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Thermal Power Systems
Small Power Systems Applications Project
ANNUAL TECHNICAL REPORT
Volume I: Executive Summary
Fiscal Year 1978

January 15, 1979

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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ABSTRACT

This report, Volume I, is a summary of the SPSA Annual Technical Report. It covers Small Power Systems Applications activities for FY 1978. Studies were conducted to address current small power system technology as applied to power plants up to 10 MWe in size. Markets for small power systems were characterized and cost goals were established for the project.

Candidate power plant system design concepts were selected for evaluation and preliminary performance and cost assessments were made. Economic studies were conducted at JPL and under contract to Burns & McDonnell. Breakeven capital costs were determined for leading contenders among the candidate systems.

An applications study was made of the potential use of small power systems in providing part of the demand for pumping power by the extensive aqueduct system of California, estimated to be 1000 MWe by 1985.

Criteria and methodologies were developed for application to the ranking of candidate power plant system design concepts.

Experimental power plants concepts of 1 MWe rating were studied by three contractors as a Phase I effort leading toward the definition of a power plant configuration for subsequent detail design, construction, testing and evaluation as Engineering Experiment No. 1 (EE No. 1). Site selection criteria and ground rules for the solicitation of EE No. 1 site participation proposals by DOE were developed.

FOREWORD

The report summarizes the activities of the Small Power Systems Applications Project for FY1978. Throughout the report the abbreviation SPSA is used. Prior to publication of this document, the name of the project was changed and is now the Point-Focusing Thermal and Electric Applications Project.

Questions concerning the contents of this report should be directed to A.T. Marriott, Assistant Manager for Point-Focusing Thermal and Electric Applications Project, telephone number (213) 577-9366 or FTS 792-9366.

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SECTION I

INTRODUCTION

The Thermal Power Systems Office of the U.S. Department of Energy (DOE) is responsible for developing the technology for low cost, long life, reliable solar thermal electric power systems suitable for a wide range of terrestrial applications. To accomplish this goal, DOE established program offices within the Thermal Power Systems Branch in two primary areas of solar thermal energy, i.e., large thermal power system applications, and small thermal power systems applications. The latter is managed by the Small Thermal Power Systems Section. Two projects formed at the Jet Propulsion Laboratory (JPL) support this Section at DOE:

(1) Point Focusing Distributed Receiver Technology Project

(2) Small Power Systems Applications Project (SPSA).

The JPL projects were created in July 1977 under an interagency agreement between NASA and DOE.

A. PROJECT OBJECTIVES

The general goal of the SPSA project is to establish the technical, operational, and economic readiness of small power systems for a variety of applications in the power range below 10 MWe. Power systems are to be developed to the point where subsequent commercialization efforts can lead to successful market penetration. The detailed objectives in support of this goal are:

(1) Identify, characterize, and quantify the electrical power needs and plant requirements for small power system users. Emphasis is to be on small community, industrial, and remote applications.

(2) Understand the user community, and develop effective communication between it and the project.

(3) Establish functional, economic, performance, environmental, and operational requirements for selected power systems.

(4) Develop cost goals applicable to each segment of the anticipated market.

(5) Identify means for early penetration of the higher cost energy markets, and define the technologies best suited to their needs.

(6) Develop power system design configurations attractive to the utility market sector that encompasses the small communities. The candidate system configurations should provide the best match with the identified applications.

(7) Identify the economic, financial, social, and institutional factors that could impede commercialization of small power systems technology.

(8) Maximize participation of the private sector in the small power systems market readiness effort.

The timing of the work necessary to attain the above objectives, and their relative priorities, are made firm by setting operational hardware objectives and completion date targets as follows:

(1) Bring several experimental power plants on-line that demonstrate the feasibility of the small power systems concept, with the first plant to be operational in 1982 as a goal.

(2) Achieve, as a first interim target by 1985, initial penetration of small power systems in various early markets. To achieve this goal, it is anticipated that capital costs in the range of 1500 to 2000 $/kWe (1978 dollars), and an energy cost range of 75 to 100 mills/kWe (1978 dollars) will be required.

(3) Demonstrate, by the late 1980's, the practicality of building power plants with potential mass produced capital costs in the range of $600 to $1000/kWe (1978 dollars), and with a levelized busbar energy cost in the range 50 to 60 mills/kW-hr.

Project milestones are discussed in Section I.C.

B. TECHNICAL APPROACH

1. General Strategy

The three successive milestones required in the development of a new technology to the point of commercial readiness are: 1) demonstrating technical feasibility, 2) verifying readiness of the technology, and 3) meeting cost goals required for commercial readiness. The three phases in the evolution of a new technology can be described as creation, manufacturing, and marketing. Participation by both government and the private sector may be necessary, with increasing activity by the latter as the commercial readiness phase is approached. Potential users are to be involved early, and to the maximum extent possible. Limited incentives on the part of government may be required.

Potential users will be sought that fall into two broad market categories: 1) the near-to-mid-term market, which is smaller, and for which costs are higher; and 2) the far-term market which largely corresponds to the utility sector for which a mature solar thermal technology is needed before penetration can be expected. Application studies and system analyses are being conducted to develop candidate system configurations best matched to the users in each category.

Selected system design concepts will be developed through study contracts let to private industry. User acceptance and technical and economic feasibility will be addressed through the operation of a series of experimental power plants. Currently, three series of experiments are planned, each employing more mature technology, and each addressing a variety of applications. These experiments are referred throughout this document as the engineering experiment series EE No. 1, 2, and 3.

A key element of the program strategy is first the identification, and later the penetration, of near-term markets that will provide a stimulus for establishing a manufacturing industry. This, in turn, will lead to cost reductions as a result of improved manufacturing methods, coupled with an increasing volume of production as lower cost markets are penetrated. The importance of this program element lies in the belief that design improvement alone will not result in a sufficiently low price to penetrate the utility market. A combination of mature technologies and mass production, however, offers the potential for economically competitive power systems with a significant environmental advantage.

2. Relationships Between Development Activities at JPL

The SPSA project is one of three related activities co-located at JPL that comprise the Thermal Power Systems (TPS) organization. The other two projects are Advanced Solar Thermal Technology (ASTT), and Point Focusing Distributed Receiver Technology (PFDRT). The ASTT effort covers a broad spectrum of component and subsystem technology development. The PFDRT project is directed specifically to developing point focusing distributed receiver systems. Both of these projects support the work of the SPSA project as illustrated conceptually in Figure 1-1.

3. SPSA Project Implementation

To implement the general strategy previously described, a number of discrete activities have been defined and are shown in Figure 1-2. The SPSA project organization includes four functional task areas that contain the various technical elements inherent in the flow of activities illustrated. The task areas are described in detail in Volume II of this report and are summarized below in terms of their primary responsibilities.

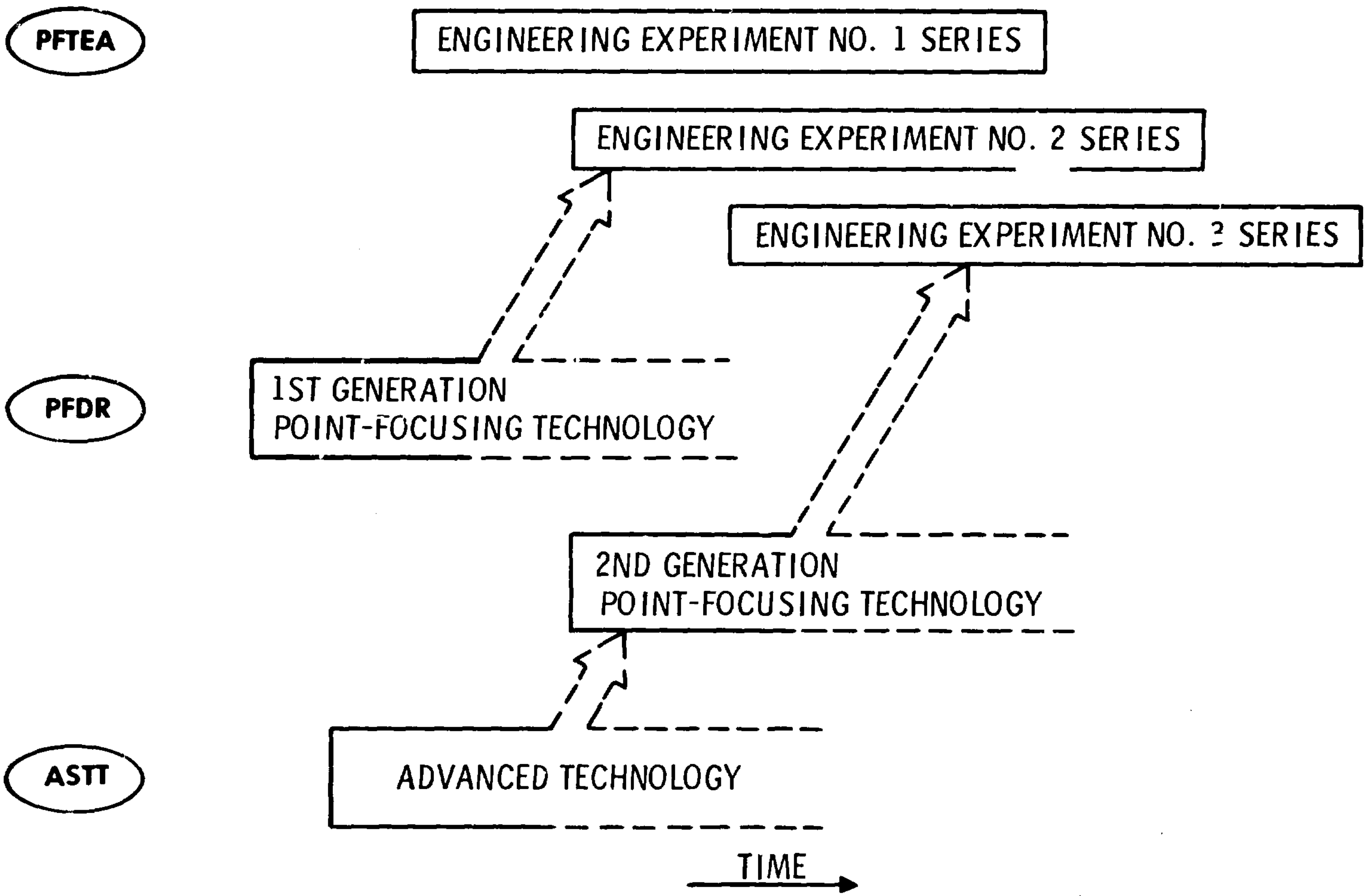


Figure I-1. Inter-relationships Between the Three JPL Solar Thermal Project Elements

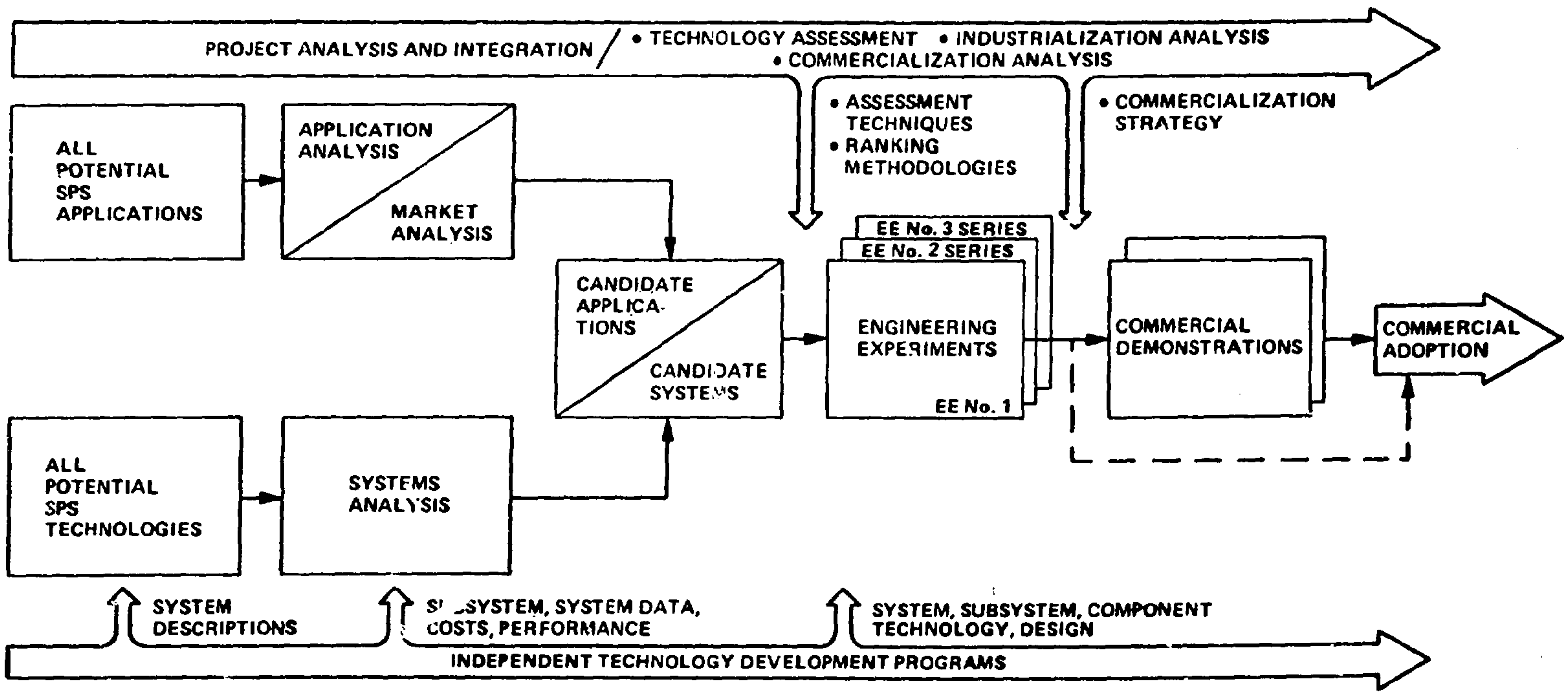


Figure I-2. SPSA Program Approach

a. Requirements Definition

The Requirements Definition Task Area is responsible for market identification, market characterization and user integration. Under this task area, appropriate market sectors will be selected for small solar thermal power systems and, through analysis of the end use of these systems, specific functional, performance and operational and environmental requirements will be determined for use in system design.

b. Systems Definition

The principal responsibilities of the Systems Definition Task Area are the analysis of requirements, determination of system design concepts to meet the application needs, power plant design, engineering experiment definition and development. A major activity in the initial phases of the project is the participation with the Solar Energy Research Institute and the Battelle Pacific Northwest Laboratories in a study to rank the candidate small power system technologies.

c. Field Test Integration

The Field Test Integration Task Area is responsible for all activities associated with the implementation of the engineering experiments. Thus, power plant siting, construction and experimental operation and integration are among the activities involving this task area.

d. Project Analysis and Integration

This task area has the broad charter to provide information to the project and to DOE that will allow decisions to be made in a way to maximize the probability of successfully meeting DOE objectives. This, technology assessment, the economics of demand and supply, the institutional considerations of a new industry and the effect of system design on commercialization are all issues to be explored by the PA&I task area.

4. Outside Support

The Aerospace Corporation supported the project in the areas of market potential and analysis of power system applications. DOE made provisions for support of the SPSA project by the Solar Energy Research Institute (SERI) and the Battelle Pacific Northwest Laboratories. The latter two organizations are performing studies leading to the ranking of small power system candidates for the long-term commercial market.

C. PROJECT MILESTONE SCHEDULE

Figure 1-3 shows the top level activities of the project through 1986. The effort is centered around the three series of engineering

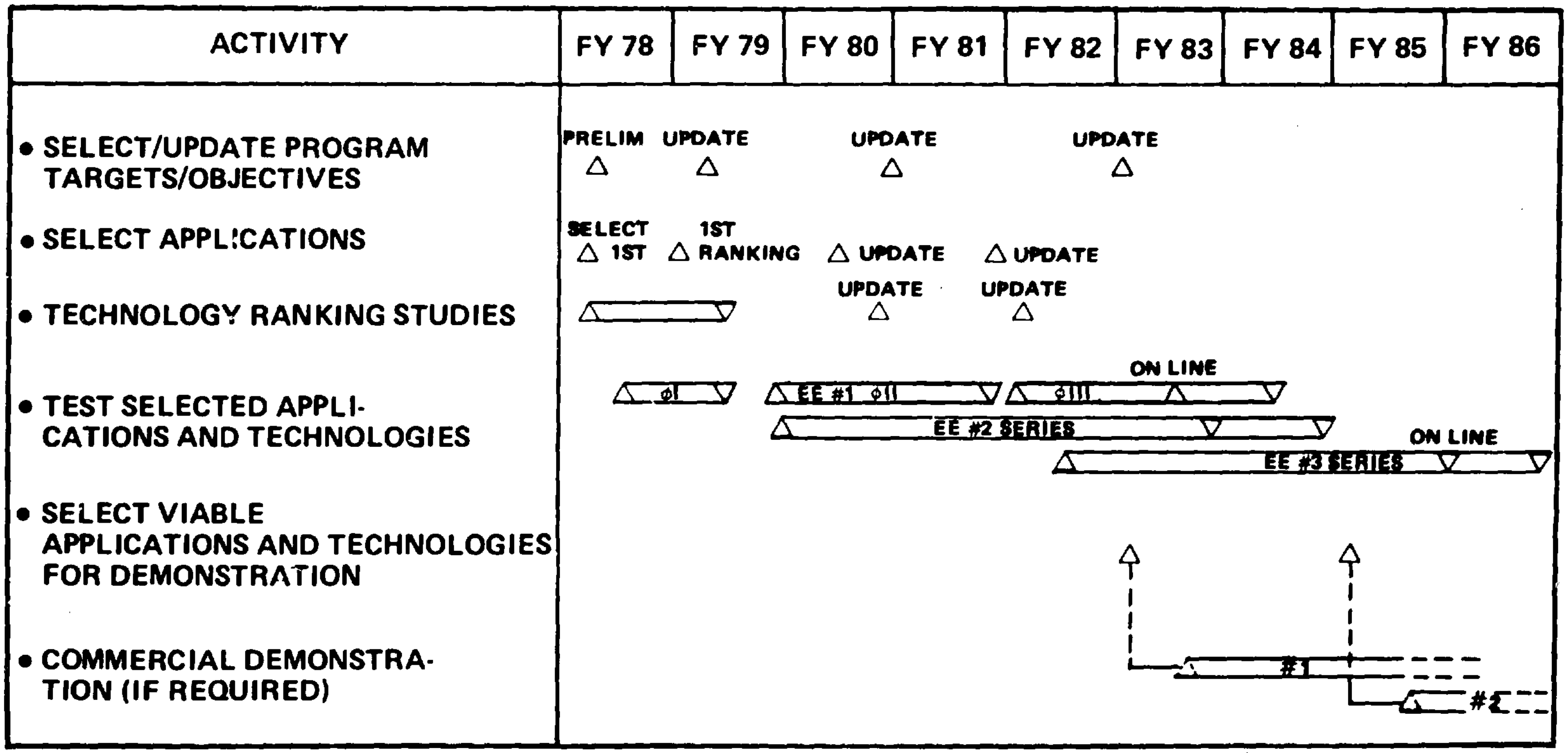


Figure I-3. SPSA Project Schedule

experiments. EE No. 1 is scheduled to be on-line in mid FY 1983. The EE No. 2 series will be initiated in FY 1979 and will be operational from FY 1983 to FY 1985. This series is followed by the EE No. 3 series, tentatively scheduled to begin in FY 1982 and be on-line between FY 1985 and FY 1987. Commercial demonstrations may be necessary and, if so, these would begin in the post-FY 1983 time period.

D. INTENT AND SCOPE OF EXECUTIVE SUMMARY

The intent of this report is to summarize the work of the SPSA Project and to provide a status report of work accomplished and work in progress. Material has been extracted from the comprehensive Annual Technical Report (Volume II) which presents its material on the basis of the work accomplished by the individual organization units, or task areas, that comprise the project. This Executive Summary, however, presents a summary of material on a functional basis in the interest of clarity and conciseness. The scope of the two documents is identical.

SECTION II

MARKET CHARACTERIZATION AND DEVELOPMENT

The success of the Small Power Systems program ultimately depends on how this energy alternative is accepted in the market place. Therefore, an understanding of the market potential, the character of the market and the requirements imposed upon the technology by the various end uses of the technology is of paramount importance at these early stages of the program. The SPSA Project has undertaken various activities to ensure that this understanding is achieved and that the appropriate information from the user is integrated into the system development. Moreover, it was recognized at the beginning of the project that the direct involvement of the potential users was important to the proper design of the energy systems as well as their eventual acceptance, and consequent development of a market. Thus, additional activities were defined and started in FY 1978 that have as their objective integration of the user's requirements into the SPSA project.

This section describes the market identification, characterization and development activities conducted in FY 1978. For the most part they are the responsibility of the Requirements Definition Task Area.

A. THE UTILITY INDUSTRY

To meet SPSA goals, significant market segments must become available in the 1985 to 2000 time period. Small power system costs must then be competitive with costs of the common alternative sources of energy. To date, the markets identified are the U.S. domestic market, the less-developed countries, and the U.S. military. Of these, the U.S. domestic market is receiving primary emphasis in the market analysis work, especially the small utility industry.

Preliminary studies have shown that the U.S. Southwest has the highest potential for solar augmented electric power by the utility industry and that the smaller utilities would tend to be the ones best served by modular additions of solar power. To acquire more specific guidance for planning and analysis in the early stage of the SPSA project, a utility user workshop was held in Aspen, Colorado, on October 10-12, 1977 to introduce the concepts and potentials of small solar thermal power, and to establish channels of communication with the utilities. The workshop was useful to the utilities and the project. Of particular value were the discussions of siting issues, economics, and the many interfaces involved in the integration of solar thermal power with existing small electric utilities.

An ecomomic analysis was conducted for the case of dispersed siting of small power systems to augment small utilities in the Southwestern U.S. Assumptions of the study included the following:

(1) Costs are in 1978 dollars.

(2) Annual hours of usable sunshine is 2800.

(3) Mean annual daily direct insolation (characteristic of the southwestern U.S.) is 6.5 kWh/m^2.

(4) Solar plant configuration is a point focus distributed receiver for which the technology and costs correspond to 1985 projections.

(5) Petroleum costs to utilities are as projected by SRI International.

(6) Storage, if used, will provide a minimum of 2 hours of operation at rated plant capacity.

(7) The applicable time period is 1985 to 2000.

(8) Two levels of technology were assumed. One corresponded to maximum efficiency and minimum collector cost, and the other to moderate efficiency and moderate collector cost.

The value of the solar thermal power plant to the user was compared with the estimated capital cost of the plant. The ratio of plant cost to value to the user was calculated for the cases studied. For cases having ratios less than unity, the potential market size was estimated. Three types of solar plants were examined, each having a rated capacity of 10 MWe:

(1) Solar with Diesel back-up and no storage

(2) Solar with Diesel back-up with storage

(3) Hybrid solar/oil-fired plant with no storage.

Hybrid plants have consistently appeared to be more economical than pure solar plants with fossil fueled back-up units, and the study further substantiated this characteristic. Results of the JPL economic breakeven analysis are:

(1) Hybrid plants appear more competitive than solar-only plants, regardless of the amount of storage assumed.

(2) Hybrid plants appear competitive with diesel-only plants.

(3) Hybrid plants could provide up to 1500 MWe in utility capacity serving small communities by the year 2000.

Regarding storage, the study found that for the fuel prices used, and for the lower assumed level of solar thermal technology, plants with storage were not economically competitive. For the higher technology cases, and independent of fuel prices, plants with storage up to 6 hours were competitive, although plants with the minimum storage (2 hours) were consistently more competitive.

Solar thermal technology, hybrid or otherwise, will face competition in the future from a wide spectrum of technologies. In view of this, two fundamental economic questions had to be addressed to provide direction to the project:

(1) What competition can be expected that small solar thermal power systems must face, quantitatively, in utility applications in the 1985 to 2000 time period?

(2) What economic goals must the project achieve to successfully compete in this environment?

To address these questions, a study was initiated in December 1977 to analyze the southwestern U.S. utility market segment and the large demand for electricity by the extensive California water aqueduct system. The scope and the assumptions of the utility cost study included the following:

(1) Time period of interest: 1985 to 2000

(2) Plant start-up dates of 1986, 1995, and 2000

(3) Capital and busbar energy costs are in 1978 dollars

(4) Fuel cost escalation rates are 1% and 2% (parametric)

(5) Annual maintenance & operating costs equal 3% of capital costs

(6) Plant capacity factors of 0.3 for intermediate to peak load plants, and 0.6 for baseload.

The study objectives are summarized below:

(1) Identify utilities in the southwest that might buy small solar thermal power systems in the time period of interest

(2) Obtain the perspectives of utility planners on solar electric applications and on conventional power plant technology and costs

(3) Establish utility industry scenarios that recognize the load growth, technologies, fuel costs and economic factors peculiar to the companies and to the technologies.

(4) Calculate projected busbar energy costs for conventional power plant technologies

(5) Compare the study results with findings by other analysts as obtainable in the literature.

Some of the results of the JPL study are shown in the following figures and tables. Figure II-1 shows projected busbar energy costs versus time, for fossil fueled plants. The sensitivity of busbar costs to fuel costs is shown in Figure II-2 for baseload systems which could come on line in 1986. Fuel costs were escalated 1% above inflation. Capital costs plus operations and maintenance costs were included. The results of the JPL economic study are summarized in Figure II-3 in terms of the anticipated range of conventional electric energy costs from mid-1980 to 2000. The SPSA cost goals are superimposed and shown to be in the competitive range.

The JPL economic analyses were followed by a contract study of the market potential for small power systems in small electric utilities conducted by Burns and McDonnell. Their work was more detailed than the JPL in-house study, and was valuable in identifying the small utilities, geographic regions, and all-solar plant configurations that should be selected for subsequent study. Tables II-1 and II-2 present the solar plant characteristics assumed in the Burns and McDonnell study. The small power system type designations they assigned to the reference systems are indicated below:

System Type	Description
I	2 MWe plant, parabolic dishes, 15 kW heat engines at focal points; and advanced battery storage
II	10 MWe, with other characteristics as for type I
III	10 MWe, variable slot concentrators, central steam Rankine engine, and thermal energy storage
IV	50 MWe, heliostat field concentrating the radiation on a central, tower-mounted receiver driving a steam Rankine engine, and thermal storage

The Burns and McDonnell study included an economic analysis of plant expansions through the year 2000 for seven hypothetical small utilities assuming, for comparison purposes, both non-solar expansion and expansion using small solar powered systems. To cover a wide spectrum for comparative analysis purposes, the peak demand was varied by 2 orders of magnitude, and the types of power generation included coal-fired, oil-fired, gas turbine, Diesel, and hydroelectric.

Study results are summarized in terms of breakeven capital costs which are arbitrarily defined as the cost that would have to be achieved for solar systems so they have enough economic attractiveness to become 10% of the utility's generating capacity by the year 2000 (10% solar mix). Breakeven capital costs were calculated for each of the seven

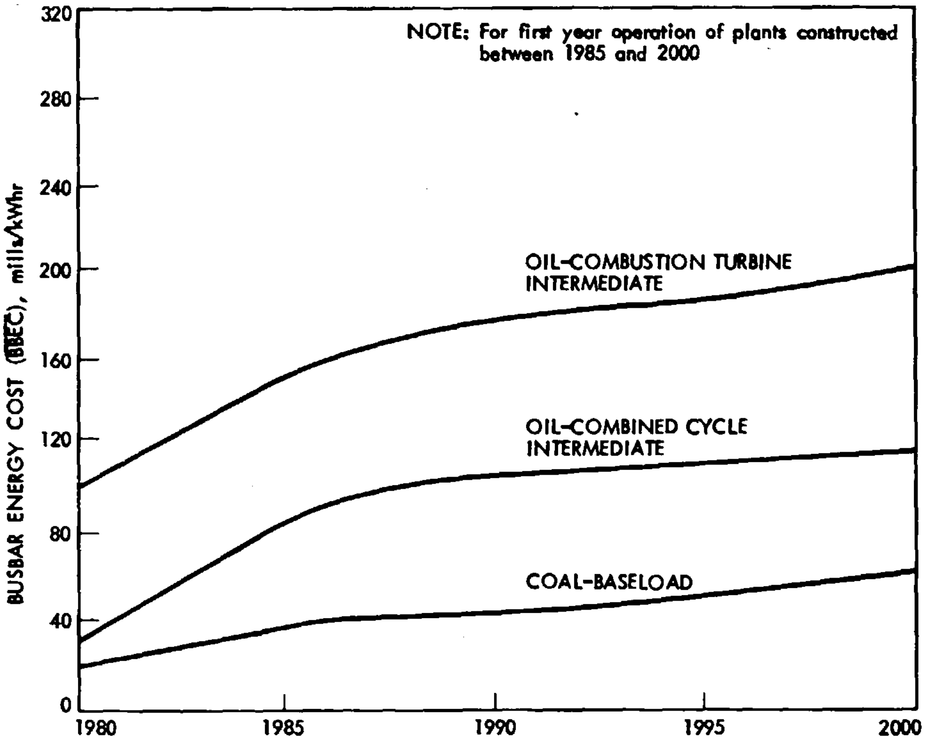


Figure II-1. Small Power Systems Energy Cost For Levelized Busbar Energy Costs

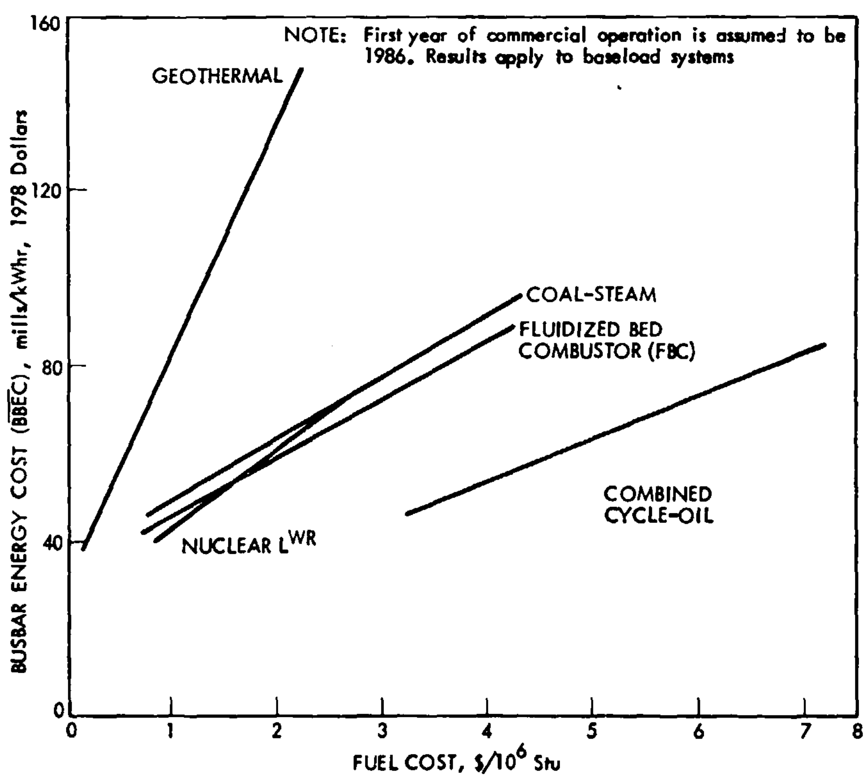
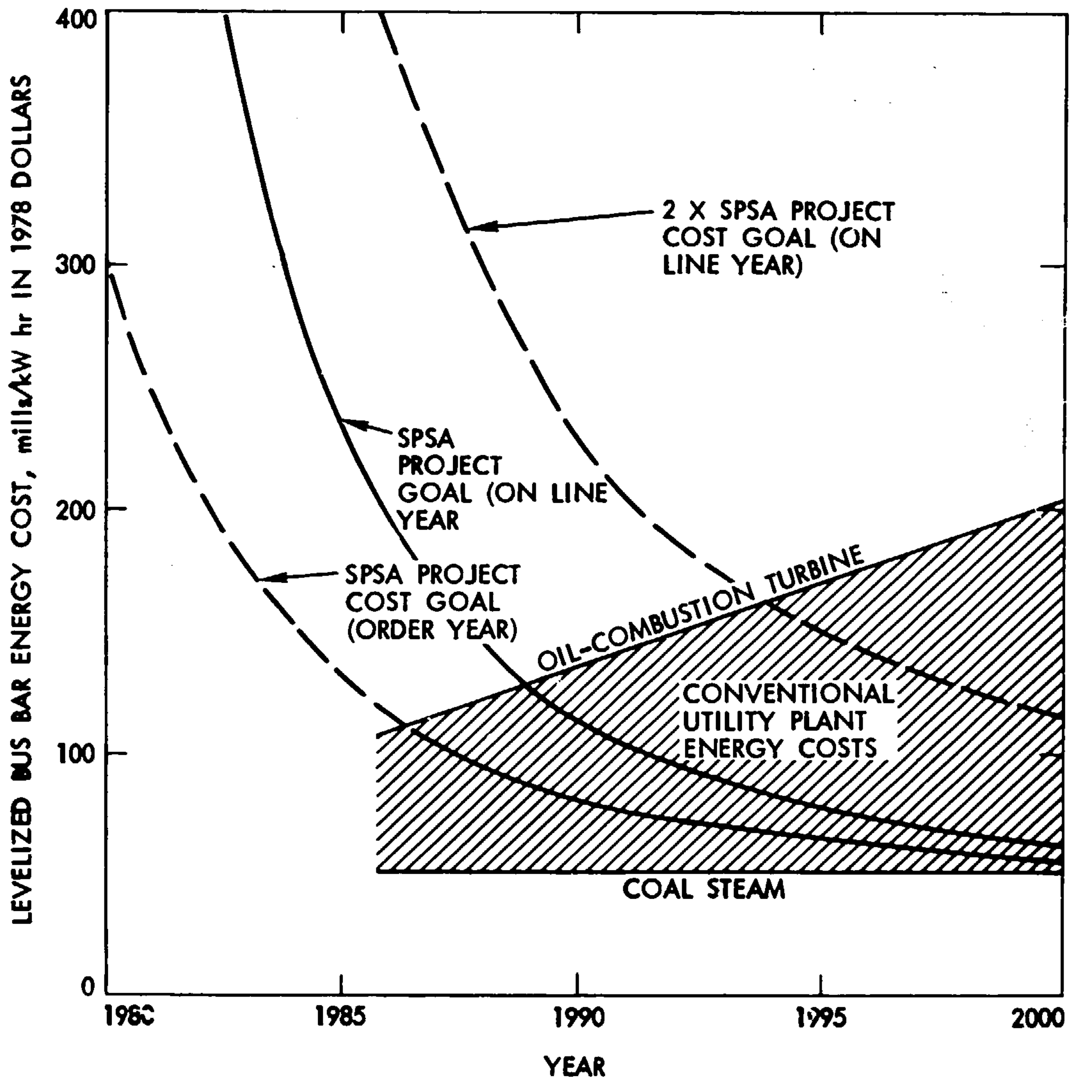


Figure II-2. Sensitivity of Busbar Energy Cost to Fuel Cost



NOTE: COSTS SHOWN ARE FOR NEW PLANTS COMING ON-LINE IN YEAR INDICATED. ALL PROPOSED UTILITY TECHNOLOGIES WILL HAVE COSTS LYING WITHIN THE RANGE SHOWN.

Figure II-3. Small Solar Thermal Electric Plant Energy Cost Goals in the Years 1986 - 2000

Table II-1. Small Power Systems Types and Characteristics

Characteristic	SPS Type I	SPS Type II	SPS Type III	SPS Type IV
Plant Size (Rated Capacity, MWe)	2	10	10	50
Commercial Availability	1983	1985	1985	1985
Cost Characteristics (1975 $)				
Capital Cost ($/kW)[1,2]	578-2,312	508-1,848	1,506-3,806	1,103-2,759
Operation and Maintenance				
Fixed ($/kW-yr)	2-14	2-14	2-14	2-14
Variable (mills/kWhr)	1-4	1-4	1-4	1-4
Other Characteristics				
Average Plant Efficiency	0.28	0.28	0.14	0.22
Equipment Forced Outage Rate	0.01	0.01	0.07	0.07
Annual Maintenance (wks/yr)[3]	0.1	0.1	1.0	1.0
Storage				
Capacity Rating (MWe)	2	10	7	35
Energy Rating (MWhr)[2]	4	20	14	70
Collector				
Area (km^2)[2]	0.063	0.040	0.112	0.422
Intensity Rating (kW/m^2)[2]	0.9	0.9	0.9	0.8
Land Area (km^2)[2]	0.026	0.133	0.373	1.407
Solar Multiple[2]	1.0	1.0	1.5	1.5
Lifetime (years)	30	30	30	30

[1]Does not include interest during construction
[2]Assumes a location in the Southwest United States
[3]Assumes most routine maintenance will be done at night

reference utilities considering each of the four small power system type plants as candidates for plant expansion. The results for economically attractive applications are shown in Table II-3. In Figure II-4, the breakeven capital costs are compared with estimated capital costs. The Burns & McDonnell study concluded that:

(1) Small power system Types I and II can be economically competitive if the low values of capital cost assumed can be realized

(2) Small power system Types III and IV, to become economically competitive, would have to achieve lower capital costs and lower operating and maintenance costs than those assumed.

(3) All four of the small power system types are more competitive when compared to oil-fired utilities and coal-fired utilities.

(4) The parabolic dish concentrator with a heat engine at the focus is more likely to be economically competitive in the small utility market than other small power system configurations if program goals are met.

Table II-2. Small Power Systems Subsystems Characteristics

	SPS Type			
	I	II	III	IV
Capital Cost (1975 $)				
Collector ($/m²)	62-192	62-192	85-171	65-145
Transport ($/kW)	18-50	18-50	75-150	150-300
Conversion ($/kW)	53-200	53-200	175-350	175-350
Storage ($/kWh)	45	45	60	60
Other ($/kW)[1]	170-1,206	100-744	185-1,274	109-764
Efficiency				
Concentrator/Collector	0.864	0.864		
Receiver	0.804	0.804	0.54	0.65
Transport	0.95	0.95	0.92	0.95
Conversion	0.42	0.42	0.30	0.36
Storage (Round Trip)	0.75	0.75	0.75	0.75
Lifetime (years)				
Collector	30	30	30	30
Transport	30	30	30	30
Conversion	15	15	30	30
Storage	15	15	30	30

[1]Includes costs of land, site development, water supply, buildings, electrical connections, and overhead. Does not include interest during construction.

[2]Types III & IV: Concentrator and receiver efficiencies are combined in a collector efficiency.

B. THE CALIFORNIA AQUEDUCT SYSTEM

As a potential user of small thermal power systems for pumping water, the aqueduct system of California was studied as a major element of the State Water Project. This statewide system of water redistribution in California consumes up to 2.5% of the electrical energy used in the state. Water is moved uphill from north of Sacramento to Southern California in the largest of the three aqueducts that comprise the system. By 1985 it is estimated that pumping power requirements will reach 5.5 billion kW-hr per year and a generating capacity between 600 and 1000 MW. The projected pumping loads for the California State Water Project are shown in Figure II-5. The state can deliver water now, using off-peak power at three mills/kWhr, for $10 per acre-foot. By 1985, the cost of electric power from new baseload plants could rise from 80 to 100 mills/kWhr (1978 dollars). The California Department of Water Resources has investigated nuclear, wind, and solar thermal electric alternatives but no renewable energy plants have yet been built. As a large consumer of electric power, the Department is a potential customer for small power systems technology. However, the conclusion reached in this study is that conventional central station baseload plants will provide the energy needed.

Table II-3. Breakeven Capital Cost for 10% Solar Mix

Reference Utility	Small Power System Type[3] I	II	III	IV
1.3-MW Municipal	-[2]	-	-	-
10-MW Municipal With Generation	968.6	-	-	-
10-MW Municipal Without Generation	1,070.1	-	-	-
35-MW Municipal With Coal-Fired Generation	746.4	716.2	1,137.4	-
35-MW Municipal With Oil-Fired Generation	1,307.3	1,138.8	1,720.1	-
35-MW Distribution Cooperative	720.7	713.0	976.8	-
200-MW Generation & Transmission Coop.	-	771.6	1,069.8	1,075.5

[1]Excluding interest during construction. Costs are $/kWe in 1975 dollars.
[2]For a 1-MW Small Power System with all other characteristics identical to Type I, the breakeven capital cost is $1050/kWe.
[3]Small Power System types are identified on previous page.

A related market for small power systems technology is the municipal water district which distributes the water to the end users. The districts generally buy power from the local utilities. Local water companies and the smaller utilities could become candidates for solar thermal electric power plants. In many cases, hydraulic (pumped) storage would be feasible, and make solar power for pumping especially attractive.

C. OTHER MARKET SECTORS

Beyond the market sectors previously discussed, lie the applications of small power systems technology to foreign countries, primarily the less-developed countries (LDC). In many of the LDC's, air transportation became a dominant transportation mode, in preference to rail.

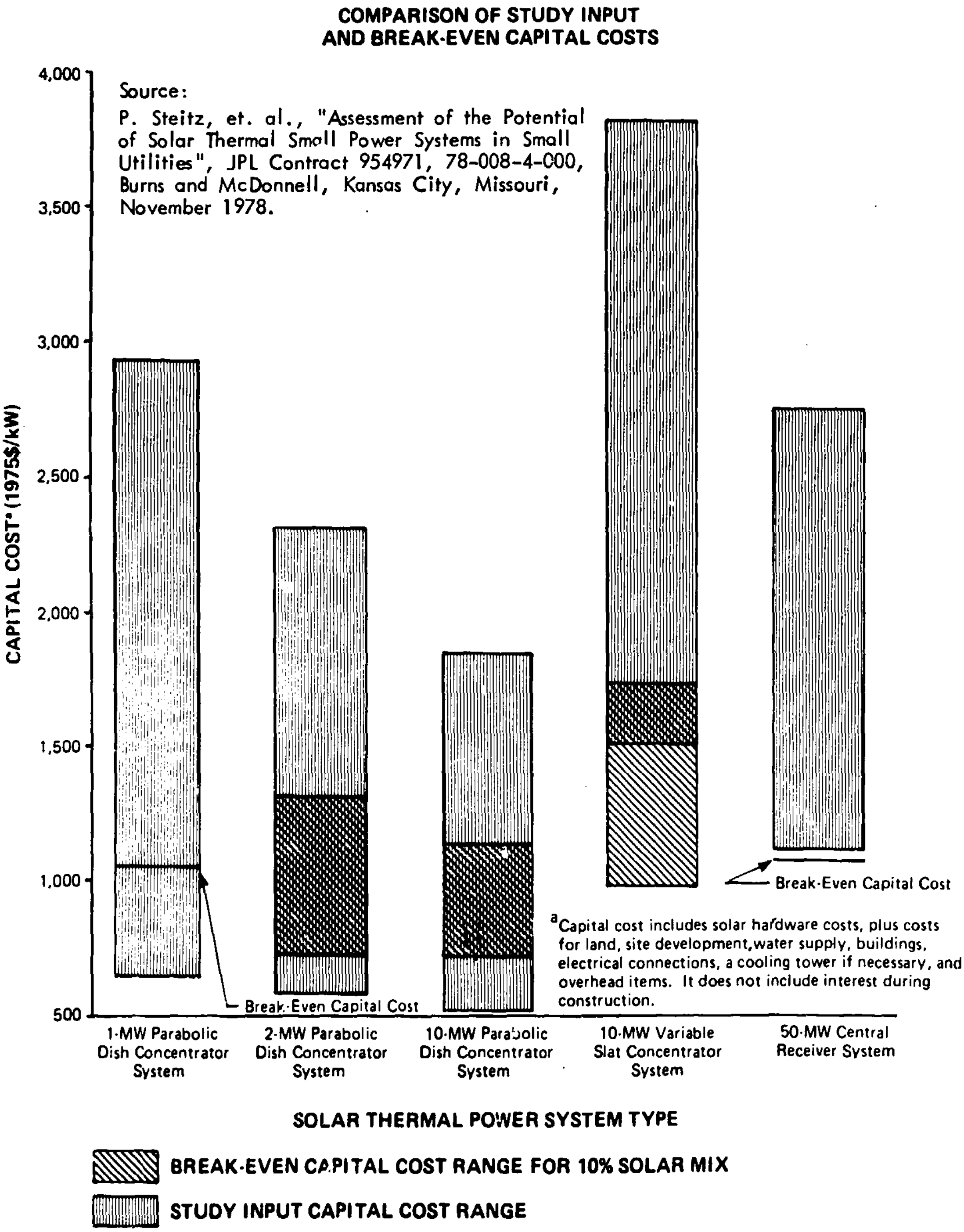


Figure II-4. Capital Costs of Solar Plants in Relation to Breakeven Costs

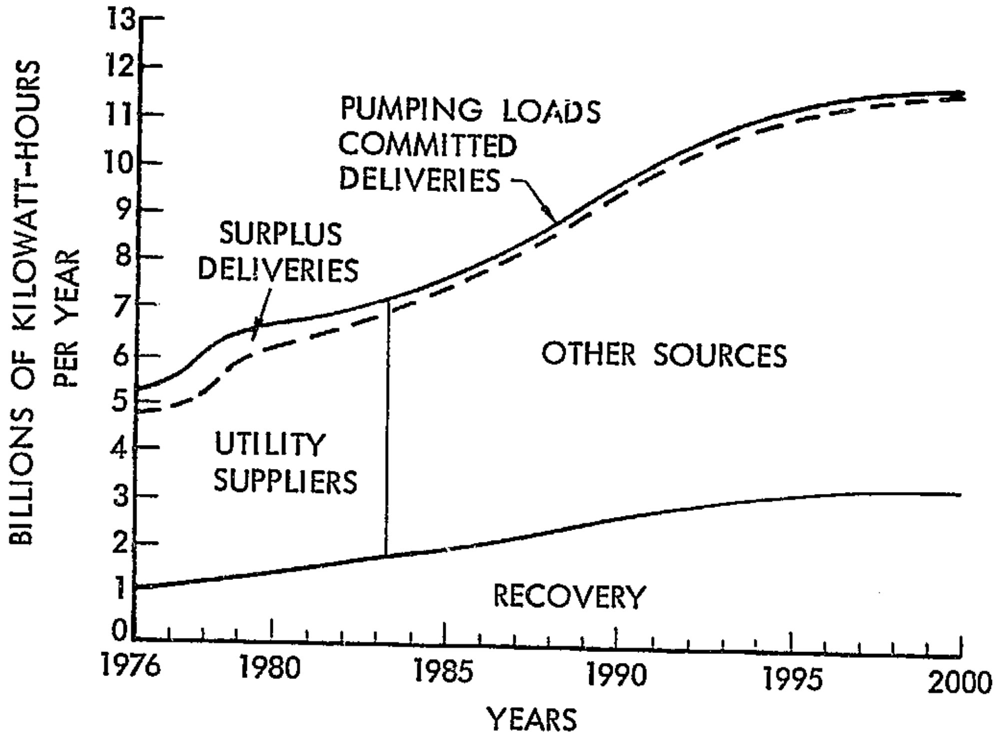


Figure II-5. California State Water Project Estimated Pumping Loads

simply because of the cost of a rail network. The idea of rural electrification using the small, dispersed power systems appears strongly analogous.

The U.S. military establishment is a potential customer for solar thermal power in both fixed base configurations and in portable configurations designed for air transportability. The Navy Civil Engineering Laboratory (CEL) is interested in shore-based solar power using parabolic dish concentrators and Brayton cycle air turbine generators. In anticipation of a near-term technology development program, with deployment of an experimental systems for testing and evaluation, an interagency agreement was signed by the Navy, NASA and DOE. JPL will manage the program, which is identified as JPL Engineering Experiment No. 2a (EE No. 2a).

D. PLANT IMPACTS AND REQUIREMENTS STUDY

The functional characteristics of small solar thermal power plant subsystems can impact the back-up requirements and investment needs of the user. Knowledge of key functional and design requirements at the subsystem level for a solar plant in particular regions of the Southwest and for particular applications is needed to plan EE No. 1 and EE No. 2. To obtain the needed insights, an RFP was released in June 1978 with contract award to occur in FY 1979.

SECTION III

SYSTEM DESCRIPTIONS

The spectrum of solar thermal power system technologies ranges from non-tracking, low concentration collectors with appropriate low temperature energy conversion subsystems, to high temperature systems based on a point-focus collector providing high density solar flux to an efficient heat engine. At one end is a low cost, low efficiency system and at the other a high cost but highly efficient system. Now a priori decision can be made regarding the suitability of a given system to a selected application. The Small Power Systems Applications Project is therefore faced with the task of examining the range of potential technologies for each application that appears worthy of investigation. This section describes the classification of technology options available and provides a brief description of the primary generic systems of interest to the small power systems program. These systems provide the basis for work being performed by the System Definition Task Area at JPL. In addition, DOE has initiated work at the Solar Energy Research Institute (SERI) and Battelle Pacific Northwest Laboratories (PNL) to conduct technology comparison and ranking studies which are described in detail in a following section.

A. CLASSES OF SMALL POWER SYSTEMS

Two major classes of thermal collection and power generation systems are currently being examined: centralized systems and distributed systems. The distributed receiver class has more variants than central receivers, and is differentiated from them in that: 1) the energy from each of a discrete number of receivers is summed in either thermal or electrical form, and 2) the receivers can generally move, in accordance with the sun tracking scheme used. Figure III-1 shows the morphological breakdown. Significant differences exist in the temperatures developed in the various concepts, depending on the concentration ratio and thermal losses in the system.

The temperature of the working fluid, together with system efficiency, increase with concentration ratio and with the number of tracking degrees of freedom. The lowest values of temperature and efficiency are associated with fixed, non-tracking collectors, whereas the highest values are found in the point focus system with 2-axis tracking. The tradeoff here is between the higher performance, greater complexity, and higher cost of 2-axis systems and the lower performance, greater simplicity, and reduced cost of one-axis or fixed systems.

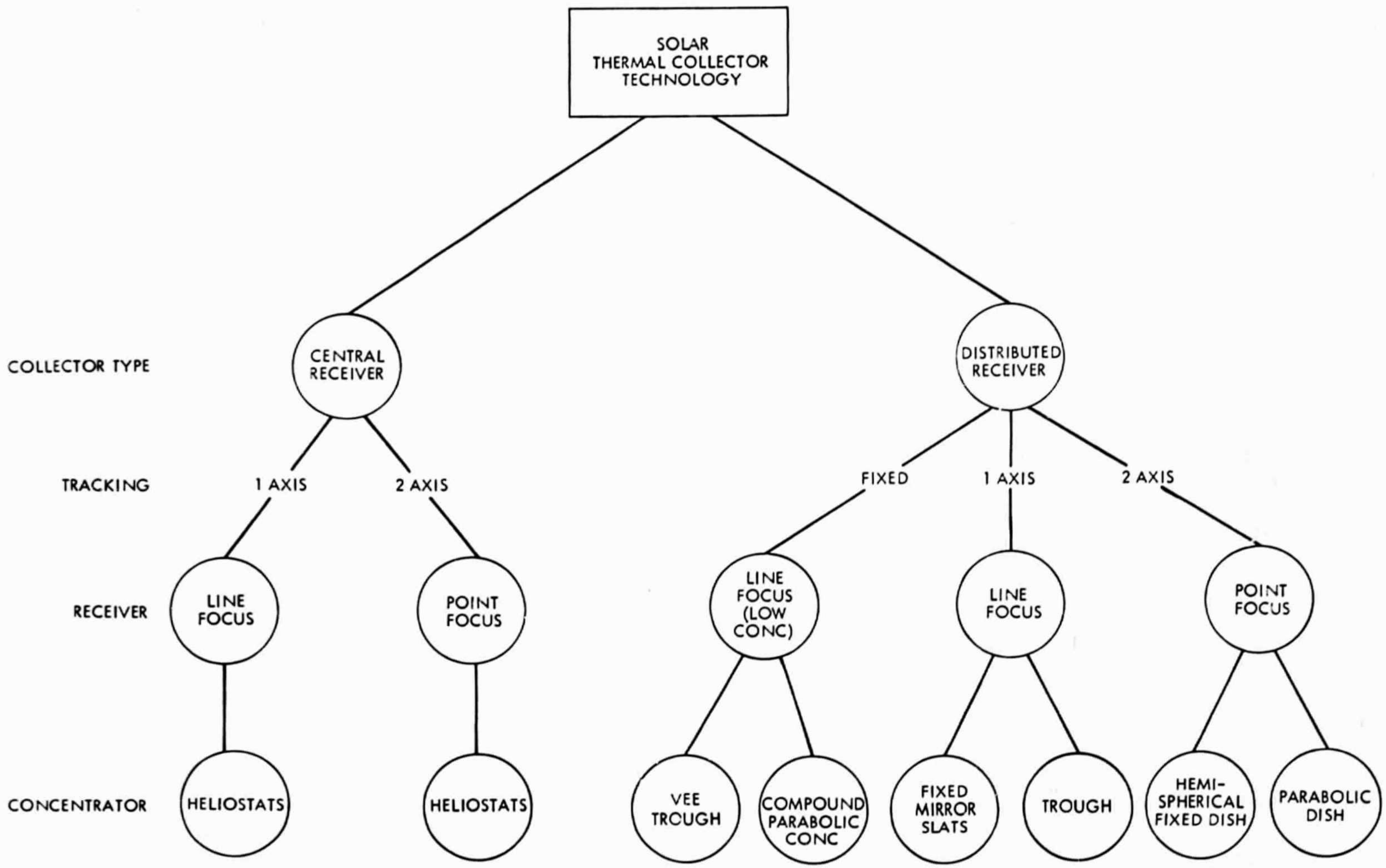


Figure III-1. Breakdown of Solar Thermal Collector Technology (Conversion Cycles not shown)

B. CANDIDATE DESIGN CONCEPTS

Application of the morphological approach described above led to the selection of seven generic collector concepts for solar thermal power plants for evaluation and comparison. They are:

(1) Point focus distributed receiver (PFDR)

(2) Point focus central receiver (PFCR)

(3) Line focus distributed receiver (LFDR)

(4) Line focus central receiver (LFCR)

(5) Fixed mirror distributed focus (FMDF)

(6) Fixed mirror line focus (FMLF)

(7) Low concentration non-tracking (LCNT)

A brief description of each system is given below.

1. Point Focus Distributed Receiver (PFDR)

Among distributed systems, point focus distributed receiver systems are capable of generating the highest temperatures and are the most optically efficient systems. A point focus distributed receiver module is shown in Figure III-2. Two-axis tracking virtually eliminates the cosine loss since the aperture is always normal to the direct beam radiation. Manufacturers claim that the paraboloidal shape allows for concentration ratios as high as 3000. The point focus collector can be used to heat a working fluid for conversion to electricity at a central location, or may be used with a heat engine at the focal point to generate electricity locally.

2. Point Focus Central Receiver (PFCR)

The point focus central receiver system, often called a "power tower," is a concept where reflected sunlight is concentrated on an elevated heat absorbing receiver. This absorbed energy is used to heat a fluid which, in turn, operates a turbine. Figure III-3 illustrates the central receiver design concept.

The large field of mirrors, or heliostats, employs two-axis solar tracking. Two major concepts exist for the placement of the heliostat field. One design places the tower near a central location in the heliostat field, and the other concept has a heliostat field only on the north side of the tower. Several options also exist in the selection of the thermodynamic cycle and coolant. Possibilities are the closed or open helium, or air Brayton cycles, and the conventional steam Rankine cycle. All of the central receiver design concepts are characterized by high temperatures and high pressures.

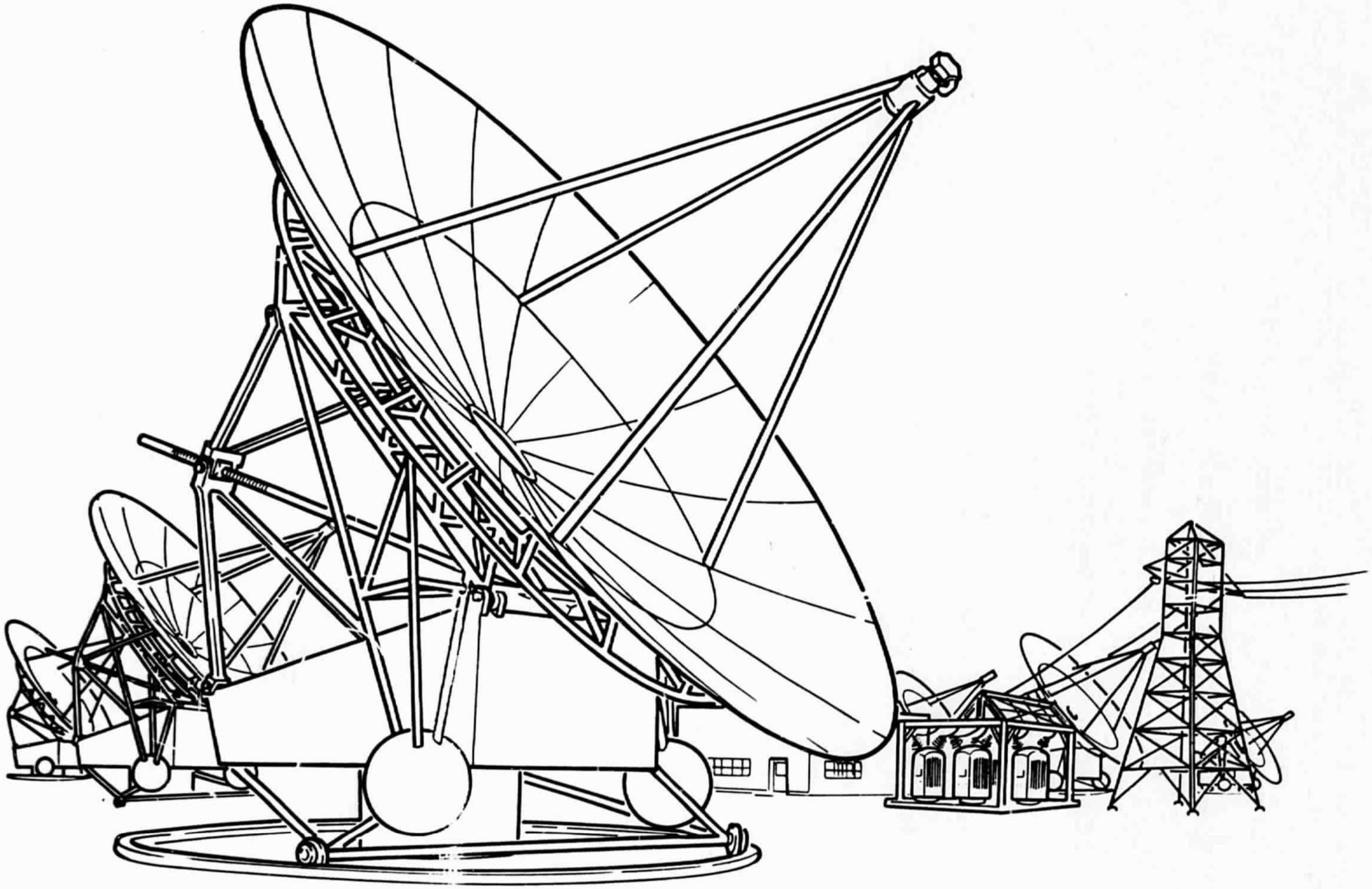
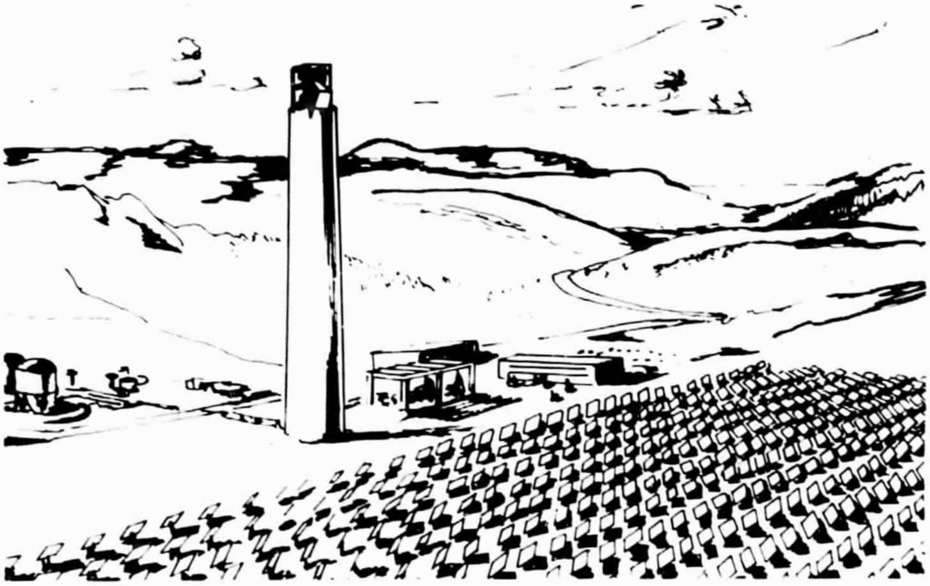


Figure III-2. Point-Focus Distributed Receiver Concept



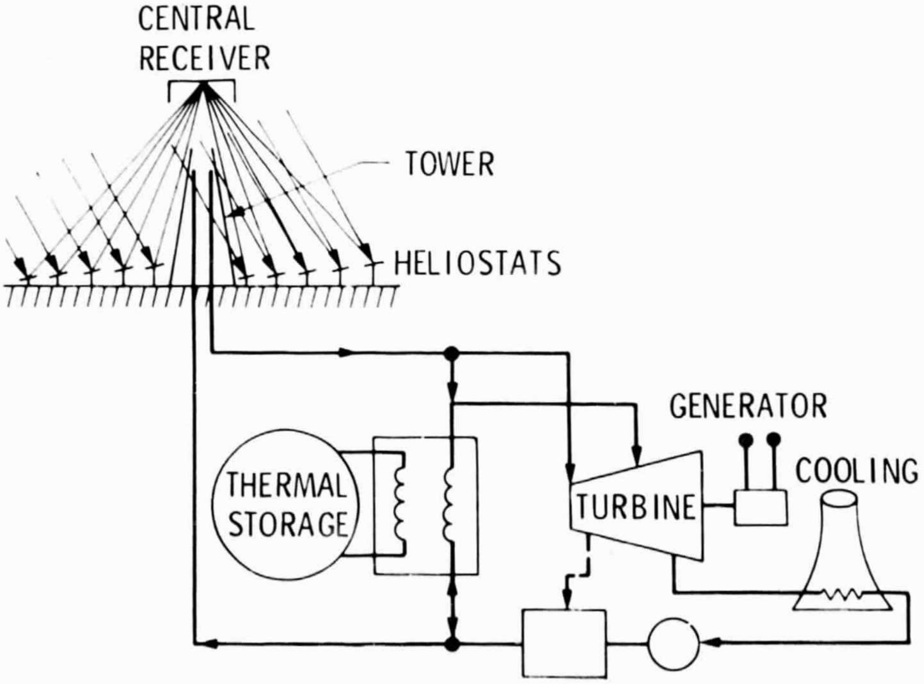


Figure III-3. Point-Focus Central Receiver Concept

3. Line Focus Distributed Receiver (LFDR)

This concept is illustrated in Figure III-4 and consists of a linear receiver located above a linear concentrator which rotates about an axis parallel to the receiver axis. The concentrator can be of the parabolic trough type, as illustrated, or it can be made in the form of segmented, movable mirrors as shown in Figure III-5. In both cases the axis can be oriented east-west, north-south, or polar (parallel to the Earth's axis). Each configuration can provide concentration ratios in the range of 30 to 40.

4. Line Focus Central Receiver (LFCR)

The line focus central receiver system is similar to the PFCR concept in that heliostats are used to reflect solar energy onto an elevated receiver. In this case, however, the receiver is linear and is supported on a series of towers as shown in Figure III-6. The receiver cavity extends along the east-west axis of the heliostat field, with the heliostat field flared on the ends to enhance early morning and late afternoon reception.

5. Fixed Mirror Distributed Focus (FMDF)

The fixed mirror distributed focus dish is a concept in which the concentrator remains stationary and the receiver tracks the focused solar energy. This system is shown in Figure III-7. The large, fixed aperture, hemispherical dish is not as optically efficient as the paraboloidal dish, but the FMDF system has fewer moving parts. The hemispherical dish concentrates reflected energy along the focal axis and requires a cylindrical receiver. The distributed focus hemispherical dish can have concentration ratios of between 200 and 300, depending on the orientation of the focal axis, which varies as a function of the sun's declination and the time of day.

6. Fixed Mirror Line Focus (FMLF)

The fixed mirror line focus concept uses a system that fixes the aperture of the concentrator, and the receiver tracks the focused solar energy about one axis as shown in Figure III-8. It is similar to the line focus distributed receiver except that the receiver rotates about one axis. Concentration ratios can be as high as 40.

7. Low Concentration Nontracking (LCNT)

This generic type includes nontracking concentrators such as the Compound Parabolic Concentrator (CPC) and V-trough. These concepts employ a variety of receiver designs to absorb solar heat and transfer the heat to a secondary fluid. Temperatures of approximately 204°C (400°F) are considered close to a maximum for low concentration systems. Concentration ratios for the CPC are in the range of 3 to 10. A CPC distributed collector module is shown in Figure III-9.

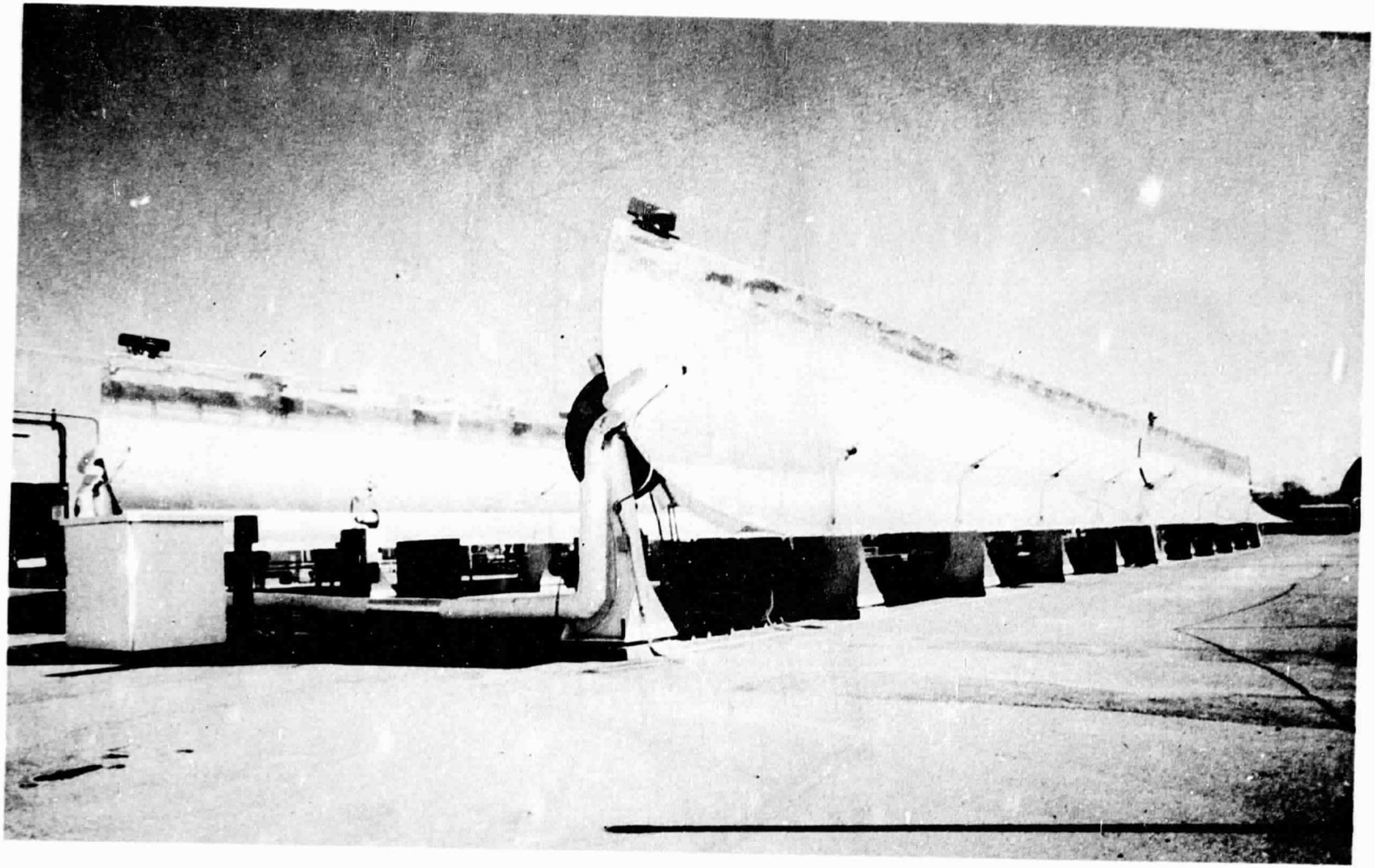


Figure III-4. Line-Focus Distributed Receiver Concept
Using Parabolic Troughs

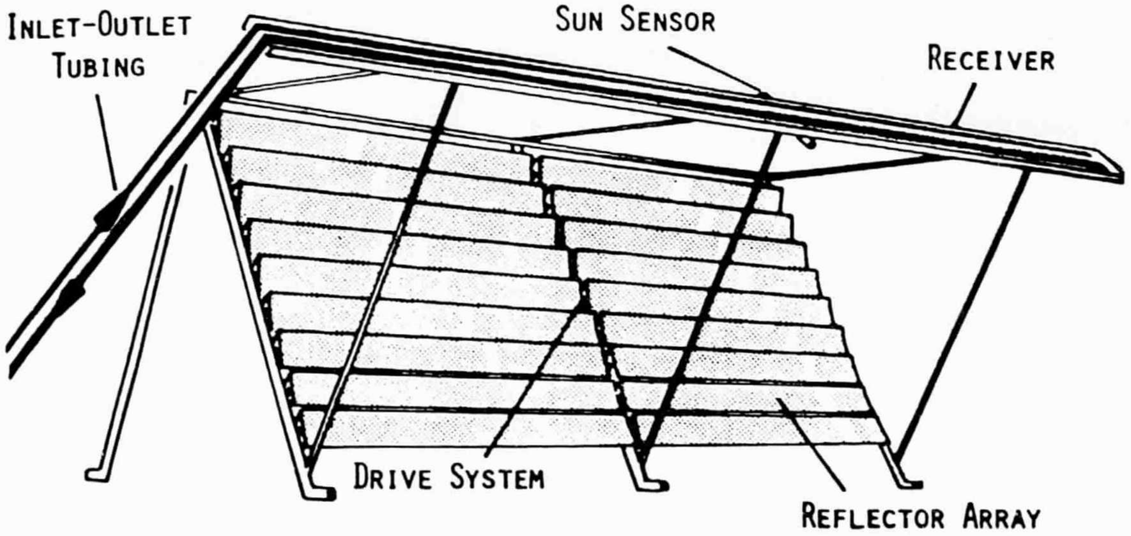


Figure III-5. Line-Focus Distributed Receiver Concept
Using Movable Segmented Mirrors

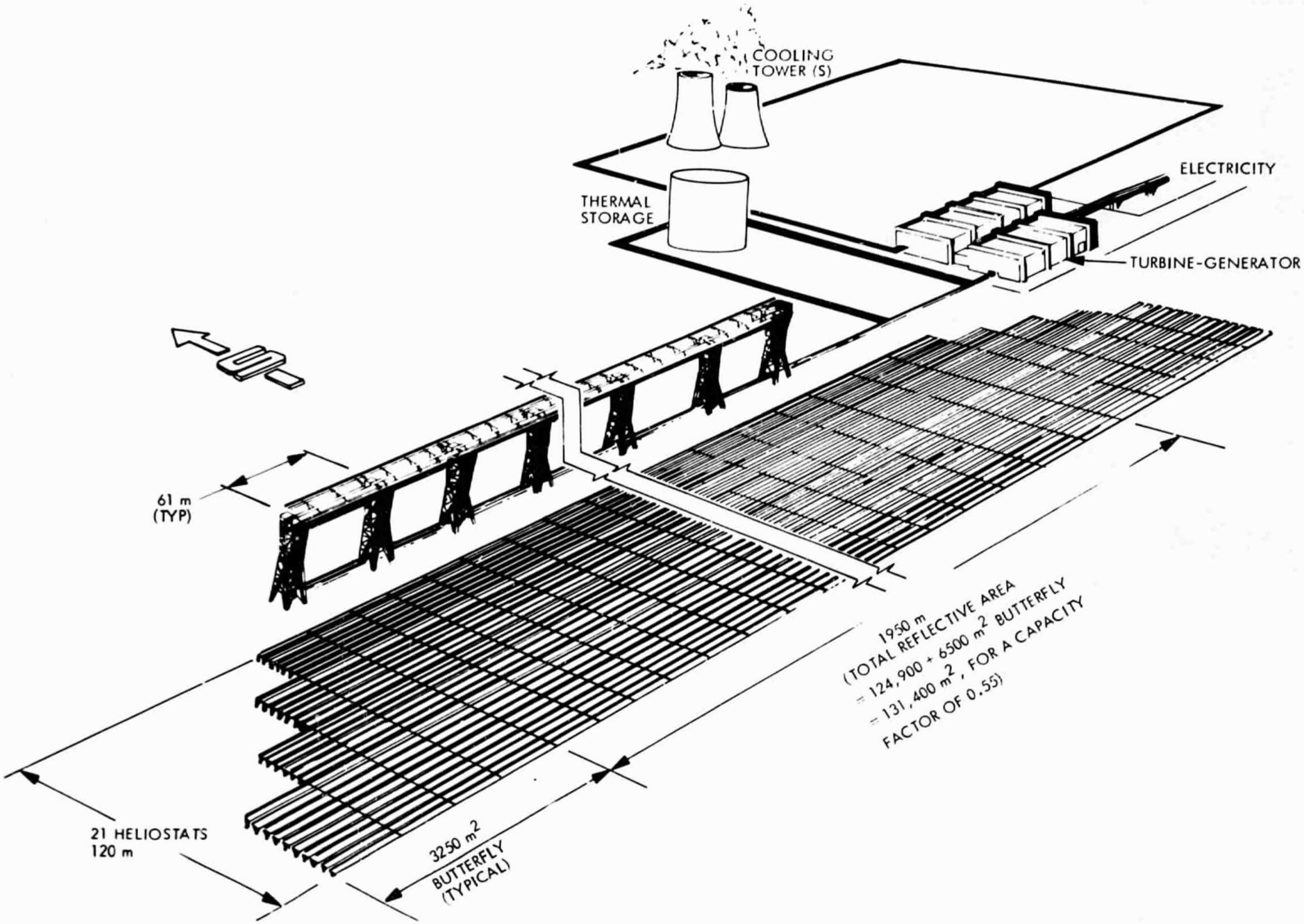


Figure III-6. Line-Focus Central Receiver Concept

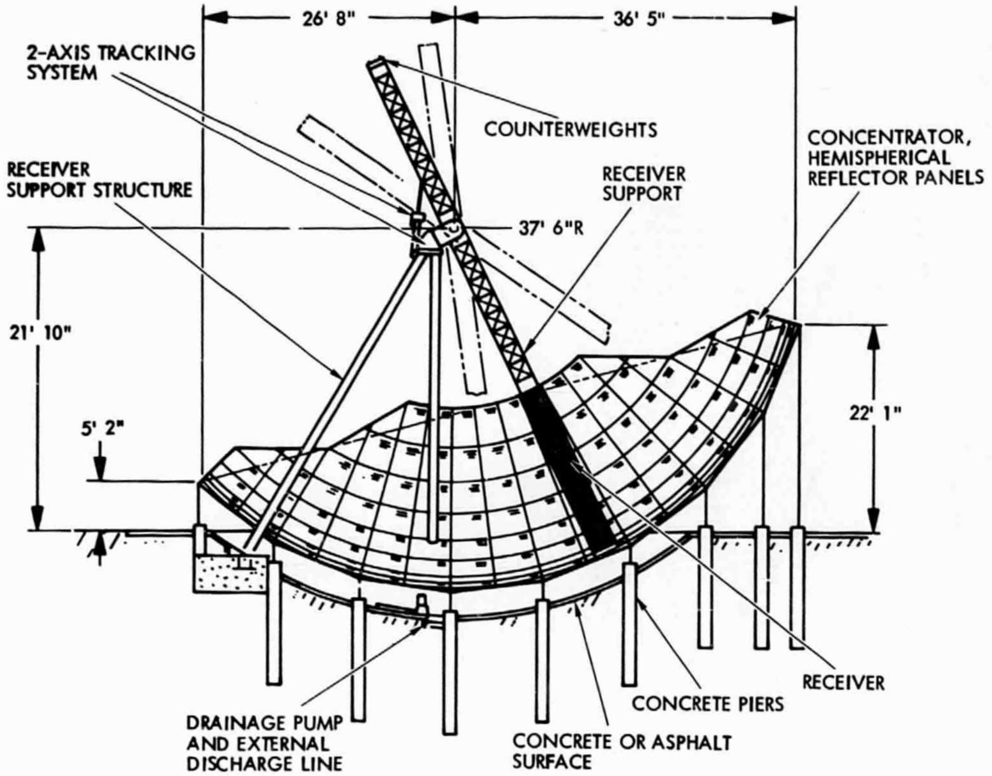


Figure III-7. Fixed Mirror Distributed Focus Concept

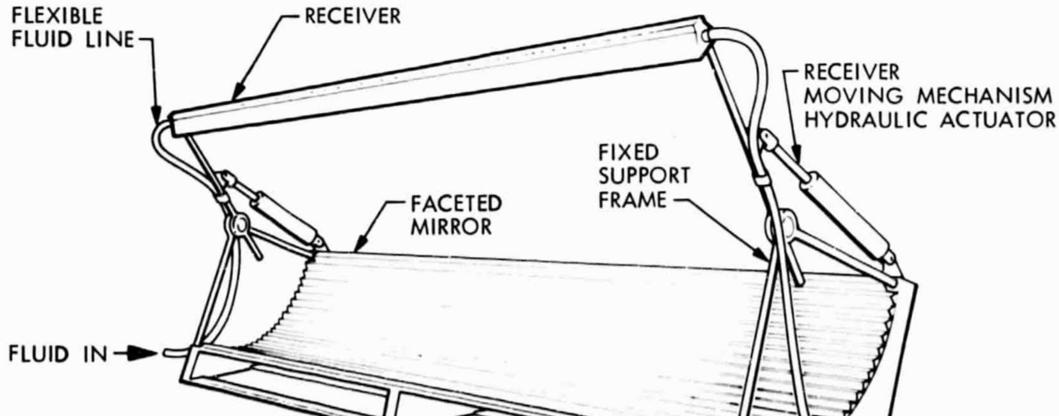


Figure III-8. Line-Focus Distributed Receiver Concept Using Fixed Mirrors and Movable Receivers

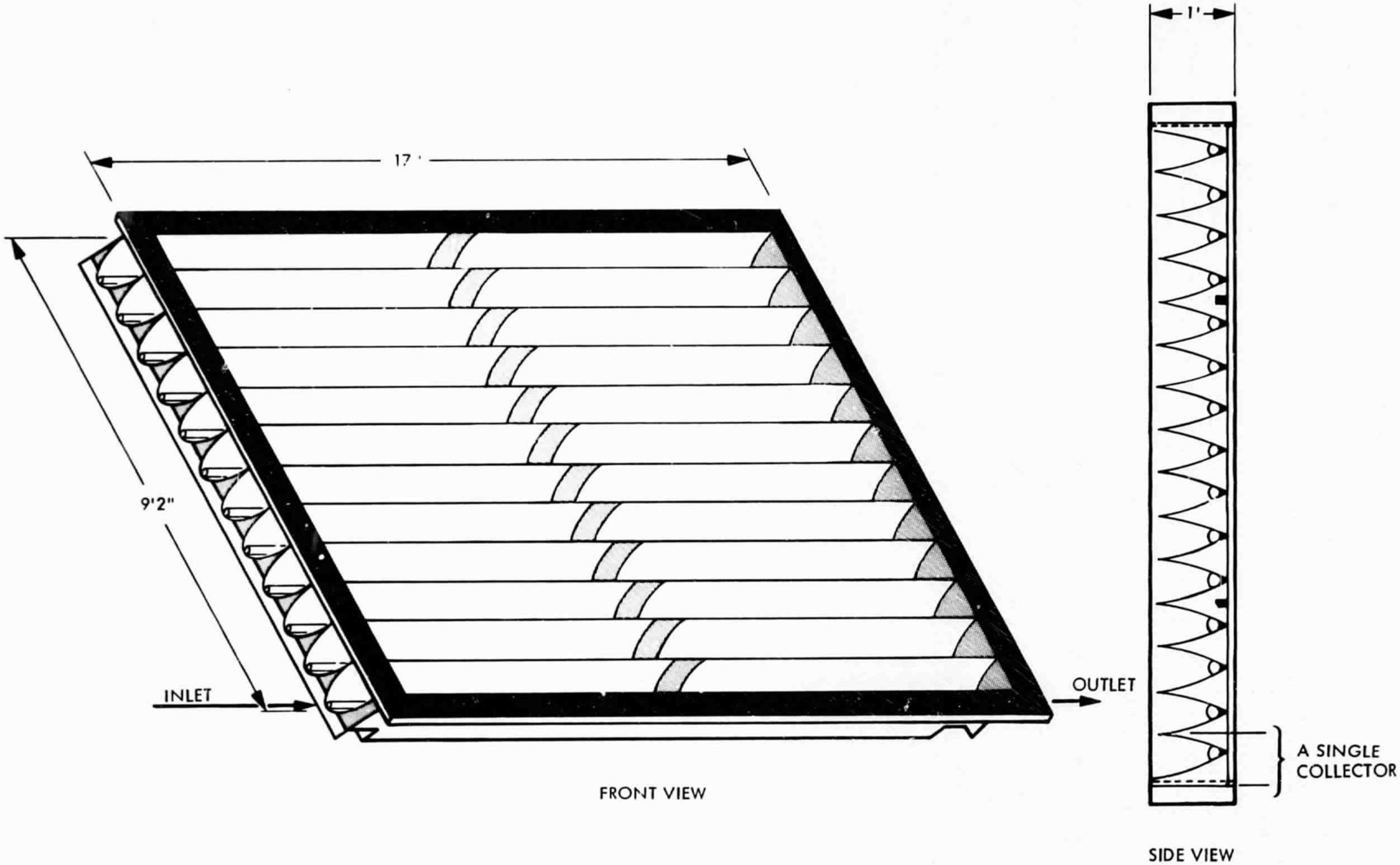


Figure III-9. Low-Concentration Non-Tracking Concept (LCNT)/ Compound Parabolic Concentrator (CPC)

C. POWER CONVERSION SUBSYSTEMS

In power conversion subsystems, differentiation also occurs between the central and distributed approach. In central conversion, thermal energy from the central receiver is converted into electricity in one large heat engine/generator unit. In distributed power conversion, many smaller heat engine/generator units are located in proximity to their respective distributed collectors, and the outputs are combined. The advantages of this approach are cost reduction due to mass production of many identical units, and the modularity feature that provides flexibility in many ways, especially in the phasing of the initial construction program, and later in maintenance and overhaul.

Among the principal candidates for heat engines are the Rankine, Brayton, and Stirling cycles. Rankine engines are limited to the lower temperature range up to about 593°C (1100°F), and have lower efficiencies. However, commercial Rankine engines exist, and future cost and performance estimates can be made with confidence. They lend themselves to both large central conversion systems and to small distributed power conversion approaches.

The Brayton cycle requires high temperature gas technology in the ranges of 704°C (1300°F) and up. Further development of the Brayton engine is required in this use. It has an efficiency greater than the Rankine engine, but requires more complex collectors operating at higher temperatures. Although large Brayton engines are feasible, most of the development to date has been on engines in the smaller sizes more suitable to the distributed collector and distributed power conversion concept.

Stirling cycle engines offer the highest potential efficiency, but demand collectors in the 815°C (1500°F) range which are correspondingly more complex. More research and development is required for this type of engine than for either the Rankine or the Brayton. Nevertheless, Stirling engines are well suited to distributed conversion systems considering the relatively small size of the engine and its need to operate at high temperature. In selecting conversion cycles, the trade-offs are high performance with increased complexity and cost vs lower performance, less complexity, and current availability. An extension of the generic breakdown of thermal power systems to include thermal to electrical power conversion is shown in Figure III-10.

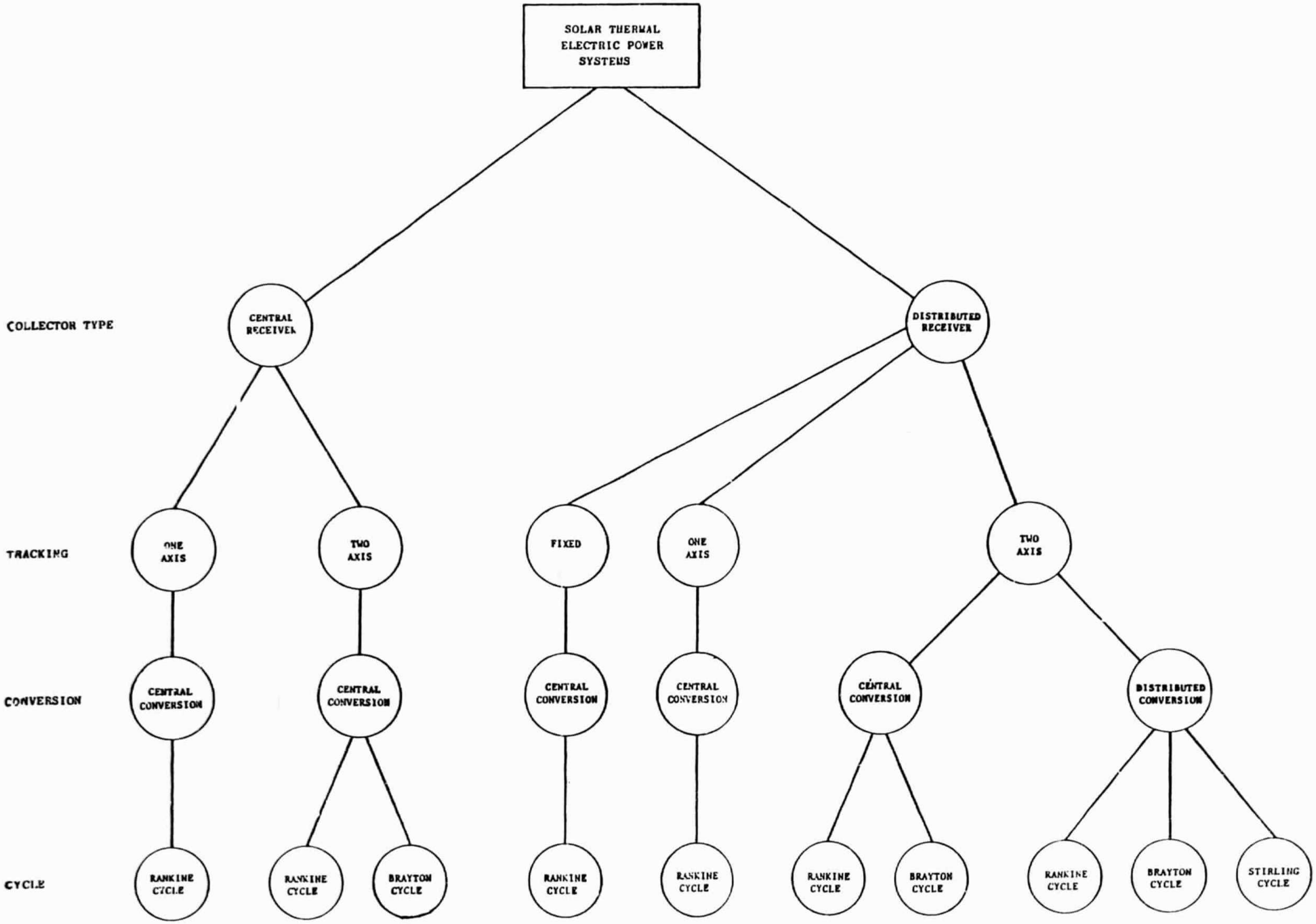


Figure III-10. Breakdown of Solar Thermal Energy Conversion Cycles

SECTION IV

SYSTEMS ANALYSIS AND POWER PLANT DESIGN

To determine the most appropriate system for a given application, a comprehensive analysis of the seven technology options described in Section III is required. Such an analysis was initiated by the SPSA project for the small community electric power application early in the fiscal year. DOE also initiated similar analyses that are being conducted by SERI and PNL to provide an independent assessment.

This section describes the system analysis work being performed at JPL and provides early results for three power plant designs and a summary of the ranking methodology which is being developed as part of this task. The Systems Definition task area is responsible for the technology comparison studies, whereas the ranking methodology is the responsibility of the Project Analysis and Integration task team.

A. SOLAR ENERGY SIMULATION PROGRAM

To assist in performing the analyses of candidate systems, a computer simulation model was developed which is identified as the Solar Energy Simulation (SES) program. It is an updated version of an existing simulation model previously developed at JPL, based on an Aerospace Corporation program. A functional block diagram is shown in Figure IV-1. For a given geographic location and the corresponding insolation and meteorological data, an optimal power plant can be derived, where the optimization criterion is the lowest energy cost at specified values of rated power and capacity factor. A typical program output of energy cost vs capacity factor is shown in Figure IV-2.

The SES simulation model consists of three major parts: 1) A FIELD program for evaluating collector performance as a function of insolation and meteorological conditions, geometry, and optical properties; 2) a POWER program; and 3) an ECONOMICS program for finding the minimum cost system within the prescribed constraints. The ECONOMICS program determines capital, operating and maintenance costs, energy costs, and optimal energy storage size as a function of collector area. Within the FIELD program is the Thermal Energy program which can be used for any configuration of distributed collectors to determine pressure drops, thermal losses, and cost-optimized pipe sizes and insulation thicknesses.

A key aspect of program utilization is the costing input. A significant costing effort was undertaken to provide detailed cost data for each of the generic power systems studied. An example cost breakdown structure is shown in Table IV-1, which also serves as a checklist

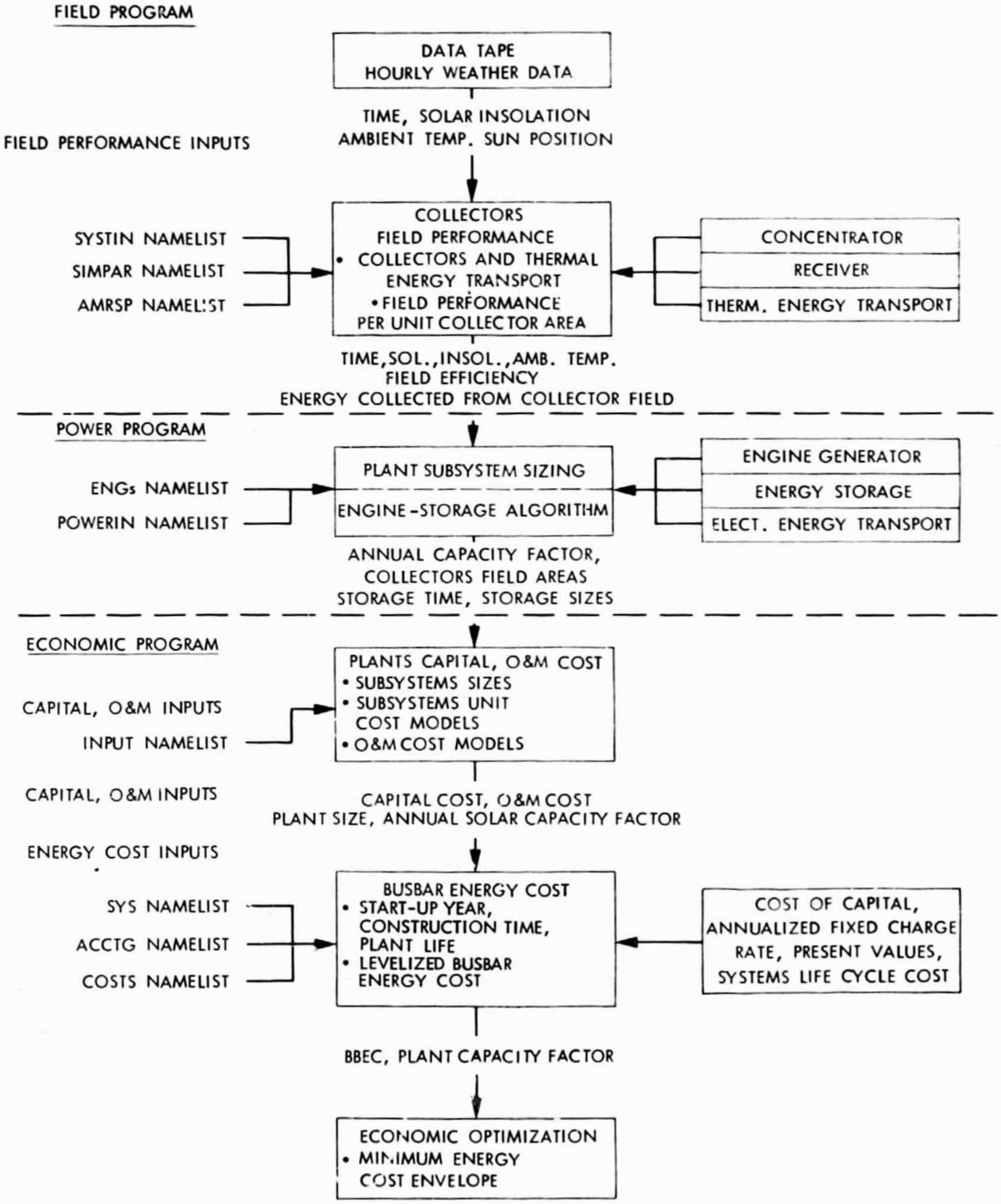


Figure IV-1. SES Computer Program Flowchart

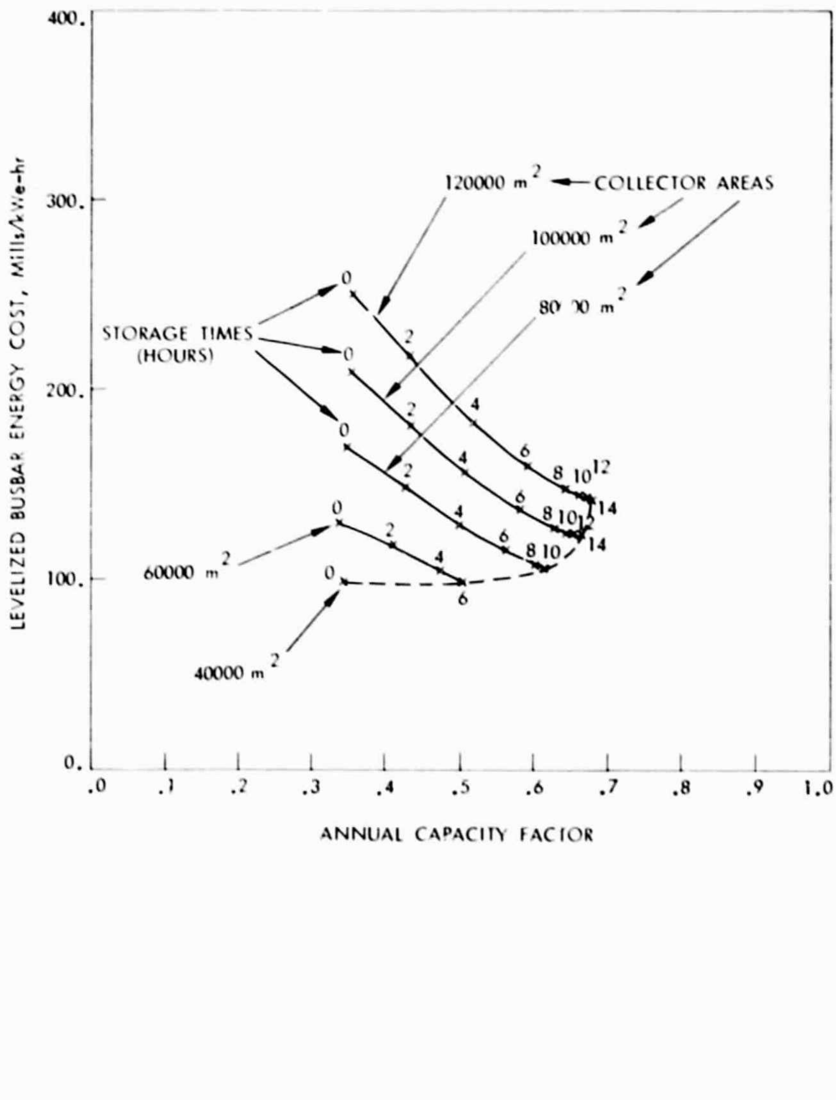


Figure IV-2. An Example of Energy Cost Sensitivity to Capacity Factor Provided by the SES Program

Table IV-1. Cost Breakdown Structure For Small Power Systems

Item
Collector Subsystem
1. Site Preparation/Foundation
2. Structural Framework
3. Reflector Surface and Support
4. Drive Mechanism and Local Control
5. Receiver and Support
6. Pipes, Valves, Fittings, etc.
7. Miscellaneous (Explain)
8. Field Installation
9. Field Supervision
10. Subsystem Checkout/Adjustment
Power Conversion Subsystem
1. Heat Engine
2. Generator
3. Heat Exchanger/Boilers/Condensers
4. Control Valves and Local Control Elements
5. Pumps and Fans
6. Heat Rejection Equipment
7. Subsystem Buildings and Facilities
8. Switch Gear, Transformers, etc.
9. Concept Peculiar (Explain)
10. Miscellaneous (Explain)
11. Field Installation
12. Field Supervision
13. Subsystem Checkout/Adjustment
Energy Transport Subsystem
Thermal
1. Piping
2. Insulation
3. Control Valves and Local Control Elements
4. Fluid Pumps and Drives
5. Site Preparation, Foundations, and Piping Support Elements
6. Miscellaneous (Explain)
7. Field Installation
8. Field Supervision
9. Subsystem Checkout/Adjustment
Electrical
1. Wiring (Material, Supports, Trenches, etc.)
2. Utility Interface Substation
3. Local Control Elements
4. Miscellaneous (Explain)
5. Field Installation
6. Field Supervision
7. Subsystem Checkout/Adjustment
Energy Storage Subsystem
1. Tanks, Insulation, Storage Medium
2. Heat Exchangers/Boilers
3. Heat Transfer Fluid
4. Pumps, Valves, Piping, etc.
5. Local Control Elements
6. Site Preparation/Foundation
7. Miscellaneous (Explain)
8. Field Installation
9. Field Supervision
10. Subsystem Checkout/Adjustment
Control Subsystem
1. Control Software
2. Processors/Computers
3. System Control Elements for Plant Operation
4. Subsystem Operation Control Elements
5. Control Lines to Subsystems and Plant Control Elements
6. Buildings and Facilities to House Equipment
7. Miscellaneous (Explain)
8. Field Installation
9. Field Supervision
10. Subsystem Checkout/Adjustment
Detail Design
Plant Construction Management
Special Features
Related Items
Other (Buildings and Other Utilities to Support System Functions, etc.)
Testing and Evaluation
Total Estimated Cost

for subsystem identification. Detail parts are costed on the basis of fabrication method and manhours per manufacturing operation. Tooling, other capital equipment, and raw material costs are recognized.

B. TECHNOLOGY RANKING METHODOLOGY

When the power plant design and cost optimization analyses are complete for all seven candidate conceptual categories, it will be necessary to have available the appropriate evaluation and selection criteria and approach. The selection methodology is being developed under the decision analysis subtask in the Project Analysis and Integration task area, and is briefly described below.

The purpose of the decision analysis effort is to facilitate ranking of the alternative, candidate, small power system design concepts to narrow the choice to those that show the highest potential for successful commercial development. The methodology for ranking technology alternatives is based on work by Keeney and Raiffa, as simplified by Miles.

The evaluation criteria selected for ranking are identified with cost, finance, performance, impacts, and potential for industrialization and commercialization as shown in Figure IV-3. One or more system attributes that could be qualified were selected for each criterion. Both the criteria and the attributes selected for use in the multi-attribute decision process are shown in Table IV-2.

C. SYSTEMS ANALYSIS RESULTS TO DATE

Application of the solar energy simulation computer program to the candidate design concepts provides a determination of subsystem sizes, performance, and cost. It has been used to date to analyze three of the seven candidate technologies. A consistent set of ground rules has been used in these analyses and are shown in Table IV-3. The highlights of these analyses are described below. All of the results discussed here are preliminary and will be updated at the conclusion of the Technology Ranking Study.

1. Compound Parabolic Concentrator (CPC)

The low concentration non-tracking (LCNT) collector with compound parabolic concentrators (CPC), illustrated earlier, was studied in a configuration having a concentration ratio of 5 and a basic module 2.7m (9 ft.) wide by 5.2m (17 ft.) long by 30cm (1 ft.) thick. The system configuration is shown functionally in Figure IV-4.

The simulation model described earlier was applied to the CPC power plant configuration, and the sizing and performance results are depicted in Table IV-4. As noted, the collector efficiency on a yearly average basis is 0.40. A capital cost summary is presented in Table IV-5. Figure IV-5 illustrates the SES computer output for this system.

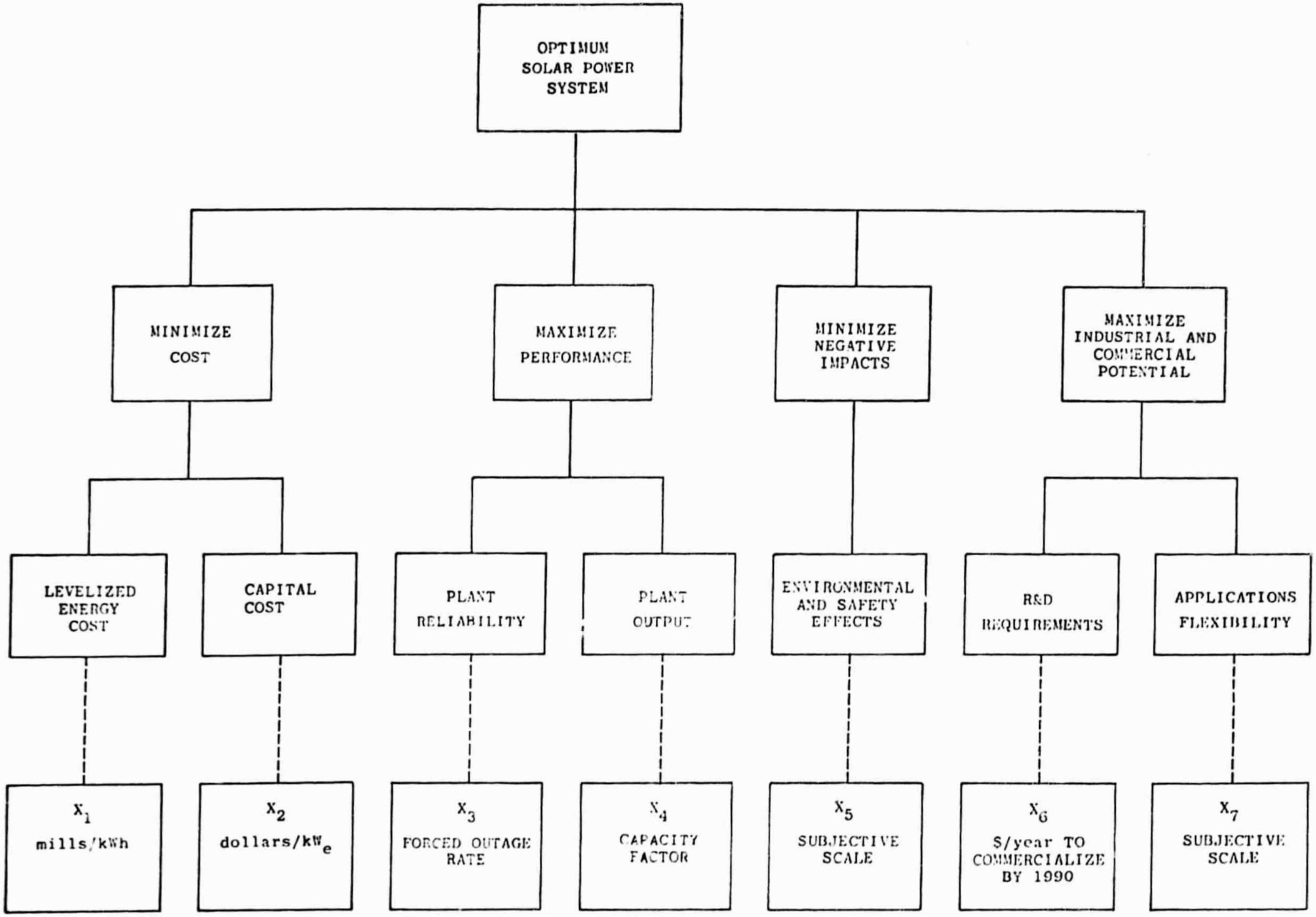


Figure IV-3. Criteria and Attributes for Ranking Small Solar Thermal Electric Power Systems Technology Alternatives

Table IV-2. SPSA Technology Ranking Criteria

Criteria	Primary Attributes	Tentative Scale (1)
Cost (2)	Levelized Energy Cost	70 to 120 mills/kWhr in 1978 $ for 1990 Startup or 40 to 80 mills/kWhr in 1978 $ for 2000 Startup
Finance	Capital Cost	$1800 to 3000/kWe in 1978 $ for 1990 Startup or $600 to 1800/kWe for 2000 Startup
Performance (3)	Plant Reliability	18 to 80% Capacity Factor (Depending on Insolation and Storage) 0 to 10% for Forced Outages (Due to Hardware Failures)
	Safety and Environmental Effects	0 to 10 Subjective Scale 0 = Effects similar to Coal Fired Steam Plant 9 = Environmentally Neutral 10 = Mildly Positive Environmental Effects
Industrial (4) and Commercial Potential	Research, Development, and Industrial Funding Requirement	10 to 50 $ Million/Year to Commercialize by 1990 for 1 Technology
	Applications Flexibility	0 to 10 Subjective Scale 0 = Few Applications 10 = Wide Applicability

NOTES:

(1) Nearly all systems ratings and therefore attribute scales are affected by hybrid systems, year of startup, and intended market penetration. Non-utility applications may be important in the 1985-1990 time period.

(2) These cost ranges reflect current goals for competitive systems. These ranges are sensitive to insolation data and to the use of storage. The levelized energy cost ranges and capital cost ranges may not coincide with each other since they were independently derived.

(3) This range includes allowances of 0 to 10% for mechanical forced outages with hybrid firing, a modular plant could theoretically go to 100%.

(4) Research, development and industrial costs are not additive for multiple technologies.

Table IV-3. Ground Rules Used for Systems Analyses

These ground rules are used in the technology comparison studies so as to limit the scope of the studies in specific areas. This is being done to most effectively focus on the critical elements of the solar thermal plant concepts for a qualitative ranking of the various concepts.

1. The nominal plant power rating to be used is 5 MWe. The plant power ratings to be used in the sensitivity analyses are 1.0 MWe and 10 MWe.

2. The plant concepts to be studied shall give the capability of delivering rated power from the collector field only to the utility grid for a direct normal insolation of 800 W/m^2 at solar noon at equinox at the reference plan location.

3. For these studies, Barstow, CA is the reference plant location (latitude 34.9°). Barstow insolation data for 1976 collected by WEST Associates and analyzed by the Aerospace Corp. will be supplied by JPL at the outset of the studies.

4. A service life capability of 30 years is assumed for all commercially available items or near-term technology items other than the collector/receiver combinations (unless a shorter life capability has already been identified for some items).

5. The power output of the plant when operating solely from the energy storage subsystem is assumed to be 0.7 of the rating of the plant for both thermal and electrical storage subsystems.

6. The electrical energy produced by the plant is assumed to be absorbed by the utility grid at all times without regard to matching the output to the load demand characteristics of the grid.

7. The following cost values are assumed for the economic portions of the analyses to provide comparable costs for ranking purposes.

a)	Raw Land		\$5,000 per acre
b)	Cost of capital to a "typical utility"	k	0.086
c)	Rate of general inflation	g	0.060
d)	Escalation rate for capital costs	g_c	0.060
e)	Escalation rate for operating costs	g_o	0.070
f)	Escalation rate for maintenance costs	g_m	0.070
g)	Capital recovery factor (8.6%, 30 yrs)	$CRF_{k,N}$	0.0939
h)	Fixed charge rate, annualized	FCR	0.1565

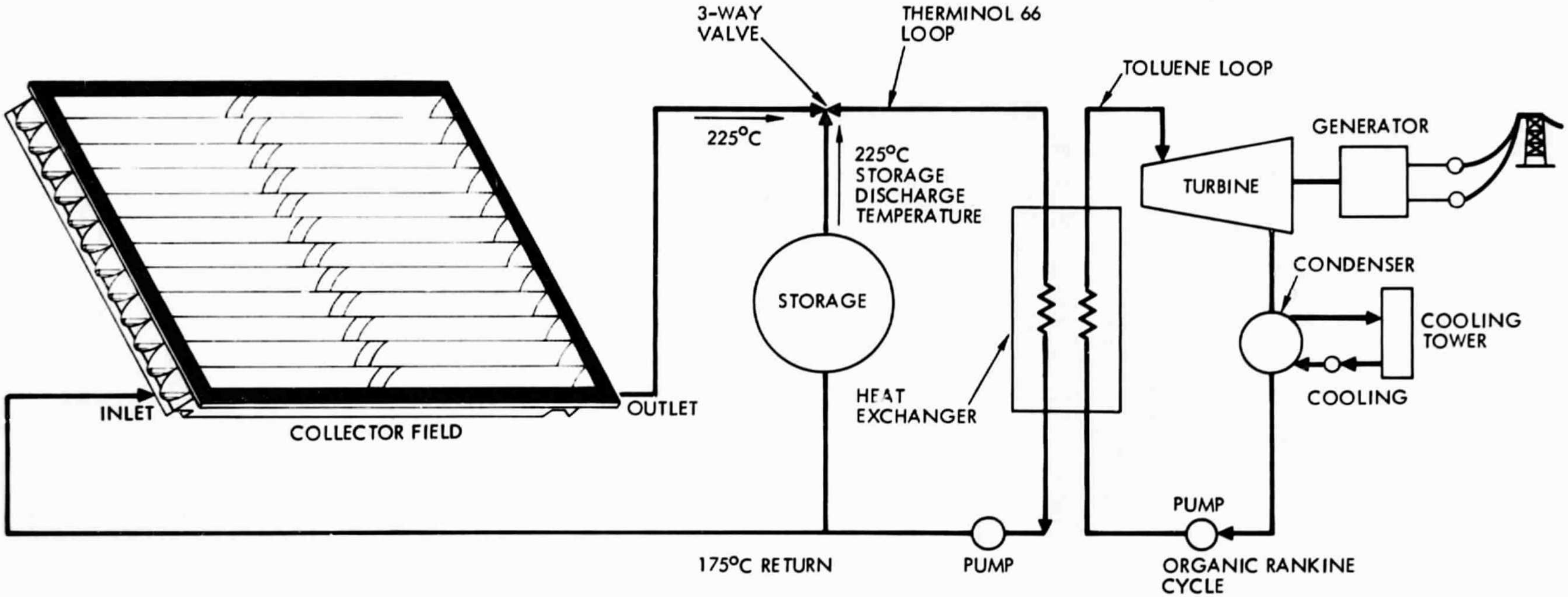


Figure IV-4. CPC Solar Power Plant Functional Diagram

Table IV-4. Sizing and Performance Results for Compound Parabolic Concentrator (CPC)

Plant rated power	5 mWe
Solar Input	2850 kWhth/m^2 year (1)
Collector Area	5000/0.0754 = 66,310 m^2 (713,420 ft^2)
Yearly Usefule Heat output per Collector Module	1130 kWhth/m^2 year at 200°C (392°F)(1) Average
Collector Yearly Average Efficiency (2) (3)	1130/2850 = 0.398
Yearly Operation Time	2700 hours
Collector Yearly Average Thermal Power Rating	1130/2700 = 0.418 kWth/m^2
Predicted Transport Efficiency(4)	η_{TR} = 0.903
Net Heat input to Turbine	Q = 0.418 x 0.90 = 0.377 kWth/m^2
Net Electricity Generation at η_{engine} = 0.20	P = 0.0754 kWe/m^2
Number of Modules Required at 12.55 m^2 (135 ft^2) each	5283
Field Array Size	72 rows of 74 modules each

(1) Based on the computer code supplied by ANL and 1976 Barstow, California insolation data supplied by the Aerospace Corporation.

(2) Collector inlet/outlet temperatures are 175/225°C, respectively.

(3) η_{coll} is defined at 200°C (392°F) average temperature.

(4) Consists of 4.3 percent thermal and pumping losses for the piping grid and 5.4 percent pumping losses internal to the collector module totaling to 10 percent energy transport loss.

Table IV-5. CPC Five Megawatt Plant Cost Breakdown

	Collector cost \$70/m^2		Collector cost \$140/m^2	
Subsystem	Capital Cost x 10^6	Percent of Total	Capital Cost x 10^6	Percent of Total
Collector	14.3	54	28.6	69.9
Transport	3.5	13.3	3.5	8.5
Engine	2.8	10.7	2.8	6.9
Storage	5.0	18.7	6	13.3
Land	0.4	1.5	0.4	0.9
O&M	0.4	1.5	0.4	0.9
Total Energy Cost	212 mills/kWhr		305 mills/kWhr	

Notes: (1) Costs are in 1978 dollars

(2) Plant start-up is assumed to occur in 1985

(3) Capacity factor is 0.55

(4) Plant configuration is based on low concentration, non-tracking (LCNT) collectors with compound parabolic concentrators (CPC).

2. Line Focus Central Receiver

A 5 MWe line focus central receiver concept by FMC Corporation was analyzed, which consists of a linear receiver and parallel rows of heliostats track the sun in elevation only. Focusing is accomplished by varying heliostat curvature; the axis of rotation is oriented east and west. The assumptions used in the JPL Solar Energy Simulation (SES) included the following:

(1) Insolation data is for Barstow, California in 1976.

(2) The steam turbine peak design point temperature is 496°C (925°F) at an efficiency of 0.325.

(3) Thermal storage is at a temperature of 343°C (650°F), and the operation of the steam turbine from storage is at 275°C (525°F).

(4) Steam transport efficiency is 0.997 for direct operation from the receiver, and 0.85 when operating from storage.

Results of the JPL study are shown in Figure IV-6. The power flow through the entire system is shown in barchart form, from solar input to electrical output. The overall system efficiency is 16.2%. Busbar energy cost was approximately 200 mills/kWhr for concentrator receiver costs of $\$100/m^2$.

3. Point Focus Distributed Receiver

The PFDR configuration selected for analysis has the following characteristics: Dish diameter 11 m (36 ft), mirror reflectance approximately 0.85; a Brayton engine operating at 815°C (1500°F) with a cycle efficiency of 0.32; argon as the working fluid; a 3600 rpm alternator; and a cavity type receiver. The engine operates in a closed cycle, recuperated mode. If a xenon-helium mixture were substituted for argon, cycle efficiency would rise to 0.36. System performance was computed assuming: Insolation corresponds to Barstow, California in 1976, optical efficiency assumed constant with time, and energy storage is in electrical form. Subsystem efficiences are as presented in the power flow chart of Figure IV-7. The overall system efficiency from solar input to busbar output is 19.2%. The levelized busbar energy costs derived from the JPL Solar Energy Simulation program were found to vary from 100 mills/kWhr to 130 mills/kWhr for concentrator/receiver costs of $\$100/m^2$ to $\$160/m^2$, respectively.

Table IV-6. CPC Energy Transport Subsystem Performance Summary

	Units	Collector Area 1,600 m^2 (17,216 ft^2)	65,000 m^2 (699,400 ft^2)	136,000 m^2 (1,463,360 ft^2)
Normal Rating	MWe	0.1	5	10
Q_T (1)	kWth	1,040	42,250	88,400
$\eta_{Transport}$		0.912	0.903	0.899
Q_{TNET}	kWth	948	38,151	79,471
Engine Efficiency		0.145	0.185	0.20
Maximum Output (2)	kWe	137	7,058	15,894

Notes: (1) The transport system is sized for the heat transport at maximum output. Performance is based on an insolation level of 1000 W/m^2 and collector efficiency of 65 percent.

(2) Since the engine will be loaded up to 120 percent of the rating during peak periods, the excess heat will be stored in the thermal storage or wasted for those systems with no storage.

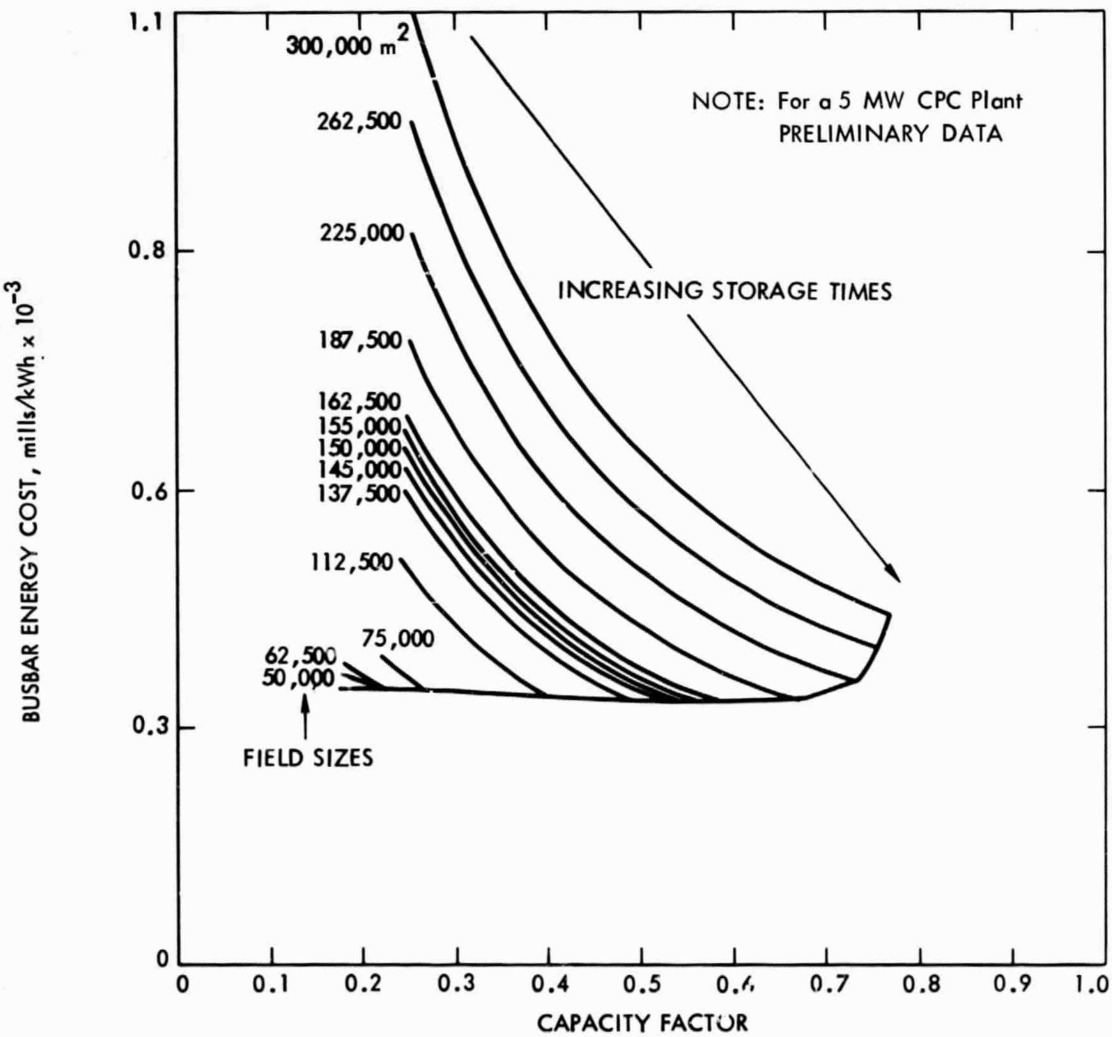
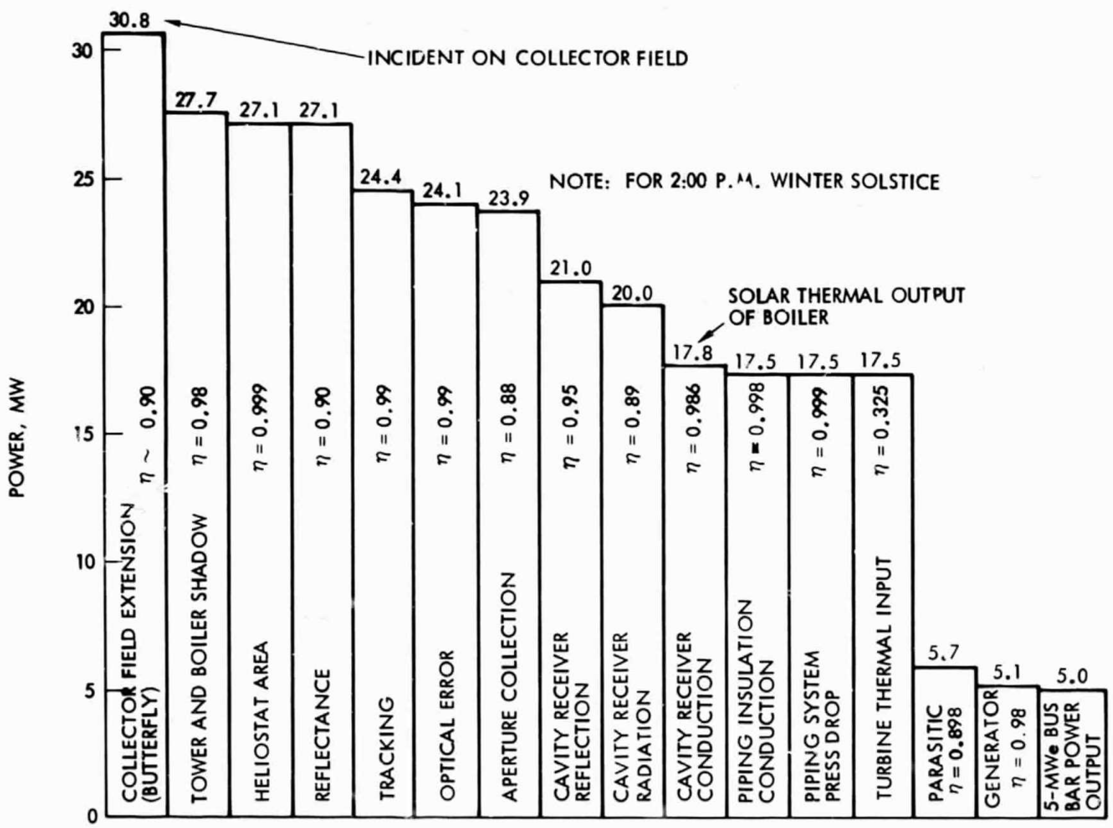


Figure IV-5. Effect of Collector Field Size and Plant Capacity Factor on Busbar Energy Cost for a CPC System



NOTES: (1) Data are for 2 pm Winter solstice

(2) Data are adapted from Solar Thermal Electric Central Receiver Research Study, Interim Report R-3617, FMC Corp., Feb. 1977

Figure IV-6. Power Flow for Line Focus Central Receiver

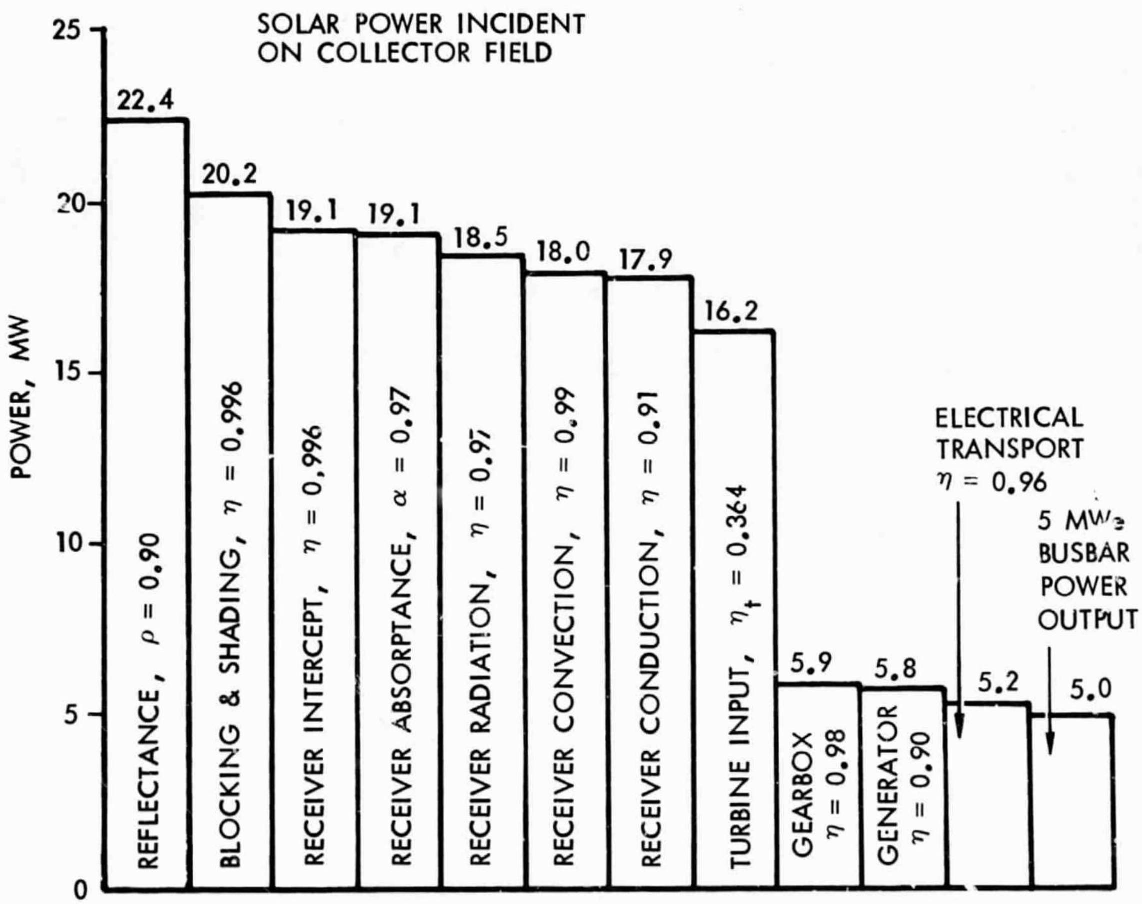


Figure IV-7. Power Flow for Point Focus Distributed Receiver Power Plant With a Closed-Cycle Brayton Engine (PFDR/B), at 800 W/m^2 Direct Insolation

SECTION V

ENGINEERING EXPERIMENTS

The general strategy of the engineering experiment series was discussed in Section I. This section describes the two experiments now underway. Engineering Experiment No. 1 (EE No. 1) is a 1 MW plant designed for small community application, and is predicated on the use of near-term technology currently under development by industry under the auspices of other DOE programs. Early deployment is sought to confront the questions of technical, operational, and institutional feasibility of the small power system concept for this application. EE No. 1 represents the first step in developing the most suitable technology for the utility market sector desiring the use of an alternative, dispersed power system situated at or close to the load center it serves.

The EE No. 2 series will employ point-focusing technology currently under development by the PFDRT Project. EE No. 2a is the first of this series of four to six small experimental power plants rated at approximately 100 to 200 kWe. Test planning is underway, and hardware implementation is to begin early in FY80.

The EE No. 1 system development activity is the responsibility of the Systems Definition task area. Site selection and field test planning and integration are within the Field Test Integration Task area. The Requirements Definition task area is responsible for the current phase of EE No. 2a activities.

A. ENGINEERING EXPERIMENT NO. 1 (EE NO. 1)

The objectives of EE No. 1 include:

(1) Demonstrate feasibility of near-term small power system technology in a community and utility environment.

(2) Determine economic, performance, functional, operational, and institutional aspects of the selected system in the user environment.

(3) Advance the acceptance of the small power system concept by the user community.

(4) Stimulate the creation of an industrial base for small power systems.

EE No. 1 is being conducted in three phases. As noted in Figure V-1, Phase 1 covers system concept definition, Phase II includes preliminary design, development testing and detailed design. Phase III comprises fabrication, installation, and systems test and evaluation. In Phase I, several candidate design concepts will be investigated from which a preferred configuration will be selected for subsequent development and installation. Candidate designs were selected as a result of a

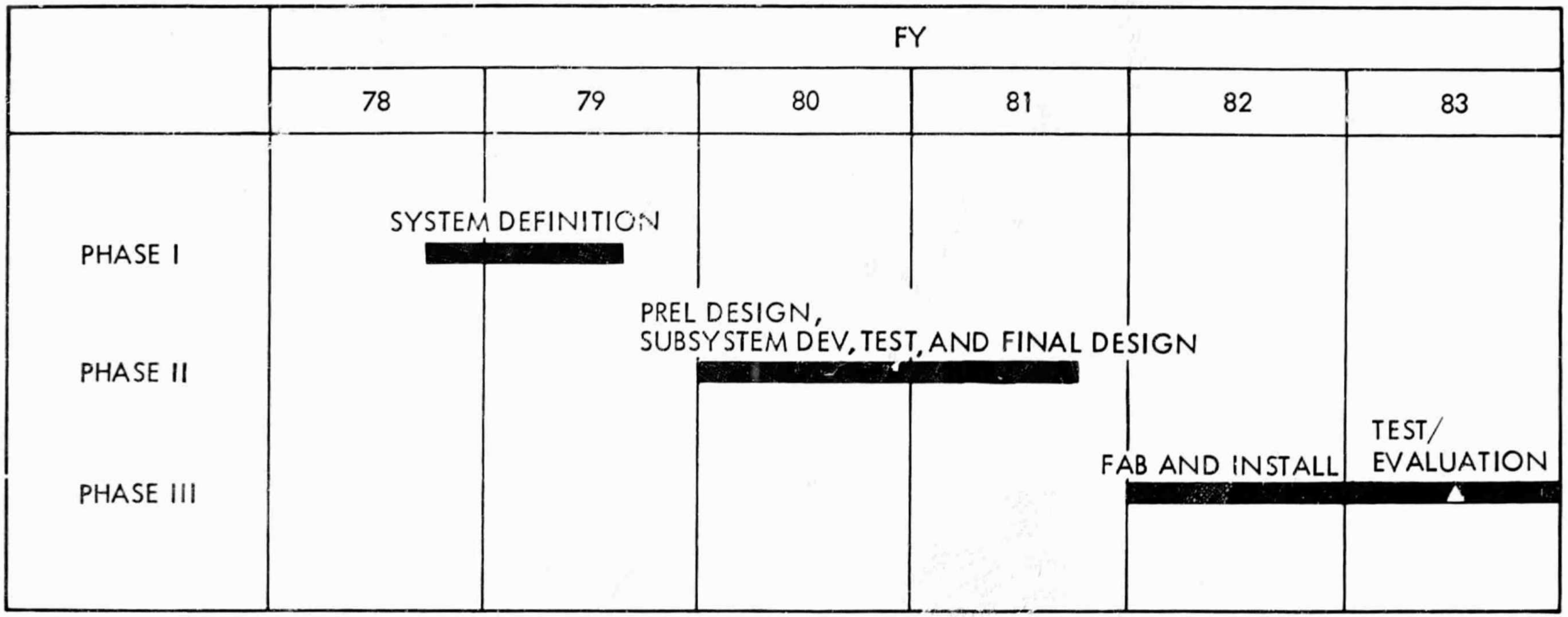


Figure V-1. Engineering Experiment No. 1 Schedule procurement in FY 1978 in which proposals were received in each of the following three categories:

Category A: To include but not be limited to central receivers and line focusing systems.

Category B: Point focusing, distributed collector, with central energy conversion.

Category C: Point focusing, distributed collector, with energy conversion at the collector.

Phase I study contracts were let in each category with industrial contractors, and are of 10 month duration. The companies are McDonnell-Douglas, General Electric, and Ford Aeronutronics, working in Categories A, B, and C respectively. In each case, the design capacity factor of 0.40, a 30 year amortization period and minimum required operating personnel is used. Each concept is for a complete system consisting of five major subsystems: collector, power conversion, energy transport, energy storage, and plant control. The three proposed concepts are described below. In each case, a number of alternate subsystem configurations are being considered in Phase I. The design selected for Phase II, therefore, may differ in detail from the description herein.

B. CATEGORY A DESIGN CONCEPT (McDonnell-Douglas)

A tower mounted central receiver and a field of 2-axis tracking reflectors (heliostats) constitute the collector. There are 160 heliostats, each of which has 38 m^2 (409 ft^2) of reflecting area. The plant occupies about 8 acres, and is illustrated in Figure V-2. Overall system efficiency is 18.5% with no allocation to storage. The energy transport subsystem is a dual fluid system. Thermal energy is conducted from the receiver to the steam generator by a working fluid called Hitec, a eutectic mixture of salts. Steam is generated at 482°C (900F). The temperature at the receiver outlet is 510°C (950°F), and the temperature at the receiver inlet is 288°C (550°F). Figure V-3 is a schematic diagram of the system.

The power converter is a steam turbine operating at 482°C (900°F) and producing 1.10 MWe at the output of the alternator. Both radial and axial turbines are being examined. The allowance made for plant operating power is 0.10 MWe. A wet cooling tower is used to condense the exhaust steam from the turbine.

The energy storage unit accumulates thermal energy that is produced in excess of the energy needed by the power converter. Hot Hitec is pumped through the storage unit, which is a tank containing a rock and sand mixture that stores energy as sensible heat. The tank is sized to provide an output of 9 MW-hr of thermal energy.

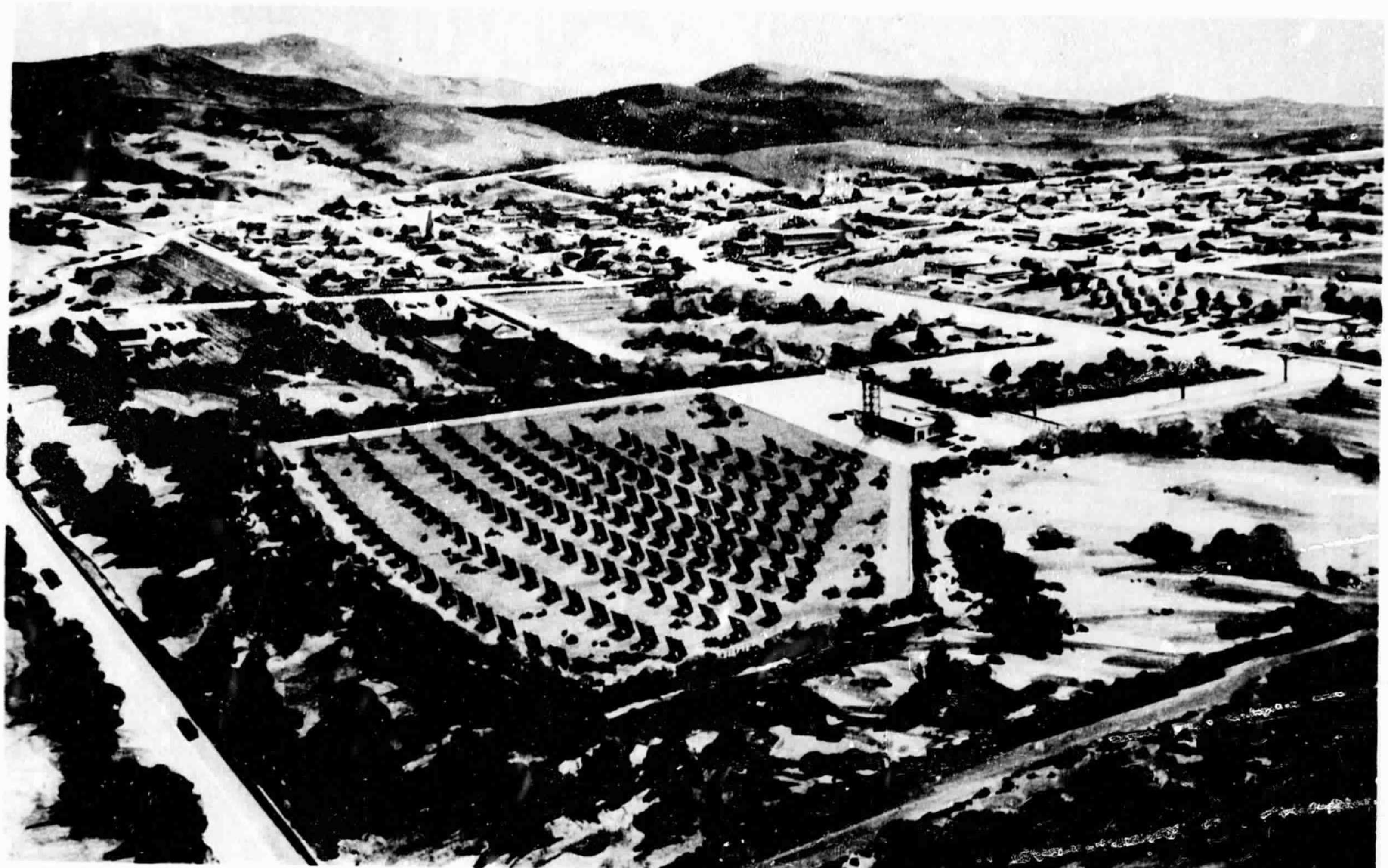


Figure V-2. Artist's Concept of McDonnell-Douglas Power Plant

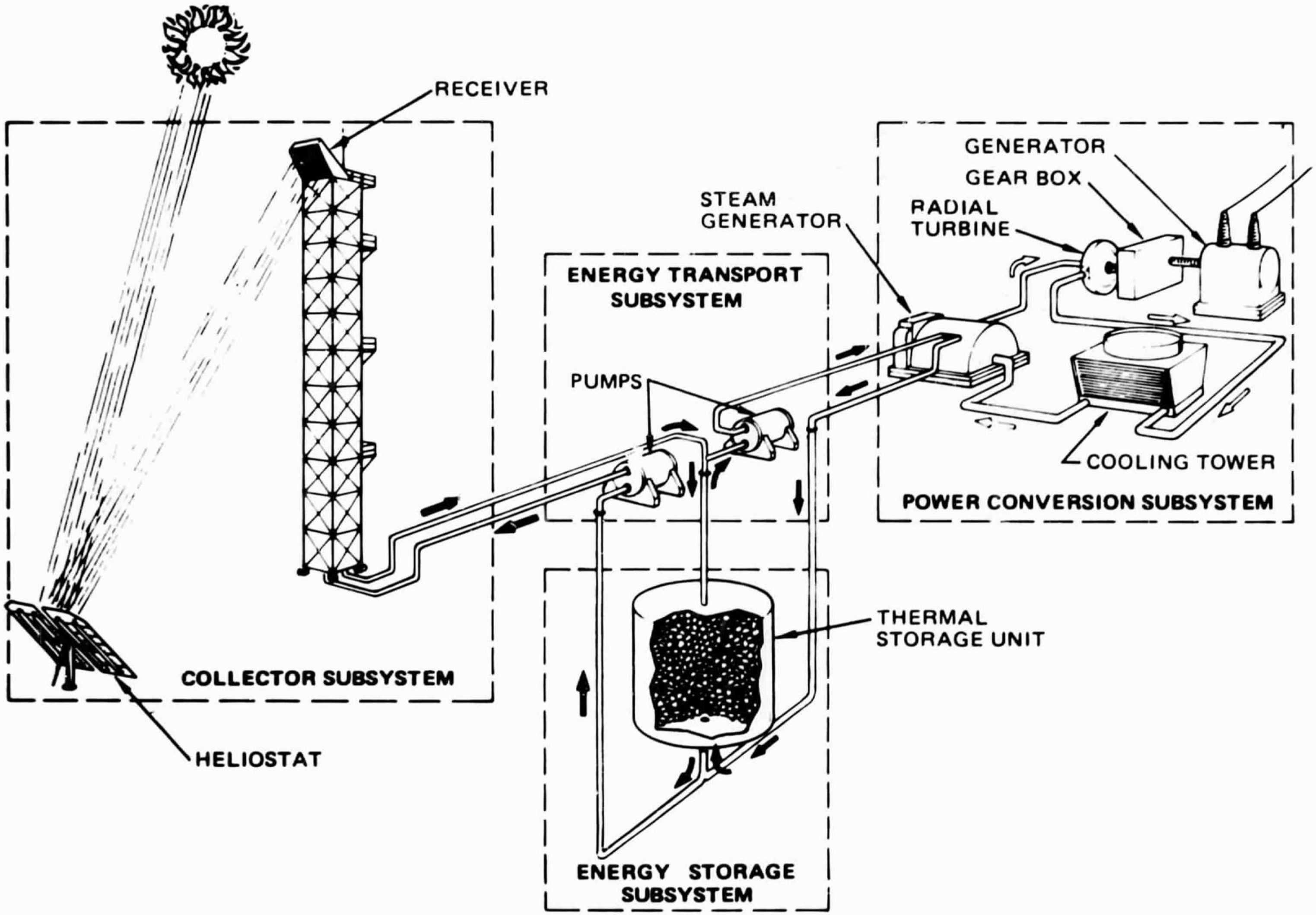


Figure V-3. System Schematic Diagram for McDonnell-Douglas Concept

C. CATEGORY B DESIGN CONCEPT (General Electric)

This system employs the point focus, distributed receiver approach with central power conversion, and has an output of 1.0 MWe. The solar collector consists of a field of approximately 150 enclosed parabolic dishes located within a total plant area of 10.9 acres. Overall system efficiency is 13.9%

The dishes are 7.9 m (25.9 ft) in diameter and are provided with 2-axis tracking mechanisms. Each dish concentrates its incident direct on a 20.3 cm (8 in) diameter receiver mounted at its focal point. The receiver remains fixed, and the dish collector-concentrator rotates about axes that pass through the spherically shaped receiver. Figure V-4 is a plan view of the plant layout, and Figure V-5 shows the configuration and construction of the dish. A system functional schematic is presented in Figure V-6 for a 1 MWe power conversion subsystem.

Connected to the receiver is a potassium heat pipe which is thermally coupled to a helical tube steam boiler where superheated steam is generated at a temperature of 510°C (950°F). The thermal energy transport system consists of vacuum insulated pipes that collect the steam from each of the 150 solar collector-concentrator dishes and conduct it to a central power converter. The vacuum piping concept is illustrated in Figure V-7 which is proposed for pedestals, headers, laterals, and expansion joints.

The power converter module, shown in Figure V-8 for a 1 MWe plant, contains a marine type steam turbine coupled to an electrical alternator. The module is designed for rail transportability. Steam is condensed at the turbine outlet by a dry cooling tower.

Energy storage is accomplished by separate treatment of the case of transient and steady state interruption in solar flux. Where intermittent cloud blockage occurs, the turbine is provided with steam from a steam accumulator. An electric storage battery system is provided to meet the requirements for a 0.4 capacity factor. Thermal storage is being looked at in Phase I as an alternative.

D. CATEGORY C DESIGN CONCEPT (Ford Aeronutronic)

This system employs the approach of a point focus distributed collector with energy conversion at each collector receiver. A field of 23 parabolic dish collector-concentrators is used where each dish is 16 m (52.5 ft) in diameter. Plant rating is 1.0 MWe, and the land area required is approximately 8 acres. An aerial view of the plant concept is shown in Figure V-9. Plant efficiency on a net annualized basis is 22.8%. A functional schematic diagram of the system is shown in Figure V-10.

The receiver is mounted at the focus of the dish, and is structurally integral with the power converter, which is a model P-75 Stirling

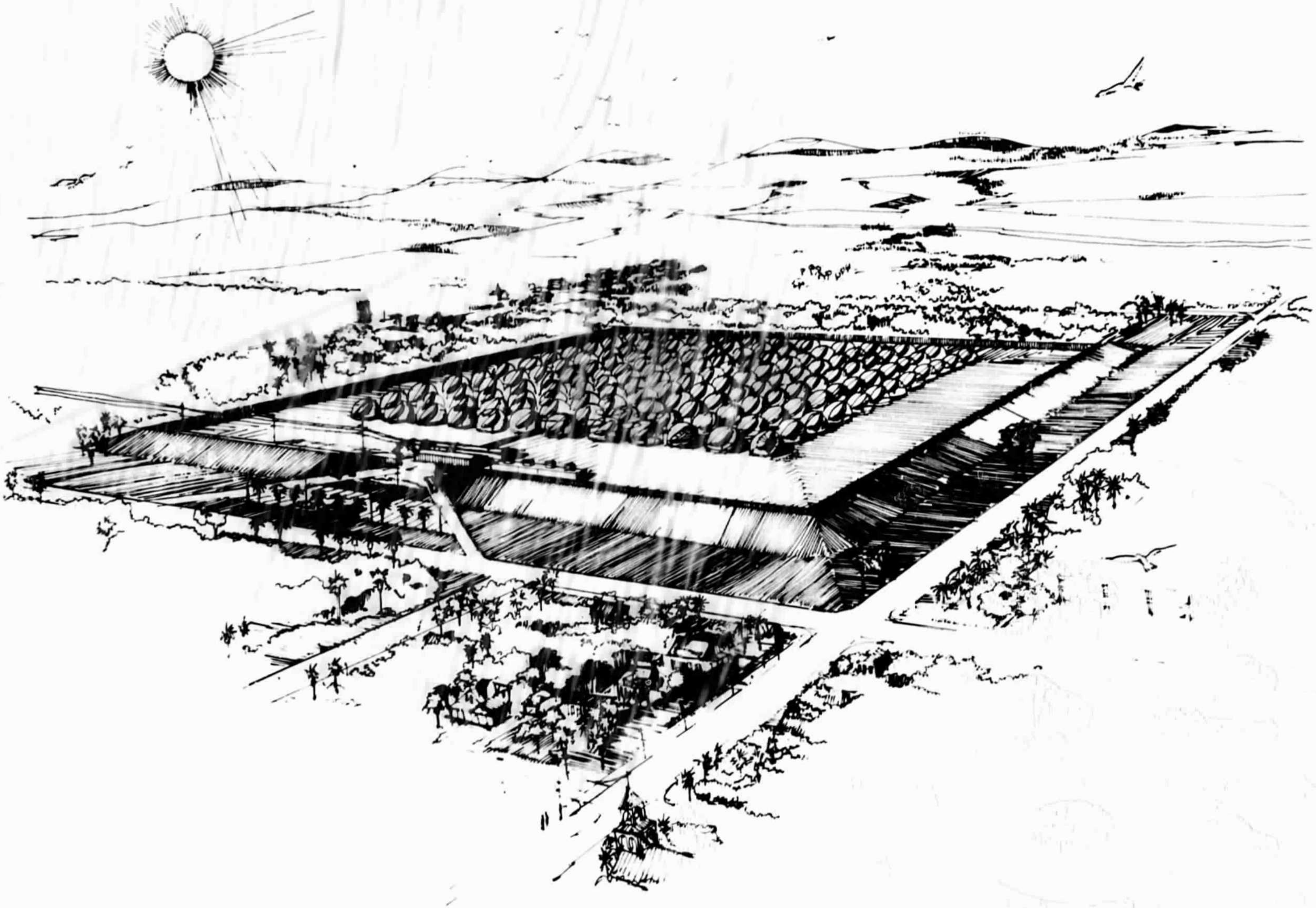


Figure V-4. Artist's Concept of GE Plant

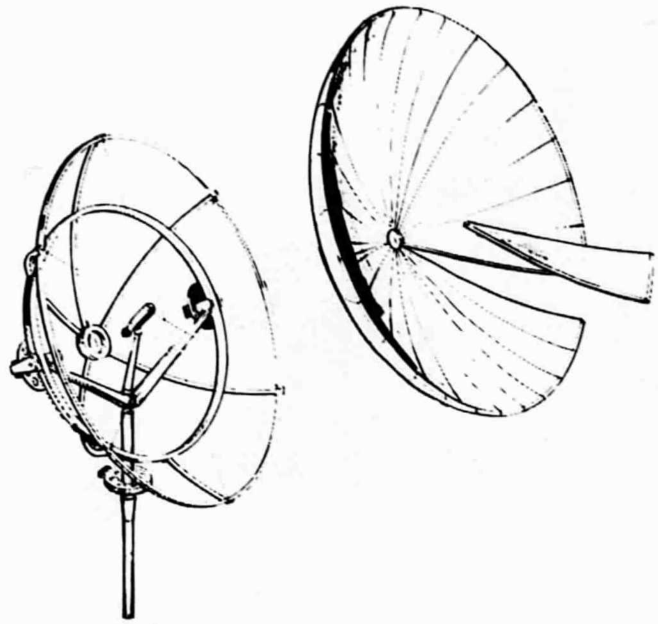


Figure V-5. General Electric Proposed Collector Assembly

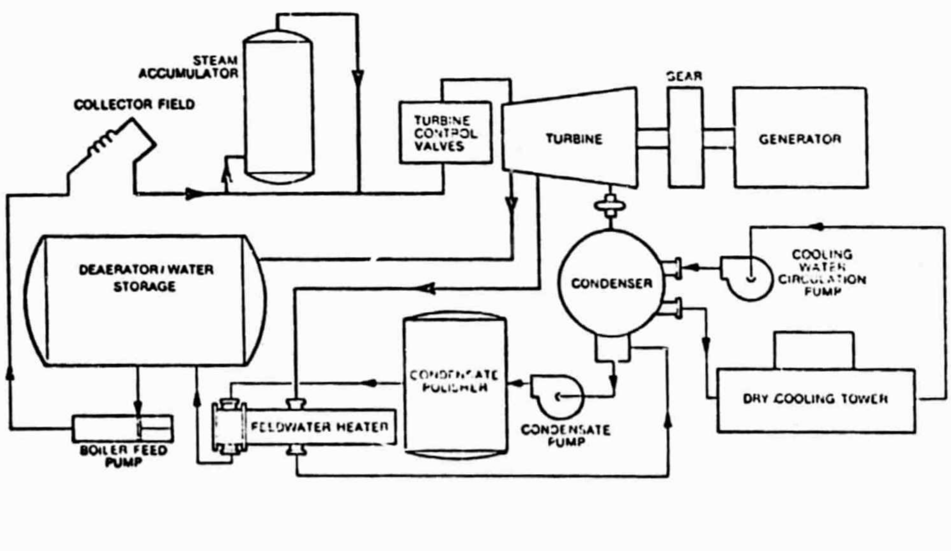


Figure V-6. (General Electric) Simplified Process Flow Diagram

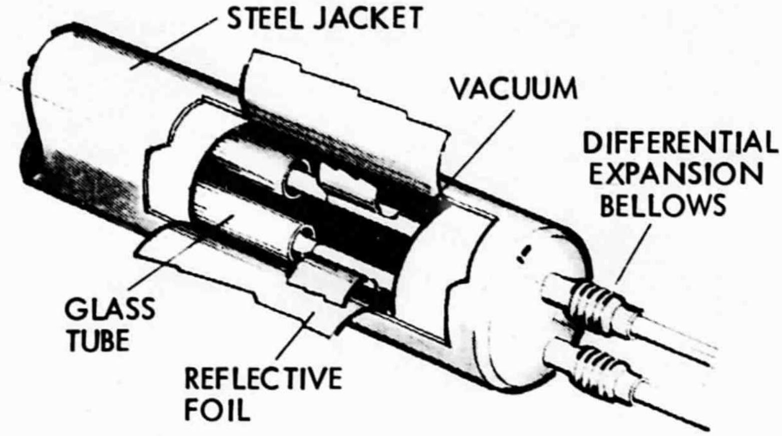


Figure V-7. GE Vacuum Piping Concept

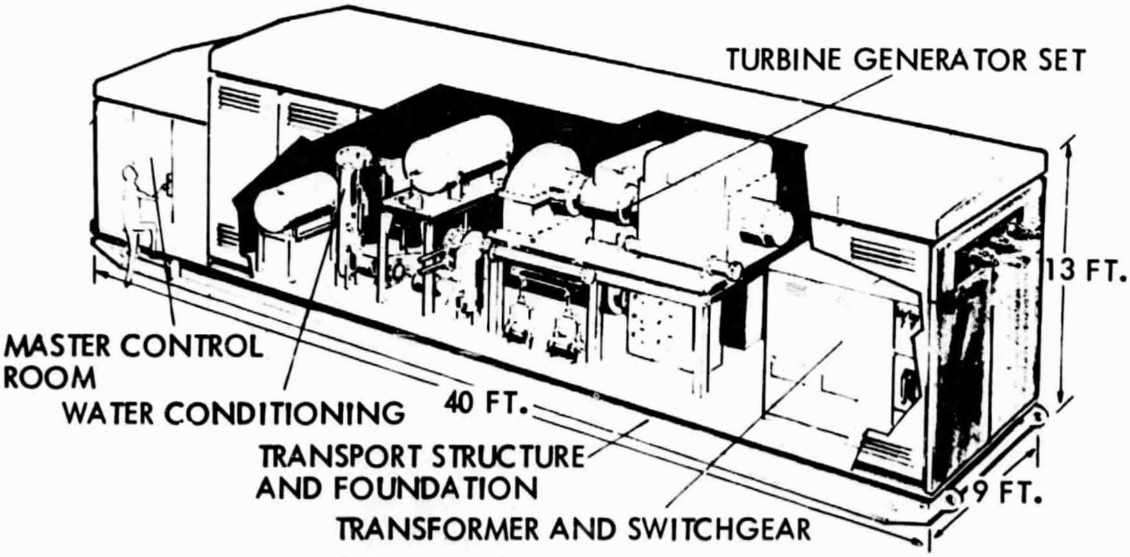


Figure V-8. GE Power Conversion Module Concept

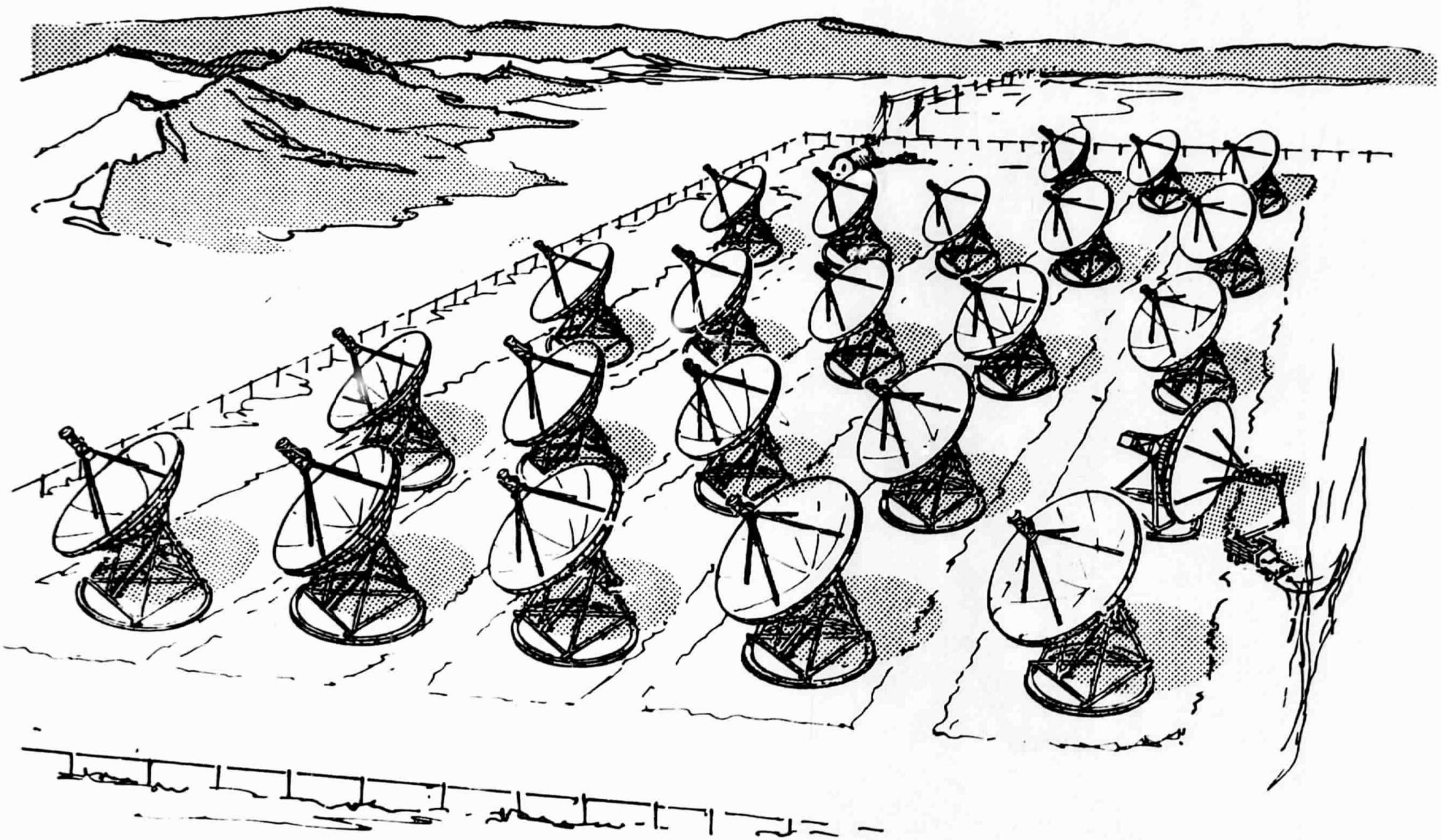


Figure V-9. Artist's Concept of Ford Plant Layout

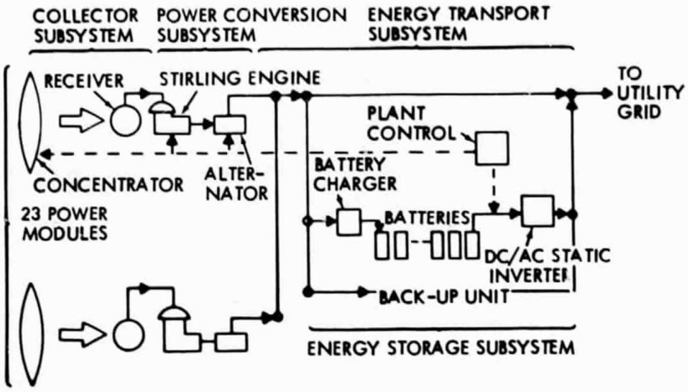


Figure V-10. System Schematic of the Ford Design

engine driving an alternator as shown in Figure V-11. The engine is produced by United Stirling of Sweden, and uses helium as a working fluid. Heat transfer from the receiver to the adjacent engine is by a liquid sodium loop operating at 750°C (1382°F). The output from each power converter is 52.7 kWe, with a net output after transmission losses and plant requirements, of 50 kWe. Heat rejected from the engine is transported down the support legs to a water/ethylene glycol heat exchanger mounted on the back side of the collector-concentrator surface.

The energy storage system, which can only be electric, consists of 541 kWhr of storage in lead-acid batteries which, with 22 power modules, meets the required capacity factor of 0.40. An extra power module is provided for maintenance and training purposes for a total of 23. Electric power from each of the modules is collected by an underground cable system that terminates in a central power conditioning unit.

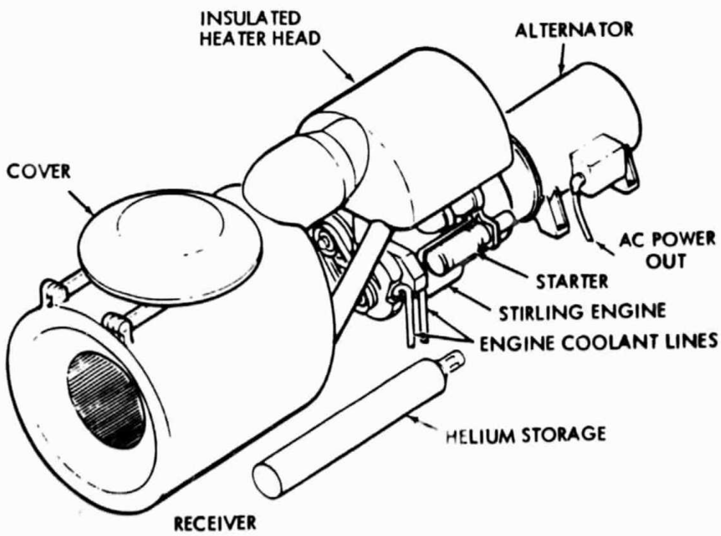


Figure V-11. Receiver Power Conversion Unit for the Ford Design

E. SITE SELECTION

1. Siting Issue Study

A siting issue study, JPL 78-75, Revision 1 "Siting Issues for Solar Thermal Power Plants with Small Community Applications," was prepared to identify relationships between solar thermal-electric power plants and the physical and social environment important to site selection. While the study's primary focus is Engineering Experiment No. 1 (EE1) siting, most of the issues identified are generally applicable to all sizes of solar thermal power plants in various applications. The objectives of the study are to provide a basis from which specific site selection criteria can be developed, to provide background material for prospective site participants, and to inform system designers of potential site specific factors which could influence system design. The siting issues identified fall into three major categories:

(1) System resource requirements

(2) Environmental effects on the system

(3) Potential impact of the plant on the environment.

The resources a solar thermal-electric power plant requires of its site are insolation, land, water, manpower and materials. The requirements of land and insolation are the most critical to efficient plant operation. It is estimated that a 1 MWe solar thermal-electric power plant will require approximately 10 acres of land. To meet the requirements of solar power plants this acreage must meet specific specifications regarding construction suitability, access, geologic hazards, environmental impacts and insolation obstructions.

Insolation is the most critical resource required by solar thermal power plants. However, optimal insolation levels were not specified because the correspondence of insolation availability and electricity demand is more important than the absolute quantities of insolation received.

The impact the environment will have on solar thermal power plants is comprised of two factors: the physical environment and the social/institutional environment. The most potentially damaging aspect of the physical environment is wind, its force and particulate content. The social/institutional environment will impact solar plants from three aspects: legal and regulatory, community support and utility interface.

The third category of issues concerns the impact the power plant will have on the environment. These impacts include: microclimate alterations, water use, land use, ecological imbalance, community impacts, air quality, noise, and public safety. Of these, solar power plants are expected to impact water use and land use most significantly. However, the impacts in these areas attributable to solar power technology appear to be less significant than those of conventional electric power generation facilities.

2. Engineering Experiment No. 1 (EE No. 1)

Selection of a site for EE No. 1 will be initiated by a DOE solicitation for proposal in the form of a Program Research and Development Announcement (PRDA) for site participation in an experimental solar thermal power plant of approximately 1 MWe. Proposal teams are expected to be formed by small communities, together with an electric utility at minimum. The land area required for siting the plant is approximately 10 acres. The proposals will be evaluated on the basis of predetermined site selection criteria by a DOE site selection board.

Background data for developing preliminary evaluation criteria was provided in a study of the dominant siting issues, discussed earlier. As determined in the study, the best sites are expected to:

(1) Have adequate insolation

(2) Require only reasonable expenditures for construction and maintenance

(3) Impose regulatory requirements that will permit adequate development of the site

(4) Have community support for the plant

(5) Have topological stability and acceptable seismicity

(6) Have access to a utility grid that can readily accept a solar powerplant interconnect

(7) Contain no environmentally sensitive features whose disruption might have a significant impact relative to the benefits derived from the powerplant as a community resource.

The community to be served shall be small, with a load demand less than approximately 100 MWe, and may be primarily residential, agricultural, or commercial. It may be served by a private or public electric utility.

Once a site is selected in accordance with the approach and criteria summarized above, the site will be procured through a preestablished procedure involving actions by both DOE and JPL. The key element is a site participation agreement drawn up by DOE, with technical management by JPL. The agreement will define the hardware and the site development activities to be provided by the government, and will also document the responsibilities of the community and local agencies, as mutually agreed, with respect to:

(1) Provision of a suitable site

(2) Filing for permits

(3) Provision for access roads and utility services

(4) Tie-in to a utility grid

(5) General plant maintenance

3. Engineering Experiment No. 2a (EE No. 2a)

Although programmatic work on EE No. 2a was initiated in FY 1978, in accordance with the experiment phasing shown on the project master schedule, the technical effort does not become fully implemented until FY 1979. The key programmatic accomplishments in FY 1978 are summarized below.

Whereas EE No. 1 is a relatively large (1.0 MWe) plant, the EE No. 2 series will deploy a number of smaller plants to test a variety of power conversion technologies. EE No. 2a, the first of this series, will be a hybrid-fired Brayton cycle gas turbine modular power system.

The EE No. 2a concept was presented to DOE on June 21, 1978, and approval was obtained for a joint experiment with the Civil Engineering Laboratory (CEL) of the U.S. Navy. An interagency agreement was drafted, and initial coordination completed between the cognizant agencies. CEL funds were obligated in September 1978, and program planning was initiated. Project work began in October.

SECTION VI

PROJECT SUPPORT ACTIVITIES

The mainstream of the SPSA project is the market analysis and the solar technology development work described earlier. Supporting analyses are needed, however, to provide the project and DOE with information of a strategic nature to facilitate the decision processes required to make the federal R&D program a success. Several such analyses have been initiated and are summarized in this section.

The SPSA project was structured from inception to deal with the broad objective of making the small solar thermal electric power concept a commercial success. Thus, it was deemed important that project decisions by JPL and by DOE be made on the basis of factors that will influence the successful execution of the program, recognizing all phases from concept definition through technology development to market penetration and widespread user acceptance. The technology development process, to be successful, must be strongly influenced by such exogenous factors as the user's special requirements, the degree to which the technology impacts the environment, whether the product can be readily manufactured, the institutional implications of developing a suitable industry infrastructure, and the economics of both supply and demand. Thus, supporting studies were undertaken with the goal of providing a framework on which sound program planning could be based. The activities are the responsibility of the Project Analysis and Integration group, and are summarized below.

A. BARRIERS AND INCENTIVES STUDY

Extensive federally supported R&D has traditionally been focused on military and aerospace programs in cooperation with the private sector. In response to the oil embargo of 1973, and in recognition of the nation's vulnerability to energy shortages, a national endeavor was undertaken by the government to accelerate the development and commercialization of new energy technologies. Acceleration of development and commercialization timetables for new technology without adequate market data would inevitably tend to create discontinuities and conflicts in an area where private industry has long been the primary source of technology innovation. The federal government is sponsoring a large portion of the technology development, whereas the marketing and the integration of the old and new technologies will take place in the private sector. This dichotomy motivates the concern of the project for anticipating and assessing barriers and incentives to the success of the small power system program. Also, the balancing of the two ingredients of "technology push" through industrialization and "demand pull" through commercialization needs to be understood and then achieved. These considerations led to a study contracted to Research Planning Associates (RPA).

The RPA study, to date, has been directed toward supporting the following project activities:

(1) Introducing potential users and suppliers to small power system concepts

(2) Opening channels of communication with a variety of participants who will be involved in some key phase of design, construction, test, evaluation, or operational use of small power systems

(3) Obtaining feedback from potential users, suppliers, and participants

(4) Identifying issues that could produce barriers and incentives to SPS commercialization

Results from the study are just beginning to emerge. A matrix of barriers vs corresponding incentives has been developed, as shown in Table VI-1 and additional results have emerged as summarized below.

It seems clear that the federal innovative process should be improved in identifiable areas, including the clarification of the ground rules for government/industry interaction. Industry must have confidence in the validity and stability of the ground rules, especially as they pertain to procurements, information exchanges, and related government policies. Industry should be involved in an integral way with technology development, of course, but also with the programmatic planning process that precedes it. Specific recommendations that can be made at this time are:

(1) Place more emphasis on market analysis

(2) Build a User Community

(3) Build a Manufacturing Community

(4) Adopt an appropriate plant demonstration strategy

(5) Avoid overdevelopment of technology.

B. INDUSTRIALIZATION STUDIES

Industrialization involves the dual requirements of developing the product and the infrastructure to supply it. The key issues in industrialization are: 1) reduction in cost of the product, and 2) identification of the best means to stimulate industrial development of the technology. Cost reduction is clearly a key to economic feasibility, and can be approached through mass production and automated assembly. In facilitating industrial development, an important element is the optimal design and execution of cost-shared demonstration projects.

	Economic Incentives: Lowering Small Solar Power Systems Cost						Economic Incentives: Raising Alternate Sources Costs					Technical Incentives		Institutional Incentives: Informational			Institutional Incentives: Market Development			Institutional Incentives: Legal/Regulatory		
	Direct Cash Subsidies	Credit Subsidies	Tax Credits	Accelerated Depreciation	Tax-Free Bonding	Extended Loss Carry Forward	Deregulation of Fossil Fuel Prices	Tax Policies	Marginal Cost Electricity Prices	Incorporate Social Costs	Removal of Preferential Treatments from Fossil and Nuclear	Hybrid Firing/Refining	Utility Capacity Expansion Models	Demonstration Programs	Component Testing Facilities	Market Studies	Increased Manufacturers Role in Component Development	Federal Power Agency Purchases	Military Purchases	Background Patents Protection	New Patents Protection	Environmental Standards
Barriers to Use in all Market Sectors No proof of economic performance														▲				▲	●			
No proof of technical performance														▲	●			▲	▲			
Not considered near term technology														▲		●		▲	▲			
Barriers to Use by Electric Utilities More expensive than competing systems	▲	▲	▲	●	●		●	●		●	●	●	▲									●
Too much land required												●										
Inappropriate size													▲	●				●				
Inability of planning models to handle these systems												●	▲	●				●				
Problems of siting dispersed systems														●				●				
Citizen opposition to unsightly collectors														●				●				
Barriers to Use in Industry Short payback required	▲	▲	▲	●	●			●	●	●		●		●								●
Unfavorable rates for utility back-up and buy-back	●	●	●							●		▲										
Lack of available land	●	●										●										
Continuous power required												▲										
Stringent health and safety regulations	●	●												●								
Barriers to Use in Farming Cost of systems too high	▲	▲	▲	●			●	●	▲	●	●	●										
Under utilization of the system	▲	▲	▲	●																		
Continuous power required												▲										
Farmer attitudes about land use	●	●																				
Barriers to Use by the Military Continuous power required												▲										
Military purchasing practices									●	●									▲			
Military budgeting practices																			▲			
Manpower ceilings																			▲			
Barriers to Use in Developing Countries Balance-of-payment problems	▲	▲																				
Limited funds available	▲	▲																				
Evolving demand for village power												▲		●								
Insolation data unavailable														●								
International banks favor grid electricity	▲												▲	▲								
Skilled manpower shortages																						
Barriers to All Manufacturers Short payback required	▲	▲	▲	●	●	●								●		●		●	●			
Inadequate patent policies																				▲	▲	
Federal research preempting private research															●		▲					
Barriers to Small Manufacturers High proposal costs																	▲					
Lack of credibility in federal contracting																	▲					

SOURCE: Resource Planning Associates, Inc.

▲ Major impact
● Minor or indirect impact

Table VI-1. Summary of SPSA Barriers and Incentives

The industrialization process covers the spectrum from the invention phase through development and introduction to the final phase of concern, diffusion. This last phase is being approached through direct contact with firms in the manufacturing and industrial supply section, and through in-house and contracted studies. A consulting contract with Hyman and Baker of the University of Washington has provided a preliminary analysis of industrialization issues, including technology transfer and pertinent patent activity.

The importance of costs and the need to gain insight regarding the potential effect of mass production on system costs led to an RFP that was released June 1, 1978, entitled, "A Study of Mass Production and Industrialization of Small Thermal Electric Power Systems." The systems included in the RFP are a parabolic dish concentrator with a Brayton cycle engine at the focus, and two advanced versions with small heat engines at the focus. The contract will include consideration of manufacturing processes, factory layouts, and the infrastructure of the supply industry. Production volumes will be examined over the range of 100 to 10,000 MWe per year. Particular attention will be paid to identification and assessment of measures that can lead to system cost reductions.

C. MARKET DEVELOPMENT STUDIES

The focus of the market development subtask is the analysis of markets for small systems and of the penetration processes for each. The purpose is to maximize the potential for their successful introduction and widespread adoption.

The previously discussed industrialization analysis seeks to understand the seller's viewpoint, which is that of the private sector. In contrast, market development, or commercialization, seeks to provide the perspective of the user and consumer. Market penetration processes are key elements, but their study depends on the prior identification and characterization of the various market segments. Then, the criteria by which investors make decisions to put venture capital at risk can be studied, and optimal strategies for cost sharing determined that meet program milestones. Determining the order in which identified markets become attractive from the "demand pull" viewpoint, along with their probable size, is inherent in the evolution of small power systems market strategies.

JPL studies to date have identified three near-term concerns in the commercialization of small power systems:

(1) The need to identify the markets where government support is most apt to be successful

(2) The need to identify, within each such market, the technical, economic, institutional, and environmental issues which must be resolved to enhance market penetration

(3) The need to determine the most appropriate roles of the federal government in the commercialization process, and the corresponding costs and benefits of the alternate intervention processes.

To assist in the market analysis task, a contract will be let for a study entitled, "The Effects of System Factors on the Economics of and the Demand for Small Solar Thermal Power Systems." Task 1 of the contract concerns estimating the demand and rate of market penetration, and the selection of attractive near-term markets for further analysis.

Task 2 is an analysis of the sensitivity of market penetration to variations in system parameters relating to configuration and performance, to ownership options and financial factors, and to technology diffusion and marketing factors. In support of Task 2, a contract with ESC Energy Corporation has been executed to develop an interactive computer program to compare the financial implications of constructing and operating candidate small power systems.

Task 3 is the development of cost-effective commercialization strategies that foster and accelerate widespread adoption in near-term markets. This work provides a necessary alignment of project perspectives with those of the private sector, and maximizes the compatibility of solar thermal technology and market place needs and demands. The studies will assist in structuring R&D programs, plant demonstrations, and commercialization strategies.

D. PUBLIC INFORMATION

In support of the communications between the SPSA project and potential users, suppliers, and participants in the small power system program, a general purpose leaflet was prepared that describes the SPSA project. A more technical brochure is in preparation, directed toward the system and subsystem suppliers as well as to users.

The SPSA project will continue to disseminate technical and programmatic information using various media. As results become available, they will be published through appropriate channels, such as conferences, seminars, workshops and various levels of documentation appropriate to the reader.