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Solar Thermal Power Systems
Point-Focusing
Thermal and Electric Applications Project

DOE/JPL-1060-31
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Annual Technical Report

Volume I: Executive Summary

Fiscal Year 1979

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January 15, 1980

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

(JPL PUBLICATION 79-118, VOLUME I)

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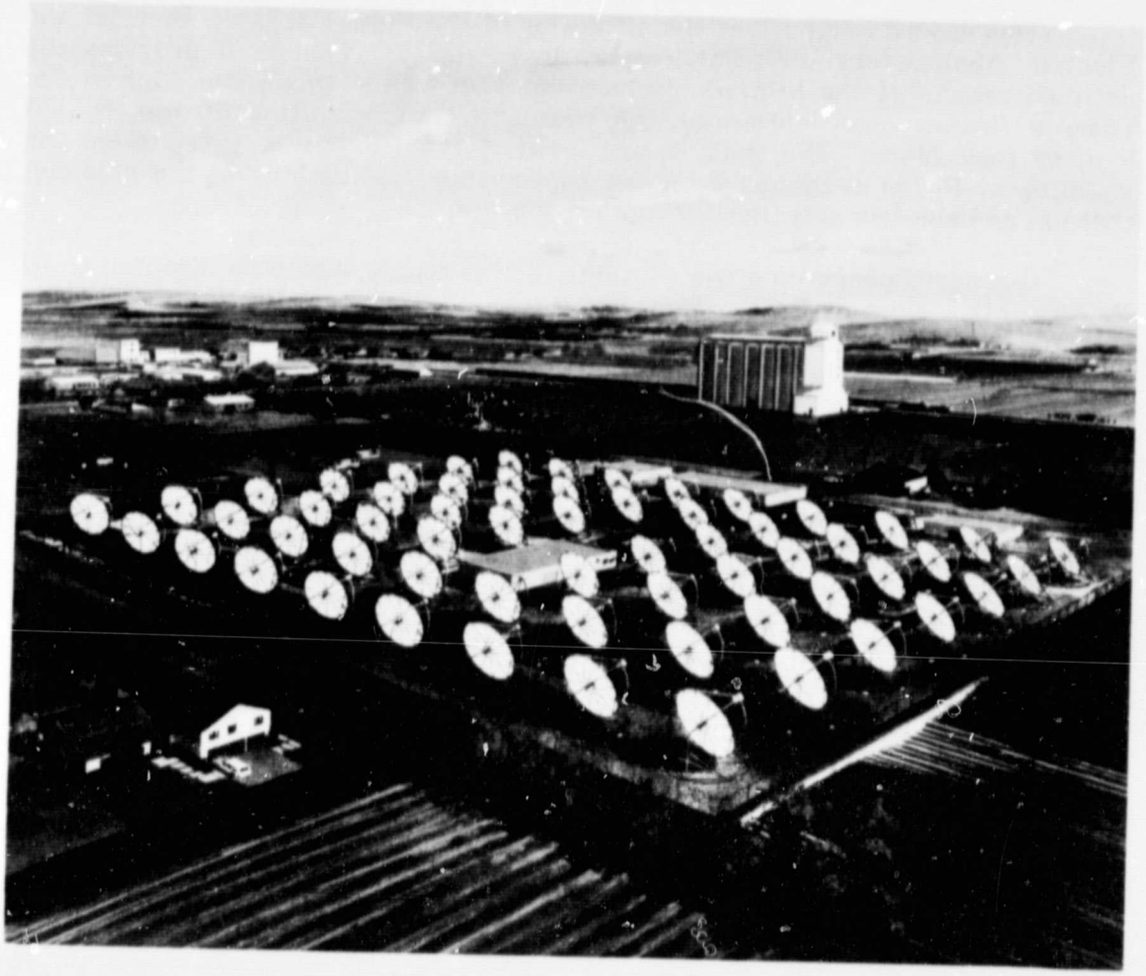
FOREWORD

This report summarizes the activities of the Point Focusing Thermal and Electric Applications (PFTEA) Project in FY 1979. Volume II provides the detailed results of the primary technical activities for this year. During the year, a further clarification of the role and responsibilities of the PFTEA Project took place. The main thrust now of the Project is to consider the viability of PFDR technology for all appropriate applications in the electric, thermal and electric plus thermal market sectors.

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



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A Parabolic Dish Solar Power System For Small Communities

ABSTRACT

This report, Volume I, is a summary of the Point-Focusing Thermal and Electric Applications PFTEA Project's Annual Technical Report for FY 1979. More detailed compilation of results for this year may be found in Volume II.

Major activities in FY 1979 centered around the definition and implementation of the engineering experiments that form the main thrust of the PFTEA Project. Phase I of the first experiment, the Small Community Solar Thermal Power Experiment, was completed. As a result of the Phase I concept definition studies that included a small central receiver approach, a point-focusing distributed receiver system with central power generation and a point-focusing distributed receiver concept with distributed power generation, Ford Aerospace and Communications Corporation was selected to pursue the last approach in Phase II.

The first experiment in the Isolated Application Series was initiated as a result of procurement activities that culminated with the release of an RFP for the Military Module Power Experiment. A 100 kWe power plant based on Hybrid Brayton technology is being developed in conjunction with the U. S. Navy.

Planning for the third engineering experiment series, which addresses the industrial market sector, was initiated in FY 1979.

In addition to the experiment-related activities, several contracts to industry were let and studies at JPL were conducted to explore the market potential for Point-Focusing Distributed Receiver (PFDR) Systems. System analysis studies were completed that looked at PFDR technology relative to other small power system technology candidates for the utility market sector.

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SECTION I

INTRODUCTION

The Point-Focusing Thermal and Electric Applications PFTEA Project is responsible for the development of systems which employ point-focusing distributed receiver (PFDR) technology for applications determined to be attractive and appropriate. The main vehicle for this activity is a series of engineering experiments that have as a primary objective the assessment of system feasibility for selected technologies in real user environments. System feasibility is achieved when a PFDR system is first successfully carried through design, installation and operation in an application setting.

During FY 1979 significant progress was made with the first engineering experiment, the Small Community Solar Thermal Power Experiment (SCSE), with the completion of the concept definition phase in which three contractors participated - each pursuing a different technology. The PFDR approach with distributed energy conversion (i.e., engine at the focus) was selected as the preferred technology for this first experiment.

Procurement activities began in FY 1979 for the Military Module Power Experiment, the first of a series of experiments planned as part of the Isolated Load Series. Both this experiment and the SCSE are discussed in detail in subsequent sections of this report.

The PFTEA project has two major elements: 1) the development and fielding of experiments as typified by the two discussed; and 2) supporting activities that provide the technical and economic basis for the management of the experiment program. Both areas will be briefly described as an introduction.

A. ENGINEERING EXPERIMENT SERIES

The engineering experiments are comprised of three series of subscale electric power plants or thermal energy systems designed and deployed to demonstrate system feasibility in selected appropriate market sectors. An engineering experiment is defined as the smallest system level test that can be expected to establish system feasibility in a real user environment. Although it is currently not a part of this program, it is expected that the engineering experiments will be followed by other demonstrations in which prototypical hardware or commercially produced hardware will be tested as a pilot plant or as a full-scale commercial plant size.

Important elements of the engineering experiment program are summarized as follows:

(1) Experiments will test various PFDR technology options consisting of a combination of concentrator, receiver, power conversion (for electric power generation), and balance of plant subsystems.

(2) Experiments will test various market sectors. Thus, a particular experiment may be characteristic of a generic market category. Its deployment in that market area will provide an assessment of the market viability as well as the suitability of the technology for that market.

(3) Experiments will address electric, electric plus thermal, and thermal applications as deemed appropriate and necessary.

(4) In general, at this time, applications of interest will be met by systems of less than 10 MWe rated capacity.

The application categories and the associated series of experiments defined to date are shown in Figure 1-1. Three broad market sectors constitute the main objectives of the three series of experiments. The grid-connected utility market sector includes such market subsets as the small community electric power application, dispersed siting in large utilities, repowering of existing fossil-fuel plants and eventually, the bulk electric market. The second isolated application series addresses the isolated load market sector typified by various remote sites needing a source of power, some applications within the military, and power needs of developing countries. These applications may have both electric and thermal requirements. The third series of experiments will be planned to explore the industrial market in small communities and will emphasize those industrial process heat applications for which PFDR technology appears best suited.

B. SUPPORTING ACTIVITIES

Three task areas provide the support and technical and economic base for management of the experiments. The primary responsibility of Systems Engineering and Development is the technical management of the design and development phases of the experiments. It draws support from the technical divisions at JPL to perform this function. The second task area, Experiment Implementation and Test, is responsible for the siting of the experiments and will be responsible for the fabrication, construction and operation phases when those stages are reached. The third task area, Applications Analysis and Development provides the information for selection of experiment applications. Thus, it is responsible for market analysis, economics of supply and demand, and user integration activities. A successful program will depend greatly on the degree of early involvement of potential users of the technologies being developed.

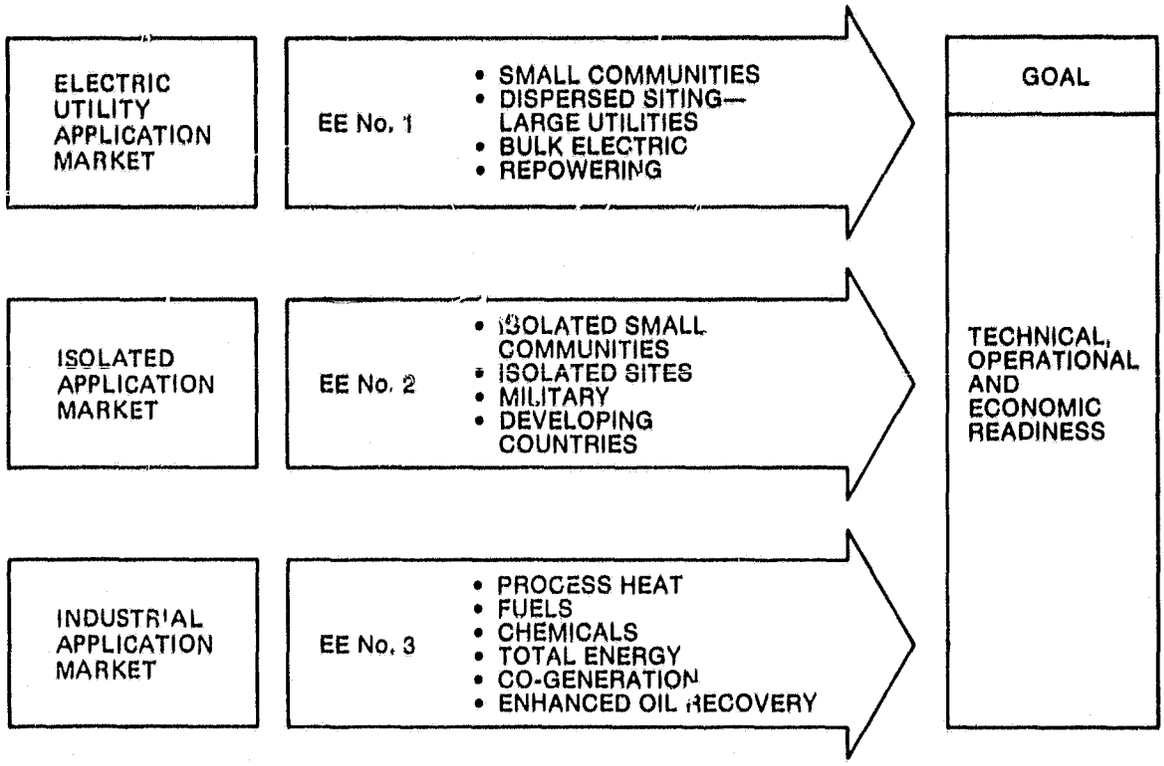

Figure 1-1. PFTEA Engineering Experiment Series

SECTION II

SMALL COMMUNITY SOLAR THERMAL POWER EXPERIMENT

A. INTRODUCTION AND BACKGROUND

The program steps of the Small Community Solar Thermal Power Experiment strongly reflect the circumstances of its origins in 1977. The Project originated as a result of strong and continuous community pressure on Congress to provide an alternative electric power source compatible with anticipated diminished reliance on non-renewable energy sources. In response to these pressures, Congress appropriated funds for a five-megawatt solar thermal demonstration. A one-megawatt experimental plant was eventually agreed upon as being valid for the range of sizes of interest in the small community application. Augmenting the experiment were studies of the small community market and eventual requirements for commercialization of solar thermal power systems which show promise for this market.

Three technology categories established for this application were the following:

(1) General (to include, but not limited to, central receiver and line focusing systems).

(2) Point-focusing, distributed collector, central power conversion.

(3) Point-focusing, distributed collector, power conversion at the collector.

A multiphase approach was adopted as the best means of meeting the objectives of the experiment in the shortest period of time. Phase I addressed the problem of exploring all competitive technologies for this application and recommended those which should be studied in greater detail. Competitive bids were received in each of the above listed categories, and awards were made on the bases of merit. One contractor was selected in each category.

B. PHASE I

At the beginning of the fiscal year, Phase I studies were underway and preliminary results were being reported at project review meetings and in periodic progress reports. As the Phase I studies progressed, the individual contractors identified the systems within each of the given categories which fulfilled the requirements set out in the RFP:

(1) McDonnell-Douglas Astronautics Company: Central tower with field of south facing heliostats.

(2) General Electric Company: Field of parabolic dishes with steam piped to a central turbine-generator unit.

(3) Ford Aerospace and Communications Corporation: Field of parabolic dishes with a Stirling cycle engine/generator unit at the focus of each dish.

Table 2-1 summarizes the design and performance characteristics of the recommended systems from each of the Phase I contractors.

During Phase I, Department of Energy (DOE) directives and ongoing technical studies at JPL and elsewhere produced two important programmatic changes:

(1) Category A and the McDonnell-Douglas Astronautics Company were eliminated by DOE from further participation in subsequent phases of the experiment in order to achieve better program balance.

(2) Budget constraints combined with promising and timely results in the Point-Focus Distributed Receiver Technology (PFDRT) development project forced the decision that subsystem development within the experiment be minimized. Instead, designs for appropriate subsystems were to come from ongoing development work or from other existing sources. Possible candidates for the concentrator were the Low-Cost Concentrator (LCC) and the Test Bed Concentrator (TBC) which were being developed in the PFDRT project.

Receivers were also being designed in JPL development projects. It was expected that some additional development would be required to match specific needs of this experiment. In spite of these constraints, it was decided that the systems contractors would continue to maintain responsibility for the selection and integration of all components and subsystems.

Meanwhile, results of the technology comparison studies performed at the Solar Energy Research Institute (SERI) and at the Battelle Pacific Northwest Laboratories (PNL) indicated that distributed power generation was preferred to central power generation when using point focus technology for plants of the one megawatt size at low capacity factors. Because the Shenandoah Total Energy Project was scheduled to be completed before the Small Community experiment and because it would serve as verification and demonstration of the point-focus central generation concept, it was decided to eliminate Category B from this experiment and proceed with Category C for Phase II. This decision meant that Ford, the successful contractor in this category, would continue in Phase II. Although the energy conversion subsystem which had been recommended by Ford made use of the Stirling cycle, the Rankine cycle engine had been ranked second and showed promise of acceptable efficiency with reliability. In the light of ongoing engine studies at the NASA Lewis Research Center and at JPL, (which indicated that Stirling engine technology was not yet ready for field experiments) it was decided to incorporate the Rankine cycle engine in the configuration selected for design and test in Phase II and III.

C. PHASE II

In August 1979, a sole source RFP was issued to Ford Aerospace and Communications Corporation soliciting their participation to act as system contractor for Phase II of the experiment.

Table 2-1. Characteristics Summary - Phase I Contractors' Recommended System

	MDAC	GE	FACC
System data			
Rating	1 MWe	1 MWe	1 MWe
Capacity Factor	0.4	0.4	0.4
Land Used	4.05 ha (10 acres)	3.24 ha (8 acres)	2.02 ha (~5 acres)
Efficiency	16.3%	14.3%	25.6%
Type	171 North field helio-stats with tower-mounted central receiver.	96, 10 m parabolic dish concentrators with cavity receiver at focal point and centralized power conversion	19, parabolic dish con-centrators with cavity receiver and engine/ generator mounted at focal point
Collector Subsystem			
Collector efficiency	60%	76.3%	74%
Concentrator Type	2nd generation version of Barstow 10 MWe plant design	JPL 1st generation Low Cost Point-Focus Concen-trator	Parabolic dish design with front-braced steel structure
Area/Diameter	A = 49 m^2/heliostat	Diameter = 10 m	Diameter = 18.6 m
Receiver Type	Partial Cavity-Cone/HITEC	Cavity/Steam	Cavity with integral Sodium pool boiler
Output Temperature	510°C(950°F)	493°C(900°F)	830°C(1526°F)
Power Conversion Sybsystem			
Type	Rankine cycle, axial, marine type steam turbine	Rankine cycle, steam turbine	USS P-75 Stirling Engine
Inlet Temperature	482°C(900°F)	482°C(900°F)	800°C(1472°F)
Efficiency	31%	24.3%	35.4%
Energy Transport Subsystem			
Type	Steel piping with HITEC *	Standard insulated piping	Standard Electrical Cabling
Efficiency	99%	93%	96.4%
Energy Storage Subsystem		**	
Type	2-tank, HITEC * sensible heat	Lead-Acid Batteries	Lead-Acid Batteries
Storage	4 hours	3 hours	3 hours
Efficiency	96.5%	72%	77.5%

* 53% KNO_3, 40% $NaNO_2$, 7% $NaNO_3$

** GE's recommended system contains no dedicated storage. If it were required, the Energy Storage Subsystem would have the characteristics as described.

The contractor is expected to conduct a preliminary design, component and subsystem development, subsystem and system level verification testing, and detailed design. Ford was also asked to complete the plans for site preparation and hardware implementation. As indicated above, the technology was restricted to distributed energy conversion using the Rankine cycle.

In its response to the RFP, the Ford Aerospace and Communications Corporation proposed the following system concept as its baseline in determining the cost of the program:

(1) Power Conversion - An organic Rankine cycle (ORC) engine/alternator; the working fluid is toluene at a maximum expander (turbine) inlet temperature of 427°C (800°F).

(2) Concentrator - The JPL-supported 12m Low-Cost Concentrator (LCC) currently under development by General Electric Company.

(3) Receiver - The JPL-supported steam receiver currently under development by Garrett AiResearch Corp., redesigned to operate with toluene.

(4) Energy Transport - The FACC-developed Phase I AC electrical system, with modification to accommodate the ORC power conversion system.

(5) Control - The FACC-conceived Phase I central microprocessor control concept with modifications to accommodate the ORC pc conversion system and the LCC.

This baseline concept was chosen based upon Phase I study results and preliminary analysis carried out by Ford to evaluate the data provided by potential subcontractors for the major subsystems. This preliminary system selection was also constrained by the requirements to: (1) select a concentrator at no additional cost to JPL; and (2) select a receiver design at minimal development cost to JPL. An additional influencing factor was the substantial effort required in Phase II to develop a comprehensive plant control system, including both hardware and software design.

The major subsystems are described in more detail in the following paragraphs. Figure 2-1 provides a sketch of a module of the proposed system.

a. The Power Conversion Subsystem. According to the Ford proposal, the most significant decision was the preference for the organic Rankine cycle (ORC) engine over a steam engine. A comparison of the performance of several Rankine alternatives is presented in Figure 2-2 which shows the sensitivity of the performance of the various systems to expander inlet temperature. The unfavorable performance displayed by the steam turbine has eliminated it from further consideration, so that only the piston expander need be considered as an alternative to the ORC turbine.

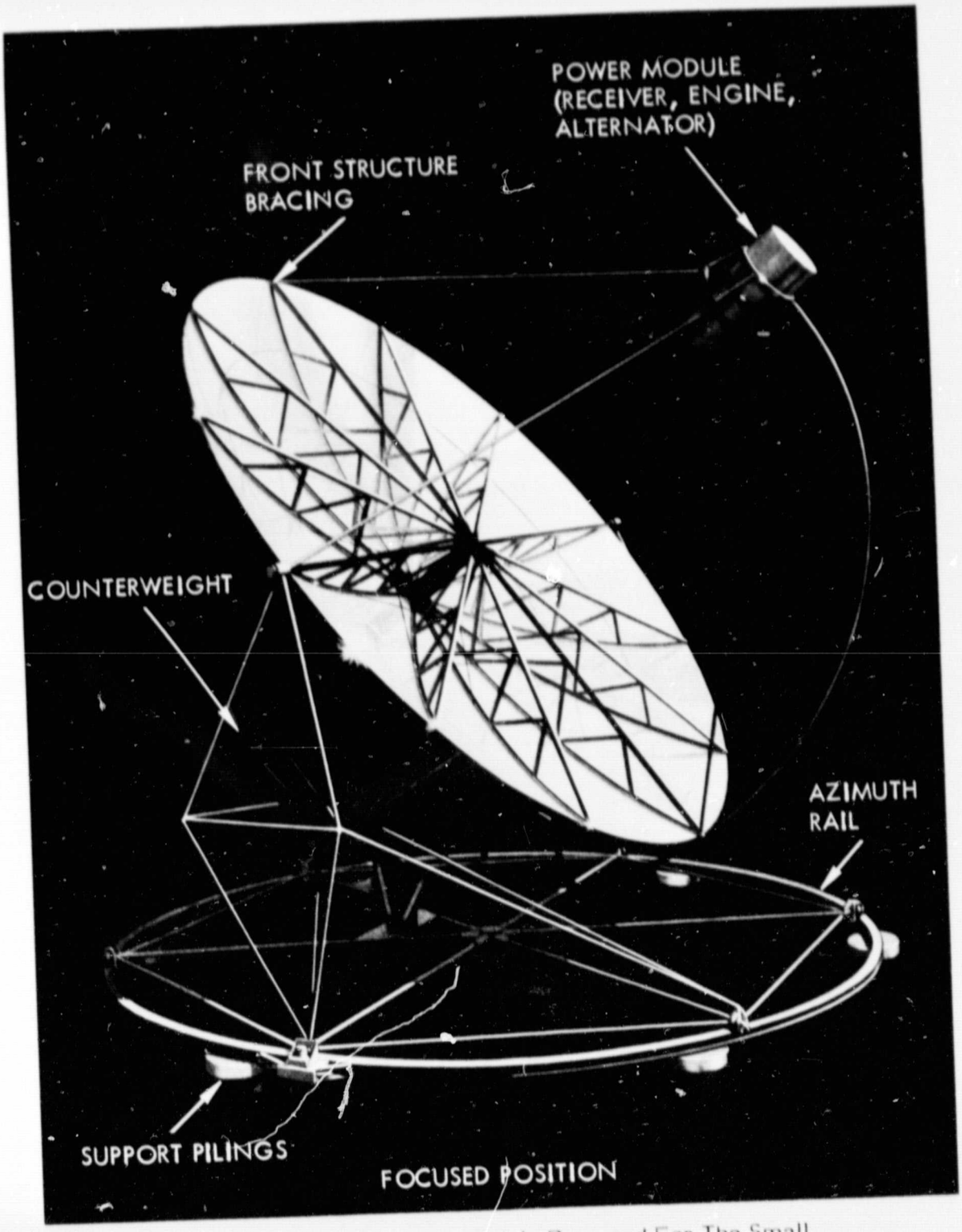

Figure 2-1. Parabolic Dish Module Proposed For The Small Community Solar Thermal Power Experiment

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b. The Concentrator. The baseline design selected by Ford for the purposes of their proposal is the first generation Low-Cost Concentrator (LCC) developed for JPL by General Electric, Valley Forge, Pennsylvania. This concentrator is shown in Figure 2-1. A brief description follows:

The Concentrator is a point-focus, single reflection parabolic dish which tracks the sun by rotation about two axes, azimuth and elevation. The reflecting surface, either glass or thin film plastic, will be mounted on plastic segments which are, in turn, attached to the welded steel supporting structure. The plastic segments are constructed from molded glass-reinforced epoxy with an integral rib pattern on the back to provide stiffness. Twelve internal ribs within the dish provide support and alignment for the segments, as well as added strength and rigidity to the assembled parabolic dish.

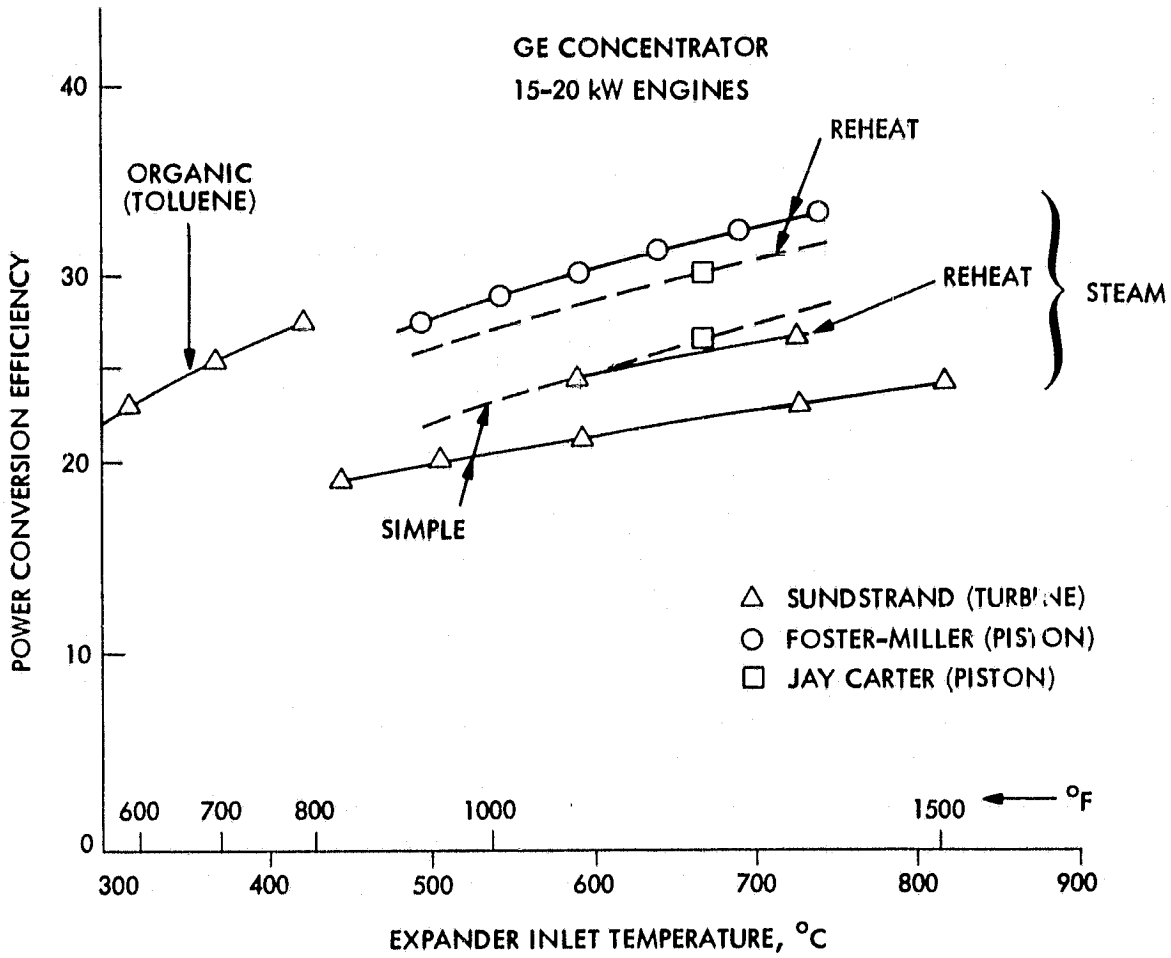


Figure 2-2. Comparative Rankine Engine Performance (Including Alternator)

The mirror surface, drive, and structural support are all designed to provide excellent performance in a configuration which offers the promise of low cost in quantity production.

c. The Receiver. Tentative receiver designs (for steam and organic) have been submitted by 6 potential subcontractors, and Ford has expressed a desire to consider a novel inhouse design of its own.

d. The Energy Transport Subsystem. The requirements for the energy transport subsystem for the proposed system are very similar to those studied during the Phase I effort, except for changes in the size and number of modules. All components selected for the entire electrical system are off the shelf items, their performance is known, and there is no risk in their use.

e. Control Subsystem. The Ford proposal defines a control system that will completely operate a 1 MWe plant without any attendants on the site. The plant control sybsystem consists of all hardware, software and related facilities required for automatic and manual control of the overall solar thermal plant.

The baseline control system concept employs a central microprocessor for direct digital control, sequencing, protection, monitoring, etc., of all plant subsystems. Most control functions will be implemented as algorithms in the microprocessor software; however, in specific cases, local analog electronic control loops will be used and only supervisory-level control will be provided by the central mircroprocessor.

D. SITE SELECTION

SCSE will be located in a small community which has been defined as a community that is either urban or rural, and has an electrical demand load of less than 100 MWe, preferably less than 20 MWe, which has a variety of electrical customers, is not within a Standard Metropolitan Statistical Area (SMSA) as defined by the U. S. Bureau of Census, and is served by a locally controlled electricity distribution network.

To support the siting activity, a study was conducted to identify the issues important to the implementation of a solar thermal power plant. A JPL report (#1060-78/2) was published titled, "Siting Issues Applicable to Solar Thermal Power Plants," where the results of the study were reported.

The siting issues identified in the report were developed into site criteria and proposal evaluation criteria. A community satisfying the "small community definition" and the site criteria developed from the siting issues will provide a realistic environment for SCSE from the perspective of utilities, system designers, the public and the sponsor, DOE. SCSE in a community of this type will provide technical information with regard to subsystem interrelationships, operational data and experience regarding utility interface, economic information regarding displaced fuel costs and solar thermal operating costs, and information on institutional interfaces regarding regulatory compliance, community socio-economic impact and public acceptance.

To identify a community which satisfies the small community definition and the site criteria, a Program Research and Development Announcement (PRDA) was released by DOE in October, 1979 soliciting site proposals. The PRDA delineates the small community definition, describes the desirable and mandatory criteria of the site to be selected for SCSE, and outlines the duties and responsibilities of the site proposer or site participant in support of experiment activities. The PRDA also delineates the proposal evaluation procedures and evaluation criteria.

The specific tasks the site participant will be expected to perform are the following:

Task 1 - Site Data Development

Task 2 - Site Acquisition and Planning

Task 3 - Site Preparation

Task 4 - Experimental Operation

Task 5 - Extended Experimental Operation

The criteria with which proposals offering sites for SCSE will be evaluated by are as follows:

1) Community Characterization and Support
2) Site Insolation
3) Energy Cost, Finance and Need
4) Utility Interface
5) Site and Permit Acquisition
6) Site Suitability
7) Site Development Characteristics
8) Environmental Impact
9) Management Plan
10) Extent of Participation

Proposals were received in late December, 1979; the evaluation will be completed by March 1980, and the site participation contract will be underway in July 1980.

SECTION III

ISOLATED APPLICATION EXPERIMENT SERIES

A. INTRODUCTION AND BACKGROUND

The Isolated Application Experiment Series is the second major activity within the PFTEA Project. This is a series of small (100-200 kWe) solar thermal experiments, each of which will address a separate isolated load application.

This series of experiments employs point-focusing distributed receiver technology with emphasis on electric and thermal power applications. The program is closely integrated with the PFDRT Project with the objective of utilizing the technologies being developed under that program.

The Isolated Application Experiment Series will be designed, installed, and operated to permit JPL, DOE, and industry a better understanding of solar thermal plant application, technical feasibility, and operational problems. The time period for deployment and test of first generation systems is 1982-86.

The objectives of the series are to:

(1) Test the feasibility of the technology at the system level and to verify that the solar thermal plant can produce electrical and/or thermal energy from solar radiation to meet energy requirements for isolated applications.

(2) Characterize the total performance of the plant (site preparation, components, subsystems, and modules) as a function of load characteristics, insolation, weather, operation and maintenance activities, safety regulations, environmental regulations, seismic factors, and legal and socio-technical factors.

(3) Identify and understand plant failure modes.

(4) Identify and quantify the impact of solar hybrid* plant operations on the daily operations activities or user personnel and on user manning requirements.

(5) Identify and quantify the impact of solar hybrid plant installation and operations on the local environment.

(6) Identify and quantify the impact of solar hybrid plant installation and operation on the acceptance of solar power plants by local public officials, local power system officials, and the local public.

*Initial experiments in this series are planned to operate in a hybrid mode; i.e., a natural gas or other fossil fuels will be used in conjunction with solar to provide high availability and capacity factor. Other experiments may not be hybrid.

(7) Economically provide testing of technologies and markets, meeting principal program objectives without large expenditures.

(8) Involve a large constituency of industrial suppliers and users.

(9) Address the potential for near-to-mid-term market for small power systems that is needed to provide the initial incentive to manufacture these systems.

(10) Increase programmatic flexibility to employ a number of small and varied experiments.

B. MILITARY MODULE POWER EXPERIMENT (MMPE)

The first experiment in the Isolated Application Experiment Series was initiated in FY 1979 and is co-sponsored by the U.S. Navy under the auspices of the Civil Engineering Laboratory (CEL). CEL and JPL have worked together to develop system requirements. The Military Module Power Experiment will be a modular system using hybrid fired Brayton cycle energy conversion. Subsequent experiments will test different versions of similar hardware in applications which are now being selected.

During FY 1979 preliminary system and operational requirements for the experiment were developed with U.S. Navy representatives. Approval to proceed on the experiment was obtained from DOE, and detailed experimental planning began. A procurement package for the experiment was completed in late FY 1979 for release to industry early in FY 1980. This procurement will select the system supplier for the military module power experiment.

This experiment will utilize JPL PFDRT First Generation hardware whenever possible. The components (concentrator, receiver, engine) will be assembled into individual power modules. A number of such modules will be interconnected to form a power plant.

The baseline for the system is the JPL Point-Focusing Distributed Receiver Technology (PFDRT) Project, first generation dish Brayton system hardware which consists of:

(1) Solar concentrator (General Electric Company, Space Division).

(2) Gas receiver (AiResearch Manufacturing Company, California).

(3) Brayton cycle engine, alternator, and hybrid fossil combustor (AiResearch Manufacturing Company, Arizona).

The degree of module self-containment for the experiment will be driven by both economics and reliability. Each module will contain (at a minimum) concentrator, receiver, hybrid combustor, turbine, recuperator, compressor, alternator, module controls, starter, concentrator drives, tracking devices and sensors, some fuel storage, and necessary exhaust hardware.

A completely self-contained module is desired with only the true plant functions centrally located. These will be power combination and conditioning equipment, module and plant performance indicators, grid interconnection equipment (if employed in the experiment), computing and data recording facilities, instrumentation, and plant safety, equipment. The normal mode of module operation will be unattended; however, each module will be equipped for safety or emergency shutdown, both manual and automatic. Although a fixed installation is expected, individual modules will be transportable, field erectable, and field serviceable.

Plant power output will be AC 60 Hz, three phase. Load-shedding devices will be incorporated if required for equipment protection. The details of the power combination/conditioning method and grid interface will be investigated by the system supplier. The plant will be connected to a three-phase electrical grid for backup and reserve power supply. The power rating of the plant will be approximately 100 kWe under nominal insolation conditions.

Long-term thermal storage will not be included in the plant. No thermal buffering will be provided except by the heat capacity of the installed components and working fluid. The hybrid combustor control system will provide the desired transient response characteristics.

Military Module Power Experiment emphasis will be on the following:

(1) High reliability and safety.

(2) Early plant deployment.

(3) Complete test and evaluation.

Site selection has been a U.S. Navy responsibility. It has been conducted in parallel with other experiment activities and has been independent of the technical tasks. Preliminary site screening and selection of three most promising candidate sites were completed in FY 1979. Visits were made to each site and technical discussions were held with site power engineers and administrative personnel. Tentative site selection at the Marine Corps Air Station, Yuma, Arizona was made late in FY 1979.

C. PLANNING FOR FUTURE EXPERIMENTS

Additional Isolated Application Series Experiments are now being planned. Applications are being selected which will support the JPL market penetration strategy with experiment deployment schedules based on technology readiness and the availability of funding. Subsequent experiments will test different versions of similar hardware in applications which are now being selected. Among those applications are foreign locations, islands, isolated mines, mills, U.S. Government sites, and isolated communities. The time period for deployment and test of these systems is 1982-86, and detailed planning for this series of experiment will be done during FY 1980.

SECTION IV

INDUSTRIAL APPLICATION EXPERIMENT SERIES

JPL has begun preliminary planning on the accelerated introduction of point-focusing distributed-receiver solar thermal power systems in industrial applications in small communities. These applications are characterized by their extremely large annual energy consumption. The experiments will be designed to test PFDR solar thermal energy systems for these appropriate industrial applications.

The key elements of the approach are as follows:

(1) Rapid deployment of existing technology.

(2) Small, low cost, low risk experiments.

(3) Near-term applications, preferably thermal.

(4) User and system supplier on contractor team.

(5) Developed hardware.

The technical feasibility of PFDR systems must be demonstrated in many different locations and applications. This is a critical point. Every major study of the attitudes of potential industrial users has arrived at the same conclusion. To be of value to a particular user, an engineering experiment must prove system feasibility in an application and region similar to the users. The number of experiments will therefore be tied to the number of unique industrial application/region combinations which can be shown to be commercially viable in the near term with mass produced hardware.

The Industrial Application Experiment Series planning was initiated in FY 1979, and the overall approach was determined. Activities during FY 1980 will include detailed experiment planning and the procurement associated with the selection of the first experiment contractors in this series.

SECTION V

SUPPORTING ACTIVITIES

Three task areas within the PFTEA Project provide support to the management of the engineering experiments. This section describes in a functional manner, the primary activites of these task areas in FY 1979.

A. SYSTEMS ENGINEERING

Two major activities comprised the systems engineering support to the project in FY 1979. The first was the effort involved with the technical management of the SCSE Phase I contacts. The second was the continuation and essential completion of the small power system comparative assessment study that was initiated in the preceding year. Both of these activities are summarized in the following paragraphs.

1. SCSE Systems Support

Three efforts in support of the engineering experiments were conducted in FY 1979; 1) technical support of the SCSE Phase I contract and evaluation of the results of Phase I constituted a major portion of the effort in the task area; 2) development of phase II system design specifications supported the writing of the Phase II RFP; and 3) completion of special studies that provided the necessary background and technical detail to evaluate experiment design alternatives. The first study was a power management study for PFDR, distributed conversion systems. The second study surveyed the work being done on advanced battery systems.

a. Phase I A summary of the Phase I contractor's results is presented in Section II. Because of the decision to proceed with the Ford Aerospace and Communications Corporation concept for Phase II, additional details are provided here in consideration of the further decision to pursue the Rankine cycle for power conversion in this experiment.

Ford considered Brayton, Stirling and Organic Rankine Cycle (ORC) power plants in their design and optimization studies to arrive at their preferred Category C system. At the outset of the study, the Stirling engine was generally regarded as a less mature technology than that of the Brayton and Rankine engines. However, Ford found that, as a result of a detailed examination of heat engines suitable for solar use, all candidates required some development effort (i.e., none of the candidates could be considered off-the-shelf hardware).

The analyses of the Stirling system utilized engine data provided by United Stirling of Sweden (USS) for their P-40 and P-75 engines. The major part of the engine data for use in the Brayton System analyses was provided by Garrett AiResearch for their CCPS-40-1 closed-cycle engine. For the open-cycle engine, Ford assumed a paper design based on the rotating components of the CCPS-40-1 closed-cycle engine. The ORC engine data were supplied by Sundstrand.

(Early in the study, Ford concluded on the basis of engine availability as well as design simplicity and state-of-the-art technology, that an ORC engine rather than a steam engine was a better choice for the Engineering Experiment.)

Major results of the analyses are summarized in and Figure 5-1. Based primarily on these results, Ford concluded that the Stirling cycle machine is a better choice for the Small Community Engineering Experiment than an alternate engine. Its higher efficiency and projected low production cost result in substantially lower energy costs and, according to data derived in the study, it has a substantially lower development cost. Ford concluded that, although the ORC system energy cost is 40-50% more than that of the Stirling system, the ORC engine showed promise and was considered a possible alternative to the Stirling engine. The Brayton system was considered by Ford least attractive for this first experiment. Based on considerations enumerated in Section II of this report a decision was made to proceed in Phase II with the Rankine cycle.

b. Phase II. At the end of FY 1979 in preparation for the start of Phase II of the SCSE (design, development and verification testing) an intensive effort was initiated to review the status of small Rankine engine technology, both steam and organic, to provide the basis for a specific engine decision early in Phase II.

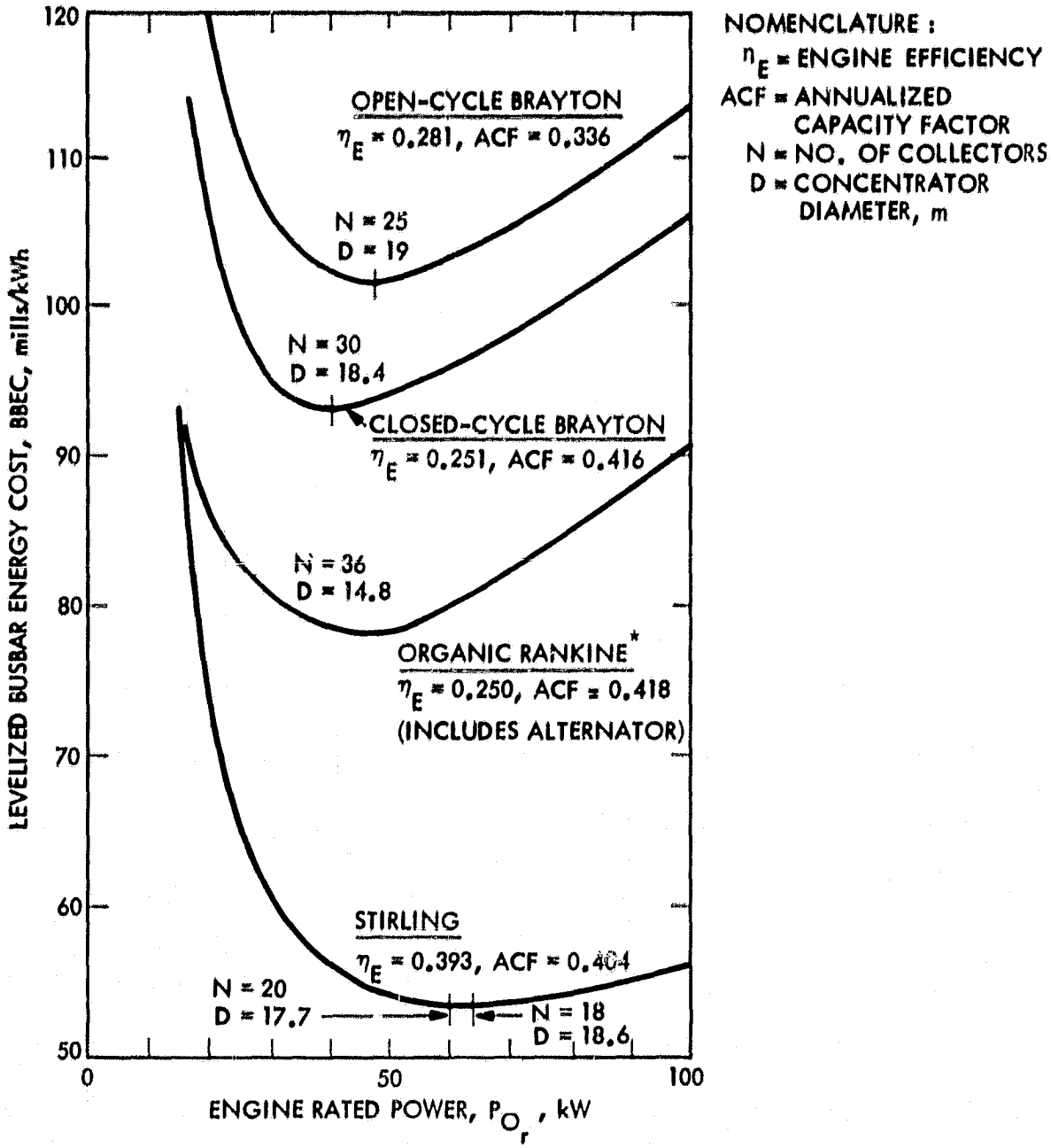
Detailed design specifications for SCSE were also prepared as part of the Phase II effort. These specifications may be found in the Phase II RFP.

c. Special Studies Distributed Generation Power Management. A study was performed by JPL to assess electrical system cost and efficiency of a solar electric plant. The baseline power plant was comprised of many small (92 m^2) Solar Generation Units (SGU) connected in parallel to provide rated output power of 5 MWe. Electrical Storage Units (ESU) were used to provide rated output power for up to six hours in the absence of solar input. An AC link operation was considered.

A 5 MWe plant with an annual capacity factor of 0.55 required about 440 SGUs and a storage system with the capacity for six hours of operation. AC power from a group of 110 SGUs is collected at 480 V, transformed to higher voltage (13.8 kV), and transported to centralized ESU at the utility bus interface. It is then combined with power from three other identical groups.

The major electrical components required to build a baseline plant using the selected conceptual approach were identified and listed. Specific cost and efficiency estimates for components in the parts list were presented to assist the Project in comparing the dish-electric approach with other conceptual approaches and in designing the dish-electric system.

Electrical component costs were grouped functionally and normalized with respect to key design parameters (concentrator field area, plant output power rating, and energy storage capacity).



• Variable turbine and fan speeds

Reference: Ford Aerospace and Communications Corporation Phase I Final Report

Figure 5-1. Comparative Energy Costs of Engine Candidates for SCSE

Estimated generator costs were found to be in the range of $13-33/m^2. Normalized electric transport costs were found to be $16/m^2. Plant control costs were not included.

2) Advanced Battery Study. A study was performed to evaluate existing and advanced electrochemical storage and inversion/conversion systems that may be used with terrestrial solar-thermal power systems. It assessed the status, cost and performance of existing storage systems, and projected the cost, performance, and availability of advanced systems. A prime consideration was the cost of delivered energy from plants utilizing electrochemical storage.

The report addressed three broad areas: (1) the electrochemical, or battery, component of the storage system; (2) the balance of system, or all components other than the battery; and (3) the overall solar-thermal plant with electrochemical storage. Included in the latter area was a tabulation of the levelized costs of delivered energy from complete plants with fifteen different advanced electrochemical systems. This tabulation ranked the systems in order of economic attractiveness.

The results of the study indicated that the five most attractive electrochemical storage systems are the following: (1) zinc-bromine (Exxon); (2) iron-chromium redox (NASA LeRC); (3) sodium-sulfur (Ford); (4) sodium-sulfur (Dow); and (5) zinc-chlorine (EDA). The key parameters describing these systems are shown in Table 5-1.

Table 5-1. Primary Advanced Battery Storage System Candidates

Battery Type	Initial Cost	# Cycles At 80% DOD	Battery Efficiency	Throughput Efficiency[3]	Projected Availability	Probability of Availability[2]
Na-S (Ford)	$43/kWeh	2500-5000	75%	69.1%	1985	0.80
Na-S (Dow)	$33/kWeh	3000	90%	83%	1990	0.20
Fe-Cr Redox (LeRC)	$132/kWe + $22/kWeh	10000	75%	69.1%	1990	0.95
$Zn-Cl_2$ (EDA)	$59/kWe + $27/kWeh	2500-3500	71-74%	65.4-68.2%	1985	0.8
$Zn-Br_2$ (Exxon)	$32/kWeh	2500-5000	80%	73.72%	1990	0.70

[1]Updated to mid-1979 dollars

[2]Predicated upon EPRI data, vendor data, and best engineering judgment

[3]Throughput efficiency (efficiency of battery + converter/inverter)

2. Comparative Assessment of Small Power System Technologies

a. Introduction and Background

The major thrust of the PFTEA project centers around a series of engineering experiments whose purpose is to test small solar thermal power systems under varying conditions in order to establish technical feasibility. The solar thermal power plant comparative study was performed to aid JPL in managing the experiment activity as well as to support decisions for the selection of the best technological approach. The study was initiated in early FY 1978. This summary identifies the systems evaluated, the methodologies utilized.

Shortly after the start of this study, DOE initiated two additional independent efforts in order to provide a more detailed base of comparative data. Thus, the Solar Energy Research Institute (SERI) and Battelle Pacific Northwest Laboratories (PNL) conducted evaluations of a similar set of small power system options.

The solar thermal power systems described in this study were rank-ordered by using the multi-attribute decision analysis methodology of Keeney and Raiffa. Various individual rankings were determined and were then aggregated into several overall rankings by utilizing formulation from the collective choice theory. This methodology was applicable because qualitative as well as quantitative criteria could be considered in the ranking of the systems. The four criteria used to evaluate the systems were cost, performance, negative impact and industrial and commercial potential (Figure 5-2).

b. Analysis

In order to establish the costs and performance necessary for the ranking procedure, two additional analyses were conducted. The costing analysis was based on manufacturer surveys, various solar energy reports, and resident JPL expertise . The performance analysis utilized a computer simulation model (SEC Computer Code) along with the results of the costing effort to establish optimal capital costs, energy costs, and the performance of each plant studied. Plant configurations and the nomenclature used to describe them are as follows:

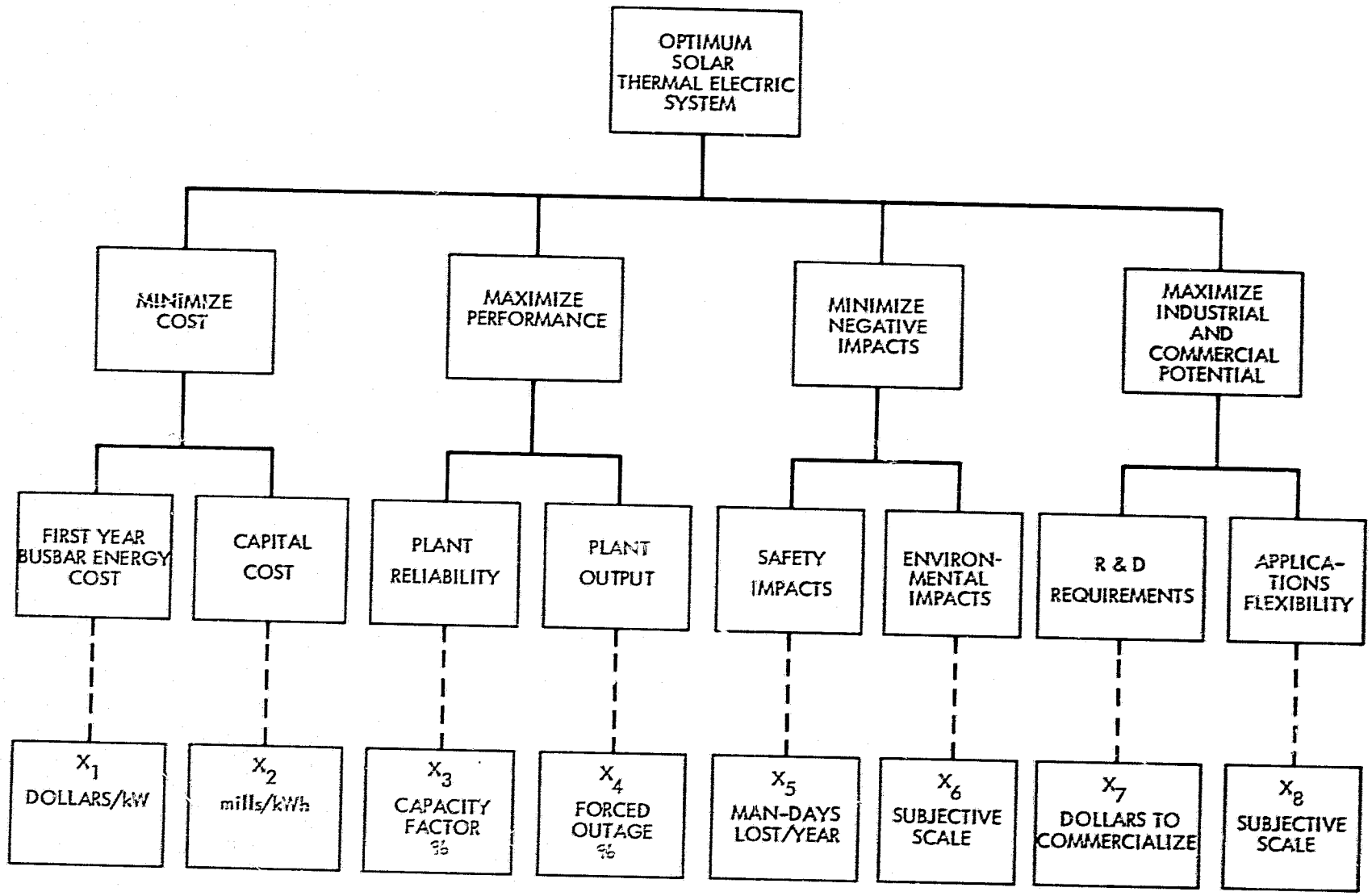


Figure 5-2. Multiattribute Decision Analysis Criteria and Factors

Abbreviation	Concept
LCNT	Low Concentration Non-Tracking
LFDR-TC	Line Focus Distributed Receiver-Tracking Concentrator
LFDR-TR	Line Focus Distributed Receiver-Tracking Receiver
LFCR	Line Focus Central Receiver
FMDF	Fixed Mirror Distributed Focus
PFCR	Point-Focus Central Receiver
PFDR/R	Point-Focus Distributed Receiver/ Rankine Engine
PFDR/B (ceramic)	Point-Focus Distributed Receiver/Ceramic Brayton Engine
PFDR/B (metallic)	Point-Focus Distributed Receiver/Metallic Brayton Engine
PFDR/S (ceramic)	Point-Focus Distributed Receiver/Ceramic Stirling Engine
PFDR/S (metallic)	Point-Focus Distributed Receiver/Metallic Stirling Engine

A complete description of each of the above systems may be found in the FY 1978 Annual Technical Report, Volume II.

The cost and performance analyses were performed for each power plant concept. The analysis required the detailed costing of the selected designs on the basis of information available from manufacturers (when real system designs were available) or, otherwise, the plant design generated for this purpose. Assumptions had to be made relative to the potential costs of mature technologies and high volume manufacturing.

A second major aspect of the analysis was the generation of plant performance and energy cost. The Solar Energy Simulation (SES) computer code was the main tool used for this analysis. In addition to cost data, the code requires the collector field to be modelled; engine efficiencies, transport and storage to be specified, and economic parameters to be provided.

At the time of publication, the document containing the results, of this analysis is in review. It is expected that this report will be published in the third quarter of FY 1980.

B. EXPERIMENT IMPLEMENTATION

Activities in this support area center around the siting of the experimental plants and the conducting of analyses that will prepare us for the implementation phases of the various engineering experiments. In FY 1979 four major activities in this regard took place. The first two pertained to the site selection activities in support of the Small Community Solar Thermal Power Experiment and the Military Module Power Experiment. The results of these efforts are summarized in Sections II and III of this report, respectively.

The third activity involved a regulatory requirements study and the fourth an analysis of site development and cost considerations. Both of these are summarized here.

1. Regulatory Requirements Study

To expedite the implementation of the experimental power plants by the Point Focusing Thermal and Electric Applications Project, a study of the regulations with which these plants must comply is being conducted. This study is being conducted in two stages. The first stage consisted of a general overview of the regulations applicable to solar thermal technology and the findings were incorporated into an interim report published in March, 1979. It identified several bodies of regulations which have the potential of prolonging the permit acquisition phase of experiment implementation.

The second stage of the study is an in-depth investigation of the regulations identified in the interim report as prolonging permit acquisition. An inventory of these regulations was conducted in which every state was requested to report on the status of specified regulations in that state. Responses were received from all but five states. Although the responses require verification, many states exempt small power plants from utility siting laws and many are implementing legislation providing a legal method to acquire solar access. Only Florida has included solar thermal electric power plants in their definition of electricity generation facilities.

A second part of this study consists of an analysis of local regulations as they are applied to solar thermal plants. Three cities have been selected for this site specific study: Alliance, Nebraska; Savanna, Oklahoma; and Yuma, Arizona. The planning agencies or their equivalents in these cities have been requested to list the regulations applicable to solar thermal power plants in their cities. The information received will be presented as case studies to improve our understanding of how localities may incorporate solar thermal power technology into existing regulatory structures. This will assist SCSE in the acquisition of permits in the most expeditious manner.

2. Site Development and Cost Considerations

A three-stage study effort is underway. The first preliminary study was based on literature information, data from other solar projects and standard construction estimation guides. This provided a basis for defining requirements for the second stage, site-specific studies by two architect-engineer firms. A third study will probe questionable areas in the earlier efforts and develop a summary report.

The first study results are described in the report "Costs and Considerations in Site Preparation for Solar Thermal Power Plants: A Preliminary Study." Most of the study information was developed from the Solar Total Energy Systems Project at Shenandoah, Georgia; the 10 MW Central Receiver Pilot Plant Project underway at Barstow, California; and from the Richardson "General Construction Estimating Standards." This study developed site preparation categories and developed rough cost estimates.

It was shown that site preparation factors and costs are very dependent on site conditions with costs varying from $14,000 per acre for minimum preparation for a Shenandoah type site to $62,000 per acre. Site preparation is also interrelated with construction, especially conduit installation, trenching, and foundations. While power systems costs will be reduced with advances in technology and increased production, this cannot be expected to occur to the same extent for site preparation and basic construction costs. Hence, system designs which simplify site preparation should be investigated.

Two architect-engineer studies utilized existing file information on sites developed for other non-solar projects. Both sites were approximately 10 acres in size located on the edge of suburban areas. Each contractor considered typical minimum preparation. Cost estimates for those sites ranged from about $ 32,000 per acre to about $57,000 per acre. Both firms emphasized the impact on site development by local agency approvals. The contractors also considered size effects. The 10 acre site development was considered sufficiently large to take advantage of low-cost construction techniques. However, perimeter costs are very size dependent primarily since the perimeter length is non-linear with area. In addition a greater proportion of "waste" perimeter area is required for smaller sites.

C. APPLICATION ANALYSIS AND MARKET CHARACTERIZATION

The Applications Analysis and Development Task contributes analyses of energy market, economics and requirements to the experiment planning and project decision making processes.

Specific decisions and plans supported in FY1979 include: 1) identification of application categories; 2) alignment of experiments with applications; 3) identification of system requirements critical to each application category; and 4) ranking of applications within each category; and 5) identification of industrial infrastructure requirements.

These support activities will be expanded in FY1980 to include thermal applications to provide an overall strategy of experiment deployment and market and industrial development.

Three application categories have been identified: isolated, industrial, and utility. The three experiment series have been defined along these lines.

In the Utility Application Experiment Series, the first experiment will utilize first generation hardware in the least complex system configuration (no storage, no hybrid) appropriate for the market. The Burns & McDonnell study

of small utility applications indicates that dedicated battery storage would not be economic until the cost of energy from PFDR plants approaches the lowest cost of energy available to utilities. Non-hybrid plants with no storage represent non-firm capacity.

JPL market studies have shown that there could be a significant market for such non-firm capacity in a few regions of the country, notably the Southwest. Consequently, the emphasis in the utility experiment series will be to evaluate improvements in the cost and performance of the basic system (engine, concentrator, receiver, and transport) and plant-level integration techniques. Improvements will be needed to compete with conventional oil-fired plants, and ultimately conventional coal-fired plants in the continental U. S. intermediate load utility market.

The small community utility market is and will continue to be an especially significant market throughout PFDR system development and commercialization. In 1990 the small utility market may approach 1350 MWe per year, based on estimates from Burns & McDonnell. JPL has identified the most attractive small utility applications to be Great Lakes Region Cooperatives (195 MWe/yr), southwest Municipals (142 MWe/yr), north central Municipals (177 MWe/yr), Great Lakes Municipals (157 MWe/yr), and southwest Cooperatives (28 MWe/yr). Peak demand growth, regional direct insolation, and regional cost of electricity were considered in ranking small utility applications. Estimates of peak demand growth were provided by Data Resources, Incorporated. The level of market penetration which may be expected will be estimated by General Electric in FY 1980.

In order to compete with oil and ultimately coal plants for the intermediate load segment of the large, firm-capacity utility market, PFDR technology will have to develop a hybrid capability. Since near-term, high cost, oil-dependent markets require firm capacity now, due to electrical isolation, JPL has chosen the Isolated Application Experiment Series to be the "lead experiment" in establishing the systems feasibility of hybrid PFDR plants and evaluating improvements in reliability. The extra cost and complexity of the hybrid feature can be justified by the high cost of energy from conventional sources.

Conversations with representatives of utilities on Pacific Islands reveal that fuel costs early in 1979 were $18.50/barrel and diesel generator installed costs were $600/kWe. With appropriate economic assumptions, levelized bus bar energy costs were calculated to be 120 mills/kWr in first quarter 1979. In the fourth quarter, fuel costs had risen to $28.50/barrel and the corresponding levelized energy cost was over 200 mills/kWh.

The BDM study and workshop addressing military applications reported that the military market, excluding military facilities, which could reasonably be met with PFDR systems is approximately 33MWe/yr at present procurement rates. Levelized energy breakeven costs were found to be 125-220 mills/kWh, corresponding to $2700/kW, assuming 1825 hours/year of operation. Thus, it is anticipated that markets such as these will be of significant interest to the PFDR program in the mid-1980's and, hence, early experiments in this sector are important.

The Industrial Application Experiment Series will be the lead series for thermal applications and systems and will emphasize near-term system configurations and first generation equipment in serving industrial loads in small communities. Thermal systems represent the least complex and least costly PFDR configuration. Many industrial thermal applications require steam at medium temperature (350 to 750°), which can be met by first generation equipment with a high degree of confidence. Preliminary results from the General Electric market penetration study indicate that, because thermal systems will be competing against on-site consumption of oil or natural gas, the breakeven energy cost could be favorable for these systems in the near-term. In addition, six attractive industrial electric applications were identified through a preliminary screening by SAI: preserved fruits and vegetables; beverages; miscellaneous foods, kindred products; metal services; commercial printing; and grain mill products. Profitability of investment and nationwide energy displacement were primary considerations in ranking industrial electric applications. Industrial applications will be analyzed in depth in FY1980 and the analysis will be expanded to include thermal applications.

In 1979 an experiment deployment strategy evolved in which each experiment series is to be the lead series for a particular system requirement, or critical element of PFDR system development. Separating the critical elements places development risks in parallel, thereby increasing the probability of success of each experiment. Aligning the experiments with applications ensures that the remaining development risks will be the minimum needed to demonstrate system feasibility in a particular market. Technical expertise in the design, fabrication, operation and maintenance of the experimental systems will be shared among all experiments.

Also in FY1979, a unified market and industrial development strategy was conceived for generating and sustaining production volume initially through the isolated load market. As production volume increases, system costs will decrease at an accelerated rate relative to the price of oil. This will allow early penetration of some oil-dependent industrial and utility markets in the contiguous United States. All three market areas must be pursued in parallel to ensure market transitions. Industrial development will follow, relying initially on existing production facilities, such as job shops, providing up to 1000 units per year. A study by Arthur D. Little, Inc., estimated that engine production would begin to shift to major facilities at about 10,000 units per year. At this level of production, component fabrication capital requirements for the steam Rankine engine are $3,000,000 and for the Stirling engine are $6,000,000. A companion study by JPL showed that if new industrial capital equipment and tooling were required to produce engines at the rate of 25,000 units per year, the capital investment required for the Stirling engine would be approximately $38,000,000 and the investment requirement would be $6,600,000 for the Brayton engine. These investment figures, coupled with an analysis of production volume based on market demand, will be used in developing a recommendation for the proper time phasing of the introduction of the Stirling engine.

Studies to date have resulted in a preliminary assessment of the market picture and this is summarized in Figure 5-4. This figure shows market sectors,

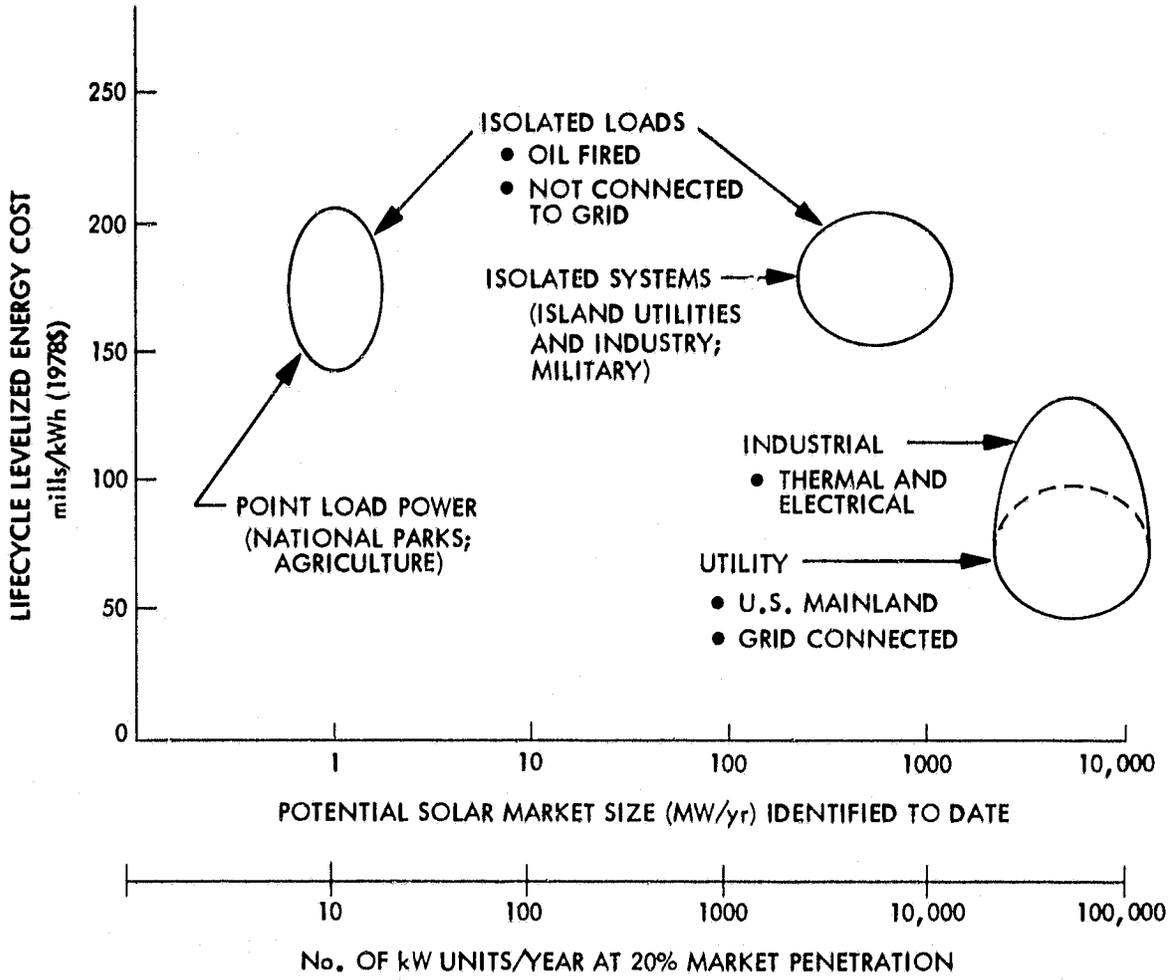


Figure 5-3. Preliminary Market Sectors for PFDR Technology

their approximate energy cost range and the potential size of market in 1990. An estimate of the number of 20 kW modules required at a 20% market penetration is also provided.

The questions of market appropriateness, market potential, and market penetration are extremely complex. It is planned that studies underway, both by contractors such as GE, SAI, Burns & McDonnell, and BDM, and at JPL, will provide data in FY1980 that will allow the first comprehensive assessment of these questions to be made. It is, therefore, a major objective of the applications analysis in FY1980 to provide a ranking and characterization of the most appropriate markets for PFDR technology.