market/technology goal on a faster time scale and at a lower technical and financial risk than otherwise possible. The objective of the DSJVP with Cummins is to develop a 5- to 10-kW_e dish/Stirling system for remote power markets. The remote power markets offer the earliest potential for commercialization. Dish/engine systems are also expected to be competitive in the much larger utility markets, both in the United States and internationally. The objective of the USJVP, which is another set of 50/50 cost-shared partnerships with industry, is to develop dish/engine systems suitable for this market.

FY95 Accomplishments

Dish/Stirling Joint Venture Program

The primary objective of the DSJVP is the commercialization of the Cummins 7-kW_e dish/Stirling system for remote power applications by the late 1990s. The DSJVP is a five-plus year, $17 million effort. The Cummins-led industrial consortium and the DOE are each cost-sharing approximately 50% of the total program costs. During the final phase of this program, production-level dish/Stirling systems will be field tested at test sites across the United States. In FY95, Cummins continued to make advances in concentrator technology, heat-pipe receiver technology, and controls/power conditioning development. Unfortunately, problems with the Stirling engine have resulted in significant delays to the original schedule. Cummins continued to field test the CPG-460 solar concentrators at locations around the world. In FY95, four systems were operational at the Cummins-South solar test facility (Abilene, Texas; see Figure 6), one at the Thermacore test site (Lancaster, Pennsylvania), one at the California State Polytechnic University test site (Pomona, California), one at the Texas Utilities Energy Park (Dallas, Texas), one at the Central and South West Services, Inc. test site (Ft. Davis, Texas), and three at the Aisin-Seiki test facilities (Nice, France, and Miyako Jima, Japan). Combined, these units have accumulated over 20,000 on-sun tracking hours. Two units installed at the Cummins test facility have each tracked the sun for over 6,000 hours. Mirror tunneling of the 3M ECP-305+ silver film and fluctuating optical characteristics as a function of weather conditions have been the most persistent issues. Because of the problems with the ECP-305+ film, Cummins made a decision during FY95 to switch to glass-mirror technology for its next-generation systems.

Cummins and Thermacore continued to advance heat-pipe solar receiver technology. In FY95, Thermacore initiated durability testing of a felt/metal-wick heat-pipe receiver and a sintered nickel-powder-wick heat-pipe receiver in Thermacore's facility in Lancaster, Pennsylvania. In this facility, the receivers are being cycle tested at approximately 30-kW_t around-the-clock on quartz lamps. The felt-wick heat-pipe receiver was developed by Sandia in conjunction with Porous Metal Products of Jacksboro, Texas. This testing is intended to address long-term durability issues associated with the thermal cycling of the high temperature receiver hardware. Thermacore and Cummins also successfully demonstrated the operation of a hybrid heat-pipe receiver. The hybrid receiver uses both natural gas and sunlight to provide heat to a gas-gap calorimeter to simulate the heater head tubes of a Stirling engine.

The DSJVP team accomplished a major milestone on May 17, 1995, when it initiated on-sun testing of the Clever Fellows Innovation Consortium (CFIC) Stirling engine/linear alternator at the Cummins

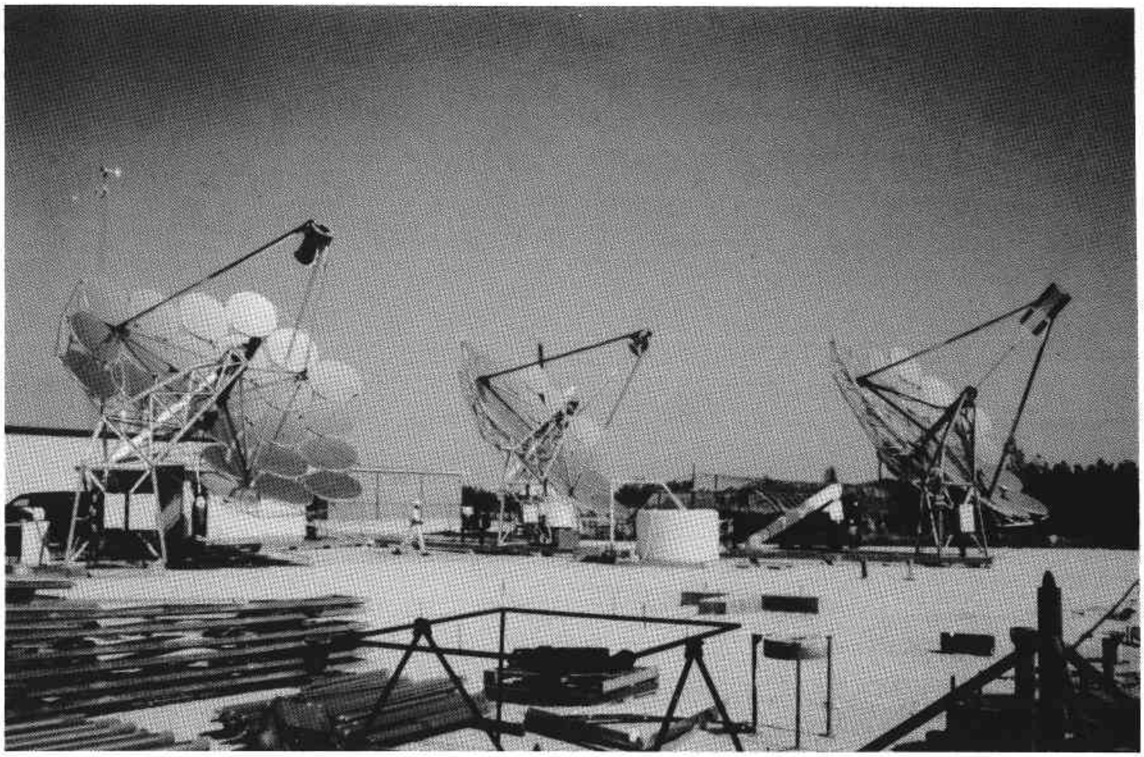


Figure 6. Cummins Power Generation, Inc. test facility in Abilene, Texas.

Abilene test site. Although engine power and efficiency were low, 3-kW_e and 12%, respectively, all of the operational aspects of the design are meeting expectations. The Cummins system controls have progressed to the point that system operation is fully automatic. Parasitics for the system operation are also reasonable—approximately 1 to 1.3 kW_e for the cooling system, controls, and drive motors.

Unfortunately, engine reliability was still inadequate to field engine hardware at the Texas Utilities, California State Polytechnic University, and Central and South West Services test sites. (Concentrators were operational at these sites.) Engine and related power conversion system hardware have been manufactured and are available for assembly and installation once sufficient confidence in engine reliability has been obtained.

SAIC's Utility Scale Joint Venture Project

The SAIC USJVP team (SAIC, Stirling Thermal Motors (STM), and Detroit Diesel Corporation) was awarded a contract for its USJVP on November 17, 1994. The team's USJVP is aimed at developing a dish/Stirling system for utility and village electrification applications. SAIC is the system integrator and is also developing the solar concentrator; STM provides the Stirling engine and thermal receiver. Detroit Diesel decided to leave the team, and its functions of manufacturing development and systems testing were assumed by STM.

In FY95, the SAIC/STM team completed Phase 1 of the project and conducted its Phase 1 final review in Denver, Colorado, July 19 and 20. The team's dish/Stirling system includes SAIC's faceted stretched-membrane dish and STM's 4-120 kinematic Stirling engine with a direct-illumination receiver (see Figures 7 and 8). A solar-only/gas-only hybrid receiver was also designed during Phase 1 but has not yet been built or tested. The team met its Phase 1 objectives, achieving more than 150 hours of on-sun operation of the system in spite of poor solar testing conditions in Golden. The system produced 17.8 kW_e during steady operation and a peak power of about 18.8 kW_e. The system goal of 20 kW_e at 1,000 W/m^2 insolation conditions appears to be achievable.

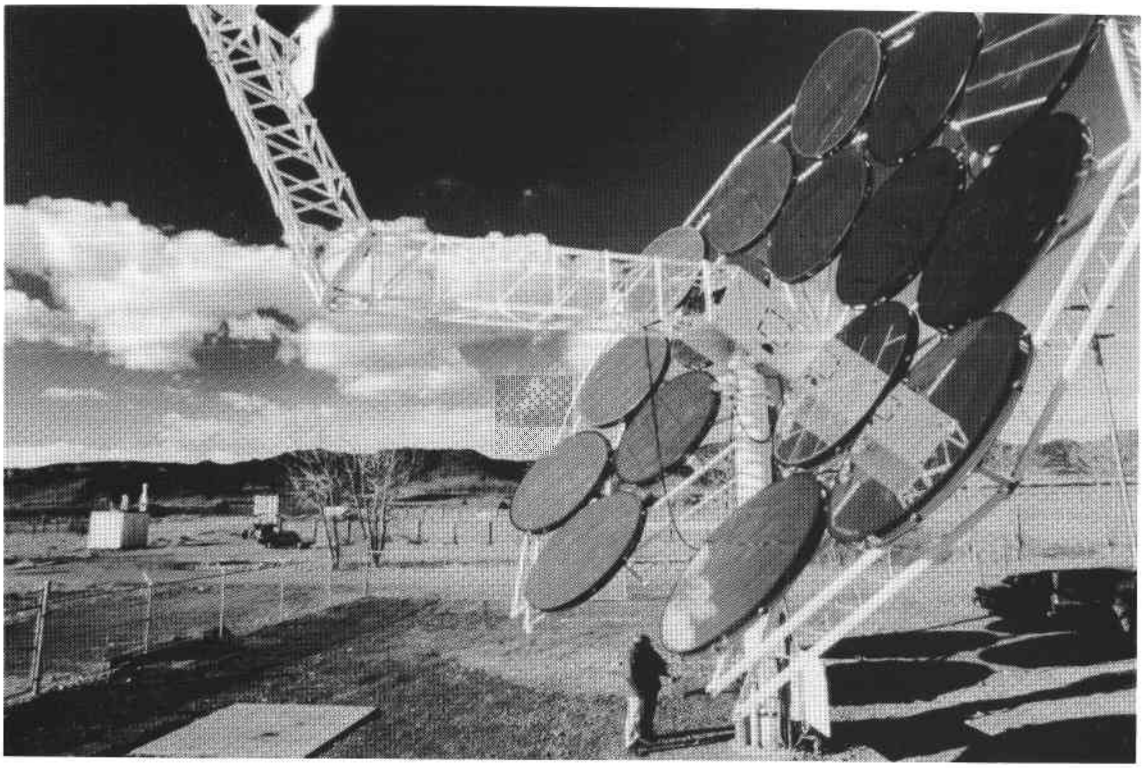


Figure 7. SAIC's faceted dish for the USJVP.

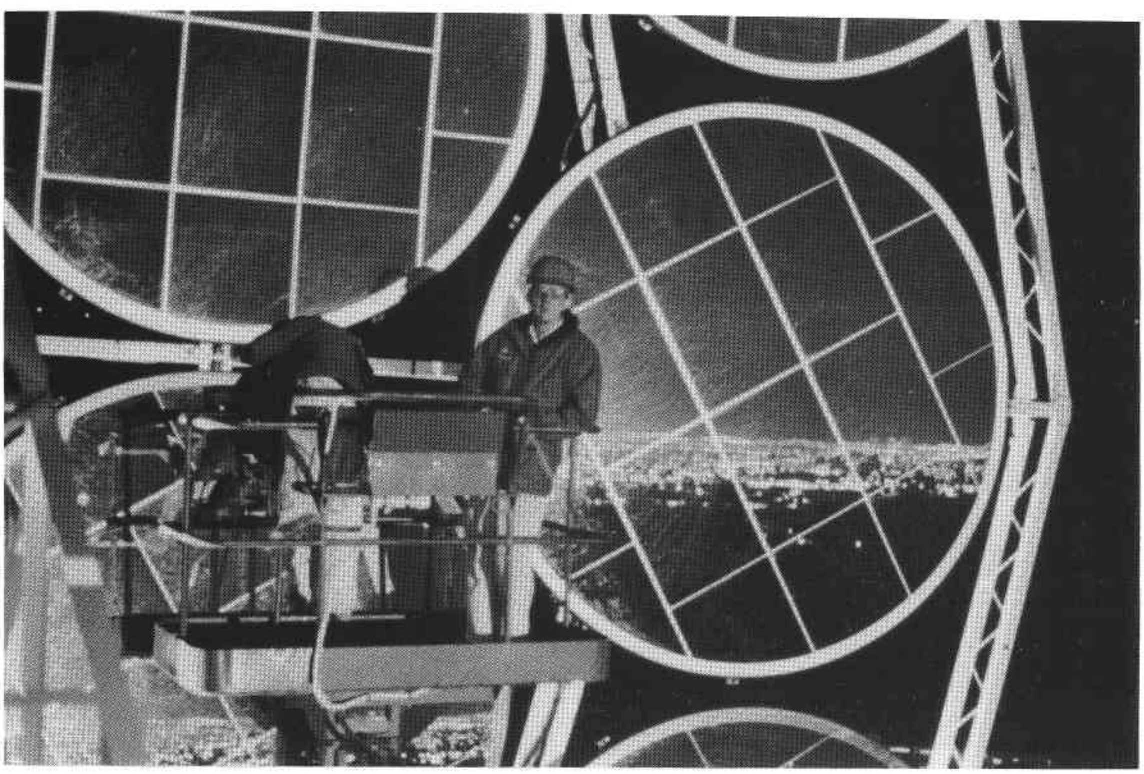


Figure 8. Night alignment of the SAIC dish.

While the SAIC/STM dish/Stirling system performed well, there are design issues that must be resolved for all three of the major components during Phase 2. The Phase 1 dish uses a Flenders drive for azimuth and elevation tracking. This drive proved to be marginal during Phase 1 testing and will have to be replaced or substantially modified if it is to be used in future systems. Achieving the required flux profile on the direct-illumination receiver with the 16-facet dish proved to be a more difficult task than was originally anticipated by the project team. As a result, STM will need to reevaluate the design of the direct-illumination receiver and is also considering a parallel heat-pipe receiver design in Phase 2. STM's 4-120 kinematic Stirling engine has progressed more rapidly than planned, primarily because of parallel development in the General Motors' Hybrid Vehicle Program. However, the projected engine performance has not yet been achieved during solar operation and this will be one of the major issues to be resolved in Phase 2 of the project.

The USJVP requires the bilateral agreement of the SAIC/STM team and Sandia to proceed into Phase 2. The team is currently preparing a detailed project plan for Phase 2 of the project, which it will submit for review and evaluation in November 1995.

Cummins' Utility Scale Joint Venture Project

Cummins is developing a completely new design for a solar concentrator for its USJVP. The concentrator diameter is approximately 15 m and uses an azimuth/elevation drive system. The reflective surface uses glass/metal technology. The design of the concentrator structure, which was a joint effort between Cummins and WG Associates, was completed and all structural members for two concentrators were fabricated. Solar Kinetics, Inc. (SKI) was responsible for building the trapezoidal, glass/metal facets for the concentrator. Because of financial difficulties, SKI only built enough facets for the first concentrator. Additionally, the focal length of the inner facets was short by about 66 cm. The difficulties in facet procurement are currently being addressed by Cummins. The first of two concentrators was erected in August. Initial calorimetry testing of the concentrator indicates that it is capable of delivering approximately 120 kW to the focal plane. The second concentrator will be erected in FY96 when a second set of facets is built.

Cummins is considering three different engines for use in the USJVP: a 25-kW$_e$ free-piston Stirling engine being developed by CFIC, a 25-kW$_e$ kinematic Stirling engine being developed by Aisin-Seiki, and a 30-kW$_e$ Brayton engine being developed by Northern Research and Engineering Corporation (NREC). Design of the CFIC engine was completed in February. Most of the engine components have been fabricated and are at CFIC. Many of the subassemblies have been completed. Once all of the components have been received, the engine will be completed. Completion is expected to occur early in FY96. Cummins has ordered two Aisin-Seiki Stirling engines. The first engine was received in June after having been operated for 100 hours at Aisin-Seiki. The engine was tested in a test cell at Cummins with a Thermacore heat pipe. The engine delivered approximately 23 kW$_e$ at an estimated thermal-to-electric efficiency of approximately 26%. Cracks developed in the heat pipe used with the engine after 30 hours of operation as a result of thermal stresses. This problem is currently being addressed by Thermacore. Delivery of the second engine is expected in FY96 and will be used for on-sun testing. NREC has completed design of the Brayton engine. All components have been ordered and some have been received. We anticipate delivery of the NREC engine to Cummins in mid-FY96.

Heat-pipe development at Thermacore has been occurring in conjunction with the development of the Stirling engines. A gas-gap calorimeter heat pipe was designed, built, and delivered to Cummins for on-sun testing. In addition, Thermacore integrated a heat pipe with both the CFIC and the Aisin-Seiki heater heads for test cell operation. Difficulties caused by thermal stresses were encountered during operation of the Aisin-Seiki engine in a Cummins test cell. The causes of these stresses are being addressed.

The control system used with the USJVP system is based on the control system developed during the Cummins DSJVP. The control system has been integrated with the concentrator and is operating very well.

FY96 Task Description

Dish/Stirling Joint Venture Program

In early FY96, Cummins expects to deliver power conversion units for the systems at Texas Utilities and California State Polytechnic University. Application-based development, such as water pump, remote village, and hybrid-receiver controls, will receive attention. However, before the 10 Phase 3 systems can be manufactured and installed at host test sites, engine durability and performance issues will need to engine durability and performance issues will need to be resolved. In addition, implementation of glass-mirror technology will require a significant design revision for the solar concentrator. Demonstration systems are scheduled for delivery to the Central and South West Services/Electric Power Research Institute site in Ft. Davis, Texas, and to the Olympic Games in Atlanta, Georgia, in early 1996.

SAIC's Utility Scale Joint Venture Project

When the decision is made to proceed with Phase 2 of the SAIC/STM USJVP, the team will begin to address the system design issues identified in Phase 1 of the project. All of the activities during FY96 will focus on installing five upgraded systems at a utility site for testing and evaluation.

Cummins' Utility Scale Joint Venture Project

Cummins will complete Phase 1 of the USJVP in the second quarter of FY96. The completion of Phase 1 will be defined by the successful operation of a complete dish/engine system. We believe that the Aisin-Seiki engine will prove successful. Phase 2 should immediately follow the completion of Phase 1 and will entail refinement of the Phase 1 system. Additionally, an engine down selection is expected to occur very late in FY96; this is needed so that the remainder of the system can be defined in detail.

C. SYSTEM OPERATION AND MAINTENANCE COST REDUCTION

The nine solar electric generating systems (SEGS) power plants located in Southern California are the only utility-scale solar power plants currently operating in the world, with an existing capacity of 354 MW. The costs associated with operating and maintaining solar thermal plants have a significant influence on the economic viability of the technology. For example, O&M costs account for more than 20% of the SEGS electricity costs. Reductions in O&M costs would enhance the marketability of solar thermal technologies currently being developed by the DOE. Examples of DOE technologies that would benefit are the Solar Two demonstration project and commercial power tower plants. Power tower plants have many of the same subsystems contained within a SEGS plant, and the O&M of these subsystems would be similar.

The goal of this project is to reduce O&M costs associated with utility-scale solar thermal power plants. This goal is being accomplished by characterizing O&M costs incurred at the SEGS plants during more than 40 plant-years of operation. Research and development aim to reduce the cost of the most important categories. The assessment of the important categories at SEGS plants indicated that roughly ***two-thirds were applicable to O&M at power tower plants.*** *This guarantees that this initiative will benefit current solar thermal technology (SEGS troughs) as well as future technology (power towers). This project is being performed on a 50/50 cost share basis between owners of the SEGS plants (primarily U.S. utilities and major investment firms) and Sandia. A significant portion of Sandia's cost share is being contributed through in-kind technical support. The contract was established with Kramer Junction Company Operating Company (KJCOC) in July 1992. The work to be performed during the three-year project was described in the Third Quarterly Report FY92.*

Rationale

The five co-located SEGS plants at Kramer Junction, California, comprise the world's first solar power park (see Figure 9). Commercialization plans by U.S. industry have recommended that future, large-scale deployment of grid-connected solar technologies be in power parks. This project is also addressing issues related to the management and optimization of these types of very large facilities.

Figure 9. Aerial view of the five SEGS plants located at the Kramer Junction Power Park. The plants produce 150 MW of electricity and comprise 1 million square meters of glass.

FY95 Accomplishments

Early in this joint-venture program, tests conducted at Sandia indicated that heat losses from the trough heat-collection elements (HCEs) increased by a factor of 2 to 4 when the glass envelope surrounding the receiver tube broke. An analysis indicated that breakage of this glass is the most significant cause of energy and revenue losses at the five Kramer Junction, California, plants. In the past, the only way to repair an HCE was to drain the system and weld a new HCE in place. This endeavor was time-consuming and costly. Consequently, Sandia and Industrial Solar Technologies (IST) developed a method for *in situ* repair of the glass envelope. The repair method involves installation of a split-glass sleeve on the existing tube, thus eliminating the costly operation of draining and welding. During the year, 35 prototypes of the glass reglazing kit manufactured by IST were installed at Kramer Junction. As a result of the successful performance and the ease of installation, KJCOC staff will purchase an additional 200 kits to use as a temporary fix until replacement of an HCE is deemed necessary. Figure 10 shows a maintenance crew replacing HCEs.

In addition to broken HCEs, another problem that has plagued the plants is broken glass mirrors caused by high wind forces. Analysis showed that only certain parts of the solar field are subject to wind damage. In an attempt to alleviate this problem, a new stronger facet was developed. The facet, developed by IST, consists of silvered ECP-305+ reflective film and a layered aluminum/plastic composite understructure. Late in FY95, 180 facets were installed at Kramer Junction. If these panels prove to be successful, KJCOC will use internal funds to install another 1,160 facets.

The field supervisory control software for the solar fields was expanded to provide the capability to monitor plant operation remotely, which is similar to the needs of a solar power park. The solar field operation of any of the five plants can now be monitored from any location on the site network. For example, management and maintenance planners at Kramer Junction

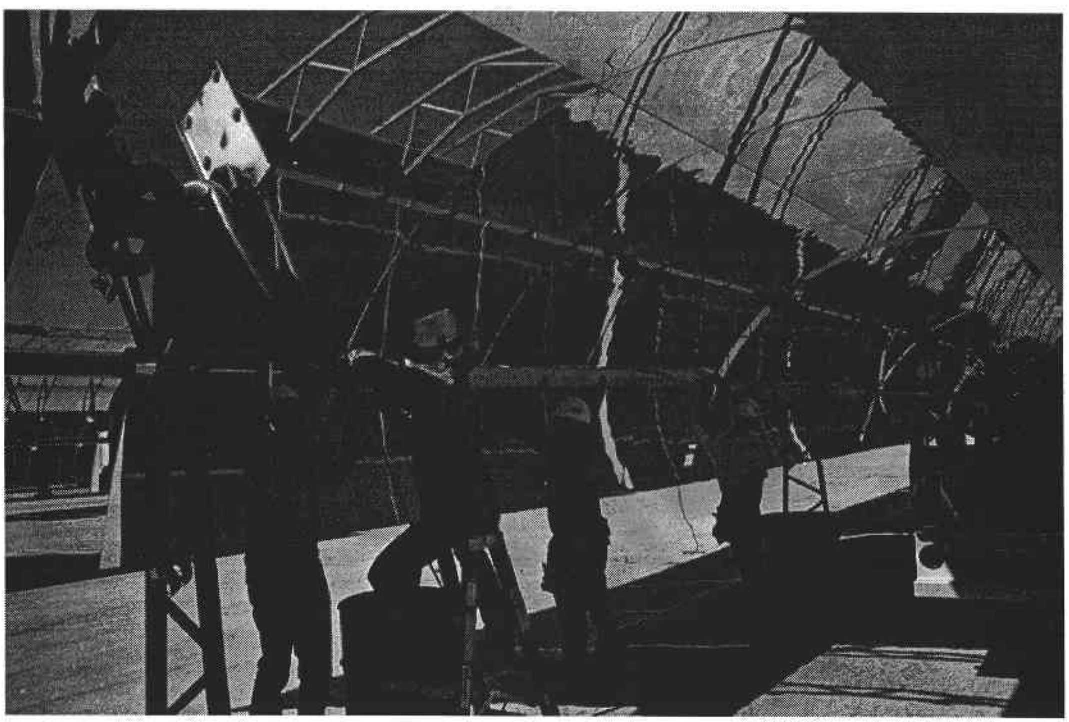


Figure 10. The O&M cost reduction program is developing improved heat-collection elements and mirror modules. Here we see the maintenance crew at Kramer Junction, California, replacing heat-collection elements.

can readily observe status and performance of the solar field and power block, including the daily history of selected parameters. The ease of information transfer has facilitated O&M planning to the point that all five plants achieved 110% of their projected on-peak performance during the year, which is a new record.

It is rare for a solar thermal power plant to operate in a steady-state condition, primarily because positions and insolation levels of the sun vary throughout the course of the operating day. During the year, state-of-the-art software was acquired and additional software was developed for installation at SEGS VI and VII. This on-line software will help the plant operators identify the values of the plant operating parameters that yield the maximum overall plant efficiency. Sandia personnel were responsible for developing the solar field portion of the software. This new analysis tool will be made fully operational during 1996.

In parallel with the above activity, Sandia conducted a part-load analysis of SEGS VI. The software tool called EASY was used in the analysis. This power plant model is more complex than any models Sandia has used in the past. Several operation strategies were compared: highest possible solar field outlet temperature, a constant mass flow rate through the solar field, and various main steam superheating temperatures. It was found that the optimum operating strategy depends on insolation conditions; that is, different superheating temperatures should be selected for use in each season.

The joint-venture program progressed to the point where a quantitative estimate of future savings in O&M can be calculated. Savings can be characterized in two distinctly different ways—benefits to the existing 150 MW operating at Kramer Junction, and benefits to next-generation solar thermal technology using parabolic troughs, power towers, and Stirling dishes.

Benefits at the existing Kramer Junction plants

There are more than 50 active and completed tasks that make up the O&M cost reduction program. Out of these tasks, nine were selected to estimate the total savings for the remaining operating life of these facilities, which is approximately 20 years.

The specific accomplishments included in the analysis (identified in Figure 11) are

- An upgrade to the solar field control system to improve performance and reduce both material costs and lost revenues that resulted from downtime (FSC),
- The replacement of solar field flexible hoses with rotating joints to reduce frequency of replacement, unit cost, and operating costs (JOINT),
- The improvement of mechanical seals on the heat-transfer fluid pumps to greatly improve reliability and thus reduce replacement costs (SEAL),
- The better measurement of mirror reflectivity to optimize mirror washing and increase average reflectance, resulting in higher performance (REFLEC),
- An upgrade of mirror attachments to reduce breakage, leading to fewer replacements and reduced lost revenue (MIRPAD),
- An improved understanding of heat-transfer fluid losses to reduce annual makeup requirements (MAKUP),
- The better measurement of heat-transfer fluid flow to more accurately measure solar field performance and increase annual plant performance (FLOW),
- The improvement of solar field alignment methods to increase performance as a result of sharper focus on the receiver (ALIGN), and
- The higher tracking accuracy of the LS-3 collectors to improve performance (TRACK).

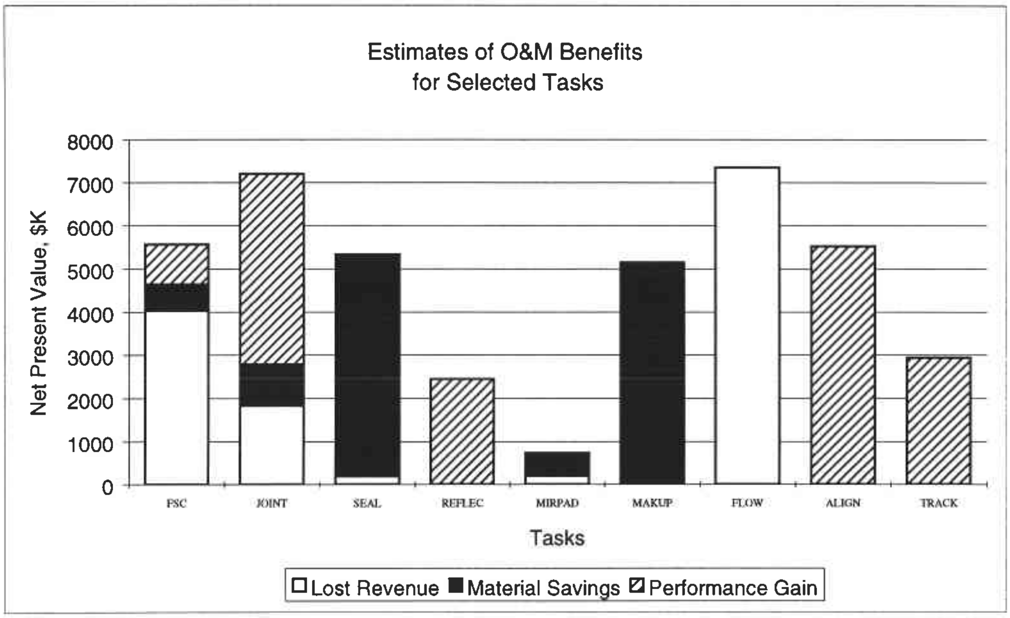


Figure 11. Projected savings for specific tasks showing the breakdown of net present value benefits.

Figure 11 shows the projected savings for these specific tasks, breaking down the contributions into the three elements of benefits. The savings given are the *net present values* (NPV) for operation over the next 20 years. Adding up contributions, **we find that the total projected NPV benefits are more than $42 million** for this period. Each of the contributing elements represents about one-third of the total. The costs for these improvements consist of development costs under the joint-venture program, as well as implementation of the improvements by the owners of the plants. Taking both of these into account, **it is estimated that the benefit-to-cost ratios average about 20.**

We have high expectations that quantification of the benefits from the other tasks in the joint-venture program will result in similar gains, showing excellent value of the overall program. It is conceivable, based on these early results, that the **total benefits could exceed $100 million** made up of approximately $30 million in material savings and $70 million in performance and lost revenue gains.

Benefits at new solar thermal electric facilities

The full value of the present program will only be realized in *new* plants where new methods, design improvements, and component upgrades are implemented from the beginning. The current program, while based on **the continuing experience at the SEGS parabolic trough plants, has many results that are also relevant to power tower and dish/Stirling technology.** Taking all of the factors into account, our preliminary estimate is that the O&M costs for a new solar thermal electric plant using parabolic troughs would be reduced by about 30%. Similarly, a rough estimate is that **comparable reductions for the other technologies as a result of the knowledge gained from this program will be 20% for power towers and 15% for dish/Stirling systems.**

FY96 Task Description

No new budget activity is dedicated to this project for FY96. However, ongoing tasks will be completed with FY95 carryover funds. The largest effort at the Kramer Junction plants will be to complete the installation and integration of the efficiency-optimization software. In addition, several reports will be initiated that summarize the findings of this four-year project.

D. DESIGN ASSISTANCE

The objective of this subtask is to accelerate the use of solar thermal systems through cooperative efforts with private industry by assisting and educating potential users, and by supporting industry and users in the selection, design, characterization, and demonstration of promising solar thermal systems. These efforts include direct technical assistance to users; testing, evaluation, and technology development; and education and outreach.

The Solar Thermal Design Assistance Center (STDAC) activities reported here are supported by (1) the Solar Thermal Electric Program and (2) the Solar Thermal Industrial Program. They are reported together for completeness and in recognition of the fact that boundaries are often not distinct within each activity.

Rationale

The STDAC at Sandia helps potential users decide when solar is an appropriate energy source. It provides users with performance data and approximate cost data needed to decide whether or not to use a solar thermal power system. The STDAC also helps improve the performance of existing solar thermal systems by applying the expertise of Sandia's Advanced Manufacturing Center and the services of the NSTTF. The STDAC's services are available to solar thermal manufacturers, installers, and users. The STDAC also provides information about solar thermal technology to interested parties; each year, its engineers respond to over 500 requests for information and technical consulting.

FY95 Accomplishments

Manufacturing support

Sandia applied its manufacturing team capabilities to help industry in several problem areas. The first effort involved the Solar Two receiver. Sandia advised Rockwell International Corporation of Canoga Park, California, in the application of Pyromark®, the receiver's absorber paint coating, to help it maintain its absorptance properties and thus improve the long-term performance of the receiver system. Sandia's assistance involved advising Rockwell, the receiver manufacturer, on the paint's application and cure process. If this process is not followed, a 10% degradation in its absorptance properties can be expected within four years of operation.

Another effort involved two small solar heat manufacturers. Engineers from Sandia's NSTTF and Materials and Process Science Center recently helped Thermal Conversion Technologies (TCT), located in Florida, solve an assembly line welding problem; this resulted in a 20% reduction in TCT's production costs for each solar module. In addition, the Sandia team helped TCT optimize its welding machine to increase its output by about 45%. This optimized performance will allow TCT to increase its production output from 175 collectors per month to nearly 250 without purchasing another $70,000 welding machine. Figure 12 shows an automatic welding machine at a manufacturing plant.

Sandia engineers visited another small solar manufacturer's facility and provided critical manufacturing process consultation and development assistance to aid the manufacturer in establishing a new, nickel-based absorber coating technology that will be part of a new high-volume, solar-collector manufacturing line. A Cooperative Research and Development Agreement (CRADA) is being negotiated with the manufacturer to develop the new coating into a manufacturing line process. The coating shows a solar average absorptance value of about 0.96 with thermal emittance (at 100°C) of about 0.15; it is also thermally stable at 350°C. The coating will be applicable for low and medium temperature systems, including flat-plate and trough concentrators.

Support to the solar thermal industry

The STDAC supported the operators of the SEGS in California. One of the requests came from SEGS VIII and IX, operated by United Constellations Operating Services, located at Harper Lake, California. The operators asked Sandia to investigate the mechanical design of the fastener securing the hydraulic ram pins on the Solar Collector Assembly drive stand. The STDAC investigated alternate fastener designs and assessed the mechanical strength of each fastener type.

In another effort, the STDAC developed a computer spreadsheet program for SEGS I, operated by the Daggett Leasing Corporation, Daggett, California. This spreadsheet is used as an aid in assessing the thermal performance of the SEGS I field as a function of mirror loss, HCE condition, solar insolation condition, and sun angle. The program gives the user

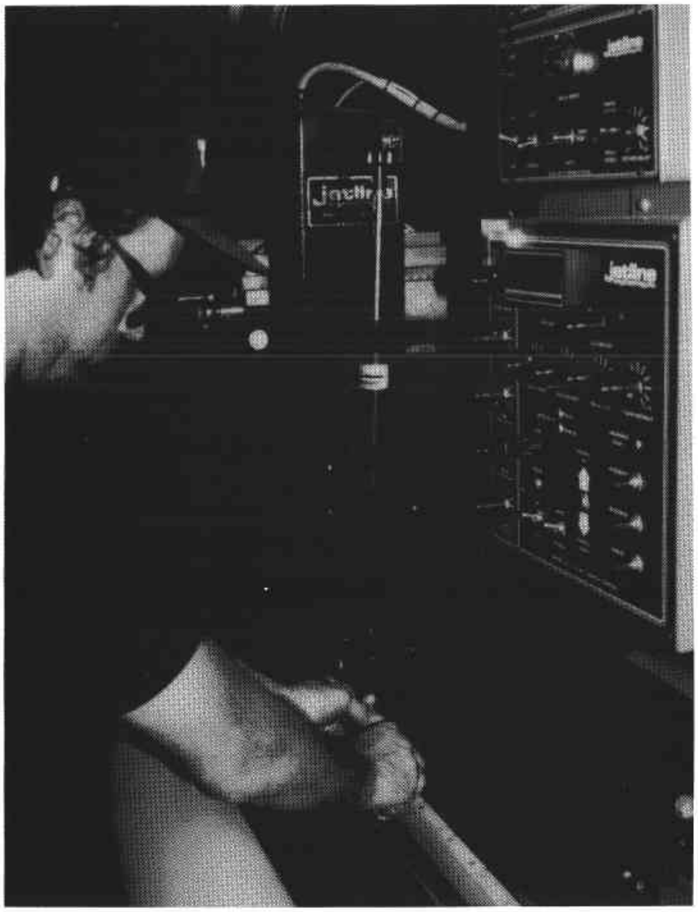


Figure 12. An automatic welding machine.

the flexibility to input field assessment data regarding the number of missing mirrors in each thermal loop, the number and condition of the HCEs within the loop, solar insolation, and time-of-year.

We developed a new model for use in the SEGS plants that will optimize the maintenance of the collector strings. The computer model is written in Quattro Pro and computes the energy performance/heat loss characteristics of a certain string of collectors based on the amount of broken glass envelopes, broken mirrors, and the optical properties of the receiver tube. Based on this information, the operators can decide if it is cost effective to remove the string from service to repair the various damaged components.

Additionally, we loaned a new reflectometer to each of the SEGS plants that will help optimize the mirror washing schedules. This reflectometer is easier to use and more quickly collects reflectivity measurements from the mirror surfaces. This allows the operators to produce a broader assessment of the reflectivity of the field and, therefore, to direct the washing activities to those areas where they are most needed.

Support to state and local governments

Under a Virginia state administrative mandate to seek out and apply cost-effective renewable energy systems in existing and new state facilities, the Virginia Energy Division (VED) asked Sandia's Renewable Energy Office to inspect a site for a new prison and to help identify renewable applications. The STDAC assembled a renewable energy team and formulated a final set of recommendations.

Additionally, the VED asked us to develop a set of criteria for performing a first-order evaluation of each renewable energy technology. In response, Sandia developed a spreadsheet analysis program, specifically tailored to Virginia to allow this kind of assessment to be done easily. The package is being field tested in various Virginia state agencies, and we expect a decision to be made in early FY96.

Support to federal agencies

The STDAC completed the review study of the U.S. Army Corps of Engineers (COE) solar thermal system evaluation methodology, the system that the COE uses to determine the applicability of solar heat systems. The recommendations included a new solar economic screening tool and 25 suggested improvements to the COE's design/installation specifications.

The STDAC developed its screening tool, which is an Excel 5.0 spreadsheet that uses flat-plate collector performance data for water heating in various cities throughout the United States; the performance data are published by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE)/Solar Energy Industries Association. The Excel program uses collector performance data, displaced fuel costs for the application, and a rough estimate of installed system costs to yield the simple payback for the application. The same information is made available in tables if the user does not have the Excel package. Based on the results of the simple payback analysis, the COE can decide if additional evaluation is warranted.

The STDAC also reviewed the COE's system design and installation specifications for solar heat systems. In addition to Sandia's in-house review, six major solar manufacturers/installers and the Army's Civil Engineering Research Laboratory (CERL) reviewed the specifications and made recommendations. The results were consolidated and 25 changes were recommended. In general, Sandia and CERL agreed that the revised specifications are reasonable for the types of solar systems for which they are intended.

The COE recommended that Sandia oversee the applications of the new specifications for a new solar hot water project at Ft. Huachuca, Arizona. The project, to evaluate the applicability of these new specifications, was funded by CERL.

Fort Huachuca, Arizona, was selected to participate in Sandia's Strategic Environmental Research and Development Program dish/Stirling program. The STDAC is monitoring this effort, which involves technical consulting and performance monitoring. Resultant data are used to compute system efficiencies and other related measures of system performance. Some of this information is useful in determining if dish/Stirling systems are appropriate for domestic military facilities.

STDAC engineers provided technical assistance to the Veterans Administration (VA). One effort involved assisting an engineer at the Little Rock VA Medical Center in Arkansas with plans to refurbish a 450-m^2, flat-panel, solar domestic hot water system. Sandia personnel developed and submitted a refurbishment plan to the VA for its use.

Another consulting effort involved the VA Medical Center in Bay Pines, Florida. The STDAC was contacted by the Energy Manager for the VA Medical Complex requesting technical assistance in the refurbishment of a 810-m^2, solar-process water system. STDAC engineers surveyed the field, measured the hot water load, and found a contractor interested in investigating an energy service contract. The VA is pursuing the project.

The STDAC also provided technical assistance to the Environmental Protection Agency, which currently leases its main offices at the Waterside Mall in Washington, D.C. The mall owners intend to use solar systems to displace electricity used for water heating. They developed a request for purchase for a solar system and asked the STDAC for technical advice. They have since gone forward with the project.

STDAC engineers assisted Fort Irwin Department of Public Works officials in California to refurbish or reapply three nonoperational solar arrays on the facility. The Department and the COE asked for Sandia's technical help in making the final decision and developing a reapplication plan, if required. Sandia engineers surveyed the system and helped on-site personnel perform a leak test; the STDAC helped perform an economic analysis for refurbishing the systems.

The STDAC also provided technical consulting to Camp Pendleton, Altus Air Force Base, and the National Park Service.

International activities

This year, Sandia launched an effort to assist U.S. manufacturers in introducing solar thermal electric technologies into the Mexican market. This effort focused on two solar thermal electric technologies: trough/electric and dish/Stirling. Its purpose is to familiarize Mexican decision-makers with the technologies, the current level of maturity of these technologies, and the status of ongoing market activities in Mexico. It is expected that by providing technically accurate and up-to-date information, Sandia can facilitate the process for the adoption of the technologies.

As part of this effort, Sandia began work to identify a dish/Stirling demonstration project in Mexico. In this effort, Sandia met with a select group of Mexican institutions to elicit interest and possibly involve them in a demonstration project. This effort focused on institutions with policy and decision-making power, whose missions encompass public energy policy, rural electrification, and rural development.

The Solar Energy Laboratory of Mexico's Autonomous National University agreed to lead in field testing of the dish/Stirling system. Testing by a Mexican institution is important because it will provide credibility to others considering a dish/Stirling demonstration program. This testing is expected to take place in 1996.

In support of technology applications in Mexico, Sandia completed an English-language draft presentation that will be used in educating key organizations about solar electric technology. Two key Mexican solar research institutions, the National University of Mexico and the Electric Research

Institute, expressed their intention to take the lead roles in demonstrating a U.S.-made dish/Stirling system in Mexico in 1996. Sandia also provided training to the University of Sonora's engineering professors and students in instrumentation and data acquisition techniques for testing/evaluating solar energy systems. A second training course (the first was given in August 1994) on testing and evaluation was held this past summer in Hermosillo, Sonora, and was tailored to fit the research needs of these and other Energy Group of the University of Sonora (UNISON) technologists.

A DOE-funded study of the market in Sonora and Baja, California, for the 7.5-kW dish/Stirling system was completed for Cummins by Meridian Corporation. Sandia expanded this effort to include the following: (a) extension of the Meridian market study to additional Mexican states, (b) preparation of Spanish-language educational and promotional literature, (c) education outreach to key Mexican state and federal institutions, and (d) pursuit of the appropriate Mexican partner institutions and of a site or sites for testing and demonstrating the Cummins dish/Stirling system.

Sandia and members of the U.S. solar industry participated in the annual conference of Mexico's National Solar Energy Association, which took place in Hermosillo, Sonora, during the first quarter of FY95. The event provided the U.S. team with the opportunity to continue developing working relationships with solar technologists from Mexico's academia and solar industry while making significant contributions to the conference itself. Sandia organized and participated in a one-day workshop on commercial, productive use of renewables and showcased U.S. technology with a Spanish-language display and exhibitions of several U.S. commercial solar systems.

Sandia's STDAC also provided technical support to the DOE/USAID Mexico renewables program team on the use of solar thermal technologies in its program. Sandia has identified and continues to develop projects involving commercial productive-use applications for solar thermal technologies that can be incorporated into the ongoing program in Chihuahua and Sonora.

FY96 Task Description

In FY96 the STDAC will be reorganized to provide technology and manufacturing support to the solar industry and major users. This new project will be called Manufacturing and Technology Support (MATS). The MATS activity will focus on integrating the capabilities of the Advanced Manufacturing Center into the solar thermal program and on bringing these capabilities to the industry to help it reduce costs and improve reliability of its products. The MATS team will coordinate its efforts with those of Solar Thermal Manufacturing Technology to ensure program continuity and efficient application of resources.

Specifically, MATS will conduct two types of activities. The first will involve direct manufacturing assistance to the industry by consulting directly with manufacturers, identifying problems, and developing solutions. The MATS team will also initiate a technology roadmapping effort for the solar thermal industry. The roadmapping is intended to identify the technology needs of the future and to develop a technology development path to achieve these objectives. The roadmapping effort will involve energy end users, solar thermal industry, university researchers, and the national laboratories. The outcome of the roadmapping effort will be the basis for the DOE's five-year plan that will be developed in FY96.

The other major MATS activity will involve technical support to the SEGS plants and to manufacturers involved with international applications. The MATS team will produce a computer code for use by SEGS that will allow the plants' operation and maintenance plans to be optimized. The team will also continue to work with the SEGS owners to identify and solve technical problems as they arise. Additionally, the MATS team will work with the solar trough and dish/engine industry to provide technical support for new international applications. In one such effort the team will work with a consortium of Mexican institutions to identify a location to field test a dish/Stirling system.

E. SOLAR MANUFACTURING INITIATIVE

The objective of the Solar Manufacturing Initiative is to develop manufacturing technology and processes that will permit cost-effective deployments of solar thermal systems in low-volume, early commercial applications; to reduce uncertainty in the cost and reliability of key solar components; to improve financing of early commercial systems and reduce the risk of performance warranties; to promote the development of system-level business plans and industrial partnerships linking manufacturing scenarios to commercial sales prospects; and to establish the manufacturing basis for achieving the substantial cost reductions possible through higher volume production.

Rationale

The Solar Thermal Manufacturing Technology (SolMaT) initiative is aimed at reducing the cost of solar thermal technologies in an environment of uncertain future sales and modest initial production volumes. In this way, SolMaT will fill a critical need by allowing solar thermal manufacturers to produce cost-effective products even before market demand will support high-volume production.

FY95 Accomplishments

SolMaT was developed conceptually during FY93 as a new activity under the Solar Thermal Electric Program. In FY94, the initiative was kicked off with the release of a request for proposals to develop manufacturing technologies for heliostats. FY95 saw the first fruits of those efforts. We placed three subcontracts with the primary objective of reducing the cost of near-term deployments of solar thermal electric technologies and began to see benefits from those efforts. In addition, we introduced Design for Manufacturing and Assembly (DFMA) workshops to the solar thermal electric community as a means for optimizing system and component designs for minimum cost.

Two industry partners, SAIC of Golden, Colorado, and Solar Kinetics, Inc. of Dallas, Texas, were contracted to develop manufacturing technologies for heliostats. Rockwell International Corporation of Canoga Park, California, was contracted to investigate several manufacturing improvements for molten-salt central receivers.

SAIC made a significant manufacturing improvement to its baseline dual-module heliostat that promises to reduce reflective area costs by 20% for near-term markets. SAIC investigated the feasibility of a multi-faceted heliostat using facets from its dish concentrator, currently under development in the USJVP. This investigation included a detailed costing study and an optical analysis to ensure heliostat performance. The primary advantages to the multi-faceted approach are increased reflective area per heliostat, dual use of the facet manufacturing line, and a dedicated, centralized heliostat assembly facility. There are additional benefits, such as elimination of focus control equipment as a result of the smaller facet size. SAIC and its SolMaT partners held a Concurrent Engineering/Design for Manufacturing session to investigate possible facet arrangements, truss designs, facet mounting methods, pedestal designs, and installation methods for further design optimization.

Rockwell is pursuing several paths for reducing the cost of central receiver components, including improved methods for fabricating panel headers, forming receiver tube nozzles from the headers, insulating completed receiver panels, and simplifying receiver control equipment and strategies. Rockwell was awarded its subcontract on September 22, 1995, so we have little progress to report for the fiscal year.

The Rockwell contract, originally planned for award in mid-FY96, was the first awarded under an NREL pilot program aimed at using best business practices, rather than the Federal Acquisition Regulations, in procurements. The streamlined process allowed an award to be made five weeks after release of the request for proposals, compared to an estimated 460 days under the old system. In addition to saving approximately 200 hours of technical staff time, the new process focuses closely on the goals of the procurement, improves proposal quality through more focused solicitation and improved competition, and significantly reduces the effort required by industry partners in preparing proposals.

DFMA workshops were held for two dish/Stirling Joint Venture partners, SAIC and Cummins, during FY95. Hughes Aircraft Company staff, who have facilitated more than 300 DFMA workshops, facilitated the workshops for SAIC and Cummins. A primary objective of the DFMA workshops is to identify design modifications that will result in significant and quantifiable cost savings for production manufacturing rates. Using ideas generated at each workshop by vendors, customers, and staff ranging from senior management to assembly technicians, a list of design modifications applicable for quantity production levels are listed, risk assessments are performed on the ideas, and cost savings for the ideas are quantified.

The SAIC workshop focused on mirror modules and the support structure for its utility-scale system. This emphasis resulted in the identification of very significant cost-reduction potential. In addition, several ideas were developed that can significantly improve system reliability, which was identified as an important customer requirement.

The Cummins workshop focused on its 7.5-kW system, specifically the concentrator, mirror modules, and support structure. Significant cost reductions as well as some new cost elements were identified. In addition, several ideas were developed that can significantly improve system reliability, which was identified as the most important customer requirement.

SAIC subsequently used the DFMA approach for its heliostat manufacturing effort as described above. SKI plans to use the process for its heliostat manufacturing effort in early FY96.

FY96 Task Description

The first phase of both heliostat contracts is scheduled for completion in FY96. At that time, both subcontractors should have evaluated one or more improved manufacturing methods for reducing the near-term cost of heliostats.

Assuming satisfactory progress, both will proceed to a second phase in FY96. While the first phase is intended to evaluate the potential of manufacturing improvements, the second phase will validate the best of those improvements via a small heliostat build. This will provide an opportunity to determine if the proposed manufacturing improvements are likely to be realized in a near-term commercial build. In addition, installing and testing the heliostats will provide experience in an application setting, reveal any unexpected real-world problems, and provide more visibility to prospective power tower end users.

Rockwell is scheduled to complete its investigation of central receiver component manufacturing improvements during FY96 and to propose a follow-on effort. As in the heliostat projects, the Rockwell project follow-on is likely to involve a validation effort.

We anticipate awarding a second component manufacturing contract in early FY96. That project is in the dish/Stirling technology area and would last approximately 12 months, ending in early FY97.

F. COMMERCIALIZATION

The objective of the commercialization subtask is to develop a deeper knowledge and understanding of the key issues in the commercialization of solar thermal technology by becoming resources on subject matter in the following four areas: (1) independent power producers, (2) World Bank funding of solar electric projects, (3) regulatory agencies as they affect renewable energy technologies, and (4) Executive Order 12902—Energy Efficiency and Water Conservation at Federal Facilities.

Rationale

One of the goals of the DOE is to promote the use of solar thermal energy in the United States and around the world. To perform this function effectively, it is necessary to understand the various factors influencing the use of solar thermal technology. The objective of this task is to develop a better understanding of the regulatory, financial, and business environments in which solar thermal technology must function.

FY95 Accomplishments

We played a supporting role in the development of the Nevada Solar Enterprise Zone (NSEZ). By adapting models previously developed for the California Energy Commission, we studied tax issues associated with solar power in the state of Nevada. The study concluded that elimination of the Nevada sales tax on solar equipment for a power tower would not significantly impact the overall cost of the energy produced. In a related study, we determined that the taxes paid by a 150-MW_e power tower would be 10 times greater than the taxes paid by a 150-MW_e gas plant: 3.22 \$/MBtu versus 0.32 \$/MBtu. Contributing to this difference are (1) the federal income tax paid by financial institutions and equity investors on profit made on loaning money to install capital equipment and (2) the taxes associated with the labor of fabricating and installing the additional equipment that is specific to solar plants, for example, heliostats.

We also played a supporting role in analyzing solar thermal facilities in foreign countries. One project we are supporting is the potential development of a hybrid solar/gas-fired plant in Mexico. We are examining the technical feasibility of such a plant and supporting obtaining funding for the project from the Global Environmental Facility (GEF).

We also joined a mission organized by the World Bank to review the status of the 35-MW_e parabolic trough project proposed for Mathania, Rajasthan, India. This project has strong support from several organizations, including the GEF and KFW, a German financial institution. Sandia is playing a significant role in defining the technologies that will be used for this project.

FY96 Task Description

This work will be carried out under other tasks in FY96.

II. TECHNOLOGY DEVELOPMENT

Technology development projects support the commercialization projects by developing, in collaboration with the private sector and the international community, solar thermal plant components and subsystems that meet the cost, performance, and reliability standards needed by industry.

A. CONCENTRATOR TECHNOLOGY

The objective of concentrator technology development activities is to bring heliostat and parabolic dish solar concentrators to commercial readiness for use in solar thermal electric systems. Heliostats are the solar concentrators used in central-receiver systems and parabolic dishes are used for dish/engine systems. The four activities that we perform under this task are research and development, optical test support, Solar Two heliostat support, and optical materials development.

Rationale

Solar concentrators, heliostats, and dishes provide the fuel for power tower and heat-engine solar systems. Heliostats are the nearly flat mirrors in a solar power tower that collect and concentrate the solar energy on the tower-mounted thermal receiver located 100 to 1,000 m distant. Parabolic dishes are the highly curved, reflective surfaces that track the sun and focus its energy onto a thermal receiver at the focal point of the dish, 10 m away. These two solar concentrators comprise similar parts, including an optical surface (typically glass), the optical element support structure, the drive, and the tracking and control systems. Power tower and dish/engine design studies show that the cost of the solar concentrator is from 40% to 50% of the cost of these two types of solar systems. Therefore, the challenge is to reduce the cost of the concentrator while continuing to maintain the high levels of performance that are demonstrated by many of the current dish designs.

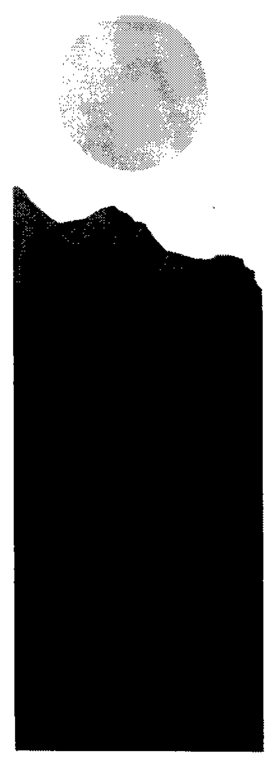
1. CONCENTRATOR RESEARCH AND DEVELOPMENT

Concentrator research and development is structured to develop new, innovative ideas and conceptual designs for solar concentrators that will lead to more cost-effective and/or high performance heliostats and dishes.

FY95 Accomplishments

In June, Sandia placed a cost-shared contract with SKI of Dallas, Texas, and AlliedSignal of Phoenix, Arizona, to evaluate the feasibility of using the single-element, stretched-membrane dish in a dish/Brayton power generator. As part of the project, AlliedSignal will perform a detailed review of SKI's dish design and SKI will evaluate the Brayton engine and receiver as a potential power generator. The project is a one-year study and will culminate in a report that describes the major technical issues that need to be addressed to develop the proposed system. SKI is transferring the rights to the concentrator to AlliedSignal so that follow-on system development can be lead by AlliedSignal with support from SKI. As their cost share, SKI and AlliedSignal will also perform a preliminary market analysis and develop a commercialization strategy.

Sun♦Lab released a request for quotation for the development of advanced concentrator components to address new and innovative ideas pertaining to fabrication approaches for point-focus solar concentrators, adaptation to point-focus solar concentrators of existing manufacturing technologies not previously applied to this area, the design of less complex or costly components, and new and innovative methods for evaluating concentrator quality or optical performance. In response to this procurement, 14 proposals were received and evaluated. Potential awards are currently being negotiated.



An in-house Sandia effort was initiated to develop a low-cost, manufacturable concentrator facet that could be used on troughs, dishes, and/or heliostats.

FY96 Task Description

In FY96, the three projects described above will continue. AlliedSignal and SKI will develop the preliminary conceptual design for a dish/engine power generation system, identify the technical barriers confronting the development of the selected system, and submit a final report. Two or three projects will begin in November of 1995 as part of the Advanced Concentrator Procurement project. In the advanced facet project, Sandia will fabricate, test, and evaluate several dish and heliostat facets during FY96.

2. OPTICAL TEST SUPPORT

The Optical Test Support project encompasses all test and evaluation support that the Solar Thermal Electric Program provides for industry, with the exception of work for Solar Two, which is documented and reported under the Solar Two Project. This task also includes developing specialized instrumentation for optical measurement and concentrator evaluation techniques. Typically, this has involved using the flux mapper to measure dish/engine project solar concentrators and using beam and heliostat characterization systems to measure the performance of dishes and heliostats.

FY95 Accomplishments

In support of the dish/Stirling projects at SAIC and Cummins, Sandia provided optical measurement support to evaluate the on-sun performance of SAIC's protective-aperture plate, to perform on-sun flux mapping and alignment of SAIC's faceted dish, and to measure the effect of moisture on the Cummins polymer-facet dish.

Two new optical evaluation tools were also evaluated during FY95, the Color 2-*f* System and the Video SHOT system. The Color 2-*f* System is a discrete optical system that uses the on-axis image (in the optical facet) of a target of colored concentric rings located at twice the focal length to provide a quantitative measure of the optical figure. The Video SHOT system is a high-speed laser ray trace system for measuring optical concentrator facets. These two systems were used to evaluate facets from the test bed concentrator, Cummins, and SAIC. The results were found to be consistent and (within instrument error bands) quantitatively the same. Also during FY95, Sun♦Lab engineers began planning and evaluating the Video SHOT system. NREL's SHOT system was also modified and used to measure the performance of the gores of Cummins' USJVP dish.

FY96 Task Description

During FY96, Sun♦Lab will continue to support the dish/Stirling development projects with optical testing. We will expand our capability by assembling another flux mapping system at NREL. We also plan to continue the development of the Video SHOT system and should have a first-generation prototype system operating in the spring of 1996.

3. SOLAR TWO HELIOSTAT SUPPORT

This activity is to support the Solar Two team by refurbishing, canting, and evaluating the heliostats at Solar Two.

FY95 Accomplishments

During FY95, Sandia provided heliostat support in a number of areas to Bechtel Corporation and its subcontractors. Sandia characterized the performance of the Solar One field heliostats and the LUGO heliostats. Sandia also provided remote control stimulators and training for Bechtel and The Industrial Company to recant the inner 17 rows (579 heliostats) of the field and to cant the LUGO flat-glass heliostats. Additionally, we helped Bechtel develop the bid specifications for its operation and maintenance package, investigated cleaning strategies for the heliostat field, and assisted with the field control software and communications. We also provided a new beam characterization system for the heliostat field at Solar Two. The new system will be used to measure heliostat tracking errors routinely during field operation, and to determine tracking and offset errors during plant startup.

FY96 Task Description

We will continue to provide support for Solar Two, including software upgrade support for the subcontractor that is developing heliostat field control software, startup support for test and evaluation of field performance, and hardware operations and maintenance support for the Solar One and LUGO heliostats.

4. OPTICAL MATERIALS

The objective of the optical materials task is to identify and develop advanced optical materials for solar-thermal applications that meet industry's goals of cost, performance, and durability. These advanced materials are necessary to achieve the cost and performance goals needed for commercialization of various solar thermal technologies. The optical materials team conducts basic research and analysis to better understand the fundamental properties that influence optical material performance; performs testing, characterization, and evaluation of candidate materials; and collaborates with the solar and materials industries to develop, test, and certify optical materials of interest.

Rationale

Lightweight, durable, and efficient optical reflector materials are necessary to achieve cost and performance goals needed for commercialization of various solar thermal concentrator technologies. The reflector material is a common element in all solar concentrators. High specular reflectance with long service life, low cost, and ease of replacement in the field are key requirements.

FY95 Accomplishments

Advanced reflector materials

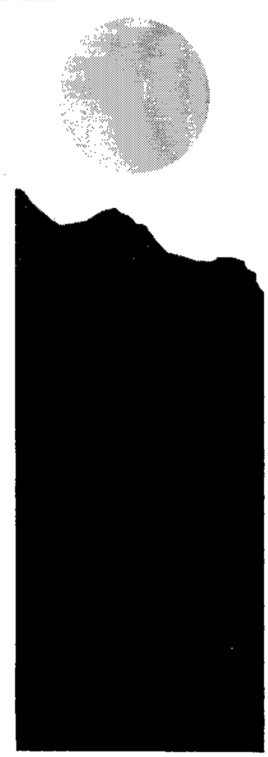
Development of a low-cost, high-durability mirror is important because the success of solar thermal concentrator systems is strongly related to the optical durability and economic viability of the reflector materials. The goals for such mirrors are to maintain high specular reflectance for extended lifetimes (typically at least 10 years) under outdoor service conditions and to keep the cost to concentrator manufacturers below $10/m^2.

Industry advisory panel

An industry advisory panel completed its first annual review of DOE optical materials research activities. The panel was formed to solicit objective feedback to help clarify the optical materials task objectives and identify current and future activities of relevance to industry. Staff presented the goals and strategy for implementing advanced reflector materials as well as information on current in-house and subcontracted research and development activities. The following is a sample of the observations that resulted from the meeting:

- The "one-size-fits-all" development approach (one reflector material for all technologies) has not satisfied the industry as a whole. The research and development of a silvered polymer reflector to be used for dishes, troughs, and heliostats should be replaced with a more concentrator-specific development program. The varied approaches for developing improved solar optical materials should be widened to include glass reflectors, selective surfaces, and other optical coatings.
- In terms of industry's needs, the long-term goals are "bare minimum" goals. The team should review goals by technology with industry input regarding system and component design issues.
- Optical materials research is widely supported by industry (and benefits all technologies), but a large budget increase at the expense of other program activities is not supported by all. However, a modestly higher level of effort is supported, given the difficulty of the issue(s), and a widened program that helps all segments of the solar thermal technologies is supported as well.
- There is much more activity in optical materials research than is generally known, even by the solar industry. We can demonstrate our commitment to this area by submitting articles to external publications, distributing an optical materials brochure (experience, capabilities, etc.), and noting ways for industry to interact with the optical materials team.
- The current range of activities is appropriate, but should be strengthened. This can be accomplished by involving industry more in systems issues that impact and govern reflector choices, strengthening ties to industry "old hands," improving field-testing activities through greater cooperation with industry, and providing support of industry through optical characterization.

The optical materials team intends to implement the findings as appropriate in FY96, and the industry advisory panel will be kept abreast of implementation plans. Given the productive outcome of the meeting, both the advisory panel members and the optical materials team have indicated their interest in meeting annually.



Organized molecular assemblies

During FY95, significant progress was made in developing advanced reflector materials for solar concentrator applications. An experimental reflector construction consisting of silver sputtered polyethylene terpthalate (PET) film coated with a proprietary organized molecular assembly (OMA) and thin methacrylate (PMMA) polymer was developed and tested. Initial results are very encouraging. A patent has been granted to researchers who developed this innovative material. A new test matrix of OMA-construction reflectors is planned for FY96.

Science Applications International Corporation

Two subcontracts were initiated with SAIC's Washington, D.C., and San Diego, California, offices to develop a process for high-volume production of enhanced lifetime solar reflector materials through the use of ion-beam assisted vapor deposition of alumina and to investigate the application of water-clear diamond-like carbon coatings as potential protective coatings for front surface silvered mirrors.

Under a subcontract issued in FY95 with SAIC-Washington, alumina hardcoats deposited over silvered PET films have performed very well under accelerated and outdoor tests. The new material is of interest to SAIC in Golden, Colorado, for possible use with future dish/Stirling systems. Under a modified subcontract proposed for FY96, SAIC will determine if the protected reflectors, deposited on PET or levelized stainless-steel substrates, are viable for solar concentrator applications. The modification will include support for engineers at SAIC's Golden office to consider manufacturing issues, attend design reviews, and support engineering-scale testing of materials developed under the subcontract. The advantage of this arrangement is that SAIC-Golden, the eventual end-user of the technology, will be brought on board early so that it can help guide the development of the material and ensure the final product matches its needs. The arrangement will also allow us to test new materials under field conditions. We hope to continue these tests, which are expected to begin at SAIC's test site in the spring of FY96, for other reflector materials so that field issues can be uncovered and corrected early in the development process.

3M Company

The 3M Company subcontract to develop a commercial version of ECP-305+ reflective film was completed in December 1994. More than 4,950 m^2 of ECP-305+ film was extruded by 3M. Accelerated testing of the films has resulted in less than 3% loss in specular reflectance (at 15 and 25 mrad) after 6,000 hours in a QUV (high-intensity ultraviolet light chamber) and 5,000 hours in an Atlas Weatherometer. Industrial Solar Technologies has successfully deployed the film for solar process heat applications and is using the film for advanced facets for deployment at Kramer Junction Company (KJC). KJC plans to use the advanced facets as replacements for broken glass facets located near the perimeter of the solar field where windy conditions are prevalent.

Apart from the successful implementation of ECP-305+ film by Industrial Solar Technologies, numerous field failures of the material occurred in FY95. Both Cummins and SAIC observed failures of the material with parabolic dish installations. Follow-on experiments have shown that these failures can be reduced or eliminated by using better manufacturing and installation procedures; however, solar industry members will not risk installing ECP-305+ film with their systems until they are confident that the material can be made more flexible to uncertainties in design specifications.

NREL began discussions with 3M Company for further development of the all-polymeric reflector, supported last year under a subcontract with Dow Chemical Company. 3M has licensed a patent with Dow for further development of an all-polymeric reflector material and is interested in applying the technology in the automotive and indoor lighting markets. NREL is currently holding discussions with 3M to find areas where both groups can benefit from continued DOE funding of the technology for solar applications. A commercial path for the technology that does not rely on the solar "niche" market may be the result of 3M's interested in these large markets.

Outdoor exposure testing

The optical durability of candidate reflector materials is evaluated on results from both real-time exposure at outdoor test sites and accelerated weathering in controlled laboratory environments. Outdoor testing is important because the durability of optical materials in actual field environments is a critical issue for success. Accelerated testing is used to screen new candidate materials on the basis of their optical durability. In addition, as new advanced reflector materials demonstrate ever-increasing lifetimes, correlation between outdoor and accelerated exposures will become necessary to predict service lifetimes because the industry cannot afford to wait 10 years to find out if materials will be capable of such lifetimes.

Significant progress in the outdoor exposure test program was made during FY95. Two new test sites were activated, completing the network of six outdoor sites that are representative of environmental conditions of prospective sites for solar system installation. The two new sites are located near Daggett, California, and Miami, Florida. The Florida test site was selected following consultation with representatives from the solar industry. Advantages of the south Florida site are its tie-in with a wealth of historical data and its recognition as a *de facto* "standard" site by the weathering industry (automotive, paint and coating manufacturers, etc.). The Miami site has historically been linked to solar-type material exposure testing. Service life data collected from the site is particularly important because of the solar industry's expressed interest in remote coastal sites for solar thermal generation of electricity.

Under the auspices of the International Energy Agency SolarPACES Task 3.3.2 (Concentrator Reflective Materials Testing), a meeting was held in December 1994 at the German Aerospace Research Establishment in Köln, Germany, to discuss cooperative efforts in outdoor exposure testing of reflector materials. Spain, Germany, and the United States were represented. Under an agreed-upon collaborative effort, each country will expose candidate solar reflector materials to outdoor weathering at its outdoor exposure sites, make reflector samples available either on a "request to be weathered" or "expose if interested" basis to all participants, and perform reflectance measurements on a set of representative candidate mirror materials in a round-robin test program to serve as a calibration of the various optical characterization instruments. All sites will be fully instrumented in terms of monitoring meteorological conditions and solar irradiance. This collaborative agreement effectively expands Sun♦Lab's outdoor exposure testing network beyond the existing six active sites with minimal impact on cost and resources.

Support for industry

The optical materials team provided significant support to the solar industry in FY95. Requests for support from the two USJVP contractors, Cummins and SAIC, were handled on an as-needed basis. Cummins requested support in evaluating field failures of its ECP-305+ film-based stretched-membrane facet. Cummins has requested help in evaluating the ultraviolet durability of anticorrosion coatings for structural elements in its dish system. Work is continuing in both these areas. SAIC requested that NREL monitor the optical durability of 0.7- and 1.0-mm thin-glass mirrors manufactured by Naugatuck Glass and laminated to stainless-steel substrates by SAIC. We will continue monitoring this material as part of an expanded effort to investigate thin-glass mirror options.

Optical materials systems analysis study

An optical materials systems analysis study was undertaken to evaluate advanced materials and to determine which research and development directions are most likely to produce more cost-effective materials than the current generation of glass reflectors. To better understand the performance and cost implications of various reflective materials, a detailed performance and economics model of the SAIC 20-kW_e dish/Stirling system was developed. Characterization of the input parameters for the various optical materials under consideration was in progress at the end of FY95.

FY96 Task Description

Both the industry panel and DOE have recommended that, while maintaining a focus on identifying, developing, and evaluating long-term reflector materials that meet DOE's goals, the team should investigate a broader range of materials and technologies in FY96. To this end, the optical materials team plans to expand its efforts in FY96 to further investigate thin-glass mirrors as a near-term reflector material and to investigate advanced selective absorber surfaces for mid- and high-temperature solar thermal applications. Specific tasks include materials testing, near-term reflector materials, long-term reflector materials, outdoor testing, absorber material development, and industry support. These changes will lead to a more balanced development approach offering near-term support to the Solar Thermal Electric Program.

The optical materials systems analysis study will be completed. A report with recommendations on future directions for optical materials research and development will be provided.

B. POWER CONVERSION

Power conversion development efforts synchronize research and development activities with the needs of users, expanding the availability of resource data and improving system performance. Power conversion systems for both dish/engine systems and power tower systems are tested at Sandia's National Solar Thermal Test Facility (NSTTF). Power tower receiver development is focusing on advanced salt-in-tube receivers, molten-salt film receivers, and volumetric air receivers. Dish receiver development, particularly of the reflux type, is critical to the long-life reliable operation of parabolic dish/Stirling engine systems. The heart of a solar thermal dish/engine system is the subsystem that converts thermal energy into electricity: the engine generator. While the program does not directly support development of these converter subsystems, it provides testing and solarization support to industry.

1. POWER TOWER TECHNOLOGY

The primary objective of the power tower technology program is to advance the development and commercialization of central receiver technologies. This work will mitigate risk of central receiver systems, support industry and utility concerns by conducting research on new concepts, and perform testing and analysis of components and procedures. The following are key tasks within this activity: (1) molten-salt component tests, (2) molten-salt stability and corrosion tests, (3) development of instrumentation to measure flux and temperature on central receivers, (4) volumetric receiver development, and (5) system studies of power tower systems.

Rationale

The primary direction of power tower development has historically focused on solar-only plants or hybrid solar/fossil plants with large solar fractions. However, the changing electric power market is likely to require new and innovative approaches if power towers are to be successfully commercialized.

The power tower cooperative projects are supporting the development of the Solar Two Project, a 10-MW_e project to validate molten-salt power tower technology, as the first step toward commercialization. Even though the molten-salt power tower technology is nearing commercialization, there are numerous areas where experimental and analytical work is necessary to demonstrate, optimize, and refine system designs and operating procedures. The program's expertise in analytical and experimental work will be used to optimize and refine system designs, components, and procedures, and to ensure the technical success of the Solar Two Project and the commercialization of this technology. Advanced power tower systems with potential performance and economic advantages are also being studied and tested to support future commercialization efforts.

FY95 Accomplishments

The power tower technology program for this fiscal year focused on supporting commercialization efforts, specifically the Solar Two project and the Rockwell International Corporation CRADA, as well as on continued technology development.

Solar Two support

As a part of the Test and Evaluation Phase of Solar Two, the procedure and preanalysis for the first test, storage tank thermal stresses, were completed and issued for review by the TAC. In addition, a temporary data acquisition system was set up to measure strains and tank temperatures on the hot storage tank during initial preheat, salt melt and conditioning, and daily thermal cycling.

Three sections of dual-element heat trace were purchased from Raychem, installed, and tested in our molten-salt flow loop at the NSTTF at Sandia to determine their performance relative to single-element heat trace. The dual-element heat trace will be used at Solar Two. It is different from single-element heat trace, which we currently use in our molten-salt system, in that it has two conductor wires in one cable versus a single conductor wire. In previous molten-salt receiver systems where dual-element heat trace was used, the heat trace failed a considerable number of times. The dual-element heat trace used by Raychem has gone through evolutionary advancement since it was used in molten-salt receivers at Sandia. The heat trace sections were installed on a relatively straight section of pipe, a valve bonnet, and a section with components that had a considerable number of bends. After nine months of testing, there were no failures or concerns.

To ensure that the Solar Two Project benefited from our years of experience in designing, fabricating, and installing heat trace, Sandia personnel met with

Bechtel Corporation and The Industrial Company staff to discuss heat-trace installation procedures. Based on several of our recom-mendations, modifications to the installation procedures were adopted and implemented.

Salt freezing experiments

Experiments have been completed to quantify damage inflicted to samples of receiver tubes under various freeze/thaw sequences. In molten-salt systems, components and piping can be damaged if the nitrate salt freezes and then is thawed. Unlike water, nitrate salt expands when it thaws. Depending on the conditions, there can be either no damage or complete yielding of the material. Considering that there are multiple drain valves in the receiver, the likelihood that a panel could fail to drain during nightly shutdown is high over the life of the receiver. From previous panel freeze/thaw experiments conducted in FY94, we measured permanent strains as high as 4% after two cycles.

Salt was melted and frozen sequentially in upper and lower sections of each tube in a two-chamber oven (see Figure 13) to measure freeze/thaw methods and to measure permanent tube strain caused by this cycling. Five series of tests were completed. The first four series were focused on understanding the freezing and thawing phenomenon and methods to mitigate the damage. We found the most severe freeze/thaw cycle was the one in which the salt in the lower part of a tube is frozen, followed by the upper section, then the salt in the lower section is thawed followed by the upper section. We also discovered that if there is a free-liquid salt surface in a tube adjacent to a section that is frozen with salt (such as in a receiver head), then when the frozen section is thawed, the salt will expand freely without yielding the tube.

In the fifth series, we measured the damage to several representative receiver materials with a range of tube diameters and wall thicknesses under the most severe freeze/thaw condition. We found that most materials ruptured after 10 to 16 cycles. The permanent strains at rupture varied between 13% and 25%. The implication of these results to the life of a receiver is that a certain amount of permanent strain must be accounted for in the design life of a receiver.

This year Sandia received two best paper awards at the 1995 American Society of Mechanical Engineers (ASME)/Japanese Society of Mechanical Engineers/ Japan Solar Energy Society International Solar Energy Conference that was held in conjunction with the Thermal Engineering Conference on March 19-24 in Maui, Hawaii. There were 29 technical sessions with 156 papers in the Solar Energy conference from an international arena of authors. The ASME Solar Thermal Power committee awarded James E. Pacheco, Mark Ralph, and James Chavez best paper among its five sponsored technical sessions for *Investigation of Cold Filling Receiver Panels and Piping in Molten-Nitrate-Salt Central-Receiver Solar Power Plants.* The ASME Testing and Measurement Committee gave Richard B. Diver the best paper award for *Mirror Alignment and Focus of Point-Focus Solar Concentrators* from the two sessions it sponsored.

The first phase of planned transient freezing experiments was completed to validate a correlation describing the distance a fluid can flow through a pipe that is below the fluid's freezing point. This information enables us to determine how feasible it is to cold start piping in a molten-salt central receiver plant. Cold starting can be an advantageous method for reducing the parasitic power consumption in a molten-salt central receiver.

The system consists of a 50-gallon ASME pressure vessel that will hold molten salt and two 18-m vertical lengths of tubing (heat traced, instrumented, and insulated). Experiments showed that it is feasible to flow molten salt (at 288°C) through an 18-m, 2.54-cm diameter pipe (at ambient temperature) at a rate of 0.15 m/sec without forming a plug of frozen salt in the tube.

A report entitled *Results of Molten Salt Panel and Component Experiments for Solar Central Receivers: Cold Fill, Freeze/Thaw, Thermal Cycling and Shock, and Instrumentation Tests*, authored by James Pacheco, Mark Ralph, James Chavez, Sam Dunkin, Earl Rush, Cheryl Ghanbari, and Matt Matthews, was completed and published as a Sandia National Laboratories report. This report summarizes molten-salt component and instrumentation tests in support of the commercialization efforts.

Internal film receiver

The internal film receiver is an advanced concept of a molten-salt central receiver. In this receiver concept, a film of molten salt flows down the face of thin plate, which is heated on its opposite side with concentrated

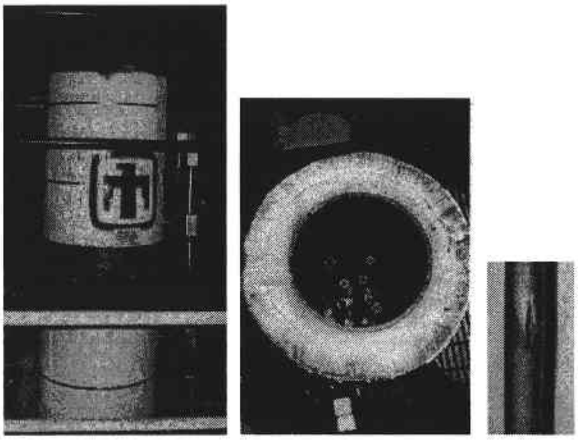


Figure 13. Two-chamber oven used to conduct freeze/thaw experiments and a ruptured tube (right).

sunlight. Advantages of this type of receiver concept are that (1) the pressure drop is much lower than salt-in-tube receivers, which, in turn, will reduce the pumping requirements; (2) the design could be simpler; and (3) the film will have better heat-transfer characteristics that translate into higher allowable flux limits. During FY95 at the Plataforma Solar de Almeria (PSA), located in the province of Almeria, Spain, testing of an internal film receiver (see Figure 14) began under a joint Spanish-U.S. program. The objectives of this test campaign are to determine the feasibility of this receiver concept, to determine the limits of incident flux and the effect of panel deflection on the flow distribution and possible dryout, to measure heat transfer coefficients between the plate and salt, and to measure receiver performance as a function of flux density and flow rate. Testing of this 500-kW_t receiver is divided into high- and low-flux experiments. The low-flux testing began recently with system checkout, panel tensioning, and flow distribution tests.

Despite some problems with thermal expansion of the panel and failed heat-trace circuits, we were able to verify that the salt-flow distribution is fairly uniform across the panel under low-flux conditions. In addition, we showed that minor disturbances in the flow field do not adversely affect the cooling of the panel (that is, disturbances do not create hot spots). Staff from Spain's Centro de Investigaciones Energeticas, Medio-ambientales y Tecnologicas (CIEMAT) and from the PSA reworked the entire system by replacing the failed heat-trace circuits, adding expansion slots in the receiver plate, and

Figure 14. Internal film receiver being tested at Plataforma Solar de Almeria, Spain.

fixing leaks in the steam generator. They plan to complete the high flux experiments next year.

Rockwell CRADA

A CRADA on advanced central receiver development with Rockwell International began in May. The CRADA will focus on advanced receiver designs and materials testing. Material characterization was initiated this fiscal year.

Corrosion tests were conducted with advanced alloy materials that are typical of evaporator materials containing silicates to stabilize the alloy against corrosion. We found that the silicates significantly reduced the corrosion susceptibility in molten nitrate salt.

An impedance heating system, which could be a potential alternative to heat trace, was designed and installed in a section of piping for testing. This heating system is different from heat trace because current flows through the pipe to heat it instead of heating a mineral-insulated cable that transfers the heat to the pipe. The impedance heating system is likely to be much more reliable and easier to install, resulting in more flexible operation as well as lower installation and maintenance costs, which could translate to lower levelized energy costs.

Solar Two conversion

A study was conducted to investigate the feasibility of converting Solar Two to a commercial plant. We found that by hybridizing and increasing plant output to 30 MW_e, a commercial plant could be created for approximately $15 million. No capital or operating subsidy appears to be necessary. Results of this analysis were documented and forwarded to Bechtel Corporation for inclusion in its power tower commercialization plan (a.k.a. SolarPlan).

The Sacramento Municipal Utility District (SMUD) and NREL completed a study that investigated design options for a small 30-MW_e Kokhala project that would be located in SMUD's service territory. Kokhala is the name given to the hybrid power tower concept that integrates a nitrate-salt solar power tower with a gas-turbine combined-cycle power plant. This integration achieves high-value energy, low costs, and lower investor risk than a conventional solar-only power tower plant. Figure 15 shows a schematic diagram of a Kokhala plant.

The study is described in the paper, *SMUD Kokhala Power Tower Study,* by H. Price of Sun♦Lab and D. Whitney and B. Beebe of SMUD, which will be presented at the American Society of Mechanical Engineers Solar Energy Division Conference in March 1996. The results indicated the optimum configuration to be a plant of about 50 MW_t in size, including thermal storage. The solar plant sizes, or thermal ratings, considered in this study were between 10 and 70 MW_t. By way of comparison, the Solar Two Project has a solar plant thermal rating of 42 MW_t.

Results were extremely encouraging, showing that the first plant could be built with solar hardware costs between $12 and $38 million, and with a benefit-to-cost ratio near one. Because SMUD places a higher value on electricity generated from renewable resources, it is possible for the Kokhala plant to have a higher benefit-to-cost ratio than the comparable sized 100% fossil-fired combined-cycle plant.

FY96 Task Description

A significant amount of the work in power tower technology will focus on supporting the commercial applications program and industry in the Test and Evaluation Phase of the Solar Two Project and in the Rockwell CRADA. In addition, the study and testing of advanced power tower components and

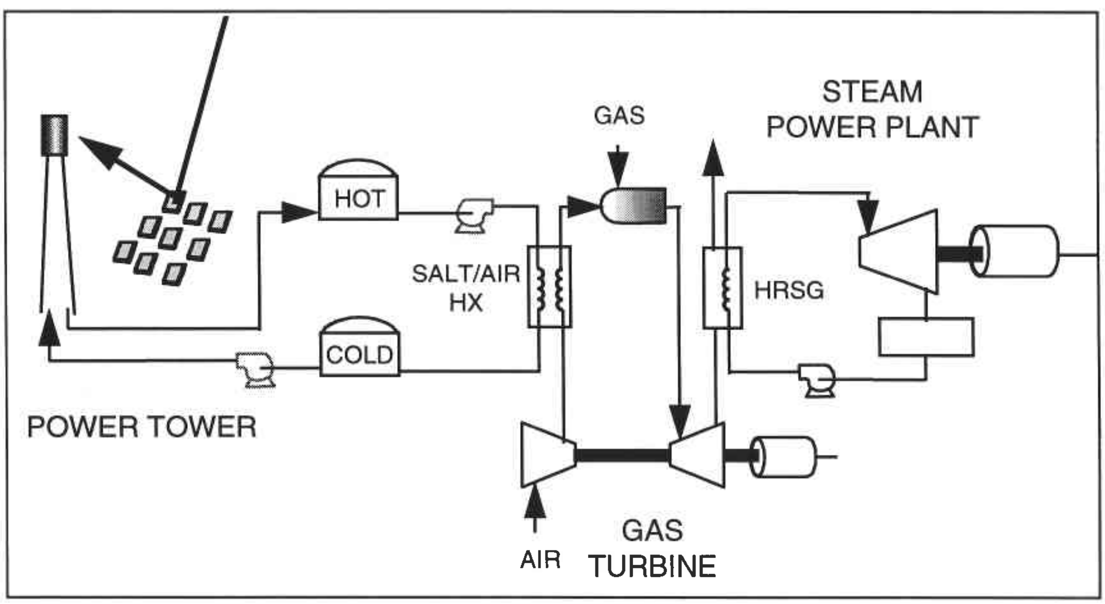


Figure 15. Schematic diagram of a Kokhala plant.

development will continue in FY96. Specifically, we will continue to support the Solar Two Project Team and the Solar Two Participants in carrying out the Test and Evaluation Phase of Solar Two. This support will be in the form of direct support, test procedure development and review, systems analysis, technical support, and testing for all aspects of the project. We will test an impedance heating system to evaluate its potential relative to heat trace. We will also continue the next phase of the transient freezing tests to evaluate the effect of tube capacitance on freezing penetration. A large effort will be expended to refurbish the NSTTF, including the data acquisition system, field controls, and master control system. We will complete planned testing of the Recepto Avanzado de Sales internal molten-salt film receiver.

A cost-shared, industry-led, power-tower commercialization study will be conducted to investigate optimum commercialization pathways for power towers. This plan is called the SolarPlan.

A detailed report that describes the SMUD Kokhala study will be completed during FY96. Follow-on Kokhala activities will include the fine tuning of cost data for the solar plant, investigating methods to reduce the operation and maintenance cost of the plant, and additional analysis on larger plant configurations.

2. DISH RECEIVER TECHNOLOGY

Reflux receivers have the potential of improving the life and performance of dish/Stirling power generation systems. The reflux receiver provides a thermal "transformer" between the dish and engine, providing isothermal, uniform flux to the heater heads. This flux results in a higher than average engine temperature, lower stresses, and fewer constraints on dish and engine design. In addition, the two-phase heat transfer allows a smaller, cheaper, and more efficient receiver. The short-term objectives of the receiver development effort are to demonstrate reflux receiver technology on-sun at scales appropriate for current dish/Stirling projects and to directly compare the performance of a reflux receiver with a directly illuminated heater head through application to the Stirling Thermal Motors power conversion system package. In the longer term, the program will pursue high-performance and low-cost concepts, develop design tools and hybrid receiver technology, and transfer the resulting technology to industry for commercialization.

Rationale

Stirling dish-electric systems have been identified as having potential for meeting industry's long-term energy cost goals. Dish-electric systems based on Stirling engine technology were successfully demonstrated by Advanco Corporation and McDonnell Douglas Corporation and operated at high efficiency. To reach the ultimate potential for dish-electric systems, a high-efficiency, low-maintenance, and low-cost receiver is required. The current thrust is to improve the longevity and to reduce the operation and maintenance costs of receivers, as well as to improve performance. The basic receiver type believed to be best suited for making these improvements is the reflux receiver. The reflux receiver is an optimum match for the Stirling engine's capability and requirements and can smooth the flux nonuniformities present in low-cost commercial dishes. In addition, reflux receivers may be applied to other solar thermal applications with significant life and performance advantages over conventional tube receivers. Some development on nonreflux receivers will be pursued in support of efforts by industrial organizations interested in commercialization of dish/Stirling systems.

FY95 Accomplishments

Activities in this area were driven primarily by the needs of our industry partners. Program goals included full-scale testing of advanced receiver wick concepts, hybrid (gas-fired) receiver development and demonstration, materials interaction studies, verification of design tools, durability testing of wick structures, and heat pipe integration with a Stirling engine.

Felt-wick heat-pipe receivers

In FY94, Sandia engineers identified a felt/metal—supplied by Bekaert Fibre Technologies and applied by Porous Metal Products—as a promising advanced wick candidate. The felt is more uniform in appearance and has finer wires than other felts previously considered and rejected. Bench-scale testing in FY94 proved the short-term feasibility of this wick material.

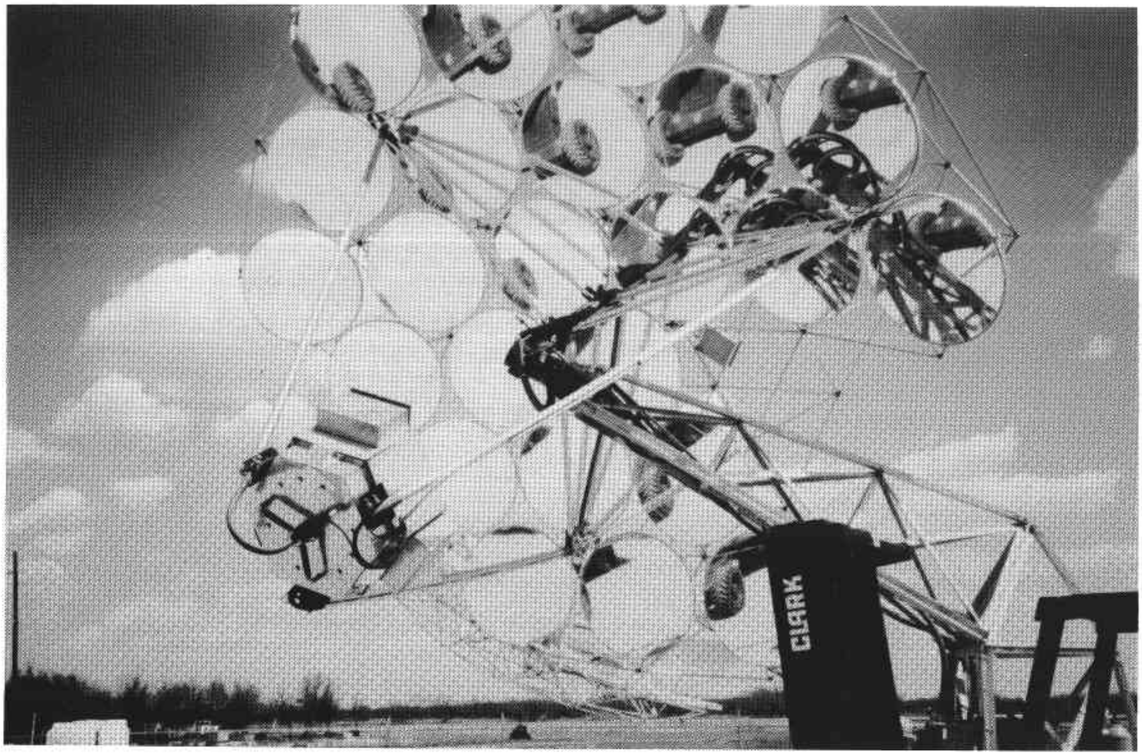


Figure 16. Cummins Power Generation, Inc. hybrid receiver in preparation for first on-sun test in Abilene, Texas.

In FY95, we completed fabrication and tested a first-generation heat-pipe receiver based on this technology. We assembled the wick in a receiver shell supplied by Cummins and did not include refluxing or arteries. We operated the receiver at up to 61 kW_t on Sandia's test bed concentrator (TBC) and also demonstrated a frozen-sodium startup at 40 kW_t incident. Cummins expressed great interest in the new wick, primarily because of the cold-start capability. Cummins tested the receiver at its Abilene, Texas, test facility for about 500 hours with no degradation in performance (see Figure 16). The receiver lifetime was limited by the weld design.

We designed, built, and tested a second-generation felt-wick heat-pipe receiver that included refluxing. We changed the receiver absorber to a 70-degree, half-sphere angle to reduce costs and improve the wick-forming process. The weld ring was replaced with a single weld between nested domes. Cummins changed its production weld design to match this new approach, and Cummins also ordered two felt-wick absorbers for its own independent testing. We tested the second-generation receiver to about 65-kW_t throughput, although 120 kW_t was predicted. Post-test sampling indicated that the wick was sparse in the area of dryout. We worked with Porous Metal Products and Bekaert to develop a quality control program for delivery and installation of the wick and changed the design of the wick to be more tolerant of defects.

We tested several bench-scale devices to address specific concerns with the felt wick. We first tested the original bench-scale device, cycling it 50 times from room temperature to 750°C. The wick performance did not degrade, but the containment failed by thermal fatigue because it was self-constrained. We tested a second bench device by cycling it 13,000 times through the sodium freeze-thaw regime. We observed no significant distortion of the wick structure. We tested a third bench device at steady state for 2,000 hours at 750°C to determine wick lifetime data. We terminated the test at 2,000 hours because a hot spot was detected during a routine startup. Although we carefully cleaned the heat pipe, contaminants in the wick were concentrated in the heated area, which plugged the wick. In the future, we will clean heat pipes to a greater extent.

We fabricated a second copy of the second-generation heat pipe for integration with the STM 4-120 Stirling-cycle engine. We fabricated and modified the engine and receiver support structure and the assembly fixtures to accept the heat-pipe receiver. When we inspected the heater heads, we found an error in the layout of the liquid return lines at the condenser and sent the heads back to STM for modification. We are still awaiting the completion of STM's modifications and now expect to test the system in FY96.

Cummins heat-pipe receivers

Thermacore has refined the 30-kW_t powder-metal-wick heat-pipe receiver to the point that it is the least troublesome component of the 7.5-kW_e dish/Stirling system.

We tested a Cummins/Thermacore 75-kW_t powder-metal-wick heat-pipe receiver on Sandia's solar power tower to test the receiver throughput capabilities for comparison to our models. We successfully operated the receiver up to 115 kW_t on two separate occasions. We used an infrared camera to detect receiver dryout, terminating the test before damage occurred. We predicted receiver dryout between 110 and 120 kW_t with our wick performance model. The location of dryout also matched the predicted location. The receiver will form the basis for the design of the Cummins USJVP receiver.

Cummins accumulated 2,073 hours of on-sun operation with an artery-free version of the 30-kW_t receiver. Cummins removed the receiver from service to test the Sandia felt-wick receiver. We cleaned and sectioned the receiver to determine the integrity of the wick structure. We found minor deposits of contaminants from the wick at the liquid low-pressure points of the wick and an extensive network of fine cracking. The cracks did not fully penetrate the wick and were not large enough to hinder sodium flow. The deposits did not appear to affect the liquid flow.

Cummins tested a second powder-metal-wick receiver in its cycle-test laboratory, accumulating 2,795 hours at temperature and 1,160 thermal cycles before a rim weld failed, ending the test. We sectioned this receiver too, and found fewer deposits but more extensive cracking of the wick.

Hybrid receiver development

Stirling Technology Company (STC) has been working under subcontract to NREL on a 10-kW_t prototype hybrid pool boiler for use in dish/Stirling systems. A key feature of the STC design is the use of a surface-type burner that provides uniform heat flux and very low air emissions. In FY94, STC completed the project with successful ground testing and on-sun testing of the receiver. In FY95, STC extended laboratory testing of the receiver to determine the effects of noncondensible gases on the startup and transition from solar to gas and back. STC also demonstrated the technology to the Arizona Public Service Company.

Cummins and Thermacore completed repairs to their first-generation heat-pipe hybrid receiver, and accumulated 260 hours of operation on their CPG-460 concentrator in Abilene. The receiver design is based on their 36-kW_t solar-only heat-pipe receiver. Thermacore began experimental investigations to improve the performance of the gas burner and developed a burner with 80% efficiency. Thermacore is currently incorporating this new burner design into a full-scale receiver design.

NREL fabricated and began testing a burner test rig. This rig will enable us to qualify and experiment with the emissions monitoring equipment expected in early FY96. The emissions equipment will then be made available to the joint-venture program partners for their hybrid receiver development programs.

Materials

As we increase the successful operation time of receivers, the compatibility and life of materials at high temperatures in contact with sodium becomes a greater issue. Of particular interest to the joint-venture program partners is the compatibility of condenser or heater-head materials. Several customers have identified Inconel 625 (IN625) as a potential heater-head material.

We have acquired several specimens of IN625 from STC. These specimens have seen up to 10,000 hours at 700°C exposed to NaK-78 in support of the NASA Advanced Stirling Conversion System program. Our metallurgists found limited damage to the material. However, analysis was difficult because of a lack of witness plugs and virgin material. Further studies are needed to match materials and fluxes that are expected in heat-pipe receivers.

We began a study of the mechanical properties of Thermacore's nickel wicks to predict the cracking seen in some receivers. We determined that the room temperature fatigue life of the Thermacore wick is 14,000 cycles. Further cycle testing is planned at higher temperatures.

We also analyzed the buckling characteristics of the absorber dome following internal pressurization. Our objective was to determine if the receiver and engine combination could be safely operated without a pressure-relief device. The pressure-relief device vents the receiver in the event that a heater head failure dumps the engine helium charge into the receiver. We are preparing to experimentally verify the predicted absorber buckling. Initial predictions indicate that the receiver can be safely run on the STM engine without pressure relief.

FY96 Task Description

We will continue to develop the reflux and hybrid-reflux receiver through analytical, design, and experimental activities. The primary objectives are continued refinement of advanced heat-pipe receivers at the 75- to 100-kW_t level, development of advanced hybrid receivers, durability testing of receiver and wick materials, transfer of technology to industry, and integration support, including the STM engine test and the joint-venture program efforts.

We will complete the demonstration phase of the felt-wick development program with two on-sun test receivers. The first is a modified second-generation receiver, with increased vapor-flow cross section and a more robust wick structure. We will demonstrate this receiver on the TBC and then determine the throughput power limit by testing on Sandia's solar power tower. The second receiver will be integrated with the STM 4-120 engine and tested on the TBC. We will compare the results of this test with those of previous direct-illumination receiver tests on the TBC. This test will demonstrate the system performance improvements of reflux receivers. Both of these receivers will incorporate improved pretest cleansing to improve the receiver durability.

Sun♦Lab will develop in-house hybrid receiver expertise. After we consider various burner options, we plan to design and fabricate an advanced hybrid receiver. We intend to identify a development path with significant differences from the joint-venture program receivers so that a viable technology option is demonstrated. This development will improve our gas-burning expertise, which, in turn, will help us respond in a timely manner to our joint-venture program partners. In addition, we will develop expertise and equipment for measuring emissions from hybrid burners and will work with regulatory agencies to develop guidelines for emissions from solar power systems.

We will change our emphasis on felt-wick receivers to long-term compatibility and durability issues. We will investigate different wick materials, condenser materials, and preprocessing techniques and their effect on receiver durability. We will accomplish this through a matrix of small capsule tests that will run simultaneously and unattended for periods of up to 10,000 hours.

We will complete on-sun testing of an NREC Brayton Engine hybrid system on our TBC. This package is an alternative to Stirling-cycle engines for the Cummins joint-venture program.

Sandia's TBC upgrades will be completed. Both concentrators have been relustered to increase the thermal throughput. The controls and safety systems will be upgraded to modern standards.

We will continue to support receiver development, integration, testing, and post-test analysis for the joint-venture programs. In addition, we will provide engine performance analysis in the areas where our skills match the needs of our partners.

3. DISH CONVERTER SOLARIZATION—

In cooperation with industry, Sandia has been engaged in a program to solarize, test, and evaluate power conversion devices that have the potential to be utilized in commercial solar thermal electric point-focus systems. The goals of the program are to engage in projects that directly support ongoing commercialization efforts; to develop solar thermal power conversion systems that are candidates for commercialization; to identify and respond to solar-specific design issues; and to increase the general industry knowledge base on system integration, packaging, and system testing techniques.

Rationale

Stirling-engine-based systems have been identified as the most efficient solar-to-electric power conversion systems available. With a demonstrated net efficiency of 29%, a dish/Stirling system holds the record for solar-to-electric power conversion. The individual components required for a dish/Stirling system and prototype, nonoptimized systems have been demonstrated. As the systems progress from demonstration phases toward commercialization, integration of the components and system optimization have become increasingly important. Brayton engine-based systems, on the other hand, have a substantially larger technology base as well as a demonstrated reliability base, but they have not demonstrated efficiencies as high as those of a Stirling system, making Brayton-engine-based systems a logical backup technology to Stirling systems.

Component integration issues involve thermal and mechanical matching of the components, startup and transient control issues, sensor location, and minimization of parasitics. The optimization process will involve trading off system parameters such as capital cost, operation and maintenance cost, system availability, performance, and system life to develop the most economically feasible system possible. Testing at Sandia will focus on performance characterization, system availability, and identification of system integration issues. The results and conclusions will be made available to the industrial community for use in optimization models and system design. These efforts will support both existing and new dish/engine joint-venture programs.

FY95 Accomplishments

Stirling and Brayton engines are the two converter technologies that are currently being pursued in support of other solar thermal programs, for example, the USJVP. A secondary objective is to identify and characterize mechanical, heat-transfer, and controls-related integration issues that are generic to all heat-engine-based solar thermal systems using the Sandia test bed concentrators.

Two projects to develop solarized versions of two existing engines were under way in FY95. Both projects involve solarization and on-sun testing of engines developed primarily for co-generation applications: the STM 4-120 25-kW_e Stirling engine and the NREC 30-kW_e Brayton engine (see Figure 17). The on-sun testing is designed to verify the predicted power conversion system (PCS) performance, characterize PCS operation, and determine the suitability of the engines for solar applications.

STM Stirling engine solarization

On-sun testing of the STM 4-120 Stirling engine with a direct illumination receiver and helium working fluid was completed in the first quarter of FY95. Plots of the PCS power and efficiency as a function of control temperature and thermal input power are presented in Figures 18 and 19. At nominal full power operation conditions, the PCS produced a net power of 16.7 kW_e at 24.8% efficiency. These values are lower than the expected values. Under transient conditions when the input power was greater than could be "processed" by the PCS, which resulted in the PCS shutting down because of a high heater-head temperature level, the PCS produced a net power in excess of 19.3 kW_e.

In addition to testing the STM 4-120 engine with helium, we tested the engine with hydrogen working fluid. This testing was only done for full-power operation at various control temperatures. Plots of the PCS power and efficiency as a function of control temperature and thermal input power are presented in Figures 20 and 21. At nominal full power operation conditions, the PCS produced a net power of 17.9 kW_e at 26.9% efficiency. These values are higher than those obtained with helium, which was expected.

NREC Brayton engine solarization

Phase 2 of the NREC project, which is the design and construction of a Brayton PCS, continued. NREC completed the detailed design of the Brayton PCS and began ordering components. Most of the components have been received at NREC. Quality problems were encountered with the turbine housings and with the recuperator. The turbine housings had to be returned to the vendor to fix a problem with voids in the castings. The recuperator problems were associated with excess leakage caused by an unsuccessful initial braze. After some work, the vendor was able to reduce the leakage problem to an acceptable level. NREC will begin assembly of the PCS early in FY96. The German Aerospace Research Establishment (DLR) completed the design, construction, and initial testing of its volumetric receiver. The receiver was tested for several hours on-sun at DLR's Lampholzhausen, Germany, test facility. This testing was successful, and the receiver will be shipped to NREC in the first quarter of FY96.

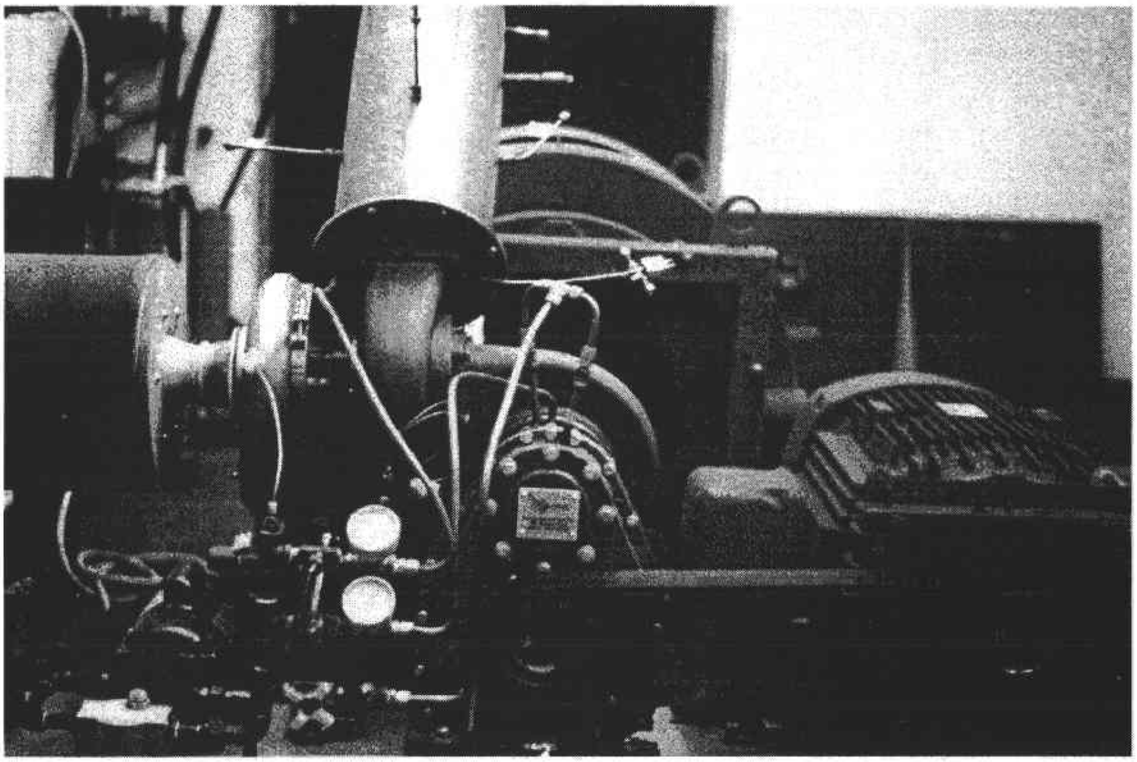


Figure 17. NREC's Brayton engine developed for the Gas Research Institute.

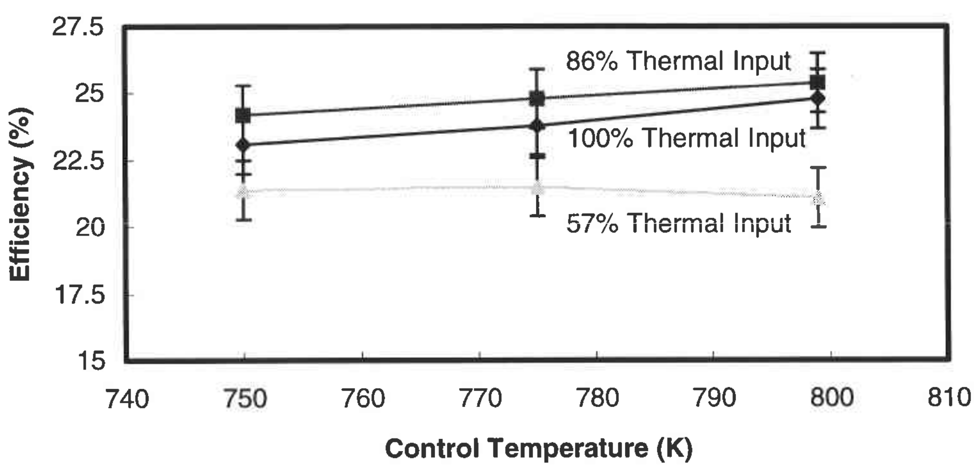


Figure 18. Efficiency of the STM 4-120 power conversion system as a function of control temperature for three different input powers. The error bars indicate one standard deviation.

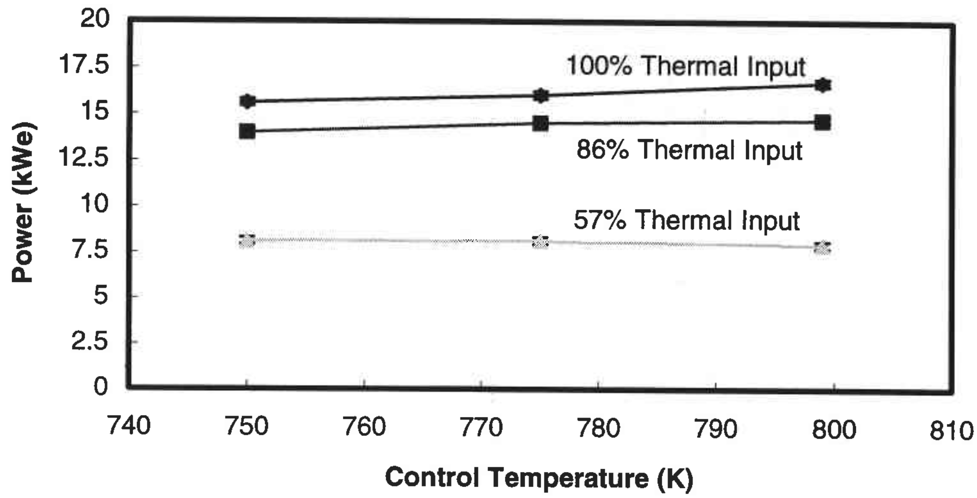


Figure 19. **Net power of the STM 4-120 power conversion system as a function of control temperature for three different input powers. The error bars indicate one standard deviation.**

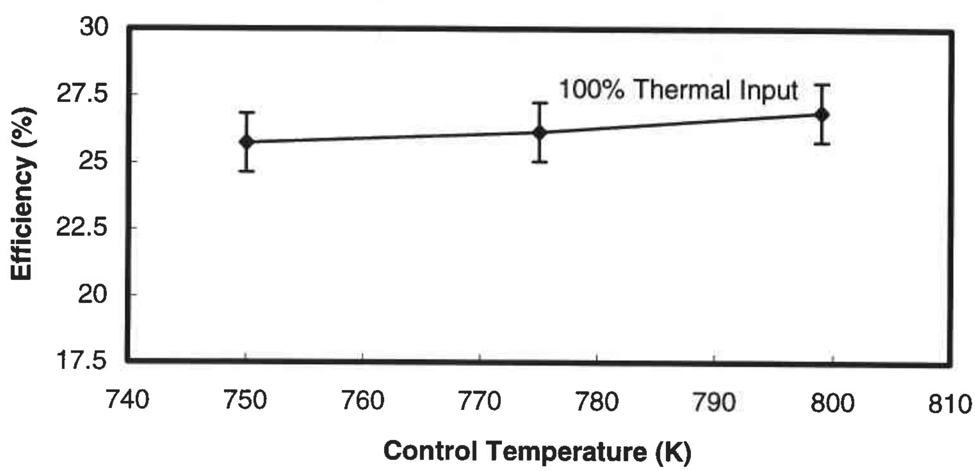


Figure 20. **Efficiency of the STM 4-120 power conversion system as a function of control temperature for three different input powers using hydrogen working fluid. The error bars indicate one standard deviation.**

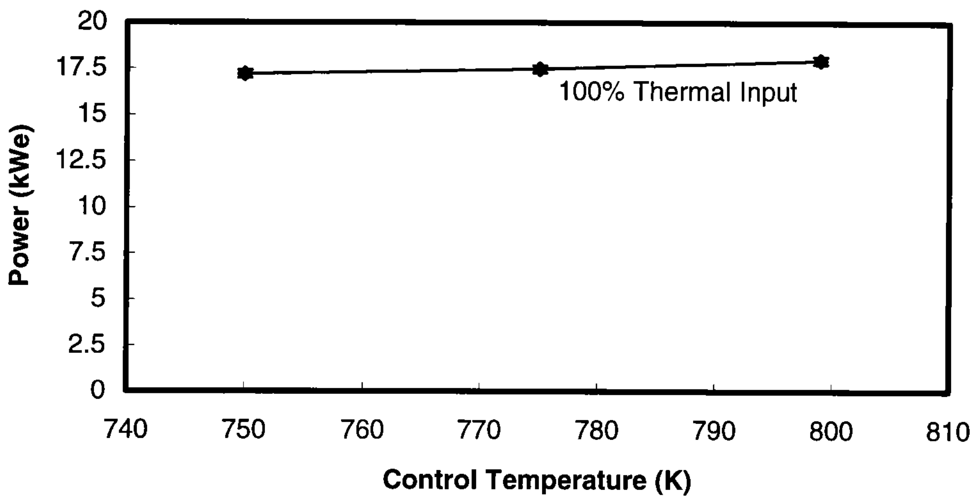


Figure 21. Net power of the STM 4-120 power conversion system as a function of control temperature for three different input powers using hydrogen working fluid. The error bars indicate one standard deviation.

FY96 Task Description

Testing of the STM 4-120 Stirling engine with a direct illumination receiver has been successfully completed. In FY96, the engine will be tested using a heat-pipe receiver. This test will provide a direct comparison of the two receiver types.

The NREC Brayton PCS will be assembled with the DLR volumetric receiver in the first quarter of FY96. After assembly, the PCS will be tested at NREC in a gas-fired mode for approximately one month. NREC will deliver the PCS to Sandia and install it on a test bed concentrator in the second quarter of FY96. Sandia will test the PCS for on-sun performance and operational characteristics.

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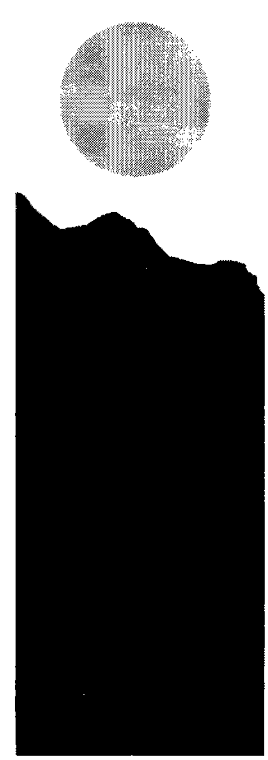

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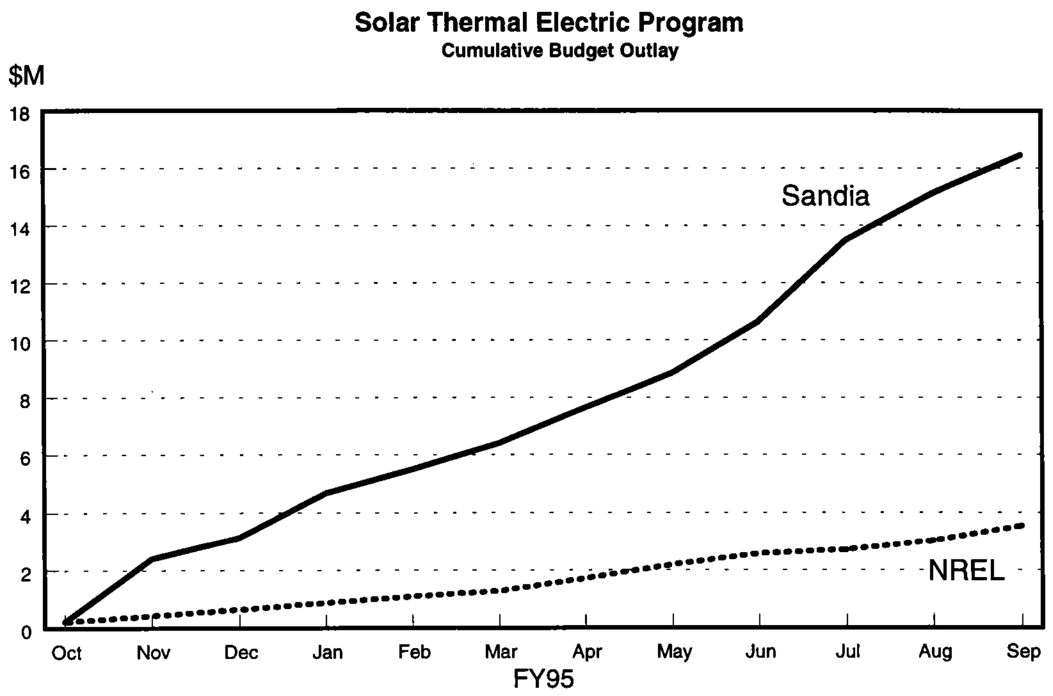
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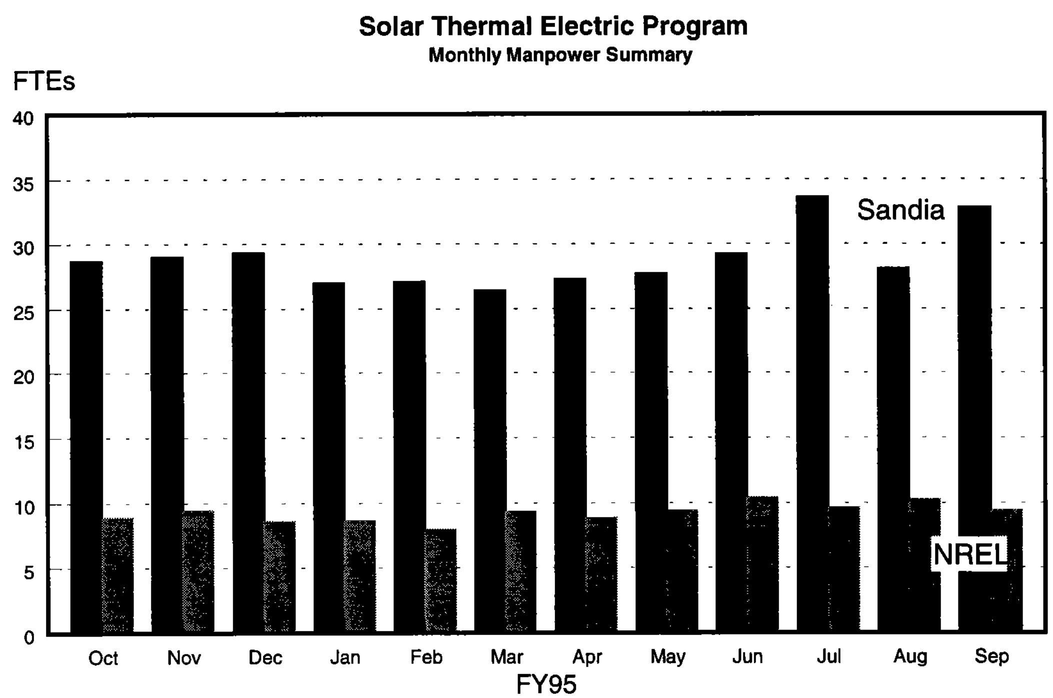
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Monthly Manpower Summary
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