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An Assessment of Solar Thermal Concentrator Research and Development

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AN ASSESSMENT OF SOLAR THERMAL CONCENTRATOR RESEARCH AND DEVELOPMENT

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ABSTRACT

Concentrator research and development has been an integral part of the solar thermal technology program since its beginning. Within the central and distributed receiver programs, a considerable amount of research and development has been successfully concluded: over twenty-five line focus (mostly parabolic trough) designs, thirteen heliostat designs, and eight parabolic dish designs have been fabricated and tested under Department of Energy sponsorship; mass-production costs have been estimated for several of these designs; and materials and components research is under way to identify areas for both cost and performance improvements. An overall assessment of this work has recently been performed to determine future research and development needs. This report describes the results of this assessment and presents recommendations for future concentrator research and development.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

Concentrator research and development (R&D) has been an integral part of the solar thermal technology (STT) program since its beginning. Within the central and distributed receiver programs, a considerable amount of R&D has been successfully concluded: over twenty-five line focus (mostly parabolic trough) designs, thirteen heliostat designs, and eight parabolic dish designs have been fabricated and tested under Department of Energy (DOE) sponsorship. Mass-production costs have been estimated for several of these designs, and materials and components research is under way to identify areas for both cost and performance improvements.

Although significant progress has been achieved, an overall assessment of concentrator R&D was required to determine future R&D needs. We have performed such an assessment and derived recommendations for future R&D on the basis of the following approach:

(1) determine the development status of each concentrator technology;

(2) assess the capability of each technology, when mass-produced, to achieve near-term and long-term cost targets;

(3) identify technology options or development approaches that offer a good potential for meeting these targets; and

(4) identify additional study areas that could lead to further concentrator R&D needs.

In this approach, we did not perform detailed engineering analyses to derive specific R&D tasks. Rather, we examined concentrator R&D needs from a broader perspective. We assessed past R&D efforts and identified an approach for using the most successful results to bring technically deficient areas to a comparable stage of development. We reviewed ongoing R&D studies to identify the most fruitful areas for achieving the long-term cost targets of the program. Finally, we identified further studies that could provide additional insights into R&D needs (concentrator as well as other solar components) but were outside the scope of our planned study.

It is important to emphasize that our assessment was limited to concentrators. Therefore, we made no attempt to assess the attractiveness of solar thermal systems for different applications. Several studies of this type have been completed for electric and industrial process heat applications and are reported in References 1 to 3. Additional system assessments will be required to determine if new program thrusts, such as the R&D of high-temperature systems for fuels and chemicals production, are justified. Our concentrator recommendations are obviously predicated on a favorable decision-to-proceed for these systems. For example, if central receiver systems are deemed unattractive for high-temperature fuels and chemicals production, then it would not make sense to conduct heliostat R&D for this application.

In this report we describe our observations and our recommendations for future R&D. In presenting recommendations, we have not attempted to establish priorities for concentrator R&D vis-a-vis other solar R&D needs (receivers, storage, etc.). However, we have set priorities within the purview of the concentrator R&D program itself.

The next two chapters present the status of the concentrator R&D. First, we describe the history of technology development for the major concentrator types: heliostat, line focus, and parabolic dish. Second, we describe the manufacturing activity and cost estimate history for each concentrator type. Our assessment of these past activities, as well as ongoing ones, is described in the following chapter. The last chapter offers our recommendations for future concentrator R&D.

2.0 HISTORY OF CONCENTRATOR DEVELOPMENT

In the STT program, two broad classes of systems are being developed: central receiver systems and distributed receiver systems. In the central receiver system, a large number of concentrating tracking elements called heliostats are controlled to reflect the sun's energy to the same centrally located receiver. In the distributed receiver system, the receiver is integral with the concentrating element, forming a modular unit. The concentrating element can be either a point-focusing parabolic dish or one of several line focus types, such as a parabolic trough or hemispherical bowl. The modular units are grouped in sufficient numbers to meet the needs of the selected application.

Concentrator development has been under way since the mid-1970's. Tables I to III summarize the heliostat, line focus, and dish designs, respectively, that have reached the prototype or production stage through DOE sponsorship. Additional conceptual design studies, materials research, and component development have been performed but are too numerous to be listed in the tables.

2.1 Heliostat Development

In 1975, heliostat development was initiated for the 10 MWe Solar Thermal Central Receiver Pilot Plant in Barstow, California. Four contractors were selected to design, fabricate, and test these first-generation heliostats. Two design approaches were used: second-surface, silvered glass mirrors mounted on reinforced steel structures; and plastic reflectors mounted inside air-supported domes of clear plastic, which protect the mirrors from wind loads and greatly reduce structural weight. Testing of the glass/steel heliostats by McDonnell Douglas, Martin Marietta, and Honeywell and of the plastic heliostat by Boeing was completed in 1977. The McDonnell Douglas central pedestal concept was then selected for the Barstow pilot plant. After production prototypes were built by McDonnell Douglas and Martin Marietta and tested at the Central Receiver Test Facility (CRTF), Martin Marietta was selected to produce and install the pilot plant heliostats. In 1981, Martin Marietta completed the installation of 1818 heliostats at the pilot plant.

A second early effort was the development of heliostats for the CRTF. These heliostats were designed to match the unique requirements of the test facility. In early 1977, Martin Marietta completed production and installation of 222 heliostats for the CRTF. The design was a variation of their original concept for the pilot plant heliostats and used smaller adjustable-focus mirrors to accommodate small test facility targets at various tower elevations.

Heliostat conceptual designs were then developed under DOE prototype heliostat contracts by Boeing, General Electric, McDonnell Douglas, and Solaramics, Inc. The purpose of these studies was to reduce significantly the cost of heliostats from those costs estimated for the Barstow pilot plant. Both glass/steel and polymer enclosure heliostat designs were

TABLE I. DOE HELIOSTAT DEVELOPMENT

PROGRAM	DESIGN ORGANIZATION	DESIGN	DEVELOPMENT STATUS
National Science Foundation	McDonnell Douglas	Front-surface, silvered glass, steel frame	Prototype
Barstow Pilot Plant Subsystem Research Experiments	Boeing	Aluminized Mylar within a plastic protective dome	Prototype
	Honeywell	Second-surface, silvered glass, steel-aluminum honeycomb-steel sandwich	Prototype
	Martin Marietta	Second-surface, silvered glass, steel-aluminum honeycomb-steel sandwich	Prototype
	McDonnell Douglas	Second-surface, silvered glass, styrofoam-steel sandwich	Prototype [a]
Central Receiver Test Facility	Martin Marietta	Laminated, silvered glass, steel frame	Production
Barstow Pilot Plant	Martin Marietta	Second-surface, silvered glass, steel-aluminum honeycomb-steel sandwich	Production
	McDonnell Douglas	Second-surface, silvered glass, styrofoam-steel sandwich	Prototype
Second Generation	ARCO	Second-surface, silvered glass, steel-steel channel-steel sandwich	Prototype [b]
	Boeing	Second-surface, silvered glass, Foamglas-glass sandwich	Prototype
	Martin Marietta	Second-surface, silvered glass, steel-paper honeycomb-steel sandwich	Prototype
	McDonnell Douglas	Laminated, silvered glass, steel frame	Prototype

[a] McDonnell Douglas fabricated and tested both inverting and non-inverting heliostat designs. Inverting designs with laminated, silvered glass and second-surface, silvered glass bonded to a styrofoam-steel sandwich and non-inverting designs with laminated, silvered glass and front-surface, silvered glass were tested. The preferred design, which was inverting, had a second-surface, silvered glass reflector bonded to a styrofoam-steel sandwich structure.

[b] ARCO has also produced 30 of these heliostats for its privately financed enhanced oil recovery plant near Bakersfield, California.

TABLE II. DOE LINE FOCUS DEVELOPMENT

PROGRAM	DESIGN ORGANIZATION	DESIGN	DEVELOPMENT STATUS
Solar Total Energy Test Facility	Sandia	Parabolic trough: aluminized Teflon, formed plywood	Prototype
	Sheldahl	Moving Fresnel reflector/fixed receiver (SLATS): second-surface, silvered glass, sheet steel-plywood sandwich	Prototype
	General Atomics	Fixed Fresnel reflector/moving receiver: second-surface, silvered glass, concrete	Prototype
	Custom Engineering	Parabolic trough: second-surface, silvered glass, fiberglass	Prototype
Willard, New Mexico Shallow Well Irrigation Pumping Experiment	Acurex	Parabolic trough: polished aluminum, sheet steel	Production
	Solar Kinetics	Parabolic trough: aluminized acrylic, aluminum monocoque	Production
Coolidge, Arizona Deep Well Irrigation Pumping Experiment	Acurex	Parabolic trough: polished aluminum, sheet steel	Production
	Acurex	Parabolic trough: aluminized acrylic, sheet steel	Production
Industrial Process Heat Projects	Solar Kinetics	Parabolic trough: aluminized acrylic, aluminum monocoque	Production [a]
	Suntec, Hexcel	Parabolic trough: aluminized acrylic, aluminum-aluminum honeycomb-aluminum sandwich	Production [b]

[a] Caterpillar Tractor, USS Chemicals, Southern Union Refining, Lone Star Brewery

[b] Dow Chemical, Ore-Ida Foods

TABLE II. DOE LINE FOCUS DEVELOPMENT (continued)

PROGRAM	DESIGN ORGANIZATION	DESIGN	DEVELOPMENT STATUS
Industrial Process Heat Projects (cont.)	Jacobs-Del	Moving trough/fixed receiver: second-surface, silvered glass, steel frame	Production [c]
	Acurex	Parabolic trough: aluminized acrylic, sheet steel	Production [d]
Crosbyton, Texas Analog Design Verification System	Texas Tech, E-Systems	Hemispherical bowl: second-surface, silvered glass, paper honeycomb-steel sandwich	Prototype
Miscellaneous	FMC Corporation	Moving Fresnel belt reflector/fixed receiver: second-surface, silvered glass, flexible belt	Prototype
	McDonnell Douglas	Moving Fresnel refractive concentrator: cast acrylic refractor	Prototype
	Scientific Atlanta	Fixed Fresnel reflector/moving receiver: second-surface, silvered glass, sheet steel	Prototype
	Polisolar (Soltrax)	Moving trough/fixed receiver: second-surface, silvered glass, sheet steel	Prototype
	General Electric	Fixed trough/fixed receiver (CPC): aluminized acrylic, sheet steel	Prototype
Engineering Prototype Trough (EPT)	Sandia	Parabolic trough: second-surface, silvered glass, steel-aluminum honeycomb-steel sandwich	Prototype

[c] Home Laundry

[d] Johnson & Johnson

TABLE II. DOE LINE FOCUS DEVELOPMENT
(continued)

PROGRAM	DESIGN ORGANIZATION	DESIGN	DEVELOPMENT STATUS
Performance Prototype Trough (PPT)	Sandia, Budd	Parabolic trough: second-surface, silvered glass, stamped sheet steel	Prototype
	Sandia, Budd	Parabolic trough: second-surface, silvered glass, sheet molding compound	Prototype
	Sandia, Budd	Parabolic trough: second-surface, silvered glass, steel frame	Prototype
	Sandia, Parsons	Parabolic trough: second-surface, silvered glass, steel-aluminum honeycomb-steel sandwich	Prototype
Line Focus Program Research and Development Annnouncement (PRDA)	Acurex	Parabolic trough: second-surface, silvered glass, sheet steel	Prototype
	Solar Kinetics	Parabolic trough: second-surface, silvered glass or aluminized acrylic, steel monocoque	Prototype
	Suntec	Parabolic trough: second-surface, silvered glass, steel frame	Prototype
Modular Industrial Solar Retrofit (MISR)	Acurex	Parabolic trough: second-surface, silvered glass, sheet steel	Prototype
	BDM, Solar Kinetics	Parabolic trough: aluminized acrylic, aluminum monocoque	Prototype
	Custom Engineering, Budd	Parabolic trough: second-surface, silvered glass, stamped sheet steel	Prototype
	Foster-Wheeler, Suntec	Parabolic trough: second-surface, silvered glass, steel frame	Prototype
	Solar Kinetics	Parabolic trough: aluminized acrylic, steel monocoque	Prototype

TABLE III. DOE DISH DEVELOPMENT

PROGRAM	DESIGN ORGANIZATION	DESIGN	DEVELOPMENT STATUS
Sandia Solar Total Energy Test Facility	Raytheon	Second-surface, silvered glass, aluminum frame	Prototype
Shenandoah Solar Total Energy Project	General Electric, Solar Kinetics	Aluminized acrylic reflective film, stamped aluminum sheet	Production
Test Bed Concentrators	E-Systems	Second-surface, silvered glass, Foamglas	Prototype
Capitol Concrete	Power Kinetics, Inc.	Second-surface, silvered glass, foam core with sheet metal skin	Prototype
Southern New England Telephone Company Experiment	Omnium-G	Polished aluminum sheet, polyurethane foam	Prototype
Rankine Module	General Electric, Ford Aerospace & Communication	Aluminized polyester reflective film, glass-reinforced plastic-balsa wood sandwich	Prototype
Rankine Module	Acurex	Second-surface, silvered glass, Foamglas	Design/ Prototype Components
Stirling Module	Advanco	Second-surface, silvered glass, Foamglas	Prototype
Brayton Module	La Jet	Aluminized polyester reflective film, vacuum shaped	Prototype [a]

[a] This concentrator is also being produced for the La Jet 4.5 MWe power plant in Warner Springs, California

studied. Each contractor developed a heliostat design with associated manufacturing, assembly, installation, and maintenance approaches. Capital as well as operations and maintenance costs were estimated. Follow-on materials development contracts were awarded to Boeing and General Electric for plastic development, while component development was pursued at McDonnell Douglas and Solaramics. The conceptual designs were completed in 1978.

In 1979 second-generation heliostat development contracts were awarded to ARCO, Boeing, McDonnell Douglas, Martin Marietta, and Westinghouse. These contracts provided for detailed heliostat design and prototype fabrication, and production planning and cost estimates. The designs were all of the glass/steel generic type but differed in how the glass and steel were coupled. Typical approaches varied from bonding the glass directly on a thin sheet of steel to coupling the glass and steel with a grease that held the glass on the steel by capillary forces. (The glass was prevented from sliding off the steel sheet by edge restraints.) A significant life-cycle cost reduction was accomplished in these second-generation designs as a result of new design concepts, design optimization, and mass production techniques. Two prototypes from each of four contractors were successfully tested at the CRTF in 1981. The Westinghouse study was terminated prior to completion.

2.2 Line Focus Development

From 1975 to 1982, over twenty line-focus collector designs were fabricated and tested at user sites or at the Sandia Midtemperature Solar Systems Test Facility (first called the Solar Total Energy Test Facility) in Albuquerque, New Mexico. These designs included parabolic troughs and a variety of alternate technology options: tracking concentrator-fixed receiver (SLATS), fixed concentrator-fixed receiver (CPC), and fixed cylindrical concentrator-moving receiver. In addition, component development was carried out in the areas of foundations, support pylons, drive systems, flexible hoses, tracker/controllers, black chrome selective coatings, receivers, trough structures, and reflectors.

In recent years, the major program emphasis has been the development of parabolic troughs. Three major activities have been performed: (1) performance prototype trough (PPT); (2) Line Focus Program Research and Development Announcement (PRDA); and (3) Modular Industrial Solar Retrofit (MISR).

The objective of the PPT activity was to design, fabricate, and test high-efficiency and high-reliability trough collectors that use mass-production technology to lower manufacturing costs. Development of PPT began in 1979 as an effort to apply lessons learned during the development of earlier parabolic trough collectors. The goal was to improve trough peak performance to 60 percent at 316°C (600°F) from the 40 to 50 percent performance of first-generation designs. Also, durability in terms of component life was to be improved from less than 3 years to 20 years. First-generation designs did not lend themselves to mass production, a feature necessary for achieving low cost; consequently, the new effort emphasized improved designs that would be suitable for mass production.

The first step in this development effort was the design, fabrication, and testing of an engineering prototype trough (EPT) which achieved a 60 percent peak efficiency at 316°C (600°F). At the same time, different manufacturing concepts were studied to adapt trough designs to mass-production processes. The PPT program built a 96 m (315 ft) long "delta temperature"* string that consisted of four drive strings, each 24 m (79 ft) long. The strings used second-surface, silvered glass reflectors with different reflector structure construction techniques: stamped sheet metal, sagged glass on stamped steel ribs (space frame), steel-faced aluminum honeycomb, and sheet molding compound. The PPT troughs were developed and fabricated by industrial firms. Testing and evaluation were performed at SNLA and successfully completed at the end of 1982: the PPT troughs achieved peak efficiencies of 62-65 percent at 316°C (600°F).

The objective of the Line Focus PRDA was to adapt existing commercial trough component and subsystem designs to mass-production techniques. In 1980, contracts were awarded to Acurex, Solar Kinetics, and Suntec for subsystem development and to Acurex and Winsmith for component development. During 1982, trough components and subsystems were assembled and tested at contractor sites.

Most recently, a modular design approach that minimizes cost and improves operational reliability is being studied for line focus systems. This project, named MISR, is developing line focus systems for the retrofit of low- to medium-temperature industrial process heat (IPH) applications. Contracts were awarded in 1981 to Acurex, Solar Kinetics, BDM Corporation, Custom Engineering, and Foster-Wheeler. Five modular trough systems have been built and tested -- four at the CRTF and one at the Solar Energy Research Institute (SERI).

Line focus systems that use parabolic trough or hemispherical bowl technologies have also been built for electric power and IPH applications. Parabolic troughs have been used in several system experiments, including the International Energy Agency 0.5 MWe distributed collector project in Almeria, Spain. They have been used in a large number of IPH experiments and in irrigation pumping experiments at Gila Bend, Arizona; Willard, New Mexico; and Coolidge, Arizona. Lastly, a prototype hemispherical bowl 20 m (65 ft) in diameter was constructed and tested for an electric power application in Crosbyton, Texas.

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*A "delta temperature" string is a group of collectors assembled together or controlled in such a way as to provide a specified difference in temperature between the inlet of the group and the outlet from the group. The difference in temperature is dictated by the thermodynamic requirements of the design and the application.

2.3 Parabolic Dish Development

Dish development has evolved into two generic dish types: dish concentrators with both a receiver and a power conversion unit mounted at the focus of the dish and dish concentrators with only a receiver at the focus of the dish. They are deemed "dish electric" and "thermal dish" concentrators, respectively, although, if desired, a thermal dish could also be mated to a power conversion unit on the ground to produce electricity. Historically, the main distinction between the two concentrator types has been the operating temperatures that they were designed to achieve in each receiver. Dish electric concentrators are high-performance concentrators, requiring a high concentration ratio to achieve a high operating temperature. Depending on the application, thermal dishes could also be required to achieve a high operating temperature, but early program emphasis has been on lower temperature applications. The distinction between the two concentrator types should lessen if the thrust of the overall program shifts to higher temperature applications.

Dish Electric Development -- The STT dish electric development program, in its early years, was similar to the heliostat development program. That is, a number of industrial firms were selected to design and develop dish concepts in a parallel, competitive fashion. In 1978, conceptual design contracts were awarded to Acurex, Boeing, and General Electric to develop a low-cost dish concentrator capable of providing high thermal flux to a receiver operating up to 816°C (1500°F). General Electric and Ford Aerospace and Communications Corporation also performed concentrator conceptual designs as part of early system design activities.

On the basis of the completed design studies, General Electric was awarded a contract for the design and fabrication of a prototype unit (PDC-1). The reflector surface consists of a metalized plastic film bonded to a glass-reinforced plastic sandwich substrate. Fabrication of the reflective panels was completed in 1981. Because of a cost overrun, the General Electric contract was rescoped, and Ford Aerospace and Communications Corporation was selected to fabricate and install the PDC-1 concentrator. Although some difficulty was experienced in assembling PDC-1, this difficulty was overcome and satisfactory test results have been achieved. Development of the Acurex design (a triangular array composed of three nested paraboloids with a common focus), the Boeing design (an enclosed, air-pressure-stabilized membrane reflector), and the Ford design (laminated glass reflectors attached to a steel truss work) was discontinued. An E-Systems Fresnel lens design and a second Boeing design that used a reflective film bonded to steel were subsequently studied but were also dropped from the program.

In 1979, Acurex was awarded a contract to design, fabricate, and test an alternate concentrator design. This design (PDC-2) uses a second-surface, silvered glass reflector bonded to Foamglas. The conceptual design of the concentrator and the development of the reflector gores were completed in 1981, but fabrication of a full-scale unit was delayed because of funding limitations.

The only other major dish electric concentrator activity has been the design, fabrication, and characterization of two Test Bed Concentrators

(TBCs). These units were built by E-Systems primarily as test vehicles for characterizing future concentrators and, specifically, for the testing and evaluation of focus-mounted power conversion units. The units were designed for durability and test flexibility but were not designed to be lightweight or low-cost in mass production.

Funding constraints, therefore, have limited the fabrication and testing of these early designs to the two TBCs, one full-scale prototype unit (PDC-1), and mirror facet (gore) prototypes for a second unit (PDC-2). The PDC-1 concentrator was originally selected for the organic Rankine module* experiment but was later replaced by PDC-2. However, plans for additional development of both PDC-2 and the organic Rankine module are uncertain at this time. Additional concentrators are being developed for Stirling and Brayton module experiments. Advanco has designed and fabricated for its Vanguard Stirling module experiment a single-pedestal design with facets like the TBCs. These feature second-surface, silvered glass bonded to a Foamglas substrate. A concentrator that was privately developed by La Jet and uses pressure-stabilized membrane reflectors has been selected for a DOE-sponsored Brayton module experiment and a privately financed 4.5 MWe power plant in Warner Springs, California. The Warner Springs plant is actually a thermal dish facility: the dish collectors generate superheated steam that is routed to a central steam turbine.

Thermal Dish Development -- Thermal dish development has emphasized, up to now, total energy (cogeneration) applications. Initially, Raytheon built and Sandia National Laboratories Albuquerque (SNLA) tested a prototype dish for an SNLA total energy facility (now deactivated). The dish used second-surface, silvered glass mirror segments mounted on an aluminum substructure. Other efforts in this area emphasized the development and characterization of concentrators for the Shenandoah Solar Total Energy Project. Four prototype concentrators with receivers were built by General Electric and installed and tested at SNLA. Alternative reflective surfaces were evaluated, and a metal acrylic reflective film surface was chosen for Shenandoah. Following completion of the prototype testing, Solar Kinetics was selected to supply and install the Shenandoah dishes. Over 100 production units have been installed at Shenandoah and are undergoing testing.

Other thermal dish designs were initially developed under private sponsorship by Power Kinetics, Inc. (PKI) and Omnium-G. These designs were subsequently introduced into the DOE program to develop dish systems. The PKI concentrator consists of rows of segmented mirrored glass tiles that are bonded to rectangular support slats. A prototype unit is presently in operation at Capitol Concrete Products and is being used to cure concrete blocks. A second unit, initially tested at SNLA, has been installed at Hill Air Force Base. Also, a unit initially designed and built by Omnium-G was used in a DOE-sponsored program with Southern New England Telephone Company. Privately-financed dish R&D has also been conducted by ESSCO, Solar Steam, Sol-Trac, Summit Industries, Teton, Transolar, Smyth Aerodynamics, and

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* A module is an electricity-generating unit composed of a concentrator, a receiver, an engine, a generator, and controls.

Charles Curnett/Mother Earth. Although a prototype dish was built by each firm, several firms are not currently active in dish R&D. Solar Steam has raised R&D funding through limited partnership financing and is designing an improved dish. The PKI concentrator has been selected by the SOLERAS project for an 18-concentrator installation in Saudi Arabia. However, as far as is known, the sales of dish concentrators to private (nongovernment) firms have been minimal, if any.*

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* The initial construction costs of the La Jet 4.5 MWe power plant are being borne by La Jet. La Jet expects to recover its investment costs by selling the plant to a limited partnership after the plant operational performance is demonstrated. The demonstration will be conducted using about 3,000 m^2 of water/steam-cooled dishes and a small steam turbine. If successful, the limited partners would purchase the equipment and provide the funding or the additional equipment needed to achieve the 4.5 MWe plant capability.

3.0 CONCENTRATOR MANUFACTURING ACTIVITY AND COST ESTIMATE HISTORY

3.1 Concentrator Manufacturing Activity

Manufacturing Activity

A number of solar thermal systems have been constructed that use heliostat, trough, or dish concentrators. The major completed projects, which are summarized in Table IV, were constructed for industrial process heat (IPH), cogeneration, and electrical applications. Except for low-temperature applications (i.e., domestic water heating, space heating, and space cooling), which primarily have been privately financed, these major projects account for most of the concentrator manufacturing activity to date.

In contrast to the projected large production volumes used to derive the mass-production cost estimates, the actual manufacturing activity is quite minute. For example, if all the projects listed in Table IV had used the same concentrator design, this concentrator could have been supplied from one month's output of a manufacturing facility designed to produce 25,000 units per year.

This relatively low level of manufacturing activity is not unexpected for a fledgling industry like solar thermal. However, the lack of manufacturing activity makes it difficult to assess the cost trends associated with early concentrator production.

Cost Trends

Figure 1 (Reference 4) displays heliostat cost trends as a function of the cumulative number of heliostats produced.* Actual average cost data are shown for the Central Receiver Test Facility (CRTF) and Barstow pilot plant heliostat purchases; costs for additional but not yet constructed (e.g., repowering) plants are based on mass-production estimates of the most recently developed (i.e., second generation) heliostat designs. The mass-produced costs of these designs are in the range of \$85-160/m^2 (1981 \$) with an average cost of about \$120/m^2 (1981 \$). The corresponding values in 1983 \$ are \$105-190/m^2 and \$145/m^2, respectively. Value-based cost targets are in the range of \$70-90/m^2 (1981 \$) or \$90-110/m^2 (1983 \$), based on the displacement of oil or gas (Reference 5).

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* Only recurring costs (materials and labor) are shown. If total costs were displayed, a similar trend in costs would be observed with perhaps a steeper slope in the cost reduction curve. At a low cumulative production, nonrecurring costs (design, tooling, etc.) represent a larger fraction of the total costs than they would for a high production.

TABLE IV. MAJOR COMPLETED PROJECTS USING HELIOSTAT, TROUGH, OR DISH CONCENTRATORS*

PROJECT	TECHNOLOGY	AREA (m^2)
Central Receiver Test Facility	Heliostat	8,250
Barstow 10 MWe Pilot Plant	Heliostat	71,130
International Energy Agency 0.5 MWe Power Plant	Heliostat	3,660
Advanced Components Test Facility	Heliostat	530
ARCO Enhanced Oil Recovery Plant	Heliostat	1,580
	Subtotal	85,150
Coolidge Irrigation Pumping	Trough	2,140
Willard Irrigation Pumping	Trough	1,280
Gila Bend Irrigation Pumping	Trough	510
International Energy Agency 0.5 MWe Power Plant	Trough	5,360
Caterpillar Tractor IPH	Trough	4,680
USS Chemicals IPH	Trough	4,680
Dow Chemical IPH	Trough	920
Southern Union Refining IPH	Trough	940
Lone Star Brewery IPH	Trough	880
Ore-Ida Foods IPH	Trough	880
Home Laundry IPH	Trough	600
Johnson & Johnson IPH	Trough	1,070
	Subtotal	23,940 [a]
Shenandoah Solar Total Energy System	Dish	4,390 [b]
	Total	113,480

[a] This subtotal includes projects for industrial and electrical applications in which DOE provided a portion or all of the financial support. The inclusion of privately financed projects, especially those which use troughs or other line focus technologies for low-temperature applications (i.e., domestic water heating, space heating, and space cooling), would greatly increase this subtotal. The inclusion of the Luz International Ltd. 13.8 MWe power plant, under construction near Barstow, California, would also swell this total. The Luz facility, when completed, will use 71,680 m^2 of parabolic troughs.

[b] The inclusion of the La Jet 4.5 MWe power plant, under construction in Warner Springs, California, would greatly increase the dish subtotal. This privately financed project, when completed, will use about 30,000 m^2 of parabolic dishes.

* The table lists only large-scale projects (>500 m^2). Federally and privately sponsored projects in the US are included, along with the International Energy Agency project in Almeria, Spain. Some privately sponsored projects may have been omitted because data were not available.

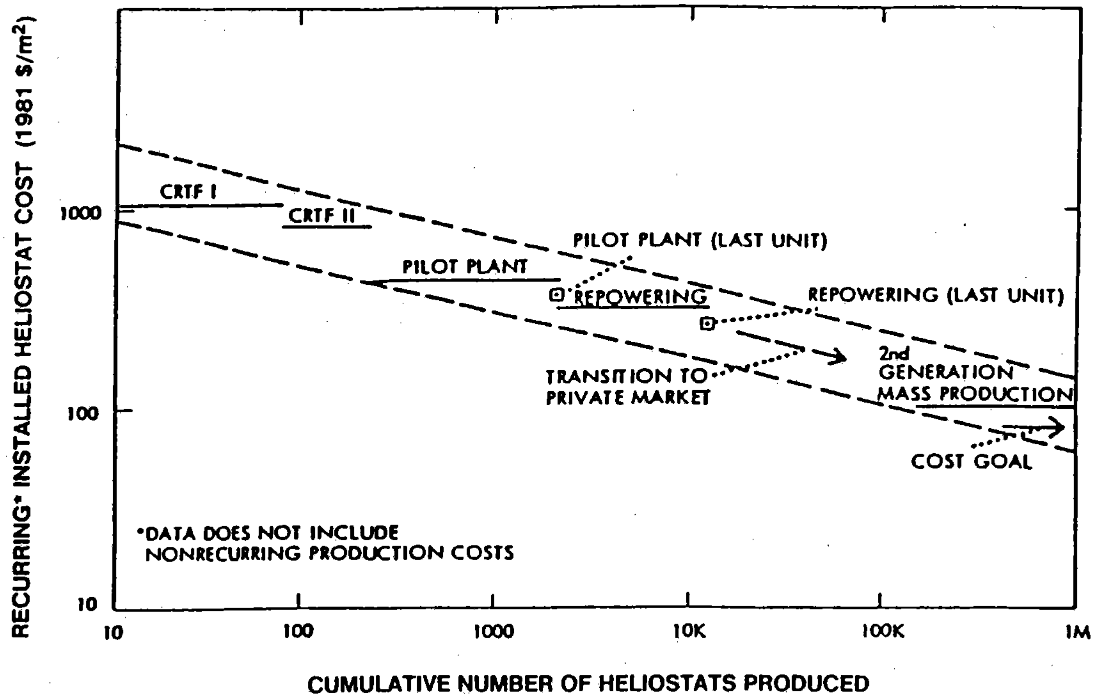

Figure 1. Heliostat Cost Trends (Ref. 4)

The CRTF and pilot plant heliostat cost data, along with the second-generation heliostat cost estimates, are an encouraging indication that the cost targets can be met. A factor-of-two reduction in actual heliostat costs has already occurred, and further reductions should be achieved as more units are produced. An additional check on the credibility of these cost trends is to determine if the data fall on a typical experience curve. The dashed lines in Figure 1 are arbitrarily drawn to bracket the actual and estimated heliostat costs. The cost reductions shown by these lines are equivalent to those predicted by an 85% experience curve. If a product, such as a second-surface, silvered glass heliostat, follows an experience curve, the cost and price (in constant dollars) normally decreases by a constant percentage as the number of units produced doubles. For an 85% experience curve, each doubling of the accumulated production is expected to reduce the unit cost by 15%. Thus, the 20th unit cost is 85% of the 10th unit cost, the 40th unit cost is 85% of the 20th, etc. This cost reduction results from every conceivable source, including labor learning, reduction in raw material costs, economies of scale, new production-facility design, and new product design.

Table V, taken from Reference 6, displays the magnitude of the cost reductions for a variety of items. In his report, Eason notes that ranges of 70 to 90% are typical, that individual items may deviate from these ranges, and that the curves can be disrupted by a variety of factors, such as consumer demand for improved performance and government antitrust actions. Eason also notes that one would expect to see a similar experience effect for heliostats with comparable performance, if cost is expressed in constant dollars and is divided by mirror area to account for size differences. Although there is limited experience on actual heliostat costs, Figure 1 shows that the available data do fall within a band of 85% curves. The

TABLE V. EXPERIENCE CURVE DATA

ITEM	AVERAGE SLOPE	COMMENTS ON CURVES
Black and white TV, wholesale price	80%	92% to 30 M units (1953) 70% to 140 M units (1968)
Free-standing electric range, average price	80%	97% to 17 M units (1957) 65% to 30 M units (1967)
Free-standing gas range, wholesale price	70%	Flat to 48 M units (1952) 60% to 76 M units (1967)
Model T Ford, list price	85%	14 M units produced 1908-1926
Turbine generator sets, direct cost/MW	90%	1946-1963 production data from GE
Electronic components	60-80%	Transistors, diodes, integrated circuits
Electric power, US utilities $/kwh	80%	55% to 10^{12} kwh (1945) 80% to 10^{13} kwh (1968)
Labor unit cost		
machine-paced	90%	Consensus of many sources in many industries
worker-paced	80%	
Raw material unit cost		
metals	80-90%	(Al, Mg, Ti) data to 1968
polymers	70-90%	(polyethylene, polypropylene, polystyrene, polyvinyl chloride)
crushed limestone	80%	Data 1929 to 1971

Source: Reference 6

horizontal lines on the figure are drawn at the lot average cost for each production lot. Within each lot the cost also decreases, but data on that effect are limited (for example, the pilot plant last unit costs are shown, but the CRTF last unit costs are not).

Similar reductions in cost have occurred for parabolic troughs. Figure 2 (Reference 7) shows installed system costs per unit collector area in 1980 $ for several trough IPH projects (these do not include design costs, which for the most recent projects amounted to about $5/ft^2). Also shown on the figure are estimates of the initial-year price of fuel oil at which the solar energy investment would break even.

Installed system costs have been reduced by a factor of two for each cycle. The reduction in system costs is attributed to several factors: (1) reductions in trough costs as a result of labor learning and improved designs; (2) improved system designs and competition among bidders; and (3) economies of scale--the Cycle 4 project field sizes are about five times larger than those of the Cycle 2 and Cycle 3 projects.

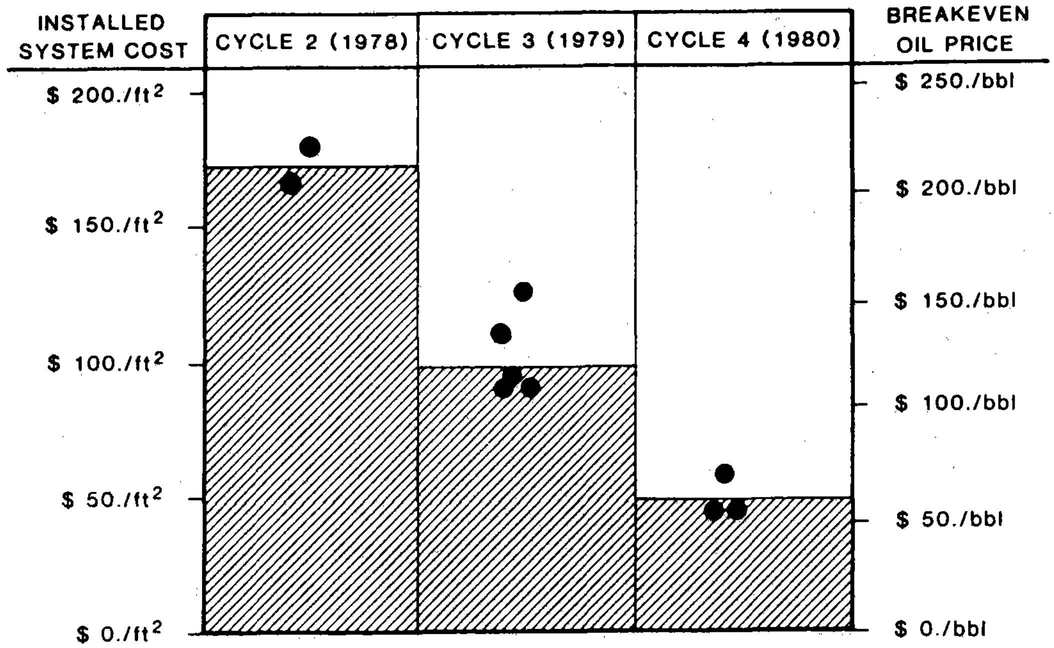

Figure 2. Cost Trends in Trough IPH Projects (Ref. 7)

If the assumption is valid that collectors typically account for about 50% of a system cost (Reference 5), then the Cycle 4 concentrator costs are about $\$25/ft^2$ or $\$270/m^2$ (1980 \$). The corresponding values in 1983 \$--$\$33/ft^2$ or $\$360/m^2$--are about 2.5 times greater than the cost estimate for the performance prototype trough based on a production volume of 100,000 units/yr.

It is evident from these results that significant reductions in trough costs have occurred and that additional reductions can be expected if manufacturing activity is increased. It is also evident that government incentives, such as investment tax credits, are required to overcome the current price advantage of fossil fuels and thereby stimulate the manufacturing activity that is needed.

Production cost data for parabolic dishes are only available for the Shenandoah Total Energy Project: the Shenandoah collector costs, including the concentrator and receiver but excluding the foundation and controls, are about $\$1200/m^2$ (Reference 8). Therefore, it is not possible to assess at this time the impact of dish manufacturing activity on dish cost reductions.

3.2 Mass-Production Cost Estimates

Mass-production cost estimates have been generated to determine if candidate designs can achieve significant cost reductions through high-volume production. These estimates are important activities in the R&D process because they can provide vital feedback to the design team in identifying the cost drivers that can lead to the most cost-effective concentrator designs. The mass-production costs of concentrators are a crucial issue in the economic attractiveness of solar thermal systems because concentrators typically account for at least 50% of the system cost.

Mass-production cost estimates typically provide a manufacturing cost or a selling price as a function of production volume. Manufacturing costs are derived from estimates of the required material, direct labor, burden, tooling, and capital equipment for each production volume. The estimates also consider various manufacturing tradeoffs for each production volume scenario (such as making versus buying components, and automation versus manual labor). A selling price results if additional factors, such as general and administrative costs and profit, are added to the manufacturing cost. The selling price is generally about 10-15% higher than the manufacturing cost.

Within the DOE STT program, mass-production cost estimates have been generated for heliostats, parabolic troughs, and parabolic dishes (References 9 to 32).* There is a large disparity in the program, however, with respect to the effort devoted to mass-production cost estimates for the three concentrator technologies. Tables VI, VII, and VIII show, for example, that the number of cost estimate studies for heliostat designs greatly exceeds the number for trough or dish designs.

Heliostat cost estimates have been developed for nine second-surface, silvered glass designs and three polymer enclosure designs. Except for the prototype heliostat program, for which only designs and limited component development were carried out, these estimates were based on fabricated, tested hardware and in-depth manufacturing analysis. Some particularly attractive designs received additional scrutiny through cost estimates by independent firms who were not the heliostat designers.

Parabolic dish and parabolic trough cost estimates, except for the mini-cost dish design, were also based on fabricated, tested hardware and manufacturing analysis (note, however, that the Parabolic Dish Concentrator No. 1 cost estimate was completed prior to its fabrication and testing). Estimates were generated for two dish and two trough designs by firms who were not the concentrator designers (the trough estimates include both the concentrator and the receiver).

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* Additional cost estimates have been generated by the private sector but generally are proprietary and are not available.

TABLE VI. HELIOSTAT MASS-PRODUCTION COST ESTIMATES

PROJECT	YEAR	DESIGN	ACTIVITIES
Barstow Subsystem Research Experiments (SREs)	1977	Second-Surface, Silvered Glass; Aluminized Mylar Within a Polymer Enclosure	Four candidate designs for the Barstow pilot plant were fabricated and tested by Boeing, Honeywell, Martin Marietta, and McDonnell Douglas. Cost estimates were generated by each contractor for a first commercial plant. Battelle also performed a cost estimate of the McDonnell Douglas design for a one-time production of 10,000 units and continuous production rates of 10,000, 50,000, and 100,000 units per year.
Prototype Heliostats	1978	Second-Surface, Silvered Glass; Aluminized Mylar Within a Polymer Enclosure	Conceptual designs of four heliostat concepts were performed by Boeing, General Electric, McDonnell Douglas, and Solaramics. Capital and operations and maintenance costs were estimated by each contractor for a one-time production of 2,500 units and for continuous production rates of 25,000, 250,000, and 1,000,000 units per year. Additional cost estimates of the McDonnell Douglas design were generated by General Motors for production rates of 25,000 and 250,000 units per year and by Battelle for production rates of 2,500, 25,000, and 250,000 units per year.
Second-Generation Heliostats	1981	Second-Surface, Silvered Glass	Four second-generation heliostat designs were fabricated and tested by ARCO, Boeing, Martin Marietta, and McDonnell Douglas. Capital and operations and maintenance costs were generated by each contractor for a production rate of 50,000 units per year. Follow-on studies with Martin Marietta and McDonnell Douglas also identified cost reductions that could result from modifications to the second-generation heliostat designs or performance requirements.

TABLE VII. PARABOLIC TROUGH MASS-PRODUCTION COST ESTIMATES

PROJECT	YEAR	DESIGN	ACTIVITIES
Performance Prototype Trough	1981	Second-Surface, Silvered Glass	Several candidate designs were fabricated and tested under the Sandia performance prototype trough development program. Cost estimates for two of these designs were generated by the Central Solar Energy Research Corporation. The estimates were based on production rates of 100, 500, 1,000, 5,000, 25,000 and 100,000 modules per year.

TABLE VIII. PARABOLIC DISH MASS-PRODUCTION COST ESTIMATES

PROJECT	YEAR	DESIGN	ACTIVITIES
Test Bed Concentrators	1980	Second-Surface, Silvered Glass	Two Test Bed Concentrators (TBCs) were designed and fabricated by E-Systems. Cost estimates for the TBC design were generated by Pioneer Engineering and Manufacturing Company for production rates of 1,000, 10,000, 50,000, 100,000, and 1,000,000 units per year.
Parabolic Dish Concentrator No. 1	1981	Aluminized Plastic	A parabolic dish (PDC-1) was designed by General Electric and fabricated by Ford Aerospace and Communications Corporation. Cost estimates for the PDC-1 design were generated by Pioneer for production rates of 100, 1,000, 5,000, 10,000, 50,000, 100,000, 400,000, and 1,000,000 units per year.
Mini-Cost Parabolic	1981	Aluminized Plastic	Pioneer designed a parabolic dish and generated cost estimates for production rates of 100 and 100,000 units per year.

The results of these studies are displayed in Figures 3 to 6. Selling price, expressed in 1983 $/m^2, is shown as a function of production volume. All prices were escalated from the values reported in each study to 1983 $ using a 10% annual inflation rate. A 10% factor was also used to convert two manufacturing cost estimates (Test Bed Concentrator and Parabolic Dish Concentrator No. 1) to selling prices. The selling prices for second-surface, silvered glass and polymer enclosure heliostat designs are shown separately because these designs have significantly different performance (i.e., reflectance) characteristics.* For some projects and production volumes, a range of selling prices is shown. The range reflects (1) the high and low prices for different design approaches (e.g., three firms--Honeywell, Martin Marietta, and McDonnell Douglas--estimated costs for second-surface, silvered glass heliostat designs for the Barstow pilot plant); or (2) the high and low prices for the same design as costed by different firms (e.g., three firms--Battelle, General Motors, and McDonnell Douglas--estimated costs for the McDonnell Douglas prototype heliostat design).

The results of these studies indicate that the STT program has made significant progress in the development of a second-generation glass heliostat technology that can meet the cost targets. Cost estimates for the second-generation designs indicate that they can be mass-produced to sell at prices in the range of $105-190/m^2 (References 22-28). The low end of this range, which reflects the McDonnell Douglas design increased in size, is within the value-based cost target of $90-110/m^2 based on the displacement of oil or gas. However, it is greater than the cost target of $40-60/m^2 based on the displacement of coal (Reference 5).

The results for troughs are similar although they are based on fewer cost estimates. The performance prototype trough is a relatively recent design that evolved from a considerable amount of earlier trough development. The costs for this trough are in the range of $130-150/m^2 (Reference 29). Because these costs include both the concentrator and receiver, and the receiver accounts for about 10% of the cost, the resultant concentrator costs are close to the upper value of the value-based cost target of $90-110/m^2.

Cost estimates, particularly those that were based on fabricated, tested hardware, are somewhat higher for parabolic dishes than either heliostats or troughs. For example, cost estimates for the TBC and PDC-1 dish designs are about $1120/m^2 and $190/m^2, respectively, at a production volume of 100,000 units per year (References 30 and 31). These results reflect the less mature status of dish development and point out a need for an increased effort to fully assess the technical and economic potential of dish systems.

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* The effective reflectance of current polymer enclosure designs is 65-70% with a theoretical limit of 85%, while the reflectance of second-surface, silvered glass designs is 90-95%.

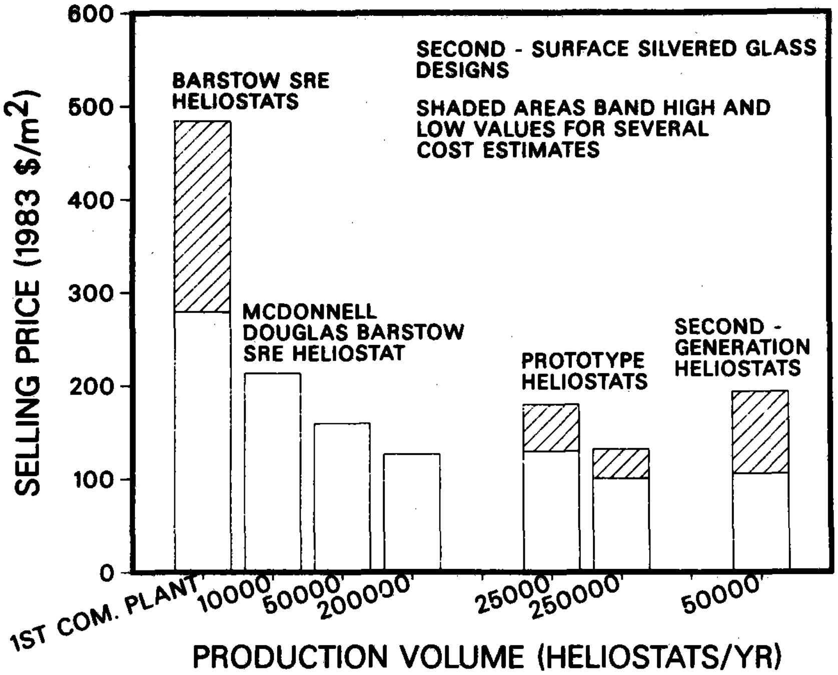

Figure 3. Second-Surface Silvered Glass Heliostat Mass-Production Cost Estimates

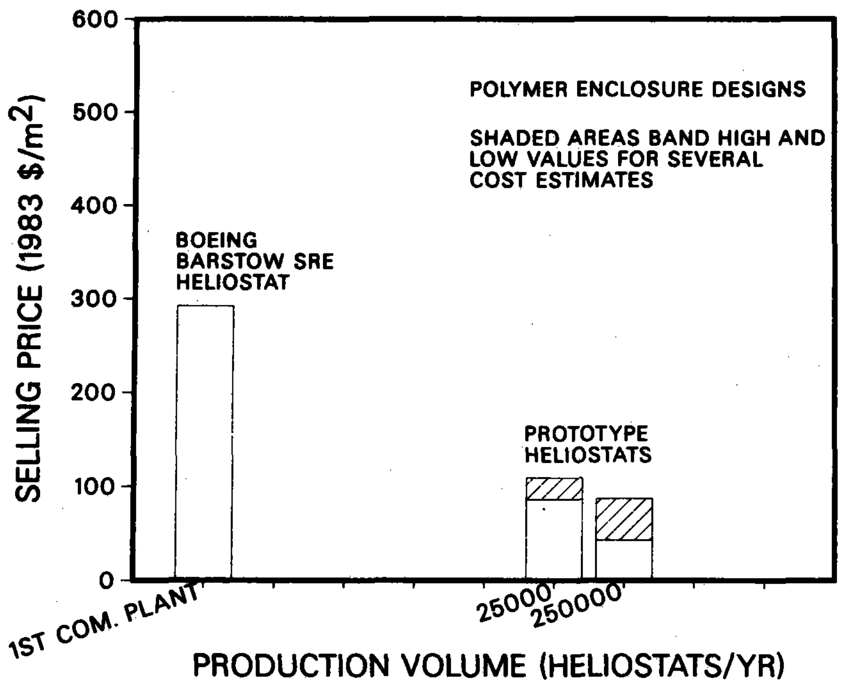

Figure 4. Polymer Enclosure Heliostat Mass-Production Cost Estimates

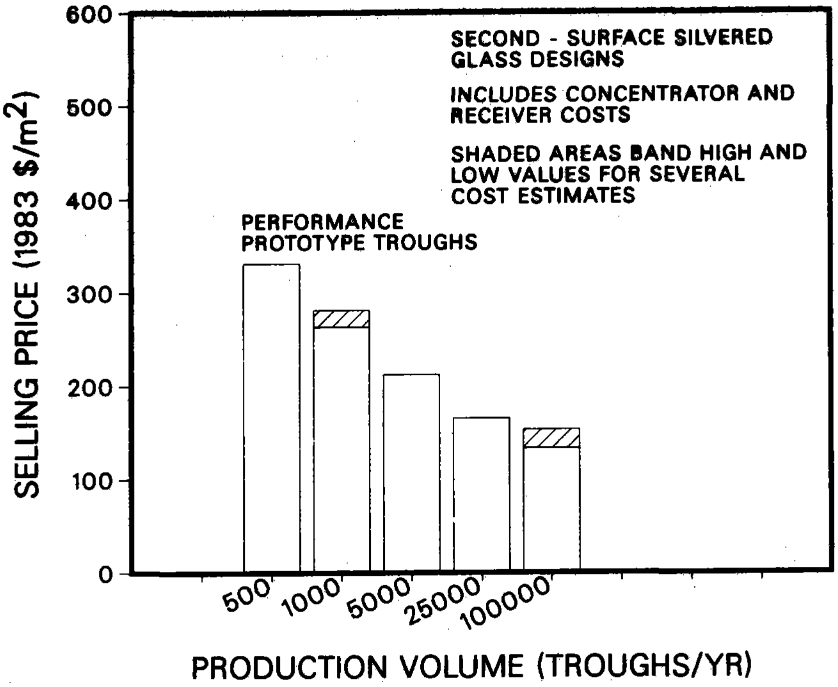

Figure 5. Parabolic Trough Mass-Production Cost Estimates

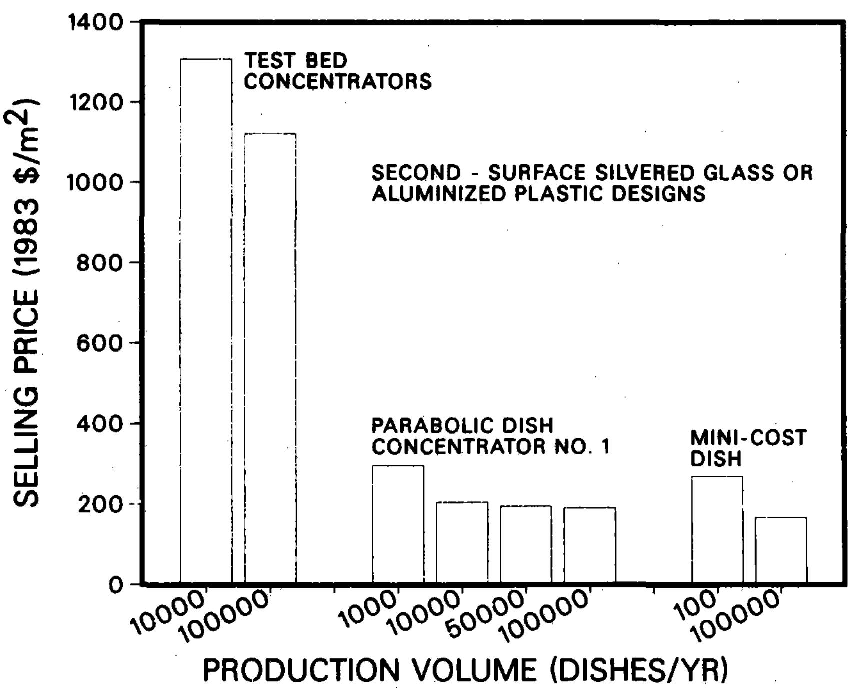

Figure 6. Parabolic Dish Mass-Production Cost Estimates

4.0 TECHNICAL ASSESSMENTS AND RECOMMENDATIONS

4.1 Near-Term R&D for Dish Concentrators

Dish Development Activity

Dish concentrator R&D, especially that for dish electric systems, initially emphasized the use of cellular glass as a reflector structural material. Cellular glass, of which Foamglas is a specific example, has characteristics which are attractive as a structural material for a concentrator reflective assembly. The characteristics are: high stiffness-to-weight ratio, low production cost (approximately $3/m^2 per inch of thickness), coefficient of expansion matchable to solid glass, ease of machining and forming even to a two-radius-of-curvature surface, and high surface accuracy.

However, celluar glass is not a well-characterized material in an engineering sense, and questions exist about its structural properties, especially slow crack growth phenomena. Long-term environmental stability with freeze/thaw cycling is another serious question that might be remedied with coatings which do increase cost. Commercial products are only available from one source (Pittsburgh Corning) and in one size at this time. Thus, other design approaches are desirable.

Cost and Production Data

Of the dish concentrators described in Chapters 2 and 3, mass-production cost estimates, similar in detail to those for the second-generation heliostats, were developed for the TBCs and PDC-1. Production cost data are also available for the Shenandoah concentrators. As described earlier, none of these designs, when mass-produced, can achieve the cost targets.

The cost-effectiveness of the other dish designs has not been assessed in this study because cost data are not available. However, the PDC-2 and Vanguard designs, although of a single-pedestal type, will probably be high in cost because their facet design is labor intensive like the costly TBC design. For example, a TBC has 228 facets while Vanguard uses 320 facets; the PDC-2 uses 64 reflector gores. In contrast to these, the number of reflector modules for the second-generation heliostats ranged from about 12 to 24.

The lack of significant cost and performance data for all but a few dish designs impairs the assessment of the technology development, and the lack of low-cost designs along with the high cost of the early production units impedes the introduction of the technology into the marketplace. Although the dish program has had a number of parallel activities initiated at the first-generation level, there has not been the multigenerational, stepped development program that has produced such solid progress as in the heliostat and trough programs. It is clear that the dish program could benefit from a return to the systematic R&D approach that characterized the early program. That is, a number of conceptual designs should be performed in parallel, followed by mass-production cost estimates and the fabrication and testing of full-scale prototypes of each design. Mass-production cost estimates of the concentrators for the three ongoing module development activities are also desirable to assess their economic potential.

Dish Concentrator R&D Needs

The need for additional dish concentrator R&D has already been recognized by DOE in its inclusion of a dish concentrator R&D task in the FY83 and FY84 programs. We recommend that at least one near-term technology feature be studied in this task: the use of existing heliostat and line focus technology features. The rationale for this recommendation is that if, for example, a glass/steel heliostat has sufficient performance and is cost effective for high-temperature applications, then it may also provide a good starting point for a dish design of similar performance and cost effectiveness.

The performance of the second-generation heliostat designs was very good. The designs displayed good pointing and surface accuracy with only minimal defocusing as a result of differential thermal expansion between the heliostat glass reflector and support structure. For example, designs that used a continuous sheet of steel to support the glass achieved a surface accuracy of 0.5 milliradian. In addition, differential thermal expansion caused by ambient temperature changes led to reductions of only 0.05 to 0.5% in annual system performance for different glass/steel bonding techniques.

These results are an encouraging indication that the glass/steel technology might satisfy the high accuracy and low thermal mismatch requirements of high-temperature dish systems. A second indication results from a preliminary study by Boeing to develop a curved steel dish facet. The facet, which used an aluminized reflective film, had a surface accuracy of about 1.45 milliradians. If a panel of this type is configured into a 12 m diameter dish, the resulting optical intercept factor for a 0.2 m (8 in.) diameter receiver aperture is about 99%. At 900°C (1650°F), the collectable thermal energy of this dish would only be 2.5% less than one with a higher quality surface, such as a TBC. An operating temperature of 900°C (1650°F) should be achievable since the dish concentrator and receiver dimensions result in a geometric concentration ratio of 3500.

The heliostat designs for 538°C (1000°F) and higher-temperature applications may therefore be transferable directly into a thermal dish design and an electric dish design, respectively, with some modifications. The translation of results from the heliostat or line focus programs to the dish program would maximize the utilization of past R&D funds in the concentrator program.

The following type of near-term R&D activity for dish concentrators is recommended:

- Several (two to five) contract awards to industrial firms for new dish designs

- Fabrication and testing of full-scale prototypes for each design

- Independent cost estimates for each design

- Performance geared to receiver operating temperatures of 400 to 1371°C (750 to 2500°F)

- Designs to incorporate heliostat and line focus technology features if appropriate

As a result, development would be completed of several concentrator designs that could be used in the planned, second-generation Stirling and Brayton module experiments or thermal dish experiments. Since no mass-production cost estimates exist for the concentrators of the first-generation electric modules, a second near-term dish activity is also recommended to determine these costs. This activity would complete the first-generation dish R&D and establish the economic potential of the first-generation technology.

4.2 Long-Term R&D for Concentrators

Completion of the recommended near-term dish R&D should bring dish concentrators to a comparable level of development with heliostat and line focus technologies. Like heliostat and line focus concentrators, it is expected that these dish designs, when mass produced, will meet the near-term cost target based on the displacement of oil or gas. However, a second major R&D effort, applicable to heliostats and dishes and possibly even to line focus technology (depending on the outcome of a system assessment study described in a later section), is also needed to develop concentrator designs that, when mass produced, can meet the long-term cost target based on the displacement of coal.

Continuing materials and components research should precipitate potentially low-cost concentrator designs, which are either innovative or have been previously discarded because of the lack of qualifying materials or components. The current thrust of concentrator research, which is toward lightweight designs such as a stretched membrane, is a valid one because the glass/metal designs are unlikely to achieve any more significant improvements in costs beyond those already identified. (For example, a potential cost reduction of 25% results for the McDonnell Douglas second-generation heliostat design if various design changes, particularly a larger reflective area (about 100 m^2), are incorporated. These changes would lower the heliostat cost to about $105/$m^2$ in 1983 $. See Reference 28.)*

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* An even larger (160 m^2) design is being privately developed by ARCO, but cost data are proprietary and are not available.

Stretched Membrane Research

A stretched membrane heliostat appears to be an attractive alternative to either a polymer enclosure or glass/steel heliostat. The membrane heliostat design uses a stretched membrane made of steel with a thin-film polymer reflective surface so that no enclosure is required to withstand the environmental loads. The membrane reflector can be focused by the use either of a second membrane and regulation of the air pressure between the two membranes or of a laminate of dissimilar materials. The mass for initial designs, including the reflective surface, membrane, support frame, and support struts (down to the drive system), is approximately 1.5 to 2.0 lb/ft^2. The corresponding mass for the second-generation glass/metal heliostats is 6.4 to 7.4 lb/ft^2.

Unit cost estimates for the stretched-membrane reflector concept are promising. Initial cost estimates for the reflector and support structure, down to the drive attachment, are approximately $\$20/m^2$ for high production levels (25,000 units/yr). This compares to costs of $\$33\text{-}54/m^2$ for the corresponding subelements of the second-generation glass/metal heliostats.

The basic design of the membrane reflector may be applicable to both dishes and heliostats. For example, the La Jet stretched reflective film design, based on circular facets attached to a structure, uses a partial vacuum for focusing. Depending on the pressure used, the focal length can be 5 m or 500 m, thus making it potentially suitable as a dish or heliostat concentrator.

Research at the Solar Energy Research Institute (SERI) has resulted in the fabrication of several 1-m diameter stretched membrane modules, and two 2-m diameter nonfocusing models, along with a potentially low-cost hydraulically driven two-axis tracking base. One of the 2-m diameter models had a variable tension capability. Two of the 1-m modules have both variable focus and tension capabilities. Various design and assembly approaches have been assessed, as well as numerous membrane attachment schemes. Initial structural and system performance assessments have been made. Seven metallized polymer reflective films have been screened. Much of the work performed during this period is documented in Reference 33. Activities in progress include a more detailed structural deformation assessment, and the fabrication of a 2-m variable-focus double-laminated module for study of the lamination process.

A stretched membrane made of silvered glass on thin steel is under study in the Germany/Saudi bilateral solar program. Two parallel, thin steel sheets which are 15 m in diameter are attached to a hoop. One sheet is thinner than the other. When a partial vacuum is maintained between the steel sheets, each steel membrane is deformed into a focusing curved surface. It is possible to have the thicker membrane only elastically stretched and to have a distant focal length (approximately 500 m). It is also possible to have the thinner steel membrane stretched plastically to some predetermined shape before the pressure is adjusted to a level that allows only elastic deformation. This side can be focused at a much shorter focal length (approximately 10 m). Thus, the faces of the same device can potentially be used for either a dish or heliostat. The details of the choice of the reflective surface and its attachment to the steel membrane may be different for each side.

Thus, stretched membrane designs using various approaches (reflective film, silvered glass, etc.) should be vigorously pursued. As the basic technique is developed, multiple contractor teams should go through the usual sequence of design, fabrication, test, and mass-production costing. Dual-capability designs (dish and heliostat) as well as single-purpose (dish or heliostat) designs should be pursued to establish what advantage, if any, exists for the single-capability designs. Commonality would have a distinct advantage during the production phase since the same production facility could be used for multiple applications of heliostat and dish technologies.

Silvered Polymer Film Research

A silvered polymer film R&D activity is also recommended. Second-surface silvered glass is currently the baseline silvered reflective surface because it has high performance, long potential life, and modest cost. However, a silvered polymer that has both high performance (i.e., at least 90% reflectance) and long life (i.e., 5-year life and resistance to ultraviolet and environmental attack) should have even lower cost. Also, the indirect cost implications for the rest of the concentrator would be favorable because of lower weight, ease of attachment, lack of breakage, and imperviousness to environmental forces, such as hail and wind (if full back support is used). Thus, this development should result in lower heliostat, trough, and dish costs. It should be pursued due to the broad implications for all classes of concentrators.

Fresnel Lens Research

An advanced concept, applicable to dish modules, is the use of a Fresnel lens to refract light to a focal zone behind the lens. The components located at the focal zone include the receiver, engine, generator, and possibly a heat rejection subsystem. Their weight is on the order of a few thousand pounds. By using a mass-produced, plastic, Fresnel lens to focus the incident light onto a receiver placed behind it, the receiver weight at the focal zone can be located adjacent to the concentrator structural support. Georgia Institute of Technology is conducting research on a spiral Fresnel lens concentrator while E-Systems studied a dome-type Fresnel lens concentrator. Early results by E-Systems indicate that an optical performance approaching that of the high-quality TBC dishes is possible. Also, the optical performance seems relatively insensitive to the accuracy of the placement of the lens. Thus, for a dish concentrator, a Fresnel refracting approach is of interest and should be explored. However, a conceptual design study is first recommended to assess the technical performance and economic potential of the Fresnel dish concept before further R&D is performed.

New Concept Development

The stretched membrane, Fresnel lens, and silvered polymer are concepts that have already surfaced as attractive alternatives to current concentrator technology. However, the STT program should also encourage an influx of other new concentrator concepts into the program. These concepts may originate at the national laboratories (SERI, SNL), but specific efforts directed at university and industrial participation should be included. Funding should be specifically allocated each year for university participation. Industrial participation can be achieved by periodically issuing (every two to three years) a Program Research and Development Announcement to solicit new ideas and concepts into the program. A similar approach was successfully used to solicit new ideas for the heliostat program in 1980.

Funding must be allocated to develop the attractive concentrator concepts that emerge from these studies. This development will include materials and component testing, small-scale and full-scale concentrator testing, and mass-production cost estimates.

Polymer Enclosure Research

An assessment of polymer enclosure heliostat designs has been recently performed by representatives from DOE, Sandia National Laboratories Livermore (SNLL), Solar Energy Research Institute (SERI), and the University of Houston (Reference 34). The assessment evaluated previous and ongoing work at Boeing, General Electric, SERI, and the University of Houston. In 1975, Boeing proposed the polymer enclosure approach for the Barstow pilot plant. Boeing's design was not selected for the pilot plant, however, because of the high cost of the protective material coupled with the inherently reduced performance (reflectance) of the design. In 1978, Boeing and General Electric designed improved polymer enclosure heliostats as part of the prototype heliostat development program. More recently, Boeing, SERI, and the University of Houston revisited the polymer enclosure heliostat to compare its cost with current glass/steel heliostat technology. Boeing's study included design improvements and updated cost estimates, while SERI and the University of Houston investigated parametrically the effect of heliostat performance and costs on plant costs. In all cases, the reference glass/steel heliostat design was the McDonnell Douglas second-generation heliostat.

The assessment of these studies concluded that the past work has been successful in identifying promising polymers for the enclosure, polymer films for improved mirrors, and improved mirrored-polymer stretched membranes. However, when busbar energy costs for power plants with polymer enclosure heliostats are compared with those for plants with the reference glass/steel design, there is at most a 15-20% advantage for the polymer design. If the larger-area (about 100 m^2) version of the McDonnell Douglas design is used, there is no cost advantage for the polymer design. This result, along with the time and costs for the additional polymer development that would be needed, led to the following recommendations:

- With currently available or reasonably obtainable plastic properties, the plastic-enclosed heliostat does not merit further development.

- Development of manufacturing processes for plastic heliostat enclosures should be stopped.

- Development and evaluation of plastic materials for heliostat enclosures should be a low-priority, low-level effort with only the current life tests for plastics continued.

Although these recommendations, with which we concur, are directed only at heliostat development, SERI has recently studied polymers for enclosed dishes, and similar results were obtained (Reference 35).

4.3 Heliostat R&D for High-Temperature Systems

If the STT program shifts the focus of its R&D activites toward increasingly higher temperature system applications, a need for new concentrator designs could surface. Up to now, heliostats have been designed and tested primarily for 538°C (1000°F) electric systems.

Future System Applications

The applicability of past designs to higher-temperature systems has received only limited attention. Several needs must be addressed for higher temperature systems: (1) a larger aperture as plant size increases; (2) a smaller aperture to limit thermal losses as the operating temperature increases; (3) a terminal concentrator to reduce the aperture size; and (4) a high-performance heliostat to reduce the aperture size. These alternatives must be traded off against one another to arrive at a preferred system configuration and heliostat performance specification.

A systems analysis is the best approach to define the performance requirements for these heliostats and to determine whether the requirements can be satisfied by current designs. For example, heliostat performance affects not only field size and layout but also receiver size and tower height. Thus, the impact of a change in heliostat performance (i.e., design) on other parts of the central receiver system, as well as the heliostat itself, must be taken into account in evaluating the change.

Several analyses of the type just described have previously been carried out for central receiver systems (References 27, 28, and 36). For instance, in 1979 SNLL investigated the value of changing any of several heliostat design characteristics by using the DELSOL computer code. Results were quantified in terms of a breakeven cost, i.e., the cost of a new design which will yield the same total system energy cost as the baseline system. Changes in mirror reflectivity, pointing accuracy, surface quality, canting and focusing strategy, heliostat size, and stow requirements were evaluated.

Other studies have also been conducted. Two follow-on studies to the second-generation heliostat development were completed by Martin Marietta and McDonnell Douglas in 1982. These studies investigated the cost-effectiveness of changes in the second-generation heliostat design or performance requirements in terms of heliostat field cost per unit of annual energy incident on the receiver. Changes in heliostat design were studied for heliostat area, aspect ratio, stiffness, drive backlash, temperature, and slew rate. Changes in the performance requirements were studied for wind, beam pointing, beam quality, and temperature. Perhaps the most significant result from these studies was that an additional 25% reduction in heliostat costs might be achieved, primarily by doubling the heliostat reflective area (the McDonnell Douglas design increased in size from about 50 to 100 m^2).

System Analysis Needs

Although these studies provided useful results and insights, they focused on 538°C (1000°F) electric applications. The heliostat design requirements associated with higher-temperature applications should now be addressed. A study is recommended that determines heliostat performance requirements as a function of plant size, receiver operating temperature, and receiver design characteristics. A specific objective should be to determine if the 50 and 100 m^2 second-generation heliostat designs can satisfy the performance requirements of the high-temperature systems. This study could be carried out as part of the trade-off analyses that are normally performed in a conceptual system design activity, such as the planned fuels and chemicals system design studies. The following system characteristics should be studied:

- Plant sizes of 30,150, and 300 MWt

- Receiver operating temperatures of 816°C (1500°F), 1093°C (2000°F), and 1371°C (2500°F)

- Receiver design characteristics including aperture size and the use of a terminal concentrator

Through the systems analysis study, the required heliostat performance for high-temperature applications will be defined. If existing designs cannot meet these performance requirements, new heliostat R&D will be required. A number of development paths should be explored:

- Use of glass/steel heliostat technology

- Reduced facet and/or heliostat size

- Focusing

- Improved tracking and surface accuracy

- Combination of the above

Funding must be allocated to satisfy any R&D needs that result from this study, including heliostat design, materials and component testing, small-scale and full-scale heliostat testing, and mass-production cost estimates.

4.4 System R&D Assessments

The STT program has been sponsoring R&D for nearly a decade. During that time a considerable amount of solar equipment has been designed, fabricated, tested, and evaluated. A logical question to ask is whether sufficient R&D has been performed to facilitate the transition from R&D to commercial activity. In the case of dishes and heliostats, some remaining R&D needs are already apparent, and they were described in the previous sections. Other R&D needs may surface, however, from additional system assessment studies.

For example, the line focus technology is considered to be in the midst of this transition, but little data are available to project the success or failure of the transition. Up to the present time, an impressive amount of line focus R&D has been completed. As a result of all this effort, the line focus program was judged to be at a crossroads, that is, at a point where government involvement in line focus R&D should stop and the private sector should take over. Therefore, within two years, the STT program initiated efforts to conclude the line focus R&D activities. At the present time the only remaining activities are the upgrading, operation, and evaluation of a few IPH experiments; the operation and evaluation of the MISR experiments; limited component development of evacuated annulus receivers and antireflective coatings; and the upgrading, operation, and evaluation of the Crosbyton hemispherical bowl.

Although documentation will be carried out for each of these activities, there is a need for a summary assessment of line focus R&D. First, this study should establish the capability of line focus technology to enter the near-term electric and IPH markets. A suggested approach is a survey of planned, ongoing, and canceled commercial ventures that identifies the factors most responsible for the success or failure of each venture. For example, the factors contributing to the go or no-go decisions for the Luz and Acurex line focus electric projects should be examined as part of this effort. This information should be used to assess whether the decision to terminate line focus R&D was timely or premature. If premature, additional steps will be defined to overcome the remaining hurdles that impede the early commercialization of line focus technology. These steps could include additional concentrator R&D, such as the R&D of low-cost, early production units.

Yet another assessment is needed to establish the capability of line focus technology to enter the long-term energy markets. First, this study should update the solar thermal system and concentrator value-based cost targets to reflect more current data for fuel cost projections and the distribution of costs among the solar thermal plant subsystems. Second, the study should determine if the completed line focus technology, when mass-produced, has the capability to meet these targets. An output of this study could again be the identification of additional concentrator R&D that must be performed.

Similar assessments are recommended for the other solar thermal technologies as they become technically mature. Central receiver electric systems are already at a comparable level of technical maturity with line focus systems, so assessments of this technology are also warranted. Assessments of other technologies and applications should be performed in later years.

5.0 SUMMARY OF RECOMMENDATIONS

Our review and assessment of concentrator R&D has identified several issues that any future program must address. For some issues we recommend specific R&D activities that, if implemented, should adequately resolve the issues. For others we recommend that further studies be performed to identify additional R&D needs. A description of each issue, along with a summary of activities that are recommended to resolve each issue, is given below. The first two recommendations, near-term dish concentrator R&D and long-term concentrator R&D, are high priorities. The third recommendation, heliostat R&D for high-temperature systems, is only important if the STT program continues to shift the focus of its R&D toward high-temperature system applications. The fourth recommendation, system R&D assessments, is very important to the overall success of the STT program. However, it is listed last because of some uncertainty in the ability of these studies to identify specific concentrator R&D needs.

The concentrator program can be conducted with a budget of $42M for the period FY84 to FY88. This represents 17% of an assumed total STT budget of $250M for the same period ($50M/yr).

1. Near-Term R&D for Dish Concentrators

Issue

How can the STT program achieve a level of dish concentrator development comparable to the heliostat and line focus concentrator developments in a cost-effective manner?

Recommendation

This activity encompasses two tasks:

(a) Award contracts to industrial firms that result in:

- Several (two to five) new dish designs
- Fabrication and testing of full-scale prototypes for each design
- Independent cost estimates for each design
- Dish performance geared to receiver operating temperatures of 400 to 1371°C (750 to 2500°F)
- Dish designs that incorporate heliostat and line focus technology features, if appropriate

(b) Issue a Request for Proposal (RFP) to industrial firms that results in a contract award for mass-production cost estimates of the concentrators for the first-generation organic Rankine, Stirling, and Brayton module experiments.

2. Long-Term R&D for Concentrators

Issue

What concentrator activities offer the best prospects for meeting the long-term cost goals of the STT program?

Recommendation

This activity encompasses four tasks:

(a) Perform R&D on lightweight concentrator designs. Deemphasize the polymer enclosure approach, which appears to offer only a slight improvement over existing glass/metal designs and no improvement over proposed ones, in favor of other lightweight design approaches, e.g., stretched membrane reflectors. Specifically, continue ongoing polymer life-testing but reduce polymer materials development and manufacturing process development. Perform materials and component testing, small-scale and full-scale concentrator testing, and mass-production cost estimates for the most attractive lightweight designs. Solicit industrial firms to perform the R&D beyond the materials and component testing stage.

(b) Perform R&D to develop silvered polymeric reflectors having the characteristics of at least 90% reflectance, 5-year life, and resistance to ultraviolet and environmental attack.

(c) Assess the potential of the Fresnel lens approach for parabolic dish concentrators. If this approach is deemed worthy of further R&D, conduct materials and component testing and issue an RFP that results in a contract award for a Fresnel lens dish design, prototype fabrication and testing, and a mass-production cost estimate.

(d) Issue periodically (every two to three years) a Program Research and Development Announcement (PRDA) that solicits new ideas and concepts into the program. Perform materials and component testing, small-scale and full-scale concentrator testing, and mass-production cost estimates for the most attractive concepts.

3. Heliostat R&D for High-Temperature Systems

Issue

What are the heliostat performance requirements for high-temperature system applications? Can existing designs satisfy these requirements?

Recommendation

Conduct a systems analysis study that determines heliostat preformance requirements as a function of plant size, receiver operating temperature, and receiver design characteristics. Study the following system characteristics:

- Plant sizes of 30, 150, and 300 MWt

- Receiver operating temperatures of 816°C (1500°F), 1093°C (2000°F), and 1371°C (2500°F)

- Receiver design characteristics, including aperture size and the use of a terminal concentrator

Determine if existing heliostat designs can satisfy the performance requirements of the high-temperature systems. Perform heliostat R&D to satisfy any R&D needs that are identified in this study.

4. System R&D Assessments

Issue

How close is each solar thermal technology to bridging the transition from R&D to near-term commercial demonstrations? Is a need for additional concentrator R&D impeding this transition? If so, what are the additional R&D needs?

How close is each solar thermal technology to potentially meeting the long-term targets of the STT program? Is additional concentrator R&D needed? What are the specific needs?

Recommendation

This activity encompasses two assessment tasks for each solar thermal technology option:

(a) To establish the capability of the technology to enter the near-term energy markets, survey the current and past marketing activities for the technology and examine the factors contributing to the success or failure of each activity.

(b) To establish the capability of the technology to enter the long-term energy markets, update the solar thermal system and concentrator value-based cost targets to reflect more current data for fuel cost projections and the distribution of costs among the solar thermal plant subsystems. Also, assess whether the technology, when mass-produced, has the capability to meet these targets.

These two assessment studies will identify additional concentrator R&D that must be performed. Initially, the studies should examine line focus electric and IPH systems and central receiver electric systems. Assessments of other technologies or applications should follow as the technologies mature.

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