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THE U. S. DEPARTMENT OF ENERGY'S ROLE IN COMMERCIALIZATION OF SOLAR THERMAL ELECTRIC TECHNOLOGY

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1. ABSTRACT

The U. S. Department of Energy (DOE) has supported the development of solar thermal electric (STE) technology since the early 1970s. From its inception, the program has held a long-term goal of nurturing STE technologies from the research and development (R&D) stage through technology development, ultimately leading to commercialization. Within the last few years, the focus of this work has shifted from R&D to cost-shared cooperative projects with industry. These projects are targeted not just at component development, but at complete systems, marketing approaches, and commercialization plans. This changing emphasis has brought new industry into the program and is significantly accelerating solar thermal's entry into the marketplace. Projects such as Solar Two in the power tower area, a number of dish/Stirling joint ventures in the modular power area, and operations and maintenance (O&M) cost reduction studies will be discussed as examples of this new focus.

2. KEY WORDS

Solar thermal electric; dish/Stirling; power towers; parabolic troughs; commercialization; partnerships.

3. INTRODUCTION AND SUMMARY

The United States Department of Energy's Solar Thermal Electric Program, in cooperation with industry and users, is developing two major types of modular solar thermal technology: power towers and parabolic dish/engine systems. Our major activities are cost-shared partnerships with industry designed to commercialize these technologies before the year 2000. Our success hinges on effectively combining the manufacturing, marketing, and management skills of industry with the solar-specific experience base and analytical and experimental capabilities of Sandia National

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Laboratories and the National Renewable Energy Laboratory (NREL). Presently, five major 50/50 cost-shared cooperative activities (with a total value over $150M) are underway within the program; and more are being initiated. Our technology development programs are targeted to support and enhance these cooperative activities, while providing ideas for the future.

In the power tower area, we have teamed with a consortium of utilities (led by Southern California Edison), industry, and DOE's Golden Field Office to initiate the $48M, 5-year Solar Two Project, a molten-salt retrofit of the 10-MWe Solar One Pilot Plant. Solar Two will bring together previously developed molten-salt components (including new receiver, steam generator, and thermal storage subsystems) into a system demonstration of a complete power plant. It will utilize the existing heliostat field, tower, and electric power generation system from Solar One. Successful operation beginning in 1995 will lead directly to the first 100- to 200-MWe commercial power tower plants by the end of the decade. Our power tower technology development activities include testing of instrumentation and other components in a molten-salt flow loop for evaluation and recommendations in support of the Solar Two Project, as well as a limited advanced development program (in cooperation with the International Energy Agency/ Solar Power and Chemical Energy Systems (IEA/SolarPACES)) to investigate internal salt-film receivers and volumetric receivers for air-based systems.

In the dish/engine area, we have initiated three dish/Stirling joint venture programs. The first, a $17M, 4-year project with Cummins Engine Company, is targeted toward remote power markets both in the U. S. and abroad, and will lead to commercially available 7-kWe systems within two to three years. The other two (one with Science Applications International Corporation and a second with Cummins) are aimed at providing 25-kWe systems for utility applications. These $18M (each), 5-year activities involve active utility participation throughout and will lead to 1-MWe demonstrations within 3 to 4 years and commercial systems near the end of the decade. Development activities supporting our dish/Stirling programs include stretched-membrane dish development and testing, liquid metal reflux receiver testing, and on-sun Stirling engine testing. We are also working in cooperation with IEA/SolarPACES partners to develop dish/Brayton systems for similar applications.

In support of all these activities, we are working cooperatively with the Kramer Junction Company on a $7M, 3-year Operations and Maintenance Cost Reduction Project to take advantage of the 50 plant-years of operating experience at the LUZ-built Solar Electric Generating Systems (SEGS) commercial solar trough plants to reduce O&M costs and improve performance of all future solar thermal plants. Although we do not currently provide financial support for trough system development activities, we do conduct limited receiver development and testing, as well as design assistance activities such as wind and earthquake load analyses, and development of anti-reflective and absorber surface coatings.

Supporting all the solar thermal areas are our optical materials program and solar manufacturing initiative. We have cost-shared collaborative research programs with several organizations that are investigating a range of alternative optical materials, including new polymer films and glass, to reduce the cost of electricity by decreasing life-cycle costs for solar concentrators. We are also initiating a solar manufacturing initiative to address manufacturing costs and issues in support of all STE technologies.

By focusing on these major cost-shared activities, the Solar Thermal Electric Program is leveraging its funding and maximizing the potential for near-term commercialization of the technology.

4. OUR PARTNERING PHILOSOPHY

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 (STE) and other alternative energy technologies in the years ahead.

To date, over 350 MWe of STE systems have been installed in the U. S., 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 a cost between 6 and 10 cents per kilowatt-hour, thus leading to direct competition with conventional technologies.

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

Our mission in the Solar Thermal Electric Program is to work with current and potential manufacturers and users of STE technology to conduct technology research, development, and validation to:

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

Our strategy to accomplish this mission is consistent with the objectives set forth by DOE's Office of Solar Energy Conversion in *SOLAR 2000: A Collaborative Strategy* [1]. The Department of Energy and its field laboratories (Sandia National Laboratories and the National Renewable Energy Laboratory) are:

- Increasing, through the following cooperative ventures, industrial participation in both the planning and execution of program elements:

- The Solar Two molten-salt power tower project led by Southern California Edison will provide the technical base for Solar 100, the first 100- to 200-MWe power tower plant.
- The Cummins Engine Company 7-kWe dish/Stirling system, designed for both remote and grid-connected applications, will be operated at utility and industrial sites.
- Two contracts awarded under the Utility-Scale Joint-Venture Program for 25-kWe dish/Stirling systems will result in at least one megawatt of dish/engine system capacity being installed by utilities.
- The operations and maintenance cost reduction study with the Kramer Junction Company will provide for lower levelized energy costs for power tower and dish/engine solar systems, as well as trough plants.

- Utilizing the analytical and experimental capabilities of the program and its laboratories to support and enlarge the technology's user, supplier, and decision-making constituency.
- Contributing to the DOE's Office of Energy Efficiency and Renewable Energy's goal of making solar thermal electric technology a viable option for both domestic and international power-generation markets.

The DOE's role in implementing this program strategy centers on the development of improved cost effectiveness and reliability of solar thermal electric components and the development of 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 continue lowering its cost. Implementation of our 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.

In this paper, we discuss advances in our power tower and dish/Stirling programs, as well as cross-cutting activities including optical materials development, operations and maintenance cost reduction, the solar manufacturing initiative, and design assistance.

5. POWER TOWER PROGRAMS

The DOE power tower commercialization program builds on the 10-MWe solar power tower experiment located near Barstow, CA. The Solar One Pilot Plant operated from 1982 until 1988 and proved the technical feasibility of solar power tower technology. Solar One used a water-filled receiver to produce steam and drive a turbine/generator. Energy was stored in an oil/rock thermocline storage tank. During its operation, Solar One produced more that 38 gigawatts of electrical power and was available more than 80% of the time, 95% during its final year of operation. Figure 1 is a photograph of the Solar One power plant.

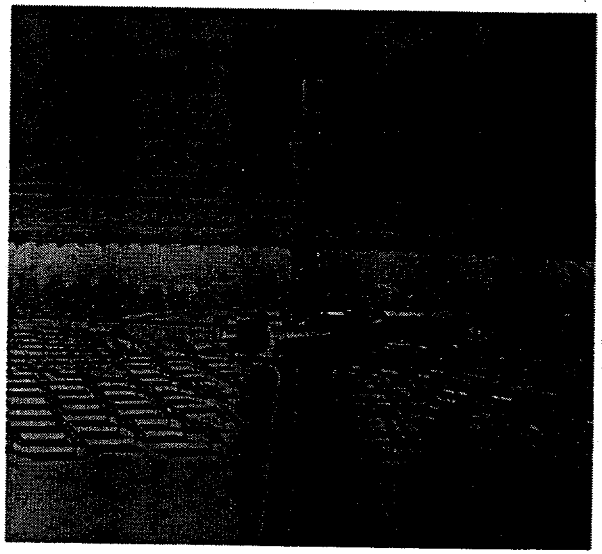

Figure 1. The Solar One Pilot Plant

In spite of its success, the Solar One Pilot Plant also demonstrated some important shortcomings: it had difficulty responding to cloud transients, the storage system was inefficient, and the direct water/steam system was difficult to operate. The next generation of power towers will utilize a molten salt system that addresses these problem areas.

Power towers utilize a field of mirrors, called heliostats, to reflect the solar energy onto the thermal receiver that is mounted on top of a centrally-located tower. The thermal energy collected is decoupled from the power generation by using a sodium/potassium nitrate salt as the working fluid. In the solar collection system, cold salt (melting point 230°C) is pumped out of a cold storage tank at a temperature of 285°C and through the thermal receiver, where solar flux at about 600-suns intensity heats the salt before delivering it to the hot storage tank at about 565°C. Electrical power is produced by removing the hot salt from the storage tank and passing it through a salt-to-steam heat exchanger, where steam is generated and delivered to the turbine/generator. Cold salt is then returned to the cold storage tank. In this way, solar energy can be collected whenever the sun shines; and power can be produced with a conventional turbine/generator system from storage whenever it is needed.

A consortium of seven U. S. utilities, led by Southern California Edison, has entered into a cooperative agreement with DOE to convert the Solar One Pilot Plant to use molten nitrate-salt technology. The objectives of the project are to reduce the economic risks of building the first generation of power tower plants and to accelerate their commercial acceptance. This project, called Solar Two, will meet these two objectives if it can demonstrate the successful operation of a molten-salt system in a conventional power production mode of operation. The six-year project will cost about $48 million (including $39 million for construction and $9 million for operations) and is cost-shared 50/50 between DOE and the utility consortium [2].

The conversion to Solar Two requires a number of changes to the existing plant. These include

- The removal of the existing rock/oil storage and thermal receiver;
- The design, fabrication, and installation of a molten-salt receiver, hot and cold salt storage tanks, and a molten-salt steam generator;
- An increase of the heliostat area in the south field to provide a more uniform solar flux to the molten-salt receiver; and
- The upgrade of the master control system and turbine/generator.

The project is in its second year with construction and installation of the components scheduled to begin in the last quarter of 1994 and initial operation of the plant scheduled for the third quarter of 1995. Once the plant is operational, it will be operated in a continuous, power production mode for up to three years.

Solar Two represents the first step in the commercialization of power tower technology. The next step will be to design and build a 100- to 200-MWe plant that will provide the necessary development, operational experience, and cost reduction to take us to the final step -- commercially accepted and economically competitive power tower plants.

6. DISH/STIRLING PROGRAMS

There are currently three major DOE projects in the area of solar dish/engine commercialization: the Cummins Power Generation (CPG) 7-kWe Dish/Stirling Project; the Utility-Scale (25-kWe) Joint Venture Project (USJVP); and an IEA/SolarPACES cooperative project to solarize a Brayton engine.

6.1 CPG Dish/Stirling Project

The CPG Dish/Stirling Project is a 50/50 cost-shared project to develop a 7-kW_e power-generation system for application in remote areas [3]. The project started in September of 1991 and will span a four-year period in which three generations of dish/Stirling technology are developed and tested. The $14 million project is cost-shared equally by CPG and DOE through Sandia National Laboratories.

The system comprises a solar concentrator, a heat-pipe thermal receiver [4], and a free-piston Stirling engine. The solar concentrator is a modification of the LaJet Energy Company LEC 460 design, which utilizes a geodesic space frame, a polar-axis drive, and stretched-membrane polymer mirror facets. The heat-pipe thermal receiver transfers the absorbed solar heat to the engine by evaporating sodium from the backside of the receiver and condensing it on the tubes of the engine heater head. The receiver design also has the ability to provide heat to the engine by burning natural gas. Hybridization of the receiver thus allows the system to generate electricity on demand, not just when the sun shines. CPG recently changed their baseline engine for this system to the Clever Fellow's Innovative Consortium free-piston Stirling engine. This system (with an earlier engine) has operated in excess of 1000 hours on-sun. Figure 2 is a photograph of the CPG dish/Stirling system.

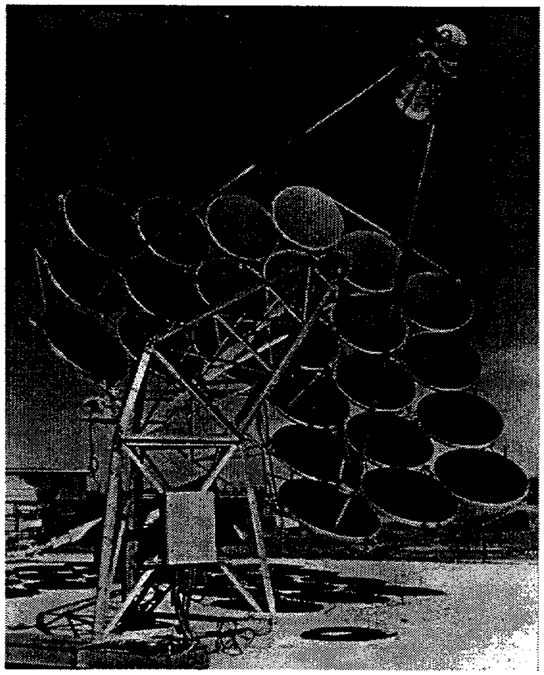

Figure 2. The Cummins 7-kWe Dish/Stirling System.

6.2 The Utility-Scale Joint Venture Program

The objective of the USJVP is to help industry develop and market commercial-scale dish/Stirling systems by the start of the twenty-first century. The five key elements of the program are:

- The projects are directed at the commercialization of dish/engine systems by the year 2000.
- There is a 50/50 cost share between the industry team and DOE.
- The projects will be ongoing about five years and will be comprised of three phases. The last phase is the production, installation, and testing of a 1 MWe plant.
- Utility involvement in the projects is required in all three phases.
- The projects are industry-led with support from the national laboratories.

Two projects were funded under the USJVP between November 1993 and January 1994: one with Science Applications International Corporation's (SAIC) Energy Projects Division in Golden, CO, and one with Cummins Power Generation, Inc. of Columbus, IN [3,5]. SAIC and CPG have both been funded for Phases I and II of the project (3 years for SAIC and 4 years for CPG) at a total cost of about $18 million each. Following the successful completion of the first two phases of the project, we will negotiate new contracts for Phase III. Phase III of the projects is estimated to cost between $15 and $20 million each, and will result in the installation of a 1-MWe plant for each contract.

SAIC leads a team comprised of Stirling Thermal Motors (STM) and Detroit Diesel Corporation (DDC) of Ann Arbor, MI, along with several utility partners. SAIC will provide the systems integration and the solar concentrator, which is a second-generation faceted stretched-membrane dish. STM will provide their kinematic Stirling engine and will lead the thermal receiver development activities. Detroit Diesel is responsible for designing parts of the engine for mass production and for manufacture of these parts in later phases of the project.

The team that CPG has brought together consists of companies and individuals that have extensive experience in their fields. The subsystems and components under development and the responsible companies are: solar concentrator -- WGAssociates of Dallas, TX, and CPG; free-piston Stirling engine -- Clever Fellows Innovative Consortium of Troy, NY; hybrid receiver -- Thermacore of Lancaster, PA.

The DOE is also working to integrate a Brayton engine with a volumetric receiver designed by the German Aerospace Research Establishment (DLR) in a cooperative IEA/SolarPACES project. In this project, the Northern Research Engineering Company, Woburn, MA, is mating their Brayton engine with DLR's receiver for testing on Sandia's Test Bed Concentrator. In addition, Israel's Weizmann Institute of Science will be providing an alternate receiver. This engine system is being considered as a backup to the Stirling engine by CPG.

7. CROSS-CUTTING ACTIVITIES

A number of our program activities broadly support the above projects. These include optical materials development, the operations and maintenance cost reduction activity, the solar manufacturing initiative, and design assistance center activities.

7.1 Optical Materials Development

Lightweight, durable, and efficient optical reflector materials are necessary to achieve cost and performance goals associated with 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 the key requirements. The objective of our optical materials activity is to develop concentrator reflector materials that have improved durability and performance, increased service lifetimes, and decreased cost.

During 1994, the optical materials program [6] has been organized around several specific tasks. Advanced reflector development continues the program started in 1992, aimed at broadening the candidates for low-cost, high-performance reflector materials. The majority of this work will be carried out in collaboration with industry. We are adding one or two promising new candidate materials to those that are currently being pursued. Outdoor optical testing will continue as a major thrust area. During 1994, we have activated two additional outdoor exposure test sites. Additional candidate materials will be placed into test as appropriate. Industry support will be aimed at providing industry with testing capabilities, responding to critical industry needs in optical materials testing and/or development, and facilitating technology transfer to the industry. Material testing includes ongoing laboratory testing of materials durability and failure mechanisms.

7.2 O&M Improvement Study

By far, the most mature of the three solar thermal electric technologies is represented by the nine trough Solar Electric Generating Systems (SEGS) operating in the Mojave Desert of Southern California. These nine plants deliver 354 MWe to Southern California Edison's power grid, which is approximately 90% of the solar electricity generated in the world today. Troughs in operation at the SEGS plants at Kramer Junction, CA, are shown in Figure 3.

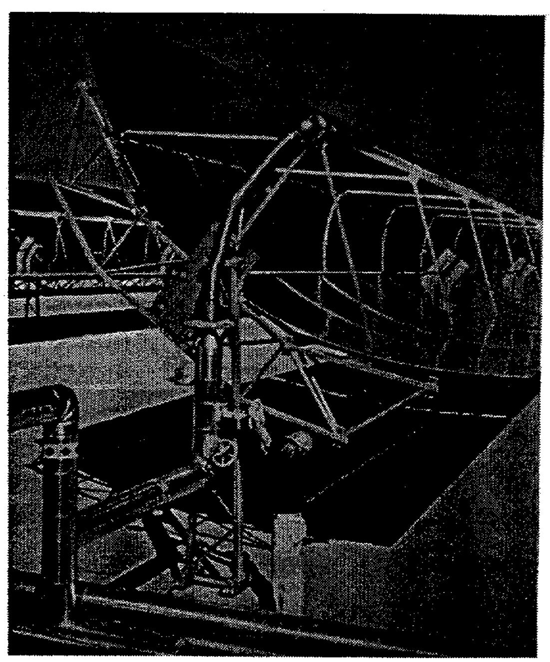

Figure 3. SEGS troughs in operation.

The nine SEGS plants utilize a total area of about 2.3 million square meters of trough concentrators to heat a synthetic oil that flows through the receiver tube along the focus of the concentrators. The oil is heated to temperatures of 300° to 400°C, depending on the plant. The hot oil is then circulated through a heat exchanger where it generates steam that powers a conventional Rankine cycle turbine/generator. When solar heat is not available, natural gas can be burned to generate peaking power. The SEGS plants were built by LUZ International Limited and are owned by private investors.

One of the major challenges facing the SEGS plants is the reduction of operating and maintenance (O&M) costs. O&M costs represent more than 25% of the electricity costs at SEGS. Reducing the O&M costs would improve the economics of the plants and the ability to sell future plants. Furthermore, since O&M costs for the SEGS plants are expected to be similar to those of both power tower and dish/Stirling plants, a better understanding of these costs will benefit all three technologies. Through Sandia National Laboratories, the DOE has developed a 50/50 cost-shared project with the Kramer Junction Company (KJC) Operating Company to evaluate and reduce the O&M costs associated with the SEGS plants III through VII. [7]

The first step in this process was to characterize the O&M costs. This was done by carefully documenting the reasons for plant outages at SEGS III through VII during a 3-year period. Key loss mechanisms included forced (24%) and scheduled (15%) outages, degraded heat collection elements (HCEs) (22%), and field alignment (13%). All of these problems were due to problems with early plants, and the development of appropriate designs and components eliminated them in the later ones. Means of decreasing costs and improving performance in these areas are being investigated.

A number of additional issues are being addressed by the KJC Operating Company and Sandia. These include improved data collection and more efficient O&M planning, improved Cermet receiver tube coatings, development of a new reflectometer to more easily determine when to wash the collector fields, and adding rotating joints to replace high-maintenance flexible hoses.

The performance of the SEGS plants has evolved from the initial performance demonstrated at SEGS I to the level represented by SEGS IX. The motivation for design has been for more cost-effective energy production. As a result, the systems have become larger (SEGS I was 14 MWe while SEGS IX is 80 MWe) and are located near one another in three energy parks so they can share O&M activities. The most recent plants are projected to operate at about 12% efficiency and are projected to produce electricity for 8 to 9 cents/kWh, with maintenance costs of about 2 cents/kWh.

The purpose of the O&M study is to help the KJC Operating Company address the issues that are causing high O&M costs. The information learned from this study will also be useful to better understand the O&M costs for power tower and dish/Stirling power plants.

7.3 Solar Manufacturing Initiative

The objectives of our solar manufacturing (SolMat) initiative are to:

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

Progress in the DOE program in collaboration with private industry has brought power tower and dish/engine technology to the point where remaining technical issues that inhibit commercial sales are expected to be resolved over the next few years. The final hurdle for these technologies is not a technical barrier but a business barrier: how to develop system designs and manufacturing processes that will allow the early sales necessary for commercial demonstration of the technology and the creation of a viable U. S. solar thermal electric industry.

The solar thermal industry today faces a market environment with opportunities, but also challenges. At least two new technologies, the power tower and dish/engine systems, will be technically ready for commercial deployment within the next few years. Utilities and public utility commissions (PUCs) express growing interest in these technologies, and there also appear to be international opportunities for sales. The market environment will, however, be difficult to penetrate quickly given fairly stable fossil fuel prices and attractive competing technologies. The 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 for allowing solar thermal manufacturers to produce cost-effective products even before market demand will support high volume production.

The majority of SolMat funding is expected to be used in collaborative, cost-shared activities with industry. Two general types of activities are being pursued in 1994:

- Manufacturing Improvement Projects are targeted toward companies that are close to having commercially viable products, but need to improve certain characteristics (such as cost or reliability) of components in order to enter the market. These projects are intended to develop improved methods of manufacturing and product deployment that will make the industry more competitive in early markets. Cost sharing will be a requirement for these projects, with the degree of cost share dependent on the total funding requirement and the risks involved in the project.
- Validation and Implementation Projects are intended to demonstrate improvements in manufacturing and deployment, and provide confidence in the cost and reliability of the components. Cost sharing will be a requirement for these projects, with the degree of cost-share dependent on the total funding requirement and risks involved in the project.

Two procurements are currently anticipated in 1994. The first procurement will be aimed at improving the market readiness of heliostats for power tower applications. The objective of the request for proposal (RFP) will be to improve existing designs and manufacturing processes for heliostats produced at 3000-10,000 units per year, in a market with uncertain out-year sales. A multiphase study is anticipated. In the first phase, contractors will focus on identifying process and design improvements for reducing manufacturing costs of heliostats. Scope and activities are up to the discretion of the manufacturer. Later phases of the studies will focus on implementing the design and process improvements, validating cost reductions, and validating performance and operating characteristics of final products. Funding for later phases of the project will be contingent on adequate performance on each phase, as established by meeting performance objectives established with industrial partners. Responses to the RFP have been received and are being evaluated.

The second procurement in 1994 will be a general solicitation to manufacturers of solar thermal components for manufacturing improvement studies. Participants in these studies will be expected to have demonstrated viable components and have business plans for bringing these components to the market. Types of components that could be included in the study include (but are not limited to) glass-metal parabolic dishes and liquid-metal reflux receivers. Activities funded in this solicitation could potentially move into validation and implementation projects (as in the heliostat solicitation) in later years, but there will be no requirements or commitments for continuing the activities. Multiple awards are anticipated.

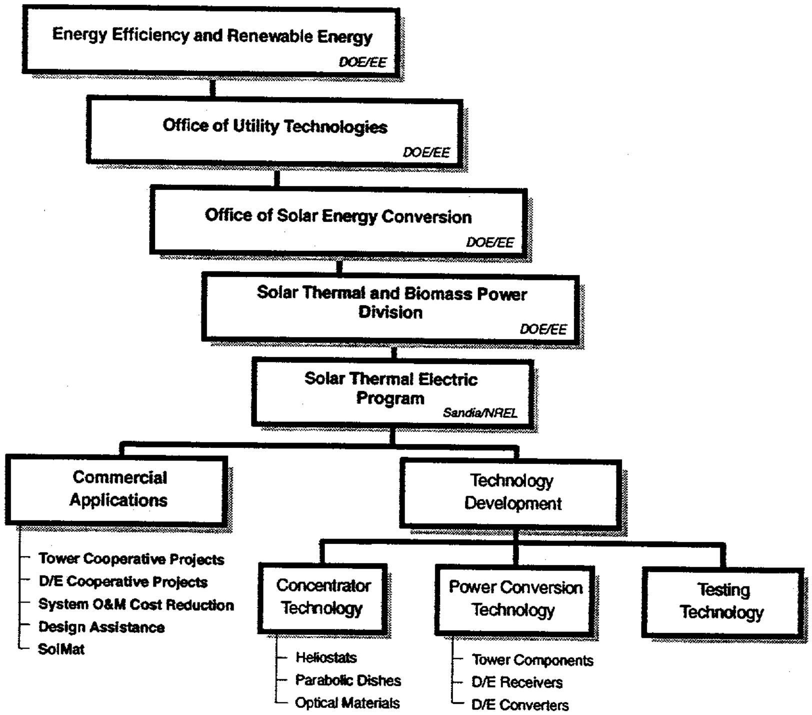

Figure 4. DOE's Organizational Chart for the Solar Thermal Electric Program

7.4 Design Assistance Activities

The objective of our design assistance activities is to accelerate the use of solar thermal systems through the following technology transfer activities: (1) direct assistance to end users of solar thermal technology by providing information about the selection, characterization, and performance of solar thermal systems; (2) cooperative solar thermal technology test, evaluation, and development efforts with the solar thermal industry; and (3) educating potential users about the economic performance and potential of solar thermal technology.

In order to be effective, the solar thermal program requires a continual flow of information to and from the industry and users. The program's dissemination of R&D results to industry, and the reciprocal communication of industry's needs to the program, are necessary to keep the R&D relevant and to ensure developments are rapidly implemented by industry. This activity is organized through the Solar Thermal Design Assistance Center (STDAC) at Sandia. The design assistance task fosters this flow of information by providing direct technical assistance to users and industry as well as through conferences, workshops, and publications. This task also provides an interface between the solar thermal program, CORECT (Committee on Renewable Energy, Commerce, and Trade), and the Solar Energy Industries Association (SEIA) to foster near-term applications of solar thermal systems in the international marketplace.

The STDAC at Sandia receives requests for assistance and coordinates efforts with NREL to provide information and to fulfill industry requests for technology evaluation and development, application screening, data, and design evaluation to assist industry and users in implementing the solar thermal option. Existing analysis tools and data are used to provide this assistance, and additional industry needs for improved techniques are being considered and acted upon.

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