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Comparative Ranking of 1-10 MW$_e$ Solar Thermal Electric Power Systems

An Executive Overview

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COMPARATIVE RANKING OF 1-10MW$_E$ SOLAR THERMAL ELECTRIC POWER SYSTEMS: AN EXECUTIVE OVERVIEW

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SEPTEMBER 1979

PREPARED UNDER TASK NO. 3526

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FOREWORD

The Small Solar Thermal Power System Program, one of several application-oriented programs sponsored by the Thermal Power Systems Branch, Division of Central Solar Technology of the Department of Energy, has been initiated to explore the technical, economic, and institutional feasibility of providing remote load centers, small communities, rural areas, and industrial users with supplementary energy sources. The specific objective of the Small Solar Thermal Power System Program is to establish the technical readiness of cost-competitive solar thermal power systems. A Small Communities Application project has been established to support the program. Jet Propulsion Laboratory (JPL) in Pasadena, California, has been delegated responsibility both for technical management of the small communities project and for development of experimental systems which achieve the goals of the program.

To identify the most likely options for long-term commercialization of small solar thermal electric power systems, a comparative analysis of the major generic solar thermal electric systems was requested by the Department of Energy. The Small Solar Thermal Electric Power Systems Study was initiated in April 1978 as parallel efforts at both SERI and Battelle Pacific Northwest Laboratories.

The main objective of the Small Solar Thermal Electric Power Systems Study is to project the mid-1990 cost and performance of selected generic solar thermal electric power systems for utility applications and to rank these systems using a set of seven criteria which reflect the most important aspects of their future commercial acceptability. The study considers plants with rated capacities of 0.1 to 10 MW_e, operating over a range of capacity factors from the no storage case to 0.7 and above.

The study is composed of three phases. The first, completed in October 1978, involved the selection of generic systems and their variations, the establishment of ground rules, the selection of a simulation technique for projecting future cost and performance, and the definition of a suitable ranking methodology. A report summarizing the selections of the generic systems and the study approach was released in July 1978 [1]. Systems of from 1.0 to 10 MW_e rated capacity were examined during the second phase. The last phase, to be completed by October 1979, considers smaller systems with rated capacities of 0.1 to 1.0 MW_e.

The conclusions of the study are to be released to the Department of Energy in a series of reports between July and October 1979. A summary of the ranking of 1.0 to 10.0 MW_e systems is included in this first volume. The second summary volume, covering the ranking of 0.1 to 1.0 MW_e systems, will be released in October 1979. Supporting data volumes containing extensive discussions of the generic system designs, the methodology, and the results and conclusions will also be released at that time.

Many people within SERI contributed to the gathering of data, site visits, and design reviews. They are listed in Appendix F. In particular, the authors would like to thank Stephen Cronin, Louise Morrison, and Doug Madison for their invaluable assistance in development of the system simulation computer codes and James Gresham for his assistance in the rankings.

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Systems Analysis Branch

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SECTION 1.0

CONCLUSIONS AND RECOMMENDATIONS

The objective of this phase of the Small Solar Thermal Electric Power Systems study was to respond, in a clear and definitive manner, to the question:

> What is the most appropriate long-term ranking of solar thermal technologies for small electric power utility applications in the 1.0 MW_e to 10.0 MW_e range?

The solar thermal technologies considered form a complete set of viable system options, and the criteria upon which the ranking judgment was based represents a careful and deliberate treatment of the concerns of interested parties. The purpose of this section is to present the conclusions reached in the study and to answer the preceding question.

The suitability of any ranking depends upon the individual or class of individuals selected as representative decision makers. Application of small solar thermal electric power systems may be possible in small communities, electric utilities of many sizes, isolated facilities of military bases, industry, agriculture, and many types of rural and undeveloped areas. In addition, nonusers with significant interests and influence will affect the development of these options, such as federal and state agencies, researchers, engineers, and public interest groups. SERI specifically incorporated the opinions of two groups of decision makers: (1) the electric utility industry and the consultants and regulators auxiliary to this industry; and (2) the research and development community, both technical and nontechnical. The conclusions that follow represent these points of view.

Based on technical, economic, social, and commercial critiera SERI finds that the most appropriate long-term ranking of solar thermal electric power systems (from Table 4-3) is:

Group I
- **Point focus central receiver with Rankine power conversion (PFCR/R)**
- **Parabolic dish collectors with distributed Stirling engines (PFDR/S)**

Group II
- **Parabolic dish collectors with central Rankine power conversion (PFDR/CR)**
- **Parabolic dish collectors with distributed Brayton engines (PFDR/B)**
- **Point focus central receiver with Brayton power conversion (PFCR/B)**
- **Parabolic trough system (LFDR-TC)**
- **Low concentration, nontracking CPC system (LCNT)**

Group III
- **Line focus central receiver system (LFCR)**
- **Fixed mirror, distributed focus bowl system (FMDF)**
- **Segmented trough with tracking receiver system (LFDR-TR)**
- **Shallow solar pond system (SSP)**

The systems are listed in rank order within each group. Two system concepts (Group I) rank significantly higher than the other systems and are the most appropriate options for development. The point focus central receiver system (PFCR/R) represents a technology with proven development history and superior performance at high capacity factors. A close second to the PFCR/R system is the distributed electric generation system using dish-mounted Stirling engine generators (PFDR/S). This system offers comparable capital and energy costs to the central receiver and occasionally ranks higher than the central receiver at low power ratings and capacity factors. Since it has received relatively less development than the central receiver, there is a greater perceived risk and uncertainty for the dish/Stirling concept. Despite this risk, the concept has excellent potential.

Five systems (Group II) achieve acceptable rankings over a broad middle range. Parabolic dish collector technology is represented twice (PFDR/CR and PFDR/B), indicating the continued viability of that collector technology. In particular, parabolic dish systems with central Rankine engine power conversion show costs and performance approaching Group I systems at capacity factors just under 0.7. Two Brayton cycle systems (PFDR/B and PFCR/B) show potential, but are subject to uncertainty and risk, and never rank higher than Rankine or Stirling cycle conversion options with identical collector technologies. Finally, parabolic trough (LFDR-TC) and compound parabolic concentrator (LCNT) systems, which operate at lower temperatures, show some potential for small power system applications but in general do not rank very high. Both of these concepts are strong contenders in other market applications such as process heat. In fact, the commercial and environmental advantages of the LCNT were so strong that it was the only concept to be significantly affected by those qualitative criteria in this ranking.

The four remaining systems (Group III) are not appropriate for small electric power applications. While other market applications may be suitable for certain systems (such as low temperature IPH from solar ponds), these systems fared poorly on important cost and/or performance criteria when considered for electric applications.

The two top-ranked systems (PFCR/R and PFDR/S) can yield busbar energy costs that are competitive with expected costs of electrical energy from conventional alternatives in the 1990s. Levelized busbar energy costs as low as 93 mills/kWh are predicted for both the PFDR/S (capacity factor < 0.4) and the PFCR/R (capacity factor > 0.7) systems.

Sensitivity studies suggest that if concentrator costs are reduced and engine efficiency increased to the levels believed possible by some, busbar energy costs as low as 75 mills/kWh could be achieved. These concentrator and engine developments are beyond those considered likely by 1990 in the baseline study and would require vigorous component and system development. Considering government incentives such as highly leveraged low-interest (6%) financing, busbar energy costs could be lowered to 50 mills/kWh.

In addition to low busbar energy costs, user groups have indicated a strong preference for low capital costs. Because utility industry capital markets are under unprecedented pressure to support capacity expansions, it is critical that solar thermal power systems not exceed acceptable levels of capital cost while providing low busbar energy costs.

Based on the conclusions of this study, the following recommendations are made:

- Vigorous subsystems and systems development should be pursued for the point focus central receiver system with Rankine power conversion (PFCR/R) and parabolic dish collector system with distributed Stirling engines (PFDR/S).
- Parabolic dish collector technology should be given high priority in solar component development.

- A limited research and development effort should be directed toward the improvement of subsystems and systems for PFDR/CR, PFDR/B, and PFCR/B concepts.
- The LFDR-TC and LCNT concepts should be actively encouraged for development in other applications and close attention paid to developments that would enhance their suitability for small electric power applications.
- Group III systems (LFCR, FMDF, LFDR-TR, and SSP) should not be included in the small solar electric power systems program.
- It is imperative to pay close attention to the requirements of user markets, which will define the performance, cost, and reliability goals to be met by any selected technology. These goals must be examined and refined as necessary on a regular basis.
- A reexamination of the various generic systems should occur periodically (e.g., 2-3 years) to include new data generated as a result of the technology development programs.

SERI

SECTION 2.0

OBJECTIVE, PRODUCTS, SCOPE, AND APPROACH

The main objective of the Small Solar Thermal Electric Power Systems Study (SPSS) is to project the mid-1990 cost and performance of selected generic solar thermal electric power systems for utility application and to comparatively rank these systems according to a set of seven criteria that reflect the most important aspects of small utility acceptability. The study considers plants with rated capacities of 1 to 10 MW_e, operating over a range of capacity factors from the no storage case to 0.7 and above.

2.1 PRODUCTS OF THE STUDY

There are three products resulting from the study: (1) a ranking of generic solar thermal electric power systems, (2) a uniform methodology for comparing solar plants of all types and applications, and (3) a flexible computer code that simulates the performance and determines the life cycle cost of these plants for a variety of operating strategies and economic scenarios. Each of these is described in greater detail in later sections of this report.

The major product is an ordered ranking of eleven grid-connected generic solar thermal electric power systems evaluated at capacities of 1, 5, and 10 MW_e, and capacity factors of 0.7, 0.4, that corresponding to no storage, and that yielding the lowest busbar energy costs. Each generic system has been evaluated according to a set of seven criteria, which in turn has been derived from a study of user preferences.

2.2 SIGNIFICANCE AND SCOPE OF THE STUDY

The rankings presented in this report apply only to grid-connected electrical generating systems. Other applications such as total energy, cogeneration, or process heat have not been considered, as these applications are outside the predefined scope of this study. Therefore, the position of any system in the rankings discussed later in this report does not automatically preclude its consideration for other applications.

Additionally, the cost estimates for each technology and the resulting energy costs do not represent either established DOE goals or the actual ultimate potential costs of a system. Emphasis has been placed upon using costs that can be expected to be achieved by the mid-1990s, as well as upon a common economic scenario, so that a credible ranking could be achieved. Further discussions concerning the costing philosophy are contained in Appendix A.

Systems were designed to meet a specific set of operating ground rules oriented around small grid-connected systems. One significant ground rule limits the maximum power supplied to the grid at any time to the rated output of the plant. This constraint affects the performance of both distributed and central generation concepts. Without this constraint, the alternative to storing electricity produced in excess of plant rating is to deliver it to the grid. This latter alternative avoids the storage charging and discharging losses and, therefore, results in a higher capacity factor. It also avoids the need for the capital cost of the storage system resulting in lower system total costs. Given this possible alternative (in the absence of the above constraint) the use of electrical storage would increase the system total cost and lower the capacity factor.

The grid was assumed to be infinite, i.e., that all energy supplied could be utilized without considering the utility load profile. It was further assumed that the value of energy delivered to the grid was independent of the time of day and day of the year.

Lastly, system performance was based upon a site at Barstow, California, primarily because of the availability of detailed meteorological data. The insolation values used in the performance code were obtained from the 1976 Barstow environmental data tape.

2.3 APPROACH

This section discusses the approach used for this study. It concentrates on selection of generic system options, system conceptual design and characterization.

2.3.1 Selection of Generic System Options

A generic collector option is defined by an optical model that represents a group of specific collector technologies. Within some generic collector categories, there are several design variations to which cost and producibility estimates could be assigned with varying degrees of confidence. The scope of this study does not allow an evaluation of all the variations in sufficient detail to distinguish between them; therefore, the analysis and ranking was confined to fundamental generic collector options. Generic power-plant systems that used generic collector options were conceptualized. In some cases, more than one generic system was conceived using the same generic collector option.

After ranking, it is possible to determine whether or not a specific design variation would significantly change the position in the ranking of any generic system. If, at a later date, promising variations of any generic system emerge, they can be evaluated. Additional effort will be necessary to conceptualize the system, derive detailed cost and performance data, run the simulation, and perform the ranking for any of these design variations.

Figure 2-1 identifies the generic options of systems selected by SERI for consideration in terms of basic collector subsystem characteristics. These collector configurations were used for the 1 to 10 MW_e systems discussed in this report. Table 2-1 describes the combinations of power conversion, transport, and storage technologies that comprise the 1 to 10 MW_e systems.

2.3.2 System Conceptualization and Characterization

System cost and performance are simulated using a system simulation model, BALDR-1.* This computer code was used to calculate the annual system performance and determine both the capital and levelized annual energy costs for a specified economic scenario. A detailed description of the BALDR-1 model is presented in Appendix B.

The system's characteristic cost and performance input data for BALDR-1 are derived from conceptual designs of the generic systems. These system designs evolved through a

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*In Scandanavian mythology, Baldr was the god of sunlight and the personification of wisdom, beauty, and brightness. The version of the code used is the original, hence "dash one."

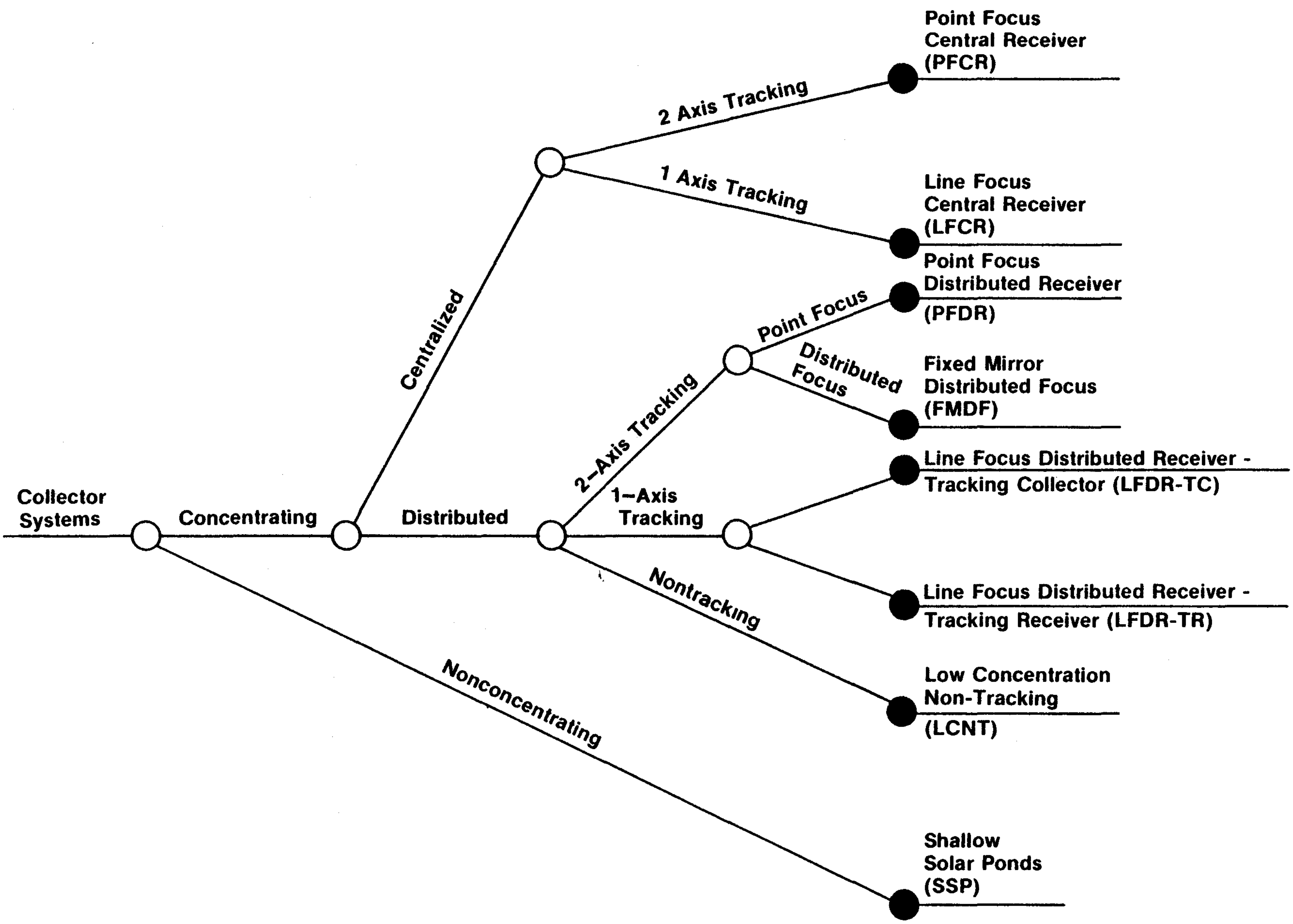

Figure 2-1. Generic Options Selected by SERI for Consideration in the Small Power Systems Study

Table 2-1. COMBINATION OF TECHNOLOGIES CONSIDERED TO CONCEPTUALIZE 1-10 MW_e GENERIC SYSTEMS

Concentrator Options	System Options												
	Conversion					Transport				Storage			
											Thermal		
	Cent-Rankine	Cent-Brayton	Dist-Rankine	Dist-Brayton	Dist-Stirling	Electrical	Water	Salt	Oil	Electrical	Oil	Salt	Water
Point Focus Central Receiver	●							●				●	
Point Focus Central Receiver		●				●				●			
Line Focus Central Receiver	●							●				●	
Point Focus Distributed Receiver	●							●				●	
Point Focus Distributed Receiver				●		●				●			
Point Focus Distributed Receiver					●	●				●			
Fixed Mirror Distributed Focus	●							●				●	
Line Focus Distributed Receiver — Tracking Collector	●								●		●		
Line Focus Distributed Receiver — Tracking Receiver	●								●		●		
Low Concentration Non-Tracking	●								●		●		
Shallow Solar Ponds			●			●	●						●

series of conceptualization and review steps. First, a preliminary advanced concept was derived for each system. All subsystems and major components were defined to the best extent possible and costs assigned. Operating temperatures were determined for thermal processes. The major data sources at this stage were the published literature, including government and contractor development reports, and manufacturers' data.

Each conceptual system design, including cost and performance parameters, was reviewed by various individuals and organizations, including advocates of the particular system. The resulting comments were in turn reviewed at SERI and incorporated into the system design where appropriate.

Revised versions of these system designs were created, subsystems defined, and the necessary cost and performance input data generated. System input data were adjusted to reflect the changes in characteristics over the full range of capacities and capacity factors. For example, the tower height for a central receiver plant, and its corresponding cost, was adjusted as the heliostat field size changed due to plant-rated capacity increases from 1 through 10 MW_e and as thermal storage size increased.

The system simulation, BALDR-1, was used to determine the annual performance of the plant, trading off between collector field area and storage time to find the minimum cost combination necessary to achieve the desired capacity and capacity factor. The output from a simulation run includes capital cost, levelized O&M, and levelized energy cost for each combination of capacity and capacity factor. Table 2-2 describes the baseline economic scenario used in the study. It is representative of typical investor-owned utilities as of 1976 [2].

Table 2-2. COST FACTORS USED IN SMALL POWER SYSTEMS STUDY

Cost Factor	Value
a. Raw land	$5,000/acre
b. Cost of capital to a "typical" investor-owned utility	0.086
c. Composite income tax rate effective	0.40
d. Rate of general inflation	0.060
e. Escalation rate for capital costs	0.060
f. Escalation rate for operating costs	0.070
g. Escalation rate for maintenance costs	0.070
h. Capital recovery factor (30 yrs)	0.0939 (8.6%)
i. Property taxes, insurance, etc.	0.0225
j. Fixed charge rate, annualized	0.1568

The capital and levelized production costs were utilized in the formalized ranking process, a multi-attribute decision analysis (MADA). Since the intent of the study was to obtain the most appropriate ranking of these generic technologies, evaluation criteria included social, environmental, and institutional impacts, as well as cost and performance data. The preferences of the ultimate users, or decision makers, were explicitly considered in the formalized multi-attribute decision analysis technique, establishing the preference profile of the decision maker. This technique insured consistent interpretation of the ranking, and established traceability throughout the analysis from input data to the final recommendations of Section 1.0.

The decision analysis methodology was based upon work by R. L. Keeney and H. Raiffa [3]. Variations of this methodology have been used in previous energy-related studies by various organizations, including utilities. An introduction to MADA is included in Appendix C.

SECTION 3.0

GENERIC SYSTEMS DESCRIPTIONS

Specific generic systems were designed to be representative of mid-1990s technology for each generic system considered. Component selection is not to be interpreted as a recommendation for the only specific design direction to be pursued within a given generic system. The system designs were based on consideration of proposed system designs, proposed component designs synthesized into a system, and conceptualized component designs synthesized into systems.

3.1 POINT FOCUS CENTRAL RECEIVER/RANKINE (PFCR/R)

The representative PFCR/R system is an advanced salt system. Draw salt is used as a receiver coolant, as the heat transfer fluid between the receiver and thermal storage, and as the thermal storage medium itself. A central Rankine steam turbine is used for power conversion. A system flow schematic drawing is presented in Fig. 3-1. One feature of this system (shared with all other systems incorporating thermal storage modeled herein) is that the temperature from the collector field is approximately equal to the temperature from thermal storage.

The concentrator field consists of two-axis tracking heliostats (Fig. 3-2) arranged in either a north field configuration (Fig. 3-3) for smaller plants, or in an elliptical surround field configuration for larger plants. Each heliostat reflective surface is back-silvered thin glass (~1 mm, .040 in) of 50 m^2 (540 ft^2) aperture.

The receiver is either a single cavity facing north (north field) or four cavities facing north, south, east, and west (surround field). The cavity walls are coated with a selective surface. The receiver is supported on a free-standing steel tower.

Thermal storage is a sensible heat thermocline of molten draw salt. The storage tanks are lined with internal insulation to permit the use of lower cost materials for their construction.

3.2 POINT FOCUS CENTRAL RECEIVER/BRAYTON (PFCR/B)

The representative PFCR/B system incorporates a closed-cycle recuperated turbine Brayton engine with electrical storage. The Brayton engine and generator are close-coupled to the receiver atop the tower. A system flow schematic drawing is presented in Fig. 3-4.

The concentrator field consists of two-axis tracking heliostats (Fig. 3-2) arranged in either a north field configuration for smaller plants or in an elliptical surround field configuration for larger plants (Fig. 3-3). Each heliostat reflective surface is back-silvered thin glass of 50 m^2 (540 ft^2) aperture.

The receiver is either a single cavity facing north (north field) or four cavities facing north, south, east, and west (surround field). The cavity and engine/generator are supported on a free-standing steel tower.

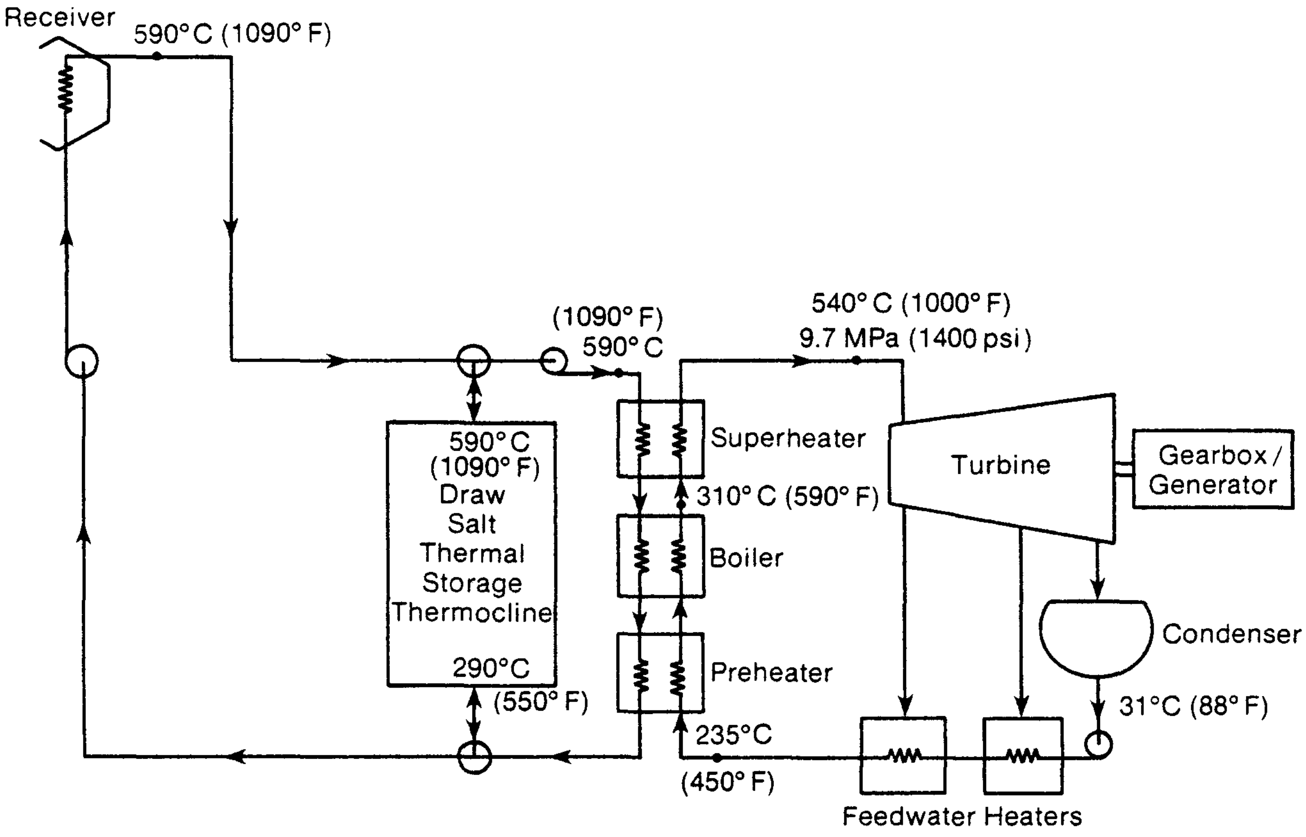

Figure 3-1. Point Focus Central Receiver/Rankine (PFCR/R) System Flow Schematic Drawing

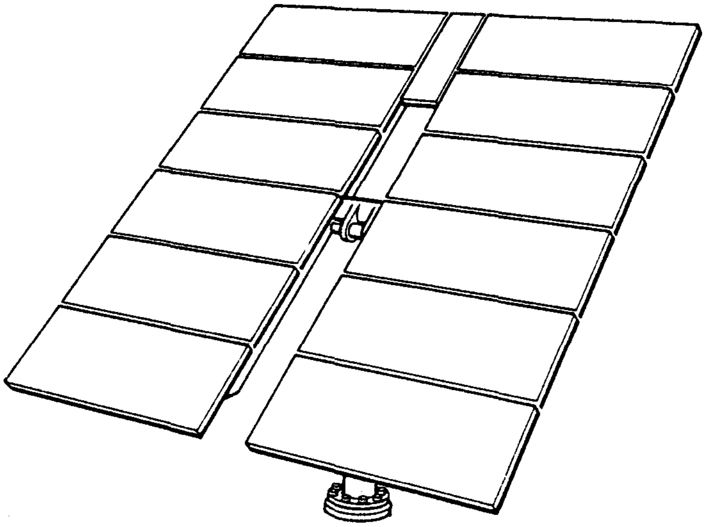

Figure 3-2. Two-Axis Tracking Heliostat (PFCR)

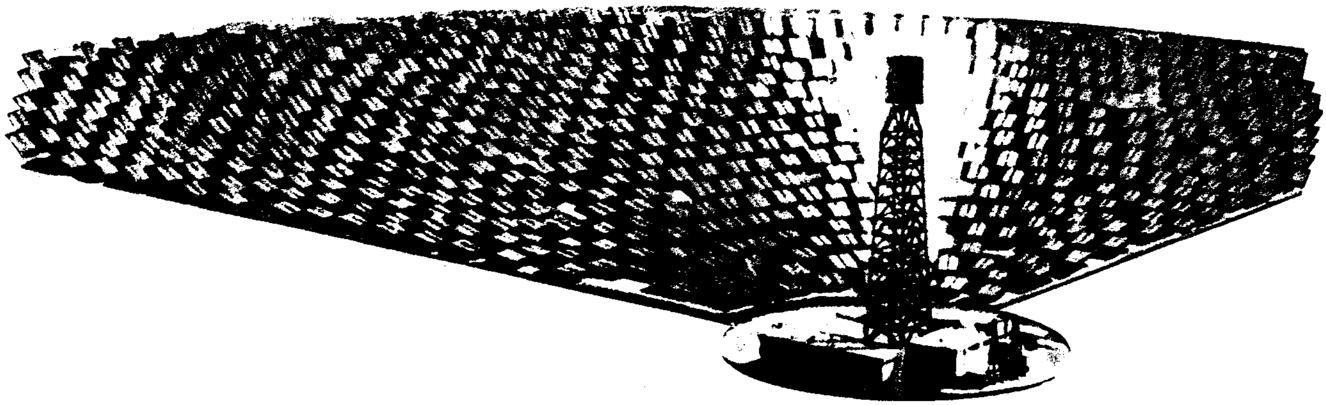

Figure 3-3. Point Focus Central Receiver (PFCR)

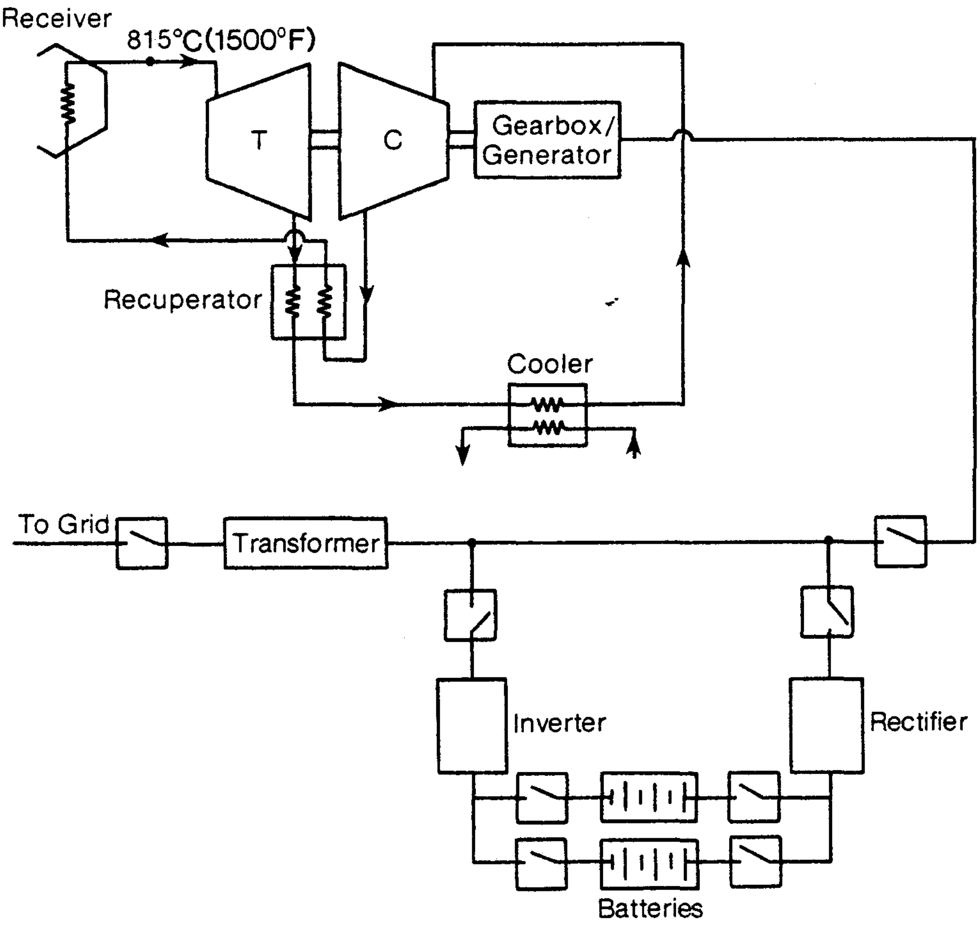

Figure 3-4. Point Focus Central Receiver/Brayton (PFCR/B) System Flow Schematic Drawing

Because of the difficulty of integrating thermal storage into the system, electrical storage is provided by redox batteries. The batteries are dedicated to the plant, and are coupled in parallel with the generator output.

3.3 POINT FOCUS DISTRIBUTED RECEIVER/STIRLING (PFDR/S)

The representative PFDR/S system is a field of parabaloidal dishes with a free piston Stirling engine located at the focus of each dish. (A kinematic Stirling engine could be substituted for the free piston Stirling engine with only minor impacts on system design and cost.) A system schematic drawing is presented in Fig. 3-5.

The collector field consists of two-axis tracking parabaloidal dishes (Fig. 3-6). The nominal dish size was chosen to be 10 m (33 ft) in diameter, although recent information suggests the system optimum may be somewhat larger. The dish reflective surface is back-silvered thin glass.

The receiver is a sodium heat pipe cavity. It permits the use of small amounts of thermal storage in the form of encapsulated latent heat salt modules.

Electrical storage is provided by redox batteries. The batteries are coupled in parallel with the generators' output and are dedicated to the plant.

3.4 POINT FOCUS DISTRIBUTED RECEIVER/BRAYTON (PFDR/B)

The representative PFDR/B system is a field of parabaloidal dishes with a closed-cycle recuperated turbine Brayton engine located at the focus of each dish. A system schematic drawing is presented in Fig. 3-7.

The collector field consists of two-axis tracking parabaloidal dishes (Fig. 3-6). The nominal dish size was chosen to be 10 m (33 ft) in diameter. The dish reflective surface is back-silvered thin glass.

The receiver is a sodium heat pipe cavity. It permits the use of small amounts of thermal storage in the form of encapsulated latent heat salt modules.

Electrical storage is provided by redox batteries. The batteries are coupled in parallel with the generator's output and are dedicated to the plant.

3.5 POINT FOCUS DISTRIBUTED RECEIVER/RANKINE (PFDR/CR)

The representative PFDR/CR system is a field of parabaloidal dishes that heat salt for transport to a central location for storage and/or steam generation for a central steam turbine Rankine engine. A system flow schematic drawing is presented in Fig. 3-8.

The collector field consists of two-axis tracking parabaloidal dishes (Fig. 3-6). The nominal dish size was chosen to be 14 m (46 ft) in diameter, somewhat larger than the PFDR/S and PFDR/B cases to minimize thermal transport costs. The dish reflective surface is back-silvered thin glass.

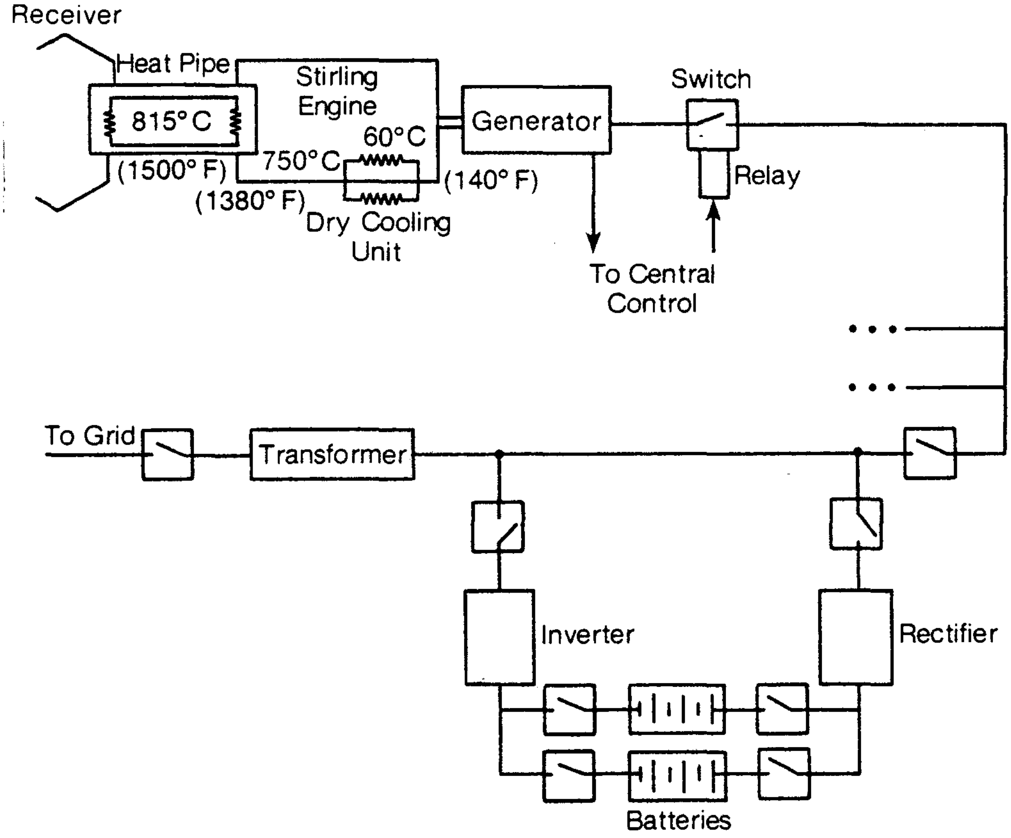

Figure 3-5. Point Focus Distributed Receiver/Stirling (PFDR/S) System Flow Schematic Drawing

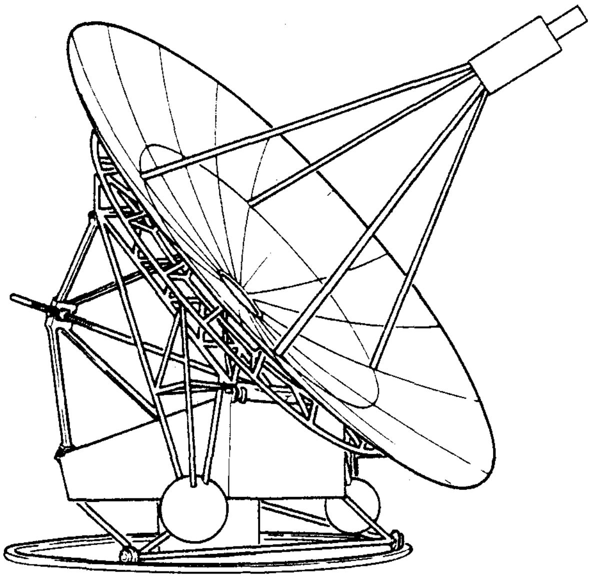

Figure 3-6. Point Focus Distributed Receiver (PFDR) Dish

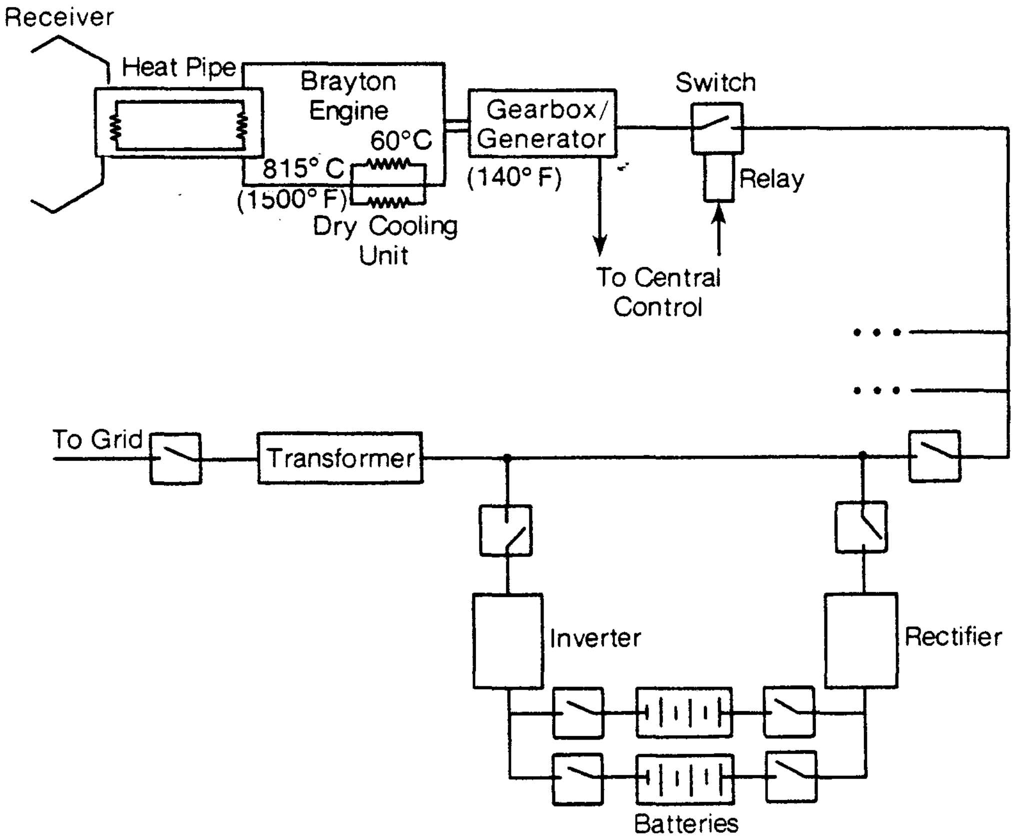

Figure 3-7. Point Focus Distributed Receiver/Brayton (PFDR/B) System Flow Schematic Drawing

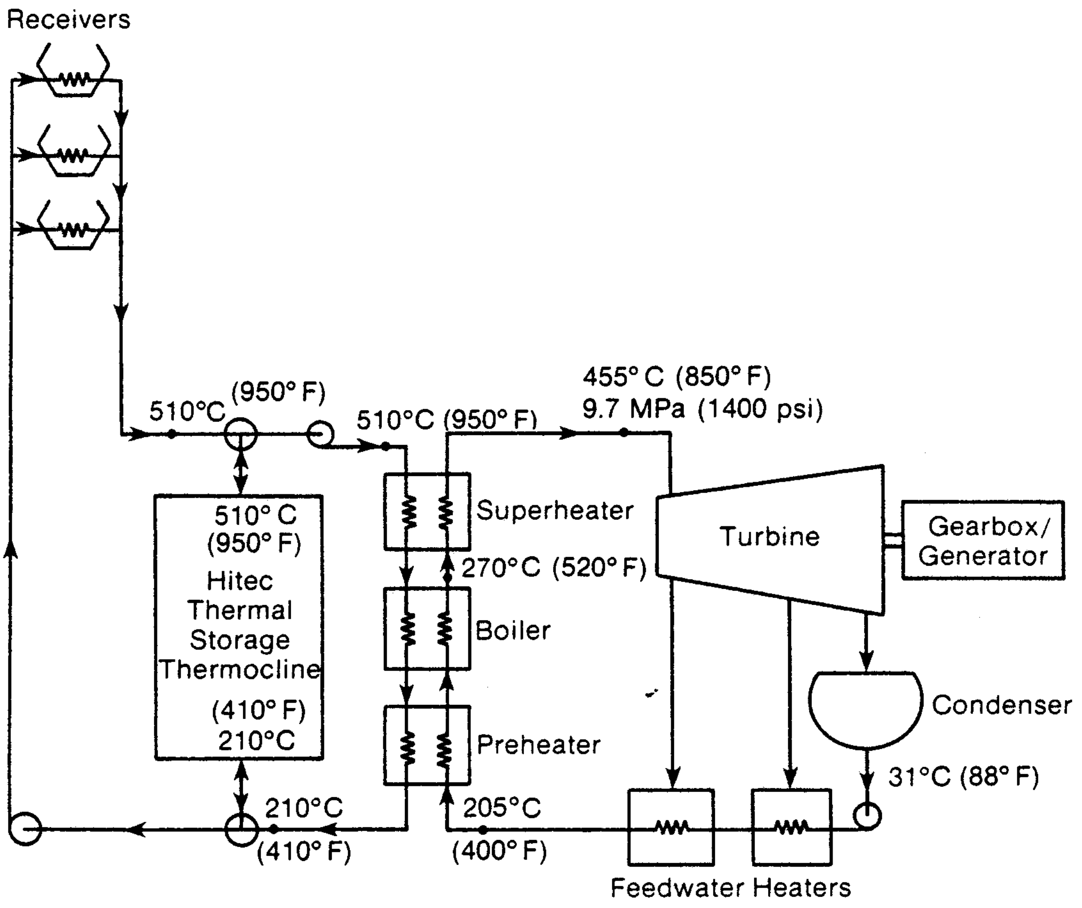

Figure 3-8. Point Focus Distributed Receiver/Rankine (PFDR/CR) System Flow Schematic Drawing

The receiver is a sodium heat pipe cavity receiver with a selective surface. Molten Hitec is used as the receiver coolant and heat transfer fluid.

Thermal storage is a sensible heat thermocline of molten Hitec salt. The storage tanks are internally insulated.

Another implementation of this generic system was also examined. It used dishes enclosed in plastic bubbles to reduce the structural requirements of the dish itself. Its lower capital cost was almost entirely offset by its higher anticipated O&M.

3.6 LOW CONCENTRATION NONTRACKING (LCNT) SYSTEM

The representative LCNT system consists of a CPC (compound parabolic collector) field, sensible heat thermocline storage and central Rankine steam turbine. Dowtherm A is used as the receiver coolant, as heat transfer fluid between the receivers and thermal storage, and as a thermal storage medium itself. A system flow schematic drawing is presented in Fig. 3-9.

The collector field consists of nontracking five-power CPC's (Fig. 3-10), the tilt of which is adjusted twelve times annually. The concentrator surface is Alglass (0.025 mm thick glass) over a polished metal reflector.

The receiver is a linear tube coated with a selective surface absorber. It is surrounded by an evacuated tube with an antireflective coating.

Thermal storage is a dual media sensible heat thermocline of Dowtherm A and rocks. It is externally insulated.

3.7 LINE FOCUS DISTRIBUTED RECEIVER—TRACKING COLLECTOR (LFDR-TC)

The representative LFDR-TC system consists of a parabolic trough field, sensible heat thermocline storage, and central Rankine steam turbine. Dowtherm A is used as the receiver coolant, as heat transfer fluid between the receivers and thermal storage, and as a thermal storage medium itself. A system flow schematic drawing is presented in Fig. 3-11.

The collector field consists of an array of single-axis tracking parabolic troughs (Fig. 3-12) aligned to track about a north-south axis. Their reflective surface is back-silvered thin glass.

The receiver is a linear tube coated with a selective surface absorber. It is surrounded by an evacuated glass tube with an antireflective coating.

Thermal storage is a dual media sensible heat thermocline of Dowtherm A and rocks. It is externally insulated.

3.8 LINE FOCUS DISTRIBUTED RECEIVER—TRACKING RECEIVER (LFDR-TR)

The representative LFDR-TR system consists of a collector field, sensible heat thermocline storage, and central Rankine steam turbine. Dowtherm A is used as the receiver

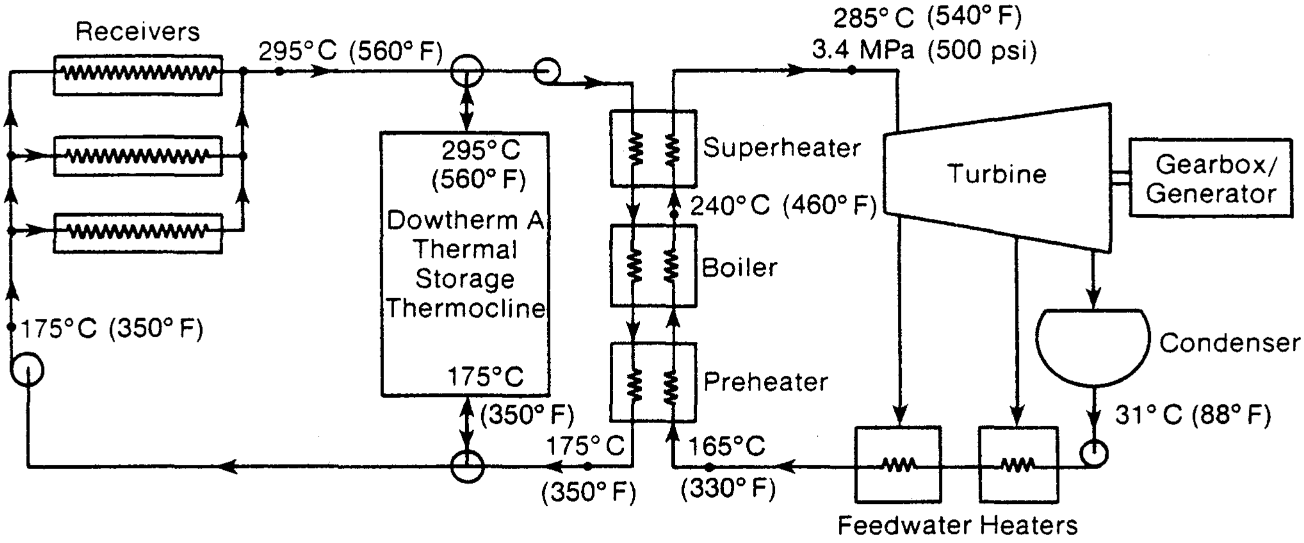

Figure 3-9. Low Concentration Non-Tracking (LCNT) System Flow Schematic Drawing

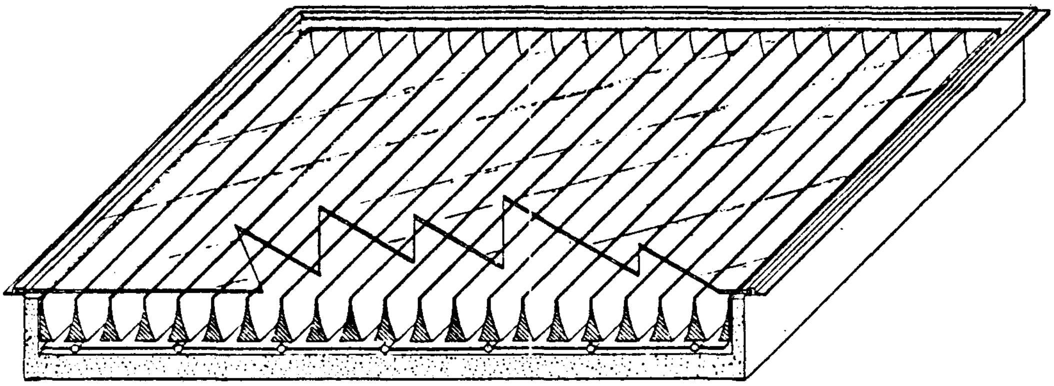

Figure 3-10. Low Concentration Non-Tracking (LCNT) Collector Module

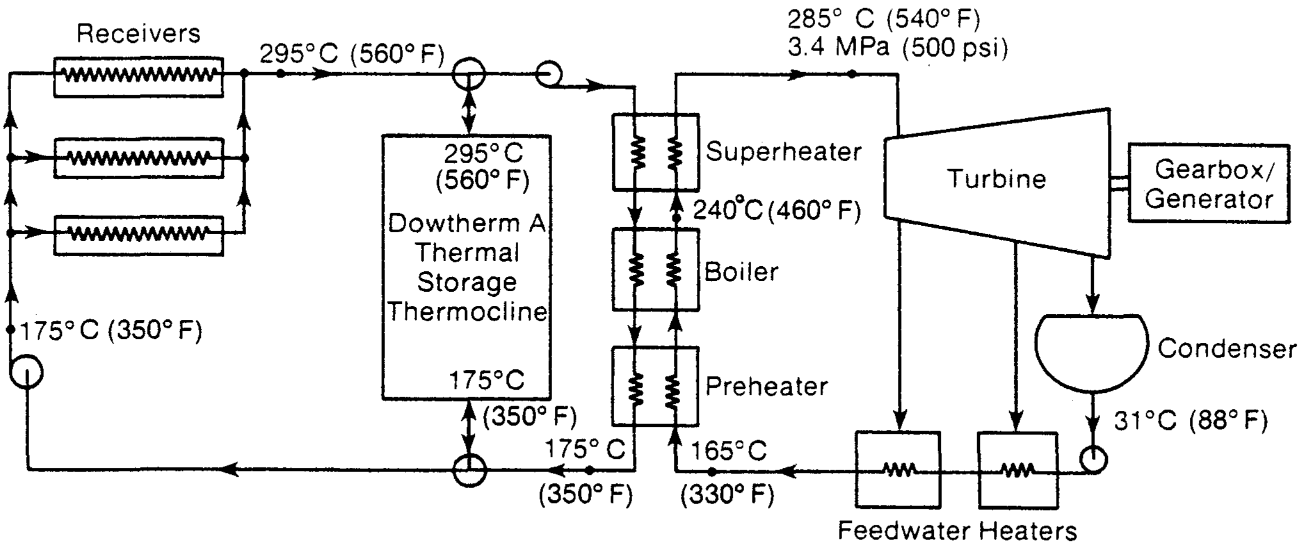

Figure 3-11. Line Focus Distributed Receiver--Tracking Collector (LFDR-TC) System Flow Schematic Drawing

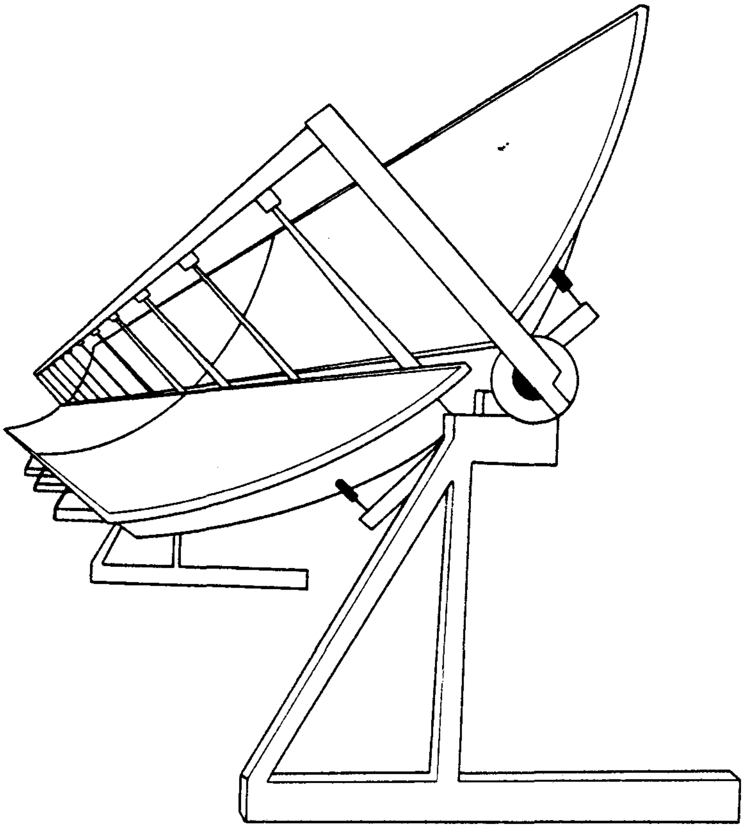

Figure 3-12. Line Focus Distributed Receiver Tracking Collector (LFDR-TC)

coolant, as heat transfer fluid between the receiver and thermal storage, and as a thermal storage medium itself. A system flow schematic drawing is presented in Fig. 3-13.

The collector field consists of an array of stationary segmented troughs (Fig. 3-14) with receivers that track in one axis (east-west). The collector substrate is concrete, although there remains some question as to the technical feasibility of achieving adequate mirror pointing precision with a concrete substrate. The reflectors are strips of back-silvered glass bonded to the substrate steps.

The receiver is a linear cavity with secondary concentration. The secondary concentrator is a back-silvered thin glass (~1 mm, 0.40 in) CPC. The receiver has a glass cover, which is treated with an antireflective coating. The cavity absorber is coated with a selective surface.

Thermal storage is a dual media sensible heat thermocline of Dowtherm A and rocks. The storage tanks are externally insulated.

3.9 LINE FOCUS CENTRAL RECEIVER (LFCR)

The representative LFCR system is an advanced salt system using a central Rankine steam turbine. Draw salt is used as the receiver coolant, as heat transfer fluid between the receiver and thermal storage, and as the storage medium itself. A system flow schematic drawing is presented in Fig. 3-15.

The concentrator field consists of one-axis tracking heliostats (Fig. 3-16) arranged in a north field configuration (Fig. 3-17). There are "butterfly" areas at each end of the heliostat rows to permit illumination of the full receiver for several hours of each day. The heliostat reflective surface is back-silvered thin glass.

The receiver is a linear cavity facing north. The cavity walls are coated with a selective surface. The receiver is supported on 60-m (200-ft) guyed steel towers that are spaced every 60 m (200 ft) in length.

Thermal storage is a sensible heat thermocline of molten draw salt. The storage tanks are lined with internal insulation to permit the use of carbon steel for their construction.

3.10 FIXED MIRROR DISTRIBUTED FOCUS (FMDF)

The representative FMDF system is an advanced salt system. Hitec salt is used as the receiver coolant, as heat transfer fluid between the receivers and thermal storage, and as the thermal storage medium itself. A central Rankine steam turbine is used for power conversion. A system flow schematic drawing is presented in Fig. 3-18.

The concentrator field consists of an array of large stationary hemispherical bowls (Fig. 3-19) tilted somewhat to the south. The bowl support structure is concrete and is lined with a reflective surface of back-silvered glass.

The receiver is a linear tube that tracks in two axes. The receiver surface is coated with a selective surface.

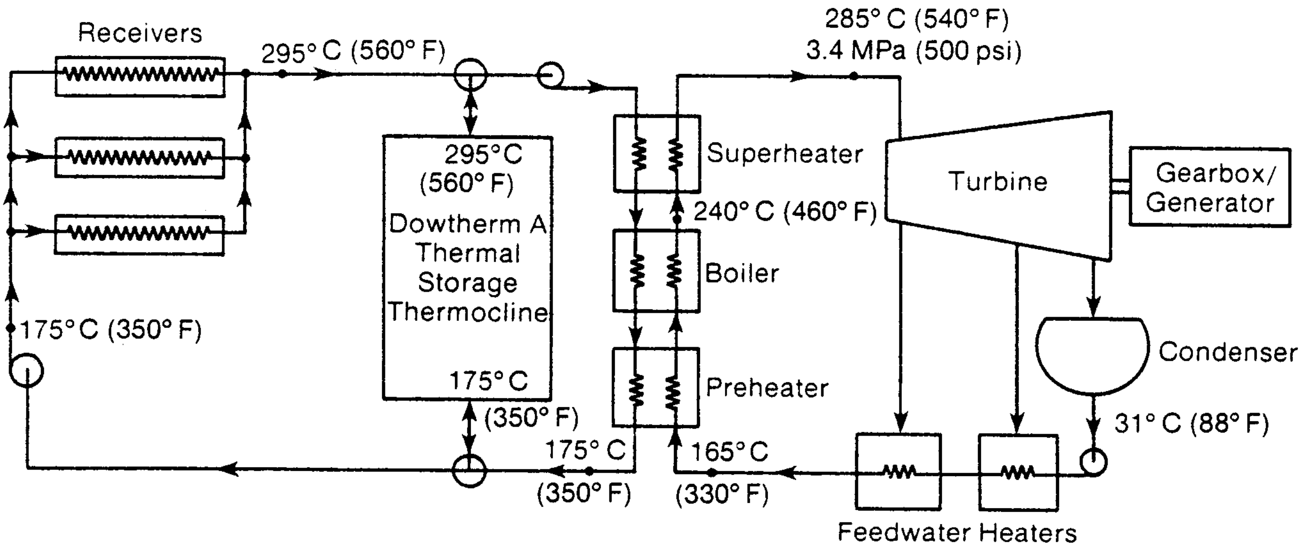

Figure 3-13. Line Focus Distributed Receiver--Tracking Receiver (LFDR-TR) System Flow Schematic Drawing

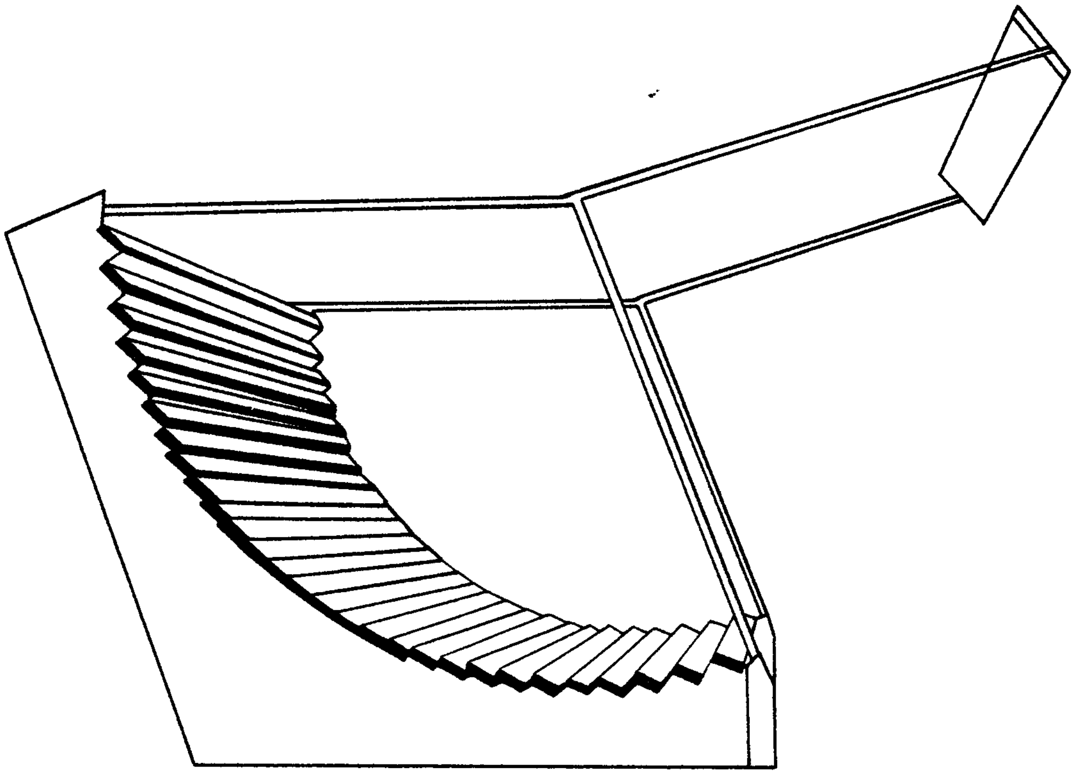

Figure 3-14. Line Focus Distributed Receiver Tracking Receiver (LFDR-TR)

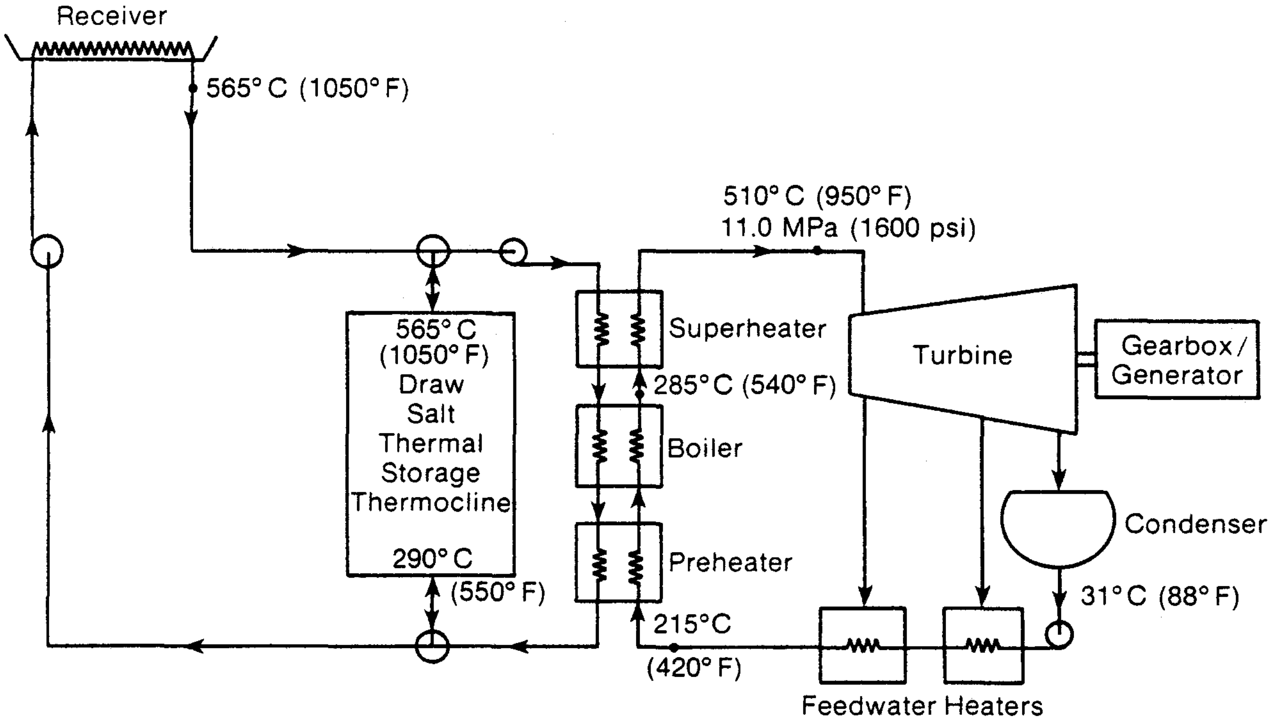

Figure 3-15. Line Focus Central Receiver(LFCR) System Flow Schematic Drawing Receiver

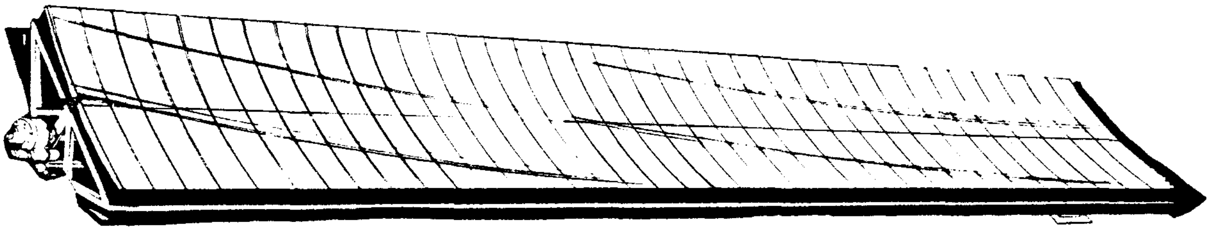

Figure 3-16. One Axis Tracking Heliostat

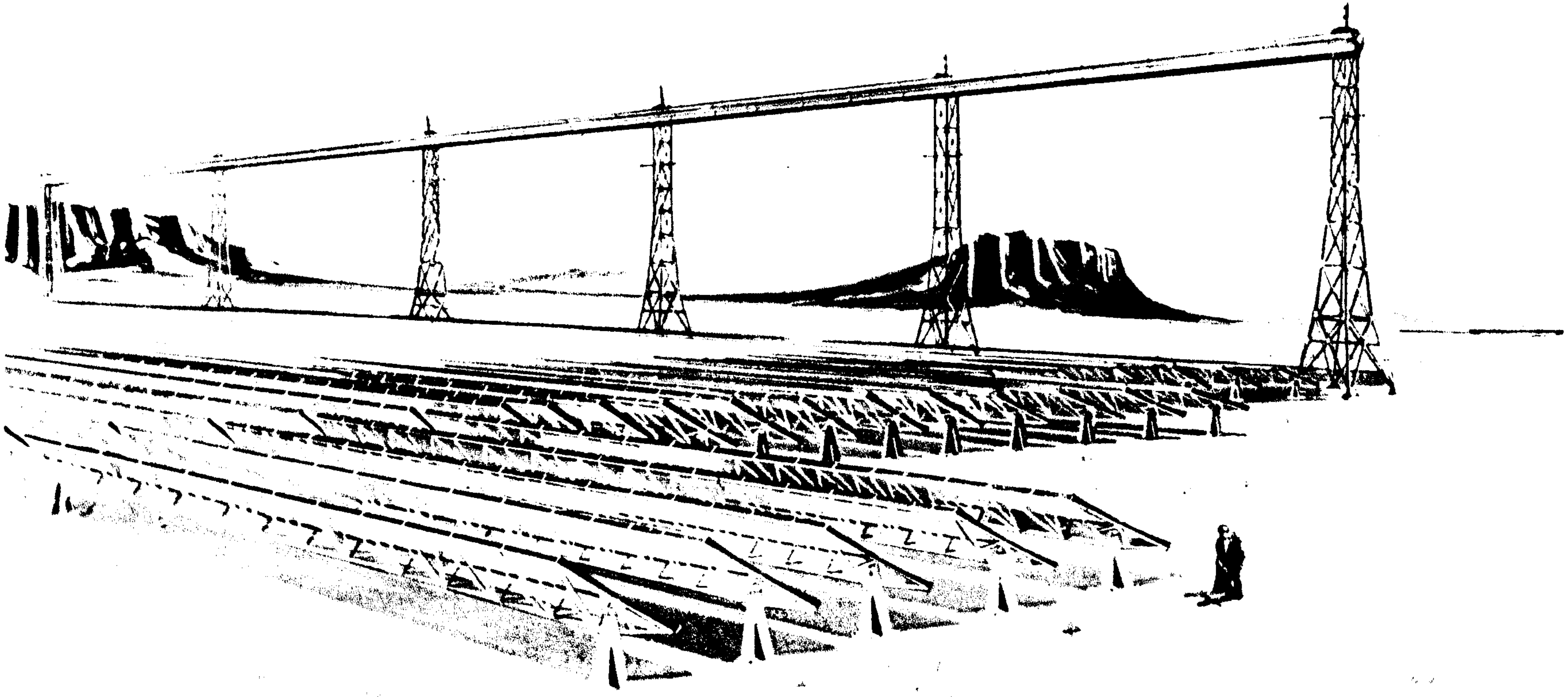

Figure 3-17. Line Focus Central Receiver System (LFCR)

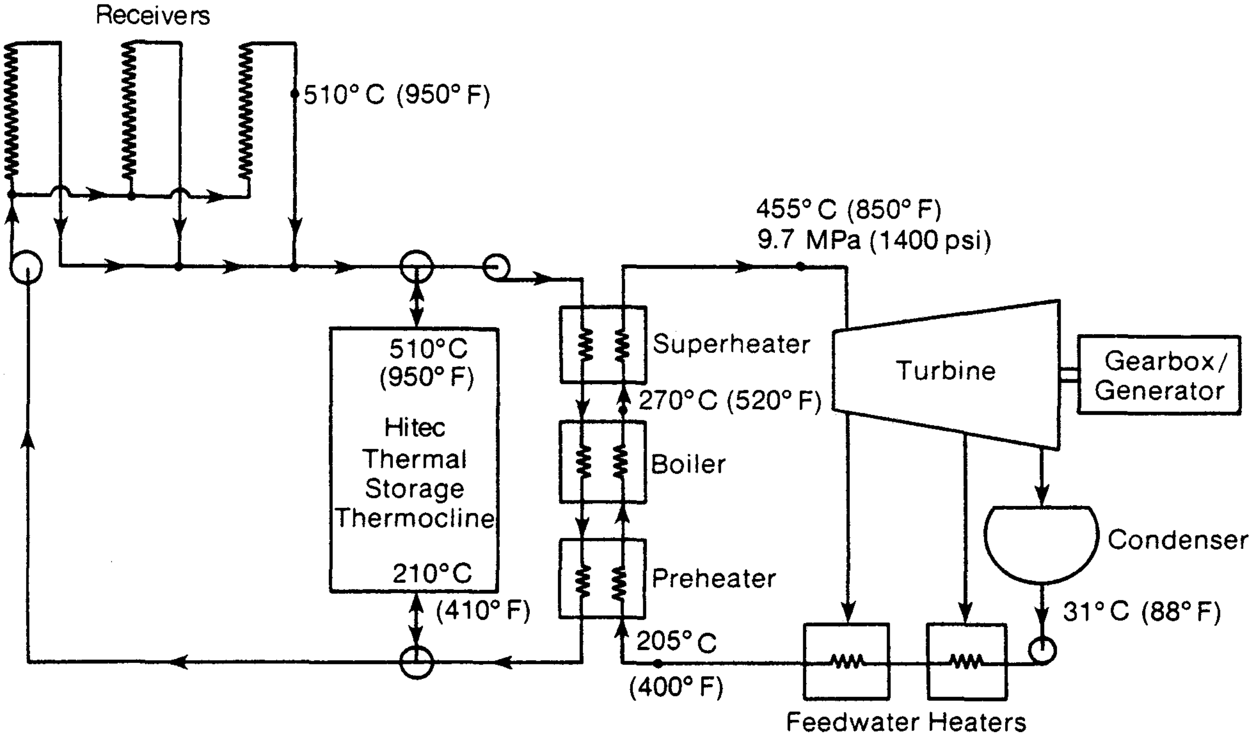

Figure 3-18. Fixed Mirror Distributed Focus (FMDF) System Flow Schematic Drawing

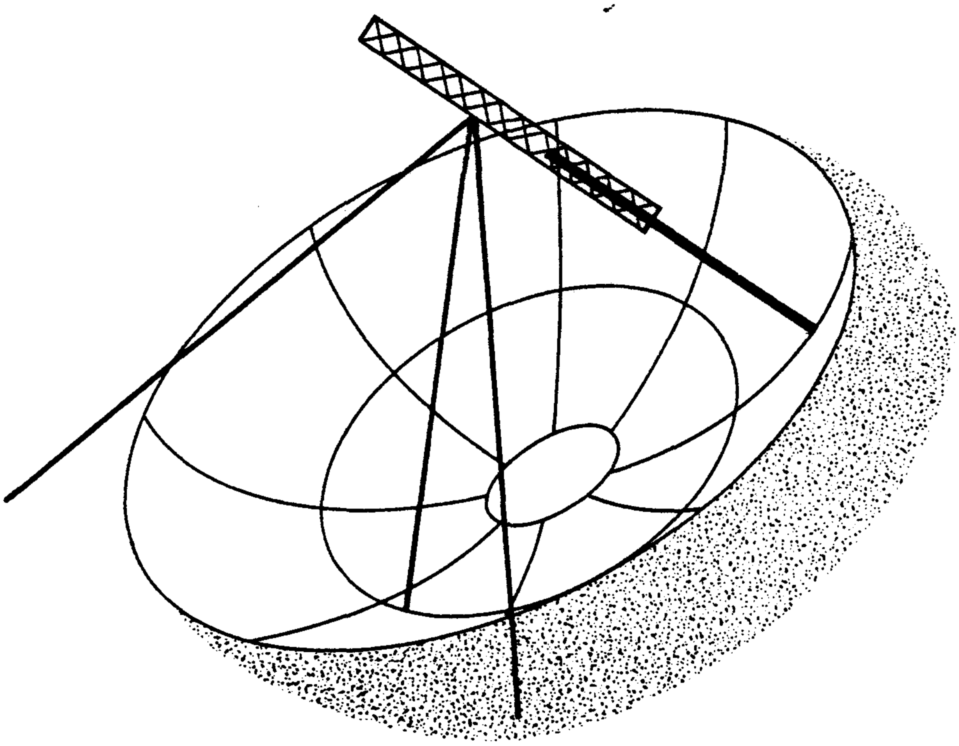

Figure 3-19. Fixed Mirror Distributed Focus (FMDF) Bowl

Thermal storage is a sensible heat thermocline of molten Hitec salt. The storage tanks are lined with internal insulation to permit the use of carbon steel for their construction.

3.11 SHALLOW SOLAR PONDS (SSP)

The representative SSP system consists of a field of saltless ponds with distributed organic Rankine cycle engines. Several ponds are coupled to each storage system and heat engine. A system flow schematic drawing is presented in Fig. 3-20.

The collector field consists of shallow solar ponds (Fig. 3-21), each of which is approximately 60 m x 5 m x 0.1 m (200 ft x 20 ft x 4 in). They are double inflatable plastic glazings that are manufactured integral with the pond itself. The field is operated in a continuous flow mode.

The receiver function is performed by the blackened bag bottom. It is an integral part of the pond itself.

Thermal storage is a sensible heat thermocline of the water used in the ponds. The storage tanks are excavated, insulated, and lined with plastic.

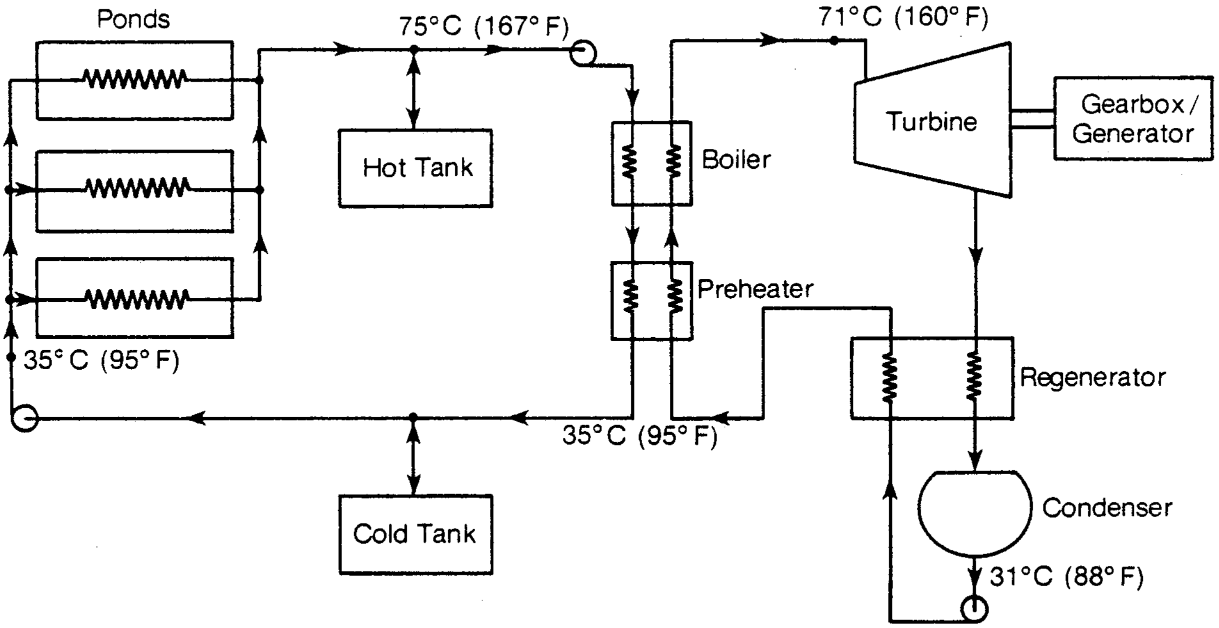

Figure 3-20. Shallow Solar Ponds (SSP) System Flow Schematic Drawing

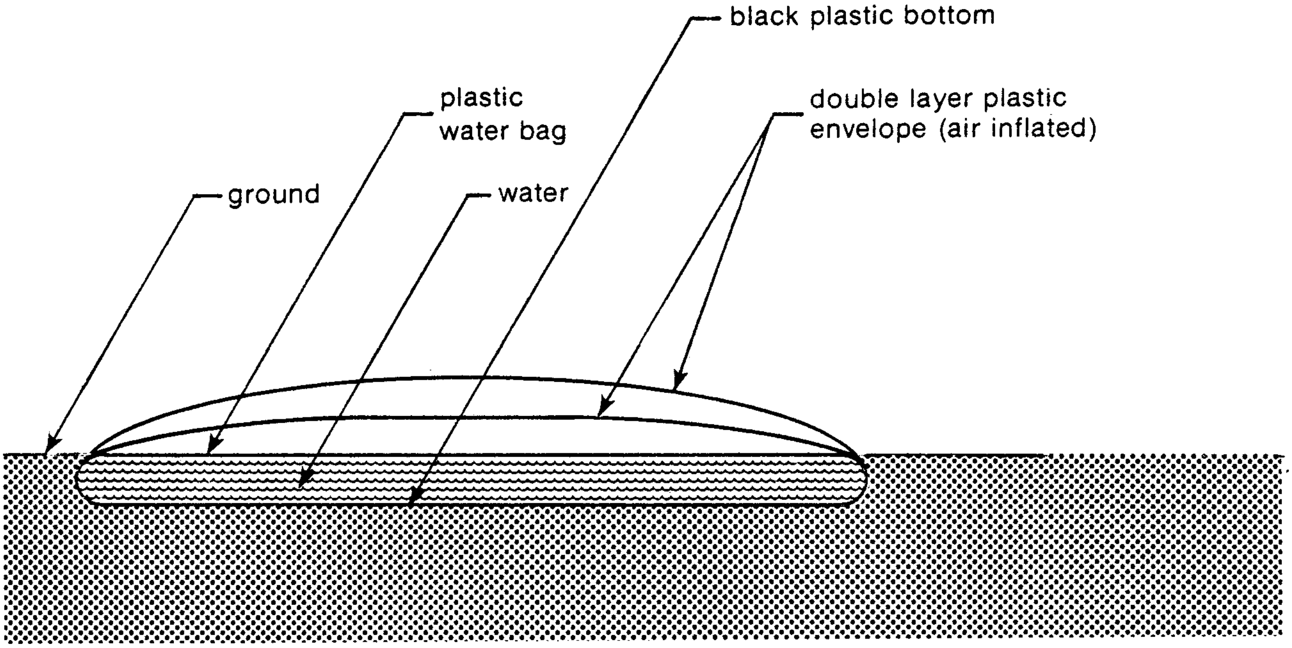

Figure 3-21. Shallow Solar Pond (SSP)

SERI

SECTION 4.0

SUMMARY OF RESULTS

The ranking of small solar thermal electric power systems, like the ranking or ordering of any set of alternatives, is a decision process. As such, it is amenable to analysis by methods evolving from a growing body of knowledge known as decision analysis. A formal method of decision analysis was adopted in this study to provide a defensible and traceable treatment of the technical results of the systems study and to provide a means of incorporating the opinions and concerns of potential users on a number of issues. In essence, this study constructs a "value" model representing the users' value to translate information from the system model, created by the study team, into resulting preferences.

The study was to reflect the perspective of the eventual user of small solar thermal electric power systems. Although electric utility applications were the primary focus in this work, small power systems can also be considered for applications to community-scale self-contained power units, remote applications or international markets. To contrast the views of electric power industry representatives, interviews with personnel representing diverse opinions in the research and development sector were also conducted. These samples allow us to compare the preferences of the user group (utilities) with those of a group that has traditionally been influential in programmatic R&D decisions (research engineers).

A methodology developed from the technique of multi-attribute decision analysis was used to formulate the value model in this study. As described in Appendix C, this methodology allows for the simultaneous consideration of many criteria in the decision process, such as the concerns for cost, performance, reliability, environmental impact, and commercial potential. The method also allows the effects of uncertainty in the system model or in inputs to the value model to be tested directly. By interviewing actual decision makers from the power industry and from the R&D sector in a manner prescribed by the multi-attribute decision analysis method, input data is obtained which allows later simulation of the individual's decision process. It is flexible, traceable, and transparent in its logic and results.

The selection of the criteria and attributes upon which the ranking decision is based and for which input data are collected in the interviews is a very important step in constructing the value model and is detailed in Appendix D. As mentioned above, the multi-attribute method is capable of simultaneously considering issues of cost, reliability, environmental impact and so on. The results of selecting a problem structure are shown in Fig. 4-1. The seven selected problem attributes are shown in relation to the objectives and subobjectives of this decision problem.

These seven attributes (capital cost, O&M, capacity factor, environmental impact, relative safety, R&D expenditure, and applicability) were explored in depth with each decision maker interviewed. The results of those interviews, including the relative weighting of the attributes and the qualitative statements made about them, are described in Appendix E. Thirty individual interviews were conducted, including representatives from several different types of electric utilities, viz:

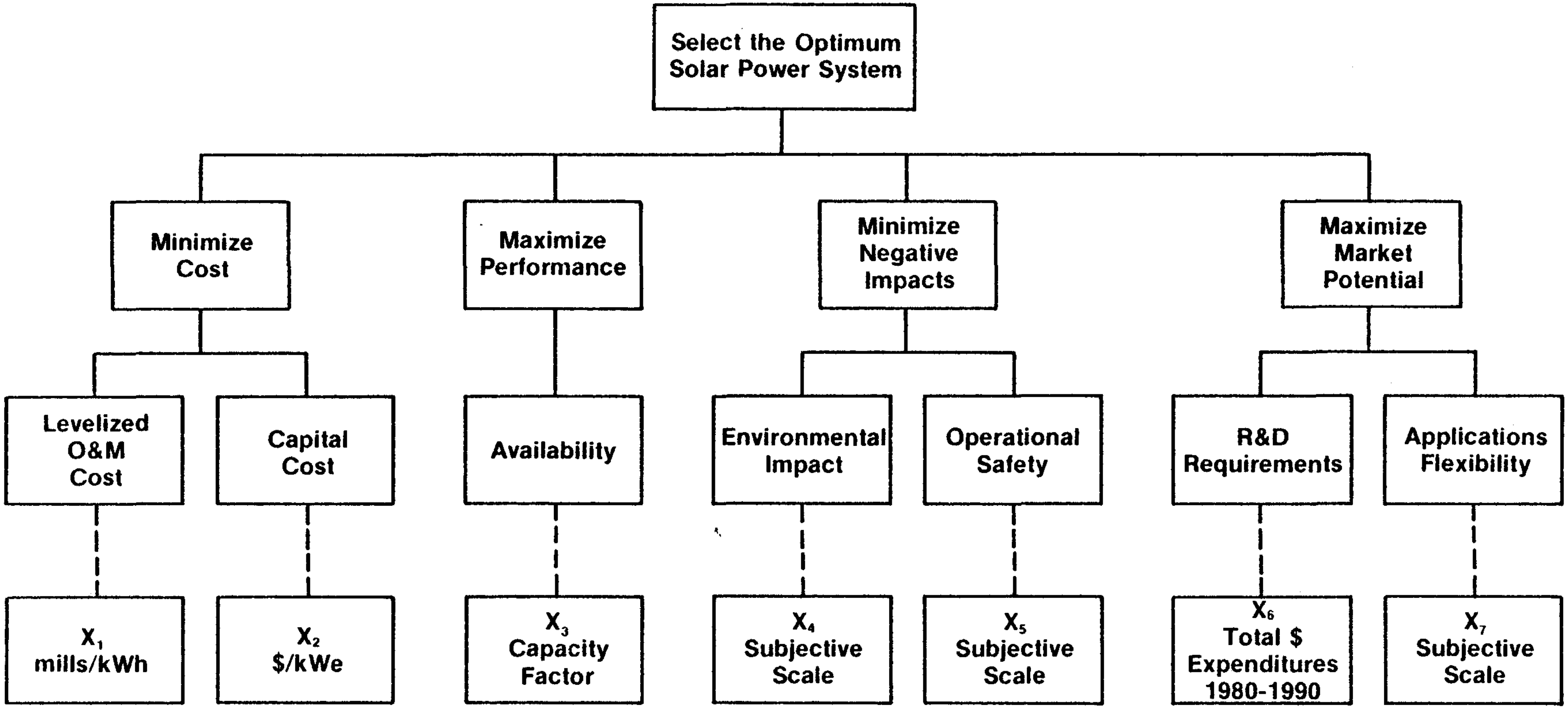

Figure 4-1. Selected Problem Structure

- Large investor-owned (>15,000 MW_e),
- Medium-sized investor-owned (>2,000 MW_e),
- Public utility (~1500 MW_e),
- Municipal utility (~300 MW_e), and
- Rural electric cooperative.

In addition, interviews were conducted with utility consultants, public utility commission members, and electric utility trade journal editors. A number of interviews with technical and nontechnical R&D staff were also conducted in order to compare and contrast those points of view.

This section summarizes the results of the decision analysis and economic sensitivity studies performed in this study. In Section 4.1, the ranking of the 11 system options is shown for various groups of decision makers and a consistent rank ordering is developed. The effects of attribute uncertainty and decision maker input uncertainty on this ranking are then described. In Section 4.2, the results of the economic analysis, including a table of levelized busbar energy costs, are presented. The important sensitivity of solar plant life-cycle costs to economic input variables is shown.

4.1 RESULTS OF THE DECISION ANALYSIS (RANKING)

This section presents the results of an evaluation and ranking of the alternative generic solar thermal electric power systems using multi-attribute decision analysis (MADA). Detailed in Appendix C, the MADA procedure produces an ordered ranking of each of the candidate generic systems for individual and synthesized "average" decision makers. This section comprises four parts: (1) definition of the participants and averaging procedures, (2) presentation of rankings produced using MADA, (3) analysis of the sensitivity of these rankings to uncertainty, and (4) a summary of the conclusions based on these results.

4.1.1 Participating Decision Makers

Of the 30 interviews conducted (as listed in Appendix F), the results of 24 interviews were selected for this analysis. Six of the original interviews were used as pretests of the questionnaire and were not included in the results. The 24 decision makers can be classified into several groups. Certain of these groups are created by selecting and synthesizing "average" decision makers among several categories (see Table 4-1).

The composition of these five groups is summarized below:

Group A - All 24 decision makers
Group B - 10 decision makers, one representing each of 10 user categories
Group C - One "average" R&D representative
Group D - One "average" utility representative
Group E - One overall "average" decision maker

Table 4-1. COMPOSITION OF DECISION GROUPS

Category (See Appendix F)	Number of Interviewees Group A	Group B	Group C	Group D	Group E
American Electric Power	3	1		3	3
Omaha Public Power District	2	1		2	2
Colorado Springs Public Utilities	1	1		1 } 1 AVG	1
Tri State Rural Electric	1	1		1	1
Public Service Company (Colorado)	1	1		1	1 } 1 AVG
Public Utility Commission	1	1		1	1
Consultants	2	1		2	2
SERI, Non Tech	3	1	3		3
SERI, Former Utility	2	1	2 } 1 AVG		2
SERI, Tech	8	1	8		8
Total	24	10	13→1	11→1	24→1

Each of the 10 members of Group B were selected as typical of a representative category of users. Groups C through E are synthesized decision makers with attribute weights and utility curves which are the average of their respective samples. Rankings for each of the five groups were explored and a sensitivity analysis conducted using the overall average decision maker (Group E) and the concensus poll of Group A. The method for arriving at concensus poll rankings is explored below.

4.1.2 System Rankings

Multi-attribute decision analysis is generally applied to problems considering only one decision maker at a time. When a decision is based upon inputs from a committee of decision makers (such as Groups A and B), the subjective influence of the decision analyst will be unavoidable, since rigorous methods of combining individual inputs have not been developed [4]. However, two informal methods of combining individual inputs may be applied. The first method is similar to that used in college basketball and football polls. This method, a variation of the Borda Count [4], scores each system according to its position in individual rankings (132* points for first, 131 points for second, etc.). The overall ranking is then determined by the sum of points over all decision makers (i.e., the largest sum ranks first, next largest second, and so on). The second method of creating committee decisions takes into account the difference in utility values for each participant by summing the utility values for all decision makers and ranking the alternatives according to this sum. In this study, the second method was used to help define statistically significant differences in the rankings of two or more alternatives.

Alternatives which were out of the range of acceptable values to the decision makers were therefore unsuitable to quantified ranking and were eliminated. For example, systems exceeding \$3400/kW$_e$ were eliminated from further consideration. Use of eliminating "screens" has been illustrated in several previous applications of this methodology (see, for example, Keeney [5]).

The results shown in Table 4-2 are ordered rankings of the best option (capacity/capacity factor combination) for each of the 11 systems considered. This table summarizes the rankings for Groups A through E plus an "average" utility ranking for Group A. The rankings are virtually identical for the five groups. To illustrate the relative difference in rankings, the accompanying bar chart (Fig. 4-2) displays the relative utility values for the average decision maker.

The final overall ranking of the systems is presented in Table 4-3. It was determined from rankings of Table 4-2, placing particular emphasis on the utility decision makers (Group D) in light of the expected users. In the case of a virtual tie, qualitative concerns and preferences of the utility decision makers were incorporated (e.g., a single central receiver, operating temperatures similar to current practice, etc.).

The plant size and capacity factor combinations ranking the highest for each concept are shown in Table 4-4. With few exceptions, the 10 MW$_e$ plants with the intermediate capacity factors were ranked highest for each system concept.

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*(11 generic systems) x (3 capacities) x (4 capacity factors) = 132 specific designs ranked.

Table 4-2. BEST OVERALL OPTION SYSTEM RANKINGS

Rank	Group A (All)		Group B (10 Select)	Group C (Overall Avg)	Group D (Utility Avg)	Group E (R&D Avg)
	Poll	Avg Util				
1	PFCR/R	PFCR/R	PFDR/S	PFCR/R	PFCR/R	PFCR/R
2	PFDR/S	PFDR/S	PFCR/R	PFDR/S	PFDR/S	PFDR/S
3	PFDR/B	PFDR/CR	PFDR/CR	PFDR/CR	PFDR/CR	PFDR/CR
4	PFCR/B	PFCR/B	PFDR/B	PFDR/B	PFDR/B	PFDR/B
5	PFDR/CR	PFDR/B	PFCR/B	PFCR/B	PFCR/B	LFDR-TC
6	LFDR-TC	LFDR-TC	LFDR-TC	LFDR-TC	LFDR-TC	PFCR/B
7	LCNT	LCNT	LCNT	LCNT	LCNT	LCNT
8	LFDR-TR	LFDR-TR	FMDF	FMDF	LFDR-TR	LFDR-TR
9	FMDF	LFCR	LFDR-TR	LFDR-TR	FMDF	FMDF
10	LFCR	FMDR	LFCR	LFCR	LFCR	LFCR
11	SSP	SSP	SSP	SSP	SSP	SSP

Indicates Virtual Tie

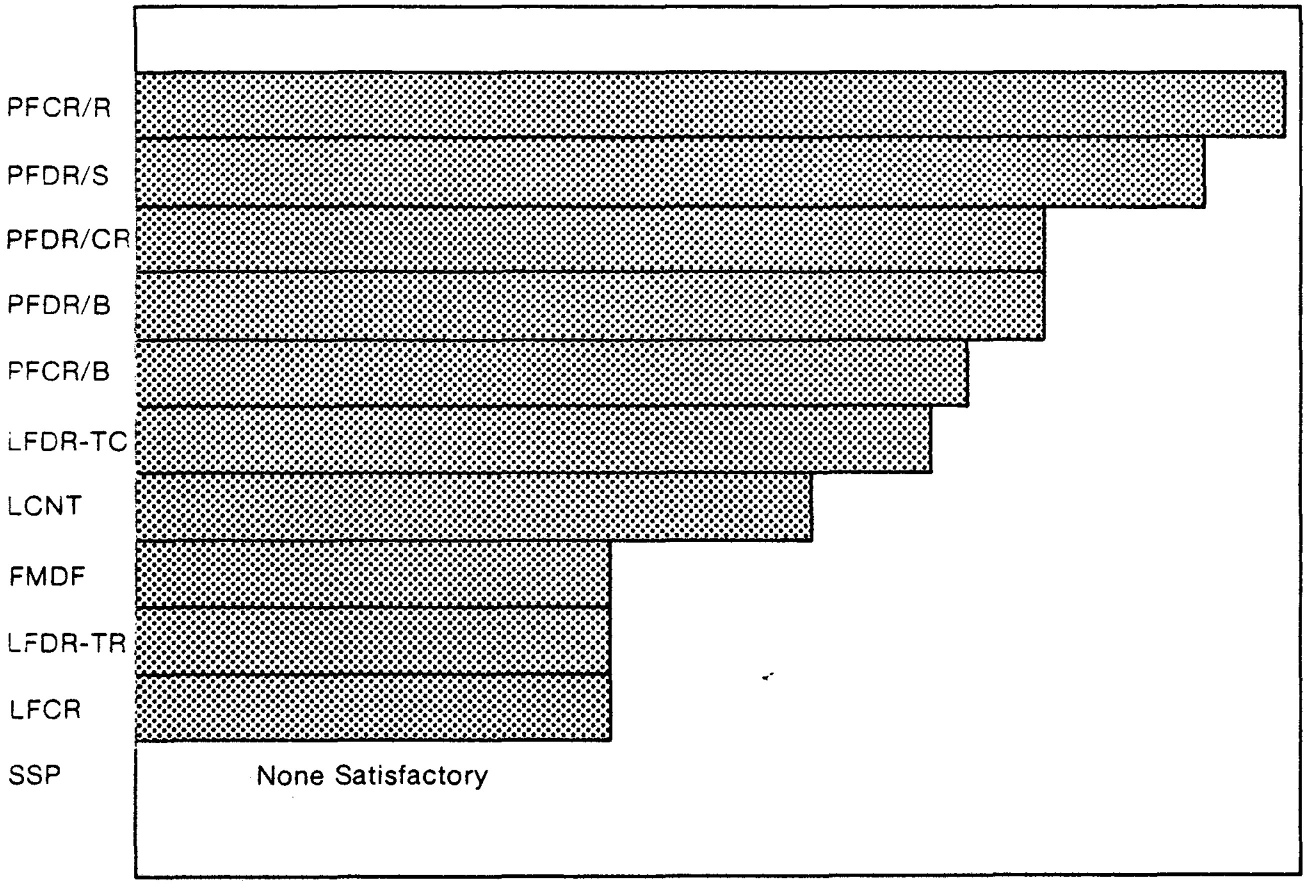

Figure 4-2. Relative System Utility (Group A)

Table 4-3. FINAL OVERALL RANKING

Group	Rank	System
I	1	Point focus central receiver with Rankine power conversion (PFCR/R)
	2	Parabolic dish collectors with distributed Stirling engines (PFDR/S)
II	3	Parabolic dish collectors with central Rankine power conversion (PFDR/CR)
	4	Parabolic dish collectors with distributed Brayton engines (PFDR/B)
	5	Point focus central receiver with Brayton power conversion (PFCR/B)
	6	Parabolic trough system (LFDR-TC)
	7	Low concentration, nontracking CPC system (LCNT)
III	8	Line focus central receiver system (LFCR)
	9	Fixed mirror, distributed focus bowl system (FMDF)
	10	Segmented trough with tracking receiver system (LFDR-TR)
	11	Shallow solar pond system (SSP)

Table 4-4. HIGHEST RATED SYSTEM VARIATIONS

System	Highest Rated Variations
PFCR/R	10MW/0.7CF
PFDR/S	10MW/0.35CF (No Storage) & 10 MW/0.7CF
PFDR/B	10MW/0.34CF (No Storage)
PFCR/B	10MW/0.27CF (No Storage) & 10 MW/0.4CF
LFDR-TC	10MW/0.34CF (No Storage) & 10 MW/0.4CF
LCNT	10MW/0.4CF
PFDR/CR	10MW/0.65CF
LFDR-TR	10MW/0.4CF
FMDF	10MW/0.4CF & 5MW/0.4CF
LFCR	10MW/0.4CF

4.1.3 Sensitivity Analysis

Two basic types of uncertainty may affect the ranking results. The first deals with uncertainty in prediction of system attribute values and the second arises from the quantification of the decision process used in the MADA. The sensitivity of the rankings was examined with respect to both types of uncertainty in order to ascertain whether a consistent and reliable ranking could be developed.

Sensitivity to attribute value variations (uncertainty in the system model) was tested in two ways. First, the systems were ranked using expected values based on assumed triangular probability distributions, instead of the median (or nominal) values originally assigned each attribute. Changes in the ranking are shown in Table 4-5. The ranking of the best four systems (PFCR/R, PFDR/S, PFDR/CR, and PFDR/B) was not affected by the change to expected value data. However, the central receiver Brayton concept (PFCR/B) moved significantly downward in the ranking, while the LFDR-TR cannot be ranked at all because its capital costs exceeded the limits of the attribute.

Table 4-5. **SYSTEM RANKING USING EXPECTED VALUE VS. NOMINAL VALUE DATA (Overall Avg Decision Maker)**

	Most Likely		Expected Value	
System	Rank	Utility	Rank	Utility
PFCR/R	1	0.58	1	0.56
PFDR/S	2	0.56	2	0.53
PFDR/CR	3	0.53	3	0.51
PFDR/B	4	0.53	4	0.49
PFCR/B	5	0.51	7	0.43
LFDR-TC	6	0.50	6	0.46
LCNT	7	0.47	5	0.47
FMDF	8	0.42	8	0.38
LFDR-TR	9	0.42	No Satisfactory Option	
LFCR	10	0.42	9	0.38

Only three attributes were used for a sensitivity analysis of variation in actual attribute values at the extremes of the probable ranges. The order of the top four concepts (PFCR/R, PFDR/S, PFDR/CR, and PFDR/B) was very sensitive to variations in capital cost. However, these four systems remained consistently well above the other concepts in all tests. Capacity factor variations had negligible effect on the ranking, while changes in O&M were generally of consequence to the ranking only where a positive change in O&M values caused O&M to exceed the scale bounds of 15 mills/kWh.

We conclude from these sensitivity tests that the ranking of the PFCR/R, PFDR/S, PFDR/CR, and PFDR/B as the best four concepts is consistent and basically imperturbable. However, changes in expected capital costs would affect the exact placement of these concepts within the top four places.

To determine the effects of uncertainty in decision analysis input factors on the decision process, several approaches were used:

- Many decision makers were sampled.
- Average ratings were used.
- Hypothetical decision makers with different attribute weighting schemes ranked the systems.
- Selective attributes were dropped and the systems were reevaluated.

In order to determine the role of uncertainty in decision maker characterization, sensitivity to variations in decision maker preferences was tested. The driving factor in the decision process is the relative weighting given to the attributes. To examine the effect of variations in attribute weighting, extreme viewpoints were represented by hypothesized weighting schemes. These schemes might be broadly representative of concerns for (1) profit, (2) social impact, (3) market value, and (4) indifference. Table 4-6 gives the weights for these four variations and the base case—the average decision maker of Group C.

Table 4-6. ATTRIBUTE WEIGHT VARIATION

	Concern				
Attribute	Base Case	Profit	Social Impact	Market Value	Equal Weight
Capital Cost	0.27	0.33	0.27	0.27	0.14
Capacity Factor	0.24	0.33	0.24	0.24	0.14
O & M	0.15	0.33	0.15	0.15	0.14
Safety	0.09	—	0.39	0.09	0.14
Environment	0.09	—	0.39	0.09	0.14
R & D Costs	0.09	—	0.09	0.38	0.14
Applications	0.09	—	0.09	0.38	0.14

Table 4-7 shows a revised ranking for each "viewpoint" tested. It is important that these rankings represent extreme variations and do not reflect viewpoints of any of the decision makers interviewed. The only significant variation occurs when the top-ranked PFCR/R drops from first to sixth place when considered by the hypothetical environmental/safety advocate. It is interesting to note the consistency of the final column (ranking for equal attribute weights) with the original ranking. Note, however, how some of the detail of the ranking is lost when equal weights are applied.

Table 4-7. ATTRIBUTE WEIGHT VARIATION RANKINGS

	Rankings				
System	Base Case	Profit	Social Impact	Market Value	Equal Weight
PFCR/R	1	1	7	1	1
PFDR/S	2	2	2T	4T	2T
PFDR/CR	3	3	2T	2T	2T
PFCR/B	5	5T	2T	4T	2T
PFDR/B	4	4	1	6T	2T
LFDR-TC	6	5T	2T	2T	2T
LCNT	7	5T	2T	6T	2T
LFCR	8T[a]	8T	9T	10	8T
FMDF	8T	8T	9T	6T	8T
LFDR-TR	8T	8T	8	6T	8T
SSP	All Variations Eliminated By High Costs				

[a]T indicates virtual tie

4.1.4. Conclusions of the Decision Analysis

This summary is a point by point litany of the major conclusions of the decision analysis.

- Larger systems (10MW, then 5MW) rank consistently higher than the smaller systems (1MW).

- The highest rated systems are:
  PFCR/R
  PFDR/S
  with the PFDR/S system ranking high over the widest range of size and capacity factors.
- At other capacity factors these systems also rank high:
  PFDR/CR
  PFDR/B
  PFCR/B
  LFDR-TC
  LCNT
- Two systems ranking consistently low are:
  FMDF
  LFCR
- The shallow solar ponds are not acceptable to this sample of users.
- Rankings are consistent across wide ranges of user groups.
- Rankings are consistent across a reasonably wide range of data uncertainty.

4.2 ECONOMIC ANALYSIS

Relatively large initial capital expenditures and generally small (O&M) costs are typical of solar thermal electric power systems. The only effective means of comparing the actual cost of solar power to the cost of conventionally generated power is through an annualization, or levelization, of all costs over comparable system lifetimes. Fortunately, it is common utility practice to calculate the present value of revenue requirements (or the levelized revenue requirements per unit of production) in comparing alternative capacity additions. Revenue requirements, as the name implies, is the total revenue which must be collected by the utility through sales of a plant's production in order to exactly cover the cost of design, installation and operation of that plant in addition to an adequate return to investors or bondholders. The need to provide adequate return to invested capital implies that the distribution of costs must be properly discounted; hence, utilities speak of the present value of all revenue requirements (or costs) over the plant lifetime.

The strong influence of the discount rate and the dominance of initial capital costs in the calculation of levelized revenue requirements for solar power systems make any economic analysis extremely sensitive to rate of return and tax preference assumptions. As a result, there is the possibility of considerable variability in the absolute magnitude of levelized busbar energy costs (levelized revenue requirements per unit of energy output) between individual utilities. This section presents the rationale behind the selection of the economic ground rules for this study, the results of that economic analysis, a sensitivity analysis for economic scenarios that represent other possible trends, and an analysis of busbar energy costs during periods of inflation.

4.2.1 Baseline Analysis

The economic ground rules adopted for this study are presented in Table 2-2. The weighted cost of capital (discount rate) of 8.6% is the after-tax return based on a debt/equity ratio of 1.0, a cost of debt of 8.0% and a cost of common equity of 11.2%. The effective composite income tax rate of 40% is less than the statutory limit of 48% because of implicit adjustment for various forms of tax preference. All of the ground rules in Table 2-2 are similar to the base case analyzed in Doane, et al. [2] and are typical of an investor-owned utility in 1976.

Figure 4-3 shows the relative influence of principal amortization, interest, taxes, O&M, and other cost elements on the total levelized busbar energy cost ($\overline{\text{BBEC}}$). The very large portion of costs associated with return to investors and interest on bonds should be noted. It is apparent that calculated power costs from solar energy are significantly influenced by the cost of capital. Levelized busbar energy costs were calculated for each system and capacity/capacity factor combination. Table 4-8 shows those values, in terms of 1978 mills per kWh.

4.2.2 Sensitivity Analyses

Changes in utility financing and, in general, economic conditions since 1976 require that other economic ground rule scenarios be tested. In particular, four scenarios are analyzed for the PFDR/S system at $10MW_e$ and 0.35 capacity factor. The relative effect of the change in ground rules will be approximately the same for other systems.

Table 4-9 gives the economic scenarios chosen and the baseline case for comparison. Case A is for an investor-owned utility showing increases in the market cost of capital and in interest (predominantly due to inflation and risk premiums for solar), increased inflation and explicit accounting for tax preference and accelerated depreciation. Case B is for a public utility financed entirely through debt issues at 8%. Tax preferences do not apply, since public utilities do not pay income taxes. Cases C and D show the effect of heavy debt financing at low interest (perhaps a government loan guarantee program) on both private and public utility costs. The significant reduction in $\overline{\text{BBEC}}$ reflects the advantages of heavily leveraged financing and low discount rates on solar economics.

While the reductions shown are encouraging, it should be recognized that Cases A and B represent the realistic requirements of utilities today.

Sensitivity runs were performed for the PFCR/R and PFDR/S systems at $5MW_e$ and 0.4 capacity factor. The nominal BBEC for the PFDR/S at those conditions was 101 mills/kWh. With an improved engine efficiency (48%) and lower concentrator cost ($\$75/m^2$ installed), the $\overline{\text{BBEC}}$ dropped to 89 mills/kWh, as shown in Table 4-10. Both the higher engine efficiency and lower concentrator costs might be achieved as a result of a vigorous R&D program. Further reduction of the $\overline{\text{BBEC}}$ to 76 mills/kWh resulted from elimination of the ground rule that required that the plant never deliver more than its rating; i.e., any "excess" electricity which could not be stored must be wasted. Using economic scenario D, described above, lowered the $\overline{\text{BBEC}}$ to 54 mills/kWh. Table 4-11 shows the assumptions and results of similar sensitivity analyses for the PFCR/R system which yielded $\overline{\text{BBEC}}$ of 50 mills/kWh.

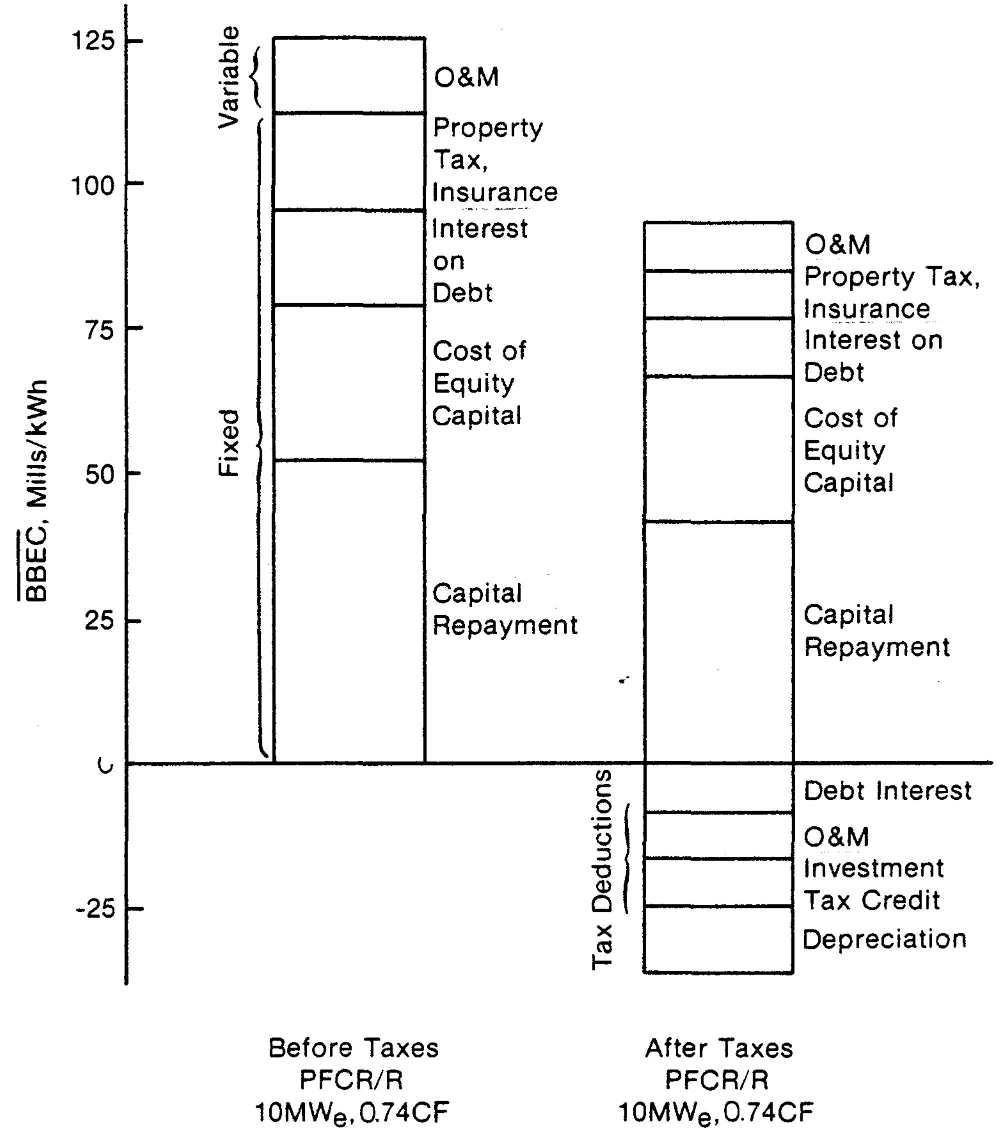

Figure 4-3. Breakdown of $\overline{\text{BBEC}}$ into Financing Components

Table 4-8. $\overline{\text{BBEC}}$ OF 1-10 MW_e SOLAR THERMAL ELECTRIC SYSTEMS (MILLS/kWh)

Rated Capacity (MWe)	Capacity Factor	Generic System										
		PFCR/R	PFCR/B	PFDR/S	PFDR/B	PFDR/R	LFCR	FMDF	LFDR-TC	LFDR-TR	LCNT	SSP
1	N/S	156	147	108	123	147	250	214	149	242	187	452
	0.4	136	151	111	125	137	202	169	143	190	155	1781
	0.7	109	124	104	118	115	167	147	131	170	136	N/A
	opt	107	123	101	117	106	163	147	131	167	131	452
5	N/S	132	130	96	111	131	186	180	126	202	159	401
	0.4	115	126	101	115	123	153	146	126	164	135	1766
	0.7	99	120	98	112	103	125	130	117	150	119	N/A
	opt	98	115	95	111	101	121	130	116	149	117	401
10	N/S	119	122	93	108	129	175	168	120	193	153	392
	0.4	106	129	99	113	127	144	143	121	159	133	1763
	0.7	94	123	96	111	108	122	123	114	147	119	N/A
	opt	93	121	93	108	103	116	123	113	146	117	392

Table 4-9. Economic Scenarios and Resultant Busbar Energy Costs for Alternative Cases

Scenario	τ	k_d	D/V	k_c	C/V	k_p	P/V	g	β_1	β_2	g_c	g_{om}	ITC	DPF	$\overline{BBEC}$
Baseline	0.40	0.08	0.50	0.112	0.50	0.10	0	0.06	0.02	0.0225	0.06	0.07	0	SL	93
Case A	0.50	0.09	0.53	0.150	0.35	0.10	0.12	0.08	0.02	0.0225	0.08	0.08	0.07	SYD	99
Case B	0	0.08	1.0	0.150	0	0.10	0	0.08	0.02	0.0225	0.08	0.08	0	-	76
Case C	0.50	0.06	0.75	0.150	0.17	0.10	0.08	0.08	0.02	0.0225	0.08	0.08	0.07	SYD	78
Case D	0	0.06	1.0	0.150	0	0.10	0	0.08	0.02	0.0225	0.08	0.08	0	-	71

Note: All Cases Assume a 30-Year System Lifetime.

where

τ = Effective Income Tax Rate

k_d = Annual Rate of Return on Debt

D/V = Ratio of Debt to Total Capitalization

k_c = Annual Rate of Return on Common Stock

C/V = Ratio of Common Stock to Total Capitalization

k_p = Annual Rate of Return on Preferred Stock

P/V = Ratio of Preferred Stock to Total Capitalization

g = Rate of General Inflation

β_1 = Annual "Other Taxes" as a Fraction of Capitalization

β_2 = Annual Insurance Premiums as a Fraction of Capitalization

g_c = Escalation Rate for Capital Costs

g_{om} = Escalation Rate for Operating Costs

ITC = Investment Tax Credit

DPF = Method of Depreciation

SL = Straight Line

SYD = Sum-of-the-Years' Digits

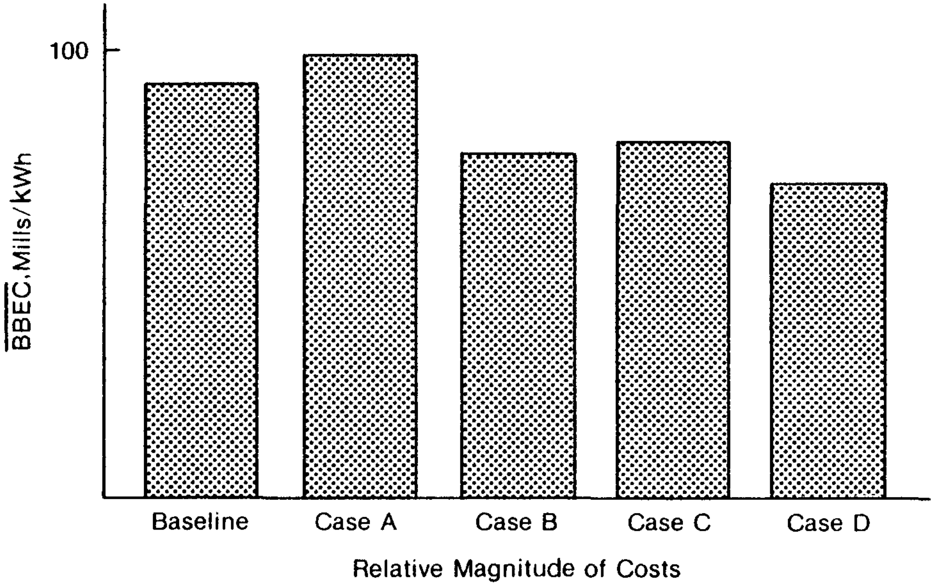

Table 4-10. SENSITIVITY ANALYSES, PFDR/S $5MW_e$ 0.4 CF

Concentrator Cost, $\$/m^2$	100	75	75	75
Engine Efficiency	.42	.48	.48	.48
Economic Scenario	baseline	baseline	baseline	D
Waste "Excess" Electricity	Yes	Yes	No	No
$\overline{\text{BBEC}}$, mills/kWh	101	89	76	54

Table 4-11. SENSITIVITY ANALYSES, PFCR/R $5MW_e$ 0.4 CF

Concentrator Cost, $\$/m^2$	75	40	40
Engine Efficiency	.34	.40	.40
Economic Scenario	baseline	baseline	D
$\overline{\text{BBEC}}$, mills/kWh	115	74	50

4.2.3 The Effects of Inflation

Levelized busbar energy costs ($\overline{\text{BBEC}}$) represent the constant cost of producing power from a solar thermal electric power system in terms of current dollars over the lifetime of the system. In this way, $\overline{\text{BBEC}}$ resembles a home mortgage payment which remains a constant numerical amount. The real cost of that payment, in terms of dollars of constant purchasing power, actually decreases over the term due to the effects of inflation. To account for this loss of real value, $\overline{\text{BBEC}}$ actually overcharges for solar electric power in the early years (in real dollar terms) and undercharges in later years. A distribution of annual energy costs that has the same present value as $\overline{\text{BBEC}}$, but which is calculated in terms of real dollars is shown in Fig. 4-4. Assuming an inflation rate of 8%, the real $\overline{\text{BBEC}}$ in year 1 (BBEC_0) is only 49.5% of the levelized charge. The two are equal in year 13, and from then on $\overline{\text{BBEC}}$(t) exceeds BBEC.

Figure 4-4 is important for two reasons. First, it is important to recognize the meaning of $\overline{\text{BBEC}}$ and of the equivalent distribution of BBEC(t) in real terms, showing the effect of inflation. Second, caution must be applied in comparing solar and conventional alternatives. If the unit cost of producing power from an oil-fired plant using first year fuel costs, fixed costs, etc., is calculated, then the solar cost for comparison is BBEC_0, not $\overline{\text{BBEC}}$. This compares costs at a common point in time without consideration of escalation and inflation. The proper cost comparison with solar levelized energy cost, $\overline{\text{BBEC}}$, is the 30-year levelized cost of the conventional alternative under the same scenario. In many cases, fuel cost escalation may make the levelized cost of fossil-fueled alternatives over plant lifetime substantially greater than currently perceived costs.

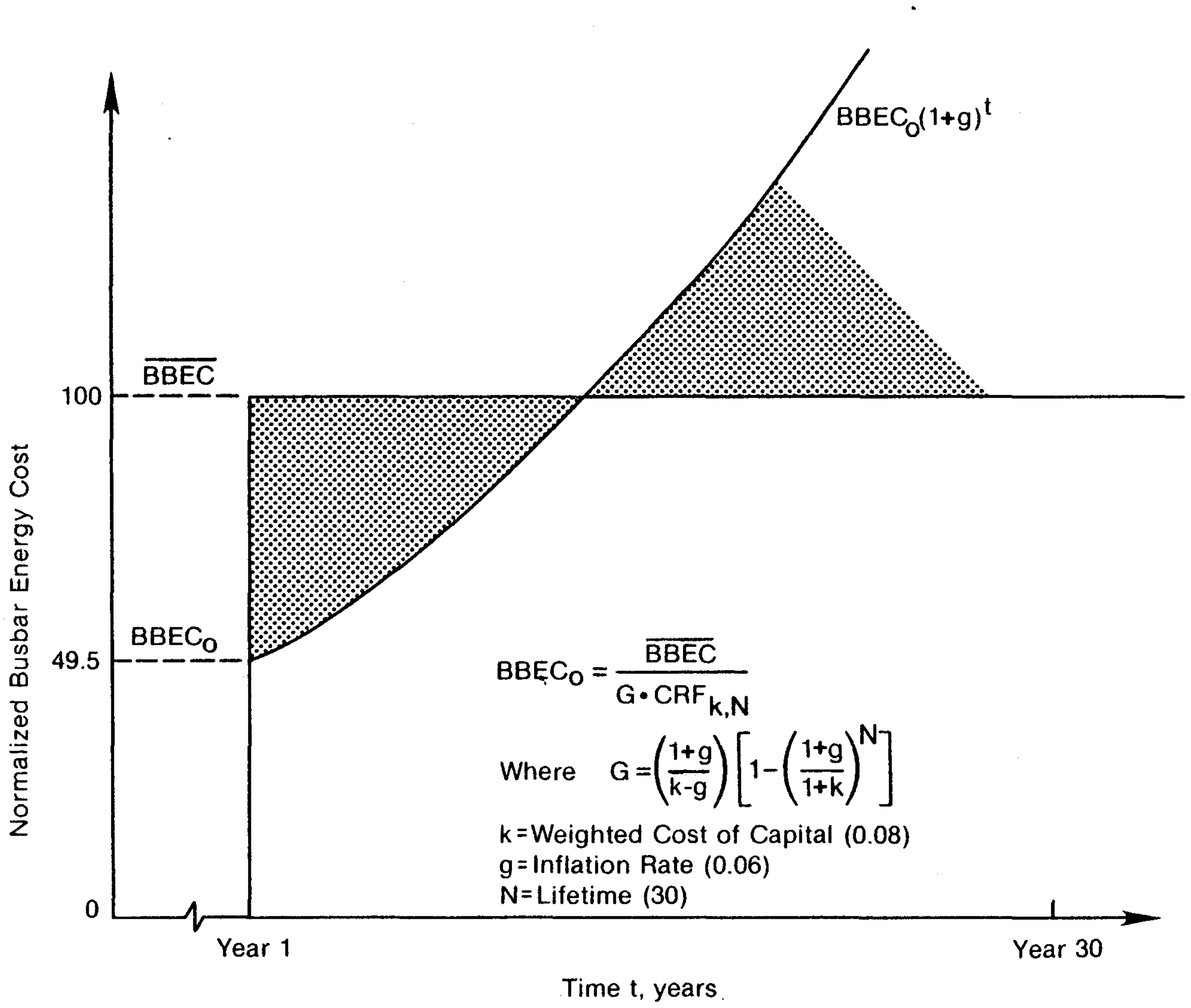

Figure 4-4. Difference between Levelized Energy Costs in Nominal and Real Dollar Terms (baseline economic scenario)

SERI

SECTION 5.0

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APPENDIX A

COSTING PHILOSOPHY AND KEY COST ELEMENTS

One of the most critical tasks has been to project the mid-1990 costs and performance of advanced subsystems and components, taking into account expected technology advances and the effects of mass production. System and O&M costs, along with performance, are combined in a specific economic scenario to provide levelized annual energy cost (mills/kWh).

The relatively undeveloped state of most solar equipment today and the lack of large scale production precludes the use of current prices. If they were used, the resulting capital and levelized energy costs would be unrealistically high for 1990. Therefore, a different technique of estimating costs was used. Cost data came from a variety of sources, including: (1) direct quotes from manufacturers, (2) estimates by consultants, (3) reports and technical papers from contractors and other laboratories, (4) comparison with established costs, and (5) SERI independent estimates.

For a given component or system element, all available cost estimates were assembled from written sources. Adjustments were made to such economic factors as contingency, so that all estimates were on a common basis. From this range of costs, a reasonable estimate was selected that: (1) would have reasonable expectation of being achieved by mid-1990; (2) assumed varying degrees of mass production, depending upon the number of components per system; (3) was substantiable through either documentation or analysis; (4) was dependent upon R&D already in progress; and (5) was based upon the necessity for making a near-term commitment to develop more promising systems at the expense of others. These cost estimates are not based upon either the goal or value of the system or the ultimate cost and performance potential of any technology. Where resulting costs differed greatly from similar costs for other systems, they were independently reviewed and rechecked by SERI and verified.

The resulting capital and O&M costs were used as inputs to the economic simulation in BALDR-1. Appendix B describes this simulation and its use. Table A-1 presents the installed unit concentrator costs for each generic system. Also shown is the corresponding net engine efficiency.

Figure A-1 shows the total capital cost breakdown by subsystem for the baseline plant design (capacity = 5MW$_e$, capacity factor = 0.4) for each of the generic systems analyzed.

Table A-1. UNIT CONCENTRATOR COSTS AND CORRESPONDING ENGINE EFFICIENCY

Generic System	Concentrator Cost Installed ($/m^2)	Nominal Engine Efficiency
PFCR/R	75	.34
PFDR/S	100	.41
PFDR/CR	100	.34
PRDR/B	100	.32
PFCR/B	75	.38
LFDR-TC	85[a]	.25
LCNT	55[a]	.25
LFCR	75	.34
FMDF	100	.32
LFDR-TR	85[a]	.25
SSP	22[a]	.064

[a] Includes receiver cost

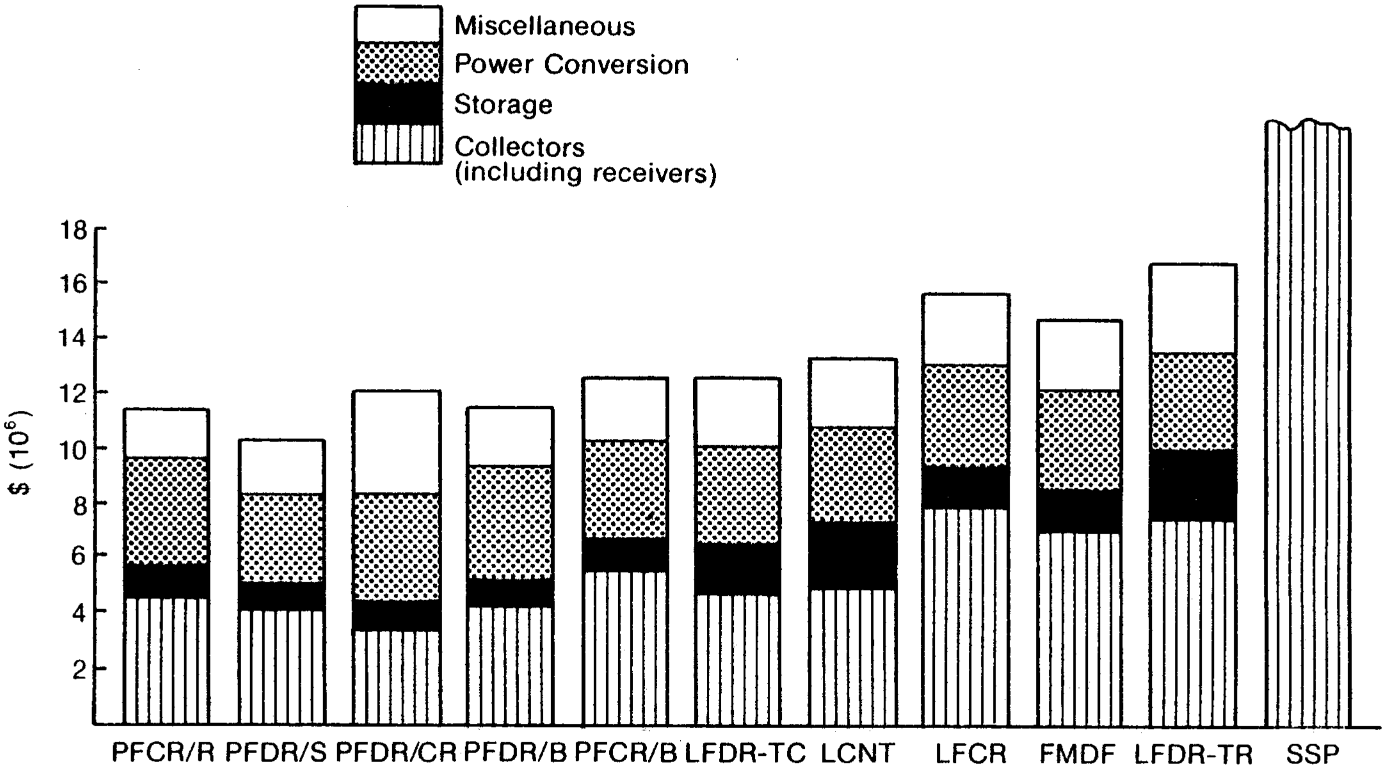

Figure A-1. Initial Plant Cost (5MW$_e$ @ 0.4 CF)

APPENDIX B

COST AND PERFORMANCE SIMULATION

The performance and life cycle cost of each generic system was modeled with the system simulation, BALDR-1. BALDR-1 consists of three interfaced computer models: FIELD, POWER, and ECON. Each of these models may be run independently, or they may be coupled and run as a set. The FIELD code models the optical and thermal performance of the collector field and thermal transport. The POWER code models the power conversion and energy storage components. The ECON code models the initial capital cost of the power plant and the life-cyle busbar energy cost. A flow chart of the system simulation is shown in Fig. B-1.

B.1 FIELD CODE

The FIELD code is a second-order simulation based on a similar code previously developed by the Aerospace Corporation with modifications by JPL [B-1] and Batelle Pacific Northwest Laboratories (PNL) [B-2]. The FIELD code uses 15-minute incremental meteorological data read from a modified SOLMET format weather tape. The FIELD code currently models the performance of collector subsystems in four different ways depending on the type of collector subsystem being modeled. There are separate modules to calculate the optical and thermal performance of each generic collector type. If the need should arise to model other collector types, additional optical and thermal performance modules can be added.

The output from FIELD is a set of daily arrays of the thermal energy collected from the field of collectors (ECF). Each daily array contains 96 records of ECF, one record corresponding to each simulation time step. The option exists to average ECF into hourly increments, resulting in 24 record daily arrays of ECF. Several other variables are also passed to the POWER code, such as ambient temperature, unit collector area, etc.

B.2 POWER CODE

Like the FIELD code, the POWER code is a second-order simulation based on the Aerospace computer code as modified by JPL [B-1] and Batelle PNL [B-2]. POWER differs from the earlier codes primarily in that it provides the option of using different control algorithms for both the operation of power conversion equipment and the dispatch of electrical and thermal storage. The control algorithm which is currently operational, CNTRL2, differs from control strategies used in previous power codes in six areas:

- The capability to model both thermal and electrical storage for the same system is specifically included;
- A weighting factor may be used to reduce the "value" of electricity delivered above plant rating;
- Overload operation of the power conversion equipment may be allowed;
- Thermal storage is modeled in series with the receiver and power conversion equipment at approximately receiver outlet temperature;

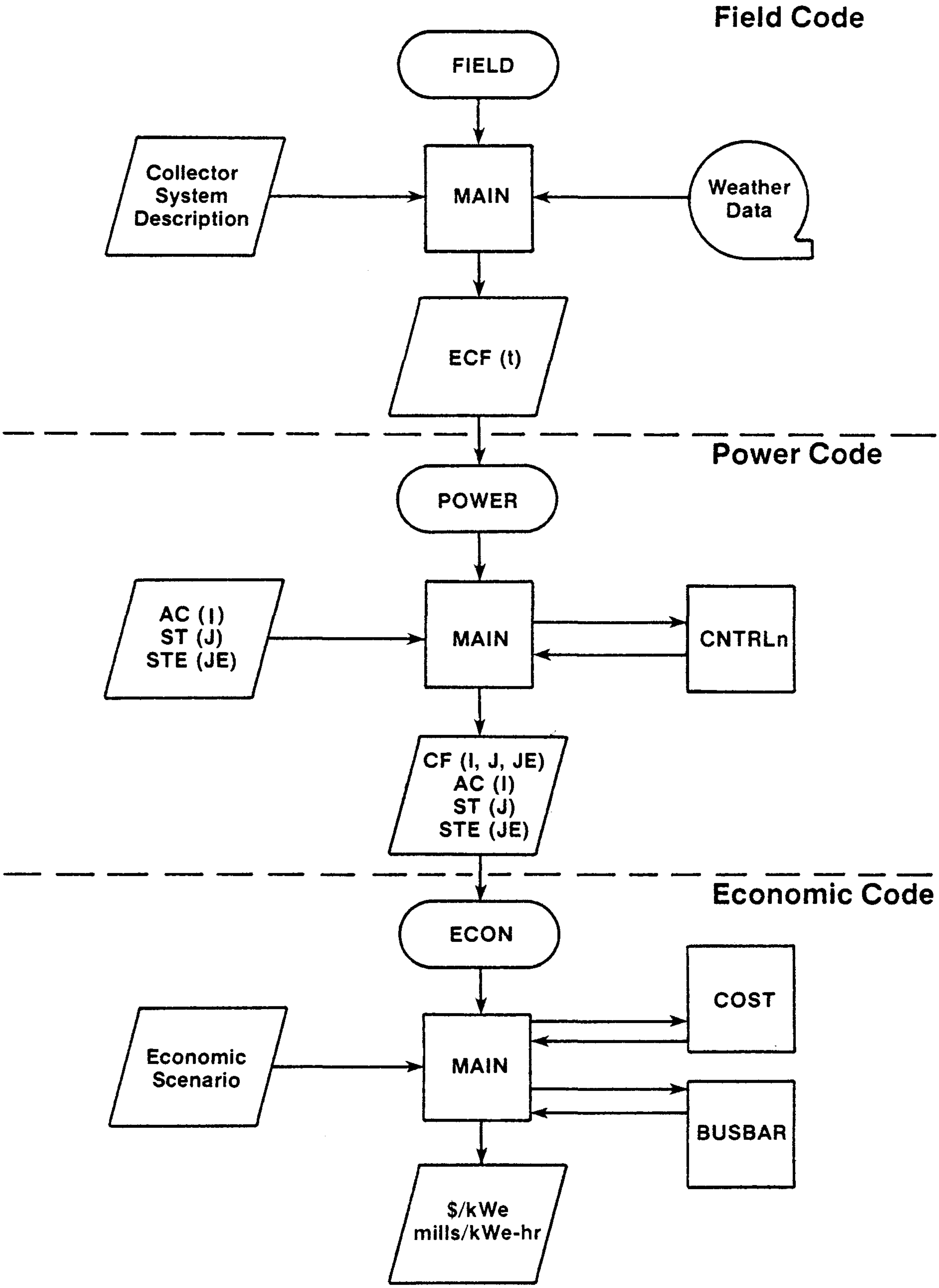

Figure B-1. Simplified Flow Chart for BALDR-1 Performance and Cost Simulation Codes

- The decision as to the dispatch of energy from the collector field is made for the current time step and models the type of control likely to be used in actual plants; and
- Depletion of thermal storage is limited to the value which will assure a hot start-up the following morning.

Component models in POWER were written in several levels of detail according to their impact on plant performance including table look-up with linear interpolation, explicit calculation based on time dependent variables, and explicit calculation based on parameters assumed not to vary with time.

The POWER code calculates the electricity delivered to the grid at each time step and sums it for one year. The total electrical energy delivered during the year is divided by the total electricity which could have been delivered had the plant operated at rated capacity for the entire year, thus yielding the plant capacity factor (CF). This capacity factor is calculated for each plant described by an element of the three-dimensional matrix of collector field sizes (AC), thermal energy storage sizes (ST), and electrical storage sizes (STE).

The calculated capacity factor, along with the corresponding collector field size, thermal storage size, and electrical storage size, is output for use by the ECON code. The plant rated capacity and generator size are also output to ECON.

B.3 ECON CODE

The ECON code includes two major subroutines (COST and BUSBAR) that are based on codes originially written by JPL [B-1 and B-3]. Using the output from POWER, ECON determines a capital cost and a life cycle busbar energy cost for each plant configuration based on either the thermal energy or the electrical energy produced, thus allowing the plant to be modeled as a producer of either electricity or process heat.

Subroutine COST uses unit costs as inputs to determine the cost streams for both capital expenditures and operations and maintenance (O&M). Capital costs are determined for each of four subsystems: (1) collector and receiver, (2) electrical and/or thermal storage, (3) power conversion, and (4) miscellaneous (including land, thermal and electrical transport, and spares and contingencies). These costs currently are distributed over the plant construction period as a uniform series of payments. With slight modifications to the code, COST could also create a nonuniform cost stream.

Subroutine BUSBAR is based on the Utility-Owned Solar Electric Systems (USES) model, a conventional present value analysis adapted for solar electric power plants by JPL [B-4]. It calculates the busbar energy cost in constant-year dollars which will generate system-resultant revenues equal to the system-resultant costs. The inputs for BUSBAR represent two types of information: system cost data and accounting information. The cost data as currently used consists of the arrays of capital costs and O&M costs that are generated in subroutine COST. Escalation rates are input for capital and O&M in addition to the general inflation rate.

The second group of input data, the accounting information, represents the variables that are used to determine the cost of capital. From this data, the discount rate, fixed charge rate, and the capital recovery factor are determined in BUSBAR.

B.4 REFERENCES

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APPENDIX C

A RANKING METHODOLOGY USING MULTI-ATTRIBUTE DECISION ANALYSIS

To provide a complete technology assessment, it was necessary to construct not only the system model, but also the value model in order to provide a defensible and rational ranking of technological options. Technology assessments very often generate large quantities of useful data concerning the performance, cost, and impacts of technological options while leaving a choice among the options to brief and subjective concluding arguments that expose few, if any, logical steps in the process of decision making. Even worse, some studies make no attempt to draw conclusions. If decisions must be made which will be based on the carefully generated results of a technical system study, it is only reasonable that a careful and deliberate analysis of choices and values also be made.

As stated by R. A. Howard, "decision analysis is a term that describes a combination of philosophy, methodology, practice, and application useful in the formal introduction of logic and preferences to the decisions of the world" [C-1]. The use of decision analysis in this study was a natural response to the need to construct and test a "value model" as described above and to provide a realistic and defensible ranking of options for solar thermal power supply in the mid-1990s. There are many methods of decision analysis in use today, not all of which are applicable to this study. For example, most ranking problems require a multi-objective optimization which allows for a large degree of uncertainty in data. The method of decision analysis described below is one procedure suited to this general class of decision problem. Other methods, such as multi-objective suboptimization, Delphi techniques, bidding games or simple pair-wise comparison techniques might have been used. However, the selected method is straightforward and has been successfully used in previous studies of a similar nature. General agreement was reached by SERI, Battelle PNL, and JPL on the application of this methodology and upon the basic merits of this type of approach.

C.1 MULTI-ATTRIBUTE DECISION ANALYSIS

During the late 1960s and early 1970s, methods for dealing with decisions involving multiple, sometimes conflicting, objectives were developed and applied by several decision analysts. Probabilistic methods of dealing with the multi-objective problem were presented in a book by R. L. Keeney and H. Raiffa [C-2]. Actual applications of multi-attribute decision analysis during this time period helped to refine and demonstrate the methodology.

The wide range of decision problems to which the method has been applied since 1960 testifies to its flexibility. For instance, the method has been applied to problems as disparate as determining optimum blood bank policies in a Massachusetts hospital [C-3] to the ranking and selection of nuclear power plant sites in the Northwest [C-4]. A short list of the applications of multi-attribute decision analysis to problems relating to energy is shown in Table C-1.

Table C-1. PREVIOUS APPLICATIONS OF MULTI-ATTRIBUTE DECISION ANALYSIS IN ENERGY-RELATED STUDIES

Problem	Sponsor
Selection of suitable sites for new large-scale nuclear generating stations in Washington and Oregon	Washington Public Power Supply System
Ranking of proposed pumped storage sites in Arizona	Arizona Public Service Co.
Environmental assessment of solar energy system alternatives	EPRI
Comparing underground vs. surface siting for nuclear power plants	Sandia
Selection for a site for a solar total energy system pilot project	Sandia

Multi-attribute decision analysis, as adopted in this study, is described in a report by Feinberg et al. [C-5]. In this report three major elements of the application of this methodology are described: definition of the problem, questionnaire development and interviews, and the actual ranking. Creation of a problem structure is described in detail in Appendix D. The following paragraphs summarize the major elements of the methodology.

The problem was first reduced from a main objective to a set of independent criteria which are measured by quantitive or subjective attributes. The complexity of the formal analysis generally does not allow the consideration of more than ten attributes. Therefore, careful consideration is necessary to select those attributes that: (1) have major importance to the decision; (2) are independent; (3) are measurable; (4) are differentiable between options being considered; and (5) are familiar to the decision maker.

During the second step, interviews were conducted with typical decision makers or their surrogates to obtain the proper data which can be used in a "simulation" of a decision maker's thought process. A simplified method of questioning was developed for use in this study. This method permits assessment of utility preferences over the scale of each attribute, and the relative weighting of each attribute, in a short series of lottery-type questions.

In the third and last step, results of the interviews were used to calculate the coefficients of a multiplicative form of the utility function. The value of this function, given the actual attribute values of a system, is an absolute and quantitative measure of the "utility" of this system to the decision maker. An ordering of these values then provided a ranking.

The absolute ranking of any one decision maker is not definitive for a technology ranking in general; therefore, comparison of the consistency in the ranking among decision makers must be performed. The methodology has an important advantage in that the sensitivity of the ranking can be tested with respect to differences among decision makers. Furthermore, the sensitivity of the ranking to uncertainties in the estimate of attribute values for each system was tested. These sensitivity tests helped insure confidence in the final ranking over a wide range of user preferences and probable system performance and cost.

The use of multi-attribute decision analysis is a significant step forward in the conduct of technology assessment studies. It forces a great deal of attention to be focused on the essential elements of the problem at hand in quantitative and well-defined ways. The method offers a complete pattern of rational analysis from initial assumptions to final conclusions; leaving few, if any, areas of informational gaps or unclear logic. Conclusions are testable, both with respect to new data and with respect to uncertainties in preferences and technical information. In short, the use of multi-attribute decision analysis allows the analyst to learn about the problem and to defend the analysis, while it allows the critic to follow and effectively question the assumptions and conclusions of the study.

C.2 REFERENCES

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APPENDIX D

PROBLEM STRUCTURE

Decisions are often made using a confusing mixture of objectives, goals, values, constraints, tradeoffs and other conflicting terms and issues which must be logically arranged in order to be comprehended. Creating a logical problem structure from a simple issue statement is a process worthy of deliberate and thorough research when applying any means of formalized decision analysis. The results of the decision analysis are very sensitive to the problem structure selected and to the class of decision makers analyzed. In this appendix, the process of selecting criteria and attributes for the small power systems ranking study are discussed. Explicit and implicit assumptions and prerequisites are outlined. It is important that these be understood, for they limit the scope to which the conclusions of this study may be applied.

D.1 THE OBJECTIVE OF THE STUDY

Decision problems must have a well-defined objective for which various available alternatives will be more or less suitable. The objective of this study, as defined in the original Statement of Work and later restated, is:

> To find the most appropriate long-term ranking of solar thermal technologies for small electric power applications in the 1 MW_e to 10 MW_e range.

The broad scope of such a simple statement is somewhat hidden. For example, applications (and therefore interested decision makers) cover a range which includes electric utility companies, small communities, isolated or remote facilities, rural villages, mines and light industrial parks, agriculture and developing countries [D-1]. A decision was made early in this study to concentrate on grid-connected utility applications of small solar thermal power systems. Furthermore, the concept of "long-term" appropriateness is somewhat unclear. For the sake of uniformity, long-term is defined with respect to small power systems commercially applied in 1990 and beyond. Finally, the word "appropriate" may take on a multitude of meanings. In this study, appropriateness was defined by the importance of various issues as viewed by the utility decision maker. It was initially determined that adequate emphasis should be placed upon issues of cost, performance, environmental and safety impacts, and commercialization prospects.

D.2 CRITERIA AND ATTRIBUTES

In order to apply the methods of Multi-Attribute Decision Analysis, outlined in Appendix C, it was necessary to obtain a set of attributes upon which the performance of the alternatives could be measured and ultimately judged. Attributes are actual, measurable "properties" of any given alternative and are the measure of the degree to which an alternative satisfies some "criteria" of performance. Criteria, then, are directly related to the stated subobjectives and relate to one or more specific aspects of the subobjective. The relationship of all of these parts of the problem structure is shown graphically in Fig. D-1.

There are many criteria which relate to any one subobjective. For example, in considering the subobjective to "minimize overall cost" of the solar thermal power system,

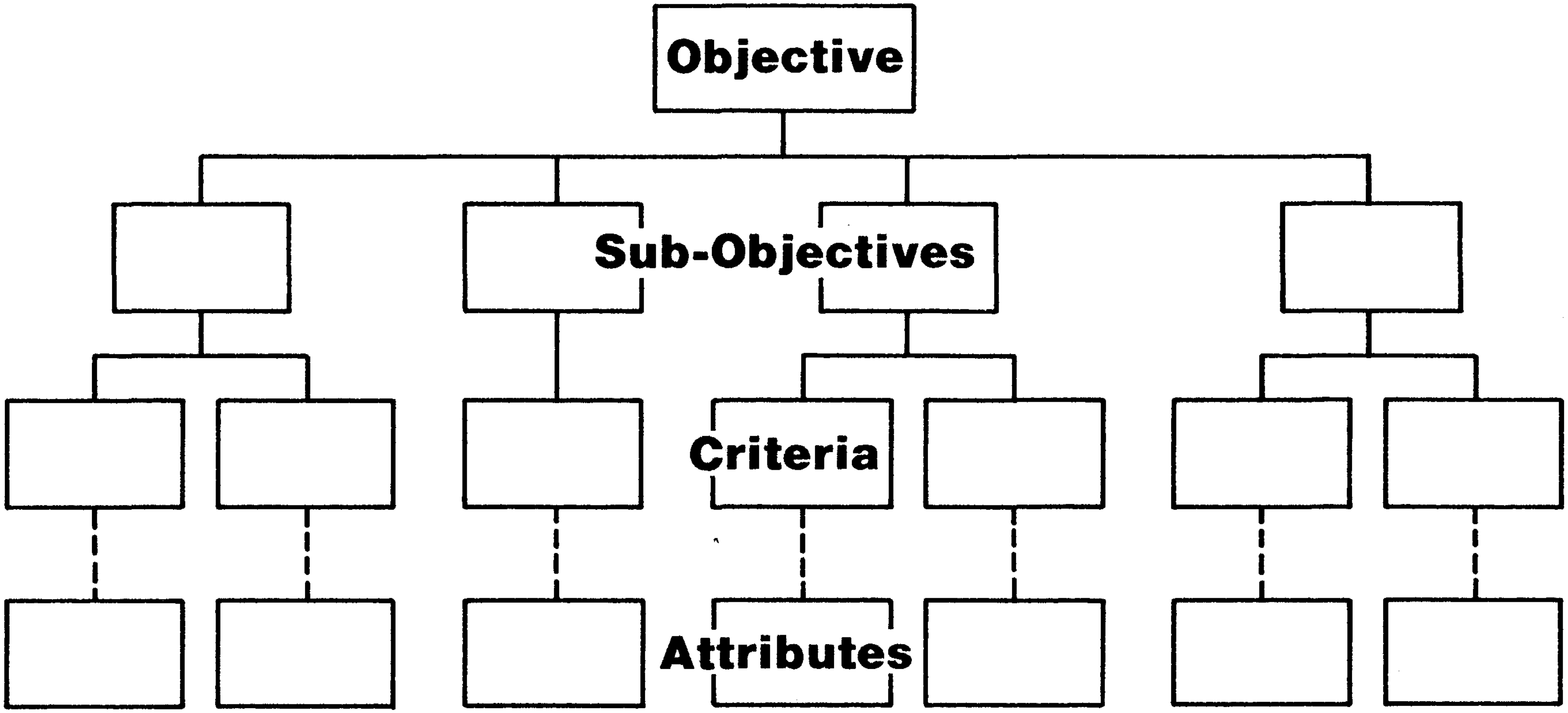

Figure D-1. Problem Hierarchy for Multi-Attribute Decision Analysis capital cost, O&M cost, levelized energy cost, annualized cost, total required revenue, operating ratios, or production cost might be considered. Each criterion represents a specific concern in the issue of "overall cost" and each may be more or less important to various decision makers. The complexity of the multi-attribute decision analysis interview would not allow more than one or two of these criteria to be considered in each subobjective. Furthermore, certain criteria represent properties of the system that are so similar that redundancy and confusion are bound to be encountered. As a result, the criteria must be selectively chosen. This is best done with the informal input of selected decision makers.

In addition to requiring a criteria set which is small enough to be comprehended in the formal interviews, several other properties should be satisfied:

- Importance - the criteria should represent significant concerns;
- Measurability - the criteria should be measurable (objectively or subjectively) in the study;
- Independence - within certain ranges, changes in one attribute should not affect preferences or tradeoffs between other attributes; and
- Differentiability - the options must not have all identical values for a given attribute.

Attributes are the specific, measurable system properties that represent criteria. For example, the criterion capital cost is represented by the attribute "total initial installed cost in $\$/kW_e$ of capacity." Capital cost might also have been represented by "the present value of total construction costs, in dollars" or by "the annualized capital cost, in dollars, over thirty years." The first attribute definition was chosen because $\$/kW_e$ is generally more familiar to decision makers.

Once the set of criteria and objectives was agreed upon, a range of values for each attribute was assigned. The scale of an attribute used in multi-attribute decision analysis must be broad enough to include all of the options deemed important enough to consider. Note that the attribute scale need not extend on its "worst" end to encompass all the alternatives. If a single criterion is deemed important enough that options not meeting some minimum (or maximum) attribute value could be dropped from consideration, then an initial screening of options can take place (see, for example, Keeney [D-2]). This avoids attribute scales in which much of the "worst" end of the scale is entirely unacceptable. Where a large unacceptable range exists the decision maker is often tempted to implicitly shorten the attribute scale, leading the decision analyst to misinterpret the results of the questionnaire unless a check is provided. On the other hand, the attribute range must be broad enough to envelope data uncertainty and/or disparity among options. The definition and range of the attributes used in this study are given in Table D-1.

Table D-1. DEFINITIONS OF CRITERIA AND ATTRIBUTES AND THEIR RANGES

Subobjective	Criteria	Attributes	Definition	Units	Range
Cost	Operating Cost	Levilized O&M Cost	The 30-year levelized nominal revenue requirement for costs associated with equipment overhaul, minor replacement, routine maintenance, site maintenance, operating labor costs, etc., for a nominal 5,000 kW_e/0.40 capacity factor plant.	mills/kWh	5.0 to 15.0
	Capital Cost	Unit Capacity Initial Costs	The total initial capital cost per unit of kW_e capacity installed, including direct transformer and switchyard costs. In 1978 dollars for a nominal 5,000 kW_e/0.40 c.f. plant installed in 1990.	$/$kW_e$ Installed	1400 to 3400
Performance	Reliability	Annual Capacity Factor	$\dfrac{\text{Total Actual Annual Energy Output (kWh)}}{\text{8760 (hrs/yr)} \times \text{Rated Capacity (5,000 } kW_e)}$	Percent	20 to 70
Impacts	Environmental Impacts	Relative Environmental Impacts	Relative environmental impacts, including effects of land use, toxic or polluting discharge, water use and/or construction impacts including requirements for scarce materials.	Subjective Scale	0 to 5
	Safety Impacts	Relative Safety	Relative safety of solar thermal plants, including hazards from concentrated sunlight, volatile or toxic fluids and high temperature or pressure.	Subjective Scale	0 to 5
Commercial Potential	R&D Requirements	R&D Expenditures	Total funding from all sources required to bring a concept from current state of cost and performance to that predicted in 1990.	$ Required Between 19980 and 1990 for One Concept	10 million 500 million
	Range of Application	Relative Market Applicability	Relative market applicability, as related to cogeneration potential, application load flexibility, siting, and construction suitability to a variety of markets.	Subjective Scale	0 to 5

D.3 REFERENCES

D-1. Feinberg, A.; Kuehn, T. J.; Miles, R. F. Jr. Decision Analysis for Evaluating and Ranking Small Solar Thermal Power System Technologies, Padadena, CA: Jet Propulsion Laboratory, January 15, 1979, Vol. II, JPL 5103-47, p. 7.

D-2. Keeney, R. L.; Nair, K. Nuclear Siting Using Decision Analysis, San Francisco, CA: Woodward-Clyde Consultants, July 1977.

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APPENDIX E

PROFILES OF DECISION MAKERS

The results of the effort in assessing basic decision-maker preferences are summarized in this appendix. Information has been obtained primarily through an interview process in which two types of information was obtained. Primarily, interviews were designed and conducted to obtain quantitative data on the form of attribute utility functions and on the relative weights placed upon those attributes (see Appendix C). Second, a great deal of information on the specific opinions of the power industry was obtained through statements made outside the context of the formal questionnaire. Together, the quantitative and qualitative results of this user preference study lend a valuable insight into the needs and values of future users of small solar thermal power systems. These results provide an independent description of the decision-maker profile.

Interviews were conducted between February and May 1979. More than 30 interviews were conducted, sampling electric utility companies (large and small investor owned, public, municipal, and rural cooperatives), utility consultants, trade journals, public regulatory bodies, and R&D personnel, both technical and nontechnical. The individuals and organizations interviewed are listed in Appendix G. A questionnaire was the primary information gathering instrument in these interviews. From the 30 interviews, the results of 24 interviews were deemed to be of sufficient quality to be included in the final sample analyzed for the rankings presented in Section 4.0. Six of the earliest interviews were used as a pretest and are not considered in the final sample.

E.1 QUANTITATIVE RESULTS

The primary purpose of the interviews was to obtain quantitative data which could be used in a multi-attribute decision analysis to "simulate" real decisions among users (utility) and interest groups (R&D staff). In particular, data was sought on:

- Reference attribute choice;
- Relative attribute weighting; and
- Utility function forms.

In the course of the interview, the decision maker chose a reference attribute and gave tradeoff information which defined the relative weights of seven attributes. The choice of a reference attribute indicates which criterion the decision maker considers most important, while the relative weights give an indication of how heavily each of the other attributes weighs in the final decision. Table E-1 summarizes the selection of reference attributes for this sample of decision makers and Table E-2 indicates the synthesis of the relative weights into a single average value for each general class of decision maker and also for the group as a whole. As might be expected, attributes related to cost (capital cost, energy cost, as reflected in capacity factor, and operating costs, O&M) are consistently rated highest. The major differences between the utilities and the R&D group are:

- R&D personnel chose capacity factor as the reference attribute more often than the utility representatives, who were evenly split between capacity factor and capital cost;

- The R&D group weighted capacity factor equally with capital cost and more heavily than did the utilities; and
- Utilities placed a higher weighting on O&M costs than did their R&D counterparts.

Table E-1. REFERENCE ATTRIBUTE CHOICE (PERCENT OF TIME CHOSEN)

Attribute	Utilities	R&D	Overall
Capital cost	50%	38%	44%
Capacity factor	42%	62%	52%
Levelized O&M	8%	0%	4%
Others	0%	0%	0%

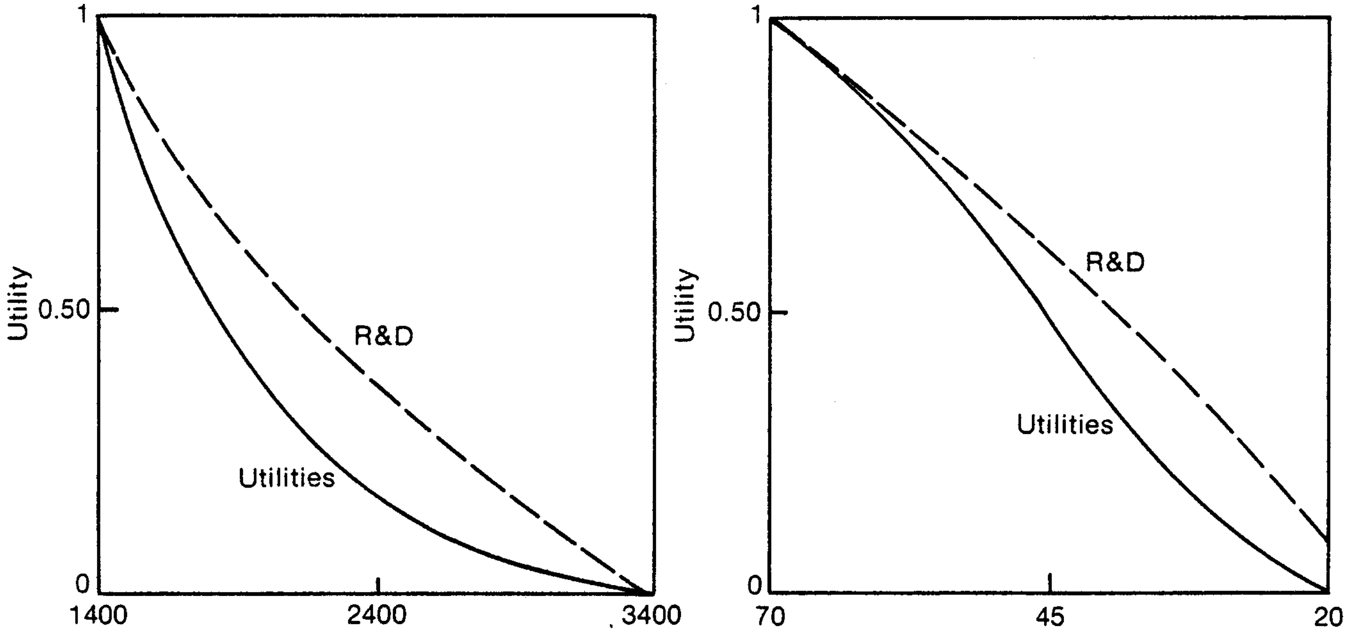
Table E-2. RELATIVE ATTRIBUTE WEIGHTS (NORMALIZED TO 1.0)

Utilities		R&D		Overall	
Attribute	Weight	Attribute	Weight	Attribute	Weight
Capital cost	0.27	Capital cost	0.27	Capital cost	0.27
Capacity factor	0.22	Capacity factor	0.27	Capacity factor	0.24
O&M	0.19	Applications	0.11	O&M	0.15
Applications	0.08	O&M	0.11	Applications	0.09
Environment	0.08	Safety	0.11	Safety	0.09
R&D	0.08	R&D	0.07	R&D	0.09
Safety	0.08	Environment	0.07	Environment	0.09

The relative desirability of specific values of the attributes, as determined in the form of utility functions, was also required. Figure E-1 contrasts the utility and R&D average utility curves for each attribute.

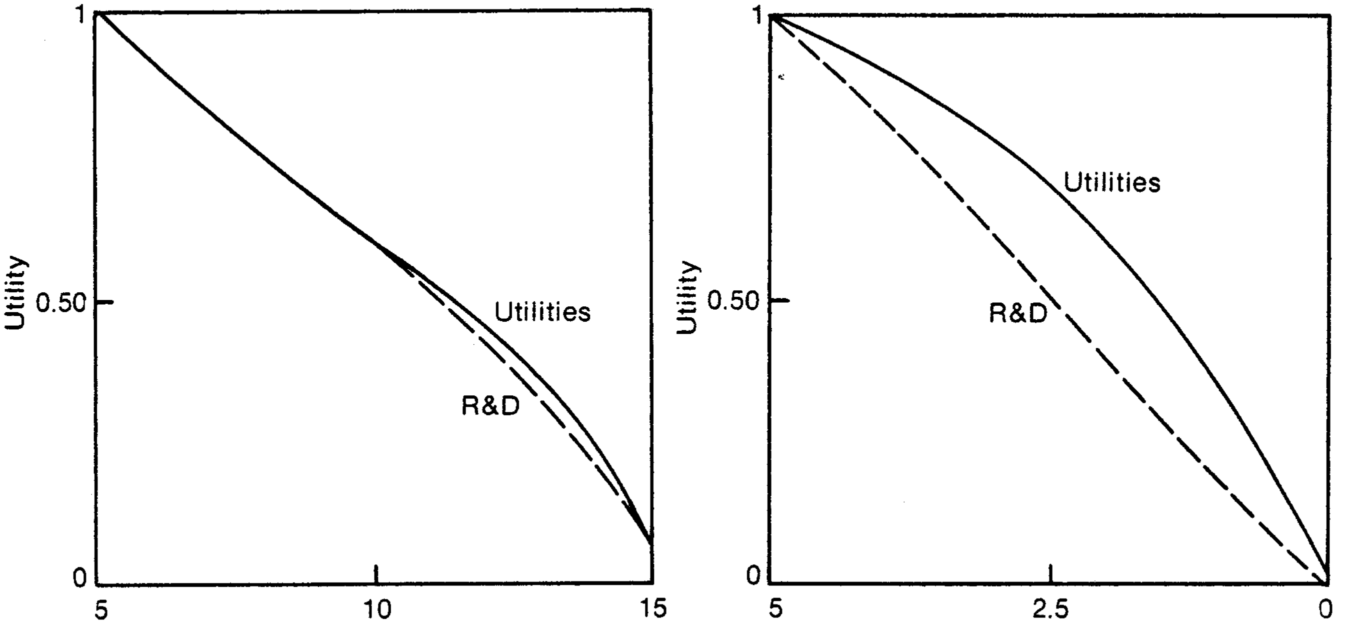
E.2 QUALITATIVE RESULTS

The interview process was not mechanical and impersonal. Instead, there was considerable opportunity to discuss issues and concerns outside the context of the very specific assessment of attribute utility functions and scaling factors. By and large, decision makers were interested in spending time (two or more hours) in order to learn more about solar technologies and to discuss the implications of responses to formal questions.



(a) Capital Cost ($/kW$_e$ Installed)

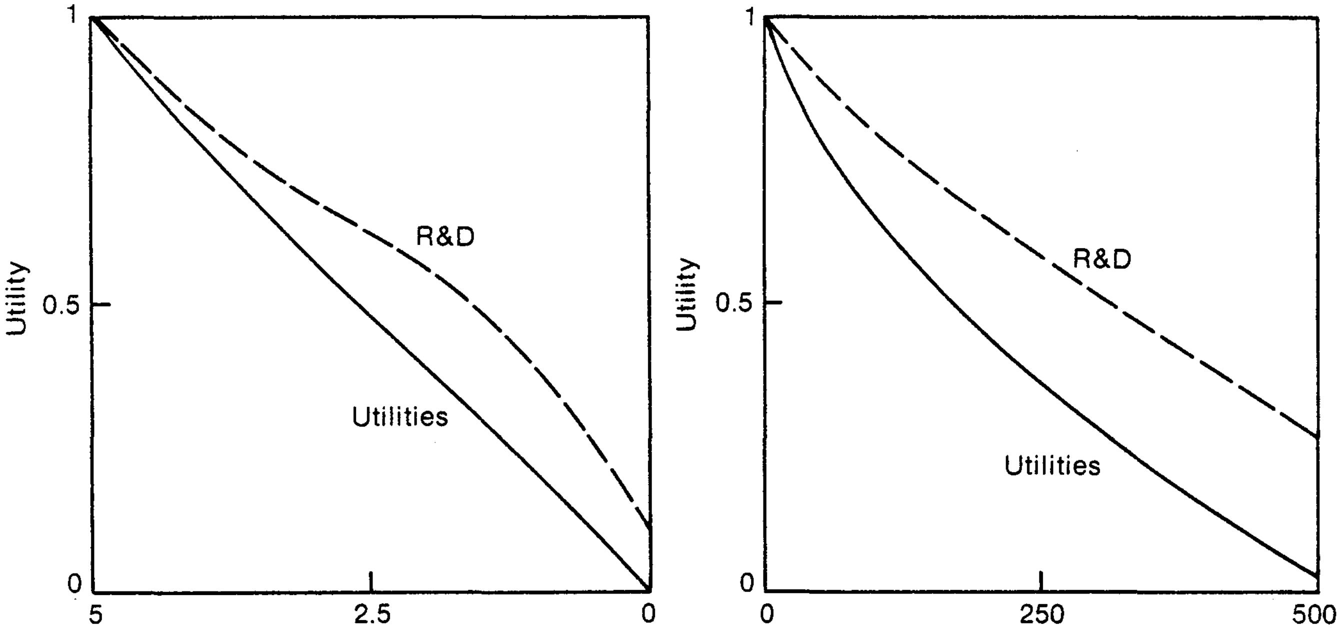
(b) Capacity Factor (%)



(c) Levelized O&M (mills/kWhr)

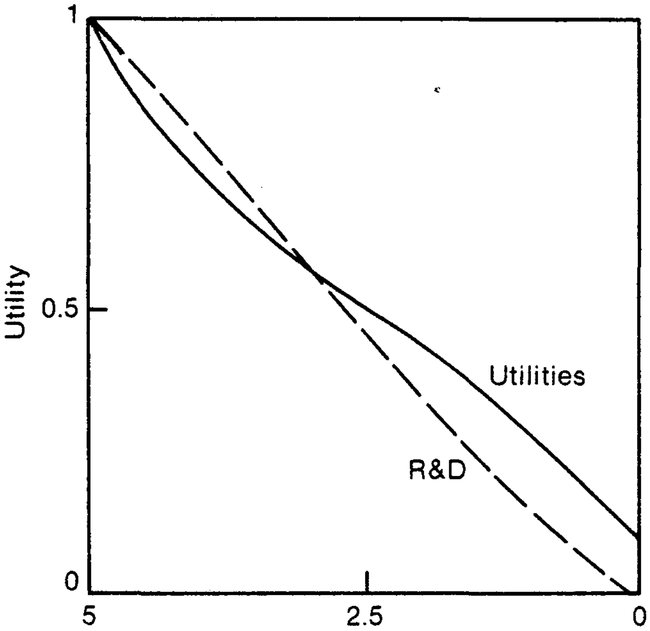
(d) Safety (subjective scale)

Figure E-1. Utility Functions



(e) Environment (subjective scale)

(f) R&D Requirements ($M spent 1980 - 1990)



(g) Applications (subjective scale)

Figure E-1. Utility Functions

Opinions were diverse on some issues, and tended to diverge as widely between individuals in the same company as between types of utility. However, certain issues surfaced consistently and are listed below:

- Capital Requirements - While many utilities recognize the strong possibility of much higher capital costs for new capacity in the next decade, they find it hard to believe that alternatives could not be found which offer initial costs less than \$2,500/kW$_e$ (1978 dollars) in 1990. If so, solar system capital costs in excess of the limit will be unacceptable, probably regardless of low operating costs.
- Ratepayer Concerns - Utilities are publicly regulated concerns. As such they are constrained to (1) provide reliable service at (2) the lowest possible price. Concerns over capital requirements and thus the utility's ability to raise capital impact rate requirements. Flow-through fuel cost adjustments have made capital cost increases a more dramatic part of the rate formula than usual. However, generation expansion still depends heavily on formulae which establish adequate reliability and minimum revenue requirements. Production costs of up to 15 mills/kWh, as the range of levelized O&M cost in this study extends, are not of particular concern. (Production costs of coal plants with scrubbers are of the order of 15 mills/kWh today.) However, most utilities believe that levelized energy costs above 60 mills/kWh to 70 mills/kWh in 1990 (1978 dollars) will be unacceptable, and anticipate being able to provide average system energy costs of 50 mills/kWh in 1990.
- Reliability - Related to ratepayer concerns expressed above are concerns for reliability and performance of systems. During the interviews this was a consistent issue. Annual capacity factor, as calculated in this study, did not adequately address this concern. Low capacity factors, while acceptable in conventional standby units where availability is high and capacity credit is available, were not generally acceptable for units where capacity credit was not available. Of more interest to the interviewees was the ability of solar systems to meet utility loads, both daily and seasonally. Concerns over fuel availability and a desire for fuel diversity (long-term reliability) were considered advantageous to solar energy.
- Regulatory Problems - According to utility personnel, solar systems would have to meet all of the minimum standards for environment and safety imposed. Some believed that this problem might not be trivial. However, most agreed that to the extent that regulatory costs and lead-time could be reduced, solar power systems could be advantageous.
- Uncertainty - Utilities expressed a uniform distrust of undeveloped technology, and therefore were unwilling or uninterested in expressing value judgements on R&D expenditures. Adequate pilot demonstration, proven and reliable hardware, and strong vendor/customer warrantees and service backup would be required before a commercial market could be expected to appear. It was also clear that most were of the opinion that solar technology would not move directly from the government laboratories into the marketplace. Rather, significant private development, testing, and marketing would have to intercede.

APPENDIX F

STUDY PARTICIPANTS

(All are SERI employees unless otherwise noted)

Task Leader:	John P. Thornton, Systems Analysis Branch
Team Members:	Kenneth C. Brown, Systems Analysis Branch Stephen D. Cronin, Computer Systems Branch Alan L. Edgecombe, Systems Analysis Branch Joseph G. Finegold, Systems Analysis Branch James Gresham, Policy Analysis Branch F. Ann Herlevich, Systems Analysis Branch John Kowalik, Systems Analysis Branch Thomas Kriz, Systems Analysis Branch Louise S. Morrison, Systems Analysis Branch Jeanne R. Pagano, Systems Analysis Branch
Support:	Dr. David Benson, Materials Branch Dr. Charles J. Bishop, Systems Analysis Branch Dr. Barry Butler, Materials Branch Dr. Pat Call, Materials Branch Dr. Robert Copeland, Systems Analysis Branch Dr. James W. Doane, Policy Analysis Branch Dr. Michael Edesess, Systems Analysis Branch Randy Gee, Thermal Conversion Branch Gordon Gross, Materials Branch Bim Gupta, Solar Thermal Program Office Jon H. Henderson, Systems Analysis Branch Dr. T. S. Jayadev, Systems Analysis Branch Dr. Frank Kreith, Thermal Conversion Branch Leroy Lacy, Computer Systems Branch Doug Madison, Computer Systems Branch Richard Mitchell, Computer Systems Branch Robert O'Dougherty, Computer Systems Branch Ari Rabl, Thermal Conversion Branch James Williamson, U.S./Saudi Arabia Program
Consultants:	Robert Barber, Barber-Nichols Engineering Company, Arvada, Calif. Frank M. Swengel, Stanley Consultants, Mascatine, Iowa

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APPENDIX G

INDIVIDUALS AND ORGANIZATIONS INTERVIEWED FOR UTILITY PREFERENCE STUDY

Representatives of electric utilities or the utility industry.

Doug Bauer, American Electric Power
Larry Ciecior, Omaha Public Power District
William Eisele, Tri States Generation and Transmission Associates
Sam Hall, American Electric Power
Gadi Kaplan, IEEE Spectrum
Henry Klaiman, Public Service Company of Colorado
Jerry Krause, Omaha Public Power District
R. F. Kuharich, Colorado Springs Department of Public Utilities
John Nevshemal, Science Application, Inc.
George Parkins, Colorado Public Utilities Commission
Les Pruce, Power
David Reid, Omaha Public Power District
Blair Ross, American Electric Power
Don Sebesta, Electrical World
Frank Swengel, Stanley Consultants
Dan Witt, Omaha Public Power District

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The SERI interviewees represent a wide range of experience, including previous employment with research organizations, architect/engineering firms, and utilities.

Frank Baylin, Program Evaluation Branch
Joseph Finegold, Systems Analysis Branch
Theresa Flaim, Economics and Market Analysis Branch
Jim Gresham, Policy Analysis Branch
Ann Herlevich, Systems Analysis Branch
Michael Karpuk, Systems Analysis Branch
Tom Kriz, Systems Analysis Branch
Joe Lavender, Systems Analysis Branch
Kathryn Lawrence, Institutional and Environmental Assessment Branch
Louise Morrison, Systems Analysis Branch
Laxmi Mrig, Systems Analysis Branch
Dave Percival, Systems Analysis Branch
Dave Schaller, Program Planning Branch
Roger Taylor, Systems Analysis Branch
John Thornton, Systems Analysis Branch

APPENDIX H

MAJOR SOURCES OF INFORMATION

In addition to the people identified in Appendix F, the following laboratories and contractors made major contributions of information, data, and constructive criticism to the Small Solar Thermal Electric Power Systems Study.

Acurex Corporation, Mountain View, California
Aerospace Corporation, El Segundo, California
Argonne National Laboratories, Lisle, Illinois
Battelle Pacific Northwest Laboratories, Richland, Washington
E-Systems, Garland, Texas
FMC, Santa Clara, California
Ford Aerospace & Communications Corporation, Newport Beach, California
General Atomic, La Jolla, California
General Electric Company, Valley Forge, Pennsylvania
General Electric Company, Schenectady, New York
Jet Propulsion Laboratory, Pasadena, California
Lawrence Livermore Laboratory, Livermore, California
Martin Marietta Aerospace, Denver, Colorado
McDonnell Douglas Astronautics Company, Huntington Beach, California
Mechanical Technology Incorporated, Latham, New York
NASA Lewis Research Center, Cleveland, Ohio
Sandia Laboratories, Albuquerque, New Mexico
Sandia Laboratories, Livermore, California
Texas Technological University, Lubbock, Texas
University of Chicago, Chicago, Illinois

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APPENDIX I

GLOSSARY

BBEC — See levelized busbar energy cost.

Capacity — The nameplate rating of the plant. In most systems in this study, this corresponds with the nameplate rating on the generator minus auxiliary load requirements.

Capacity factor — This factor is the ratio of the total energy actually produced on an annual basis to the total energy possible from the plant if operated continuously at rated capacity for a full year. In a solar power plant, increased capacity factor is achieved with increased thermal or electric storage.

Collector — In this study, the term collector includes both the concentrator and receiver.

Concentrator — This term refers only to the solar energy concentrating device exclusive of the receiver, e.g., a heliostat.

Continuous flow mode — Operation of a system with continuously circulating fluid as opposed to batch mode.

CPC — Compound parabolic collector, sometimes called a Winston collector.

Draw salt — A commercial heat transfer salt composed of 40% potassium nitrate and 60% sodium nitrate. Its freezing point is approximately 225° C (440° F) and its highest usable temperature is approximately 510° C (950° F).

Dowtherm A — A commercial organic heat transfer fluid composed of a eutectic mixture of biphenyl and biphenyl oxide.

FMDF — Fixed mirror distributed focus collector, a fixed hemispherical mirror bowl with a two-axis tracking linear receiver.

Generic system — A typical system representative of systems employing a specific technology.

Grid-connected — Connected to the utility's distribution system. All plants were assumed to be grid-connected in this study.

Heliostat — A sun-tracking reflector used for focusing the insolation on a central receiver.

Hitec salt — A commercial heat transfer salt composed of 53% potassium nitrate, 40% sodium nitrite, and 7% sodium nitrate. Its freezing point is approximately 140° C (290° F) and its highest useful temperature is at least 590° C (1100° F).

Internal rate of return — The average interest rate which can be obtained by the utility on investments within the company.

LCNT — Low concentration non-tracking collector, such as a CPC.

Levelized busbar energy cost (BBEC) — The price per unit of energy which, if held constant throughout the life of the plant, would provide the required revenue, assuming that all cost flow interim requirements or excesses are borrowed or invested at the utility's internal rate of return.

LFCR — Line focus central receiver system, composed of one-axis tracking heliostats and a tower-mounted linear receiver.

LFDR-TR — Line focus distributed receiver, wherein the entire collector tracks, such as a conventional parabolic trough collector.

LFDR-TC — Line focus distributed receiver, wherein only the receiver tracks. Examples built to date have segmented concentrators.

PFCR — Point focus central receiver system, composed of two-axis tracking heliostats and a tower-mounted receiver.

PFDR — Point focus distributed receiver, such as a two-axis tracking parabaloidal dish with a receiver mounted at the dish focus. A heat engine or a heat exchanger can be mounted at the receiver to use the collected heat.

Redox battery — Electrical storage battery in which one or two pairs of liquid electrolytes produce electricity in a reactor: one fluid is oxidized while another is reduced. The electrolytes are stored in tanks separate from the reactor.

Second-order simulation — A computer simulation in which the system components and processes are modeled based on empirical relationships as opposed to a first-order simulation in which the system as a whole is modeled based on empirical relationships, and a third-order simulation in which the system components and processes are modeled based upon the presumed actual forces of nature which control them.

Selective surface — A surface whose effective emissivity and absorptivity are different due to its having different optical properties at different light wavelengths. For solar applications, the selective surface is highly absorbant of the solar spectrum, and has low emittance in the infrared region.

Sensible heat storage — Thermal storage wherein an increase in heat stored results in a rise in temperature of the storage medium, as opposed to latent heat storage wherein heat is absorbed by a phase change.

SSP — Shallow solar ponds, a saltless solar pond wherein thermal storage is provided exterior to the pond itself.

Thermocline storage — A thermal storage system wherein the hot medium is separated from the cold medium by a relatively sharp temperature gradient. This gradient rises and falls in the storage tank(s) as heat is added to and withdrawn from storage.

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16. Abstract (Limit: 200 words)

Recent studies have suggested a significant potential for small solar thermal electric power generating plants to be used by small communities, rural areas and remote load centers. SERI was contracted by the Department of Energy to perform a comparative analysis and ranking of generic solar thermal electric systems in the 0.1 to 10 MWe capacity range. The following report summarizes the comparative ranking of 1.0 to 10.0 MWe systems and describes the groundrules, methodology and systems considered during the study.

17. Document Analysis

a. Descriptors Central Receivers ; Distributed Receivers ; Point Focus ; Line Focus ; Parabolic Collectors ; Tower Focus Collectors ; Parabolic Dish Collectors ; Parabolic Trough Collectors ; Heliostats ; Solar Ponds ; Solar Tracking ; Solar Heat Engines ; Stirling Engines ; Rankine Cycle Engines ; Brayton Cycle Power Systems ; Brayton Cycle Engines ; Evaluations ; Comparative Evaluations ; Decision Making ; Cost ; Market ; Performance ; Environmental Impacts ; Safety ; Reliability ; Power Range 1-10 MW ; Solar Thermal Power Plants

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