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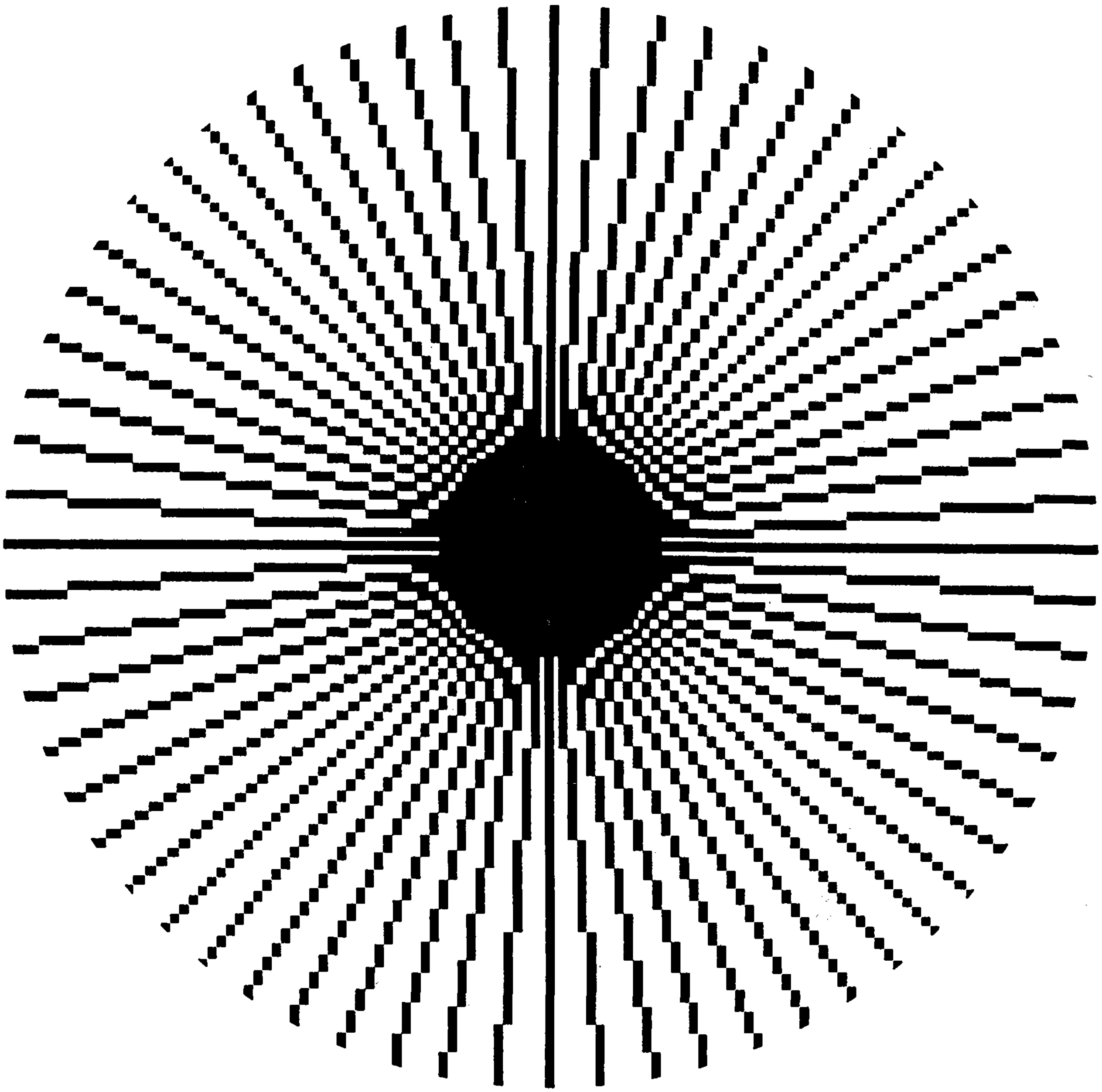
National Solar Thermal Technology Program



Five Year Research and Development Plan 1985-1989

The Department of Energy has prepared this draft plan to summarize the technical challenges that face industry and government in confirming the viability of the principal solar thermal options. As a result of the large amount of constructive input received to date from experts in industry, universities, DOE laboratories, and utilities, the program plan is much more focused than previous drafts. The Department of Energy expects that further refinements in priorities and strategies will accrue from comments received in response to this draft plan as well as from several collaborative analyses currently being conducted by industry and government.

A final plan will be prepared based on comments received from the technical community and will include areas where technical priorities and strategies for the program can be more focused.

National Solar Thermal Technology Program

Five Year Research and Development Plan

1985–1989

December 1984

This document does not reflect official Department of Energy planning information and is subject to further revisions, additions and approvals.

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United States Department of Energy

Contents

I. Summary and Introduction

The objective of the solar thermal technology program is to conduct, in cooperation with the private sector, the research necessary to establish solar thermal technologies as viable energy supply alternatives.

Through concentration and heat absorption, solar thermal energy can be converted into electricity or incorporated into products as process heat. Concentration is achieved through the use of highly reflective surfaces or refractive lenses arranged geometrically to focus on a receiver, which converts the radiant energy into transportable heat (Figure 1). Solar thermal technologies can supply energy for applications over a broad range of sizes and temperatures. Solar thermal energy can also be stored thermally extending operation into non-daylight hours. A further option, useful in cases where reliability is paramount, is hybridization with a back-up fossil fuel combustor.

The Department of Energy has prepared this draft plan to summarize the technical challenges that face industry and government in confirming the viability of the principal solar thermal options. The large amount of constructive input received to date from experts in industry, universities, DOE laboratories, and utilities has contributed to a program plan that is much more focused than previous drafts. The Department of Energy expects that further refinements in priorities and strategies will accrue from comments received in response to this draft plan as well as from several collaborative analyses currently being conducted by industry and government.

This plan systematically identifies technical objectives that can be potentially accomplished by industry and government over the next five years within a collaborative program. Within this framework, federal activities will be increasingly focused on research that is unlikely to be carried out by the private sector because of scientific, technical, or financial risks. The private sector will be relied upon to develop nearer-term products at a rate consistent with perceived market viability. In certain limited instances, a technical and financial collaboration may be necessary to perform applied research that is beyond the capacity of the private sector but necessary to advance the mutual knowledge base. Throughout the program, effective communication is a prerequisite to technical progress, and technology transfer is considered a vital ingredient in developing an industrial capacity to exploit the promise of solar thermal technology within the competitive arena of the marketplace. Success in these areas will make a major contribution toward achieving the cost targets of 5¢ per kilowatt hour (electric) and 9 dollars per million Btu (process heat).* Achieving these cost targets will eventually assure widespread usage of solar thermal technologies.

*System goals levelized in real dollars; values levelized in nominal dollars (assuming 7% inflation) are 11¢/kWhe and \$14/MBtu. The \$9/MBtu (84\$) industrial process heat target is the levelized cost of delivered energy from fossil sources in the 1990's. Current fossil fuel costs of \$5/MBtu (84\$), a real fuel cost escalation rate of 1.5% per annum, and 85% conversion efficiency would provide a levelized cost of 9\$/MBtu.

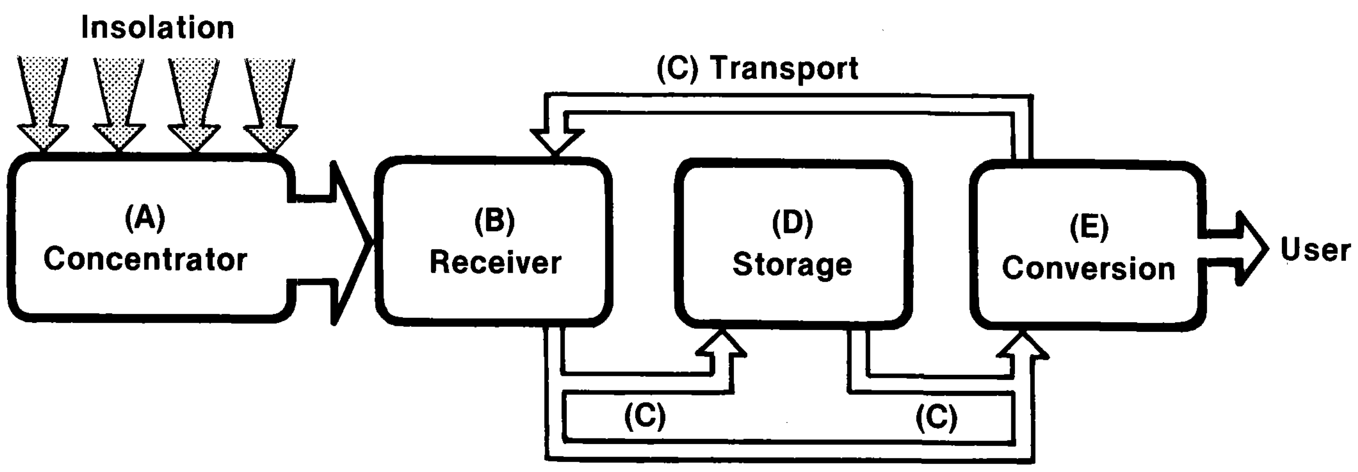


Figure 1. Solar Thermal System. Solar thermal systems convert the sun's radiation to useful products (such as electricity, fuels, or direct heat) via a thermal process. The basic elements of any solar thermal design are (A) the tracking optics used to concentrate the sun's energy, (B) the receiver which converts the photons to heat in a fluid, (C) transport piping to transfer the fluid to (D) storage for later use or directly to (E) the conversion device, which consumes the solar heat and produces the user's product.

Technology Description

The three primary solar thermal technologies (central receivers, parabolic dishes, and line focus parabolic troughs) employ various mirror and/or lens geometries to concentrate sunlight (Figure 2). Central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Presently, heliostats vary in size from less than 50 to over 100 m^2, and systems have been built consisting of 20 to several thousand heliostats. Groups of point-focusing parabolic dishes and line-focusing parabolic troughs are called distributed receiver systems. Parabolic dishes up to 15 meters in diameter have been constructed. Dishes track the sun in two axes and focus sunlight onto receivers located at the focal point of each dish. Dish modules can be used alone or in a multimodule system. A parabolic trough uses a tracking collector that concentrates sunlight onto a receiver tube at its focal line. Current trough modules are up to 3 meters wide and 7 meters long. Individual modules are combined in rows to meet large capacity needs. In addition to these three primary technologies, a fourth type, the hemispherical bowl, has also been investigated. This system uses a fixed mirror to concentrate sunlight onto a moving line receiver.

The concentrated radiant energy is absorbed by a circulating working fluid in the receiver. The heated fluid, which can range from 100°C in low-temperature trough systems to over 1500°C in dish and central receiver systems, has numerous applications. It can be used to supply process heat in plants and factories or to run a turbine or some other heat engine to generate electricity. Other systems, now in the early stages of research, replace the receiver with a receiver-reactor. The high temperature or high flux properties of solar thermal energy drive endothermic chemical reactions for the production of energy-intensive fuels and chemicals.

In addition to concentrators and receivers (together called collectors), most solar thermal plants utilize thermal transport and have the valuable option of including thermal energy storage. Storage can improve the system's cost competitiveness and can be used to shift the plant's energy output to any time of day it is needed. Thus storage provides energy on demand, not just when the sun is shining. To complete a solar thermal system, energy conversion subsystems and balance of plant items are required. Energy conversion includes equipment related to a plant's particular application, such as heat engines and heat exchangers. Balance of plant includes the control subsystem, heat rejection equipment, buildings, land, water quality equipment, and other subsystems required for plant operation.

Solar thermal systems can be built to satisfy almost any desired capacity. Dish-electric modules, each containing a heat engine, can produce as little as a few kilowatts of electricity with a single module, or fields of these modules can be assembled for larger capacity needs. Large central receiver systems, in various stages of development, could generate upwards of 100 megawatts of electric power, which (with potentially inexpensive thermal storage) would be sufficient for a city of 50 thousand people. Modular trough systems have been manufactured that can satisfy commercial or industrial process heat needs over a wide range of temperature (100°C to 400°C) and capacity requirements.

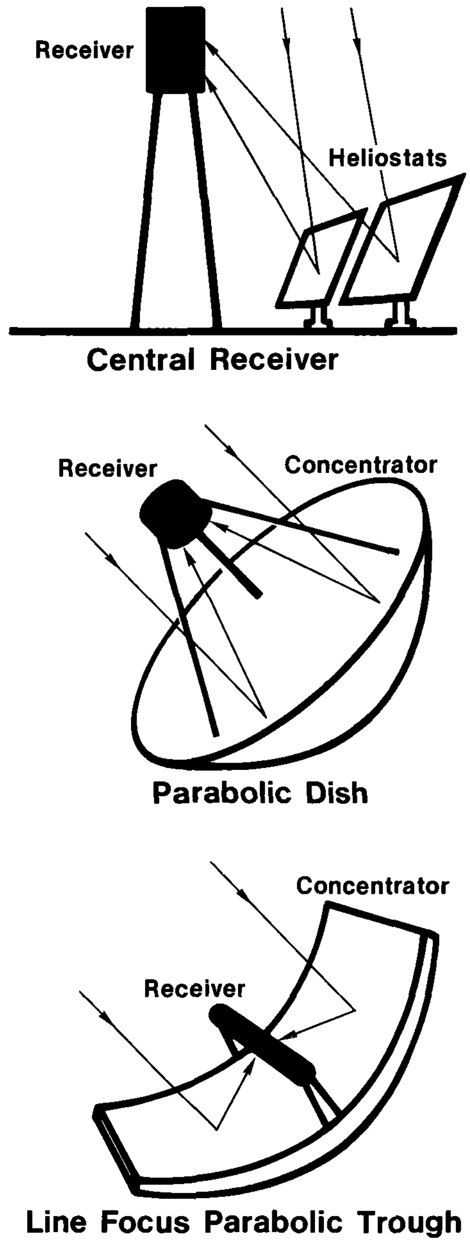


Figure 2. Solar Thermal Technologies
(not to scale)

Progress To Date

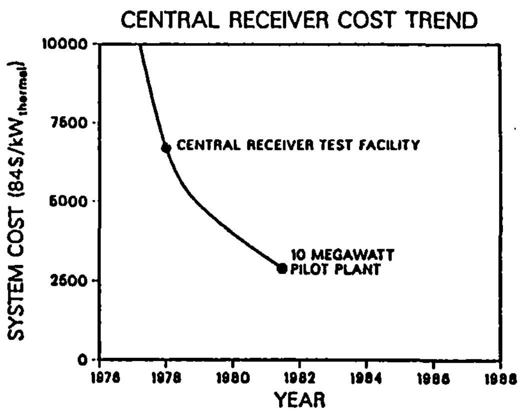
Basic concepts for concentrating solar flux to achieve high temperatures were demonstrated before the turn of the century. The first federally funded studies were conducted by the National Science Foundation and the Atomic Energy Commission. In 1975, solar thermal technology emerged as a program in the newly formed Energy Research and Development Administration. Since 1977 the program has been under the direction of the Department of Energy.

The 10-MWe Central Receiver Pilot Plant at Barstow, California (Solar One) has demonstrated the concept of electric power production using the steam-Rankine conversion cycle with water serving as the receiver heat transfer fluid. Improved system performance and lower costs may be achievable with fluids such as sodium or molten salts, which have better heat transfer characteristics and can be used directly for thermal energy storage. These alternate fluids provide a new focus for central receiver research applications. In Albuquerque, New Mexico, the 750-kWe Central Receiver Molten Salt Electric Experiment (a joint government/industry effort) is evaluating the technical and economic feasibility of molten salt as a heat transfer fluid. A sodium receiver panel has also been tested successfully in Albuquerque, and the International Energy Agency is currently testing a central receiver system with a sodium working fluid at the Small Solar Power Systems Project in Almeria, Spain.

Parabolic dish designs are evolving toward higher operating temperatures to take advantage of their potential high solar flux concentrations. The earliest dish electric systems utilized lower temperature heat transfer fluids. For example, in the 3-MWt system at Shenandoah, Georgia, in operation since 1982, a heated silicon-based fluid provides process heat, air conditioning, and electric power. The current thrust of dish module development is for high-temperature (up to 1370°C) electric power production using high-efficiency Brayton- or Stirling-cycle heat engines. A 32% gross energy conversion of sunlight into electricity has been accomplished with a Stirling-cycle engine in a dish module. Materials research and progress on heat-engine development carried on outside the solar program support much of this activity. Further research is needed to provide all-ceramic designs for achieving the high efficiencies possible at higher temperatures.

The parabolic trough concept is the most highly developed of the major technologies. It has a well-defined range of applications at temperatures below 400°C. Numerous field test installations have been built and operated, and analysis of their performance has provided valuable guidance for the private development of commercial prototype equipment. Research in support of this concept is now aimed primarily at improved cost effectiveness through lower system costs, better performance, and increased lifetime.

In 1970 there was no established industrial capability for designing and building solar thermal systems and little data on which to base such designs. However, spurred by the realization of the vulnerability of our heavy dependence on nonrenewable and imported energy sources, we are overcoming these obstacles. Many different solar thermal concepts for producing electric power and heat are now technically feasible, and the cost performance of these systems is rapidly improving. The progress to date for central receiver and trough systems is shown in Figure 3 (an insufficient number of complete dish systems have been built to present a parallel comparison). Advances in component



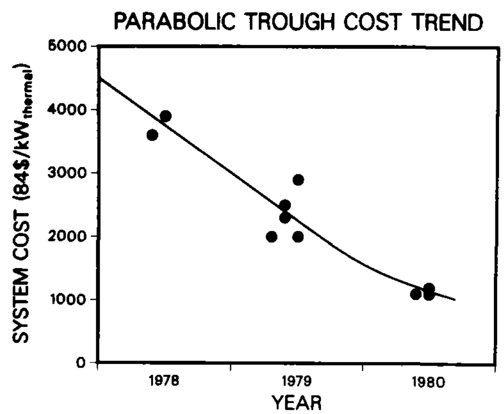


Figure 3. Progress to Date for Central Receiver and Trough Systems. Central receiver and trough systems have both shown significant cost reductions in recent years due to improved design and experience gained. There have not been a sufficient number of complete dish systems fielded to present an equivalent figure.

cost, performance, and reliability have decreased maintenance expenses, while system operating experience has significantly reduced operating expense and down-time.

Federal Role

The federal role in solar thermal technologies consists of five partially overlapping responsibilities:

(1) program planning
(2) applied research, design and testing of components and systems to show technical feasibility
(3) analysis and guidance in support of economic feasibility
(4) risk sharing as appropriate and
(5) technology transfer to the private sector.

Program planning consists of prioritization, funding allocation and program coordination to maximize the rate of progress while applied research, design and testing are the mainstays of assuring technical feasibility. Economic feasibility is equally important, but is not as easily demonstrated; the federal role here is an emphasis on cost effective designs and support of economic analyses. The federal government supports research and development which presents too large a financial risk for any single private firm (manufacturer or owner) to assume, yet will lead to long-term national benefits. Finally it is the federal government's responsibility to transfer to the private sector elements of the maturing technology as quickly as possible. The federal industrial partnership in research and development (embodied in vigorous, inherent technology transfer) will accelerate the wide acceptance of solar thermal technologies.

II. The Program

Substantial progress has been made in the Solar Thermal Technology Program but there is much more that remains to be accomplished. Solar thermal central receivers, dishes, troughs, and bowls have all been successfully built and tested. A balanced, comprehensive plan for the program has been established by comparing the current development status of the technologies with the cost-performance goals developed in this Five Year Research and Development Plan. This comparison provides the basis for identifying and assessing the magnitude of the *remaining* technical and economic barriers to widespread use of solar thermal technologies. By ensuring that the program is consistent with this Plan, solar thermal technologies will be reduced in cost and improved in performance and reliability.

Purpose

To develop the balanced, flexible source of affordable and abundant energy mandated by the National Energy Policy Plan, the Solar Thermal Technology Program supports research and development to improve cost performance and broaden the areas of applicability. This work complements that done by private industry and will provide technically proven options for eventual incorporation into the Nation's energy supply.

Federal/Industrial Partnership

A strong partnership between industry and the federal government is critical to the success of the Solar Thermal Technology Program. Industry (suppliers and users) will benefit substantially from government-sponsored research and development of the technology. In return, industry's cooperation and capability help to expedite the solutions to the problems facing solar thermal technology and bring to the Nation a more secure energy future. The partnership elements include:

- Federally funded research and development into areas with significant long-term benefits
- Cost sharing between industrial teams and the federal government
- Government-provided test facilities for component testing
- Technology transfer activities

In this flexible partnership, industry focuses most of its efforts in the more-developed technologies for commercial application, while the government's efforts are concentrated on promising, but less-developed options. Long-term planning and broad strategy development are the responsibility of the Solar Thermal Technology Division at DOE Headquarters.

Industry, as a partner in the future of solar thermal technology, plays a significant role in creating Five Year Plans and plays a key role in their implementation.

Planning Concept

The system-level energy-cost targets in Table 1 have been selected as a compromise between minimizing the risks inherent in attaining the goals and maximizing the potential market penetration. Although the goals are ambitious, achieving them would yield large returns in the form of an inexpensive and widely applicable source of renewable energy.

The long-term prospects for solar thermal technologies attaining the system goals have been judged on the basis of systems analyses, cost projections, and data from operating systems. Separate goals for electricity and heat are required due to differing solar thermal efficiencies and market-based economic requirements. The Appendix contains the levelization procedures, bases, and assumptions involved in creating the targets. While the system targets are judged to be potentially attainable by the three primary solar thermal technologies, different degrees of uncertainty exist. First, the future rate of progress toward the goals cannot be assured; setbacks will occur as well as breakthroughs. Second, the research and development requirements may grow too large to warrant continued support of a given technology/application combination. As a result, a continuing process of reappraisal will be needed to determine the direction and optimum levels of effort for the Solar Thermal Program.

Table 1. Solar Thermal Long-Term Targets

The ranges of efficiencies, capital costs, and capacity factors arise from the differences between the solar thermal technologies; Table 2 contains more detailed costs.

	Electricity	Heat
System Annual Efficiency	22–28%	56–68%
System Capital Cost (1984$)[a]	$1300–1600/kWe	$390–470/kWt
Capacity Factor	0.25–0.50	0.25–0.30
System Energy Cost (1984$)[b]	5¢/kWhe	$9/MBtu

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

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

Within both the electricity and heat markets there exist potential applications for solar thermal energy at a range of delivered energy costs. This means that solar thermal technology could have significant applications well before achieving the system cost targets. Of course, as the delivered price of solar thermal energy decreases, the number of potentially economically feasible applications increases.

To date, the efforts of industry and the federal government have led to steadily decreasing energy costs from solar thermal systems. Continuing evolution of system components and designs will further decrease costs, increasing the number of potential applications. As the manufacturing rates for solar components gradually rise, economies of scale will be realized, contributing to further decreases in the cost of solar thermal energy.

III. The Technical Plan

Progress in solar thermal technology in the past decade has resulted in significant decreases in the cost of delivered energy from solar thermal systems. In the presence of energy tax incentives, a number of solar thermal applications are economically attractive today. To be competitive without special tax incentives, solar thermal must further decrease delivered energy prices to meet the cost targets described in Section II.

Research and development activities have been structured as tasks specifically directed toward achieving component targets. These tasks fall into the general areas of collection technology, energy conversion technology, and systems and applications technology. The objective of each is to reach the long-term cost/efficiency target of the component, and thereby contribute toward achieving the overall energy cost target.

Table 2 shows a matrix of the major solar thermal research tasks and their component targets. The long-term prospects for heat and electricity applications indicate the component targets for each research and development task in terms of annual efficiency and installed cost. Two of the tasks, Direct Conversion devices (Task 5) and Innovative Concepts and Applications (Task 7), do not have quantitative goals associated with them since they represent substantially different approaches to solar thermal utilization and appropriate goals are currently unknown.

The targets for Central Receiver Systems (Task 9) and Distributed Receiver Systems (Task 10) represent the average annual efficiency of a total system and the total system installed cost (including indirect costs). These system targets would be achieved by meeting the component targets for each of the preceding research tasks, or they could also be achieved by other paths since a large number of tradeoffs are possible among component efficiencies and costs. For example, if improvements in concentrator efficiency and cost exceed the component target, the system level target could be met with a higher cost and/or lower efficiency for another component.

The final research task, System Experiments (Task 11), has as its objective the achievement of the system energy cost targets discussed in Section II. Any of the technologies will meet their system energy cost targets if their goals for system efficiency and cost in Tasks 9 and 10 are met.

The current capabilities of solar thermal systems in Table 2 highlight the amount of progress required for each technology. These capabilities are based on projections of the performance and cost of the next system that could be commercially built. Thus, an individual component cost, for example, may not be the lowest achieved to date, but rather represents the cost of that component from the projected lowest-cost system. The components then are assured of being physically compatible, with their costs summing to the overall system cost. The energy costs for the current systems are calculated on the same basis as for the long-term systems (levelized energy costs assuming no energy tax credits) to provide a consistent comparison with those long-term systems. When comparing current systems to other energy sources in use today, applicable energy tax credits must be considered and the energy costs for the other energy source must be levelized.

Goals to be achieved within five years for each research task are described in Table 3. A five-year goal is needed to supply a focused orientation for each research activity. These five-year goals, and the program milestones (developed in Section IV, the Management Plan), provide near-term targets for each task that can be used to measure their progress. The relationships between the five-year goals can best be understood from the perspective of Figure 5 in Section IV, which shows intermediate program milestones. The five-year goals provide a logical progression for moving from the current capabilities to the long-term targets described in Table 2, and represent expectations of attainable progress in each area, assuming continued funding at present levels.

Collection Technology

In a solar thermal process, collection encompasses the concentration of solar flux and its absorption as thermal energy by the receiver. The research and development tasks for collection technology are divided into three areas: optical materials, concentrators, and receivers. Optical materials (mirrors and lenses) are a part of any concentrator; their improvement is so pivotal to concentrator cost reduction, however, that a separate task has been allocated to optical materials research. Its goal is the development of low-cost, lightweight, durable optical materials. Since concentrators typically are the largest single cost element of a solar thermal system, and their performance has a strong effect on overall system efficiency, their development will continue to be emphasized. Receivers likewise play a major role in system efficiency and applications selection, and have a potential for cost reduction. Receiver materials and fabrication techniques determine the system temperature limitation while optimum design configurations can minimize thermal losses.

The research and development descriptions below are cursory and should be supplemented by reference to the program schedule in Figure 5.

1. Optical Materials

Optical materials include reflective, refractive, and transmitting elements for concentrators, and transmitting and absorbing elements for receivers. Research on optical materials seeks to identify surfaces that are inexpensive, yet will survive hostile environments in long-term exposures (typically 20-30

Table 2. Current Technology Capabilities and Long-Term Targets

	Current Capabilities				Long-Term Targets			
	Electricity		Heat		Electricity		Heat[c]	
Research Tasks	Annual Efficiency	Cost (84$)	Annual Efficiency	Cost (84$)	Annual Efficiency	Cost (84$)	Annual Efficiency	Cost (84$)
1. Optical Materials ($/m²)	92%	20	92%	20	94%	10	94%	10
2. Concentrators[a] ($/m²)								
Central Receivers	55%	210	55%	210	64%	100	64%	100
Dishes	62%	650	62%	650	78%	140	78%	140
Troughs	—	—	44%	200	—	—	65%	110
3. Receivers[a] ($/m²)								
Central Receivers	90%	80	90%	80	90%	45	90%	45
Dishes	90%	350	90%	200	90%	70	95%	30
Troughs	—	—	75%	40	—	—	90%	30
4. Heat Engines ($/kWe)								
Central Receivers	34%	1000	n.a.	n.a.	39%	350	n.a.	n.a.
Dishes	33%	2900	n.a.	n.a.	41%	300	n.a.	n.a.
5. Direct Conversion	To be determined				To be determined			
6. Transport[a] ($/m²)								
Central Receivers	99%	75	99%	75	99%	25	99%	25
Dishes	99%	10	93%	110	99%	7	94%	65
Troughs	—	—	98%	40	—	—	98%	30
Storage ($/kWht)								
Central Receivers	98%	95	98%	95	98%	20	98%	20
Dishes	—	—	—	—	—	—	98%	20
Troughs	—	—	—	—	—	—	98%	20
7. Innovative Concepts and Applications	To be determined				To be determined			
8. Balance of Plant[a] ($/m²)								
Central Receivers	n.a.	70	n.a.	120	n.a.	50	n.a.	50
Dishes	n.a.	310	n.a.	120	n.a.	50	n.a.	50
Troughs	n.a.	—	n.a.	120	n.a.	—	n.a.	50
9. Central Receiver Systems ($/kWe or kWt peak)[d]	16%	4600	48%	1300	22%	1600[e]	56%	460[e]
10. Distributed Receiver Systems ($/kWe or kWt peak)[d]								
Dishes	18%	8500	52%	1800	28%	1300[e]	68%	470[e]
Troughs	—	—	32%	760	—	—	56%	390[e]
11. System Experiments (¢/kWhe or $/MBtu)								
Central Receivers	16%	16¢	48%	30	22%	5¢[b]	56%	9[b]
Dishes	18%	38¢	52%	45	28%	5¢[b]	68%	9[b]
Troughs	—	—	32%	30	—	—	56%	9[b]

a Dollars per square meter of concentrator aperture

b System goals levelized in real dollars; values levelized in nominal dollars (assuming 7% inflation) are 11¢/kWhe, $14/MBtu. The $9/MBtu (84$) industrial process heat target is the levelized cost of delivered energy in the 1990's; it is derived from current fossil fuel costs of $5/MBtu (84$). See Appendix.

c Includes production of fuels and chemicals.

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

e Capacity factors are 0.5 central receiver electric, 0.26 dish electric, 0.29 central receiver thermal, 0.28 dish thermal, 0.24 trough thermal.

n.a. — Not Applicable

Table 3. Research and Development Task Five Year Goals

Research Phase/Task	Five Year Goal*
Collection Technology	
1. Optical Materials	Develop polymer reflective materials with 93% lifetime averaged reflectivity, costing $15/m^2, lasting 5 years.
2. Concentrators	Improve annual efficiency by 5 percentage points and reduce cost to 120, 300, and 150 $/m^2 for heliostats, dishes, and troughs, respectively.
3. Receivers	Design receivers for higher temperature applications while maintaining efficiencies. Reduce costs by 30% from the current capabilities.
Energy Conversion Technology	
4. Heat Engines	Reduce dish-mounted engine costs to $1000/kWe(peak). Obtain 35% efficient (annually averaged) dish-mounted engines.
5. Direct Conversion Devices	Conduct exploratory research on promising high-flux/high-heat rate/photon-specific processes.
6. Transport and Storage	Obtain a 25 $/kWht cost for storage while maintaining high efficiency. Reduce transport costs to 40, 75, and 30 $/m^2 for central receivers, dishes, and troughs, respectively.
Systems and Applications Technology	
7. Innovative Concepts and Applications	Conduct research on novel concepts and applications. Select the most promising for further study.
8. Balance of Plant	Characterize balance of plant requirements. Strive for automated control.
9. Central Receiver Systems	Study system integration issues through detailed designs. Achieve at least a 40% capital cost reduction while maintaining or improving efficiencies.
10. Distributed Receiver Systems	Study system integration issues through detailed designs. Obtain 5 percentage point efficiency improvements with at least a 40% capital cost reduction.
11. System Experiments	Obtain the necessary information to verify full system operating characteristics and identify technical requirements for further collection, conversion, and systems research. A 40% energy cost reduction will be sought.

*Annual Efficiencies; $/m^2 of concentrator aperture area.

years) while imposing a minimum of design requirements on their supporting structures.

For concentrators, durable, long-lasting materials and high-reflectivity silvered reflectors that resist degradation of their mechanical and optical properties from exposure to ultraviolet radiation, weathering, and atmospheric pollutants are important for reducing costs and improving lifetimes. The current focus is on developing silvered polymer and silvered steel reflective surfaces which will match the performance and durability of state-of-the-art laminated silvered glass technology, while reducing costs from a current level of $20/m^2 to long-term targets of $10/m^2. Modest optical performance improvements are also sought (roughly 2%) but the primary goal is lowering costs of the reflective film and its support structure by eliminating the inherent weight, high cost, and poor impact resistance of silvered glass. Other cost benefits should accrue due to ease of handling, fabrication, and installation of a lightweight silvered polymer on thin steel surfaces.

For polymer reflectors, laboratory analysis and accelerated environmental testing are under way to characterize degradation mechanisms induced by ultraviolet radiation as well as silver/polymer interfacial chemical effects caused by water, air, and pollutants. For silvered steel, substrate smoothing techniques required to achieve high reflectivity will be evaluated as a necessary first step, in concert with the identification of front-surface transparent coatings (applicable to polymers as well) to protect the silver reflective surface. Optimized polymer and steel reflective surfaces will undergo extended environmental testing and evaluation to verify near-term goals of 93% specular reflectivity averaged over a five-year life, and $15/m^2 cost.

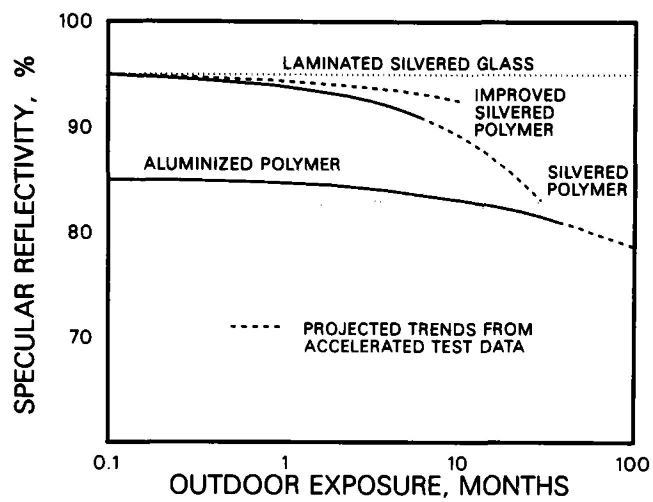
Optical elements for receivers include transparent envelopes or windows and selective absorbing surfaces with high absorptivity and low emissivity to enhance receiver thermal efficiency. The development of selectively absorptive coatings with improved durability and performance and transparent materials that can serve as windows to transmit concentrated solar flux to a receiver cavity are particularly important for efficiency improvements in high-temperature applications. Windows may also be of critical importance to direct conversion concepts, allowing photons to impinge upon the working fluid while isolating it from the external environment.

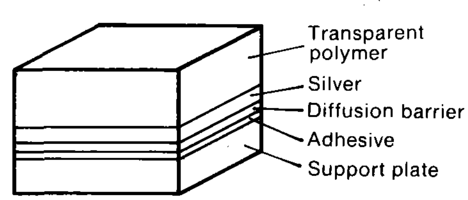
Window materials and absorber coatings for receivers and receiver/reactors must survive when exposed to concentrated

Polymer Reflector Research

To achieve concentrator cost and efficiency targets using silvered polymers, a specular reflectivity over 92% must be maintained for an extended service life. Currently-available silvered polymer films are inexpensive, lightweight, and have high initial reflectivity—equivalent to state-of-the-art silvered glass (94 to 95%) and significantly higher than aluminized polymer films. Unfortunately, as can be seen in the figure, the accelerated environmental tests and limited outdoor exposure data show rapid deterioration of silvered polymer reflectivity, in contrast to laminated silvered glass and aluminized polymers, which retain all or almost all of their initial reflectivity for a period of years.

Ultraviolet exposure is particularly damaging to silvered polymers when trace amounts of certain chemical species such as chlorides are present. Specular reflectivity is reduced by ultraviolet-induced degradation of the polymer film and the adhesive backing and by photochemical reactions that cause deterioration of the silver reflective layer. Improved life for silvered polymers is sought through the use of polymer additives which absorb and dissipate ultraviolet energy harmlessly, by diffusion barriers to prevent access of harmful chemical species to the silver layer, and by opaque layers to reduce degradation of the adhesive backing. Progress is being made: preliminary accelerated test data show much less rapid loss in reflectivity for an improved silvered polymer. However, further research and extended exposure tests are needed to meet a near-term target of 93% reflectivity averaged over a minimum 5-year life for low-cost concentrator applications.





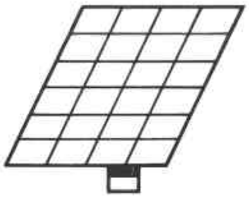
Polymer Reflector Sample Cross Section

solar flux, high temperatures, corrosive environments, and cyclic thermal stresses. Current research seeks to characterize the mechanisms leading to degradation of receiver window materials and high-temperature absorber coatings and to identify methods for improving their performance and durability. The results will be used to focus research on the evaluation of optical properties and service performance of optimized window materials and receiver absorber coatings.

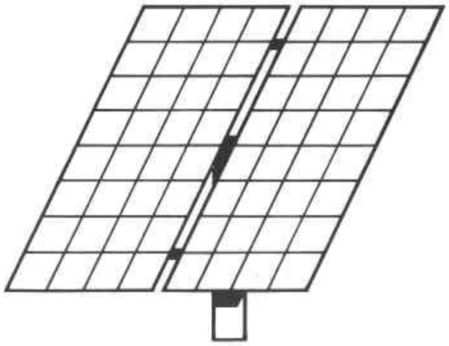
2. Concentrators

Focusing the solar flux onto the receiver, concentrators are a critical element of a solar thermal system. Concentrators must accurately track the sun and efficiently reflect or refract the radiation. Since concentrators typically comprise the largest cost element of a system and their performance has a direct effect on overall system efficiency, it is imperative to minimize costs without significantly sacrificing performance. But because the cost and performance limits for optimized concentrators using state-of-the-art silvered-glass technology are relatively well defined at this point, further significant reduction in concentrator cost depends on the development of new concepts, such as the stretched-membrane concentrator, lightweight, low-cost reflective surfaces, and low-cost drive systems.

Current capabilities of the major concentrator technologies are 55% annual efficiency for heliostats at a cost of $\$210/m^2$,



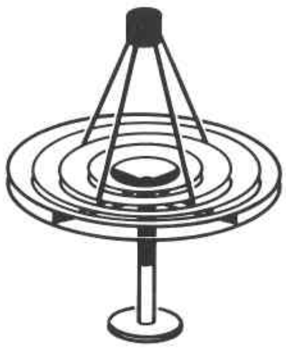
A. 50 m^2 Heliostat



B. 160 m^2 Heliostat

C. Membrane Heliostat

D. Multi-Membrane Dish



E. Segmented Ring Reflector

F. Dome Fresnel Dish

Concentrators

Concentrators provide avenues for major improvements in the cost of delivered energy for solar thermal systems. Innovative concentrator designs are being developed to achieve these cost/performance improvements through enhanced reflectivity, longer life, and lower initial cost. Substantial increases in heliostat reflective area (compare A and B) can result in lower costs without loss in performance or lifetime.

Using the stretched membrane concept, lightweight, low-cost concentrators can be constructed of high-reflectivity silvered polymer films or thin silvered glass (C,D). Other new concepts are also being investigated, including segmented ring reflectors (E) and the use of Fresnel lenses (rather than reflectors) to concentrate sunlight at the receiver (F).

62% and $\$650/m^2$ for dishes, and 44% and $\$200/m^2$ for troughs. The long-term objective is to reduce the cost of these concentrators to $\$100/m^2$ for heliostats, $\$140/m^2$ for dishes, and $\$110/m^2$ for troughs, while improving the annual efficiencies to 64%, 78%, and 65%, respectively. In the nearer term (the duration of this five-year plan), goals of 5% annual efficiency improvement and and at least a 25% cost reduction are sought for heliostats and troughs; the cost goal for dishes (which have not been produced in quantities as large as heliostats or troughs) is to reach $\$300/m^2$.

Materials and components research has identified areas for cost and performance improvements. Both silvered steel and silvered polymer-on-steel designs have the potential to reduce costs for existing collector designs by replacing expensive silvered glass. Research on concentrators utilizing silvered polymers will aim at development of potentially lightweight, low-cost, durable concentrators with high performance; the stretched membrane heliostat and dish concepts will be considered as the primary applications. Several other innovative concentrators are also being examined to determine their feasibility and cost effectiveness; these include segmented-ring reflectors and point-focusing Fresnel lenses. The general research approach will be analysis and design followed by prototype fabrication and testing.

Experimental work will continue to explore methods to reduce the ultimate wind loads on concentrators and to study the effects that wind reduction techniques have on the concentrator structures. Reductions in weight and wind loading may allow the major concentrator structural elements to be fabricated from composite materials. Research on concentrator drive mechanisms is also being conducted; a 50% cost reduction in drives for the next generation of concentrators is anticipated from this effort.

Combining the optical materials from Task 1 with these wind mitigation techniques, low-cost drive designs, and advanced structural materials, will lead to much-improved concentrator designs.

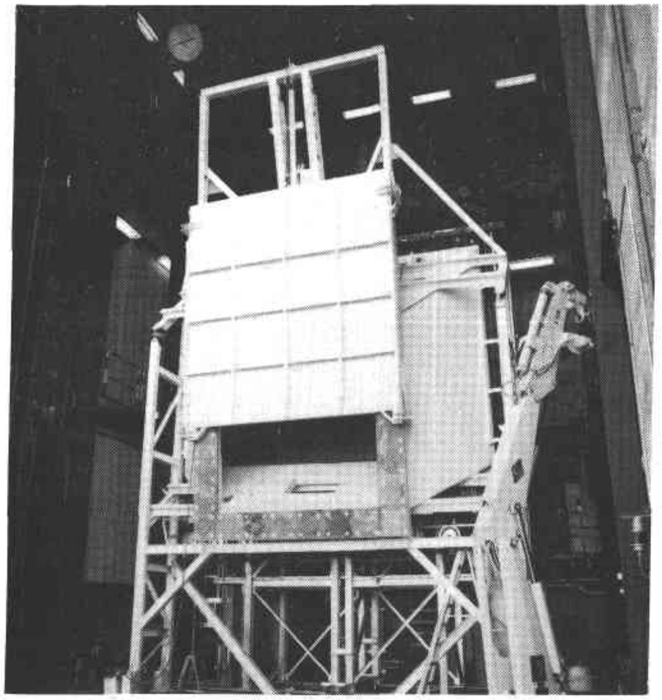
3. Receivers

Receivers are the components which convert solar radiation into thermal energy. (In the case of central receivers, the tower is also included.) Receivers have been built and tested using water/steam, molten salt, liquid sodium, oil, and air as the heat transfer fluids. Most of these receivers operate at temperatures less than 600°C, with efficiencies between 75 and 90%, and with costs (expressed in dollars per square meter of concentrator aperture area), of $\$80/m^2$ for central receivers, $\$200\text{-}350/m^2$ for dishes, and $\$40/m^2$ for troughs.

To improve efficiencies and lower costs, thermal loss mechanisms must be better characterized, allowing improved structural and thermal designs to be developed. Central receiver research is focused on finding the best cost/performance receivers in two distinct ranges: up to 600°C, and greater than 800°C. At 600°C nitrate salts and sodium working fluids will be compared. Above 800°C other working fluids, such as solid particles and higher temperature carbonate salts, will be investigated. Appropriate containment

Receivers

In 1980, this 5-MWt molten salt receiver was tested at the Central Receiver Test Facility in Albuquerque, New Mexico (See Task 9, Central Receiver Systems). Built and tested by Martin Marietta under contract to Sandia National Laboratories, the receiver heats salt entering at 288° up to 566°C. The salt is forced through 18 serpentine passes of tubes which have an overall active area of 13 by 18 feet. Over 500 hours of testing were completed, showing the sunlight to thermal efficiency of the receiver to be 85%. This receiver has been refurbished and is currently being used as a major component in the Molten Salt Electric Experiment.



materials that are compatible with the heat transfer medium at the required temperatures will be identified and evaluated. For even higher temperature applications other receiver concepts may be necessary, such as direct absorption of solar radiation, terminal concentration by secondary reflection at the receiver, and receiver-reactors for production of fuels and chemicals. For distributed systems both trough and dish receivers will continue to be refined. Dish receiver research will emphasize engine compatibility and trough research will investigate higher efficiency evacuated tube receivers.

The long-term goal is to achieve 90% efficiency for high temperature receivers (600° to 1000°C) and reduce the cost of receivers (expressed as dollars per square meter of concentrator aperture) to \$45/m^2 for central receivers, \$30-70/m^2 for dishes, and \$30/m^2 for troughs. In the nearer term, the five year goal is to reduce receiver costs by 30% for all technologies and attain higher temperature capability for dish and central receivers while maintaining or improving current efficiencies.

Energy Conversion Technology

Energy conversion technology includes processes and components to convert the thermal energy provided by the receiver into electrical, mechanical, or other usable energy forms such as energy-intensive fuels and chemicals. It also includes thermal energy storage, thermal or thermochemical processes for transporting energy, and either heat exchangers or reactor technology required to interface between the heat transport system and the receiver, storage, or end-use application. (An exception is in process heat applications where the output heat exchanger is included in the balance of plant category.) Efficient, low-cost energy conversion components are a major objective of the solar thermal program.

The principal research and development tasks for this area are (1) adaptation of heat engines for dish electric applications, (2) the investigation of direct conversion devices, and (3) the development of lower-cost, higher-efficiency energy transport and storage.

Heat engines provide the principal means for converting solar thermal energy to electricity. Most current systems are based on the Rankine conversion cycle, but as technology to achieve higher receiver operating temperatures is developed, increased emphasis is being placed on higher-efficiency heat engines using the Brayton or Stirling conversion cycles.

Concepts for direct conversion are also being investigated as potential alternatives to thermal-to-electric energy conversion or thermally driven fuels production processes. These include photochemical, catalytic-surface-induced photoelectrochemical, and thermochemical reactions.

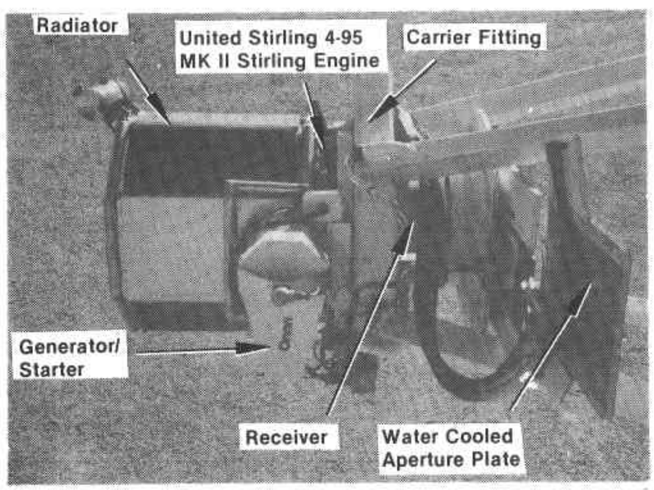
Energy transport and storage technologies are important factors in determining the cost and performance of most solar thermal systems. The capability of extending operation into nonsolar hours using storage is a key element in the usefulness of solar thermal energy.

4. Heat Engines

Heat engines are thermodynamic devices that convert thermal energy to work, which then can be converted to electricity. The engine's conversion efficiency directly impacts the total system efficiency and hence is a major concern, but the capital cost, maintenance expenses, and lifetime are also important. All of these concerns must be resolved if solar thermal electric plants are to have a major impact in the 1990's. Heat engines for solar thermal systems are adapted from existing nonsolar applications. Central receiver systems for electricity currently use Rankine-cycle steam turbines, while higher-temperature designs could use Brayton-cycle gas turbines. Parabolic dish electric modules can use small Rankine-cycle heat engines or higher temperature Brayton- or Stirling-cycle engines adapted from automotive applications.

Heat Engines

Installed on a parabolic dish module at Rancho Mirage, California, this Stirling engine, is rated at 25 kWe (maximum) and converts thermal energy to electricity with 38% peak (33% annually averaged) efficiency. The engine is a United Stirling of Sweden four cylinder, 1800 rpm automotive engine modified for solar application, operating at an input temperature of 700°C using hydrogen as the working fluid. An alternator converts the mechanical energy of the engine to electric power. This engine, its concentrator, and its receiver constitute a module which produces electricity from solar energy with a gross efficiency of 32% and a net efficiency of 29%, currently a world record.



Since engine development costs are extremely high, the dish electric program is closely following the automobile engine development scheduled for completion in the early 1990's. The strategy is to adapt these automobile engines to yield a solar-compatible heat engine. The small automobile engines are being designed for low cost and very low maintenance, but their design lifetime (3500 hours) is far too short for a solar engine, whose desired lifetime is over 50,000 hours. Activities are planned to address these uncertainties as well as the development of new engine concepts such as a hybrid engine capable of augmenting the solar energy with fossil energy.

The dish engine development will begin with completion of testing of the current-generation organic Rankine cycle engines. The next step will be testing of a small Brayton at about 900°C to be followed by a similar temperature Stirling designed especially for durability in solar operation. Success in these tests will lead to a higher temperature (1150°C) and higher efficiency Brayton experiment. A preferred small engine design will result from these experiments.

Presently, the peak cycle efficiencies of solar-compatible engines range from 27 to 39% and costs range from $1000 for large Rankine turbines to $2900/kWe for small Stirling engines. The long-term objective is to achieve an annually averaged 39% efficient large engine and a 41% dish-mountable engine, each costing in the range of $300-350/kWe. In the nearer term (five years) dish-mounted engines should have annual net efficiencies of 35% and costs near $1000/kWe.

5. Direct Conversion Devices

In addition to the conversion of solar flux to thermal energy, solar flux can be converted directly into either chemical energy or electrical energy without a heat engine. For example, chemical energy could be produced by using an appropriate photon-absorbing catalyst to split water into its constituents, hydrogen and oxygen. Alternatively, electrical energy could be produced directly by thermoelectric or other solid state devices that use the Seebeck effect (by which a current is generated in certain dissimilar materials if the junctions are maintained at different temperatures, as in a thermocouple).

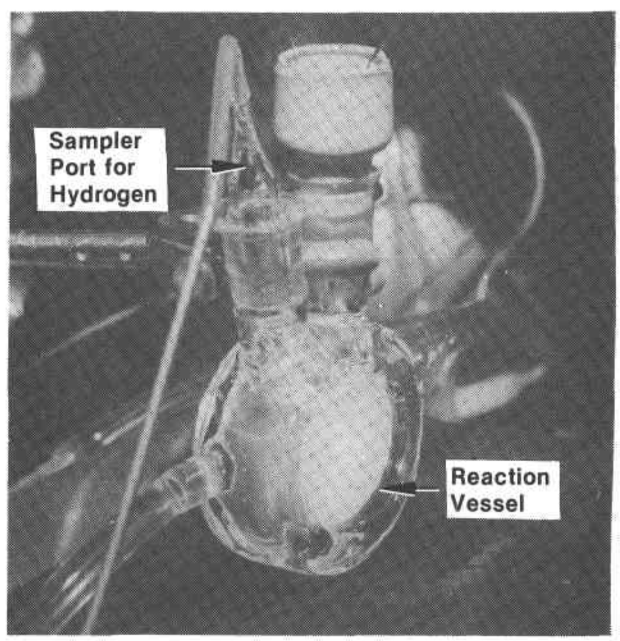
Chemical conversion research is focused on identifying and understanding promising reactions for chemical and fuel production. Thermochemical, photochemical, and catalytic-surface-induced photoelectrochemical reactions are being considered. As a first step, potential solar-unique or solar-beneficial processes will be sought; feasibility, cost, and performance are major issues. In particular, improvements of chemical production efficiency as well as the limits on direct flux, surface reaction kinetics, and efficiency are under study in this combined analytical and experimental program. Concepts for enhancing overall system efficiency (such as splitting the solar radiation spectrum and using as thermal energy the portion that cannot directly induce the chemical reaction) are also being investigated.

Direct conversion to electricity using sodium heat engines and other thermally regenerative electrochemical systems will continue to be investigated. A prototype sodium engine will be

Direct Conversion Technology

Photoelectrochemical decomposition of either water or hydrogen sulfide (in aqueous solution) is a promising direct conversion technology. In the experimental apparatus illustrated, light from a xenon lamp is absorbed by catalytic photoelectrodes to generate free electrons and positively charged holes which participate in the appropriate decomposition reaction. The photoelectrodes are colloidal suspensions of a semiconductor base material, e.g., CdS, W_3, Fe_2O_3, which have catalytically active metals, e.g., RuO_2, on the surface. The fuel produced is monitored in the jacketed reactor vessel by an electrochemical detection system.

It is hoped that direct conversion processes like photolytic fuels generation may provide highly efficient ways to utilize the sun's energy for fuels and chemicals production.



designed, fabricated, and tested in a solar module to determine the feasibility of this technology. Efficiencies of 32% at 800°C are projected for this prototype engine; even higher efficiencies may be possible at higher temperatures.

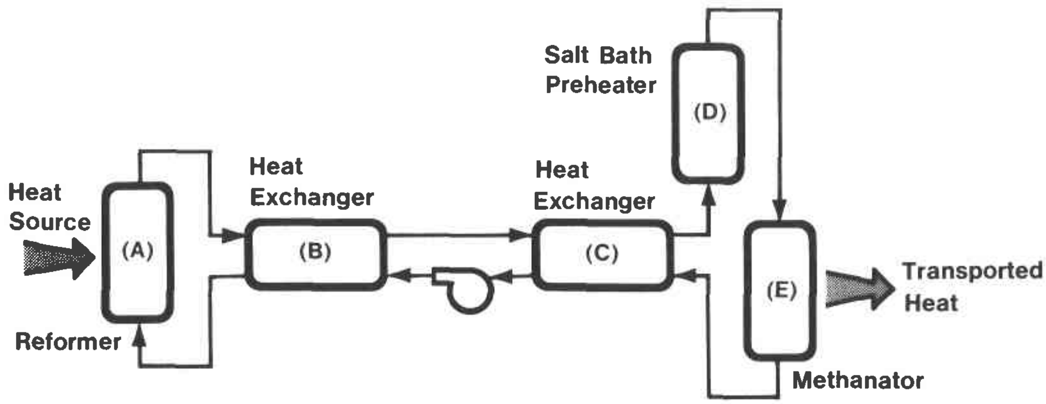
From research into chemical and direct electrical conversion, the potential attractiveness of these concepts will be assessed in terms of expected cost and performance. If positive results develop, long-term objectives will be established and activities initiated to achieve them. It is, however, premature to state formal cost or performance goals for direct conversion at this time because of the diversity of possible technical approaches and lack of concrete data.

6. Transport and Storage

The primary objective of the transport and storage task is the development of high-efficiency, low-cost systems that can provide an effective match between the fluctuating solar energy resource and the thermal or electrical load demand. Efficient, high-temperature storage will allow economical increases in electrical generation capacity factor and allow solar systems to provide energy at the time of day it is needed most. The primary emphasis of energy transport research is to identify and develop effective and economical systems for transporting thermal energy from the point of collection to a storage subsystem and/or the point of use.

Storage research activities have already led to some promising options for near-term applications. Oil, oil/rock, air/rock, liquid sodium, and molten nitrate salt are all being investigated as possible storage media. An overall storage efficiency of 70% and a cost of $70/kWht have been achieved for a 300°C oil/rock system that was installed in the Barstow 10-MWe Pilot Plant. Liquid-sodium storage technology has been successfully tested, and the current capability cost and efficiency numbers in Table 2 ($95/kWht and 98% annual efficiency) are typical of near-term commercial designs that might be built using sodium. Molten nitrate salt storage was demonstrated in a small scale experiment with a high efficiency (above 95%) and high operating temperature (up to 570°C). A large system based on this technology might cost as little as $25/kWht.

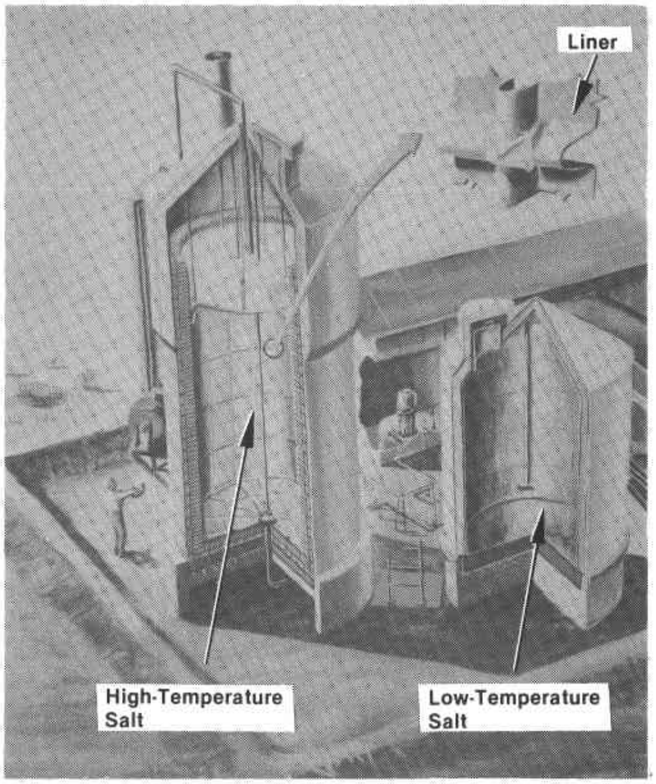
Future storage research activities include the continued study of storage materials, containment techniques, heat transfer techniques, and heat exchanger technology required for the interface between storage and the heat transport system. Solid particle and molten carbonate salt storage media, externally and internally insulated tank designs, raft thermoclines, and direct contact heat exchangers will be investigated for high-temperature sensible heat storage systems. A study assessing the feasibility of storage versus fossil hybridization is expected to be completed in 1986.



Transport Technology

The Closed Loop Efficiency Analysis Project is investigating the feasibility of thermochemical energy transport based on reversible carbon dioxide reforming of methane followed by methanation of the synthesis gas.

In the catalytic reformer (A) carbon dioxide and methane react endothermically (using thermal energy from a source such as a parabolic dish) to form carbon monoxide and hydrogen. In the heat exchanger (B) the gases are cooled before being transported at ambient temperature to a second heat exchanger (C) and a salt bath preheater (D) where they are heated. The transported thermal energy is released in this methanator (E) by the exothermic reaction of the carbon monoxide and hydrogen back to carbon dioxide and methane. After leaving the methanator the gases again pass through heat exchanger C, where they heat incoming gases, before being pumped to heat exchanger B, where they are heated before entering the reformer. The heat exchangers thus not only preheat the gases going to the reactors but also reduce the temperature of the transport gases and thereby reduce heat loss during transport over a distance. The salt bath preheater is required to start the exothermic reaction and for system control.



Storage Technology

Molten nitrate salt sensible heat storage appears to be a potentially inexpensive way to store high-temperature thermal energy. A $NaNO_3$-KNO_3 salt mixture is particularly attractive because of its low cost, high energy density, and potentially high operating temperature. Shown here is the design of a 7-MWht experiment that is scalable to a full-size storage subsystem.

The design approach is to contain the high-temperature (566°C) salt in a lined and internally insulated hot tank and to contain the low-temperature (288°C) salt in a separate tank made of carbon steel. The liner is a liquid-tight, waffled membrane design of the type used in storing liquefied natural gas. Because the hot tank is internally insulated, the shell material can be less-expensive carbon steel. The experiment, which was successfully conducted at the Central Receiver Test Facility in Albuquerque, New Mexico, advanced the state of the art in high-temperature containment.

The long-term goal of storage research is to expand the range of storage operating temperatures while achieving high efficiencies (greater than 95%) and low costs ($20/kWht). In the nearer term (five years) cost reductions to below $25/kWht with 95% efficiency will be sought.

Research on transport systems includes the investigation of conventional sensible heat transport in a suitable fluid through an insulated piping network and thermochemical transport using reversing endothermic and exothermic chemical reactions at the receiver and point of use, respectively. Dish transport in heat applications would especially benefit from the success of the thermochemical approach. The initial test of the thermochemical transport system is to be completed at the end of 1985 and a molten salt pump and valve experiment is scheduled for 1986. Current thermal transport efficiencies range from 93 to 99% while the costs range from $40 to $110/m². (Dish electric transport cost and efficiencies are based on distributed engines, hence only electrical transport is required.) Although only modest long-term efficiency improvements can be expected, long-term cost objectives are $25/m² for central receiver systems, $30/m² for troughs, and $65/m² for dishes supplying heat, which represent sizable improvements. In the nearer term, more modest cost improvements (25%) are targeted.

Systems & Applications Technology

System-level research and development activities are important for the development of solar thermal technology, since they provide the springboard for subsequent development by industry. The process begins with the identification of new, promising applications and exploratory research on innovative concepts. Systems studies and parametric analyses are conducted at an early stage to assess the long-term economic potential and to define critical components and technology development issues. In concert with supporting component research activities, more detailed systems studies and designs are performed for site-specific as well as generic applications, including balance-of-plant definition. Utilizing the results of these studies, small-scale systems experiments may be performed to resolve issues of component integration, cost potential, full-system operation and performance, reliability, and maintenance.

The principal research and development tasks for this area are (a) the assessment of innovative concepts and applications, (b) the adaptation of balance-of-plant components to the solar environment, (c) the analysis, design, and experimental testing of central receiver systems, (d) the analysis, design, and experimental testing of distributed receiver systems, and (e) evaluations of complete systems at user locations.

7. Innovative Concepts and Applications

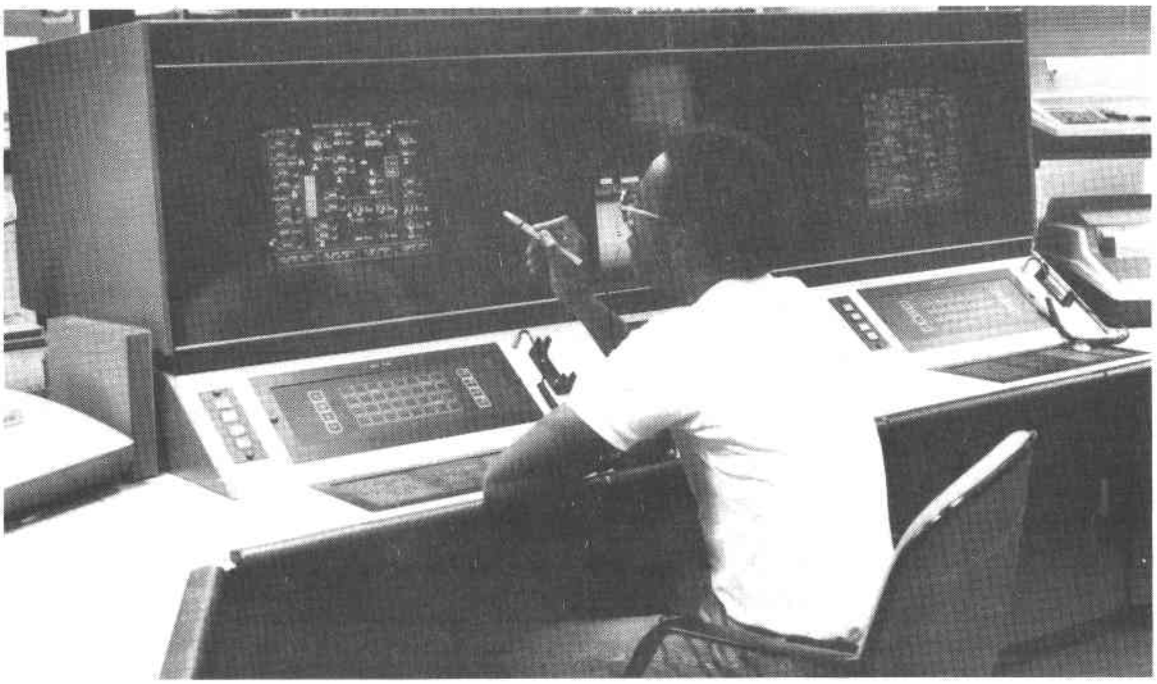
The objective of innovative concepts and applications research is to identify and foster the most promising novel approaches to, and applications of, solar thermal collection and conversion technology. This task provides an entry point into the mainstream of solar thermal research for promising but untried concepts and applications.

Yearly public solicitations invite and support the participation of private industry, university researchers, and the solar thermal community to recommend promising concepts and applications for the program. Following the exploratory research phase, those concepts showing the most promise are funded for further development.

Some of the futuristic concepts currently being investigated are a holographic concentrator, a number of collector wind avoidance approaches, and the solar production of ammonia. Holographic concentrators with no moving parts that are able to track the sun and concentrate the sun's rays appear feasible. The holograms can use low-cost polymer materials, which lead to lower fabrication costs. They are easy to handle and appear to have high impact resistance. The wind load reduction investigations are examining the effects of spoilers for individual concentrators and berms or screening approaches for fields of collectors. Photochemical ammonia production at ambient temperatures is also under investigation.

8. Balance of Plant

This task addresses research on the nonsolar components necessary to construct, maintain, and operate a complete solar thermal facility. The research activities include characterization and optimization of site construction, plant service facilities, power conditioning equipment and spare parts inventory, and the design and development of plant controls. The primary goals are the reduction of balance-of-plant capital costs, minimization of parasitic and auxiliary power requirements, and characterization and reduction of operation and maintenance costs for solar thermal installations.



Balance of Plant Technology

The controls for Solar One consist of eight linked minicomputers commanded from consoles similar to the receiver controller shown here. Instructions to the system can be entered either through the keyboard or with a light-pen on the screen itself (shown). Typically, the subsystems are displayed to the screen one at a time and the state variables compared with the set points. Automatic alarms function when values deviate significantly from normal. More advanced supervisory controls are currently being developed to reduce the number of operating personnel required for future plants, with a goal of almost completely unattended operation.

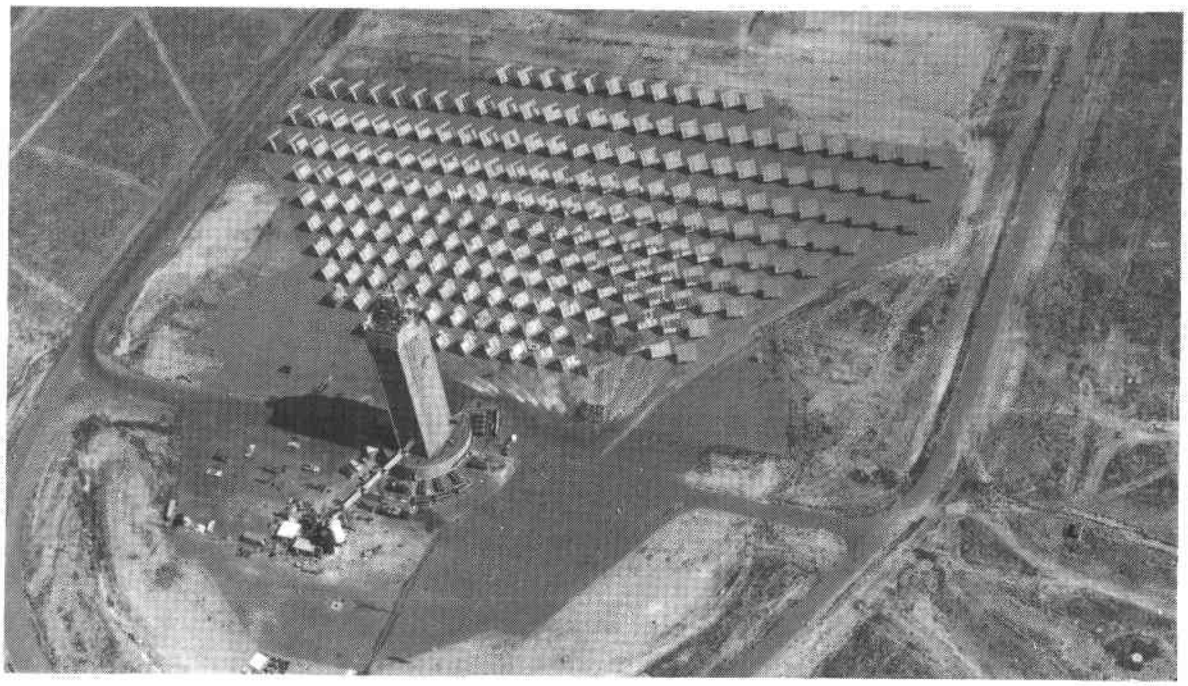
The main research and development activity in this area will be the optimization of control systems for solar thermal facilities. Expenses related to operating personnel are a major fraction of the operation and maintenance costs. Reducing maintenance costs of solar components, particularly concentrators, will be another activity since mirror cleanliness has a significant impact on system performance. Operating schemes and cleaning mechanisms are under development to minimize losses due to reflectivity degradation and to reduce the costs of cleaning mirrors.

The five-year goals are to develop automated control systems that will allow for unattended operation and to complete characterization of balance-of-plant requirements. This should lower balance-of-plant costs to $75/m^2 in the near term (five years) from the current cost of $120/m^2 for heat applications. The long-term (1990's) targets are capital costs of less than $50/m^2 and operation and maintenance costs held to a minimum through automation.

9. Central Receiver Systems

Central receiver systems research and development activities include the development of designs, the analysis of system parameters, and the experimental testing of groups of components, all leading to system experiments (Task 11). The integration of components and subsystems into a complete system is necessary to analyze properly the cost and performance tradeoffs and to identify critical technology development requirements. The experimental testing of groups of components furnishes valuable data on subsystem interfaces and performance in a solar environment. Such operational experience is key to the success of the central receiver program.

Two current central receiver systems projects are the Molten Salt Electric Experiment at Albuquerque, New Mexico, and the International Energy Agency Small Solar Power Systems Central Receiver System in Almeria, Spain. The Molten Salt



Central Receiver Systems

An advanced central receiver system with molten salt as the working fluid is under test at the Central Receiver Test Facility in Albuquerque, New Mexico. The 750-kWe experiment, named the Molten Salt Electric Experiment, integrates the three major components of a molten salt system—the receiver, the thermal storage unit, and the steam generator—with the test facility heliostat field and a turbine-generator. The cost of the project is shared (50/50) between DOE and a consortium consisting of utilities, industries, and the Electric Power Research Institute.

The Central Receiver Test Facility is part of the Solar Thermal Test Center, which also includes the Distributed Receiver Test Facility.

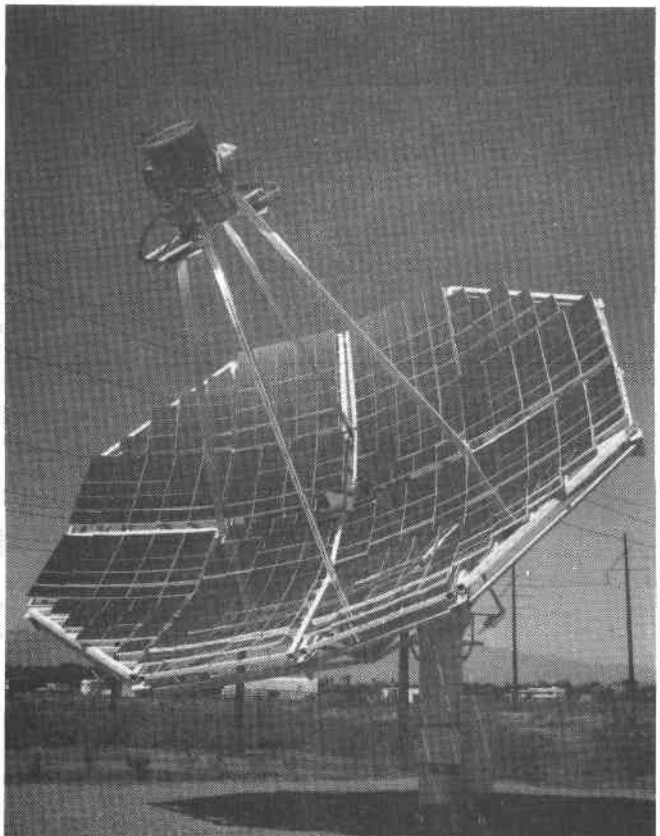
Electric Experiment uses previously tested molten-salt receiver and storage systems integrated with the Central Receiver Test Facility heliostat field, a steam generator, and a steam turbine to generate 750 kWe of electric power. Cost-shared (50/50) by DOE and several private firms (the Electric Power Research Institute, utilities, and industrial suppliers), this experiment will continue into 1985. The International Energy Agency central receiver system utilizes sodium as the working fluid and generates 500 kWe that is fed into the utility grid. Activities at this plant will be supported through 1984. These two projects will lead to a feasibility study for determining a more optimized Rankine-based design. Following the feasibility study and the conceptual design, a decision will be made as to the appropriateness of a full system experiment.

Beyond the 600°C range are the possibilities of Brayton-cycle electrical systems, high-temperature process heat, and fuels and chemicals applications. One possibility for the high-temperature (greater than 800°C) Brayton is a system based on the solid particle receiver (see Task 3); a conceptual design is planned in support of a construction decision five years hence. Other high-temperature activities include preliminary systems research on the most promising process heat/fuels and chemicals concepts.

Current capabilities for central receiver systems are an annual efficiency and capital cost of 16% and $4600/kWe peak, respectively, for electrical applications and 48% and $1300/kWt peak for process heat. The long-term target for electricity is 22% annual efficiency and $1600/kWe peak and for heat 56% efficiency and $460/kWt peak. The near-term (five year) goal is to achieve at least a 40% cost reduction from these current costs while maintaining or improving system annual efficiencies for both electrical and process heat applications.

10. Distributed Receiver Systems

Research in this task includes distributed system concept definition, application analyses, integration of component characteristics, specification of new component requirements,



Distributed Receiver Systems

The Parabolic Dish Stirling Engine Module, installed at Rancho Mirage, California, represents the state of the art in modular conversion of solar energy to electricity. The system is rated at 25 kWe (maximum) and converts solar energy to electricity with a projected annually averaged system efficiency (net) of 18%. The Stirling (described under Heat Engines) is a Swedish automotive engine modified for solar application and uses hydrogen as the working fluid. The entire module is controlled by a single microprocessor and has been in operation since January 1984.

and system-level experimental testing to obtain data to verify theoretical modeling. The objective is to develop distributed line and point receiver systems that collect thermal energy for the production of heat and electricity at costs that are competitive with the projected costs for conventional energy forms.

Distributed line focus (trough) research and development has addressed electrical and industrial applications at temperatures above 300°C. Experiments and commercial systems have been built, and the trough technology has been thoroughly evaluated. A very large parabolic trough system is currently being installed at Daggett, California; when completed it should have a net electrical output in excess of 40 MWe, making it the world's largest solar electric generating station. Trough-directed research includes the design and testing of a trough that synthesizes the most promising state-of-the-art components.

Distributed point focus (dish) technology is less well developed, with only a limited number of proof-of-principle units for generating electricity having been tested under laboratory conditions and a few modules having been tested with solar input. The largest dish system to date is the cogeneration experiment (part of Task 11) in Shenandoah, Georgia. System analyses have examined the concepts to extend the point focus technology above 600°C for industrial process heat and have identified thermal transport (Task 6) as the key area needing improvement. Research will continue to identify the most suitable working fluids and methods of affordable, efficient heat transport. Conceptual designs for a 700°C dish thermal system and a central engine for distributed thermal systems will be completed in 1985 and 1986, respectively. Considerable research is also in progress on electric systems with a heat engine (Task 4) at the focal point of the dish. Several different modules with different types of heat engines will be tested during the next five years.

To support experimental activities, a distributed receiver test facility is being constructed in Albuquerque, New Mexico. Experimental evaluation of both concentrator systems and modules of generating units for field experiments is planned for that facility.

Current capabilities for dish electric systems are an annual efficiency of 18% at a capital cost of $8500/kWe. For distributed thermal systems the current annual efficiency is 52% for dishes and 32% for troughs with capital costs of $1800/kWt and $760/kWt, respectively. The long-term (1990's) bulk electric commercialization target for distributed systems is $1300/kWe peak with 28% annual efficiency. For heat applications the dish goal is $470/kWt peak with 68% annual efficiency and the trough goal is $390/kWt peak at 56% efficiency. In the nearer term (five years) the research effort will strive for five percentage point efficiency improvements with 40% or larger capital cost reductions from the current capabilities of the technologies.

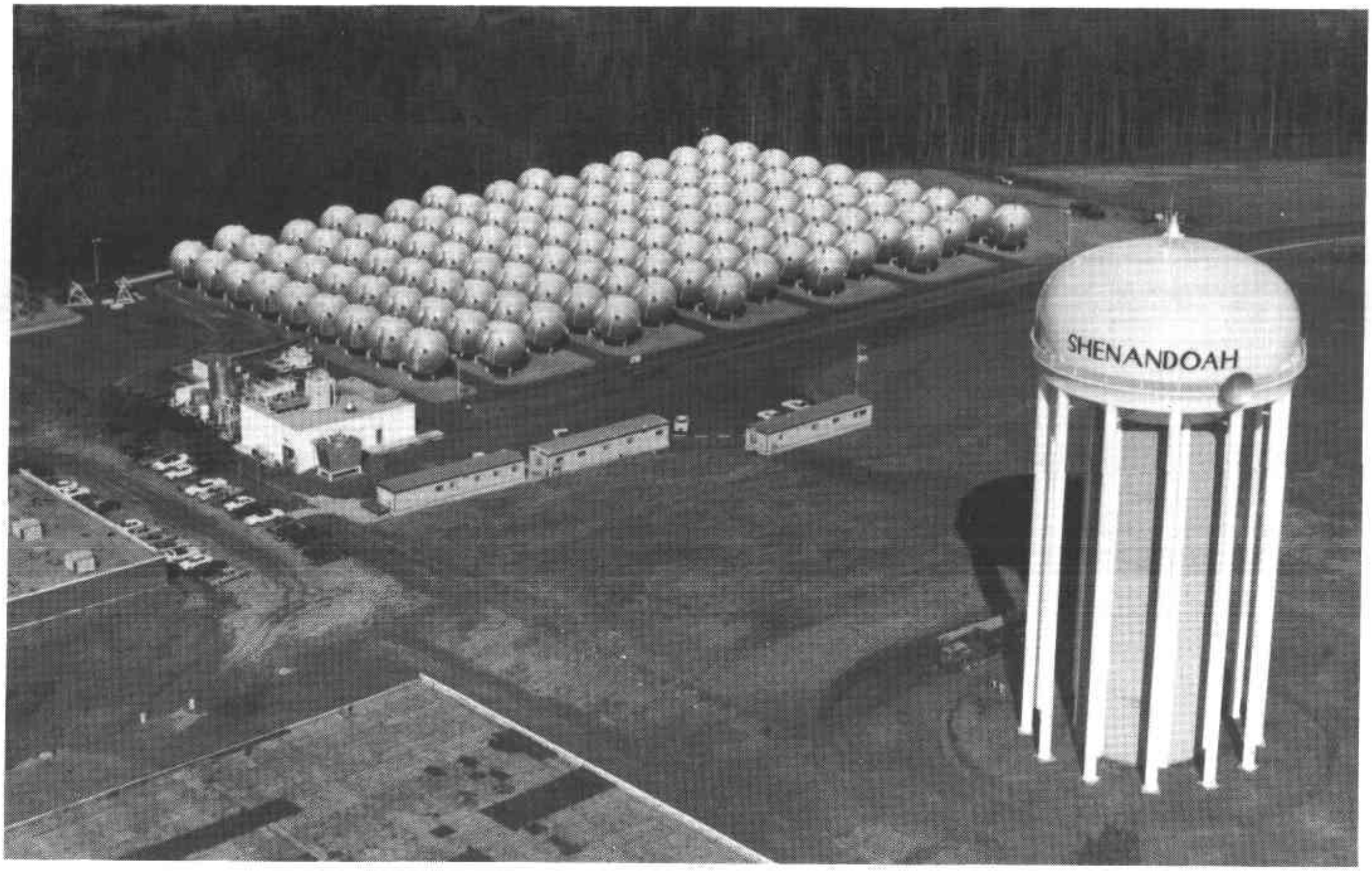
11. System Experiments

System experiments at user sites provide valuable data on capital cost, performance, and operations and maintenance of complete solar thermal systems. The system experiments are conducted with major participation from both solar equipment manufacturers and potential users. These experiments lead to the establishment of technical feasibility, to the development of a valuable cost and performance data base that can be used in private sector decisions, and to the identification of future research needs. The experience gained by full system experimentation directly addresses a potential user's perception of risk in the technologies.

Several major system experiments are now on line. Operations and maintenance data are being evaluated from the 10-MWe Solar Central Receiver Pilot Plant near Barstow, California, the 3-MWt parabolic dish total energy (cogeneration) plant at Shenandoah, Georgia, and several trough process heat experiments at various user sites. To establish the system feasibility and identify operations and maintenance costs of these experiments, several years of operating experience are needed. During this period, operational experience will be accumulated for all the plants' operating modes, and the plants' system and component performance will be evaluated. Some of the experiments will also be upgraded to evaluate improved components and techniques for reducing plant staffing levels, thereby broadening system operating experience even further. The Solar Thermal Technology Program will operate and evaluate the Shenandoah experiment through 1984, the trough process heat experiments through 1985, and the Barstow experiment through 1987.

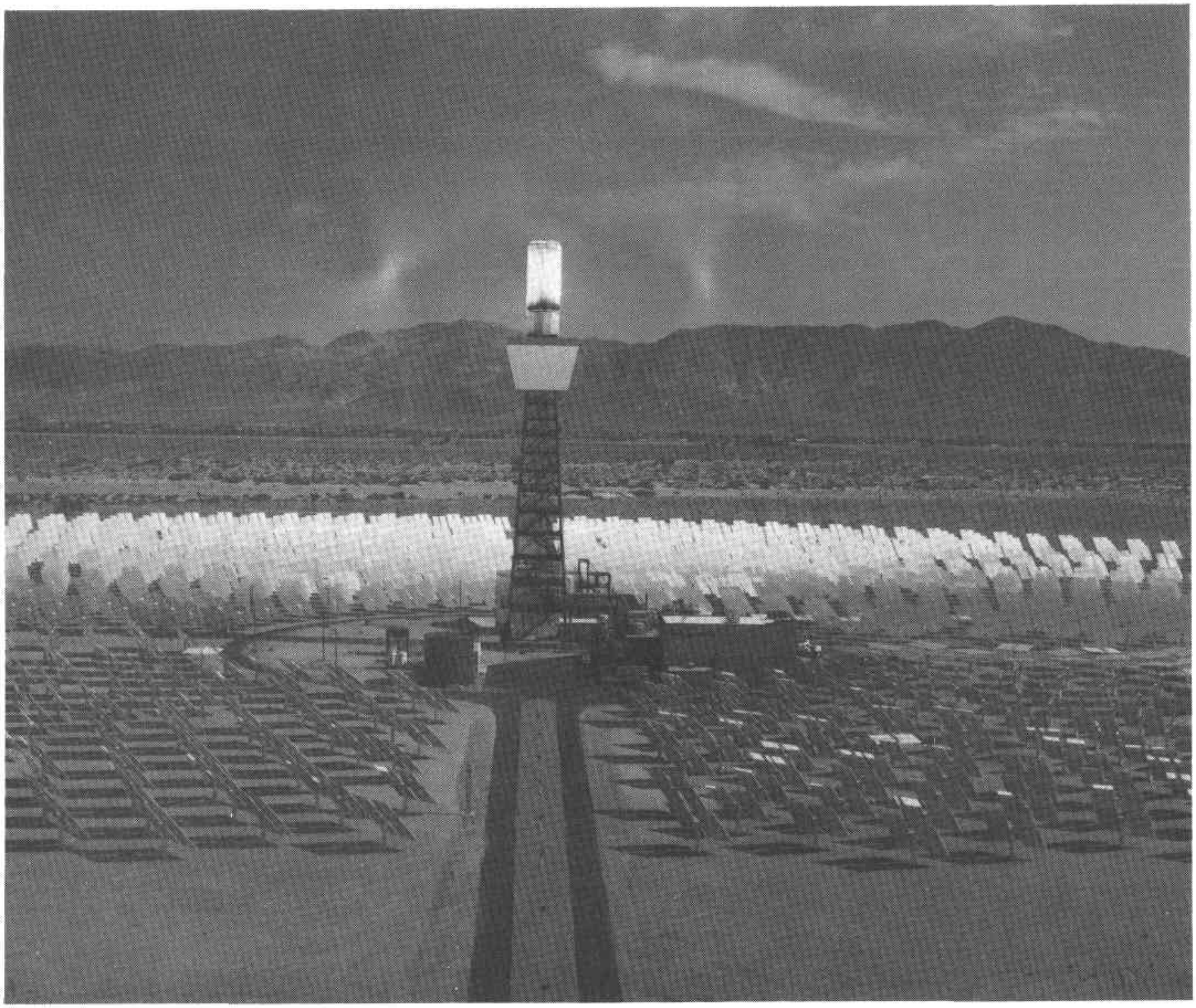
Over the next five years additional system experiments will come on line. Two Small Community System Experiments (dish), cost-shared with the private sector, will be built and operated. A conversion of the 10-MWe Barstow Central Receiver Pilot Plant is being evaluated as an intermediate step, leading to the possible construction of a large-scale (30-100 MWe) system. Over the next five years Central Receiver Systems (Task 9) will generate one or more conceptual and detailed designs for an electric plant scalable to utility size. A decision will be made in fiscal 1989 as to the readiness of the technology for a scale-up experiment based on these designs. System experiments provide valuable scale-up experience and data essential to the future of solar thermal systems.

The long-term energy cost objective for significant market penetration in the 1990's is 5¢/kWhe for electricity and $9/MBtu for process heat (see Table 2). In the near term (the five year duration of this Plan) the goal is to reduce energy costs by 40% relative to current capabilities. The next five years' operational experience should allow us to (a) obtain the necessary information to verify full system operating characteristics and (b) identify the technical requirements to further collection, conversion, and systems research.



System Experiment—Shenandoah

The Shenandoah Total Energy Project at Shenandoah, Georgia, produces 3 MW of thermal energy at 400°C. This thermal energy is converted to 400 kWe, 630 kg/h of 175°C steam for clothes pressing, and 1430 MJ/h of chilled water for air conditioning. The system consists of 114 seven-meter-diameter parabolic dish collectors connected in a closed hydraulic system, a steam Rankine-cycle turbine/alternator with steam extraction from the turbine, an integrated control system, and an absorption chiller. A silicone heat transfer fluid circulates through the field, absorbing the solar energy at each collector. Construction of the system was completed in 1982; it is currently undergoing an operational phase to evaluate the solar total energy (cogeneration) concept.



System Experiment—Solar One

In 1978 the DOE and the Associates (Southern California Edison, Los Angeles Department of Water and Power, and the California Energy Commission) entered into a cooperative agreement to share in the cost of the design, construction, and operation of a 10-MWe Central Receiver Pilot Plant (Solar One) near Barstow, California. Construction of the plant was completed in 1981, and operational testing and evaluation are under way. Initial tests for the plant have been very successful: the plant has achieved its rated power capability of 10 MWe net when operating directly from the receiver and 7 MWe net when operating from storage. The current five-year operational test period will permit the collection of adequate data and valid evaluation of the plant.

Solar One, the world's largest solar-electric plant, has generated more than 10,000,000 kWhe since April 1981. Over 100,000 persons have visited Solar One and observed operations there. Utility operating and maintenance personnel have complete responsibility for plant operations, demonstrating both the acceptability of the technology to utilities and the adaptability of the technology to conventional utility practice.

IV. The Management Plan

The management and direction of the Solar Thermal Technology Program is structured to be responsive to national energy policy. That policy is provided by the Secretary of the Department of Energy and incorporates recommendations from the Executive Office and national energy advisory boards. Sound management of the program is essential to ensure that overall technology targets are met and that research and development tasks leading to those targets proceed in an orderly, cost-effective manner. Coordination of the efforts of a number of organizations is necessary for the program's success. These organizations consist of DOE Headquarters, DOE operations offices, research centers, universities, and private industry.

Program Organization

The National Solar Thermal Technology Program is managed by the Director of the Solar Thermal Technology Division at DOE Headquarters (Figure 4). The Division Director provides centralized leadership and control. Implementation of the activities that make up the program is a decentralized function utilizing specialized management and technical expertise. Decentralized program management support to the Solar Thermal Technology Division is provided by the San Francisco Operations Office and the Albuquerque Operations Office. Three research and development centers provide technical expertise and management of activities in specific areas of the program.

DOE Headquarters

The Solar Thermal Technology Division is responsible for research and development policy formulation, and the allocation of technical and budgetary resources. Specific responsiblities include:

- Development of program policies, objectives, and priorities consistent with the requirements of national energy policy.
- Formulation of long-range program plans and operating strategies for achieving objectives.
- Review and evaluation of program activities on a regular basis.
- Dissemination of information on program activities in response to requests from DOE, other government agencies, and Congress.

Research and Development Centers

Three research and development centers—the Solar Energy Research Institute in Golden, Colorado, and Sandia National Laboratories in Livermore, California, and Albuquerque, New Mexico—are responsible for implementing the research and development tasks that have been formulated to meet program objectives. Activities are conducted at the three

Figure 4. Office of Conservation and Renewable Energy

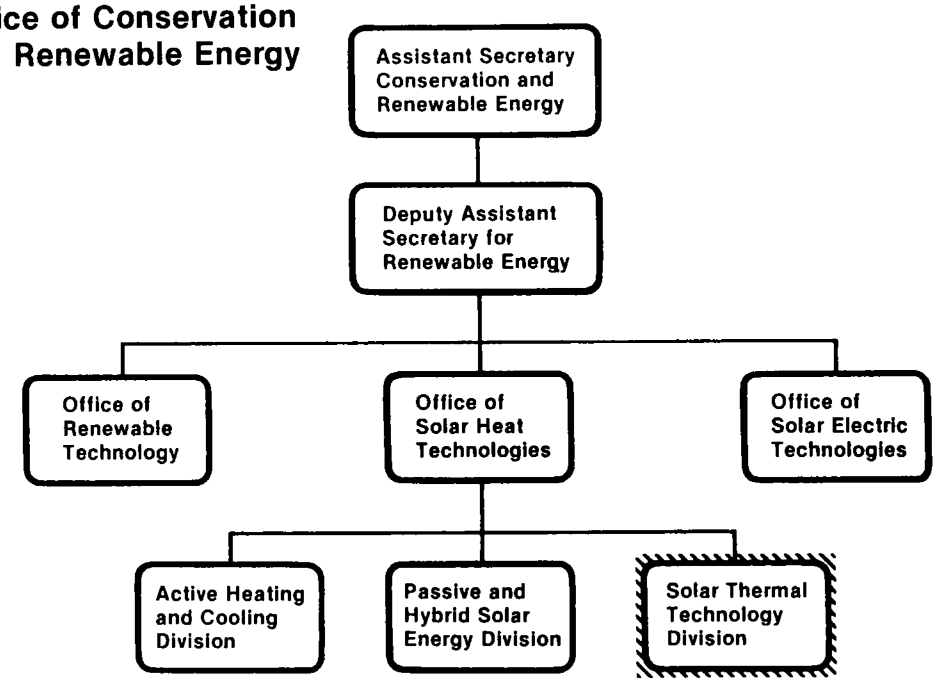


Figure 5. Solar Thermal Technology Program Schedule and Decision Points

▲ = Program Milestone
☆ = Program Decision Point

Task/Objectives	FY 85 (1985)	FY 86 (1986)	FY 87 (1987)	FY 88 (1988)	FY 89 (1989)
Collection Technology					
1. Optical Materials					
Develop Durable, Low Cost, Silvered Polymer Reflective Surfaces	▲ Identify Degradation Mechanisms	▲ Coating Developed for Silver; ▲ Complete Accelerated Aging Tests	☆ Assess R&D Direction	▲ Complete Environmental Aging Tests	▲ 93% Reflectivity 5-Year Life, $\$15/m^2$
Improve Optical Performance and Durability of Low Cost Silvered Steel Reflective Surfaces	▲ Identify Substrate Smoothing Techniques	▲ Coating Developed for Silver	▲ Complete Accelerated Aging Tests; ☆ Assess R&D Direction	▲ Complete Environmental Aging Tests	▲ 93% Reflectivity 5-Year Life, $\$15/m^2$
Develop High Temperature Absorber Coatings and Transmitters (windows)	▲ Identify Window Degradation Properties	▲ Identify Selective Absorber Coatings	▲ Optical Properties Known; ☆ Assess R&D Direction	▲ Absorber Development Complete	▲ Large Window Prototype
2. Concentrators					
Establish Technology for a Durable Cost-Effective Heliostat	▲ Wind Load Reduction Study Complete	▲ Membrane Element Prototype; ☆ Assess R&D Direction	▲ Design and Fabricate Adv. Heliostats	▲ Advanced Prototype Development Complete	▲ $\$120/m^2$; ▲ Complete Comparison Tests
Establish Technology for Durable Cost-Effective Parabolic Concentrators	▲ Innovative Designs Completed	▲ Silvered Steel Evaluation Complete	▲ Begin Test of Prototype Designs	☆ Assess R&D Direction	▲ $\$150/m^2$ Trough $\$300/m^2$ Dish
3. Receivers					
Establish the Technology for Efficient, Reliable, Cost-Effective Receivers for Central Receiver Systems	▲ Begin Particle System Conceptual Design	▲ Liquid Receiver Technical Feasibility >800°C; ▲ Complete Sub-Scale Salt Exp. $70\$/m^2$ 600°C	☆ Select 600°C Concept; ☆ Select >800°C Concept	▲ 600°C $60\$/m^2$	▲ 75% Efficiency >800°C
Establish the Technology for Efficient, Reliable, Cost-Effective Receivers for Distributed Receiver Systems	▲ Complete Dish Receiver Optimization Study	▲ Complete Evacuated Tube Trough Tests	▲ Complete Thermal Shock Research; ▲ Complete Adv. Dish Receiver Comparison	☆ Assess R&D Direction	▲ $150\$/m^2$ Dish Receiver
Conversion Technology					
4. Heat Engines					
Establish Technology for Cost-Effective Dish Engines	▲ Prototype Rankine Tests Complete	▲ 900°C Brayton Test Complete Peak 28% Efficiency	▲ Stirling Life Test Complete Peak 40% Efficiency 5-Year Life	▲ 1150°C Brayton Test Complete Peak 35% Efficiency	☆ Select Preferred Engine; ▲ 1000\$/kWe Annual 35% Efficiency 5-Year Life
5. Direct Conversion					
Explore Potential for Photon-Driven Conversion Processes	▲ Potential Processes Identified	▲ Complete Direct Flux Surface Reaction Model	☆ Select Promising Approaches; ▲ Prototype Sodium Engine Complete	▲ Complete Sodium Engine Tests	▲ 32% Efficient Sodium Engine
6. Transport and Storage					
Establish Technologies for Cost-Effective Moderate and High-Temperature Storage		▲ Complete Storage/ Hybridization Study			▲ >800°C Feasibility
Achieve Cost and Efficiency Goals for Thermal Energy Transport	▲ Initial Thermochemical Transport Tests Complete	☆ Assess Dish R&D Direction; ▲ Central Receiver Salt Pump Experiment Complete	▲ $40\$/m^2$ Central Receiver 600°C	▲ 700°C Dish $75\$/m^2$ 80% Efficiency	▲ $30\$/m^2$ Trough

Figure 5. Continued

▲ = Program Milestone
☆ = Program Decision Point

	1985	1986	1987	1988	1989
Task/Objectives	**FY 85**	**FY 86**	**FY 87**	**FY 88**	**FY 89**
Systems & Applications Technology					
7. Innovative Concepts and Applications					
Select Novel Components and Applications	☆ Selection	☆ Selection	☆ Selection	☆ Selection	☆ Assess R&D Direction
8. Balance of Plant					
Develop Cost-Effective Control Systems and Minimize Operations and Maintenance Costs		▲ Advanced Heliostat Washer	▲ Central Receiver Automatic Controls		▲ Evaluate Dish Automatic Controls
9. Central Receiver Systems					
Resolve System-Level Concerns for Up to 600°C Systems	▲ *Molten Salt* Electric Experiment Complete	▲ System Improvement Studies Complete	☆ Select 600°C System	▲ Large System Preliminary Design Complete	☆ Assess Technology Readiness for Scale-up Experiment
Resolve System-Level Concerns for High-Temperature Systems	▲ Begin Initial Conceptual Fuels Designs	▲ Complete Initial Conceptual Fuels Designs	▲ High Temperature R&D Study Complete	▲ Complete Advanced Conceptual Fuel Design	☆ Assess Technology Readiness for Scale-up Experiment
10. Distributed Receiver Systems					
Establish the Technology for Cost-Effective Dish-Electric Modules	▲ Complete Stirling Tests	▲ Complete Prototype Rankine Tests	▲ Complete 900°C Brayton Tests	▲ Extended Life Stirling Tests ▲ 1150°C Brayton Tests	▲ 4000$/kWe ☆ Assess R&D Direction
Integrate Research Components Into Cost-Effective Thermal Systems	▲ Complete 700°C Dish Thermal Conceptual Design	▲ Dish Central Engine System Conceptual Design	▲ Optimized Trough System Test Complete 600$/kWt, 40% Efficiency	☆ Assess R&D Direction	▲ 57% Efficiency $1100/kWt Dish System
11. System Experiments					
Complete Full System Experiment at User Site, Scalable to Commercial Installations — **Central Receivers**	▲ 16¢/kWhe	▲ Barstow Conversion Preliminary Design Begins	▲ Barstow Conversion Preliminary Design Complete		▲ 9¢/kWhe
Distributed Receivers	▲ Shenandoah Evaluation Tests Complete ▲ 38¢/kWhe	▲ 20$/MBtu Heat	▲ Small Community System Experiments Operational		▲ 15¢/kWhe

research and development centers and through contracts placed with universities, other laboratories, and private industry. Important specific functions of the centers include:

- Planning and scheduling research and development tasks to meet program objectives.
- Conducting research and development activities and preparing and awarding technical contracts.
- Monitoring and managing in-house and contracted research and development.
- Preparing periodic formal reports and reviews of program tasks for the Solar Thermal Technology Division.
- Providing technology transfer support for DOE Headquarters, other federal agencies and laboratories, private industry, and universities.

Management Control

Management control of the Solar Thermal Technology Program is exercised at DOE Headquarters, the operations offices, and the research and development centers to ensure that research and development activities support the policy and objectives of the program. Planning documents are prepared and periodic reporting and reviews are conducted to coordinate and communicate program objectives, plans, and issues. The Five Year Research and Development Plan presents the general technical direction for the program. Specific tasks each year are determined through the development and approval of program plans, contracts, milestones and deliverables, and resource allocations. Approved plans serve as management control documents for measuring the progress of specific tasks.

The research and development centers prepare written reports for DOE Headquarters on a regularly scheduled basis to provide information on technical activities, progress toward milestones, and resource utilization. Headquarters reviews technical progress, resource expenditures, and future planned activities each quarter. Program-wide meetings are conducted semiannually to promote technology transfer activities and to ensure continuing exchange of technical information and issues between DOE Headquarters, the research and development centers, and industry and university participants in the Solar Thermal Technology Program. The research and development centers also conduct reviews to exchange technical information on specific program areas.

Schedule and Implementation

Program subtasks, milestones, and decision points have been formulated to guide the organizations responsible for implementing program tasks and to assist management in monitoring progress toward achieving the long-term cost/performance targets established for the program. The research and development centers use the milestones shown in Figure 5 and the five year goals shown in Table 3 as interim targets. The decision points provide management and the centers with formalized control over direction of the technical progress. These decision points are supported by timely analyses used to approve or redirect further activities. Program milestones and decision points are also subject to review and rescheduling as required by programmatic and budgetary considerations. While all the component cost/performance targets and milestones are attainability-based and balanced in their probability of success, milestones and program direction are reassessed periodically to maintain this balance. The research and development centers and DOE operations offices are responsible for managing the pace and direction of program tasks such that technical milestones are achieved and coordinated.

Table 4 summarizes the distribution of program resources for FY84. Actual funding levels for fiscal years 1985-1989 will depend on annual budgetary considerations and level of technical accomplishments made to date as well as required in coming years. Resources are typically expended in the following proportions: 10% for division-level and field-level program management, 40% for in-house research at the DOE research centers, and 50% for outside contracts placed with universities, private industry, and with other laboratories.

Table 4. Resource Requirements (millions of dollars)

	FY84
1. Optical Materials	1.9
2. Concentrators	3.7
3. Receivers	7.6
4. Heat Engines	2.9
5. Direct Conversion	3.0
6. Transport & Storage	2.8
7. Innovative Concepts & Applications	1.9
8. Balance of Plant	2.8
9. Central Receiver Systems	4.6
10. Distributed Receiver Systems	1.7
11. System Experiments	10.3
Total	43.2

V. The Prospects

Solar thermal technology has the potential to harness substantial renewable energy resources for this country. By capturing the sun's radiant energy as heat and either producing electricity or utilizing the heat directly, solar thermal can become an integral and environmentally acceptable part of our energy supply network in the next decades.

The path to this goal is challenging. Significant improvements in component performance and reliability and reductions in the cost of delivered energy are required before solar thermal technology can provide an appreciable contribution to this country's diverse energy needs. To this end, aggressive long-term targets have been selected and will be pursued vigorously by the government/industry partnership. These system-level targets have been translated into component goals to facilitate accurate tracking of cost/performance progress and balancing of priorities through trade-off studies. Through cooperation and commitment, bright prospects are assured for solar thermal energy.

APPENDIX—SYSTEM AND COMPONENT GOALS

Developing a plan to foster the solar thermal technologies requires an understanding of their capabilities and promise in the context of the energy sources that solar energy will compete with in the economic marketplace. Quantitative long-term goals are developed to address two fundamental questions: (1) what energy cost must solar thermal systems achieve to have a significant impact in the energy market and (2) how must the components of a solar thermal plant be developed so that this energy cost is technically attainable? These issues are approached through system- and component-level goals. System goals are energy price targets which should be met for solar thermal to have significant economic impact in a given market (e.g., utility electric). They are determined by the primary competition to solar thermal, i.e., competing fossil energy sources. Component goals are performance and cost targets for the primary elements of a solar thermal plant, such as concentrators and receivers. They have been developed based on considerations of projected improvements in component efficiency and cost.

Approaching goals from both the system and component level naturally leads to some tradeoffs in the development of goals; the desire for the lowest possible system goal (being economically superior to all energy sources would maximize the return for technology development) must be balanced by component goals which are expected to be technically achievable. The set of goals that emerges represents a compromise between minimizing the risks inherent in attaining the component goals and maximizing the potential return represented by the system goal.

System Goals

The two primary applications chosen for the development of system goals are bulk electricity and industrial process heat. The electric system goals are based upon utility-owned, grid-connected power production. System goals for industrial process heat applications assume industrial ownership of a solar thermal plant producing mid- to high-temperature (200 to 600°C) process heat. Thus, two system goals are required rather than a single one because utility-electricity and industrial process heat represent not just different applications but also substantially different markets. The markets differ in terms of competing energy sources, economic, financial, and regulatory considerations, and other factors. A number of other applications, such as remote solar thermal power plants and electricity-producing plants owned by third parties, potentially represent significant markets for solar thermal technology, but have not been considered in developing the long-term system goals.

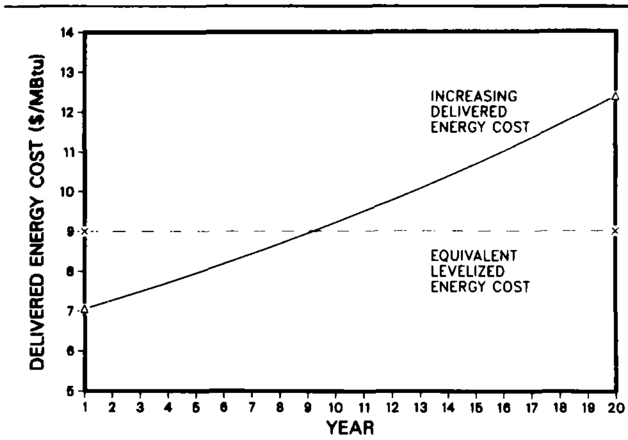
System goals are based on the projected levelized energy cost of competing energy sources in the middle to late 1990's time frame. These goals do not represent a threshold energy cost that solar thermal must achieve to allow initial sales, but are even more ambitious targets that would allow solar thermal to compete with many energy sources and achieve significant market penetration.

The levelized cost methodology for calculating system goals (and component goals) is a standard approach often used in the utility industry and is described in more detail elsewhere (Refs. 1, 2). This approach considers all relevant elements of an energy source cost, including capital costs, operating costs, and return on investment. After assessing the net present value of all costs, the methodology calculates an equivalent energy cost which is level (i.e., constant from year to year) over the plant's lifetime.

These calculations for the goals are carried out on a constant dollar (also known as a real dollar) basis, which removes the effects of general inflation. A constant dollar approach results in energy costs that are steady over time when expressed in dollars of constant purchasing power. An alternative approach is to use nominal dollars (dollars of a particular year) assuming a general rate of inflation. Either approach will yield the same relative comparison of one alternative to another (and also the same set of component goals discussed in the next section). Costs levelized in nominal dollars are higher than those levelized in real dollars since the former factors in an inflation assumption. (A 7% inflation has been assumed when calculating energy costs levelized in nominal dollars.) No inflation assumption is required when levelization is performed in real dollars, our standard approach in this Plan.

Figure A-1 shows an example showing a levelized energy cost (excluding capital and operation and maintenance cost) for a

Figure A-1. Comparison of an Annual Energy Cost and an Equivalent Levelized Energy Cost



fossil fuel source with an initial price of $6/MBtu. The delivered energy price (accounting for the 85% system efficiency) rises from approximately $7/MBtu in the initial year to over $12/MBtu (in constant dollars) in the final year owing to fuel price escalation. A levelized energy cost with the same present value as the rising energy cost is approximately $9/MBtu. Levelizing in nominal dollars (now assuming a 7% general inflation rate) the equivalent energy cost becomes $14/MBtu.

Electricity Goal

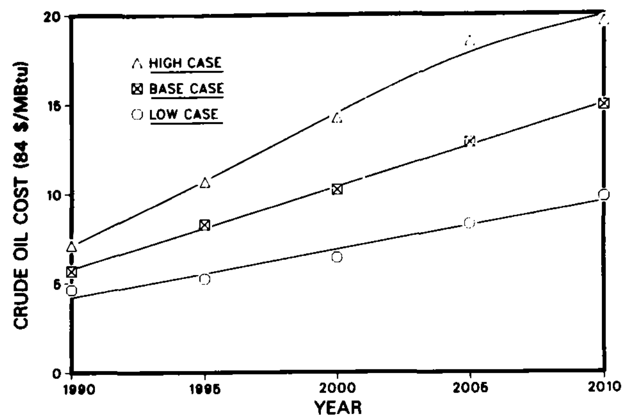
The system goal for electricity is based upon solar thermal competing with a mix of energy-generating technologies on the utility grid. In order to have the potential for a sizable market it was assumed that solar thermal electricity will need to be considerably less expensive than oil- or gas-fired generation, which are expected to be phased out over time. A system target of 5¢/kWhe was chosen, which is much lower than projected energy costs from oil- or gas-fired plants and which is competitive with the projected levelized cost of electricity from new intermediate-load coal plants to be built in the late 1990's. Characteristics of coal-fired power plants were taken from a DOE/Energy Information Administration study and an industry source (Ref. 2, 5).

Industrial Process Heat Goal

In developing a system energy cost target for the industrial process heat market, the energy competition to solar thermal was assumed to be premium fossil fuels such as natural gas, low-sulfur residual oil, and distillate oil. Solar thermal is expected to supplement fossil systems for industrial process heat (rather than be a stand-alone source of heat), so the system goal for industrial process heat is directly determined by the value of the fuel. Premium fuels are generally expected to have substantial real price increases by the end of the century and beyond. Figure A-2 shows world crude oil price projections through the year 2010 for several scenarios based upon analysis in support of the National Energy Policy Plan (Ref. 3). Another detailed report by DOE/Energy Information Administration projects 1990 prices (updated from the report to 1984 dollars) in their base-case scenario of $6.70-$7.20/MBtu for residual fuels and $8.70/MBtu for distillate fuels (Ref. 4).

Using the basic price projections from References 3 and 4, a levelized system energy cost target of $9/MBtu for delivered thermal energy (accounting for efficiency) was developed. This target was based on a number of analyses of different fuels, initial operation dates, initial prices, and fuel escalation rates. The cost target of $9/MBtu is conservative in that it is significantly lower than required to compete with either the high-case projections or base-case projections of fuel prices from References 3 and 4.

Figure A-2. World Crude Oil Price Projections (Costs updated to 1984 dollars from Reference 3)



A summary of the important factors and assumptions used in developing the system goals is shown in Table A-1. The system goals themselves are shown in Table A-2. Differences in economic assumptions required for the utility-electric market and the industrial process heat market do not allow a direct conversion between the energy cost of heat and the energy cost of electricity.

Table A-1. Levelized Energy Cost Assumptions For System Goals *(Fossil Energy Source)*

Parameter	Electricity	Heat
Plant Construction Time	3 Years	n.a.
Economic Life	30 Years	20 Years
Depreciation Time	15 Years	n.a.
Depreciation Schedule	ACRS	n.a.
Investment Tax Credit	0.1	n.a.
Discount Rate (Real, After Tax)	0.0315	0.10
Efficiency of Fossil Fuel Alternative	0.38	0.85
Base Year for Prices	1984	1984

n.a. — Not applicable. System goal for IPH based on fuel replacement only, without credit for replacing capital equipment of fossil system.

Table A-2. Solar Thermal System Goals

	Levelized Energy Cost* (1984 dollars)
Electricity	5¢/kWh
Process Heat	$9/MBtu

*Levelized in constant dollars using assumptions in Table A-1

Component Goals

Compared with the system goals, which are determined by the price and characteristics of competing energy sources, component goals focus on the performance and cost of solar thermal technology. Component goals are directed toward providing a path for solar thermal technology development that will result in achieving the desired system levelized energy cost. Component goals are developed based upon improvements expected in component performance and cost through vigorous research and development.

Component goals are developed for the portions of a solar thermal plant that are major cost elements, important drivers of plant efficiency, or areas of significant interest for research and development. Based on these criteria, eight areas were devised for component goal development: concentrators, receivers, energy transport, energy storage, energy conversion, balance of plant, total installed system cost, and operations and maintenance costs. Table A-3 is a general description of the items encompassed in these areas (the items differ slightly among the three solar thermal technologies). The eight areas provide a suitable level of detail to allocate targets to the individual research task activities discussed in Section III.

The component goals must be technically attainable through research and development and yet make the system energy cost goal achievable. The attainability of component goals is judged from assessment studies and analysis by personnel at the research centers and industry. Achievement of the system energy cost target is determined by calculating the energy costs from solar thermal plants using the performance and cost developed in the component goals. These energy cost calculations are carried out on the same levelized basis as used for calculating the system goals. Important assumptions for calculation of the solar thermal plant energy cost are shown in Table A-4.

Table A-3. Description of Areas For Component Goals

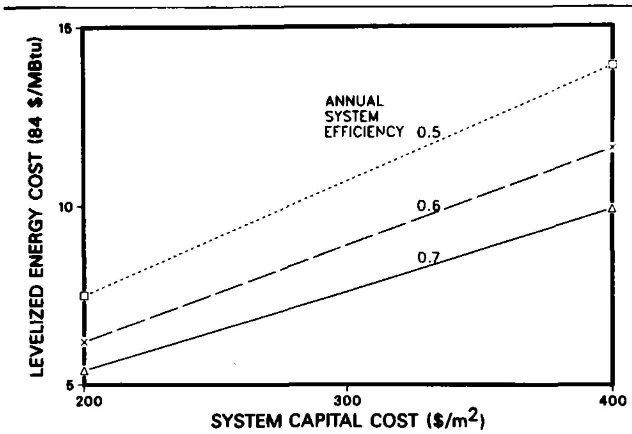
Concentrators	All concentrator costs including field installation, power and control wiring, field controllers.
Receivers	Receiver structural support (including towers in the case of central receivers), heat exchanger surfaces, cavity or cover glass, integral receiver controls.
Transport	Thermal transport includes piping, pumps, valves, surge and storage tanks, transport media. Electric transport (for dishes) includes field wiring of engines.
Storage	Storage tanks, insulation, storage circulation equipment, storage control system, storage medium, storage heat exchangers.
Conversion	Energy conversion equipment including heat engines, heat rejection equipment, and generators.
Balance of Plant	Buildings, land and site improvements, master control system, spare parts, and plant service facilities.
System	Total installed system including standard cost allowances for indirect and contingency cost.
Operations and Maintenance	Annual cost for routine plant operations and maintenance.

Table A-4. Levelized Cost Assumptions For Solar Thermal Component Goals

Parameter	Electricity	Heat
Average Peak Insolation	0.95 kW/m^2	0.95 kW/m^2
Average Annual Insolation	2690 kWh/m^2	2690 kWh/m^2
Plant Construction Time	3 Years	3 Years
Economic Life	30 Years	20 Years
Depreciation Time	10 Years	5 Years
Depreciation Schedule	ACRS	ACRS
Investment Tax Credit	0.1	0.1
Discount Rate (Real, After Tax)	0.0315	0.10
Base Year for Prices	1984	1984

Many degrees of freedom exist in the development of component goals since component efficiency and component cost can be traded off. As a result there is no unique set of component goals which alone satisfies the system goal; a number of solutions are feasible. Figure A-3 illustrates the fact that for the overall system there are a number of possible combinations of annual efficiency and initial cost which will result in a given energy cost.

Figure A-3. System Energy Cost—Tradeoff of Initial Cost and Annual Efficiency



Component goals for electric and industrial process heat applications are shown in Table A-5. For the majority of the components, the goals are the same for industrial process heat and electric applications, reflecting the fact that the performance and cost of a component is independent of the end use of the system. In the instances where a difference in component goals exists between applications, it is due to significantly different design requirements for the component. For example, the receiver goal for the dish-electric system has both a lower efficiency and higher cost than the receiver for dish-process heat; this difference is caused by the much higher dish receiver operating temperature for electricity than for process heat. A similar case occurs for energy transport for dishes, which for electricity is done with field wiring (interconnecting individual generators at each dish) and for process heat is done with piping.

While the component goals in Table A-5 establish a path for all three solar thermal technologies to meet the system energy cost targets, each technology will not necessarily be able to achieve the goals for all possible system sizes and design conditions. In general, the distributed receiver options using thermal energy transport are best suited to smaller scale, lower temperature operations. Central receiver options, because of economies of scale, appear best suited for larger scale installations. Dish electric applications are insensitive to system size but are best applied in low-capacity-factor operations because of the limitations of expensive electric energy storage when using distributed generation.

All component goals are developed with the objective of being attainable through future research and development efforts. Predicting the amount of future improvement in a component's efficiency or cost is of course subject to uncertainty, and this uncertainty is difficult to quantify. The best allocation of component goals may change in the future as solar thermal technology development proceeds or as improvements in some solar components occur faster than in others.

Table A-5. Long—Term Component Goals

Component	ELECTRIC Annual Efficiency	ELECTRIC Cost (1984$)	PROCESS HEAT Annual Efficiency	PROCESS HEAT Cost (1984$)
CONCENTRATORS				
Central Receiver	64%	$100/m^2	64%	$100/m^2
Dish	78%	$140/m^2	78%	$140/m^2
Trough	—	—	65%	$110/m^2
RECEIVERS				
Central Receiver	90%	$ 45/m^2	90%	$ 45/m^2
Dish	90%	$ 70/m^2	95%	$ 30/m^2
Trough	—	—	90%	$ 30/m^2
TRANSPORT				
Central Receiver	99%	$ 25/m^2	99%	$ 25/m^2
Dish	99%	$ 7/m^2	94%	$ 65/m^2
Trough	—	—	98%	$ 30/m^2
STORAGE				
Central Receiver	98%	$ 20/kWht	98%	$ 20/kWht
Dish	—	—	98%	$ 20/kWht
Trough	—	—	98%	$ 20/kWht
CONVERSION				
Central Receiver	39%	$350/kWe	n.a.	n.a.
Dish	41%	$300/kWe	n.a.	n.a.
Trough	—	—	n.a.	n.a.
BALANCE OF PLANT	n.a.	$ 50/m^2	n.a.	$ 50/m^2
SYSTEM				
Central Receiver	22%	$1600/kWe	56%	$460/kWt
Dish	28%	$1300/kWe	68%	$470/kWt
Trough	—	—	56%	$390/kWt
OPERATIONS & MAINTENANCE				
Central Receiver	n.a.	$ 6/m^2–year	n.a.	$5/m^2–year
Dish	n.a.	$10/m^2–year	n.a.	$5/m^2–year
Trough	—	—	n.a.	$5/m^2–year

n.a. — not applicable
System costs in $/kW are based on theoretical power available from receiver.

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