SOLAR THERMAL ELECTRIC POWER SYSTEMS

FINAL REPORT

VOLUME 1

EXECUTIVE SUMMARY

Prepared for

The National Science Foundation

Research Applied to National Needs

Washington, D. C.

Supported by NSF Grant GI-37815

Initiated May 1, 1973

Prepared by

Colorado State University

Fort Collins, Colorado

and

Westinghouse Electric Corporation

Pittsburgh, Pennsylvania

NOVEMBER 1974

Report: NSF/RANN/SE/GI-37815/FR/74/3

COLORADO STATE UNIVERSITY

Solar Energy Applications Laboratory

Engineering Research Center

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The final report consists of three volumes: (1) an Executive Summary, (2) System Studies and Economic Evaluations, and (3) Appendices.

The objective of the research program is to develop design parameters of systems for thermal/mechanical conversion of solar energy to electric power at minimum cost per kilowatt-hour generated. Systems of 3MW to 300MW sizes in a public utility network are considered. Parametric performance and cost models are derived for key elements of the system. A sequential optimization program was developed using these models to determine optimum subsystem sets and combinations which yield the least capital cost plants. A dynamic simulation program was developed to determine annual electric power produced by solar power systems at specific locations. Electric energy cost comparisons are made to select promising systems for generation of electricity from solar energy.

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PREFACE

The final report for the study of Solar Thermal Electric Power Systems (STEPS), conducted by Colorado State University and Westinghouse Electric Corporation and financially supported by The National Science Foundtaion, Research Applied to National Needs, under Grant GI-37815, is in three main volumes and one supplementary volume. Volume 1 is an Executive Summary which contains brief summaries of the procedures, results, conclusions and recommendations developed from the study. Volume 2, titled System Studies and Economic Evaluations, contains descriptions of methodology, parametric performance and cost models, descriptions of solar power plants which have the potential to produce low-cost electric energy, and detailed conclusions and recommendations. Volume 3, Appendices, contains the details of the study which are summarized in Volumes 1 and 2. The Supplementary Volume, is a compilation of reprints of the computer printout from the optimization runs. Although each is self contained, reference to other volumes is sometimes made to guide the reader.

The final report was prepared by the staff of the Solar Energy Applications Laboratory at Colorado State University, Fort Collins, Colorado, in collaboration with the Westinghouse Electric Corporation. Westinghouse participants included the Georesearch Laboratory in Boulder, Colorado, the Research and Development Center, the Power Generation System Division and the Manufacturing Development Laboratory in Pittsburgh, Pennsylvania.

The International System of Units (SI) has been used throughout the report. Some English units are used in a few instances where it is considered to be in such common usage in the United States that results in unfamiliar metric units would handicap the reader unnecessarily.

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1.0 PURPOSE AND SCOPE

Project was Supported by NSF/RANN

The National Science Foundation, Research Applied to National Needs, awarded a research grant (GI-37815) to Colorado State University and the Westinghouse Electric Corporation in May, 1973 to conduct a study of Solar Thermal Electric Power Systems, (STEPS).

Purpose is to Develop a Methodology for Analyzing Solar Thermal Power Plants

The objective of the STEPS study is to develop a methodology for evaluation of solar plants to convert solar energy to thermal, mechanical and electrical energies. By using this method, together with economic and performance evaluations of subsystems, a companion objective is to identify the types of systems that have the potential to produce low-cost electrical energy.

Methods involve Selection, Elimination, and Optimization of Solar Power Systems

Solar power plants were optimized through sequential optimization of subsystem components. The selection of subsystem components is made by evaluating performance and costs of many types of subsystem designs. Many subsystem designs were eliminated from further consideration in a solar power plant when costs were found to be significantly higher in comparison to other designs for equal performance.

When subsystems are combined in a sequential manner, candidate systems can be selected on the basis of minimum costs for the electrical energy produced.

The details of analysis increase in complexity in stages of the selection and elimination process depicted schematically in Figure 1-1, until only a few systems remain as candidates.

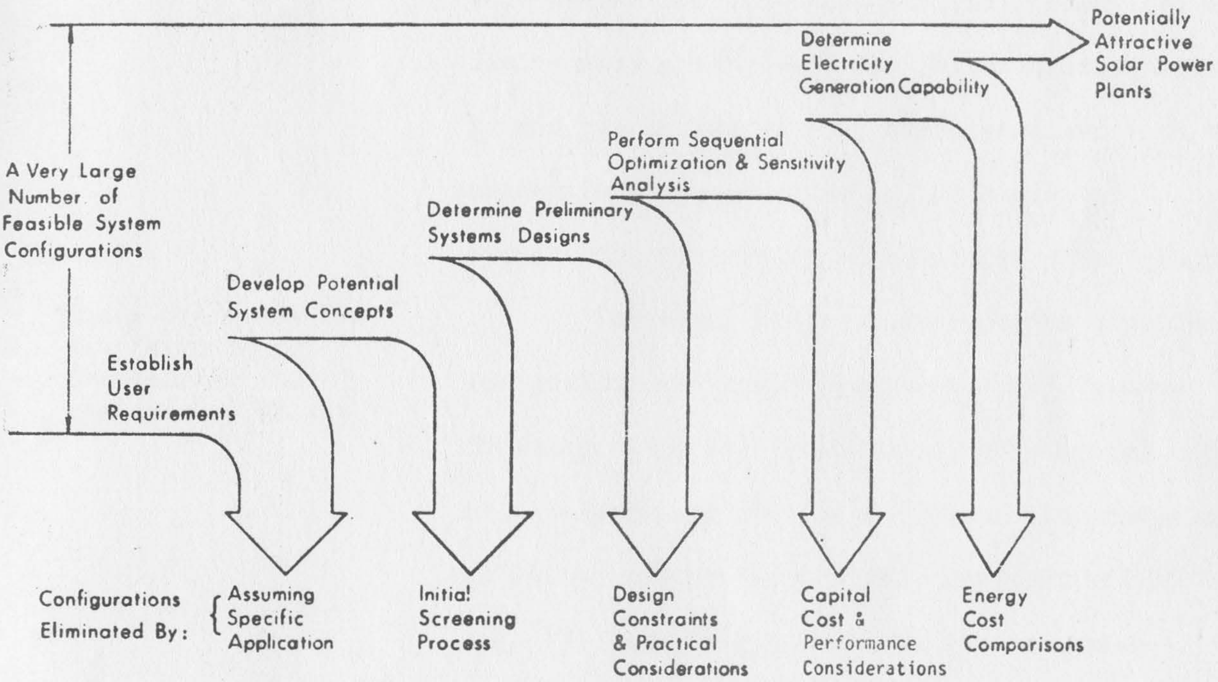

Figure 1-1. Schematic Representation of System Selection and Elimination Process.

Solar Power Plants are Assumed to be Tied to a Regional Power Grid

The solar power plants in this study are directed toward supplying power to a regional electric power grid by an electric utility industry. The value of electrical energy supplied to an electric power grid, as it generated, would achieve lower energy costs than plants which are not tied to a power grid with an auxiliary power generating capability. The sizes of plants considered range from 3 MW_e to 300 MW_e.

Economic, Physical and Performance Ranges were Established by Preliminary Designs

After an initial screening process, preliminary designs of three system concepts were developed and preliminary electrical energy costs were determined for these designs. Practical design limits were established for solar power plants by the preliminary design exercise as well as by constraints on the economic, physical and operational parameters of the solar power plants.

Costs are Evaluated for Three Basic Concepts in the Preliminary Designs

The three basic plant concepts considered for preliminary evaluation are: (1) a non-focusing collector system using pressurized water at a temperature of 150 ^{o}C (2) a line-focusing collector system using steam transport at 250 ^{o}C and (3) a multiple tower/heliostat system generating steam at a temperature of 350 ^{o}C. Sketches of solar thermal power plant configurations and concepts of some components are shown in Figures 1-2 through 1-7.

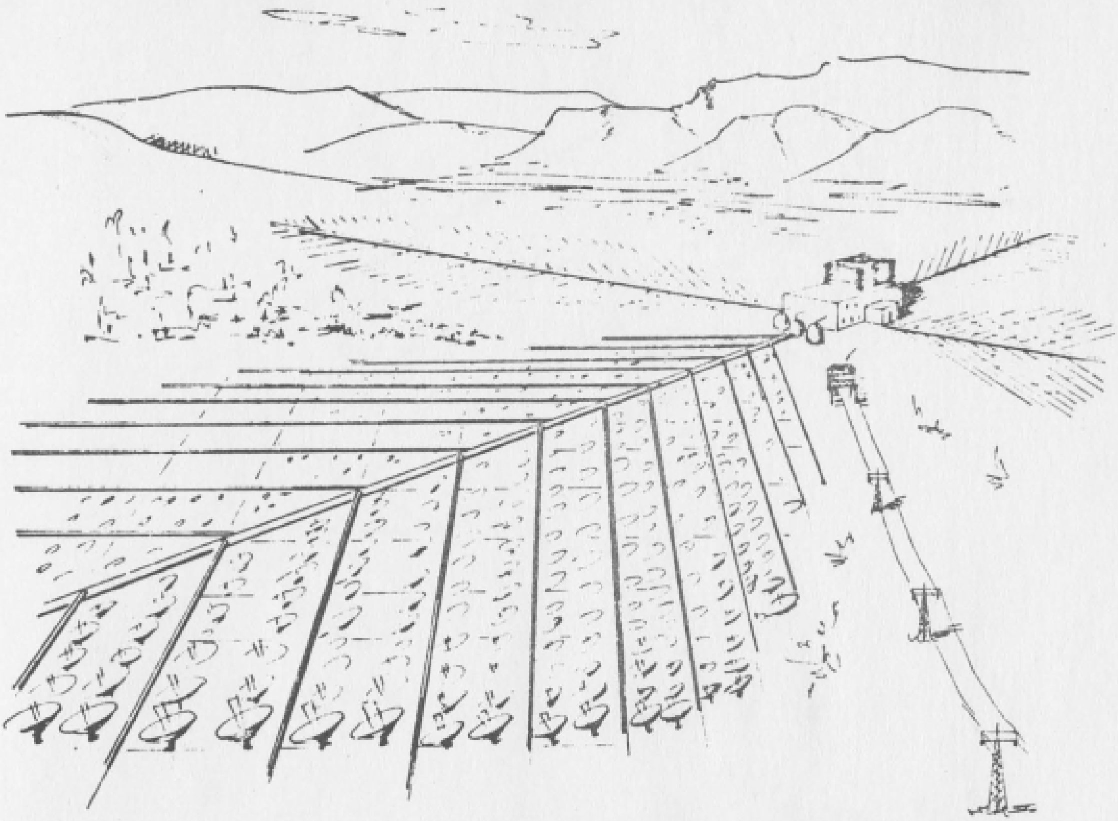

Figure 1-2. Distributed Collector Station Using Focusing Collectors.

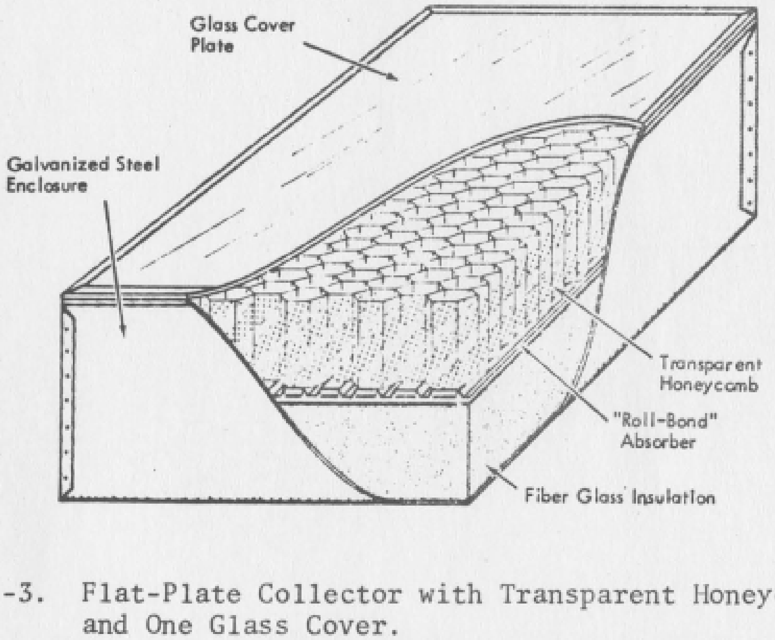

Figure 1-3. Flat-Plate Collector with Transparent Honeycomb and One Glass Cover.

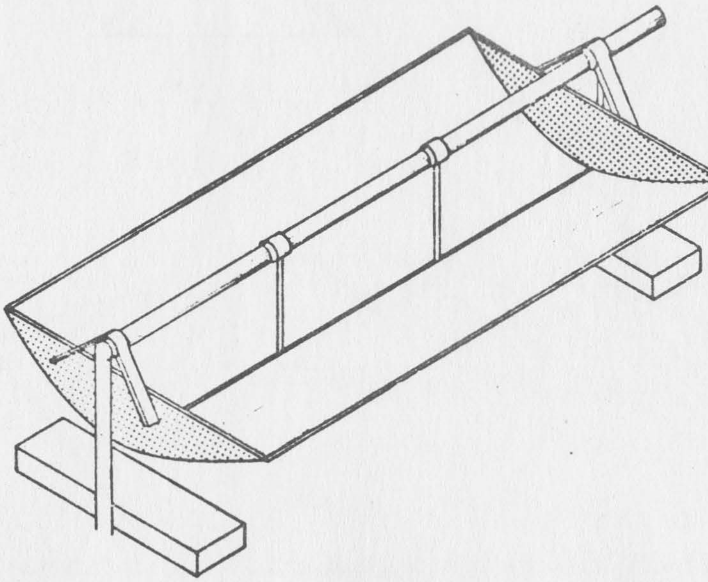

Figure 1-4. Parabolic Trough Collector.

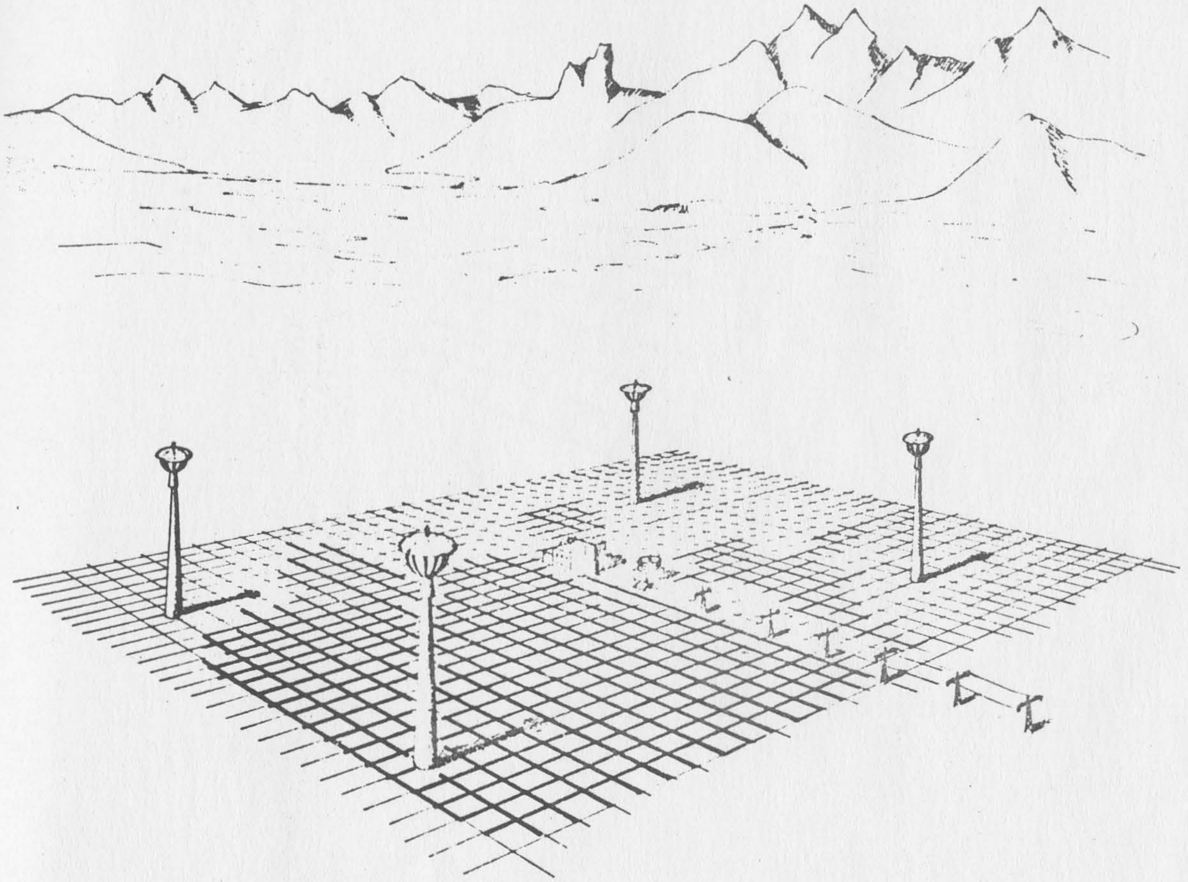

Figure 1-5. Multiple Tower/Heliostat Station.

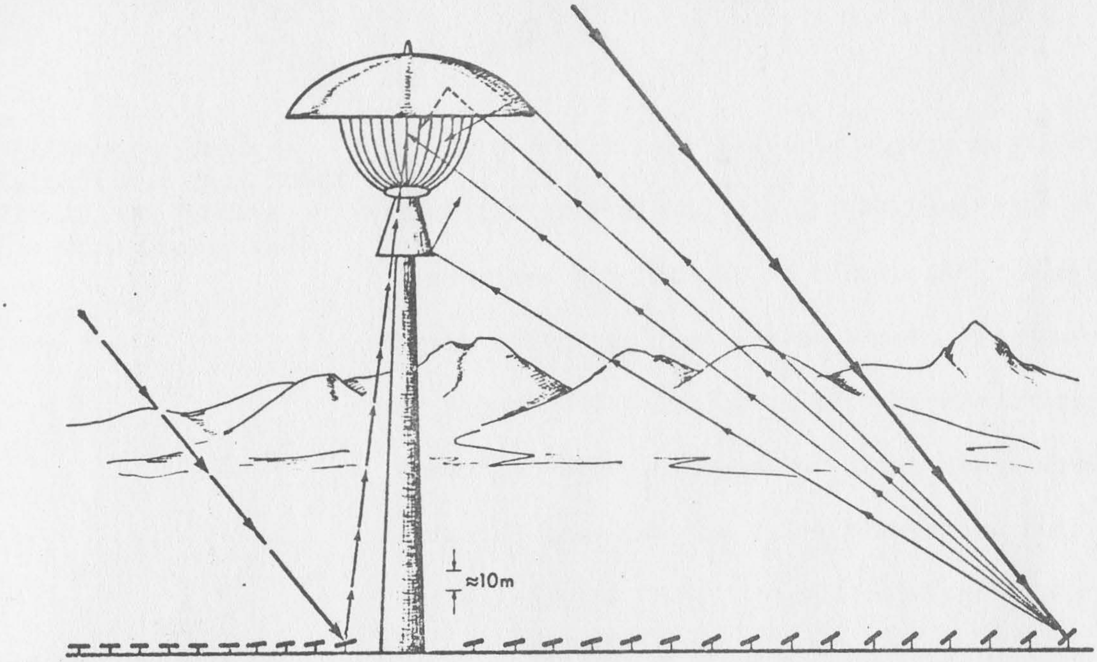

Figure 1-6. Tower Supported Absorber and Heat Exchanger.

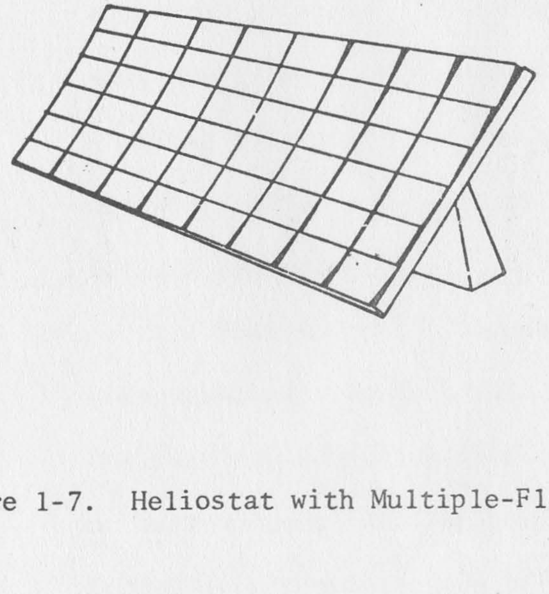

Figure 1-7. Heliostat with Multiple-Flats.

Preliminary Designs Established that Solar Plants can Produce Low-Cost Electricity

Preliminary electric energy costs determined from the preliminary designs and analyses are summarized graphically in Figure 1-8. Energy costs estimates from fueled plants are shown in Figure 1-9. The costs of electric energy are shown in terms of collector costs and thermal storage times for the solar plants and fuel costs for oil-fueled, coal and nuclear-fueled plants.

System Concepts are Classified by Energy Concentration Methods

The three basic system types chosen in the preliminary design studies represent three energy concentration methods. Flat-plate collectors do not have optical concentration and deliver heat energy by accumulation of thermal transport to a central location. Focusing collectors deliver heat energy by optical and thermal concentration Tracking heliostats and the tower-supported absorber-boiler provide heat energy entirely by optical concentration.

Water or Steam is Selected as the Transport Fluid

Numerous heat transport and working fluids were examined. Factors such as cost, safety, toxicity and experience indicate water and steam as best choices for transport and working fluids. Schematic representations of solar power systems using water and steam are shown in Figures 1-10 and 1-11.

Non-Focusing Collector Systems are not Promising for Solar Power Plants

Collector designs were limited to providing pressurized water to a steam generator, or steam directly to the turbine. Optimization of the

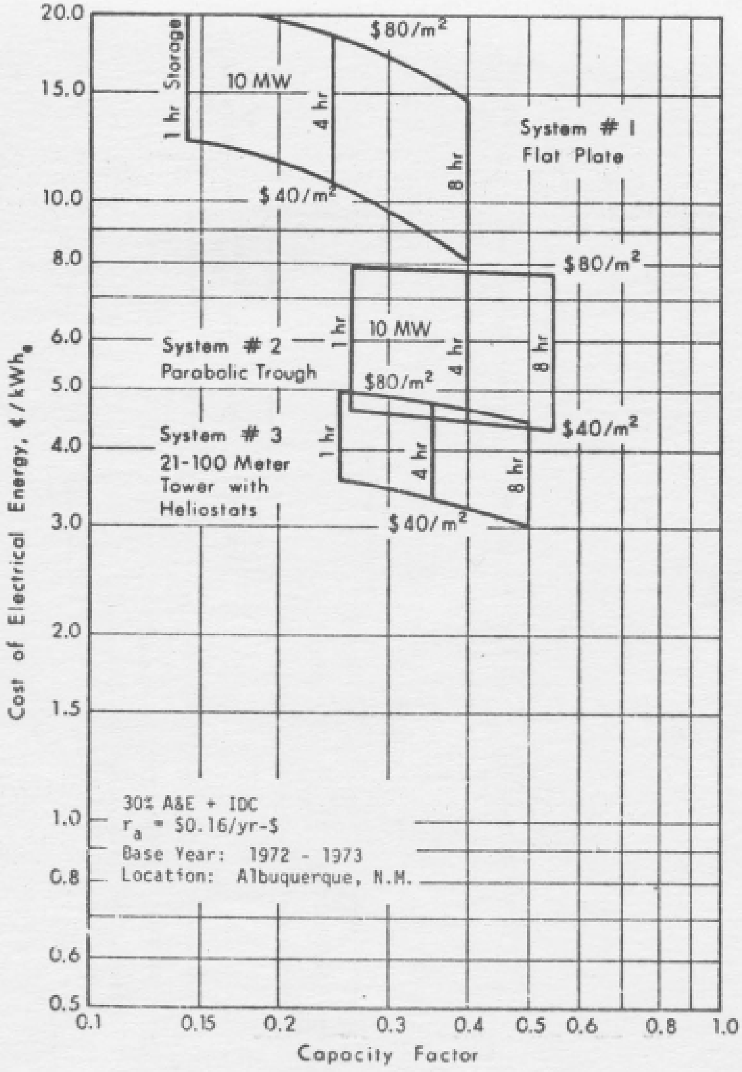

Figure 1-8. Electric Energy Costs from Solar Thermal Power Plants Determined from Preliminary Design Phase of the Study.

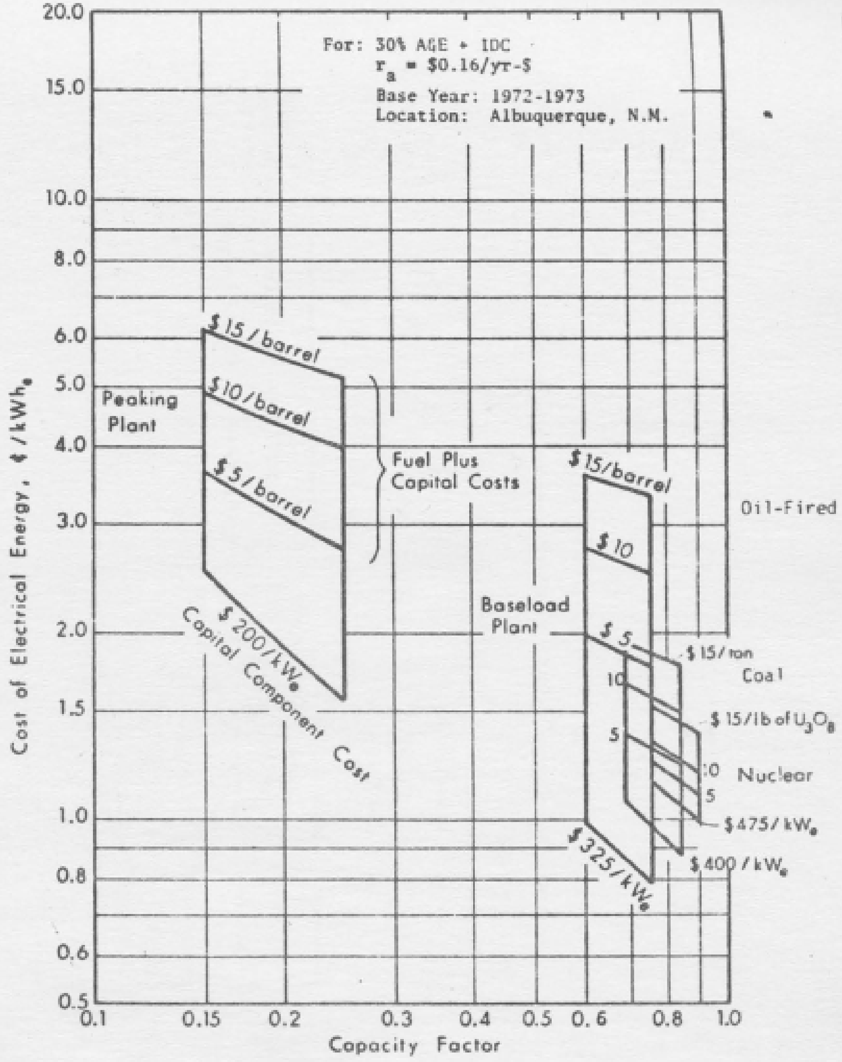

Figure 1-9. Electric Energy Costs from Oil Fueled, Coal and Nuclear Power Plants.

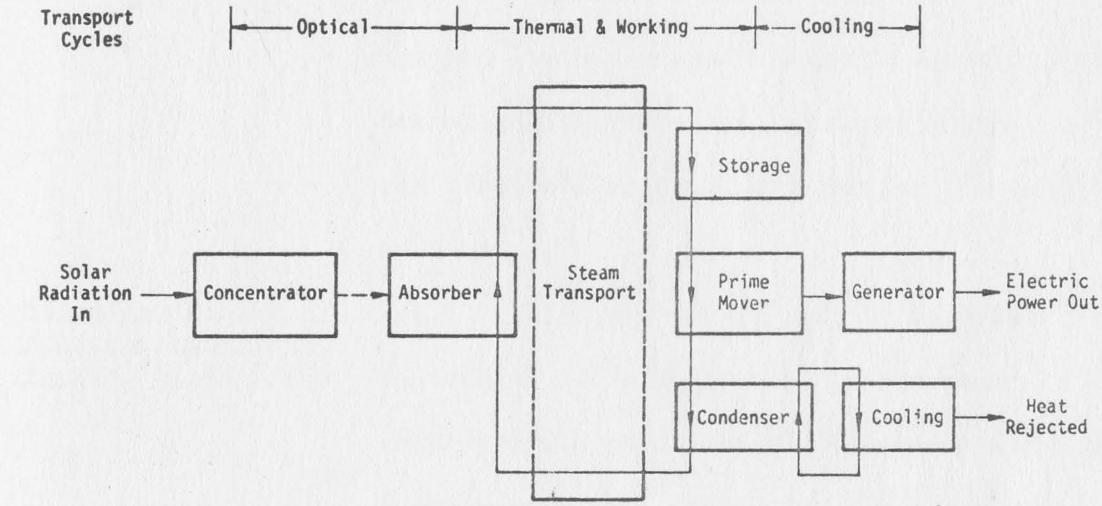

Figure 1-10. Steam Transport System.

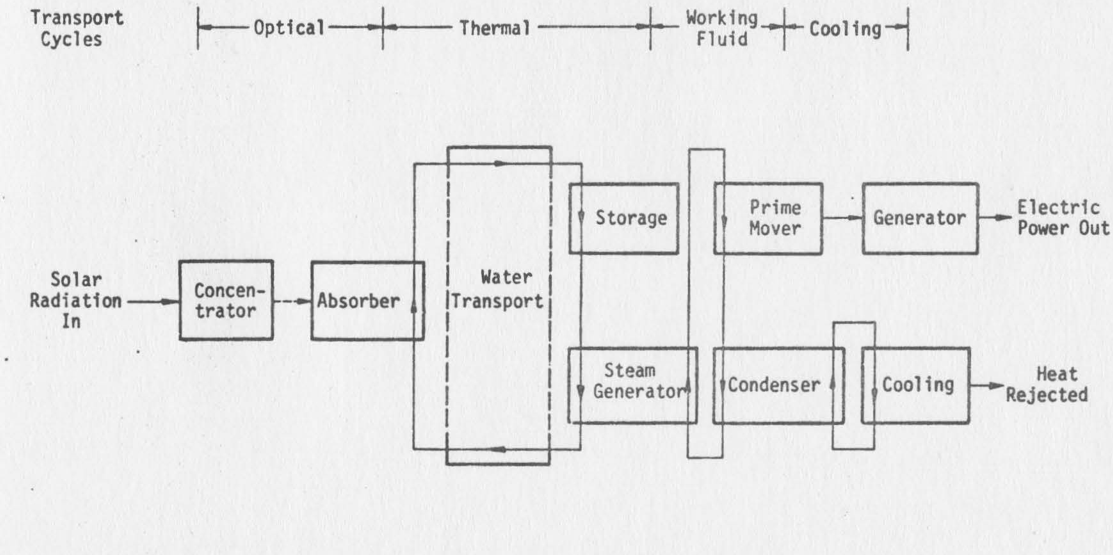

Figure 1-11. Pressurized Water Transport System.

collection subsystem is important because the collectors and piping costs comprise a large portion of the total system costs. Non-focusing collector systems are non-competitive with focusing systems because collector costs are approximately equal and plant efficiencies are low for low temperature systems.

Increase in Turbine Efficiency Reduces Collection Field Costs

Collection field size is inversely related to turbine efficiency, thus any increase in turbine efficiency reduces collection field costs. Turbine-generator efficiency can be maximized by proper designs of heat rejection systems. Also, introduction of some storage capacity permits extended operation at peak turbine efficiency during the day.

2.0 BASIC APPROACH TO OPTIMIZATION

Parametric Cost and Performance Models were Developed and Electric Energy Costs are Determined

A major effort in this study involves development of parametric cost and performance models for subsystem components of solar thermal electric power plants. The performance and cost models are used in designing and selecting optimum systems for electric power production.

Sequential Optimization is used to Select Subsystems for an Optimum Solar Power Plant

The sequential optimization process used to select subsystems and minimum-cost solar thermal electric power systems is a generalized approach which includes consideration of many possible different types and designs of subsystems. The performance and cost functions are parametric which are readily adaptable to different subsystem designs.

Performance Models for Concentrators were Compared with Available Experiments

Theoretical predictions of concentrator performance were compared with published experimental results. Performance of other components such as transport, storage, turbine-generator and cooling subsystems for water and steam are considered to be well established by existing practice, in conventional power plants and related heat generating plants.

Cost models for collectors were developed with the assistance of a specialized group of manufacturing development experts at Westinghouse Electric Corporation. Their experience in making cost estimates for large scale production of manufactured goods was particularly valuable in estimating collector costs. Costs for the more conventional components, such as piping, insulation, storage vessels and turbine-generators are made on the basis of wide experience.

Particular attention is devoted to estimating costs of collector subsystems because this is a major cost component of the total system. Alternative manufacturing processes for concentrators are considered, and different surface materials and surface characteristics relating to performance and cost are examined. The properties of shell materials such as quality, weight, forming ease, and durability are important considerations in this selection. Cost analyses include many concentrator types and forms such as paraboloids, parabolic cylinders, Fresnel lenses, Fresnel reflectors, and heliostats for tower systems.

The cost models incorporate detailed considerations of methods of tracking, contour and tracking accuracies, gearing, controls, sensors, support structures, installation, replacement life, maintenance and operating costs. Sketches of a few of the collector concepts are shown in Figures 2-1 through 2-9.

One Example of a Low-Cost Collector Design Produces Thermal Power at a Cost of $\$76/kW_t$.

The dimensions and properties for one example of a minimum-cost paraboloidal collector design are tabulated in Table 2-1. This collector is the lowest-cost, high performance design for a singly-mounted paraboloidal concentrator with a pancake absorber, heating pressurized water from 150 °C to 202 °C at a flow rate of 0.08 kg/sec. The concentrator used in this example was selected from more than 300 paraboloidal designs, each of which was the lowest cost concentrator but for different performance characteristics.

Dynamic Simulations were used to Determine the Variations of Electric Energy Produced at Different Locations

Two optimal distributed systems were simulated dynamically to determine the temporal and spatial variations of electric energy production. Variations in solar radiation and operational environment were taken into account in the dynamic simulations.

The solar power plants are analyzed sequentially by subsystems beginning with the concentrator. Discussion of results are arranged to follow the sequential analysis.

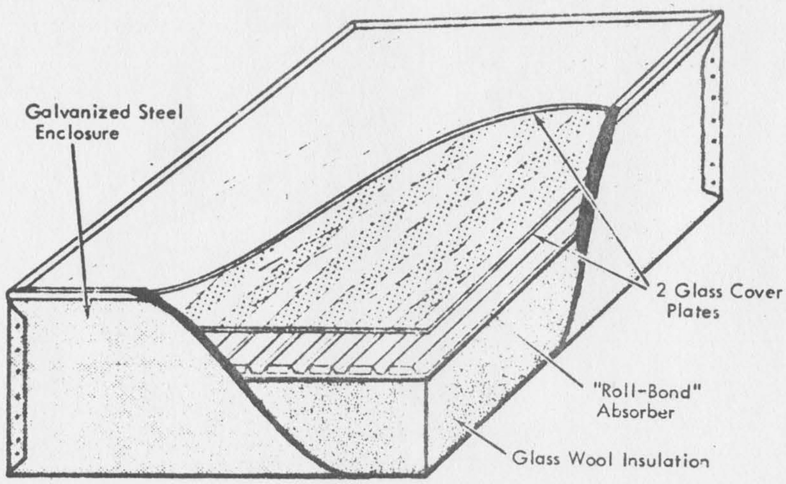

Figure 2-1. Flat-Plate Collector with Two Glass Cover Plates.

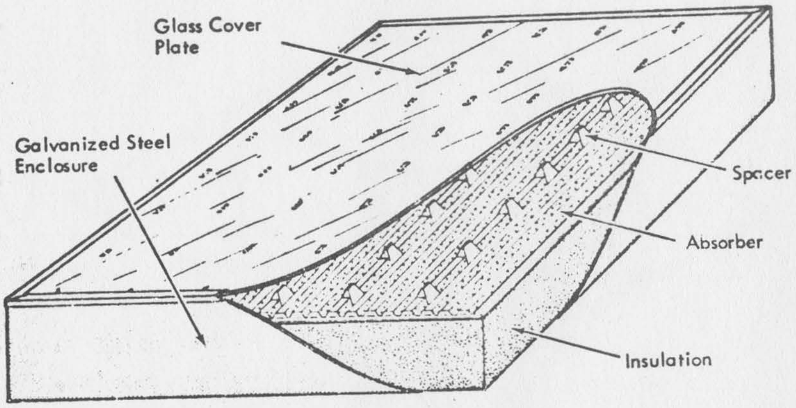

Figure 2-2. Evacuated Flat-Plate Collector with One Glass Cover Plate.

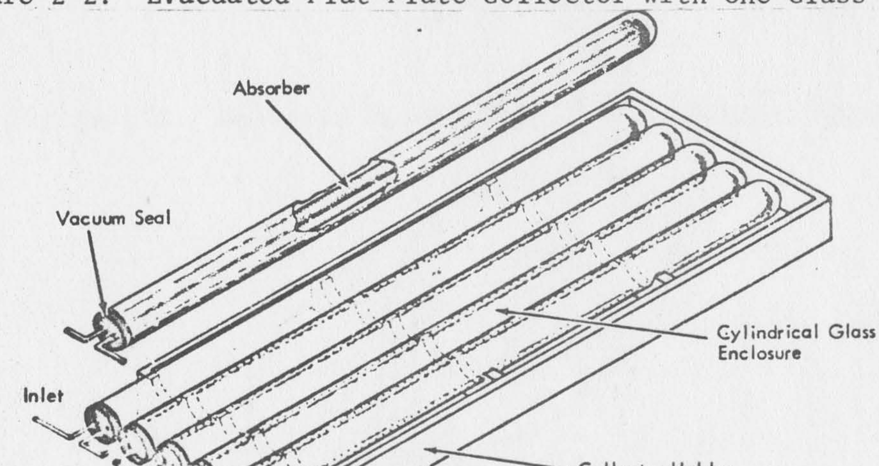

Figure 2-3. Flat-Plate Collector with Evacuated Glass Tubes.

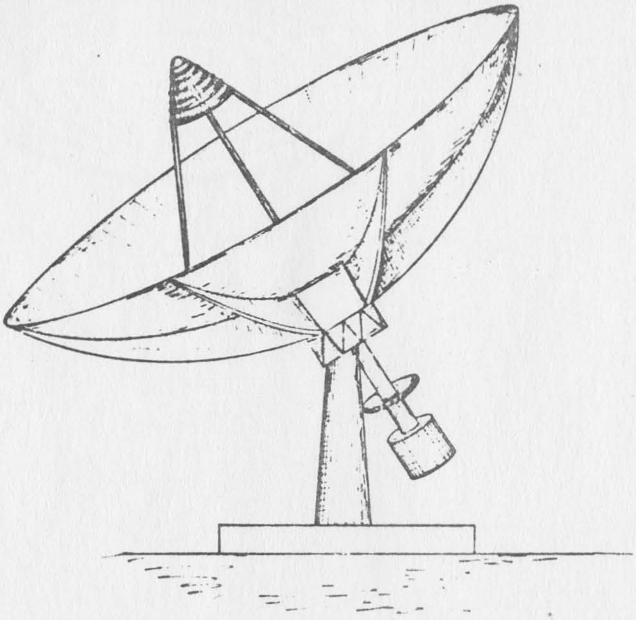

Figure 2-4. Paraboloid with Cavity Absorber.

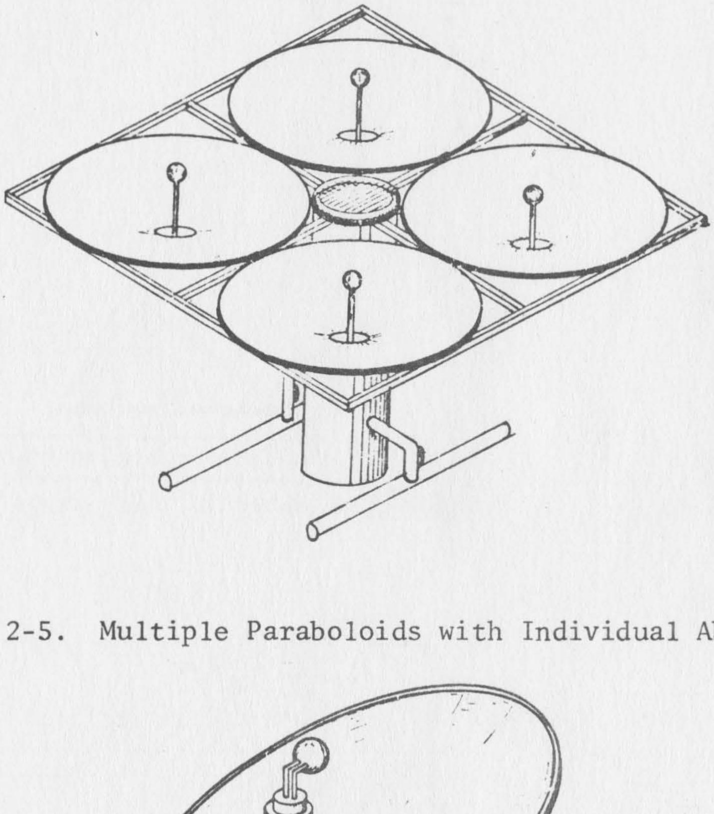

Figure 2-5. Multiple Paraboloids with Individual Absorbers.

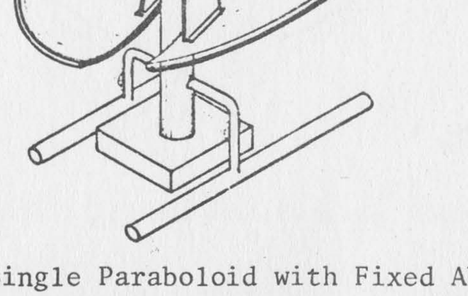

Figure 2-6. Single Paraboloid with Fixed Absorber.

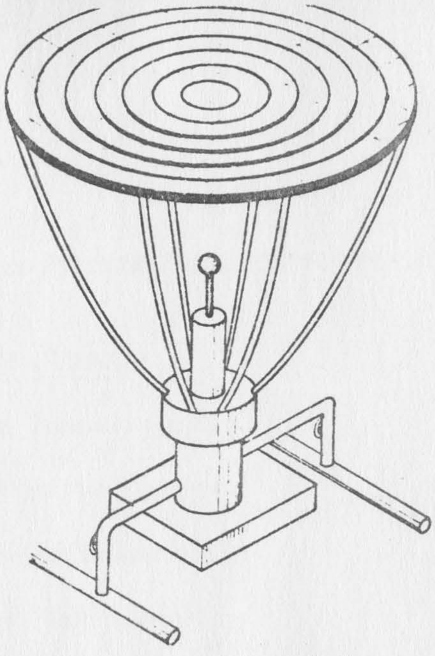

Figure 2-7. Fresnel Lens

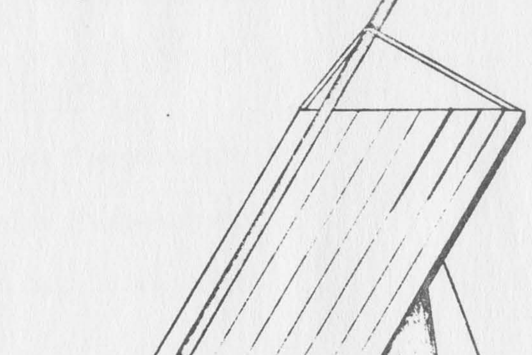

Figure 2-8. Fresnel Reflector

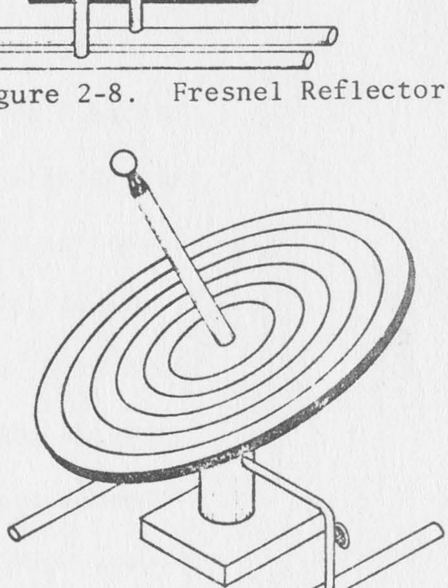

Figure 2-9. Cylindrical Fresnel Reflector

Table 2-1

Example Minimum-Cost Paraboloidal Collector Design

ENVIRONMENTAL CONDITIONS			
Ambient Temperature:	T_{amb}	=	40 ^oC
Average Wind Velocity:	V_a	=	5 m/s
Maximum Wind Velocity:	V_m	=	60 m/s
Sky Temperature:	T_s	=	15 ^oC
Insolation:	I_D	=	1000 W/m^2
OPERATING CONDITIONS			
Fluid Outlet Temperature:	T_o	=	202 ^oC
Fluid Inlet Temperature:	T_{in}	=	150 ^oC
Mass Flow Rate:	$\dot{m}$	=	0.08 kg/s
OPTIMUM DESIGN PARAMETERS			
Maximum Rim Angle:	θ_m	=	75^o
Aperture Area:	A_p	=	24.2 m^2
Aperture Diameter:	D_{Ap}	=	5.55 m
Reflectivity:	ρ_{ave}	=	0.85
Focal Length:	f	=	1.81 m
Contour and Pointing Accuracy:	$\sigma_{\phi,\lambda,\delta}$	=	0.255 degrees
Irradiated Area:	A_L	=	0.0224 m^2
Absorptivity:	α	=	0.9
Pipe Diameter:	d	=	1.9 cm
Pipe Length:	L	=	1.18 m
PERFORMANCE CHARACTERISTICS			
Effective Aperture:	$\mathcal{E}$	=	20.59 m^2
Radiation Spread:	g	=	44.85 cm^2

Table 2-1
Continued

Efficiency:	η_c	= 0.75
Geometric Concentration Ratio:	A_p/A_L	= 1080
Thermal Power Out:	P_o	= 18.2 kW

COST ESTIMATES

Absorber Cost:	\$ 19
Concentrator Cost:	\$1361
Total Collector Cost:	\$1380
Cost/Unit Aperture Area:	\$ 58/m^2
Cost/Thermal Power Out:	\$ 76/kW_t

3.0 RESULTS

Concentrator Parameters are Effective Aperture and Spread of Radiation on the Target Surface

The performance parameters for concentrators of all types are characterized by effective aperture, E, and spread of radiation, g, on the target surface. Effective aperture is the product of aperture area, A_p, and average surface reflectivity, ρ_{ave}. The parameter g, is affected by the geometric smoothness of the reflector surface, accuracy of tracking, and accuracy of reflector form.

The diameter of individually-mounted paraboloids is limited to 7.3 metres because of manufacturing methods, standard material sizes and transportation limitations. It is recognized that wind loading could substantially affect the structural support needed to resist forces, particularly vibrations, for satisfactory operation of large concentrators in medium to high winds. However, in this study, performance of concentrators is considered in winds with speeds only to 5 m/sec, structural designs are made for wind speeds up to 70 m/sec, but it is assumed that the power plant will not be operational when wind speeds affect performance.

Factory-Built Concentrators are Less Expensive than field Units Constructed

Field construction or assembly of very large size collectors by segments is more expensive in comparison to complete factory assembly of units. The costs are not greatly affected by combined contour shape and pointing errors in the range from 0.14 to 2 degrees. Concentrators with more accurate surface shapes and tracking capabilities are expensive. While there is a decrease in spread of radiation (ultimately resulting in an increase of temperature at which heat is generated), with concentrators that are accurately constructed, the effect is insufficient to off-set the increased costs to obtain increased performance. The rim angles for the minimum-cost paraboloids are between 60 and 75 degrees. The larger rim angles are more appropriate for larger aperture paraboloids.

Modular small paraboloids mounted on a common rack with individual absorbers are much greater in cost per unit of effective aperture area than the larger individually-mounted paraboloids. Rack-mounted paraboloidal reflectors focused on to a common target are reasonably competitive in costs with individually mounted paraboloids, in the effective aperture size range from 5 to 20 m^2.

Fresnel Reflector Concentrators are Found to be Lowest in Costs

The circular Fresnel reflector has the lowest installed capital cost among point-focus concentrators with comparable performance. Fresnel grooves pressed into front silvered plastic and backed by a light wood frame is a reasonable reflector design. Comparisons of minimum capital costs for rack-mounted paraboloids, individual paraboloids, Fresnel lenses and Fresnel reflectors are shown in Figure 3-1.

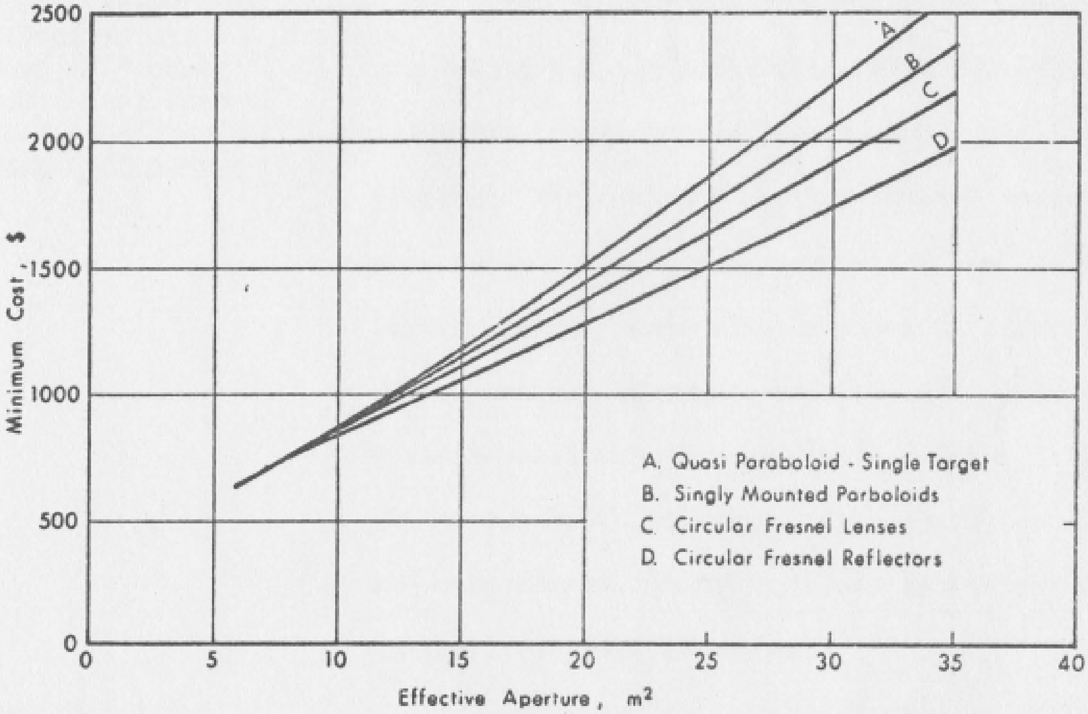

Figure 3-1. Comparison of Minimum Costs for Four Types of Point-Focusing Concentrators.

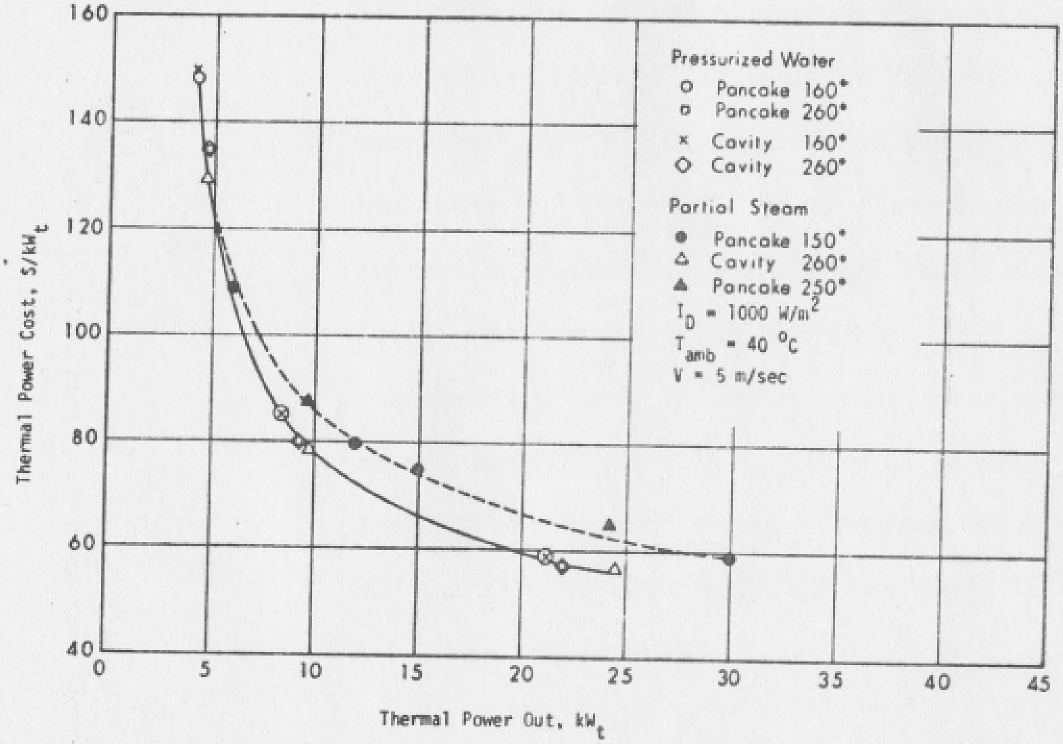

Figure 3-2. Minimum Cost of Heat from Fresnel Reflector Collectors with Various Absorber Types and Fluid Temperatures.

Fresnel Reflecting Collectors are Found to Produce Lowest Cost Thermal Power of All Point-Focus Collectors

The thermal power costs at the collector are lowest for the point-focus Fresnel reflecting collector, for both pressurized water and steam systems. The cost per unit of thermal power from point-focus Fresnel reflectors reduces with increasing collector size as shown in Figure 3-2. With a pancake absorber, unit thermal power cost from the collector for pressurized water is less than for steam. However, with a cavity absorber, the unit thermal power costs are the same for pressurized water and steam.

Tower/Heliostat Systems have Lowest Thermal Power Costs for Plant Size of about 200 MW_t.

Collector systems consisting of heliostats and tower-mounted absorbers were included in the optimization study. These systems have potential advantages in reduced thermal transport costs for larger plants. Systems with flat heliostats were designed in a circular field surrounding the tower. Unit thermal power costs for these systems increase with increasing fluid temperature because with non-focused heliostats the losses are greater at the absorber for mirrors at the edge of the field. Costs of thermal power in the form of steam at temperatures of 150, 200 and 250 degrees centigrade are shown in Figure 3-3.

Cylindrical Fresnel Reflecting Collector is Found to Produce Minimum-Cost for Thermal Power Among Line-Focus Collectors

Among the line-focus collectors considered, the cylindrical Fresnel reflector collector is a candidate subsystem for a solar power plant. There is no particular cost advantage for different collector fluid temperatures, nor for collectors with evacuated glass envelopes around the absorber as compared to non-evacuated absorbers. The advantage in heat gained by absorbers with evacuated glass envelopes are off-set by greater costs as compared to non-evacuated envelopes. The costs of thermal power from cylindrical Fresnel reflector collectors are shown in Figure 3-4.

Non-Focus Collectors are not Candidates for Solar Power Systems

The installed costs per unit of thermal power from flat-plate collectors are only slightly lower than costs of focusing collectors. Thus, with low fluid temperatures for flat-plate collectors, the overall plant efficiency is low making the cost of electricity produced greater with flat-plate collectors than with focusing collectors

General Conclusions from Collector Analysis

General Results from collector analysis are as follows:

(a) The costs of thermal power from concentrating collectors are insensitive to fluid temperature over the range considered.

(b) The cost of thermal power decreases as aperture area increases over the range examined.

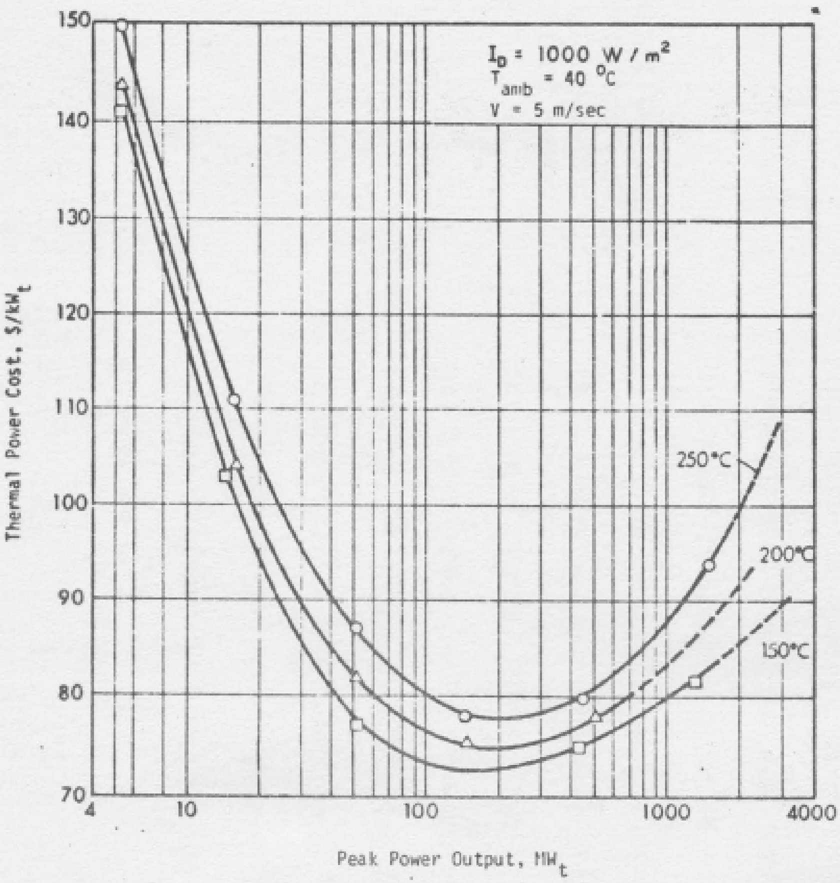

Figure 3-3. Cost of Thermal Power from Tower-Heliostat Collectors for Various Sizes and Operating Temperatures.

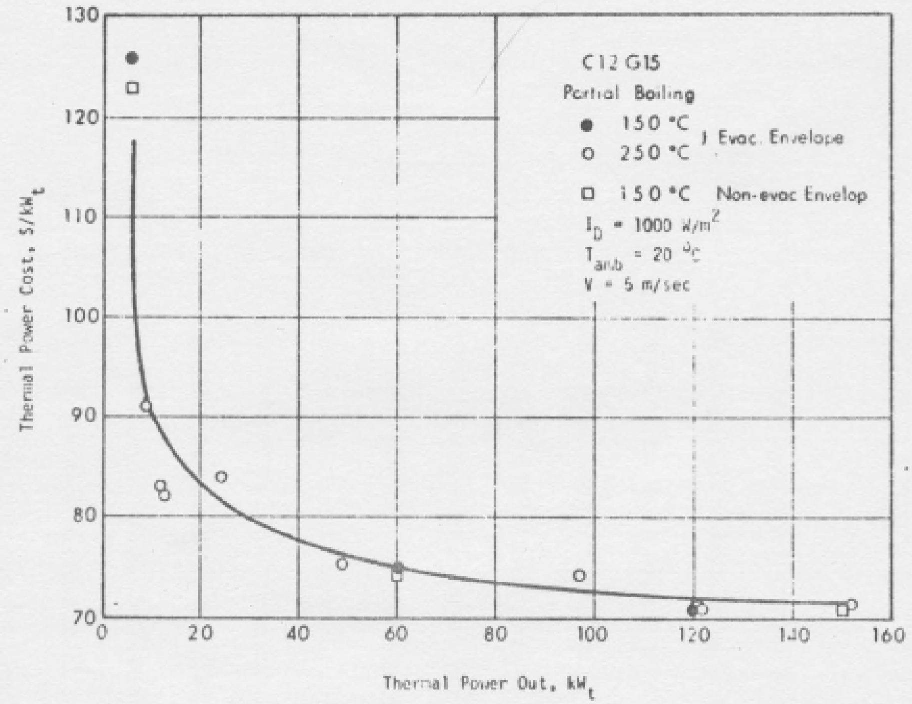

Figure 3-4. Cost of Thermal Power from Selected Line-Focusing Fresnel Reflector Collectors.

(c) Collectors with absorber boilers, in size range considered, should be connected in series to maintain high mass flow rates and high efficiencies.

(d) The differences in cost of thermal power delivered from various types of absorbers in concentrating point-focus collectors are small. For line-focus collectors, the cylindrical absorber has an advantage over a flat absorber.

(e) Circular Fresnel reflector collectors yielded lowest thermal power costs among the concentrating collectors considered.

The costs for thermal power from the lowest-cost point-focus, line-focus and non-focus collectors are shown in the bar chart of Figure 3-5.

Fresnel Reflector Collectors Deliver Heat to Central Plant at Lowest Cost.

Fresnel reflector collectors, arranged in a square field with steam transport, delivered heat to a central power plant at lowest cost per unit of thermal power. The thermal power costs from the distributed collector field, as shown in Figure 3-6, is a function of fluid temperature. The costs increase with increasing fluid temperature, because of higher insulation, piping, pumping, and control costs.

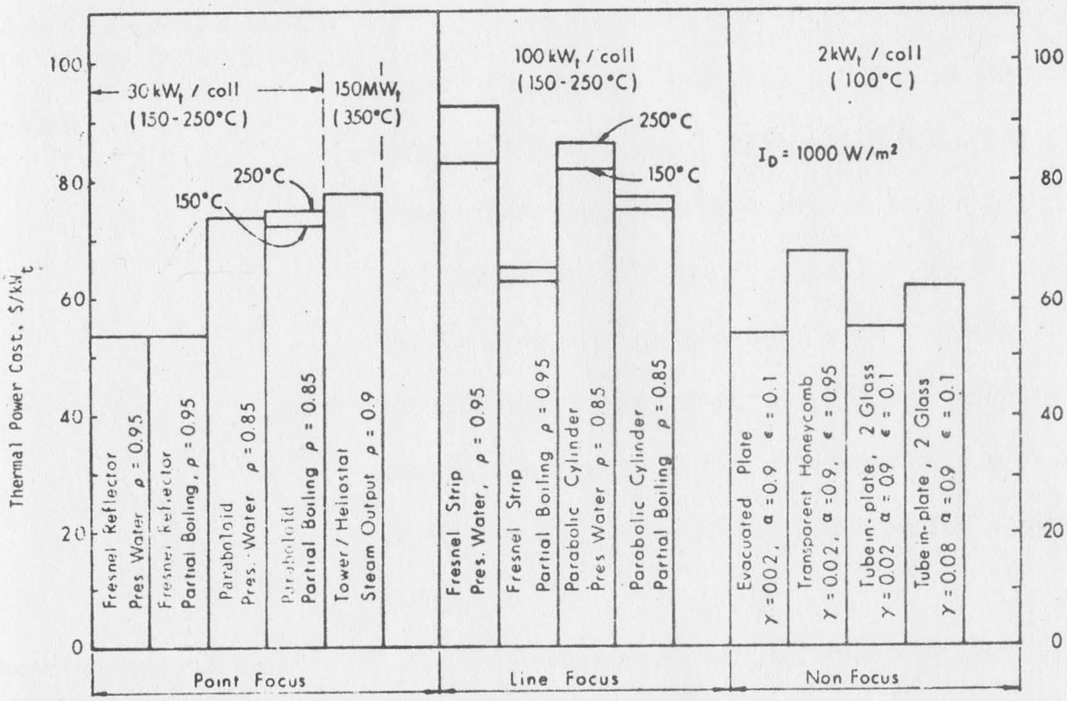

Figure 3-5. Comparison Between Low-Cost Collector Subsystems. (Clean Surfaces.)

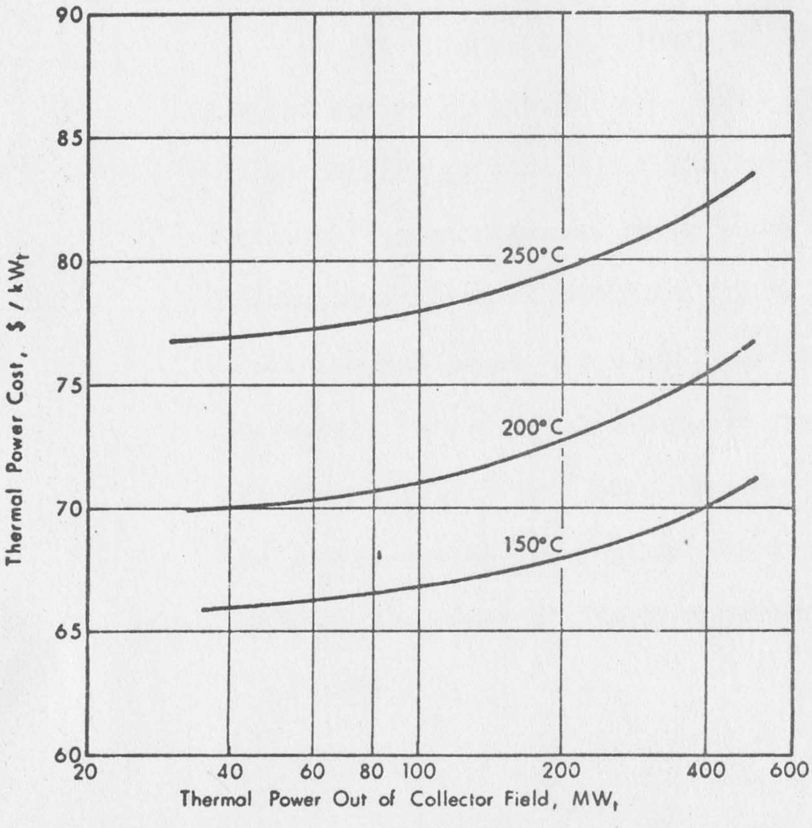

Figure 3-6. Cost of Thermal Power from Distributed Collector Field, Delivering Steam.

Steam Transport systems have Lower Costs than Water Transport Systems

Comparisons of pressurized water and steam systems at fixed fluid temperatures and various thermal power capacities indicate that steam systems are lower in costs per unit of thermal power than pressurized water systems. The systems, in this comparison, include the collectors, piping, insulation, pumping and control costs. The differences are evident in Figure 3-7 for fluid temperatures of 200 and 250 ^{o}C.

Tower/Heliostat and Distributed Field Systems have Low-Cost Thermal Power in Different Plant Size Ranges

Comparisons of unit thermal power costs at 150, 200 and 250 ^{o}C from tower/heliostat and distributed collector systems are shown in Figure 3-8 for a wide range of plant sizes.

At a fixed temperature of 150 ^{o}C, distributed collector systems are less expensive than tower heliostat systems in the range considered. At 200 ^{o}C, unit thermal power costs are approximately equal at a plant capacity of 325 MW_t, and at 250 ^{o}C unit thermal power costs are equal at about 125 MW_t capacity. These results suggest that a choice between a distributed collector and a tower/heliostat system for a given plant size may be made on the basis of fluid temperature as indicated in Figure 3-9.

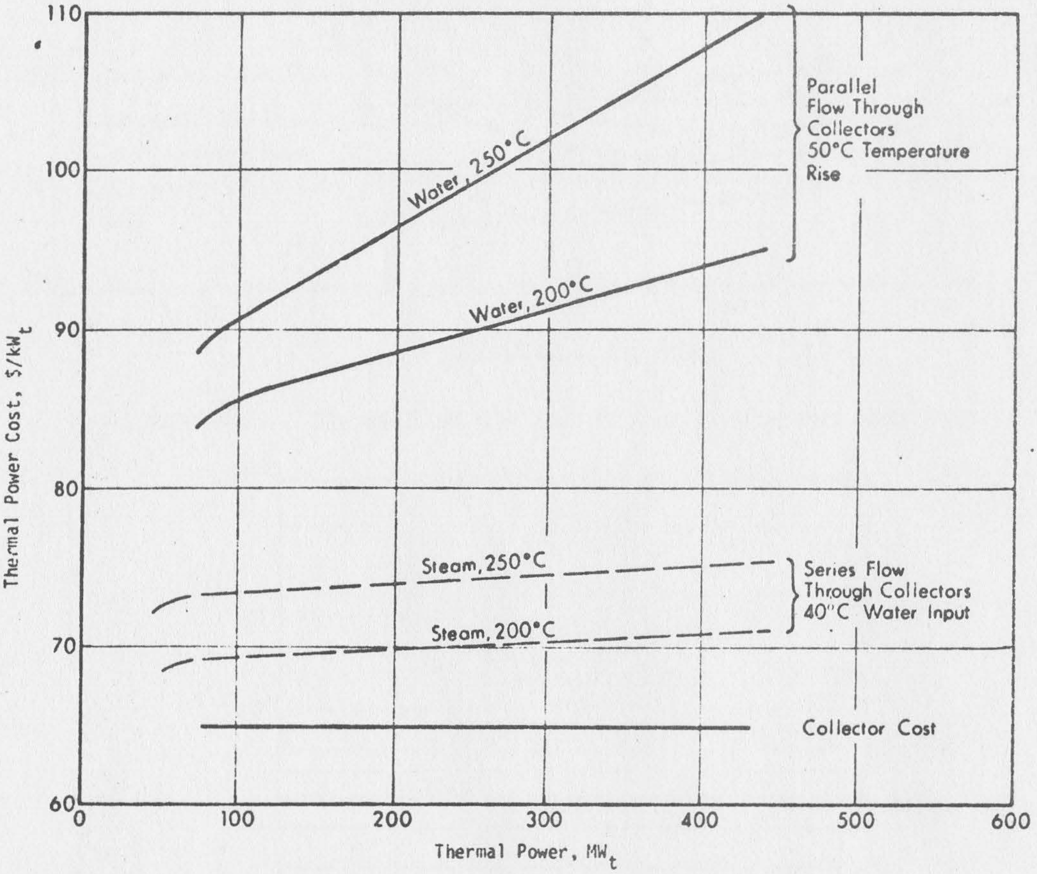

Figure 3-7. Comparison of Cost of Thermal Power from Distributed Collector Field.

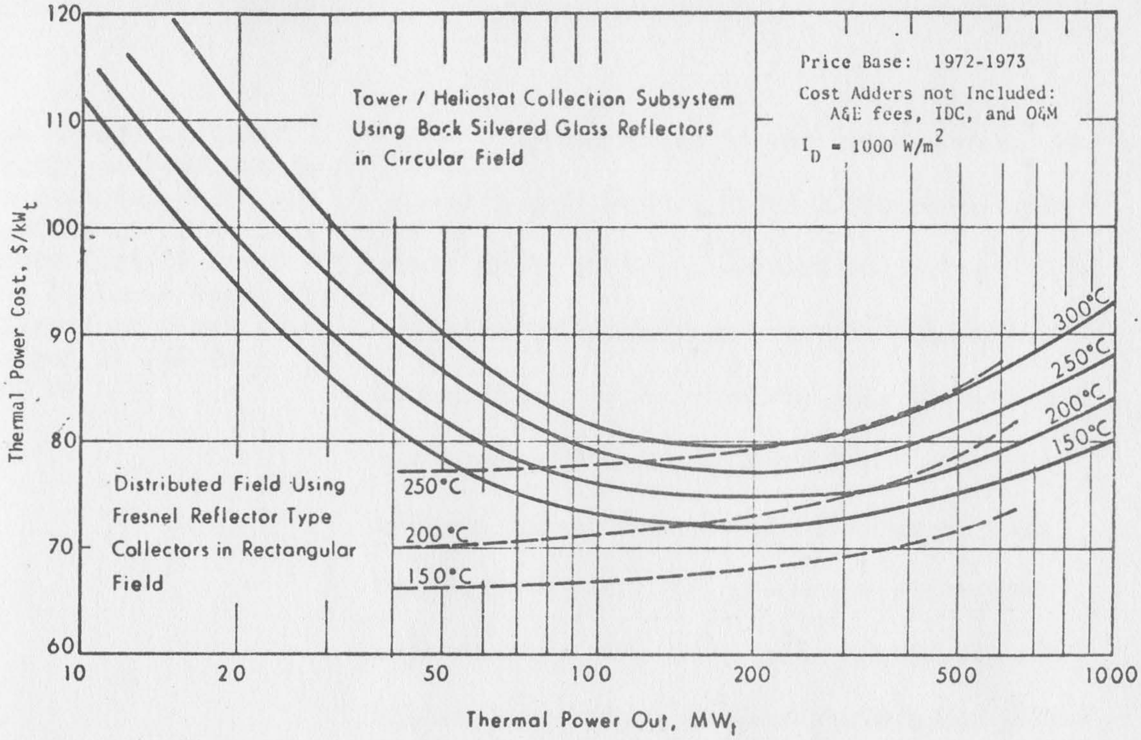

Figure 3-8. Thermal Power Costs for Collector Subsystems.

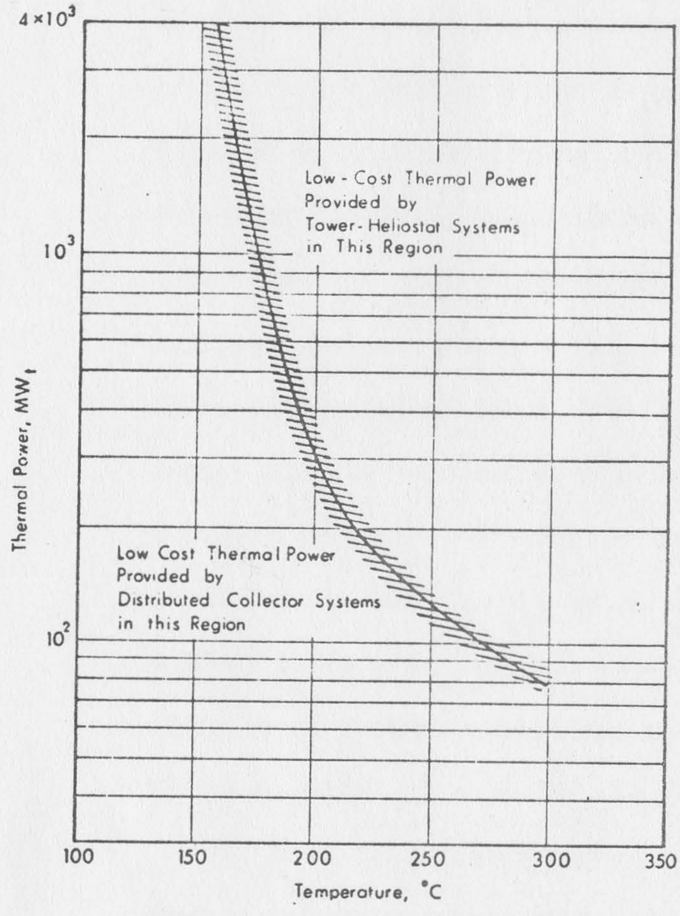

Figure 3-9. Thermal Power and Saturated Steam Temperature Range for Selection Between Distributed Collector Systems and Tower-Heliostat Systems for Lowest Cost Thermal Power.

Least-Cost Electric Energy is Produced by Distributed Collector Systems in Plant Size Range from 20 to 60 MW_e, and by Tower/Heliostat Systems in Plant Size Ranges of 100 to 300 MW_e

Optimization of the solar thermal electric plants for different fluid temperatures and power plant sizes, and based on a statistical distribution of direct solar insolation at Albuquerque, N. M., for the year 1959, produced the results shown in Figure 3-10. There is a broad range of power plant sizes at each temperature which can produce minimum-cost electricity. For the range considered, the higher temperature systems yield lower-electric energy costs because of greater turbine efficiencies at the higher temperatures. The costs of electric energy produced by a distributed field of point-focus Fresnel reflecting collectors for saturated steam temperautres of 150 ^{o}C is lower than the cost of electricity from tower/heliostat systems for the same fluid temperature. For a steam temperature of 200 ^{o}C, electric energy cost is the same from either system for a power plant size of about 60 MW_e. For plant sizes larger than 60 MW_e, tower/heliostat systems produce lower cost electric energy than distributed systems, while the converse is true for power plant sizes which are smaller than 60 MW_e.

At a steam temperature of 250 ^{o}C, the cost of electric energy produced by the two types of systems are about equal for a plant size of about 40 MW_e. These results are for Albuquerque, N. M. for the year 1959.

The electric energy costs shown in Figure 3-10 must be increased by an appropriate cost adder for architect and engineering fees (A&E), interest during construction (IDC) and operation and maintenance (O&M) costs if a comparison is to be made with the preliminary design phase cost estimates in Figure 1-8. If the amortization rate is reduced from the rate used ($0.16/yr-$) because of lower interest rates, lower taxes, or larger plant life, the cost of solar electrical energy will be reduced.

The component costs of a solar power plant consisting of point-focus Fresnel reflector collectors and a power plant consisting of heliostats and a tower are shown in Figure 3-11. The radiation collection and heat conversion subsystems, that is, the collectors in the one case and the towers, absorbers and heliostats in the other, dominate the system costs. Reductions in electric energy costs will be achieved by corresponding reductions in capital costs for the collection subsystems.

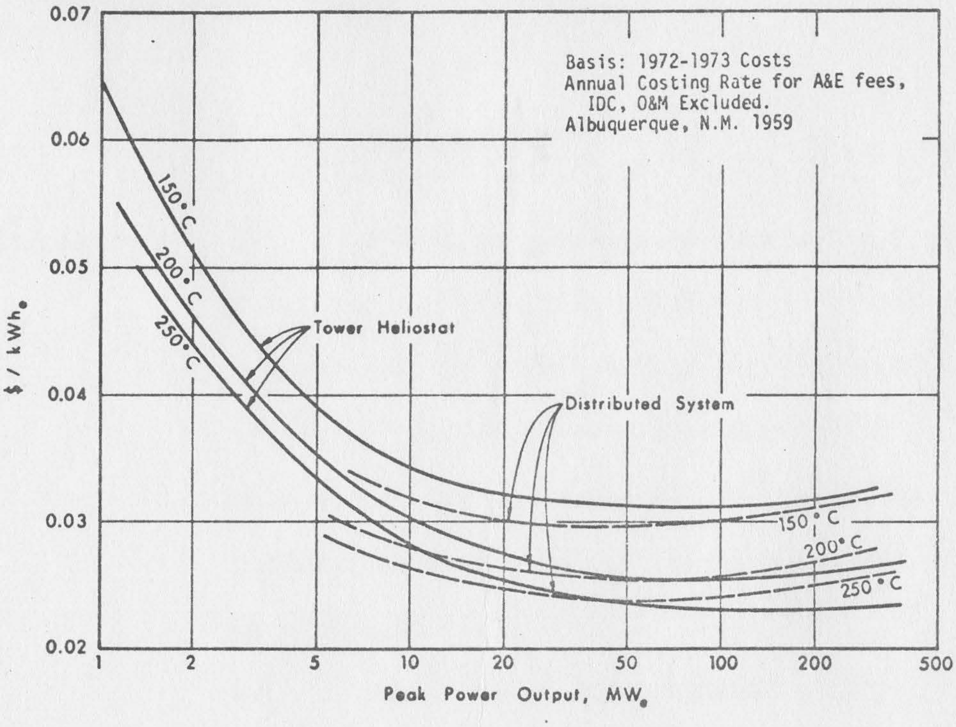

Figure 3-10. Impact of Plant Size and Operating Temperature on Cost of Electrical Energy for Two Basic System Configurations.

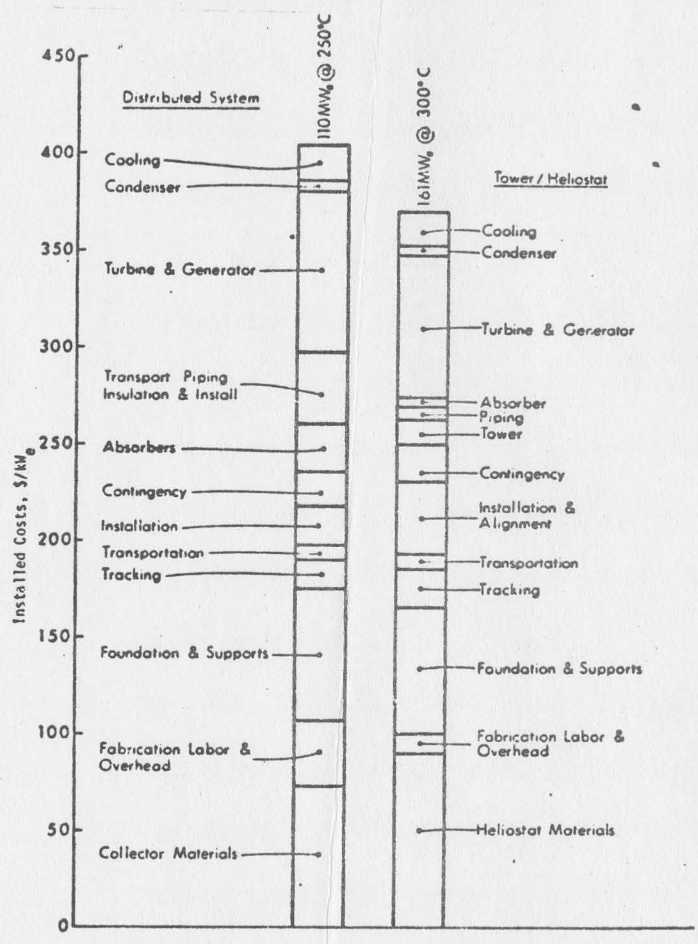

Figure 3-11. Component Cost Breakdown for Distributed and Tower Heliostat Systems.

4.0 CONCLUSIONS

Principal Conclusions

A general optimization methodology was developed for selecting, analyzing and comparing key elements of solar thermal electric power systems. Performance and cost models for subsystems were developed and the impact on performance and costs was examined as designs were changed.

- Two types of solar thermal electric power systems are found to have the potential to produce electricty at costs competitive with present conventional systems. Both distributed collector and tower/heliostat systems should be able to produce electricity at costs between 2 and 3 cents per kWh_e (on 1972-73 price base) in a wide range of plant sizes with saturated steam temperatures between 200 and 250 ^oC. The estimated electricity costs include only capital costs. Cost adders for interest during construction, architectural and engineering fees, operation and maintenance should increase the electricity cost from 20 to 50 percent.

- There is only about 10 percent difference in electric energy costs between the two systems in plant sizes ranging from 20 to 300 MW_e. For plant sizes less than about 50 MW_e, distributed collector plants have a small cost advantage. For plant sizes greater than 50 MW_e, tower/heliostat systems have a cost advantage.

- The flat-plate collector systems examined yielded high costs of electrical energy resulting from low temperatures and high collector costs. The low overall conversion efficiency for solar power plants using flat-plate collectors could only be compensated by very low-cost collectors.

- Point-focusing collectors are better choices than line-focusing collectors for solar power plants. The losses of radiation at the reflector and of heat at the absorber make line-focusing collectors less cost effective than point-focusing systems.

- Individual collectors and heliostats should be designed for the largest practical sizes that can be manufactured and transported as completed units. Even if transportation limitations can be overcome by on-site portable factories, wind loads and other structural problems will limit larger collector sizes.

- A 7-meter diameter Fresnel reflecting collector is identified as having the best potential on the basis of performance and estimated costs, for consideration in a distributed collector system. Other collectors, such as paraboloids and Fresnel lenses, are within 20 percent of the estimated costs of Fresnel reflectors and should also be considered candidates for use in solar plants.

Supplementary Conclusions

There are several conclusions resulting from the project which are supplementary to those concerning performance and costs of specific systems. These findings are the results of analysis in the early months of the project; conclusions which have been adopted by and incorporated into the programs undertaken by other investigators of solar thermal power systems.

- An important contribution of this work is the concept of a solar power plant in a network rather than as a separate facility with some sort of auxiliary, on-site power capability or very large solar energy storage.

- While heat storage for several days or even for one day of plant operation is presently out of economic reach, there is an advantage in short-term storage for a few hours for the purposes of (a) smoothing the power output during passage of occasional clouds, (b) reduction in size and cost of turbogenerator and associated equipment without reducing total daily output, and (c) providing for equipment operation at full capacity and efficiency for longer periods than would be possible with no storage. These conclusions led to the adoption of steam storage, in the form of pressurized hot water and steam, as a practical and economical solution.

- A stimulus to consideration of more than one or two types of solar power plants was provided to others by the early indications in this project that paraboloidal reflectors are in a position competitive with other types of systems. These findings have provided a basis for other groups to consider these systems in their work.

- The procedure for obtaining cost estimates, by methods used in pre-construction cost estimating for commercial products, is another significant step. The costs thus obtained are believed to be the most dependable yet available.

- The optimization procedure coupled with performance analysis and manufacturing costs provide a basis for examining economic and performance interrelationships. The methods permit quantitative evaluation of the trade-offs between performance and cost. Choice between expensive, efficient plants and low cost, inefficient plants can thus be soundly made.

- Consideration of small, central station plants has also been introduced in this study. A hitherto common belief among many investigators that solar plants should be as large as fossil fuel or nuclear plants has been dispelled in this investigation. The costs of transport of heat or radiant energy in the solar plant itself limit the economic size. Solar power plants of 20 to 300 megawatts have thus been found to have significant potential.

- The process of analysis developed in this program permits the comparison of alternate systems and designs on a completely uniform basis. Comparison of one type of plant with another can thus be made without inbuilt error or bias.

5.0 RECOMMENDATIONS

Two types of solar power plants have been identified as having greatest potential for production of electrical energy at least cost. However, before proceeding with plans for design and construction of pilot solar power plants it is recommended that the following be included in the National Solar Energy Program.

The optimization Study should be Expanded to Include Other System Concepts

- Continue the optimization study to expand the scope of solar power systems, particularly toward high temperature systems, but also to include low temperature systems with alternative heat engines. The procedures developed in this study should be used to investigate capital cost improvements for components of candidate solar power plants and methods for energy cost reductions. These recommendations have been further detailed in a proposal which was submitted to the Energy Research and Development Administration

Experimental Research and Development Program Should be Undertaken for Candidate Collectors and Heliostat Absorber Systems

- Initiate an experimental research and development program to develop highest efficiency, least-cost collectors and heliostat/absorber subsystems. Collectors and heliostats with tower mounted absorbers constitute the major portion of total plant costs. Therefore, these subsystems should receive emphasis in the research and development program. Research on materials, both for the reflectors and absorbers is needed.

The experimental program is needed to develop manufacturing methods to achieve low-cost, mass production of collectors and heliostats, consistent with high optical performance. Emphasis on manufacture of long-life, high-reflectivity surfaces is needed, and test modules should be fabricated and subjected to environmental conditions to determine performance at selected sites with normal cloudy conditions and wind loads.

Control Strategies for Solar Power Plants Need to be Developed

- Control strategies for operating solar power plants to provide reliable generation of electric energy need to be developed. Cloud shadows on the collector or heliostat fields require control of heat flow alternatively from collectors and storage to prevent undesirable load fluctuations on the turbine-generators and the electric network. The strategy of controls in the field, of controls or designs for unequal heating of tower mounted absorbers, of efficient and effective heat storage discharge is needed.

Methodology and Results of this Project can be Applied to Solar Energy Conversion for Process Heat Uses

- The methodology developed in this study and the results obtained from detailed evaluations of radiation concentration and heat generation subsystems should be applied to studies of the uses of solar energy to generate process heat in the forms of pressurized water and steam for use by industry.