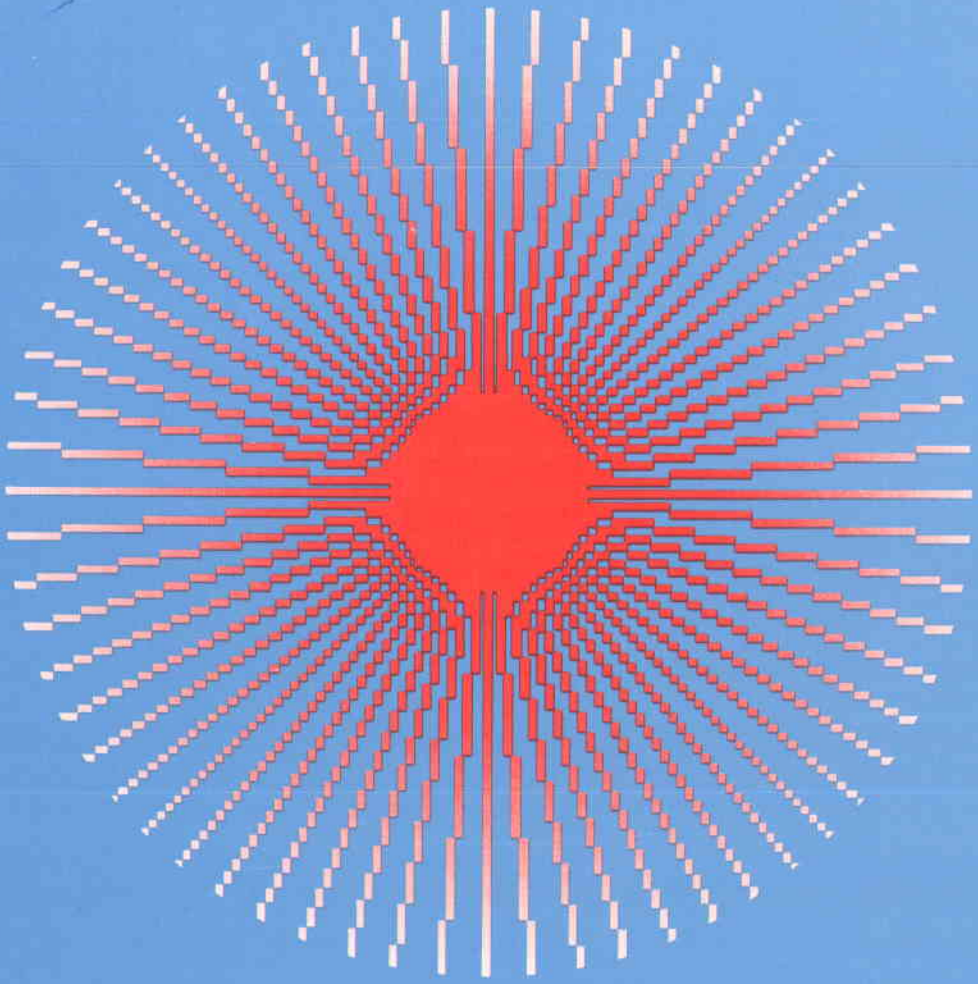
OE/CE-0160

National Solar Thermal Technology Program

Five Year Research and Development Plan 1986-1990

U.S. Department of Energy
Office of Conservation and Renewable Energy

September 1986



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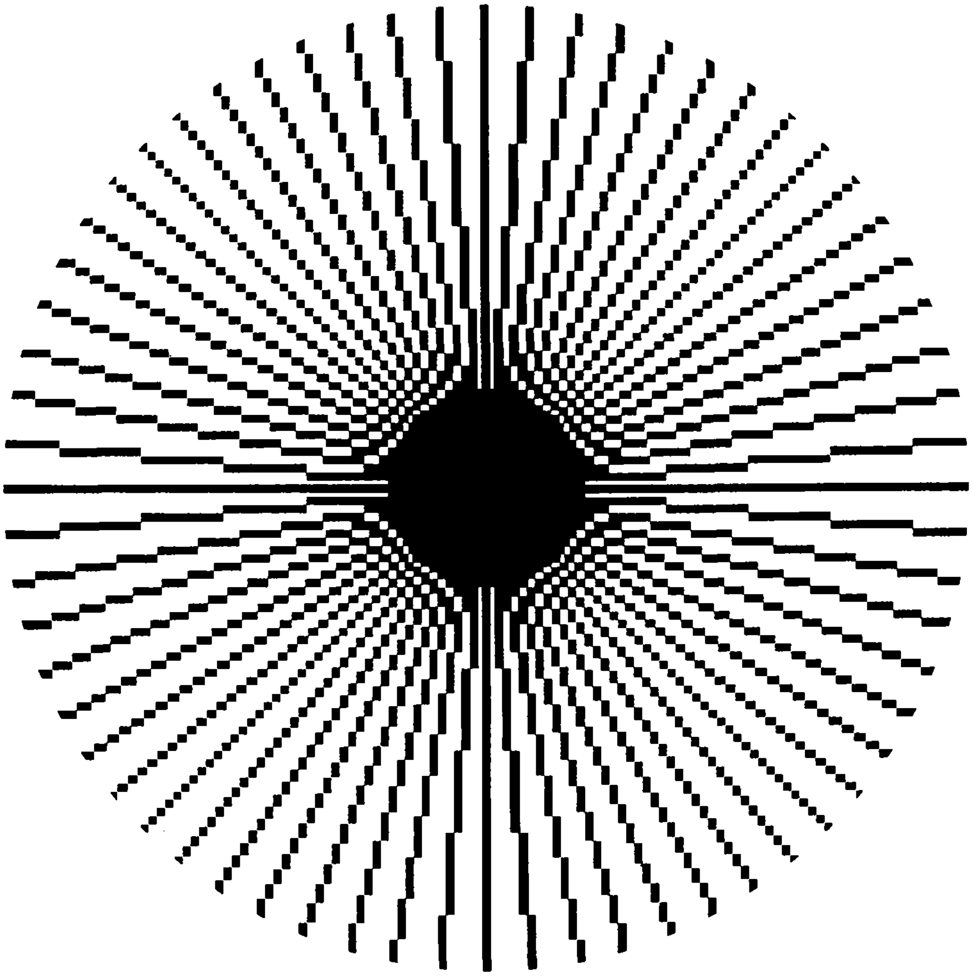

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Summary and Introduction

The long term energy needs of the United States and the world will require the development of renewable energy resources. In the short term, this nation has an abundance of coal and oil; but this may not always be true. Eventually, alternative sources of energy will be required. More than half of the nation's energy needs could be supplied by the sun's radiation. It is renewable, non-polluting, and free.

Solar thermal technology converts the sun's radiation into useful products such as electricity, fuels and heat (Figure 1). The market potential of solar thermal technology is immense since it can provide electricity for large population centers as well as for small, modular applications. Also, process heat can be supplied in a wide range of temperatures for a variety of industrial uses. Solar thermal energy has been proven technically feasible at a series of experimental installations and its costs have decreased dramatically. Performance has increased steadily in the last decade and projections lead to economic competitiveness with fossil fuels and other renewables in the mid- to late-1990's.

This Solar Thermal Technology Program Five Year Research and Development Plan discusses the planning process and describes in more detail the first five years of the long term strategy for the development of solar thermal technology. The overall strategy is to focus and structure the activities which should lead to broad economic competitiveness for solar thermal. The state of each of the technologies is first assessed to determine the characteristics of the next system which could be built. These are referred to as "current capabilities". Cost/performance goals are then determined which would allow solar thermal technology to compete in the free marketplace for electricity and heat production and appear to be technically achievable in the 1990's. The critical advanced components and development decisions are identified and finally, tasks addressing each of these are delineated.

National Energy Perspectives and the Federal Role

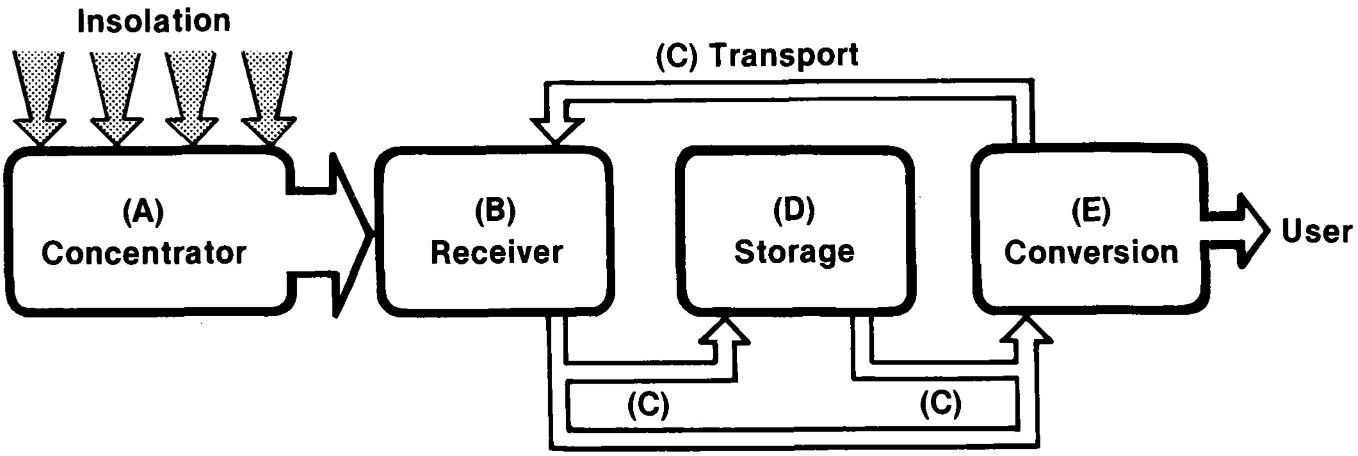
The energy policy goals of the Nation are to promote efficient and economic use of currently developed energy resources and to increase the range of future technological options available to the private sector thereby increasing the energy security of the United States. For renewable energy research and development, the National Energy Policy Plan emphasizes:

- Renewable energy technology options having the potential to make a significant contribution to the energy supply system as a consequence of successful research and development;
- Activities which can be most effective in advancing technology towards the performance objectives most critical to realize that potential; and
- Generic materials science to support industry development of reliable and efficient systems.

Consistent with this policy, direct federal funding responsibility for all renewables are generally focused in areas of basic or applied research where incentives for and availability of private investment are severely limited or non-existent. As technologies develop and become more defined, the private sector is expected to assume increasing responsibility for technology development in response to the greater perceived returns. Well conceived technology transfer programs are necessary to provide adequate information to facilitate informed decision making within the private sector.

As specifically applied to Solar Thermal Technology, recent analyses (Reference 1) have identified both high energy contribution potential and high risk research elements where a Federal role in the development activities may be useful. Those research activities which cut across all of the solar thermal options, such as materials and concentrator development, are especially appropriate.

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 energy to heat in a fluid, (C) piping to transport the heated fluid to (D) storage for later use or directly to (E) the conversion device, which converts the heat in the fluid to a useable form such as electricity or process heat.

An effective collaboration 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 will help to expedite the solutions to the problems facing solar thermal technology. The elements of this informal relationship 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

Industry devotes most of its efforts in the more developed and cost effective technologies, while federal efforts are concentrated on promising, but more remote options and approaches.

Technology Description

Solar thermal technology utilizes highly concentrated sunlight to produce thermal (or heat) energy which can be used in that form or converted to electricity. Solar thermal technologies can supply energy up to temperatures approaching 1650°C (3000°F). This energy can also be stored thermally, thus extending operation into non-daylight hours. Hybridization, combining a solar thermal facility with a fossil fuel source, is also a useful option.

The basic building blocks of solar thermal systems are relatively simple. Concentrators are arrays of concave mirrors or lenses which adjust in orientation during the course of a day to maintain their illumination of a target as the sun moves through the sky. The target, or receiver, of the illumination from the mirror elements is usually a bank of tubes (blackened to increase absorption of the solar input) through which a fluid circulates and absorbs the heat. The fluid's temperature is raised many hundreds of degrees, depending on design and the desired use of the energy. Storage of the solar heat for cloudy or non-daylight hours can be as simple as placing the heated fluid into insulated tanks. Conversion of the heat into electricity can be done in a conventional manner using turbines driven by the receiver fluid directly or after heat exchange with a more efficient turbine working fluid.

The simple and common nature of solar thermal components belies the complexity of their combination into reliable, efficient, cost-effective systems. Each of the components can be designed in many ways to provide special features, such as very high temperature capability, ease of storage, low cost, or insensitivity to solar transients. Not all of these features are attainable simultaneously or with any one design concept, nor is it desirable or necessary to have them all for certain applications. The flexibility of design and ability to combine various characteristics has led to both a diversity of solar thermal design options and broad applicability of energy supplied from solar thermal systems.

The three primary solar thermal technologies are central receivers, point-focus parabolic dishes, and line-focus parabolic troughs. All three employ the same principle of concentrating sunlight and are distinguished by the various mirror or lens geometries utilized (Figure 2). Central receiver systems use fields of two-axis tracking mirrors called heliostats to focus the sunlight onto a single tower-mounted receiver. Heliostats up to 150 square meters have been built and systems containing more than 1800 heliostats have been constructed and operated.

Groups of point-focusing parabolic dishes and line-focusing parabolic troughs are called distributed receiver systems. Parabolic dishes up to 17 meters in diameter have been constructed. Dishes track the sun in two axes and focus the sunlight onto receivers located at the focal point of each dish. Dish modules can be used alone or in a multimodule system.

Parabolic troughs use tracking collectors that ncentrate sunlight onto a receiver tube at the focal line of each trough. Sizes of current trough modules are up to 3 meters wide and 52 meters long. Individual modules can be combined in rows to meet large capacity needs.

Solar thermal systems are highly flexible and can be built to satisfy almost any desired capacity. Promising applications include central receiver systems for the production of upwards of tens of megawatts of electric power; electricity generation with parabolic dish modules, each containing a heat engine, for producing as little as a few kilowatts, or large fields of dishes which collectively produce tens of megawatts; and process heat generation with parabolic trough systems for industrial process heat needs.

The ability of solar thermal technology to provide facilities of different production capacities will be a key advantage in the next decade when utilities are expected to require new capacity in increments of anywhere from 10 to 100 megawatts.

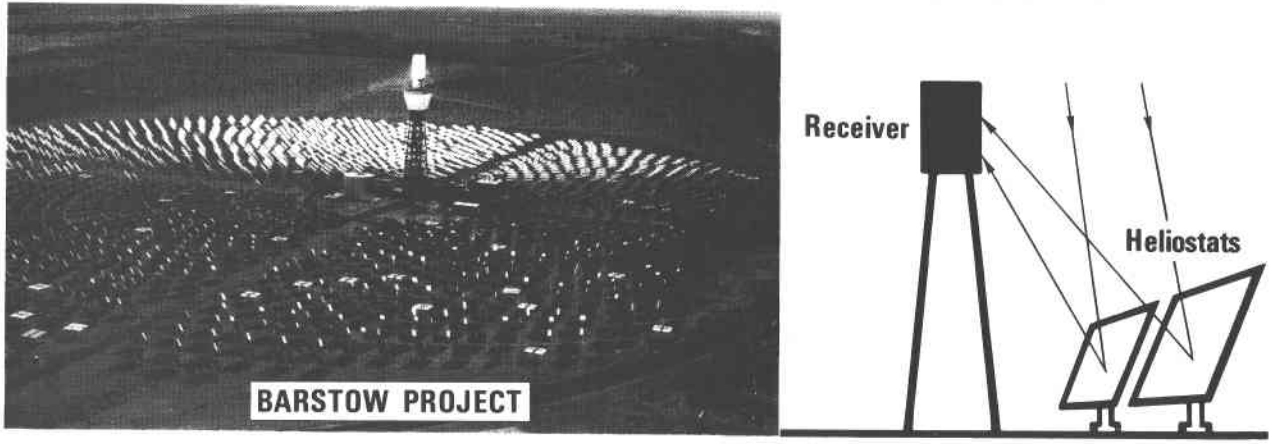
Progress to Date

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 in the early 1970's by the National Science Foundation and the Atomic Energy Commission. But in 1975, the year that solar thermal emerged as a program in the newly formed Energy Research and Development Administration, there was no established industrial capability for designing and building solar thermal systems, and little data on which to base such designs. However, in the decade since, a number of solar thermal concepts for producing electric power and heat have been proven to be technically feasible. Now part of the Department of Energy, solar thermal technology's progress continues as the cost/performance and breadth of applicability of these systems improve.

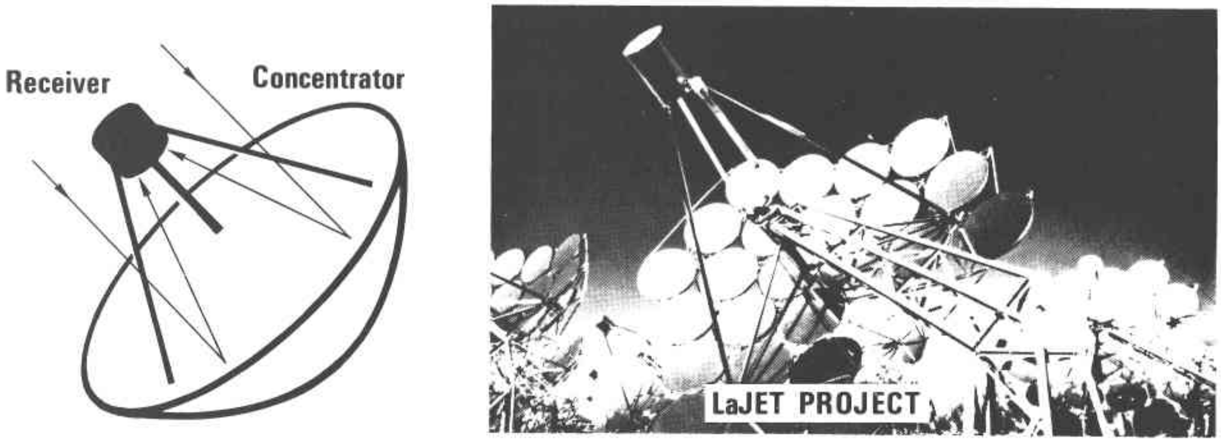
Within the central receiver option, system concepts utilizing water/steam, molten nitrate salt, and liquid sodium as heat-transfer fluids have reached a good level of understanding. The earliest and most detailed work has been on water/steam.

Figure 2. Solar Thermal Technologies

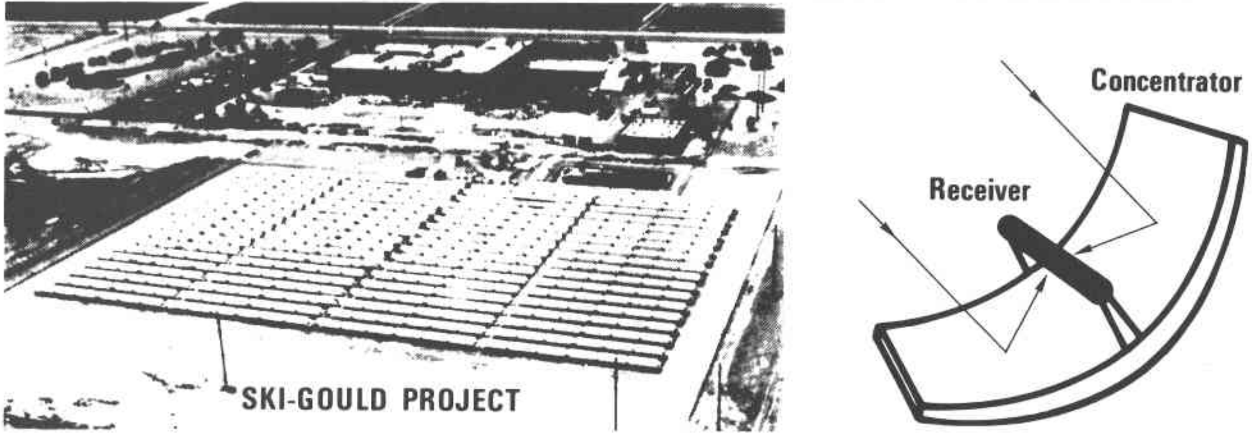
CENTRAL RECEIVER ELECTRICITY PRODUCTION



PARABOLIC DISH ELECTRICITY PRODUCTION



PARABOLIC TROUGH PROCESS HEAT PRODUCTION



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. While water/steam receiver technology is relatively straightforward, storage for such a system requires the use of another medium since steam itself cannot be stored economically. Nevertheless, valuable lessons have been learned at Barstow especially in the areas of construction, system integration, startup, controls, and automation.

In Albuquerque, New Mexico, the 750-kWe Central Receiver Molten Salt Electric Experiment (MSEE) has demonstrated the technical feasibility of molten salt as a heat transfer fluid. Lessons learned from this experiment are providing an invaluable technical basis for advanced testing of molten salt receivers, pumps, valves, and controls. With 14 different sponsors from the industry, the MSEE also demonstrated that development projects can be successfully co-sponsored by government, industry, and utilities. A sodium receiver panel has also been tested successfully in Albuquerque; and the International Energy Agency has recently completed testing a central receiver system with a sodium working fluid at the Small Solar Power Systems Project in Almeria, Spain.

While salt and sodium are not as widely used as a heat transfer fluid as water, they have several advantages. Their better heat transfer characteristics allow higher flux (and hence smaller and more efficient receivers) and the fluids need not vaporize. Perhaps their biggest advantage is that they can be used directly as a very efficient (and in the case of salt, inexpensive) thermal energy storage medium. All of these fluids provide the present focus for central receiver research applications since they have great promise; however many issues, especially optimum component design, system integration of components, and scaleup, remain to be resolved.

Parabolic dish system designs progressed along two paths: (a) conversion of the thermal energy to electricity at the focal point of each module and (b) transport of the thermal energy to a central point for conversion. Applications where heat is the desired product must use the second approach, but electricity may be generated with either approach. Engines at the focal point of the dish make for a very simple system although small, high temperature engine availability, cost, reliability and maintenance are major issues.

The larger dish/electric systems to date utilize lower-temperature heat transfer fluids. At the 3-MWt system in Shenandoah, Georgia, the receiver-heated silicon-based fluid provides process heat, air conditioning, and electric power using the thermal energy centralization approach. A new 5-MWe field of 700 parabolic dish concentrators which produce superheated steam to drive two central turbine generators has recently been built by LaJet Energy Company in Warner Springs, California. The facility was entirely supported by private funding and has shown significant system cost reduction for parabolic dish applications using a new multi-facet stressed membrane concentrator design.

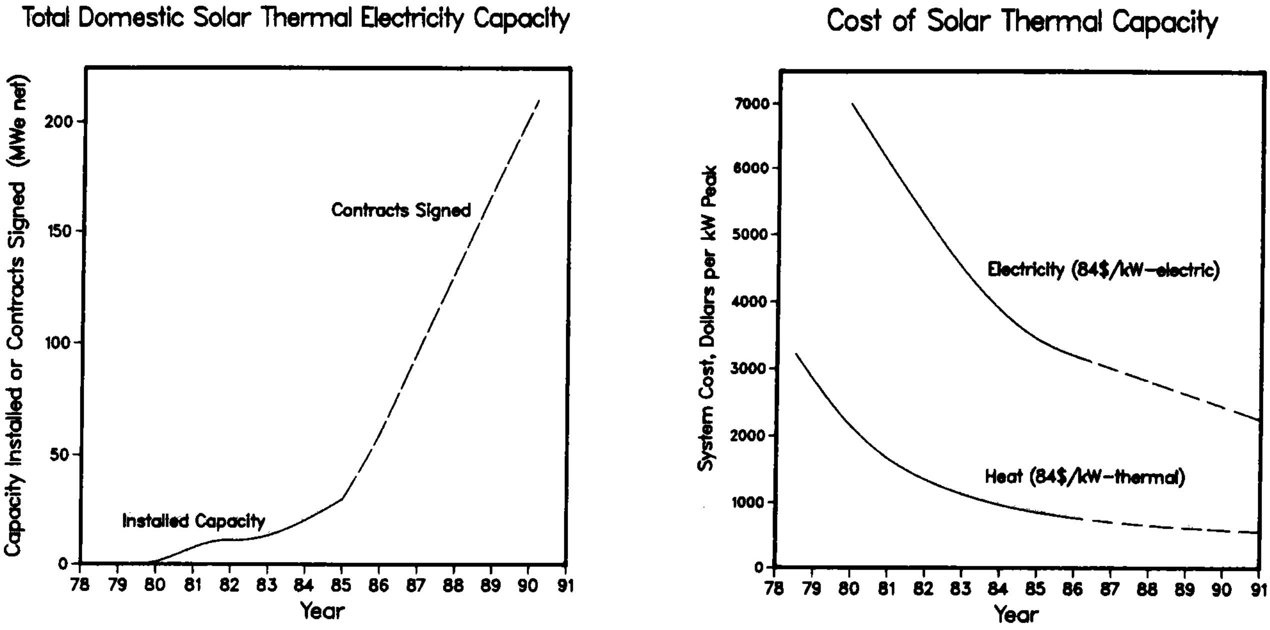
The other current thrust of dish module development is for electric power production using high-efficiency heat engines at the focal point. A 31% gross energy conversion of sunlight into electricity has been accomplished with a Stirling-cycle engine in a dish module at Advanco's Vanguard facility near Rancho Mirage, California. Significant private industry interest has been shown in advancing the dish electric state-of-the-art. Research continues to explore options for economical, high-reliability heat engines at maximum efficiencies.

The parabolic trough has a well-defined range of applications at temperatures below 400°C which makes it particularly useful for process heat production. Numerous field test installations have been built and operated, and analysis of their performance has provided valuable guidance for the private development of prototype equipment such as the successfully operating Solar Kinetics-Gould industrial process heat parabolic trough project at Chandler, Arizona.

The Luz trough/electric installation in Barstow, California, the first phase (13.8 MWe net) of what is already the world's largest solar thermal electricity generating station, has recently initiated operation. The system uses strings of evacuated-tube, insulated receivers which raise the heat transfer fluid temperature to 310°C before it enters the steam generator. A fossil hybrid boost is used to superheat the steam and the efficiency of the system. This facility was built by private funding; and current plans would expand this facility to nearly 200 MWe in the next few years.

Recent greatly increased activities by private industry confirm the viability of solar thermal systems in high-value markets with the aid of existing tax credits. Figure 3 shows both the capital cost reductions and installed capacity additions (and projections) for solar thermal systems. Both electricity- and heat-producing installations have dramatically improved over time. Construction rates, which have averaged 6 MWe per year in the last five years, will be 40 MWe per year in the next five years if all contracts signed to date are honored. The installed capacity is dominated by the planned Luz construction program.

Figure 3. System Cost Trends and Electricity Production Capacity for Solar Thermal Facilities.



Note: Other thermal projects (approximately 23,000 square meters) would have produced no more than 2MWe if designed for electricity production.

Central receiver, dish, and trough systems have all shown significant cost reductions in recent years due to improved design and experience gained. As solar thermal electricity generating systems have become more reliable and cost-effective, planned energy production capacity has risen dramatically.

II. The Program

For a given application, there are many parallel approaches to potential technical and economic success. Some of these options appear to have reached a level to warrant major involvement by industry while other areas are at the opposite end of the research spectrum, being currently of long range interest only. Some activities span almost the entire Solar Thermal Technology area in applicability (e.g. stressed membrane concentrator research) and hence deserve extra emphasis.

System Goals

Electricity and process heat are the applications of major interest for solar thermal technology. Within both the electricity and heat markets there exist potential applications for solar thermal energy at a broad range of delivered energy costs. The solar thermal program energy goals are listed in Table 1. The long-term (late 1990's) system-level goals have been selected as a compromise between maximizing the probability of attaining the goals and maximizing potential market penetration in competition with fossil fuels. Although the long-term goals are highly ambitious, achieving them would yield large returns in the form of an inexpensive and widely applicable source of renewable energy.

Solar thermal technology will have significant applications and early market penetration well before achieving the long-term goals. Such intermediate term goals, also shown in Table 1, are based on the projected costs of solar thermal energy which are thought to be attainable in that time period, with further research and development. These five year goals may be sufficient to penetrate solar thermal markets to a depth that would sustain growth of the technologies. As the delivered price of solar thermal energy decreases, the number of potentially economically feasible applications will increase.

The long-term prospects for solar thermal technologies attaining the system goals have been judged on the basis of systems analyses, economic projections, industry and laboratory consensus, and actual operating data. Separate goals for electricity and heat are required due to differing solar thermal efficiencies and market-based economic requirements. While the system goals are judged to be potentially attainable by the three primary solar thermal options, different degrees of uncertainty exist.

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 volume production for solar components increases, economies of scale will be realized, resulting in further decreases in the cost of solar thermal energy.

Current Status

The current solar thermal capabilities are defined as the best system which could be designed currently and confidently, and then fielded at close to full scale. These are shown in the Appendix Table A-6 in some detail, but are summarized here:

Central Receiver/Electric

Current status for central receiver/electric is based upon the assumption of a utility-owned power production plant with a 100-MWe rated capacity, a 50% capacity factor, and an annual efficiency of 17%. Two collector fields contain a total of 9300 95m^2 glass/metal heliostats costing \$150/m^2. Two molten salt cavity receivers are used, each with a maximum rating of 320 MW$_t$. Receiver outlet temperature is 560°C, and receiver costs are \$80/m^2. A molten salt/steam heat exchanger provides super-heated steam to drive the steam-Rankine turbine-generator. A dual-tank hot and cold molten salt thermal storage system has a capacity of 2600 MWh$_t$. Total overnight installed system cost is \$2900/kWe peak.

Dish/Electric

Current status for solar thermal parabolic dish/electricity production is based upon the LaJet 5-MWe rated capacity plant utilizing the thermal-transport/central-engine concept. The plant's 700 parabolic dish concentrators are each made up of 24 1.5 meter diameter individually-focused polymer film stressed membrane modules. The receiver at each dish focal point contains a molten nitrate salt heat storage fluid. Water circulating through the receiver/heat exchanger is heated to a 270°C water/steam mixture, recycled through superheating concentrators to 370°C, and then transported through insulated piping to two steam-Rankine turbine generators, the main 3.7-MWe turbine and a 1.3-MWe peaking turbine. The plant has a 29% capacity factor and an annual efficiency of 13%. System cost is $3400/kWe peak, concentrator cost is $157/m^2, receiver cost is $39/m^2, and transport cost is $70/m^2. Minimal buffer storage with a capacity of 6.5 MWh_t is provided.

Trough/Process Heat

Current status for a parabolic trough/process heat production plant is based upon an industrially-owned solar thermal plant producing process heat in the form of 200°C steam. The solar only (no fossil backup) plant has a 1.50 MW_t rated capacity with a 15% capacity factor and a 32% annual efficiency. The sensible heat transfer fluid in the receiver tubes is oil, and the concentrator area totals 2300 m^2. The system cost is $200/m^2, receiver and transport costs are each $40/m^2, and no storage or energy conversion equipment is included.

Focus for Success

Comparisons of the current capabilities with long term system and component goals show that progress will be required on all fronts to reach those goals. The component goals sum to the system-level costs required, but they are not unique in that respect. Other component goals with different values could also be used as long as they add up to the required system level cost. The goals must be, and are, representative of a feasible design allocation. The required quantitative advancements in capital cost and annual efficiency are only one aspect of the advancements required in solar thermal technology. Also required are the confidence in the technologies to perform as projected, high reliability, system availability, and low maintenance costs.

To assist in focusing the solar thermal technology program, the Electric Power Research Institute sponsored a technical workshop in early 1985 to develop a consensus within the solar thermal community on the state-of-the-art for solar thermal energy systems and to evolve strategies for future research initiatives. Involved in the deliberations were key representatives from industry, utilities, and universities, as well as program managers from the Department of Energy Solar Thermal Program and its research and development laboratories.

It was the consensus of the participants (Reference 2) that solar thermal energy systems in their present state have indicated their technical capabilities and the potential to become economically viable options for renewable energy generation which will be required by the users in the 1990's and beyond. What is needed for solar thermal systems to attain their potential are well-focused development programs based upon prudently applied financial resources. This implies structured programs with development milestones that satisfy user requirements including:

- Near-term benefit, goal-oriented technology development with an emphasis on central receiver electricity generation, dish electricity generation, and trough process heat production, the three technologies showing the greatest potential for reaching the quantitative program goals, and

- Long-term benefit, high-payoff research to reveal and explore innovative new concepts which can be nurtured into development thrusts of the future.

Table 1. Solar Thermal Five-Year and Long-Term Goals

The ranges of efficiencies, capital costs, and capacity factors arise from the differences between the solar thermal technologies:
Five-year and long-term goals are expressed in this format: Five-Year/Long-Term

	Electricity		Heat
	Central Receivers	Dishes	Troughs
System Annual Efficiency	20%/22%	17%/28%	36%/56%
System Capital Cost[a] $/kW peak (1984$)	$1800/$1000	$2100/$1300	$590/$370
Capacity Factor	0.5/0.5	0.26/0.26	0.24/0.24
System Energy Cost[b] (1984$)	8¢/kWhe/4¢/kWhe	7¢/kWhe/5¢/kWhe	$23/MBtu/$9/MBtu

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

[b] System goals levelized in real dollars; long-term values levelized in nominal dollars (assuming 7% inflation) are 11¢/kWhe, $14/MBtu. The $9/MBtu (84$) industrial process heat long-term 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.

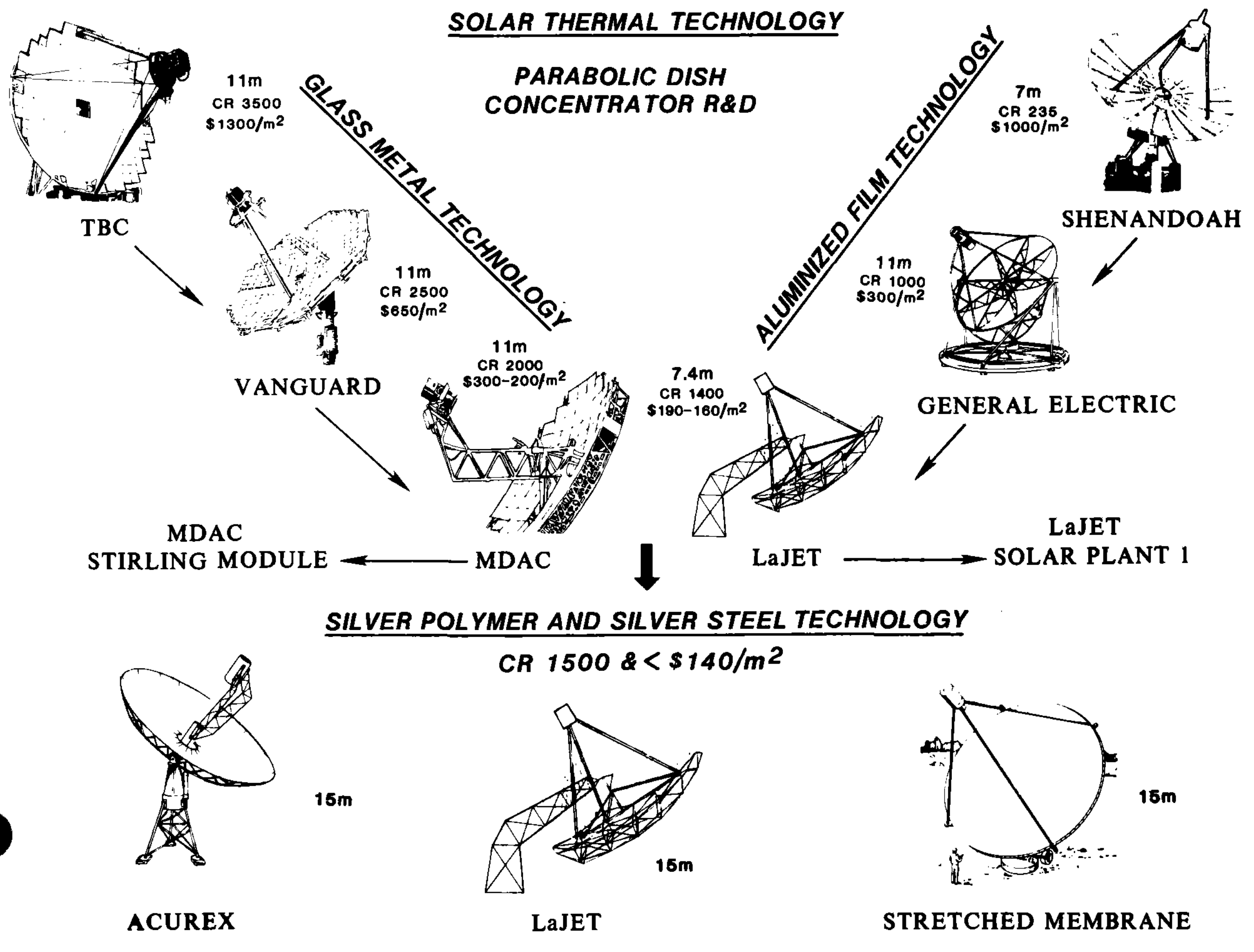
III. The Technical Plan

Solar thermal program research and development activities have been structured as tasks specifically directed toward achieving component goals. These tasks are divided into the three general technology areas of Collection, Energy Conversion, and System and Applications. The goals for Central Receiver Systems and Distributed Receiver Systems would be achieved by meeting the component goals for each of the component's research tasks. They could also be achieved by other paths since a large number of tradeoffs are possible among component efficiencies and costs.

The final research task, System Experiments (Task 11), has as its objective actual demonstration of the achievement of the system energy cost goals. Each of the system experiment technologies will meet its system energy cost goal if its goals for system efficiency and plant cost are met.

The current capabilities of solar thermal components and systems demonstrate the progress required for each technology. These capabilities are based on projections of the performance and cost of the next system that could be built. Energy costs for the current systems are calculated on the same basis as for the long-term systems (i.e., 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, all applicable energy tax credits should be considered, and the energy costs for the other energy source should be levelized also.

Five-year goals for each research and development task have been developed to supply a focused orientation for each activity within the tasks. These five-year goals and corresponding program mile-



stones can be used to measure progress. The five-year goals represent expectations of attainable progress in each area, assuming continuation of current funding levels. Meeting these intermediate goals also supports early penetration of the solar thermal technologies into the energy sales market.

Collection Technology

In the solar thermal process, collection encompasses the concentration of the sun's radiant energy (solar flux) and its absorption as thermal energy by the heat transfer fluid in the receiver. The research and development tasks within collection technology are: optical materials, concentrators, and receivers.

1. Optical Materials

Optical materials include reflective, refractive and transmitting elements for concentrators, and transmitting and absorbing elements for receivers. The current program 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. This improvement would permit innovative new heliostats and concentrators with costs that could also be cut in half. By reducing the weight associated with silvered glass, additional benefits will accrue due to ease of fabrication, installation, and handling.

For polymer reflectors, laboratory analysis and accelerated environmental testing are underway to characterize degradation mechanisms induced by ultraviolet radiation as well as effects caused by water, air, and pollutants. For silvered steel, the substrate smoothing techniques required to achieve high reflectivity will be evaluated along 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 the accomplishment of five year goals of 90% specular reflectivity (averaged over a five-year life) and \$15/m^2 cost.

Research activities in optical elements for receivers include development of a) selectively absorptive coatings with improved durability and performance and b) transparent materials that can serve as cavity receiver windows transmitting concentrated solar flux while reducing thermal losses, which is particularly important for efficiency improvements in high-temperature applications.

Window materials and absorber coatings for receivers and receiver/reactors must survive when exposed to concentrated solar flux, high temperatures, corrosive environments, and cyclical thermal stresses. Current research seeks to characterize the mechanisms leading to degradation of potential receiver window materials and high-temperature absorber coatings and to identify methods for improving their performance and durability.

Research and development of durable, low-cost reflective surfaces and high-temperature absorber materials contribute to all technology options. The emphasis in this research should increase over the next several years and the specialized high-risk nature of the research indicates primary government support.

2. Concentrators

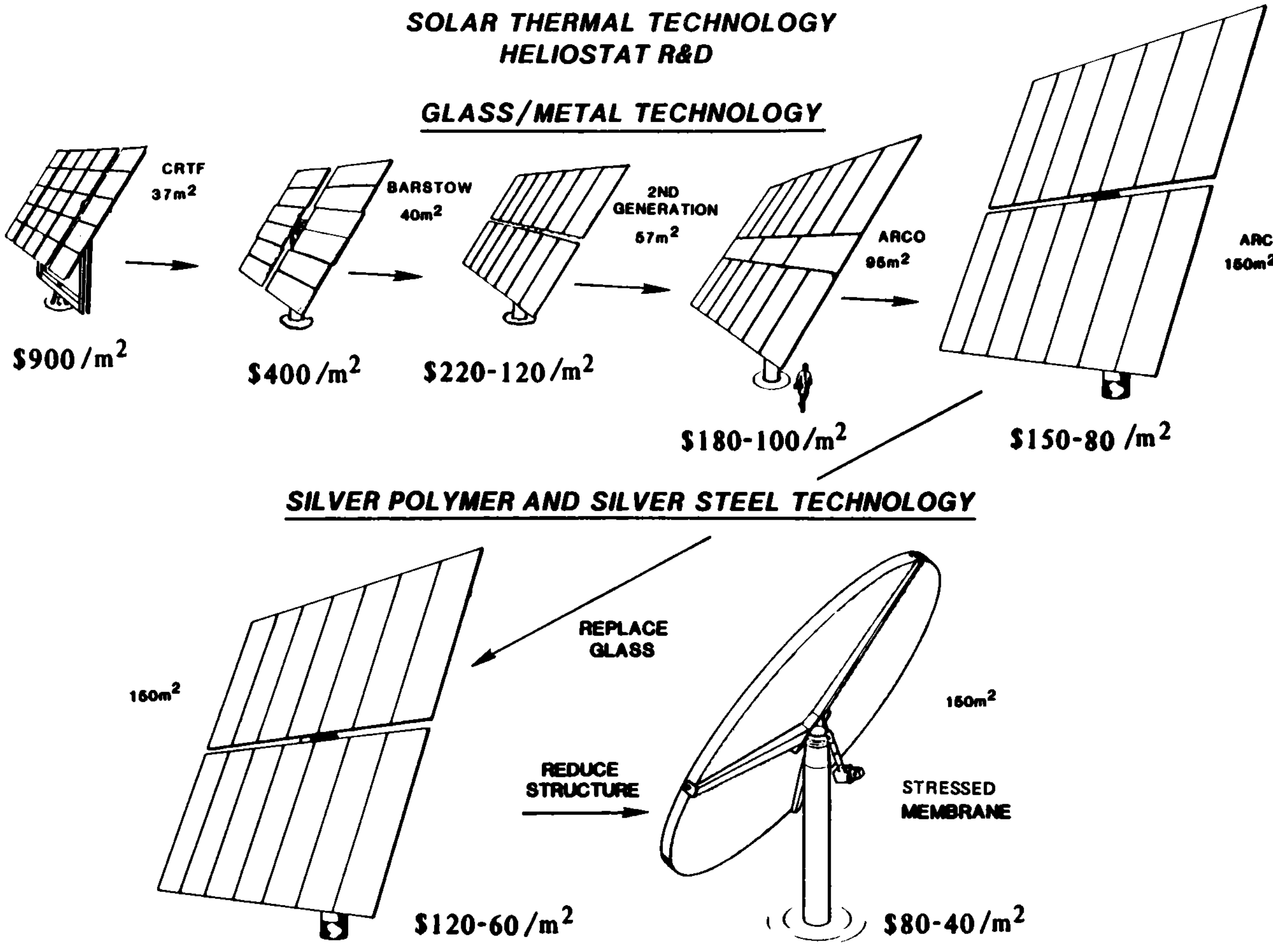
Concentrators must accurately track the sun and efficiently reflect or refract the radiation to the receiver. Since concentrators typically comprise the largest cost element of a system, and their performance has a direct effect on overall system efficiency, it is imperative to minimize costs without significantly sacrificing performance. But because the cost limits for optimized concentrators using state-of-the-art silvered-glass technology appear to be near \$100/m^2, reduction in concentrator cost below this level depends on the development of innovative new concepts, such as the stressed membrane concentrator, utilizing lightweight reflective surfaces and novel drive mechanisms.

Materials and components research have 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 stressed membrane heliostat and dish concepts will be considered as the primary applications.

For central receiver concentrators, the advent of a lightweight flexible polymer or sol gel surface reflective material could reduce large (150m²) stressed membrane heliostat costs to \$40/m², just one tenth of the cost of the heliostats at Solar One, if manufactured in large quantities. LaJet's recent multi-membrane parabolic dish concentrator experience has dropped costs dramatically in the past year from \$650/m² to \$160/m², and is nearing the dish long term goal of \$140/m².

Several other innovative concentrators are also being examined to determine their feasibility and

Concentrators



Concentrators provide avenues for major improvements in the cost of delivered energy for solar thermal systems. 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 can result in lower costs without loss in performance or lifetime.

Using the stressed membrane concept, lightweight, low-cost concentrators can be constructed of high-reflectivity silvered polymer films or thin silvered steel. For central receiver system use, large 150m² single module, silvered polymer, vacuum-focused stressed membrane heliostats are being studied because of their potential high performance, lightweight, low cost characteristics.

cost effectiveness; these include an integrated silver-film segmented-ring reflective panel/panel support structure (for weight and cost reduction), and point-focusing Fresnel refractive lenses. The general research approach will be analysis and design followed by prototype fabrication and testing. The high-risk nature of this research also implies a primary Federal role continuing over the next several years.

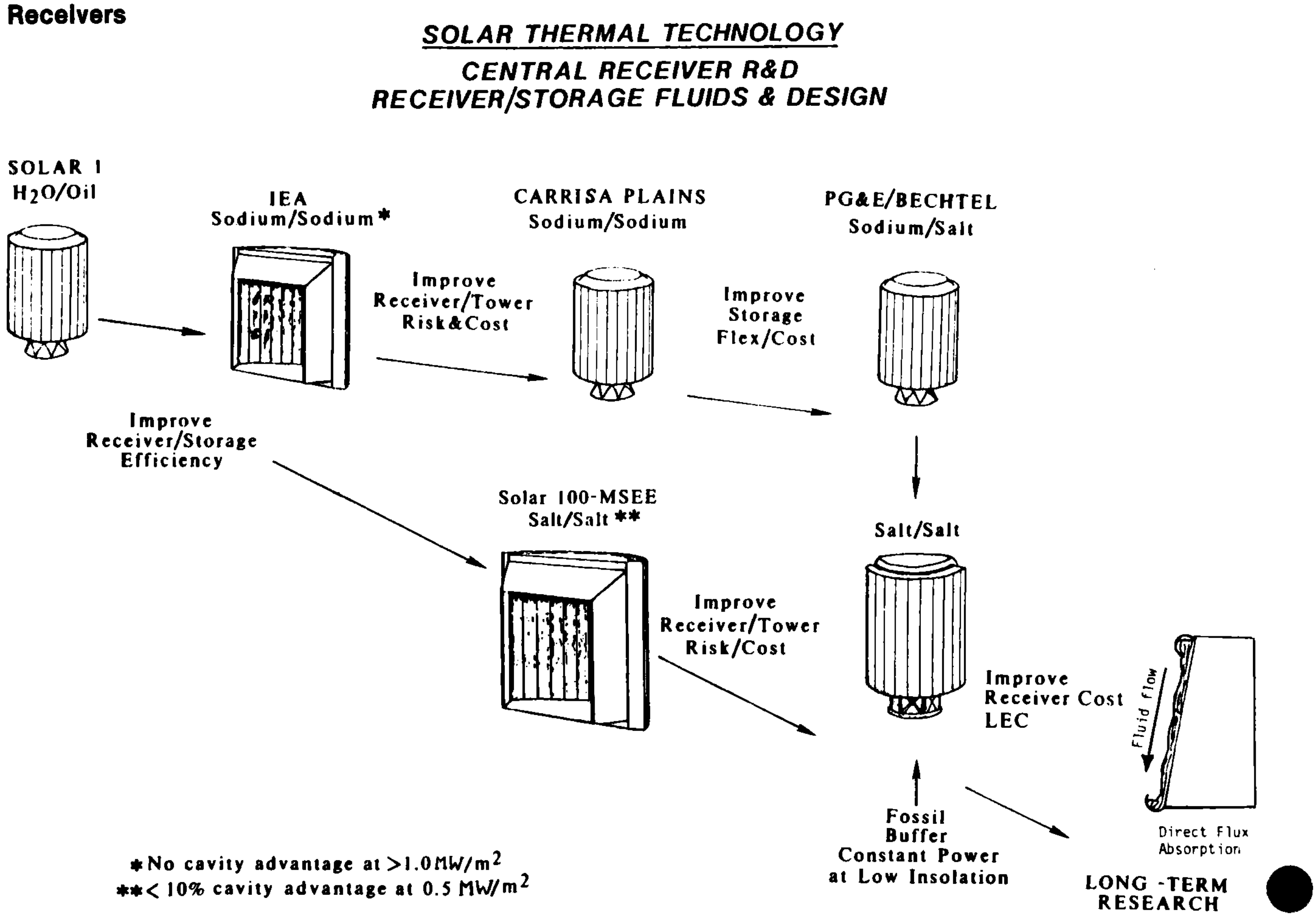
Experimental work will continue to explore methods to reduce the ultimate wind loads on concentrators and to study the effects that wind reduction techniques have on the concentrator structures. Reductions in weight and wind loading may allow the major concentrator structural elements to be fabricated 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, should lead to much-improved concentrator designs.

3. Receivers

Receivers are the components which convert solar radiation into thermal energy. To date receivers have been built and tested using heat transfer fluids such as oils, water/steam, molten nitrate

Receivers



Central receiver research and development has encompassed the studies of many different receiver and storage fluid combinations in its efforts to find the best cost and performance systems.

salt, liquid sodium, and air. Most of these receivers operate at temperatures less than 600°C, with annual efficiencies between 75 and 90%. Current costs of receivers (expressed in dollars per square meter of concentrator aperture area and including the tower in the central receiver case) are as low as \$80/m^2 for central receivers, and \$40/m^2 for dishes and troughs. The long term goals are to reduce these costs to \$30/m^2.

Central receiver research is focused on finding the best cost/performance systems (and hence receivers) in two distinct ranges: up to 600°C, and greater than 800°C. The lower temperature range is a main element in the nearer-term technology development thrust, while the upper is a key part of longer-term high-payoff research. Below 600°C receivers utilizing both nitrate salts and sodium working fluids are under study since each has its own unique advantages. Above 800°C other receivers with heat transfer media such as solid particles and carbonate salts are being investigated, and basic receiver element testing has been initiated. Appropriate containment materials, compatible with the heat transfer medium at the required temperatures, are also being identified and evaluated. For the longer-term applications, direct flux absorption receivers (with the working fluid *not* in tubes) may be less complicated than tube designs, smaller due to higher allowable flux, and capable of providing the higher temperatures needed to couple into more efficient electric cycles or higher valued chemical products.

For distributed systems, both dish and trough receivers will continue to be refined. Dish receiver research will emphasize high temperature engine compatibility, and trough research will investigate higher efficiency evacuated tube receivers.

The LaJet dish receiver cost of \$40/m^2 is significantly below the long term solar thermal program dish-receiver goal of \$70/m^2. However, due to the remote turbine/generator design of the system, piping the superheated steam long distances from each receiver to the centralized generator(s) results in current capability transport costs of \$70/m^2, much higher than the solar thermal program long term goal for dish/electric transport of \$7/m^2.

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, and thermal or thermo-chemical processes for transporting energy. Heat exchangers or the reactors required to interface between the receiver, heat transport system, storage, and/or end-use application are also included. In process heat applications the output heat exchanger is included in the balance of plant category. Efficient, economical energy conversion components are a major objective of the solar thermal program.

The principal 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.

4. Heat Engines

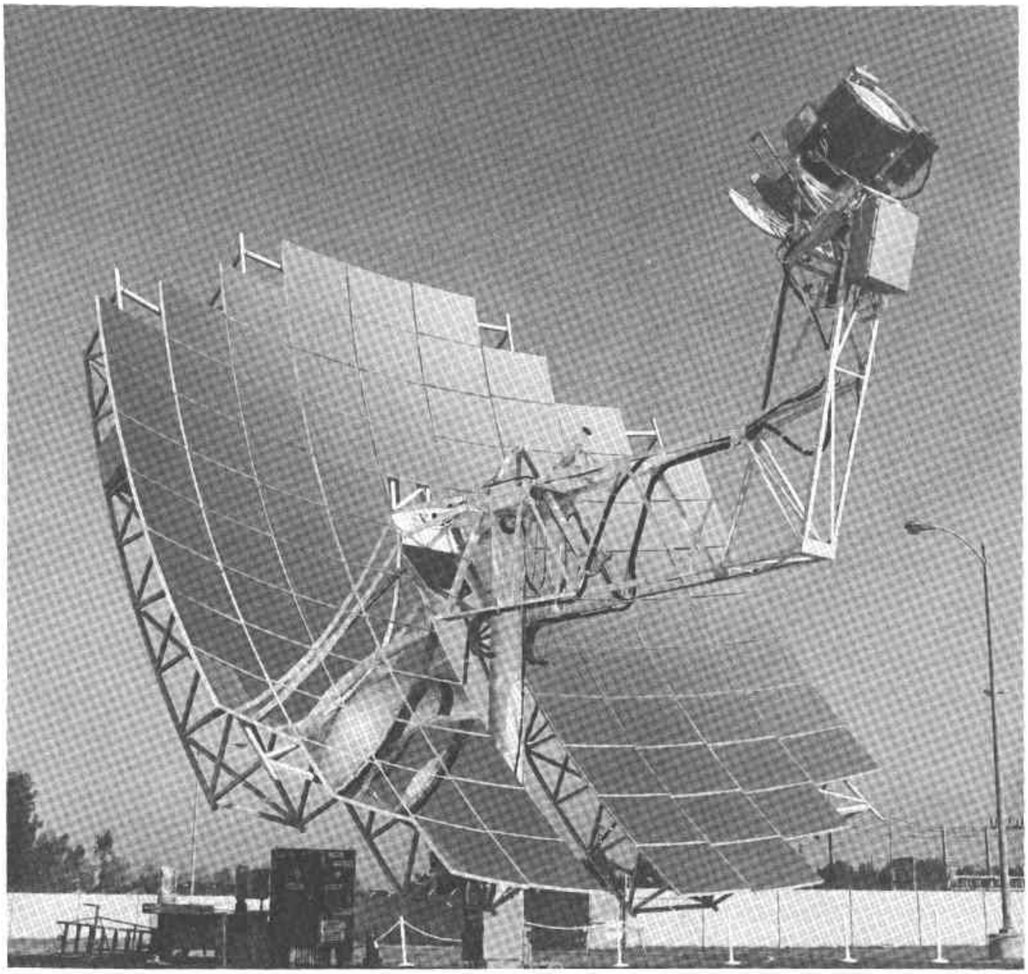
Heat engines are thermodynamic devices that convert thermal energy to work, which then can be converted to electricity. The engine's conversion efficiency directly impacts the total system efficiency and hence is a major concern; but the capital cost, maintenance expenses, and lifetime are also important. All of these concerns must be resolved if solar thermal electric plants are to have a major impact in the 1990's.

Recent heat engine comparison studies suggest that dish electric systems which employ free-piston Stirling engines have a good chance of meeting long-term solar thermal cost goals. Kinematic-Stirling and organic-Rankine cycle-based systems exhibit the potential of meeting near-term cost goals. Also, the direct conversion liquid metal thermoelectric and thermochemical processes have shown particular promise of meeting long term solar thermal cost goals and are the object of an ongoing development and testing program.

Heat engines for solar thermal systems are adapted from nonsolar applications such as automotive and aerospace. Large steam-Rankine engines cannot be mounted at the focal point of the dish and are better suited for both central receiver and dish electric/central engine facilities. As discussed previously, a dish electric/central engine facility has low receiver costs but high sensible heat transport costs because of the need to pipe the hot working fluid from the individual receivers to the central engine/turbine. Smaller Stirling engines mounted at the focal point of dishes have been achieving higher operating temperatures for electric conversion resulting in increased efficiency. However, these high temperature receiver/heat engine combinations are costly (both in initial cost and maintenance), while their electricity transport costs are low. Therefore, both dish electricity-production concepts are still being researched and developed in order to determine the optimum performance/cost combination.

Small Rankine cycle engines can also be used at the focal point of dish electric modules. Four of these modular systems will be used for the Small

Heat Engines



The McDonnell Douglas/United Stirling electricity-generating module combines a two-axis tracking concentrator with a 25 kWe heat engine at the focal point. These dish Stirling power modules can be combined in any number to provide the desired plant output. Key features of the system are high overall efficiency, automatic (unattended) operation, and siting flexibility due to minimal water requirements of the Stirling engine.

Community Solar Experiment at Osage City, Kansas. One 25-kWe Kinematic-Stirling engine has undergone performance and life tests in the Department of Energy-sponsored Vanguard Project at Rancho Mirage, California. Private industry has taken on responsibility for further development and support of this engine in dish electric applications.

Since engine development costs are extremely high, the dish electric program is closely following automotive, military, and space power engine development. Solar engines require high efficiency and long lifetimes as well as low capital and maintenance costs. Many of the engines designed for other applications meet the solar criteria except for their engine durability. Activities are planned to address this shortcoming and to evaluate other engine concepts as well.

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. 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 are being sought, and concepts developed for other applications are being assessed to determine their suitability to solar thermal systems. 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.

From the 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 demand. The main 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. 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 most valuable.

Research on transport systems includes the investigation of heat transport in a suitable fluid through an insulated piping network, and the study of thermochemical transport using reversing endothermic and exothermic chemical reactions at the receiver and point of use.

Pumps and valves are an integral part of a sensible heat transport subsystem, and a molten salt pump and valve experiment is in progress at the Central Receiver Test Facility in Albuquerque, New Mexico. The goals of the tests are to resolve technical uncertainties related to molten salt subsystems and components and to provide a technical base for molten salt solar plants.

A performance/economic analysis comparing sensible and thermochemical energy transport for a field of dish collectors suggests that for high-temperature applications, dishes would especially benefit from the success of the thermochemical transport approach. Initial laboratory experiments have produced encouraging results with successful closed-loop operation of two systems: sulfur trioxide dissociation and carbon dioxide reforming of methane. Additional laboratory efforts are investigating scale-up and systems questions as well as the issues of materials survivability and catalyst selectivity.

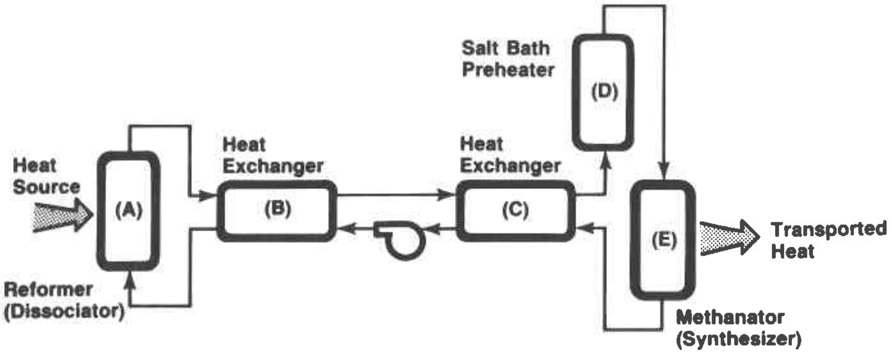
Storage systems utilizing oil/rock, liquid sodium and molten nitrate salt have all been successfully demonstrated. Future storage research activities include the study of new and better storage materials, containment techniques, heat transfer techniques, and heat exchanger technology required for the interface between storage and the heat transport system. Oil and air/rock systems are being studied for near-term applications. Molten salt storage media, externally and internally insulated tank designs, raft thermoclines (which allow dual-temperature storage in one tank), 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.

System and Applications Technology

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

Utilities, important future users, believe that solar thermal systems in their present state have demonstrated the technical capabilities and potential to become viable economic options in the 1990's and will be needed as a part of a diversity of renewable and conventional generating resource options to satisfy capacity additions ranging from peaking to baseload requirements (Reference 2).

Transport and Storage



Laboratory experiments are investigating the technical feasibility of thermochemical energy transport and storage based on two reversible chemical systems: (1) carbon dioxide reforming of methane followed by methanation of the synthesis gas, and (2) dissociation followed by synthesis of sulfur trioxide.

To illustrate, consider the carbon dioxide/methane system. 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 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 endothermic 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.

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 innovative concepts currently being investigated are a holographic concentrator, a number of collector wind avoidance approaches, and photo-enhanced catalysis. Holographic concentrators with no moving parts that are able to track the sun and concentrate the sun's rays appear feasible.

Other Solar Thermal Program/university research projects on innovative concepts and applications include the investigation of photo-enhanced catalysis and solar-assisted bond breaking at the University of Houston, the solar production of fuels and chemicals at the University of New Hampshire, and the solar detoxification of hazardous wastes at the University of Dayton. These efforts will provide the technology base to assess the use of concentrated sunlight in chemical conversion. The end result may be important new applications of solar energy for the manufacture of fuels, chemicals, and electricity.

8. Balance of Plant

This task addresses the nonsolar components necessary to construct, operate and maintain a complete solar thermal facility. The primary goal is the reduction of operation and maintenance costs for solar thermal installations. This includes development of automatic plant controls to reduce labor and minimization of plant operating power requirements.

Expenses relating to operating personnel are a major fraction of the operation and maintenance costs. The main research and development activity in this area will be the optimization of control systems for solar thermal facilities. Automatic controls will also allow maximum plant performance during startup, shutdown, and periods of transient conditions such as cloudiness.

Figure 4. Automated control systems will result in significant savings in plant operating costs.

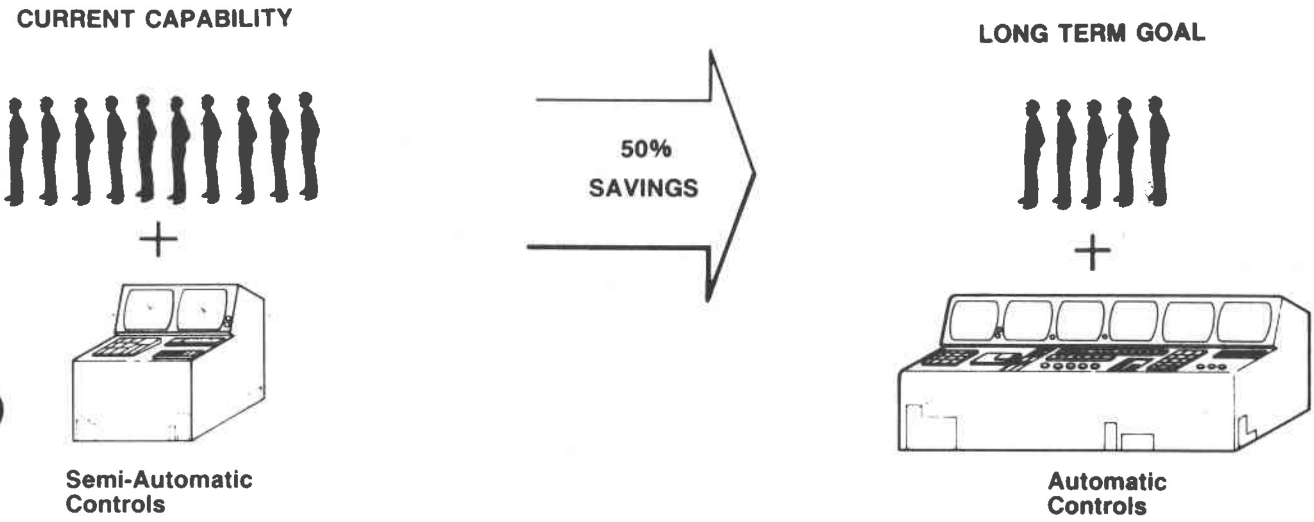
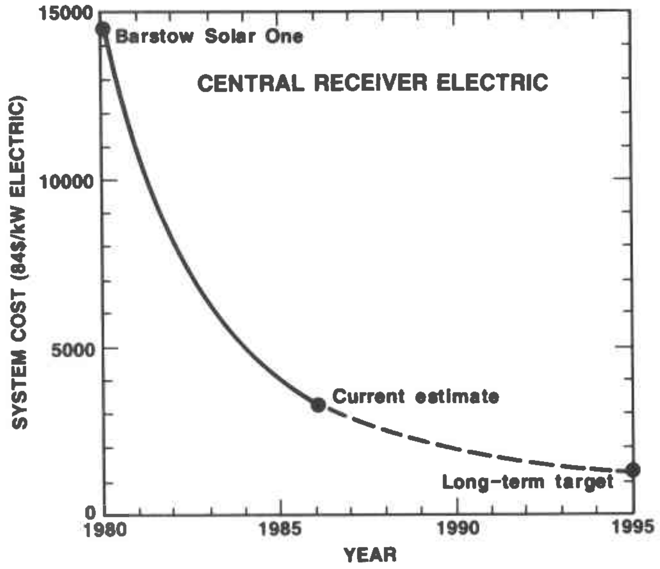


Figure 5. Central Receiver/Electric System Cost Trend



Central receiver/electric system costs have decreased significantly in the past five years. The long term goal competes with intermediate load coal plants.

Central Receiver Systems

The 5-MWt Central Receiver Test Facility in Albuquerque, New Mexico, provides the capability and operational support required for testing and evaluation of central receiver systems, subsystems, and components.

Reducing maintenance costs of solar components, particularly concentrators and receivers, will be another activity. Maintaining mirror cleanness and receiver surface conditions has a significant impact on system performance. Operating schemes and cleaning mechanisms are under development to minimize losses due to reflectivity and absorptivity degradation and to reduce the costs of cleaning and maintaining mirrors and receiver surfaces.

Balance-of-plant goals are to develop cost effective control systems that will allow for automatic operation and to complete characterization of balance-of-plant requirements, including the determination of ways to minimize components and simplify subsystems to reduce parasitic and auxiliary power requirements.

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 component groups, subsystems, and system experiments. The integration of components and subsystems into a complete system is necessary to properly analyze 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 central receiver systems projects, the molten salt experiments at the 5-MWt Central Receiver Test Facility in Albuquerque, New Mexico, and the International Energy Agency Small Solar Power Systems Central Receiver System in Almeria, Spain, are providing invaluable technical data and operating experience using molten salt and sodium working fluids. New or planned activities at the Central Receiver Test Facility include the molten salt pumps and valves experiment described in Task 6, advanced testing with a subscale molten salt cavity receiver (Task 3), and testing of an advanced, unattended control system (Task 8). Private firms, utilities, and the Department of Energy are jointly involved in the molten salt experiments. International cooperation is being demonstrated by the participation of nine countries including the United States in the Almeria, Spain, project.

Several systems studies are under way which involve applications of the solar central receiver technology. They are directed at understanding various design and economic tradeoffs in the context of actual data from the operating central receiver systems and will indicate optimum techniques for reducing the delivered energy cost for central receiver systems while improving performance and reliability and decreasing risk.

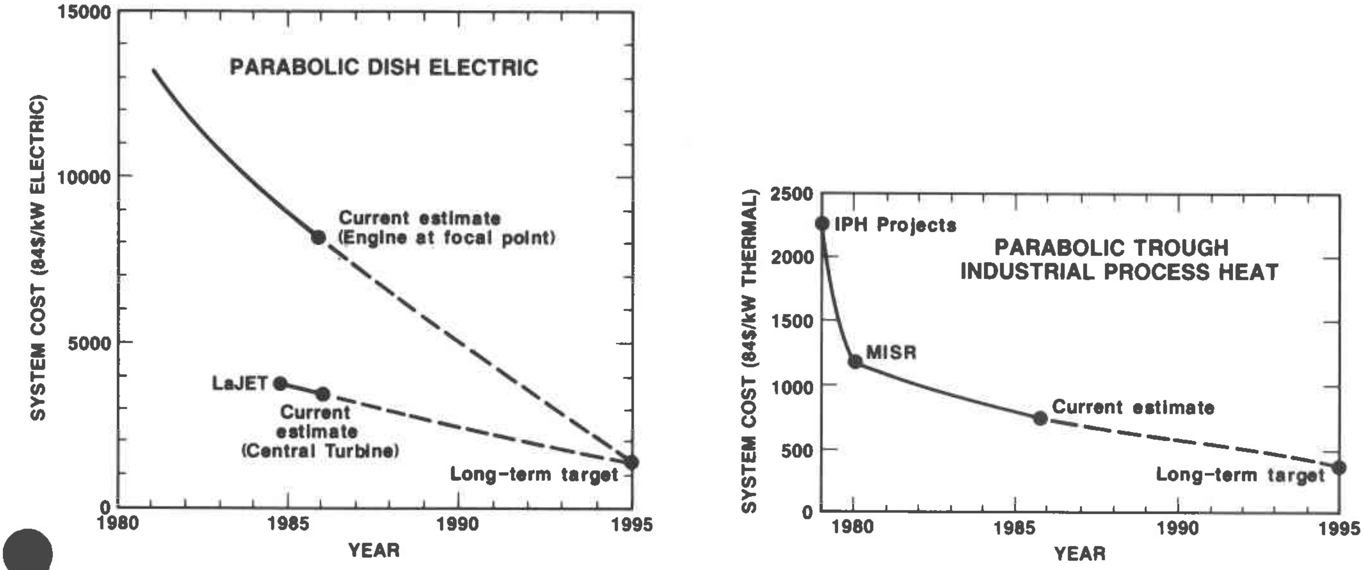
Current capabilities for central receiver electric systems are an annual efficiency and capital cost of 17% and $2900/kWe peak. The long term goal is 22% annual efficiency and $1000/kWe peak and the near-term (five-year) goal is to achieve a capital cost reduction to $1800/kWe peak while improving system annual efficiency to 20%. As shown in Figure 5, central receiver electric system estimated costs have decreased significantly in the past five years, and the effectiveness of the central receiver program in achieving its critical objectives has been high.

10. Distributed Receiver Systems

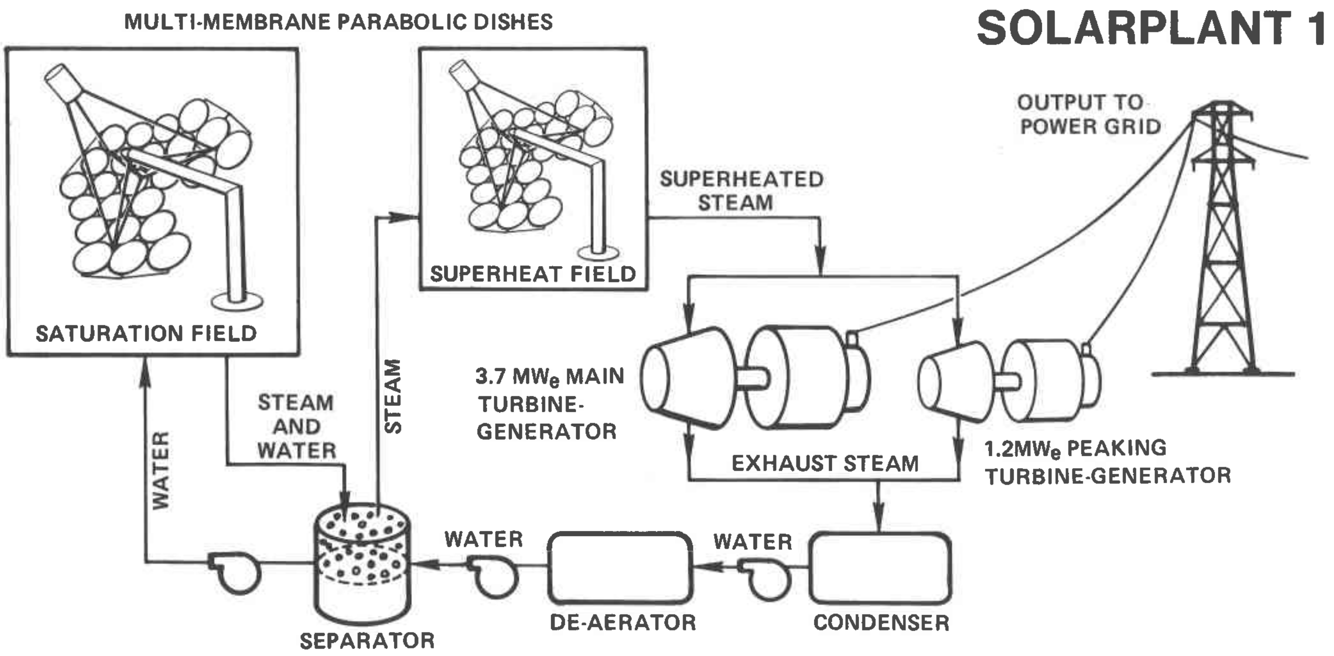
The objective of the distributed receiver systems task is to develop distributed point-focus and line-focus receiver systems that collect thermal energy for the production of heat and electricity at costs that are competitive with the projected costs for conventional energy forms. Research in distributed receiver systems includes concept definition, application analysis, integration of component characteristics, specification of new component requirements, and system-level experimental testing to obtain data to verify theoretical modeling.

Two basic types of parabolic dish/electricity systems are gaining prominence: (a) modular units with electricity generated by a heat engine at the focal point of the dish (such as the Advanco/Vanguard and McDonnell Douglas dish/Stirling modules) and (b) designs where heat is absorbed by a transfer fluid passing through a small receiver at the dish focal point and is then transported to a central turbine-generator (as in the Shenandoah and LaJet facilities). The former approach requires a more costly heat engine but very little transport cost, while the latter central engine approach

Figure 6. System Cost Trends for Parabolic Dish/Electric and Parabolic Trough/Industrial Process Heat Systems



Dish and trough systems have also shown significant cost reductions in recent years due to improved design and experience gained. The long-term electric goals compete with intermediate-load coal plants; the long-term industrial process heat target competes with premium fuel plants.



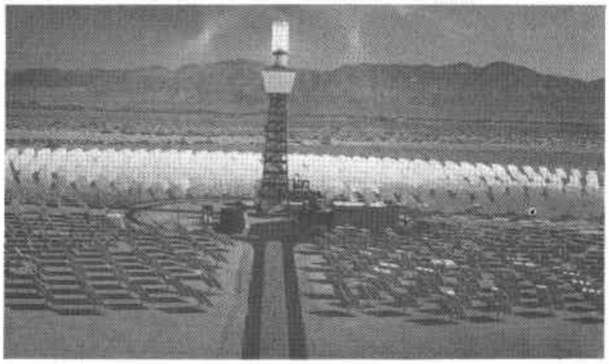
Solarplant 1 built by LaJet Energy Company is a privately funded 4.9-MWe solar thermal electricity generating facility near Warner Springs, California. Its 700 parabolic dish concentrators are each made up of 24 1.5-meter diameter individually-focused polymer film stressed membrane modules. The sun's rays are focused on individual receivers at each dish's focal point which contain a molten nitrate salt heat storage fluid. Water circulating through the receiver/heat exchanger leaves the concentrator as a 274°C water/steam mixture, is recycled through superheating concentrators to 371°C, and then is transported through insulated piping to two turbine generators. The main turbine has a capacity of 3.7 MWe and the second turbine, with a capacity of 1.2 MWe, is used for start-up, shutdown, low insolation and peak generation periods. The LaJet facility, with its low system cost, is a prime example of early penetration of the solar thermal electricity-generation market by private industry.

utilizes a relatively inexpensive receiver and standard Rankine turbine, but more costly (sensible heat or thermochemical) transport system.

As shown in Figure 6, cost data from the LaJet facility indicates a dramatic decrease in parabolic dish system costs. Both dish/electric technologies will continue to be developed to find the best combination of receiver/transport costs and efficiencies. Utility and industry input will be key factors in this research. Maximum exploitation of central receiver progress in areas such as silver reflectors, stressed membranes, terminal concentrators, absorber coatings, reflector washing, controls, test facilities, etc., will be emphasized as will the identification of the most suitable working fluids, transport methods, and heat engines.

Distributed line-focus (trough) research and development has addressed electrical and industrial applications at temperatures in the 200-400°C range. With experiments and full-size systems, the trough technology has been extensively evaluated. A very large privately-funded parabolic trough system is currently being installed by Luz Engineering Corporation near Barstow, California; when completed it should have a net electrical output in excess of 190 MWe, making it the world's largest solar electricity generating station. Trough-directed development includes component upgrade and evaluation as well as a design study of a trough that synthesizes the most promising state-of-the-a components.

Central Receiver System Experiment—Solar One

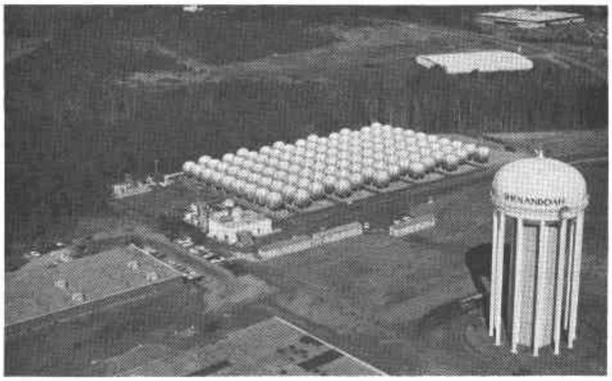


Construction of the 10-MWe Central Receiver Pilot Plant (Solar One) near Barstow, California, was completed in 1981. During its successful two-year experimental testing and evaluation period, operating experience was achieved with all the plant's operating modes including outputs of 10 MWe net when operating directly from the receiver and 7 MWe net when operating from storage. Also plant displays were upgraded, semi-automatic controls were installed, and the pilot plant's system and component performances were extensively evaluated.

A three-year Power Production Phase now in progress is demonstrating the operational capability of the plant to supply electrical power reliably to the utility grid. Of particular importance while operating the plant in a utility environment will be the determination of operating strategies to maximize the energy output of the plant. Component design and plant maintenance improvements are also being applied to further improve power production.

Solar One has generated more than 16,000,000 kWhe net since turbine roll in April, 1982; and is successfully performing its role as the world's first large solar central receiver pilot plant and learning facility. 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.

Distributed Receiver 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 in a closed hydraulic system, a stream-Rankine 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, and an operational phase has successfully demonstrated the solar total energy (cogeneration) concept. Operational and financial responsibility for the distributed receiver system experiment has now been assumed by its utility/user, Georgia Power, and has become a test bed for component and operations modifications to improve reliability and reduce costs.

The Distributed Receiver Test Facility in Albuquerque, New Mexico, supports experimental activities for dishes and troughs. Evaluation of both concentrator systems and modules of generating units for field experiments is conducted at this facility as will be research on parabolic dishes to be used in the Small Community System Experiments at Osage City, Kansas, and Molokai, Hawaii. Trough-directed development includes the design and testing of new trough components at the Modular Industrial Solar Retrofit project at the test site.

11. System Experiments

System experiments at user sites lead to the establishment of technical feasibility, the development of a valuable cost and performance data base to be used in private sector decisions, and the identification of future research needs.

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, the LaJet 4.9-MWe parabolic dish facility near Warner Springs, California, the large Luz parabolic trough electricity generation plant near Barstow, 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. Daily operations at the Barstow central receiver experiment and at the Shenandoah parabolic dish facility are now the responsibility of their respective utility/users, Southern California Edison and Georgia Power.

Over the next five years, additional system experiments will come on line. Small Community System Experiments (dish), cost-shared with the private sector, will be built and operated at Osage City, Kansas, and Molokai, Hawaii. The utilities/users strongly feel that a 30-100 MWe central receiver system experiment will definitely be needed in the near future and are developing a plan for selection of the technology development which will lead to a future project at the least cost with minimum risk.

IV. The Management Plan

Program Organization

The National Solar Thermal Technology Program is managed by the Solar Thermal Technology Division of the Department of Energy. The Division provides centralized leadership and control. Decentralized program management support to the Solar Thermal Technology Division is provided by the Albuquerque Operations Office and the San Francisco Operations Office. Two research and development centers provide technical expertise and management of activities in specific areas of the program.

Department of Energy Headquarters

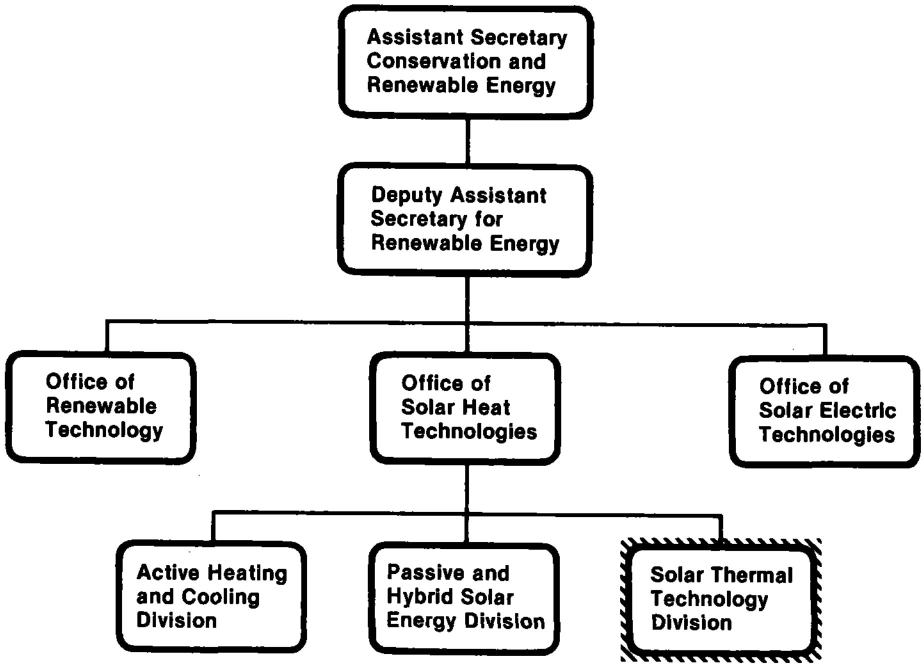
The Solar Thermal Technology Division is responsible for research and development policy formation and the allocation of technical and budgetary resources. Specific responsibilities include:

- 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 Department of Energy, other government agencies, and Congress.

Research and Development Centers

Two research and development centers-the Solar Energy Research Institute in Golden, Colorado, and Sandia National Laboratories in 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 research and development centers and through contracts placed with universities, other laboratories, and private industry.

Figure 7. Office of Conservation and Renewable Energy



Management Control

Management control of the Solar Thermal Technology Program is exercised at Department of Energy 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 publish technical reports and periodic progress memos 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 annually to promote technology transfer activities and to ensure continuing exchange of technical information and issues between Department of Energy 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.

Program Planning, Scheduling, and Implementation

Input for this Five Year Plan was solicited from the entire solar thermal community including private industry, utilities, solar thermal laboratories, and universities. This input was obtained through workshops, conferences, management reviews, research and development plans of the solar thermal laboratories, periodic and subject-specific reports, and ongoing one-on-one communication throughout the community. Key guidance for developing the focus of this 1986-1990 Plan was obtained from the deliberations and conclusions of a technical workshop sponsored early in 1985 by the Electric Power Research Institute to develop a consensus within the solar community on strategies for the future (Reference 2).

Utilizing this input, program subtasks, milestones, and decision points are formulated by the Solar Thermal Technology Program to guide the organizations responsible for implementing program tasks and to assist management in monitoring progress toward achieving the five year and long-term cost/performance targets established for the program.

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 prices 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, that is, the competing fossil energy sources. Component goals are performance and cost for the primary elements of a solar thermal plant, such as the 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 trade-offs in the development goals; the desire for the lowest possible system goal must be balanced by a need for 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 meeting the system goal.

Technology goals are developed for the middle-to-late 1990's time frame using a levelized energy cost methodology for comparing solar thermal plants to conventional energy sources. This method is a standard approach often used in the utility industry and is described in more detail elsewhere (References 5 and 6). The levelized energy cost approach considers all relevant costs including the initial capital cost, annual 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. The calculations for the technology goals are carried out on a constant dollar (also known as a real dollar) basis, which removes the effects of general inflation. To facilitate comparison of the technology goals in this plan with the goals of the 1985-1989 plan, all discussion and data in this plan are expressed in 1984 dollars.

System Goals

System goals represent the overall performance and cost which must be achieved by a solar thermal system to be economically competitive in a given application. These are ambitious goals that would allow solar thermal to compete with many energy sources and achieve significant market penetration, not merely a threshold energy cost that solar thermal must achieve to allow initial sales. Near-term sales of solar thermal systems for high-value applications are expected to continue at energy costs significantly higher than the systems goals. Applications such as peak-load or remote solar thermal power plants and electricity-producing plants owned by third parties potentially represent significant midterm markets for solar thermal technology, but have not been considered explicitly in developing the long-term system goals. It is likely that such higher-valued applications will provide the key impetus for the penetration of larger, higher capacity factor solar thermal systems into the marketplace.

The two primary applications chosen for the development system goals are bulk electricity and industrial process heat. The electricity system goal is based upon utility-owned, grid-connected power production while the system goal for industrial process heat applications assumes 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. Assumptions used in the levelized energy cost calculations for both applications are shown in Table A-1.

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	0.33-0.35	0.85
Base Year for Prices	1984	1984

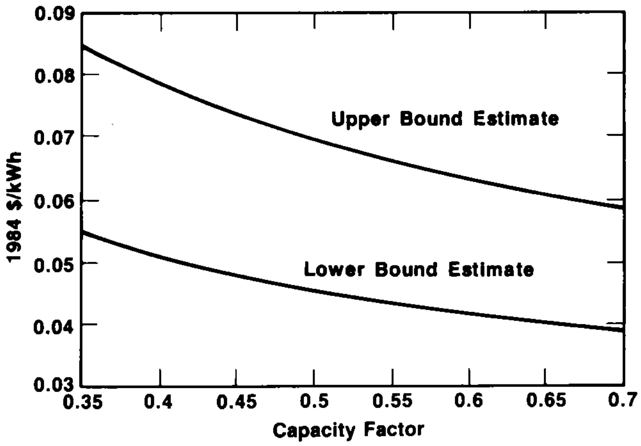
n.a.—Not applicable. System goal for IPH based on fuel replacement only, without credit for replacing capital equipment of fossil system.

Electricity Goal

The system goal for electricity is based upon solar thermal competing with coal, one of the lowest cost long term options of the many generating technologies on the utility grid. Because coal-fired power plants are expected to be one of the most economical energy sources in the coming decades, (gas- and oil-generated electricity is expensive and expected to be phased out over time), the energy cost from intermediate-load coal-fired power plants is used as the competing technology target for establishing electricity system goals. Baseload plants were not selected because the solar thermal technology cost performance optimum occurs in the intermediate load range. By choosing one of the lowest energy-cost technologies as the basis for setting system goals, solar thermal could expect to be competitive with several other alternatives (oil and gas) if the goals are met. The energy cost from coal-fired power plants was selected as a reasonable target for widespread adoption of solar thermal energy, not to indicate that solar thermal could displace a large amount of existing coal-fired capacity.

In estimating the future energy cost from coal-fired power plants, projections of basic plant characteristics (such as capital cost, heat rate, fuel cost, etc.) were taken from several studies (References 4, 6, 7 and 8). These studies' coal plant characteristics were used with the levelized energy cost methodology and assumptions to derive the upper and lower bound energy-cost projection estimates, as a function of plant capacity factor which are shown in Figure A-1. For intermediate-load coal plants (capacity factor range of 0.4 to 0.5), the levelized energy cost can be seen to range from slightly under $0.50/kWh to nearly $0.08/kWh. The solar thermal system goal selected for electric applications was $0.05/kWh. This energy cost would allow electricity from solar thermal plants to compete to some extent with electricity produced from newly constructed intermediate-load coal power plants at the end of the next decade. The system goal would also allow solar thermal to compete with electricity from oil-fired power plants, which under the same economic assumptions are projected to have levelized energy costs of $0.10/kWh or more.

Figure A-1. Energy Cost Projection Estimates



Industrial Process Heat Goal

In developing a system energy cost goal for the industrial process heat market, the energy competition to solar thermal was assusmed 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 a fossil backup is assumed to exist. With the fossil backup, the benefits of the solar thermal system are in fuel savings only, so the industrial process heat system goal is determined by the value of the fuel only.

The primary source for fuel price projections and escalation rates used in the industrial process heat system goal was a report supporting the National Energy Policy Plan (DOE 1983). Estimates established in support of that plan cover a time horizon between 1990 and 2010, which is close to the planning period for the technology goals. The National Energy Policy Plan estimates for three scenarios (base-case estimates, high world oil price and low world oil price) for residual fuel, distillate fuel, and natural gas were analyzed using the levelized energy cost methodology. The results of this analysis are shown in Table A-2. Based on these levelized energy cost projections, a system goal of $9/MBtu was selected, which would allow solar thermal industrial process heat to compete with all three fuels in either the base-case scenario or the high world oil price scenario. The industrial process heat goal applies to solar thermal applications in the broad temperature range of 200-600°C. The use of a single value for industrial process heat over this temperature range is an approximation, since in actuality process heat at high temperatures may be more valuable than process heat delivered at lower temperatures.

Table A-2. Levelized Energy Cost Projections for Industrial Process Heat from Fossil Fuels

	Low World Oil Price Scenario ($/MBtu)	Base-Case Price Scenario ($/MBtu)	High World Oil Price Scenario ($/MBtu)
Residual Fuel	7	11	14
Distillate Fuel	9	13	17
Natural Gas	7	9	12

As discussed previously, the market differences between electricity and industrial process heat applications require different economic assumptions to be used in the levelized energy cost calculation, which substantially impacts the results. Because of these differences, the system goals for these applications cannot be directly compared on a purely thermodynamic basis. While a system goal of $0.05/kWh for electricity might at first seem to imply an achievable goal for industrial process heat lower than $9/MBtu, the differences in economic assumptions account for the higher goal for process heat. The system goals for both applications are shown in Table A-3.

Table A-3. 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.

For each solar thermal technology, the selected component goals represent only one possible development path which would allow the system energy cost goal to be met. Many other paths exist because of the trade-offs between efficiency and cost both among components and for a specific component. For example, some heliostat designs may not be able to achieve the concentrator efficiency goal but may substantially surpass the cost goal; this would be equally acceptable. Trade-offs among components can also provide alternative development paths; if a component is able to exceed its goal, it creates flexibility for other components

Table 4-A. Description of Areas For Component Goals

Concentrator	All concentrator costs including field installation, power and control wiring, field controllers.
Receiver	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. For industrial process heat applications conversion includes steam generators.
Balance of Plant	Buildings and site improvements, master control system, spare parts, and plant service facilities.
System	Total installed system cost including land and an allowance of 20 percent of total component costs for indirect costs incurred during system construction and integration.
Operations and Maintenance	Annual cost for routine plant operations and maintenance.

to have lower performance/higher cost and still meet the system energy cost goal. The component goals are not to be considered rigid but rather a general guide to component development which will be revised as progress occurs in individual components.

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: concentrators, receivers, energy transport, energy storage, energy conversion, balance of plant, total installed system cost, and operations and maintenance costs. Included in Table A-4 is a general description of the items encompassed in these areas (the definitions differ slightly among the three solar thermal technologies). The eight areas provide a suitable level of detail to allocate goals to the individual research task activities discussed in Section III. (Although the cost of land is included in calculating the levelized energy costs, it is not included in the component goals.)

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 goal 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 was used for calculating the system goals. Important assumptions for calculation of the solar thermal plant energy cost are shown in Table A-5.

Component long-term cost/performance goals for all central receiver, dish, and trough solar thermal applications are shown in Table A-6 along with the current capabilities of these technologies.

Table A-5. Levelized Cost Assumptions for Solar Thermal Component Goals

Parameter	Electricity	Heat
Average Peak Insolation	0.95 kW/m²	0.95 kW/m²
Average Annual Insolation	2690 kWh/m²	2690 kWh/m²
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
Percentage of Capital Cost for Indirects and Contingencies	20%	20%
Cost of Land	5000 $/ACRE	12,000 $/ACRE

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 dish receiver operating at a much higher temperature (800°C) for electricity than for process heat (200-600°C). A similar case occurs for energy transport for dishes. In this plan energy transport for the long-term dish/electric systems is assumed to be electrical, accomplished with field wiring interconnecting the individual generators at each dish. (The new LaJet dish/electric facility, however, uses piping to transport thermal energy to a central turbine generator.) For process heat, transport is done with piping.

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 which is difficult to quantify. The best allocation of component goals may change in the future as solar thermal technology development proceeds and as improvements in some solar components occur faster than in others.

Current Capabilities and Five-Year Goals

The current capabilities were developed to provide an indication of the amount of improvement required to reach the long-term goals. The five-year goals were developed to indicate how much of the improvement is expected to be achieved over the next five years with continued development at the current level of activity.

To facilitate comparison between the current capabilities, five-year goals and the long term goals, some common assumptions were made. The cost/performance estimates are based on the assumption that the constructed plant is a full-sized plant, not a laboratory model or prototype. The plant must be made up of components that assemble into a fully workable system; for example, components designed to use different heat transfer fluids are not put into the same system unless provisions for their compatibility (such as a heat exchanger) are made. Levelized energy costs are all calculated using the same economic assumptions.

Although comparable, the current capabilities, five-year goals and the long-term goals do represent different scenarios. A current capability system is defined as the next plant which could be constructed based on the current level of knowledge. It is recognized that this definition of current capabilities leads to uncertainties in cost and performance estimates. However, using the next plant paints a more accurate picture of current capabilities of solar thermal plant energy production than would use of the most recently fielded system. A long-term system is defined as a plant that could be built in the late 1990's that is competitive with fossil-fired plants. A five-year system is defined as the solar thermal plant that could be built having the advantages accrued from five years of current-level-activity research and development.

The current capabilities shown in Table A-6 are based on a preliminary design of a 100-MW_e central receiver electricity plant, a 5-MW_e dish electricity plant operating in Warner Springs, California, and a preliminary design of a 1.5-MW_t trough process heat plant.

Component current capabilities may change dramatically from year to year as they reflect the most recent plant design concept changes. The most notable component differences in this year's plan from the previous plan are in the receivers, heat engines (or power conversion units), and transport components for dish/electric facilities. Component designs and costs have changed considerably from the engine-at-the-focal-point concept used as current capability in the 1985-1989 Five Year Plan to the thermal-transport/central-engine approach used as current capability in this 1986-1990 Plan. This yearly fluctuation in current capability figures reflects a healthy, active research and development program which is looking at many possible solar thermal technological concepts in order to find the best for the long term. The long-term goals of the program have remained steady, as they should, to reflect the cost of energy which must be met to be competitive with other energy sources.

The five-year goals must reflect both the flexibility of the current capabilities as well as the steadfastness of the long-term goals. Given all of the varied technologies in the Solar Thermal Program, the establishment of generally applicable five-year goals for all components or concepts is an almost impossible task. Certain contingencies, assumptions and judgment calls must be allowed. To the best degree possible, these decisions have been documented either formally or informally.

The greatest value of the Five Year Plan is that it presents specific sets of goals (both intermediate and long-term) with their supporting economic assumptions, which can be used throughout the Solar Thermal Program. Studies done on different concepts and in different laboratories thus all have a common basis from which to begin and common goals for which to strive.

Table A-6. Current Technology and Long-Term Component Goals

	Current Technology(a)			
	Electric(b)		Process Heat(b,c)	
	Annual Efficiency (%)	Cost (1984 $)	Annual Efficiency (%)	Cost (1984 $)
OPTICAL MATERIALS	88	20/m^2	88	20/m^2
CONCENTRATORS				
Central Receiver	55	150/m^2(d)	55	150/m^2
Dish	70	160/m^2	70	160/m^2
Trough	(e)	—	44	200/m^2
RECEIVERS				
Central Receiver	90	80/m^2	90	80/m^2
Dish	87	40/m^2	87	40/m^2
Trough	—	—	75	40/m^2
TRANSPORT				
Central Receiver	99	45/m^2	99	45/m^2
Dish	93	70/m^2	93	70/m^2
Trough	—	—	98	40/m^2
STORAGE				
Central Receiver	98	25/kWht	98	25/kWht
Dish	—	—	—	—
Trough	—	—	—	—
CONVERSION(f)				
Central Receiver	36	600/kWe	99	50/kWt
Dish	23	380/kWe	99	50/kWt
Trough	—	—	99	50/kWt
BALANCE OF PLANT				
Central Receiver	NA(h)	65/m^2	NA	65/m^2
Dish	NA	35/m^2	NA	35/m^2
Trough	—	—	NA	35/m^2
SYSTEM(g)				
Central Receiver	17	2900/kWe	48	800/kWt
Dish	13	3400/kWe	56	780/kWt
Trough	—	—	32	760/kWt
OPERATIONS & MAINTENANCE				
Central Receiver	NA	12/m^2-year	NA	15/m^2-year
Dish	NA	8/m^2-year	NA	8/m^2-year
Trough	—	—	NA	15/m^2-year
ENERGY COST(i)				
Central Receiver	NA	0.13/kWhe	NA	21/MBtu
Dish	NA	0.13/kWhe	NA	17/MBtu
Trough	—	—	NA	30/MBtu

(a) Central receiver systems use molten salt, trough systems use oil, dish near-term electric system uses water/steam with sensible heat transport to a central engine, dish long-term electric uses helium (high temperature) with an engine at the focal point of each dish with electric transport, and dish heat systems use water/steam.

(b) Capacity factors are 0.5 central receiver electric, 0.26 dish electric, 0.29 central receiver thermal, 0.28 dish thermal, and 0.24 trough thermal.

[illegible]) Includes production of fuels and chemicals.

(d) Dollars per square meter of concentrator aperture area.

Table A-6. Current Technology and Long-Term Component Goals — Continued

	Long-Term Component Goals(a)			
	Electric(b)		Process Heat(b,c)	
	Annual Efficiency (%)	Cost (1984 $)	Annual Efficiency (%)	Cost (1984 $)
OPTICAL MATERIALS	92	10/m^2	92	10/m^2
CONCENTRATORS				
Central Receiver	64	40/m^2(d)	64	40/m^2
Dish	78	130/m^2	78	130/m^2
Trough	(e)	—	65	110/m^2
RECEIVERS				
Central Receiver	90	30/m^2	90	30/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(f)				
Central Receiver	39	350/kWe	99	40/kWt
Dish	41	300/kWe	99	40/kWt
Trough	—	—	99	40/kWt
BALANCE OF PLANT				
Central Receiver	NA(h)	30/m^2	NA	20/m^2
Dish	NA	20/m^2	NA	20/m^2
Trough	—	—	NA	20/m^2
SYSTEM(g)				
Central Receiver	22	1000/kWe	56	270/kWt
Dish	28	1200/kWe	68	430/kWt
Trough	—	—	56	370/kWt
OPERATIONS & MAINTENANCE				
Central Receiver	NA	9/m^2-year	NA	9/m^2-year
Dish	NA	10/m^2-year	NA	6/m^2-year
Trough	—	—	NA	6/m^2-year
ENERGY COST(i)				
Central Receiver	NA	0.04/kWhe	NA	7/MBtu
Dish	NA	0.05/kWhe	NA	9/MBtu
Trough	—	—	NA	9/MBtu

(e) No goals established for this option.

(f) Electric conversion is with heat engines; thermal conversion is with heat exchangers.

(g) System costs are normalized to turbine or process capable of handling peak field thermal output; includes indirect and contingency costs of approximately 50% of direct costs for current capabilities and 20% of direct costs for long term.

(h) NA = Not Applicable

(i) Energy costs are levelized in real dollars. The 0.05 $/kWhe and 9 $/MBtu long term goals are the levelized costs of electricity and heat in the 1990's. In nominal dollars (assuming a 7% inflation rate) the goals are 0.11 $/kWhe and 14 $/MBtu.

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*U.S. GOVERNMENT PRINTING OFFICE: 1986-491-176:40125

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