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Thermal Power Systems Point-Focusing Distributed Receiver Technology Project

Annual Technical Report

Fiscal Year 1978

Volume II: Detailed Report

March 15, 1979

Prepared for
U.S. Department of Energy
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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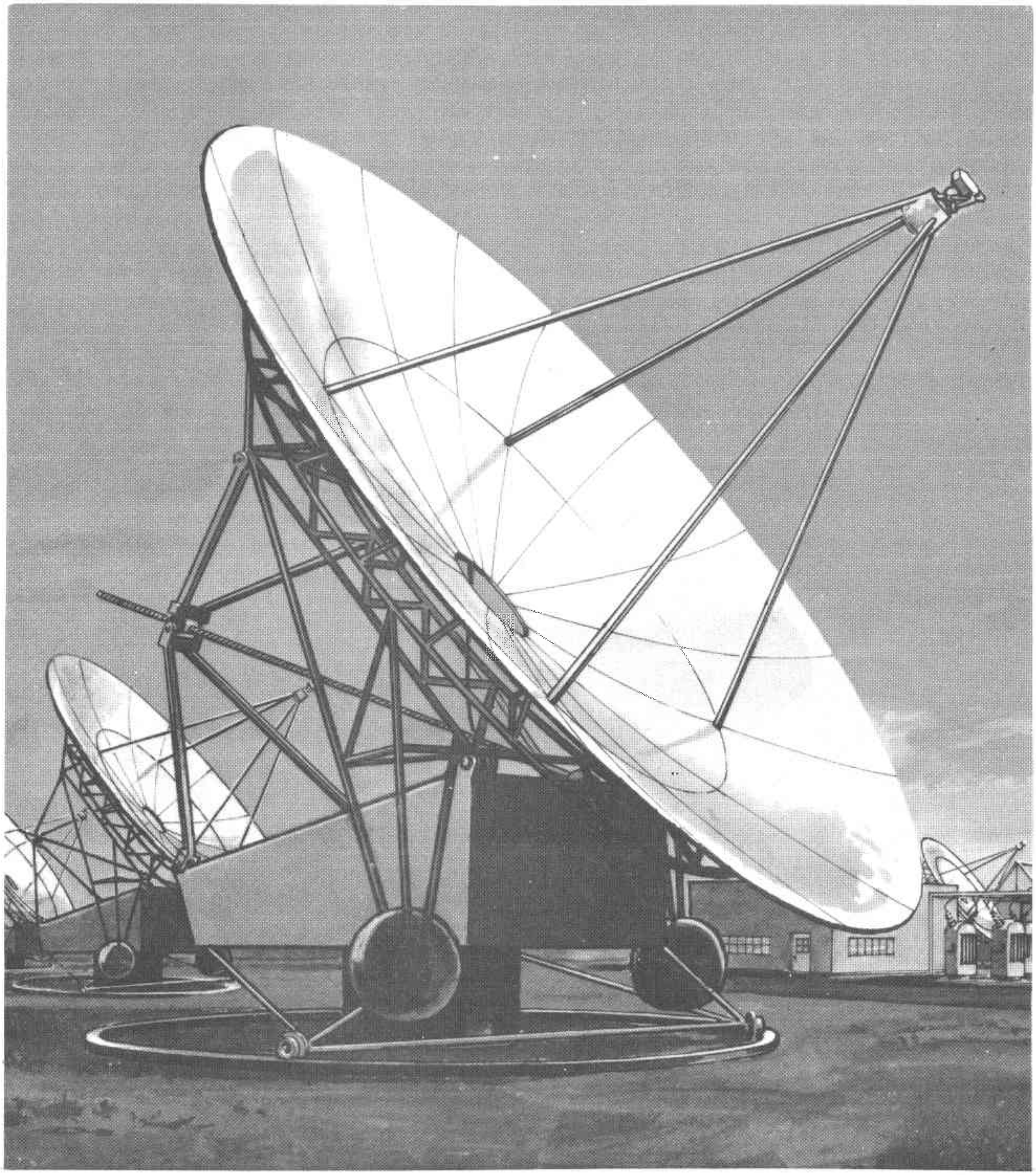
Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy by agreement with the National Aeronautics and Space Administration.

The JPL Solar Thermal Power Systems Project is sponsored by the U.S. Department of Energy and forms a part of the Solar Thermal Program to develop low-cost solar thermal electric generating plants.



Artist's Concept of a Tracking Point-Focusing
Parabolic Concentrator and Receiver

ABSTRACT

Thermal or electrical power from the sun's radiated energy through Point-Focusing Distributed Receiver technology is the goal of this Project. The energy thus produced must be economically competitive with other sources. This Project supports the industrial development of technology and hardware for extracting energy from solar power to achieve the stated goal. Present studies are working to concentrate the solar energy through mirrors or lenses, to a working fluid or gas, and through a power converter change it to an energy source useful to man. Rankine-cycle and Brayton-cycle engines are currently being developed as the most promising energy converters for our near future needs. This report details accomplishments on point-focusing technology in FY 1978.

FOREWORD

The Small Power Systems Section is a part of the Thermal Power Systems Branch of the Department of Energy's (DOE) Division of Central Solar Technology. The Section's task includes development of technology and applications for small power systems.

This report presents the results of activities conducted by the Jet Propulsion Laboratory during FY 1978 in support of this DOE program. Specifically, it discusses the Point-Focusing Distributed Receiver (PFDR) Technology Project.

The PFDR Technology Project was initiated in August 1977 as a result of an interagency agreement between the National Aeronautics and Space Administration (NASA) and DOE. The Jet Propulsion Laboratory (JPL) was named as the manager and the NASA Lewis Research Center (LeRC) was named to provide specific support to the project in the power conversion area. These two organizations, working with federal agencies, industry and universities, are to lead in developing point-focusing technology for use in applications projects.

This Technical Report covers the accomplishments during Fiscal Year 1978, the first year of the project. It is intended as a means of publishing results produced to date and disseminating them to industry and universities. If additional information is needed or if the reader wishes to discuss any items, please contact John Lucas, the PFDR Project Technical Manager, at Jet Propulsion Laboratory, FTS792-9368, Commercial (213) 577-9368 or write him at Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91103.

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SECTION I

INTRODUCTION

A. GENERAL

The Point-Focusing Distributed Receiver (PFDR) Technology Project is in the Thermal Power Systems (TPS) organization at JPL, TPS is part of the Office of Energy and Technology Applications, the organizational structure of which is shown in Figure 1-1.

Point-Focusing Distributed Receiver systems are one form of dispersed power systems that can generate electricity for rural communities and farms, municipal customers and industrial users by use of modular, sun-tracking collectors. The thrust of the present technology development is to bring prototype systems into operation by 1982 and to further improve systems, both in cost and efficiency, by 1985. An artist's conception of a typical PFDR module is shown in the frontispiece of this document. The basic subsystems include the concentrator and receiver, combined called the collector, and the power conversion unit which consists of a suitable heat engine, alternator, and associated controls. Currently, the leading candidates for engines are the steam Rankine, the gas Brayton (open and closed cycle), and the Stirling engine.

In contrast to central receiver power generation systems, which utilize a field of reflectors to concentrate solar energy into a single central receiver, PFDR systems utilize small concentrator dishes to furnish energy to their own individual receivers and power conversion systems. These modules each supply power to a utility grid. There are, of course, options such as using several dishes to drive a single appropriately-sized power conversion system.

The concentrator is a circular, parabolically dished mirror, which collects and focuses the incoming solar rays. Typical dish diameters might be in the range of 6 to 12 m. The hole in the center of the dish is a non-usable area arising from shadowing and blockage. The concentrator is mounted on a swivel mechanism that allows it to accurately follow the sun's movement throughout the day. A continuous, smooth-surfaced mirror is only one of many possible fabrication methods.

At the focal point of the concentrator, the focused solar energy passes through the aperature of the receiver into its cylindrical cavity. In the cavity the solar energy is absorbed and transferred to a working fluid that transports heat to the engine. The receiver and entire power conversion system may be mounted at the focal point but ground-mounted engines have been considered as well. Figure 1-2 indicates how several modules might be arranged to deliver electricity to a transmission grid. Many other arrangements are possible.

The goal of the Point-Focusing Distributed Receiver Technology Project is to develop the technology within industry for cost-effective, environmentally benighn, point-focusing distributed

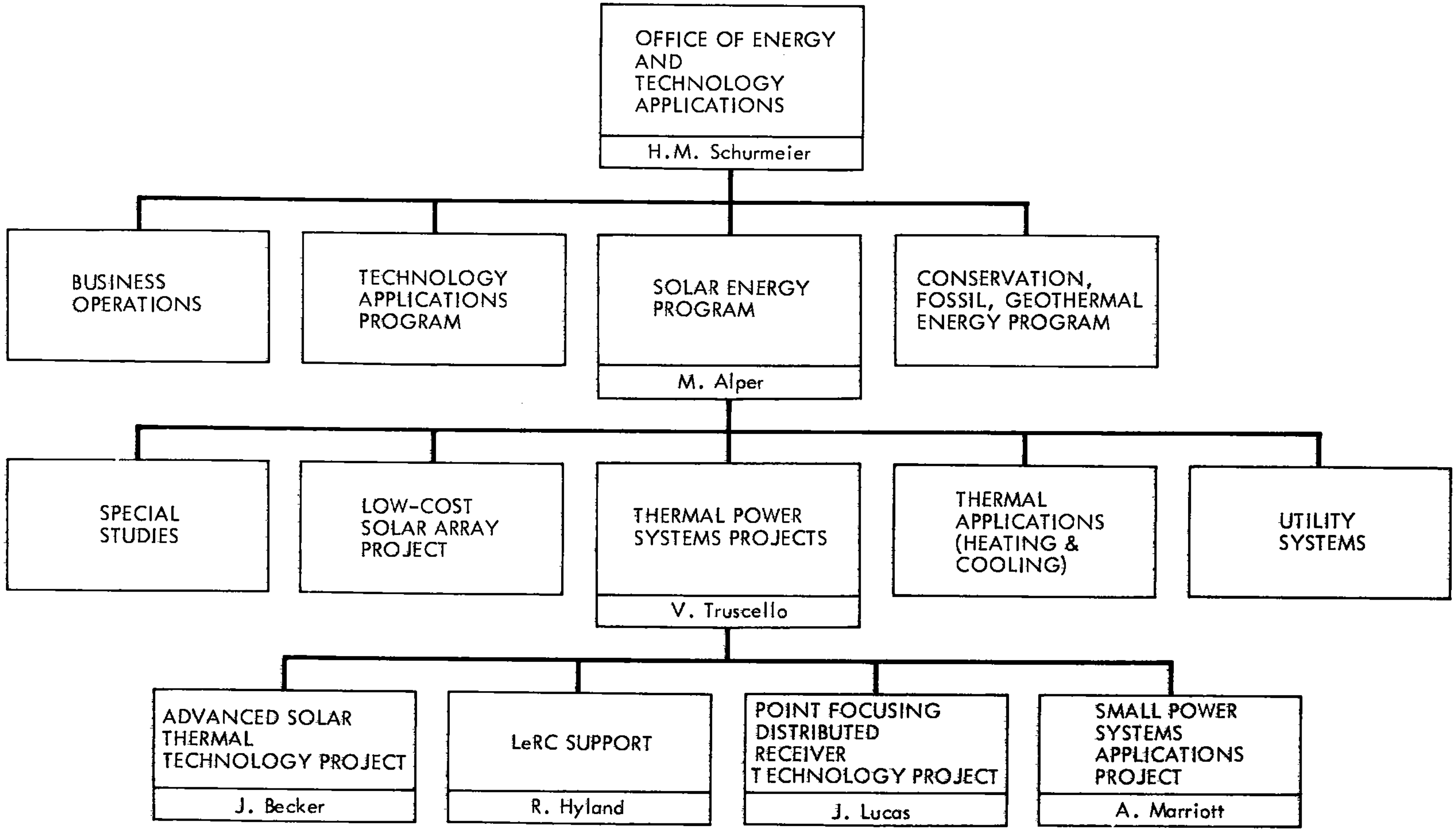


Figure 1-1. Thermal Power Systems Projects Organizational Structure

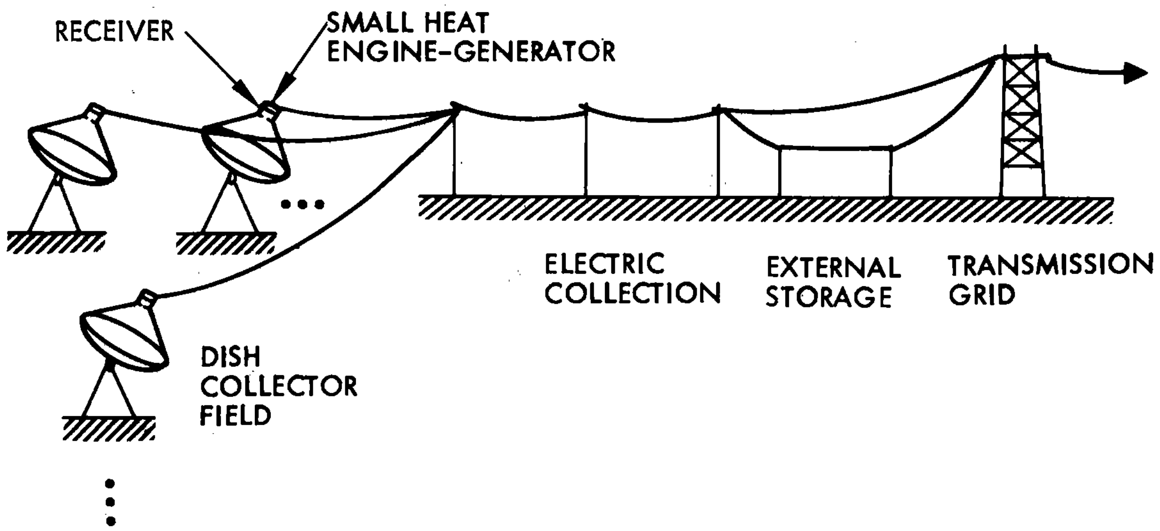


Figure 1-2. Parabolic Dish -- Electric Transport

receiver systems for electric and thermal applications. To meet the stated goal of this project, objectives are to make technology and mass production techniques available beginning in the early 1980's for applications experiments and to meet the preliminary cost and performance targets shown in Table 1-1. It should be noted that the target costs shown include expected reductions in cost due to mass production. For concentrators and receivers the expected reduction in cost due to mass production is a factor of five, and of ten for engines. In addition to the initial cost targets appropriate attention will also be given to operating and maintenance costs.

A central activity of the project is the development of the major subsystems listed in Table 1-1. The first generation subsystems are to be completed in FY 1982 as shown in Figure 1-3 to meet the associated cost and performance targets. The second generation is to be completed in FY 1985 for the corresponding targets. The parallel effort to bring mass production costs down is shown at the bottom of the figure.

B. JUSTIFICATION

A market exists for thermal power in the areas of industrial process heat, agricultural process heat, and heating and cooling.

A market exists for electric power for small communities, small utilities, remote locations, rural users, the Department of Defense and foreign countries.

Table 1-1. Preliminary Cost and Performance Targets

Subsystems	Targets for FY	1982	1985
Concentrator	Cost in mass production	$100-150/m^2$ $570-850/kWe	$70-100/m^2$ $400-570/kWe
	Mirror Reflectance	90%	92%
Receivers and Energy Transport	Cost in mass production	$9/kWt $30/kWe	$8/kWt $20/kWe
	Efficiency	80%	85%
Power Conversion	Cost in mass production	$75/kWe	$60/kWe
	Efficiency	25%-35%	35%-45%

Preliminary indications are that systems based on the two-axis tracking, point-focusing distributed receiver concept with the attendant modular features have a potential of leading to cost-acceptable commercial solar power plants. This project provides a framework for structured, coordinated point-focusing solar thermal technology development.

The modularity of the point-focusing approach can satisfy the diverse needs of dispersed thermal or electric applications, while offering the possibility of utilization in central generating plants. There is a good match of system characteristics to the needs of dispersed customers. Modularity of design permits quantity manufacturing with the attendant low costs for fabrication. Another consideration is that development will be done on small units, and scale-up design can be done with a high degree of confidence.

Additional advantages of modularity are ease of maintenance and transportability which are possible because of standardization, relative simplicity, and large numbers of identical units. Also, revenue production can be obtained during construction of the remaining modules.

Development of point-focusing technologies will result in power plants with good reliability based on modular units; inherent in these units is simplicity and standardization.

The point-focusing distributed receiver power plant offers a concept that is well suited to the distributed nature of the resource.

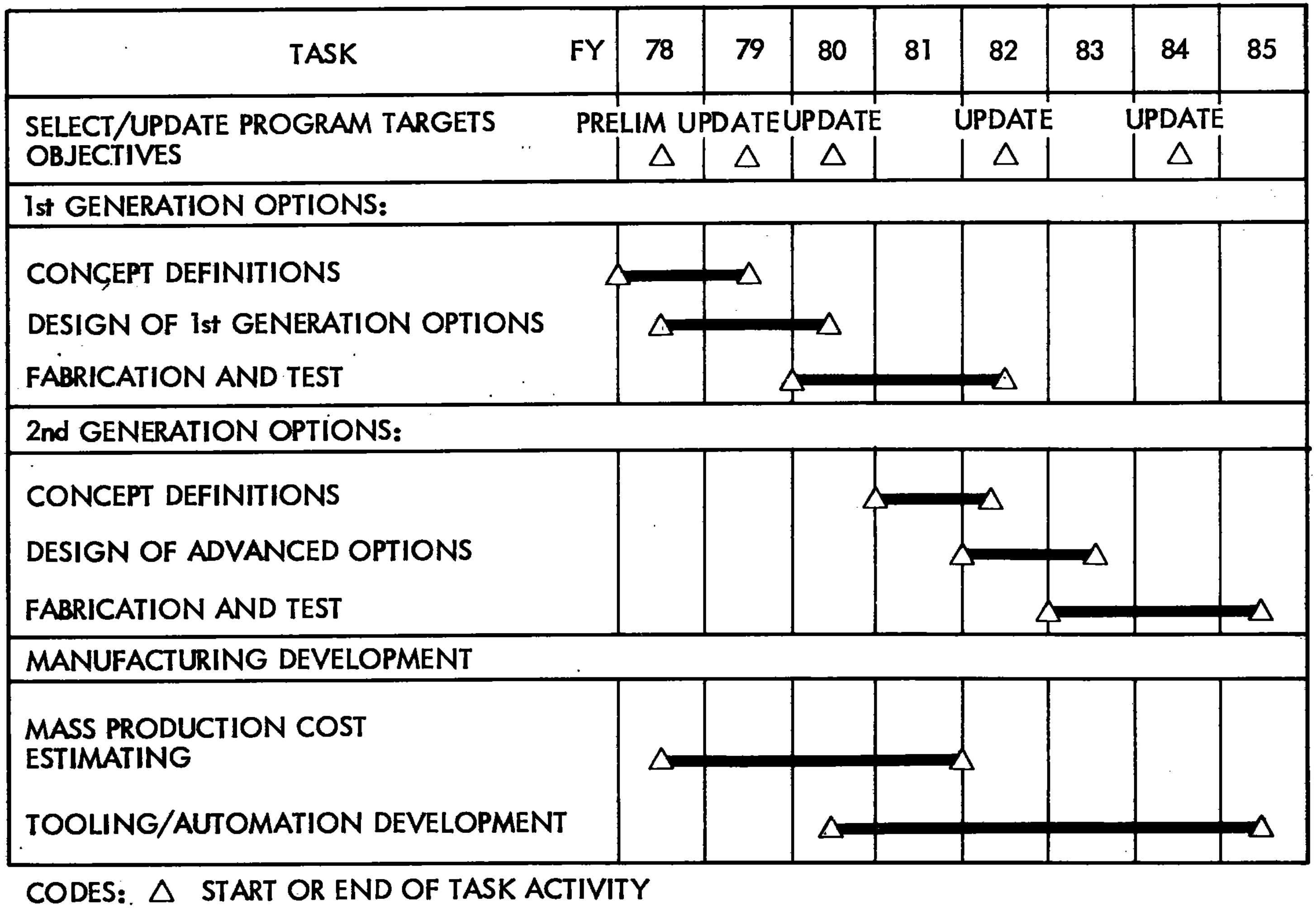


Figure 1-3. Overall Schedule of Subsystem Development

Dispersed power systems offer particularly interesting possibilities for the generation of electricity for rural communities and farms, municipal customers, and individual users. Some 65% of the U.S. population live in communities of less than 25,000 people, and these users are presently served by relatively small local municipal utilities or other remote sources. Such power sources are generally higher-cost producers than the large centralized power plant. Thus it would appear that there is a high probability of an early, sizable and varied market potential for the point-focusing distributed receiver generating capability. Associated with these plants will be sizeable quantities of medium grade heat, which may provide additional application possibilities when combined thermal and electric energies are considered.

SECTION II

TECHNICAL APPROACH

A. GENERAL

It is intended that the large majority of the requirements of this Project be met by contracts to industry and universities. JPL will maintain a staff to manage the Project and will develop a base of technical expertise to properly coordinate, monitor, direct and support, as required, the activities under contract. In those instances where independent analyses are deemed desirable by DOE, JPL will provide the resources and management to conduct such studies.

The seven tasks of the Project are as follows:

(1) Project Management

(2) System Engineering

(3) Concentrator Development

(4) Receiver Development

(5) Power Conversion Development

(6) Subsystem/System Test and Evaluation

(7) Manufacturing Development

Table 2-1 summarizes the major objectives of each task.

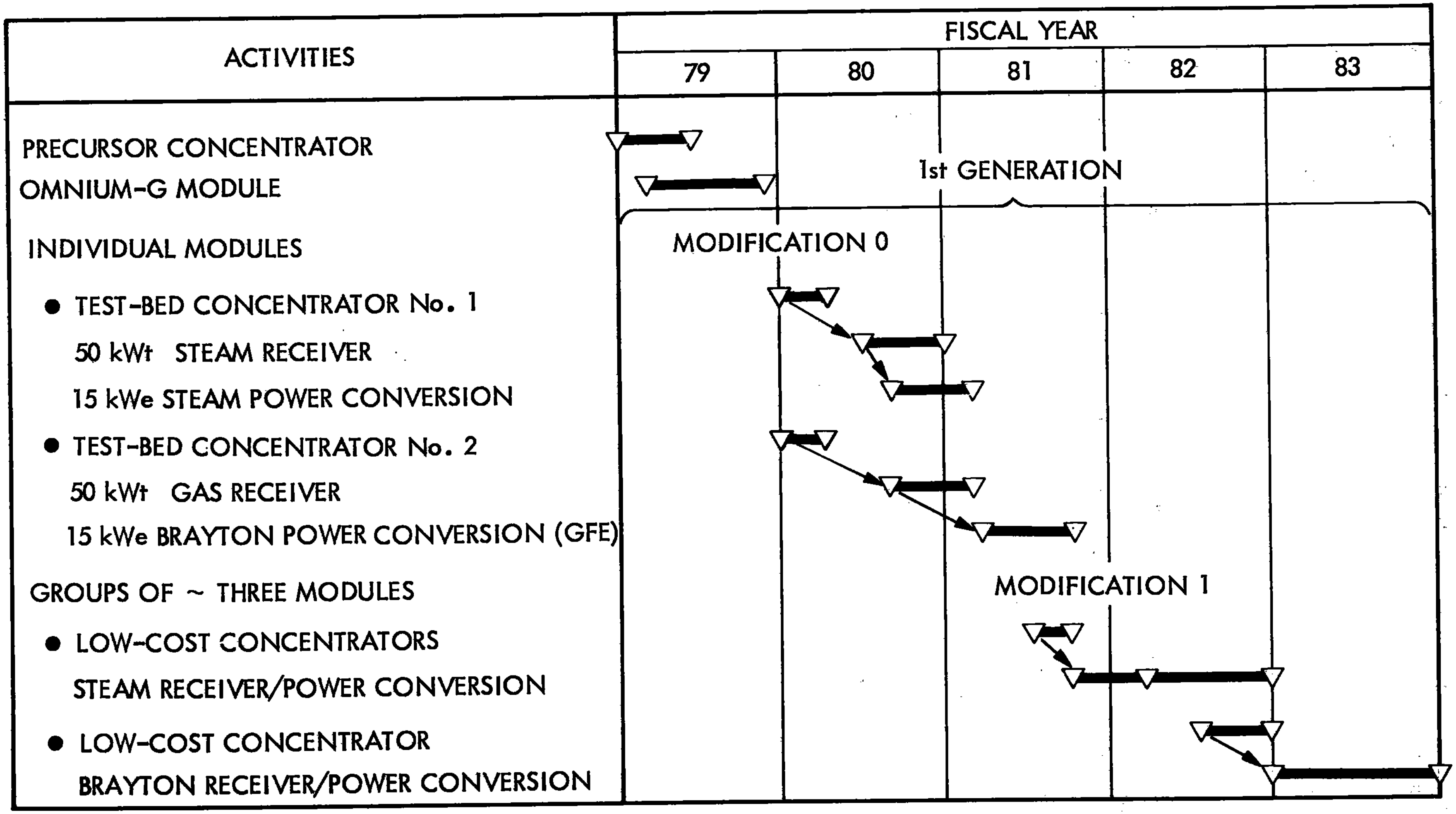
B. PLAN AND SCHEDULE

The technology effort centers on the development of key subsystems for point-focusing distributed receiver systems. Emphasis is on the major subsystems of low-cost concentrators, receivers and associated energy transport, and power conversion. Systems engineering coordinates the establishment of interfaces and functional requirements for each subsystem.

The major test periods are shown in Figure 2-1. Continuation of testing of the Omnium-G system module is shown in the upper portion of the figure. It should be noted that concentrator, receiver and power conversion units assembled together make up an individual module for electric power generation. Testing of Test-Bed Concentrator No. 1 will begin in the latter portion of FY 1979. After test and evaluation, the steam receiver will be installed on it and tested. The Modification-O steam power conversion unit will then be added to the assembly and tested. This process will be used with Test-Bed Concentrator No. 2 for the gas Brayton cycle. Testing will be carried out at the JPL Point-Focusing Solar Test Site (PFSTS).

Table 2-1. Project Objectives by Task

Task	Objectives
Project Management	Manage the project in order that project goals are met within the available budget, on schedule and in accordance with the annual operating plans.
System Engineering	Lead and provide support to design team. Define and analyze system configurations. Establish and monitor system and subsystem performance/cost targets.
Concentrator Development	Develop point-focusing concentrators to provide sufficient energy for steam Rankine, gas Brayton, and future advanced cycles such as the Stirling. Optimize designs for low cost in large quantity production.
Receiver Development	Develop cost effective receivers. Provide superheated steam and gas receivers.
Power Conversion	Provide efficient, cost-effective power conversion. Provide Rankine engines initially, and Brayton and Stirling engines following early development by the Advanced Solar Thermal Technology Project.
Test and Evaluation	Provide a test site at minimum cost. Perform testing and evaluation of point-focusing distributed receiver subsystem modules.
Manufacturing Development	Accurately estimate mass production costs of subsystems. Develop tooling for mass production. Design associated automation techniques.



CODE: ▽ START OR END OF TESTS

Figure 2-1. Five-Year Subsystem Test Periods

After individual Modification-0 modules have been developed and tested, modules in a group of approximately three will be assembled and tested as scheduled in the lower part of Figure 2-1. These modules will consist of Low-Cost Concentrators and Modification-1 steam Rankine and/or gas Brayton receivers along with power conversion units. The purpose of these tests will be to evaluate improved subsystem designs and to determine interactions among the modules on a small scale.

It is planned to make periodic assessments of the technology to assist in the determination of which configurations should be pursued in the following time period. These assessments will be based upon criteria approved by the Department of Energy and will include inputs from both systems and each subsystems area. Examples of assessment results will be recommendations for the type of subsystem, steam Rankine versus advanced cycle engines, and the temperature and power levels for each subsystem.

Initial work will be on the steam Rankine and gas Brayton subsystems (exclusive of Brayton power conversion units which will be provided to this project for test by the Advanced Solar Thermal Technology Project) indicated in the respective task descriptions. As progress is made, work on advanced types may be added while effort on earlier ones may be completed or terminated.

SECTION III

TECHNOLOGY INFORMATION DISSEMINATION

This Project is ultimately concerned with the creation of a new product and beginning development of an industrial capability for supplying the product. Every study on the advancement of technology has shown that the time from laboratory to marketplace generally takes from 20 to 50 years, and sometimes even longer, unless there is some special stimulation or other effort to speed up the process. There is a national need to establish options for new energy sources as rapidly as possible; therefore, this Project must have, as a major component, a plan for accelerating the technology transfer process.

An effort to accelerate the transfer process must include both communication of Project results to the supplier, user, and regulatory communities of interest, as well as early involvement of representatives of these communities to ensure commercial practicability of the results. Communication to and participation by the communities of interest will be a major effort.

The supplier community of solar energy industries is, at present, relatively small. Interest in solar energy, however, is growing rapidly and a large industrial community can be anticipated. The user community, in contrast, is already large and very complex. The largest segment of potential users is the public and private utilities. Other users could include industry, commerce, and agriculture. The regulatory community is also large, since it includes state and local governments, public utilities commissions, and environmental protection agencies.

The technology transfer plan has two major components: (1) efforts associated with this Project's activities and (2) active participation and interface with DOE and other appropriate governmental technology transfer activities.

This Project's technology transfer activities consist of early, continuous and major involvement of industry, and dissemination of technical results. The industrial involvement will be significant and widespread.

The Project's technology dissemination plan contains the following activities:

(1) Publication of results in scientific, technical, and trade journals.

(2) Presentations at scientific, technical, and trade conferences representative of government, industry and universities.

(3) Making computer codes available to industry and universities.

(4) An outreach to industry to encourage it to directly utilize the technology in commercial products.

(5) Project integration meetings which bring together government and industry participants in the technology developments.

(6) Exchange fellowships from industry to government and vice versa.

TECHNICAL INFORMATION PAPERS

*Thermal Optical Surface Properties and High Temperature Solar Energy Conversion, L. Wen., Second AIAA/ASME Thermophysics and Heat Transfer Conference, Palo Alto, California, May 24-26, 1978.

*The Parabolic Concentrating Collector, V. C. Truscello, Solar Thermal Concentrating Collector Technology Symposium, Denver, Colorado, June 14-15, 1978.

*Thermal Performance Trade-Offs for Point Focusing Solar Collectors., L. Wen., 13th IECEC, San Diego, California, August 20-25, 1978.

Point Focusing Distributed Receiver (PFDR) Solar Thermal Power Systems: A Project Description, J. W. Lucas, J. Roschke, AIAA/ASERC Conference on Solar Energy, Phoenix, Arizona, November 27-29, 1978.

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*Presented

SECTION IV

CONCENTRATOR DEVELOPMENT

A. INTRODUCTION

Solar concentrators considered in this Task are of a generic configuration which nominally focuses the intercepted thermal energy at a point where it is absorbed by a receiver and transported to a power conversion unit which may be mounted near the focal point or on the ground. The thermal energy could also be used for process heating applications. The point-focusing concentrator is considered by many to be one of the more attractive forms of solar energy collection. It has modularity and high efficiency, and can provide quality thermal energy in the 1000-2000°F range.

The focusing of energy may be accomplished by either a reflecting surface or a lens. In either case the concentrator must be capable of tracking the sun with its optical axis. This is accomplished by incorporating two axes of motion into the mount or support structure, together with the controls, sensors and drives for tracking. The concentrator also includes the support structure for the receiver/power conversion package located at the focus.

Because the concentrator accounts for the largest part of a complete module cost, 50% to 75%, it must be characterized by a high thermal output per dollar ratio (kWt/$), when mass produced, in order for this technology to achieve a competitive position in the energy market.

This is the motivating driver behind the Concentrator Development Task.

B. TASK OBJECTIVE

The objective of this task is to make concentrator technology available and to develop high temperature point-focusing concentrators which offer low cost when manufactured using mass production techniques. This objective will be accomplished principally through development contracts with industry. This is especially appropriate since the technology must be disseminated to industry in order to achieve the overall solar thermal program goals.

Preliminary cost and performance targets have been set and are shown in Table 4-1.

C. APPROACH

The task objectives will be approached by a development effort having three primary thrusts. The first is to acquire concentrators to be used in an early testing program. Included are a Precursor Concentrator and two Test Bed Concentrators. Sections of reflector

Table 4-1. Concentrator Cost and Performance Targets

	Targets For	FY 82	FY 85
Concentrator	Cost in mass production	\$100-150/m^2	\$70-100/m^2
	Reflector efficiency	90%	92%

surfaces, simulating full size concentrators, will be mounted on the Precursor for evaluation. The Omnium-G concentrator obtained via the Systems Engineering Task is a part of this test activity. The Test Bed Concentrators' performance parameters will be well characterized by tests for use as a data base for point-focusing concentrator performance. Additionally, they will be used at the test site for testing of other subsystems. The test bed concentrators are being acquired by a procurement to modify an off-the-shelf microwave antenna design. Modifications will incorporate sun-tracking capability and a reflector surface using JPL-supplied spherical mirror facets. These concentrators will provide receiver cavity working fluid temperatures in the 1000-1500°F range.

A mirror facet development activity was undertaken in support of the Test Bed Concentrator. This work was an extension of an earlier development activity at JPL which uses a second surface mirror bonded to a Foamglas* substrate. The FY 1978 activities included the evaluation and selection of materials comprising the facet and the procedures required for their fabrication. Additionally, a computer program was developed to analyze the performance of a faceted concentrator.

The second thrust is the initiation of a low-cost paraboloidal concentrator development. Procurements have been placed for the evaluation of concentrator design concepts for low-cost fabrication and will be followed by design, fabrication and test phases. Three contracts have been implemented for the preliminary design phase. In the interest of obtaining concentrator hardware as early as possible, it is planned to combine the design and fabrication phases. One of the three Phase 1 contractors will be selected by a competitive procurement to implement this combined effort.

The initial series of contracts, is for a first generation Low-Cost Concentrator to operate efficiently in the 1000-1500°F range with a mass-produced cost target of 100-150 \$/m^2. This effort is directed toward having a concentrator capable of being integrated with the relatively high temperature Brayton Engine/Receiver. It could also be used with the steam Rankine Engine/Receiver although a concentrator with lower performance may be more cost effective for those conditions.

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* ® Pittsburgh Corning Corporation

The third thrust is the development of a second generation of Low-Cost Concentrators of improved design. Separate contracts for steam and gas cycle utilization will be initiated in FY 1980. These are expected to utilize design concepts initiated by the Advanced Solar Thermal Technology Project. The second generation concentrators will have a mass-produced cost target of 70-100 $\$/m^2$.

The five-year schedule for Concentrator Development is shown in Figure 4-1.

D. STATE-OF-THE-ART

Solar concentrators have received attention in this country down through the years, but have never been made economical enough to be seriously competitive with other means of producing energy for general use. Several examples can be found in the historical literature dating to about the turn of the century. The sixties saw another flurry of activity related to space power applications.

Recently, many studies have been conducted using point-focusing concentrators as the means for concentrating solar energy. In most cases, antenna technology has been used as the basis. This is illustrated by the Honeywell Deep-Well Irrigation (Ref. 1) and the General Electric Shenandoah studies (Ref. 2). The Honeywell study used reflective film on a typical large antenna construction (approximately 15m diameter) reflector, while General Electric proposes to use Alglas bonded to a panel, formed by stamping as is often done for small antennas (5-6m diameter). Raytheon has built a 6.7m diameter concentrator to operate in the medium temperature range. It uses sagged glass, second surface mirror sheets of spherical curvature to approximate a parabolic reflector surface (Ref. 3).

More recently, the Small Power Systems Applications project has two point-focusing concentrator design approaches being studied in the System Definition Phase (Phase I) effort of Engineering Experiment No. 1 (Ref. 4).

The only point-focusing concentrator available commercially in this country is the Omnium-G 6 meter diameter module. This is available in relatively low quantities with 90 day delivery. Petals made of Alzak, on a substrate of polyurethane foam, form the reflecting surface. This concentrator, in today's production quantities, costs some $\$1100/m^2$.

Much remains to be done to reach our cost/performance targets. We must devise point-focusing concentrator designs which are amenable to mass production techniques, and are probably of unique concept. These designs must be built and tested, to demonstrate that performance can be achieved with structures that are representative of those obtainable when mass produced. The Concentrator Development Task of the PFDR Technology Project is directed toward meeting that challenge.

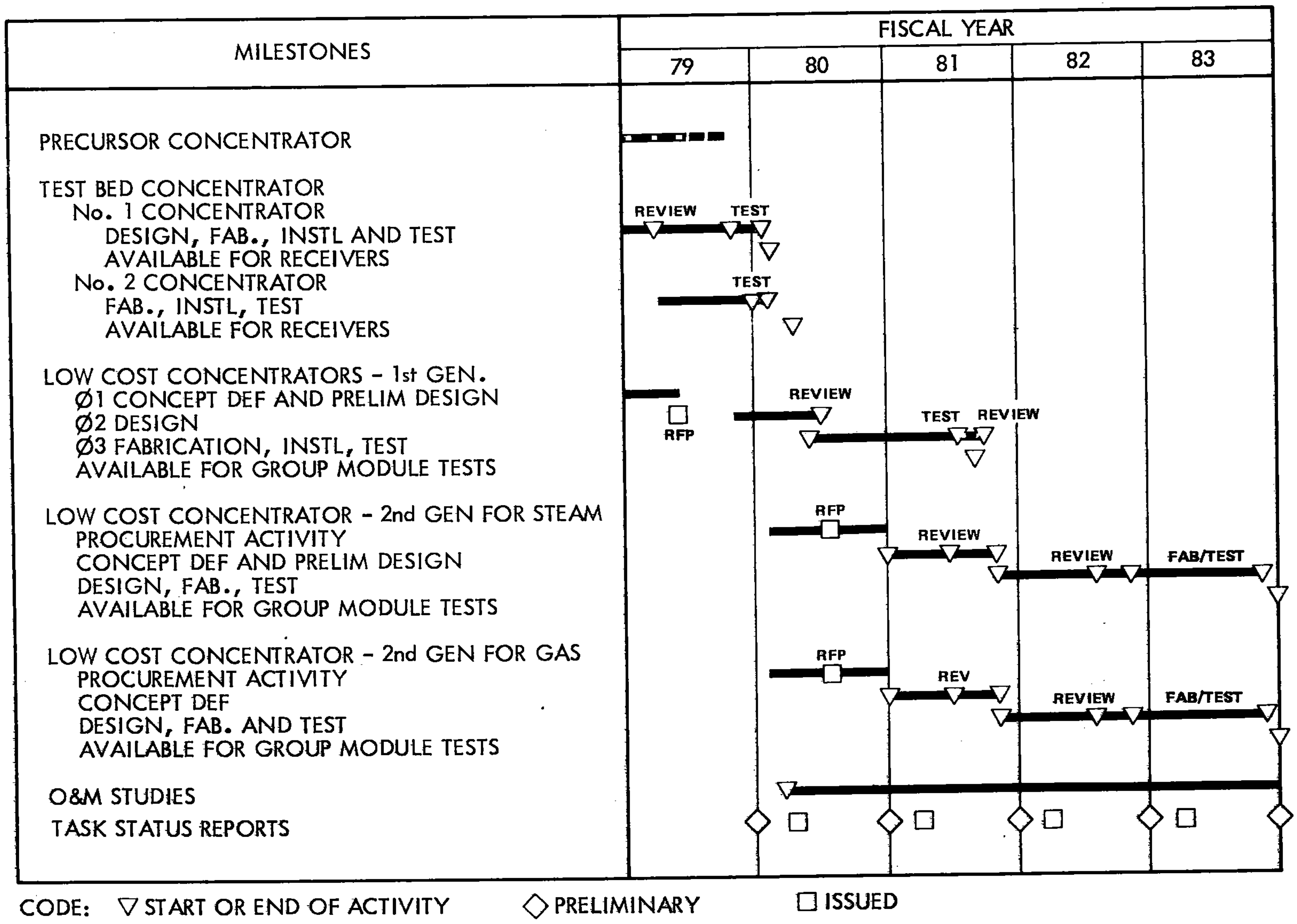


Figure 4-1. Five-Year Concentrator Development Milestones

E. PRECURSOR CONCENTRATOR

The Precursor Concentrator is a simulation of a section of a concentrator with mirror facets such as used in the Test Bed Concentrator. It will be used primarily as a tool to measure mirror performance and to evaluate alignment techniques. Figure 4-2 shows a configuration used to evaluate mirrors in an earlier development program. In the current Precursor configuration, facets from the mirror development program will be mounted on an arm to simulate a row of reflector facets in a near on-axis orientation. This arm will accommodate mirrors of the Test Bed Concentrator configuration, and with modifications, it will be able to simulate a radial row of mirrors to include the extreme off-axis orientation. It is planned that other mirror configurations could also be tested on the Precursor Concentrator.

A cold water calorimeter has been modified for use with the Precursor. It will measure the thermal performance of the mirrors, one at a time or combined. Test plans for the Precursor include preliminary evaluation of degradation of mirror performance caused by dust and film accumulation on the mirror surfaces.

A flux mapper is being fabricated under the Receiver Task for use in characterizing the intensity of the image on the Omnium-G concentrator. The Precursor Concentrator will be used for development of that equipment.

The base support for the Precursor is an antenna Hour angle - Declination mount which was removed from storage. The boom and arm have been designed and fabricated. Assembly and checkout is nearly complete. The Precursor will be tested at the Solar Thermal Test Site where it will interface with instrumentation and operational equipment.

F. OMNIUM-G MODULE - CONCENTRATOR

The plans for evaluation of the Omnium-G point-focusing module are described in the Systems Engineering Section of this report (Section 8). The approach will involve three steps: (1) evaluate the equipment at the subsystem level, (2) integrate the subsystems one at a time, and (3) conduct an all-up systems test evaluation.

In keeping with this approach, the concentrator will be delivered first and will be evaluated as a subsystem.

A preliminary plan containing test requirements for this subsystem testing has been written. The planned tests include mirror alignment, controls checkout, thermal performance with a cold water calorimeter and mapping of the flux intensity at, and behind, the focal spot.

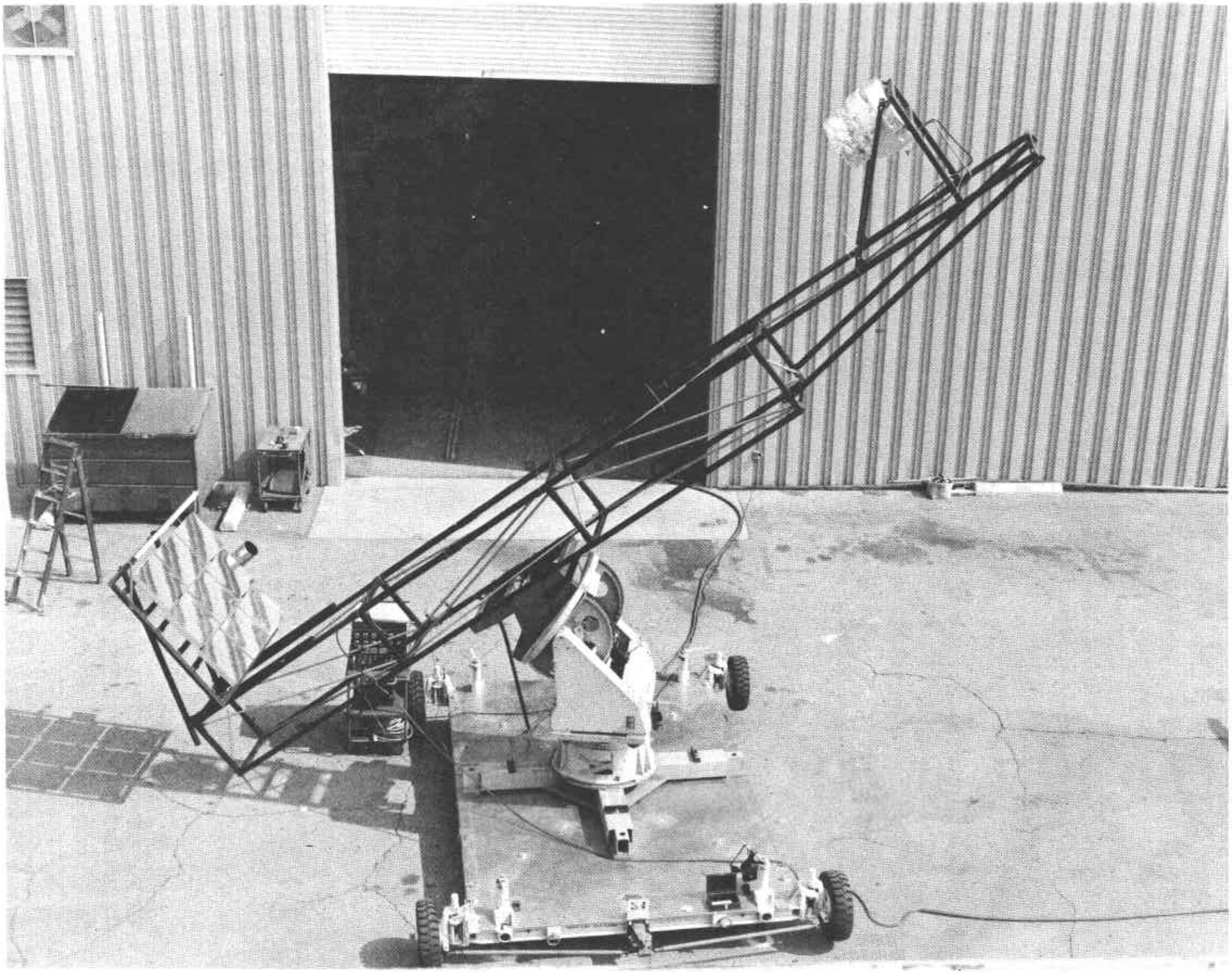


Figure 4-2. Early Mirror Performance Test Apparatus

G. TEST BED CONCENTRATOR

The Test Bed Concentrator is an early versatile concentrator to provide performance and operational experience. It will also be used as a test bed for development testing of receiver and power conversion hardware at the Solar Thermal Test Site.

The approach to obtaining this capability in a fast, cost effective way was the procurement of a microwave antenna, (a) modified to accommodate mirror facets of the JPL developed configuration as the reflector surface, (b) to provide solar tracking, and (c) to support the receiver/power conversion package at the focal point. A diameter in the 10-15 meter range was chosen for this concentrator.

A Request for Proposal was released in December 1977 to the antenna manufacturers on the solicitation list. The response did not satisfy the requirements established for the procurement, and this necessitated a resolicitation. E-Systems was selected as the contractor. The contract start was further delayed several weeks because of detail procurement problems. The contract was started September 14th. Initial efforts centered on preliminary design of the concentrator with emphasis on mirror geometry and support approaches and on the Az-El tracking implementation.

The selected design will nominally be 11 meters in diameter, have two tracking axes, elevation over azimuth, and will track in either a closed loop sun sensor control mode or a position memory mode. The design is adapted from an antenna control system. Wheel and track azimuth drive will be used. The JPL supplied mirror facets will mount to the reflector support structure and have adjustment capability in the mounting hardware to permit individual facet alignment. A bipod with lateral guys will support the receiver and power conversion subsystems. Two identical units will be installed at the PFSTS.

H. CONCENTRATOR PERFORMANCE ANALYSIS

The Test Bed Concentrator utilizes a reflector surface of mirror facets having a spherical surface. A computer program, based on cone optics, was developed to evaluate the optical performance of a concentrator with spherical facets, of different shapes, supported on a paraboloidal substrate. The computer program consists of two sequential parts. The first part is used to evaluate the individual solar image size from a single facet as a function of the facet location and the mirror radius of curvature. Each facet is subdivided into many small elements to improve the computation accuracy. The second part of the computer program computes the solar flux intensity distribution at the receiver/absorber location. Distribution may be on planes perpendicular to the concentrator axis but at different locations relative to the local plane. Also flux distributions on the inside surfaces of a cavity receiver may be determined.

Representative results from a typical analysis are shown in Figures 4-3, 4-4, and 4-5. The preliminary analysis of a typical TBC

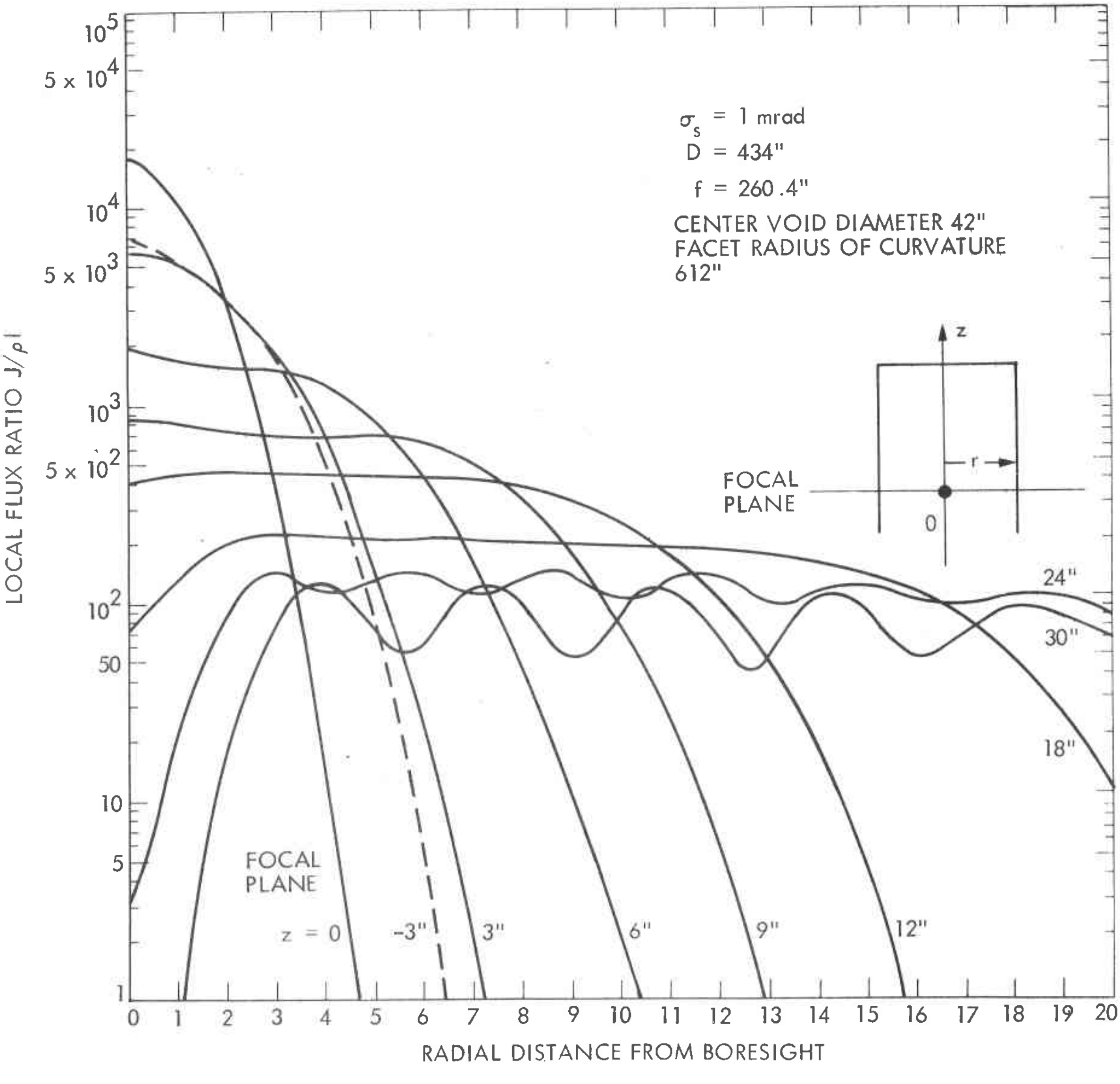


Figure 4-3. Representative Flux Mapping with Mirror Having 1 mrad Slope Error

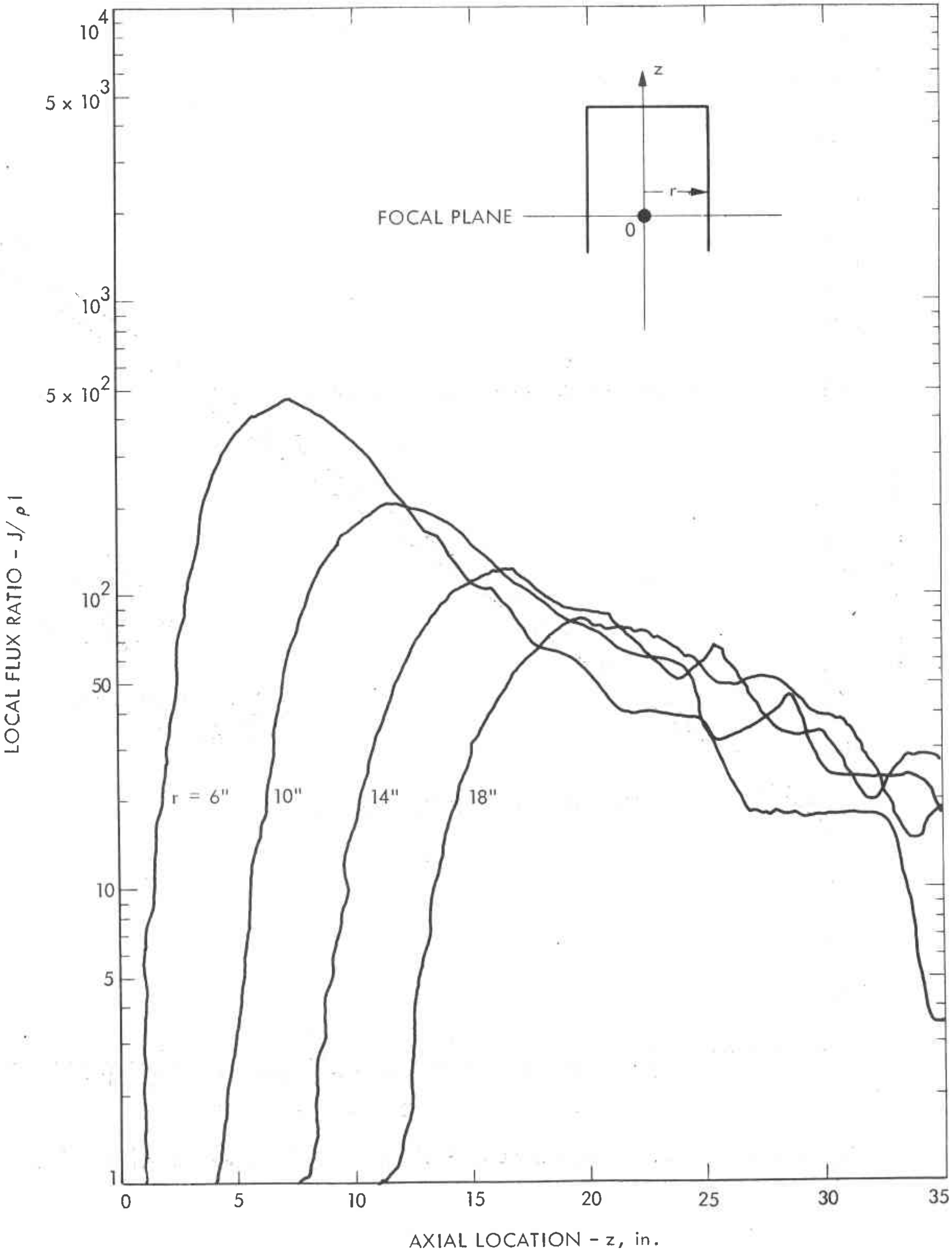


Figure 4-4. Solar Flux Distribution Along Receiver Wall

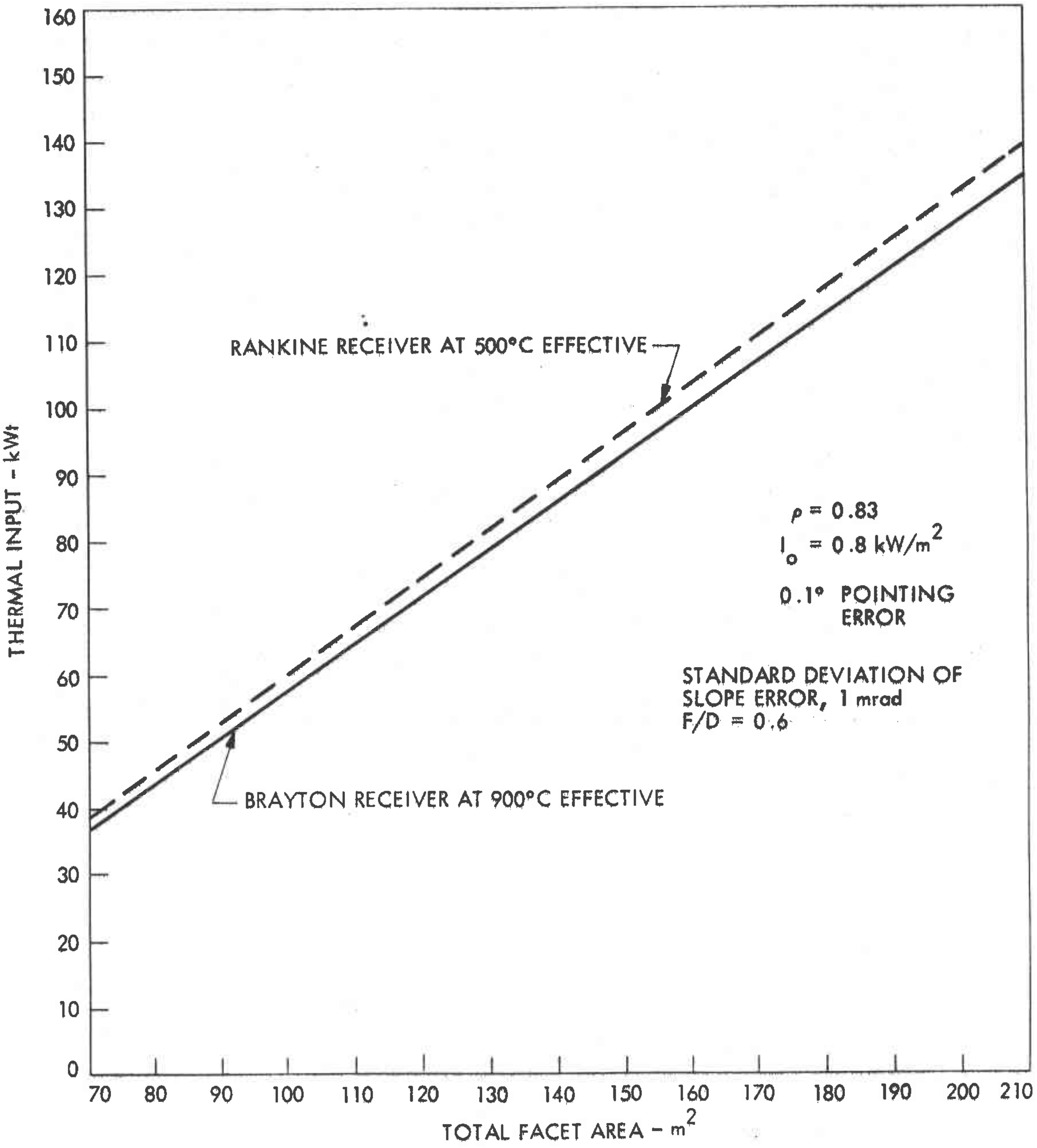


Figure 4-5. Test Bed Collector Sizing vs Effective Thermal Output

configuration showed that the multi-facet concept is a viable approach and that a common radius of curvature for all facets gives acceptable performance.

I. MIRROR FACET DEVELOPMENT

In an earlier program at JPL, development work was performed on mirror facets made by bonding a second surface mirror to a spherically contoured block of Foamglas. This effort is reported in Ref. 5.

Foamglas is a soda-lime cellular glass material used as an insulating material in many varied applications. It is commercially available from Pittsburgh Corning in two grades. Coefficient of expansion compatibility with the mirror, its light weight, ease of shaping and its general stability and durability are the significant characteristics for selecting Foamglas as the substrate for the mirror facet. The High-Load Bearing grade was chosen because of its more consistent quality.

Blocks, 18" square, were the largest available, therefore facet shapes were restricted to a maximum area of 2.25 sq ft. Tests indicated that mirrors, fabricated with a radius of curvature of 43 ft, had slope errors less than 0.1° (1.74 mr). Figure 4-6 shows one of the mirrors at that early stage of development.

A review of the facet designs that existed at the time a choice had to be made for the TBC reflector surface resulted in several activities including revisions in block size, selection of materials for use in actual fabrication and structural characterization of the Foamglas.

Analysis showed that sizes greater than 18 inches would give satisfactory performance. Somewhat larger sizes would be no more difficult to fabricate and a smaller number of facets would be required for the Test Bed Concentrator. Pittsburgh Corning Company was successful in making a 24" x 28" x 2" block as a special run through their commercial process. This was adopted as the maximum envelope from which the Test Bed Concentrator mirrors were to be made.

The rectangular facet configuration was analyzed for its structural adequacy to withstand 100 mph wind loads. A support geometry was chosen based on using 3 flexure tabs bonded to the edges of the facet substrate.

Tests were conducted, using candidate adhesives to establish allowable stress values in shear and peel strength for the tab to substrate joint. Additionally, static tests on full-sized facets subjected to the simulated design wind loading were conducted.

Little data on the strength properties of cellular Foamglas were available for use in the structural analysis. A modest test program was conducted to determine needed properties. Four point bend tests using rapid loading to failure were used to obtain strength variation and the strength-size relationship. Static fatigue resistance which

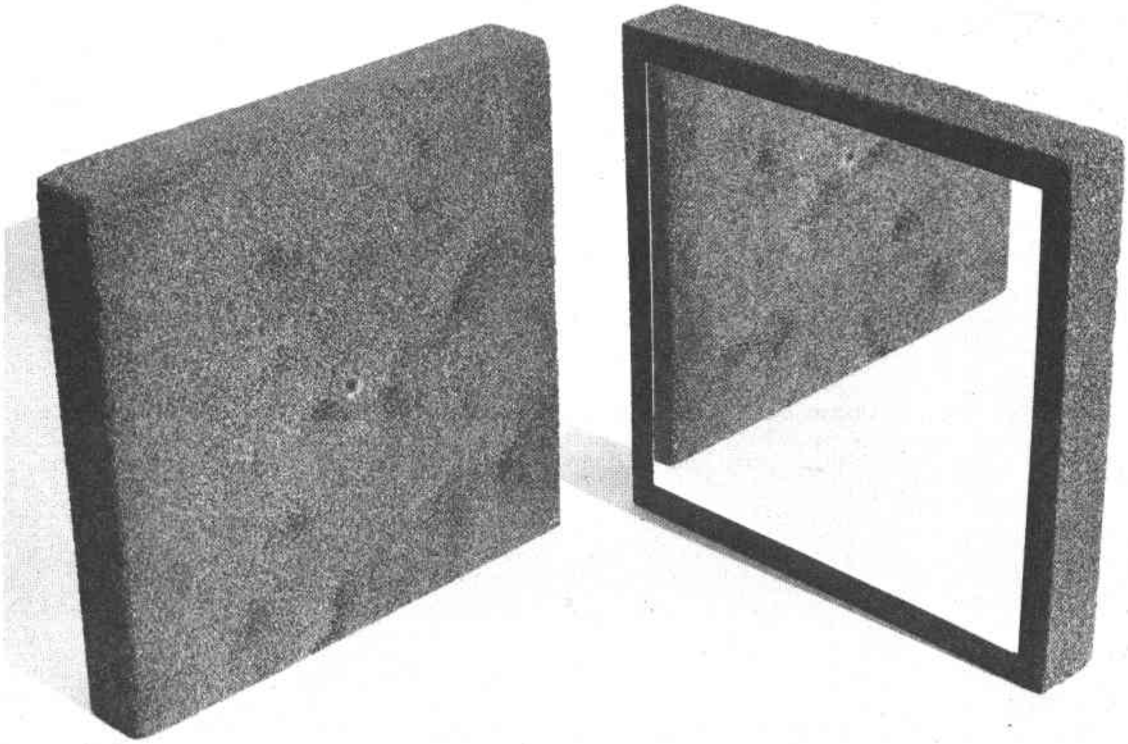


Figure 4-6. Early Development Mirror Facet

determines the life expectancy of the facets was also evaluated by statically loading test specimens to different stress levels and noting the time to failure. Figure 4-7 is a presentation of the results of this testing. Wind velocity and facet bending stress are correlated in this figure for the specific facet design being reviewed. A survey of wind velocities at the installation site and these test results indicate a more than adequate life expectancy for the facet.

An investigation was made of readily available materials which could best perform the functions required for the facet. This included the mirrors, the bonding adhesive for the mirrors and for the support tabs, and the sealing coating for the substrate and the edge of the mirror to substrate interface. Several candidates were reviewed for each function.

A composite test program was undertaken to select the combination to be used for fabrication. In addition to the important criterion of ease of workability an environmental test was used to screen the materials. A severe temperature-humidity cycling test was used, with demonstration of mechanical integrity of the materials combination as the primary purpose. This test cycle consisted of three cycles per day, two from 23°C to 65°C and one from 23°C to -13°C. Humidity was maintained at over 95% during the heating cycles and ice was formed on the mirrors during the freezing cycle.

The testing uncovered no mechanical degradation. However, after as few as 16 days, degradation of some mirror surfaces in the form of black speckles, began to occur and progressed over essentially the entire surface. The initiation of degradation and its degree of progression varied with the epoxy system used. Water was found over the entire interface between the mirror and Foamglas, apparently pumped through the edge seal during the test cycling. Hydrogen sulfide, which is the foaming gas in the Foamglas, in the presence of this water was suspected to be the cause. Preliminary testing to verify this was negative. However, more controlled tests on mirror samples in the laboratory have shown the sulfide anion is required for the reaction and that it is pH dependent. The most neutral material caused the slowest reaction. A test series, of mirrors fabricated with adhesive systems characterized by pH ranging from very basic to near neutral, is nearing completion. From the results of these tests an adhesive will be selected for fabrication of the facets.

The selection investigation has resulted in a facet design using the following materials.

Mirror - Corning 0317 glass silvered by Falconer Plate Glass

Substrate - 24 x 28 x 2 Foamglas High Load Bearing

Foamglas Sealer - Pittcote 404

Paint - Chemglaze, White

Edge Seal - Vulcum 116

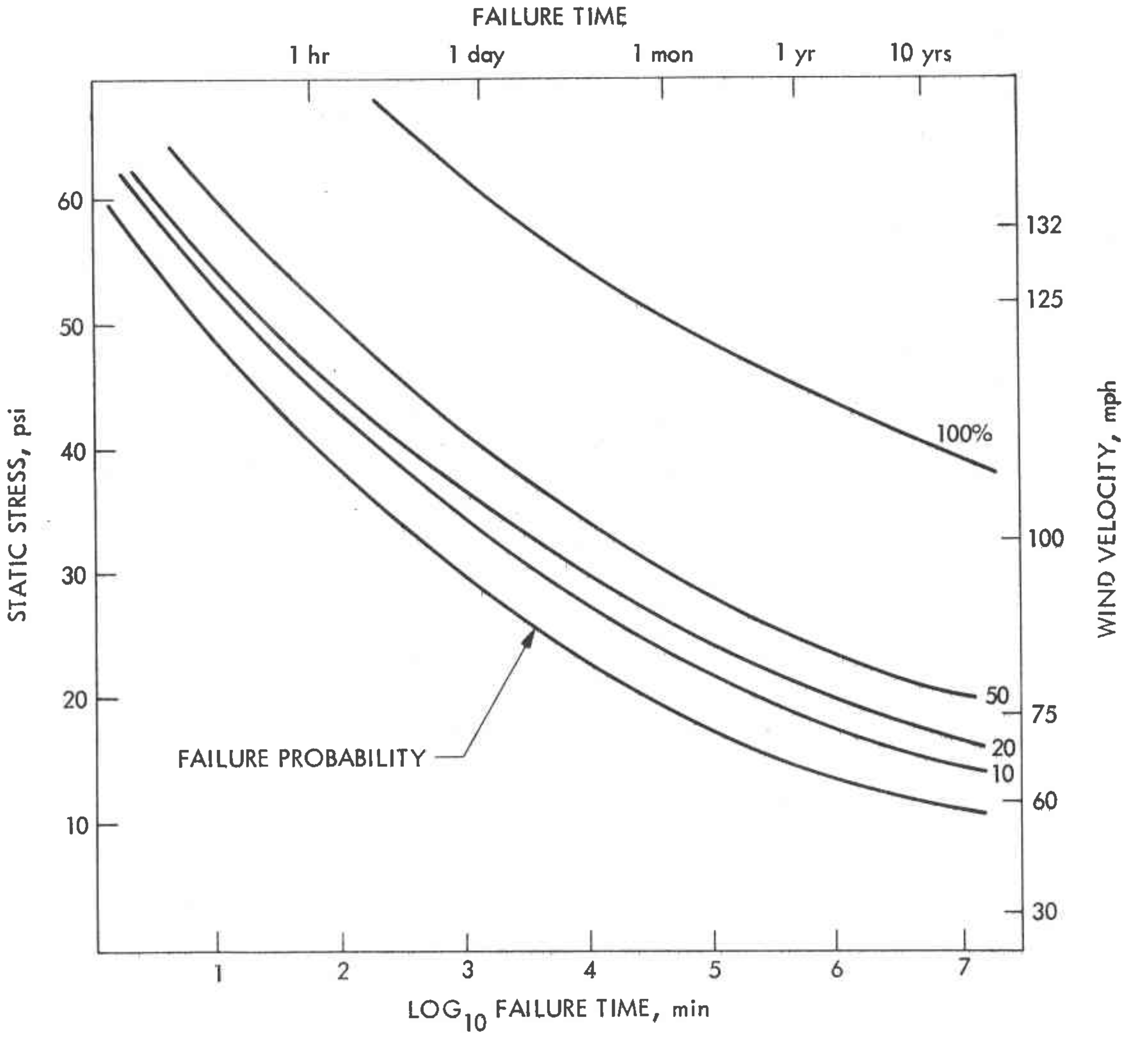


Figure 4-7. Foamglas High-Load-Bearing Static Fatigue Design Criteria

Mirror Adhesive - An epoxy system of near neutral pH, to be selected

Support Attachment Adhesive - PC88

Figure 4-8 shows a fabricated facet.

Hail is not expected to be a severe hazard at the Solar Thermal Test Site, however, tests were conducted with ice balls, to simulate hail, impacting the facet perpendicular to the surface. Balls 1-1/4, 1 inch and 3/4 inches in diameter were impacted on the mirror surface and 1-1/4 inch diameter balls were fired into the coated Foamglas back side. All tests were at approximately 60 mph. Figure 4-9 shows the effects. The 3/4 inch diameter ball caused no damage. Additional tests are planned with impact on the edge of the facet.

Mirror facets fabricated by the technique developed at JPL will be quite consistent in reflected image quality. However, a rapid optical test is desired to verify the acceptability of the mirror. Further, placement of the mirrors exhibiting the best quality at the outer locations on the concentrator will result in the best quality image spot.

A technique has been devised to determine rather quickly, the amount of light that is reflected from the mirror that passes through an aperture of a prescribed size. A threshold value will be set for mirror acceptability and the improvement over threshold will be logged as a rating for each mirror. Mirrors will then be grouped according to this rating.

The basic technique is also adaptable to determining the distribution of slope error on the mirror. For our case, disks of varying sizes determined by the calculated aperture size of cones of 1 to 6 minutes (0.29 mr to 1.74 mr) slope error will be mounted sequentially on the optical axis of the system. Each disk will block out all light from points on the mirror with slope errors less than that for which the disk is sized. Thus, a photograph of the lighted image will show the area with slope errors greater than the error represented by the disk diameter.

A photograph of the lighted image can be processed by computer or other means to determine the percent of the area which is of lesser quality than the referenced slope error.

By using this technique with a range of slope error disks, a plot of slope error versus area can be generated. This information will be generated for samples from each mirror grouping and will be used in making a better prediction of the Test Bed Concentrator performance. It is a time consuming and costly technique and is not planned for use on each individual facet. Figure 4-10 illustrates an image pattern for a mirror using disks sized for 1 minute (0.29 mr) through 6 minute (1.74 mr) slope errors. The lighted positions of the image represent areas of quality less than the value noted on the photo.

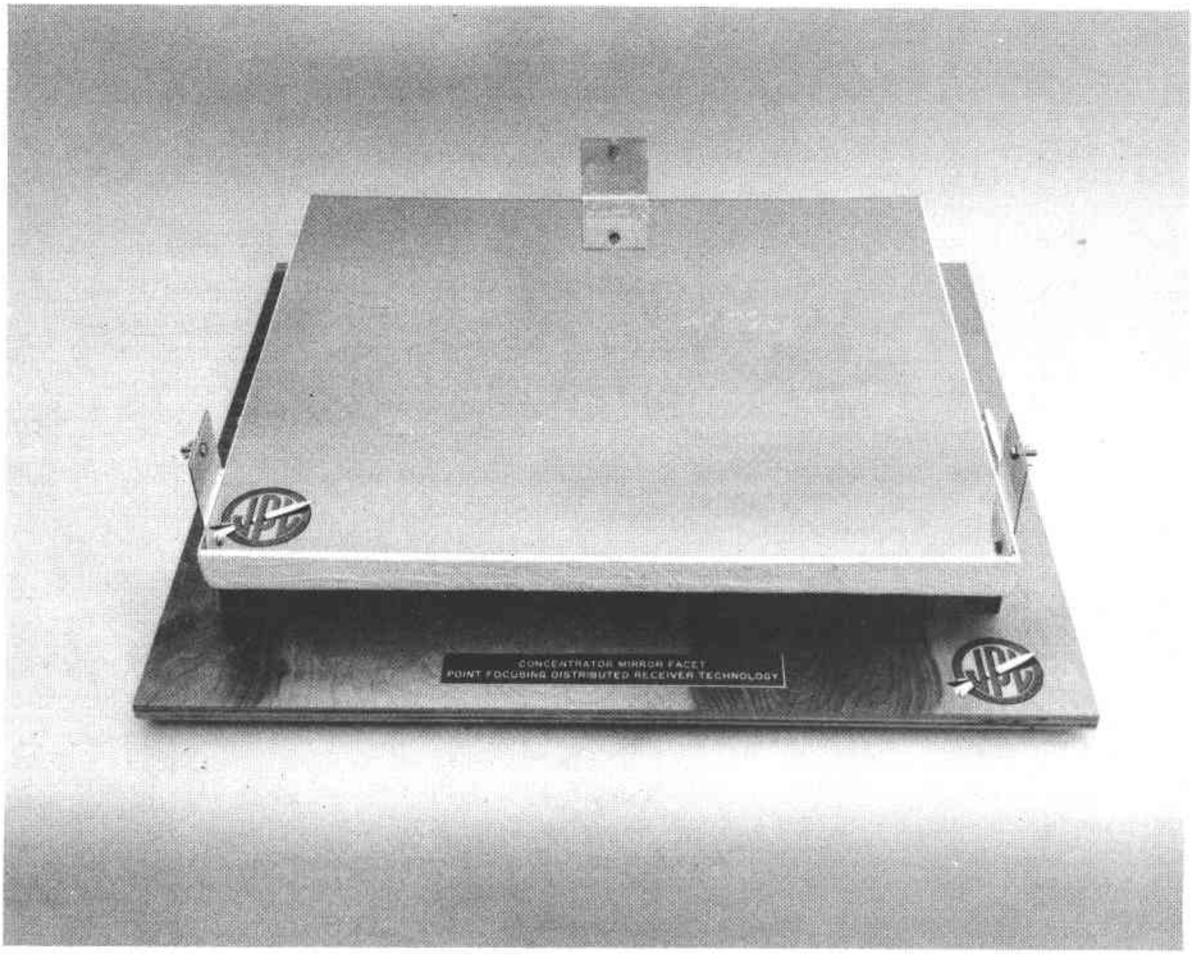
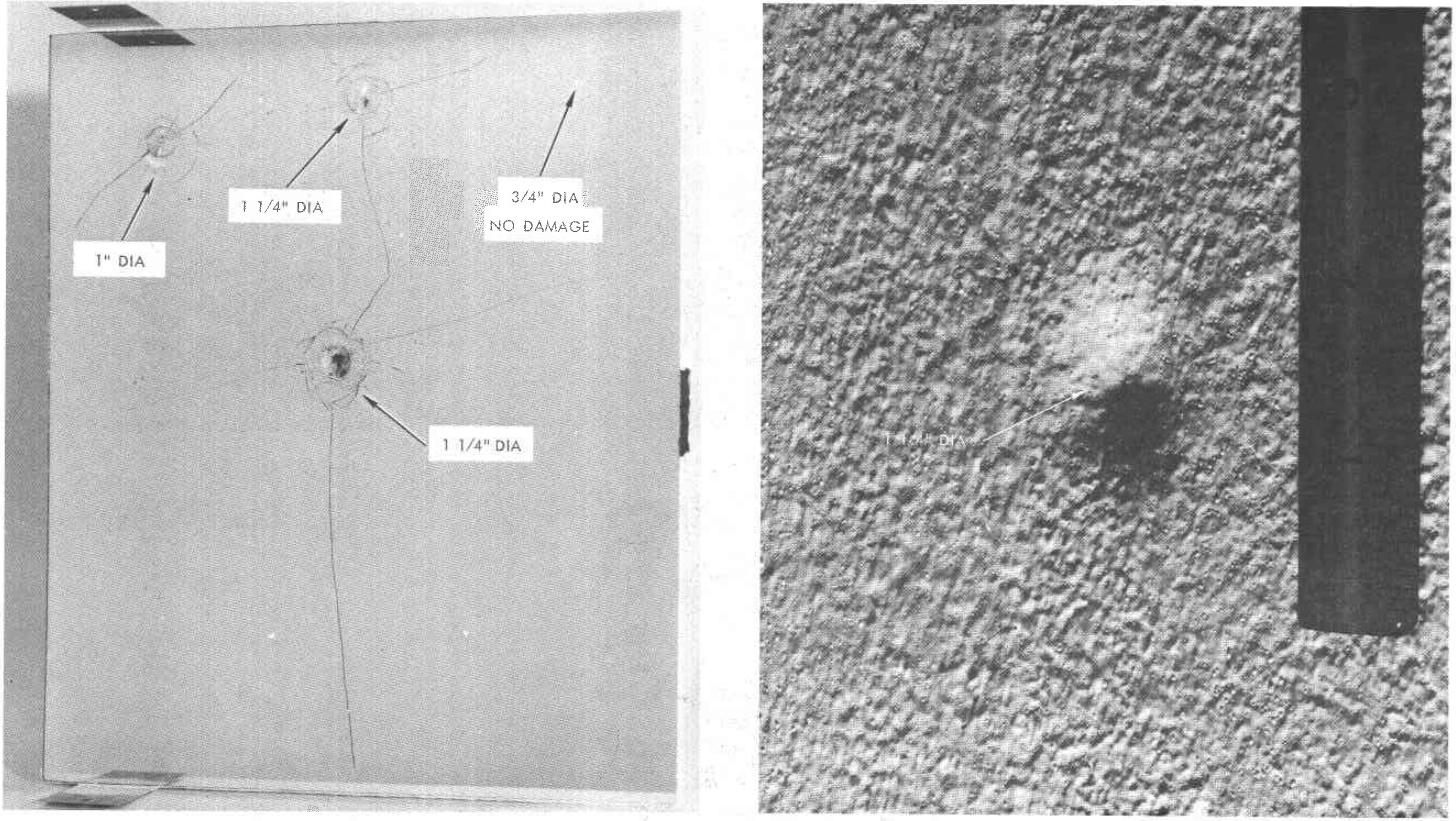


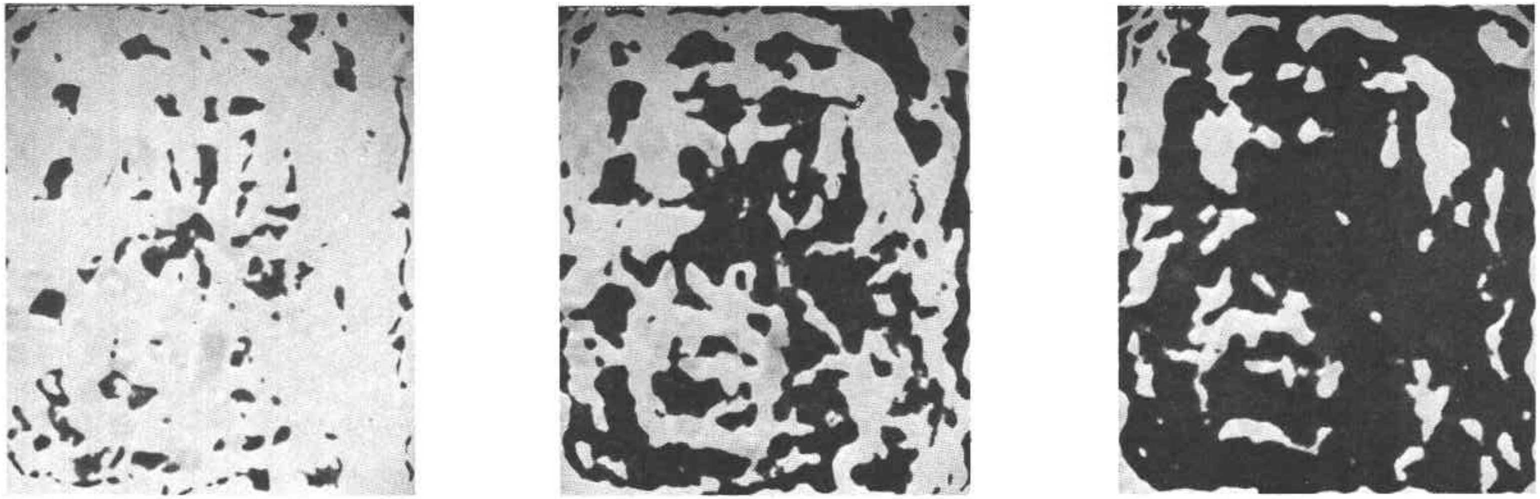
Figure 4-8. 24" x 28" Mirror Facet Foamglas Substrate



FACET MIRROR FRONT

FACET BACK

Figure 4-9. Results of Hail Tests (Velocity of 60 mph)



<1' (0.29 mr)

< 2' (0.58 mr)

<3' (0.87 mr)

<4' (1.16 mr)

<5' (1.45 mr)

<6' (1.74 mr)

Figure 4-10. Distribution of Scope Error on a Typical Facet (Lighted area has scope errors greator than magnitude given)

J. LOW-COST CONCENTRATOR

The dominant thrust of the Concentrator Development Task is to develop through industry, by contract, technology and designs that will result in low cost and high performance concentrators. Economically feasible solar thermal systems are only possible through the development of concentrators having a high kW thermal/$ ratio. An initial cost target of 4 to 12 kWt/$1000 was selected for the first generation Low-Cost Concentrators.

A three phased procurement was conceived to design, develop, fabricate and install, at the Solar Thermal Test Site, paraboloidal point-focus concentrators that could provide high thermal flux to a receiver operating at 1500°F, supplying thermal energy to power a Brayton engine/generator in a solar thermal electric test module.

Three contractors are participating in the Phase I effort. Each will optimize the design parameters for its individual concepts, to give the maximum predicted kWt/$. A preliminary design will then be made using these parameters. Phase I will last five months and is being performed under fixed price contracts.

At the completion of Phase I, the three contractors will submit proposals for Phase II and III, which will include the detail design, fabrication, installation, and acceptance testing. It is estimated that it will require 18 months to complete these combined efforts. One of the Phase I contractors will be selected to continue the development of its concept through the acceptance testing of up to six concentrators at the Solar Thermal Test Site. These units would be prototypes, but, in particular, the reflector surfaces and optical properties are to be representative of what can be expected when mass produced.

The concentrators will be tested for performance and study of the maintenance and cleaning requirements. They will then be utilized as development tools for testing receivers and engines, and for total system operation and performance evaluation. In addition to hardware, the contractor will provide predictions, updated in each phase, of concentrator costs when mass produced. They will investigate the changes to the design parameters which have potential for improving the kWt/$ ratio.

The original program as described in the RFP had three phases. Phase I, already described. Phase II, 9 months duration, involved two contractors selected to continue their detail design concepts and the required fabrication tooling. Phase III, 15 months duration, one contractor fabricating, installing, and acceptance testing at the Solar Thermal Test Site. It is estimated the original three phase plan would have lasted 10 months longer than the present plan due to less efficient operation and additional procurement between Phases II and III.

The RFP for Phase I was issued on 19 May 1978 and sent to 80 potential contractors, most of whom had responded to a Commerce Business Daily notice. The RFP stated that small business was to be awarded at least one of the three contracts. If no small business proposals were ranked in the top three, one of the top three would be replaced by a small business proposal which was evaluated as acceptable. Twelve proposals, including nine from small business, were received. Since the total program value to the contractor who performs all three phases is estimated to be over 1 million dollars, the proposals were evaluated by JPL's Source Evaluation Board process. Contractors selected for Phase I are the Acurex Corporation (a small business) Boeing Engineering and Construction, and General Electric Company (contracts executed September 15).

The Acurex Concentrator concept, Figure 4-11, is based on a faceted compressed paraboloidal reflector. The reflector is made up of a number of triangular facets which are independently mounted on a triangular frame and focus at a common point. The array of facets does not form a continuous parabolic surface, but is stepped to reduce the depth of the reflector, representing portions of 3 paraboloids of different focal length. The reflector tracks the sun with a conventional two-axis tracker which controls a hydraulic drive system. Two hydraulic motors allow the concentrator to rotate about a pivot on a wide-base circular track. The reflector structure is hinged at the base and is elevated by a hydraulic cylinder. This design allows the reflector surface to be stored in a horizontal position. The reflector panels will be designed for light weight; the base-line calls for honeycomb sandwich panels with a metallized plastic film for the reflective surface.

In the Boeing concept, Figure 4-12, the critical components are housed within an inflated plastic enclosure for protection from the elements. The air supported transparent enclosure protects the solar concentrator, plus the solar receiver, heat engines, and electric generator, from all environmental loads, thereby permitting the use of lightweight, less costly internal structures. Laboratory and field tests for solar, wind, and hail resistance indicate that the enclosures will have a service life in excess of 15 years.

In this concept, the benign environment permits the use of a thin aluminized polyester film as the parabolic solar concentrator. The final parabolic contour is obtained by applying a slight pneumatic pressure (0.01 psi) to the reflecting surface. Air used in the power conversion system is drawn into the enclosure and exhausted through ducts. The reflector tracking of the sun is by azimuth and elevation motions controlled by a computer-generated ephemeris.

The General Electric concept, Figure 4-13, utilizes a reflector constructed of petals attached around a central hub. General Electric's approach is to form the segments of the dish by injection molding structural plastic. The design freedom inherent in the molding of plastics enables integral structural ribs and stringers, attachment points and alignment pins to be readily formed in one automated process. Further, low-cost reflective surfaces can be molded into the part, thus eliminating the labor intensive reflector application step. Since the plastic part will replicate the mold with high accuracy, the optical quality of the paraboloid can be made very high.

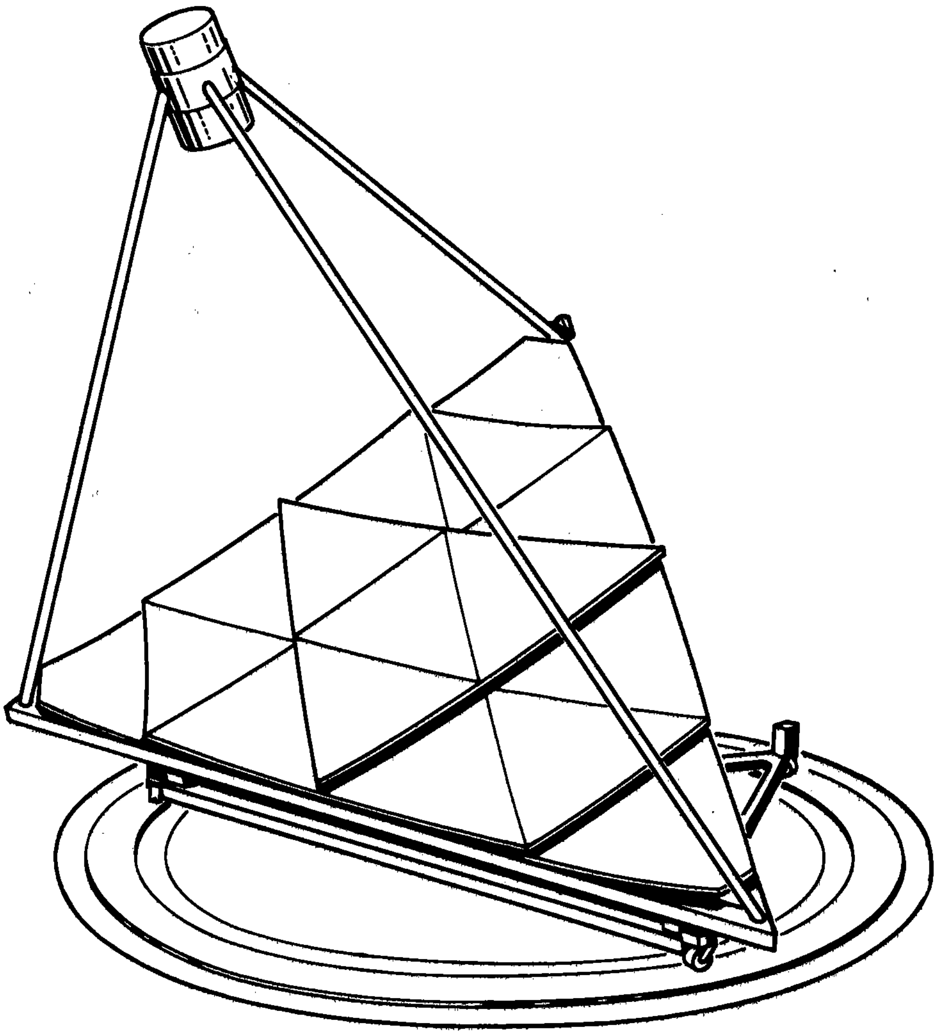


Figure 4-11. Acurex Concept

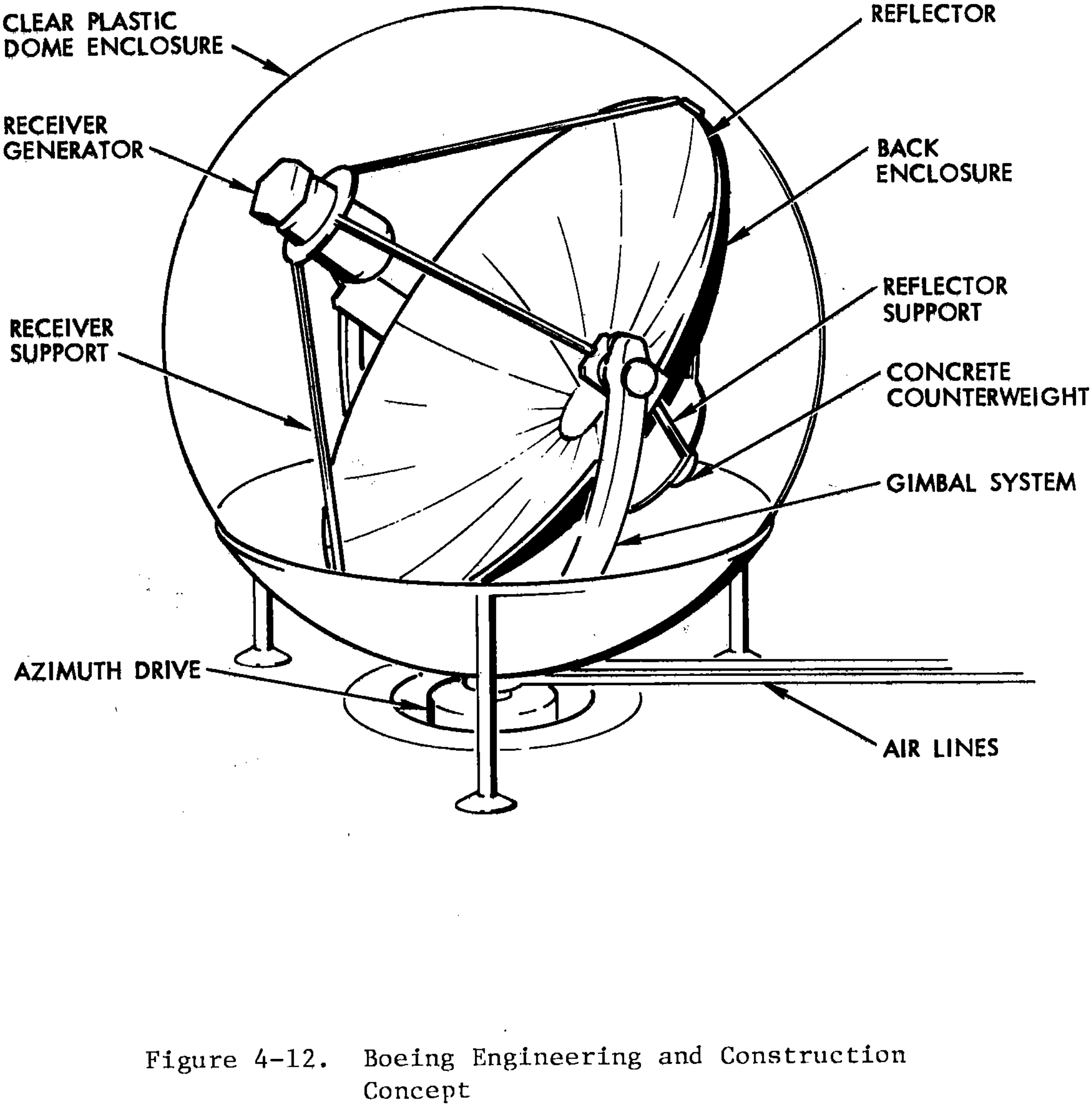


Figure 4-12. Boeing Engineering and Construction Concept

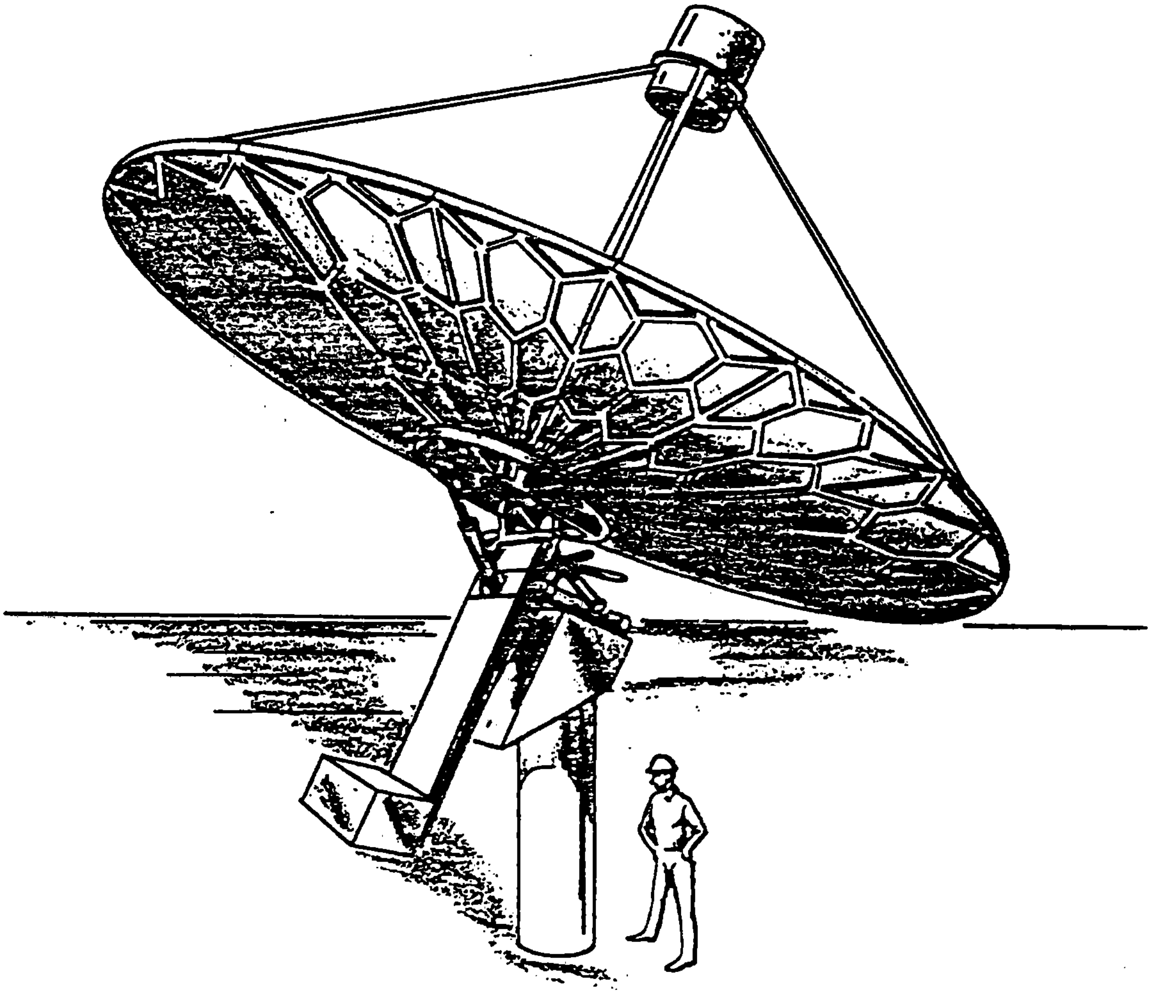


Figure 4-13. General Electric Concept

The reflector is mounted on an equitorial mount on top of a pedestal. A two-axis solar tracker system controls the screw jacks which steer the concentrator. The concentrator stows at -15° elevation.

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SECTION V

RECEIVER DEVELOPMENT

A. INTRODUCTION

The solar receiver is a key element in the chain of processes to convert sunlight to electricity. In the receiver, the radiant energy of the sun is converted to useful thermal energy. In this central position, the receiver not only serves as the energy converter but links the concentrator and power conversion unit into an efficient total system.

The initial thrust of the receiver project was to have industry move out on the design of both steam Rankine and open cycle air Brayton receivers. Contracts were let for conceptual designs and plans made for prototype fabrication in the future. Early results from the design contracts indicate that efficient, cost effective receivers are now within the state-of-the-art.

B. OBJECTIVES

The basic objective of the receiver development task is to provide efficient, cost effective receivers as required. Preliminary cost and performance targets have been set for point-focusing systems and are shown in Table 5-1.

Table 5-1. Receiver Development Targets

Target for FY	1982	1985
Cost in Mass Production	\$30/kWe	\$20/kWe
Efficiency	80%	85%

Implied in these targets is not just a maximized subsystem efficiency but a total system compatibility; that is, the combined concentrator, receiver, and power conversion unit together must be optimized to achieve both low capital investment and competitive busbar energy costs.

C. APPROACH

The basic approach, consistent with other subsystem plans coordinated by the Systems Engineering Task, is to have a multi-phase development process beginning with conceptual designs and continuing through final design, prototype fabrication, and field testing. As the technology matures and develops, new types of receiver systems will be introduced into the development process. All actual development work, design and prototype fabrication will be carried out by industrial contractors. When a design is fully characterized technically and economically, the subsystem will be transfered to an applications project to be considered for inclusion in their future programs.

Currently, six conceptual receiver design contracts are in progress. Four are for gas receivers suitable for an open cycle air Brayton system with an 800°C (1500°F) turbine inlet temperature. The remaining two are for steam receivers, once through to superheated steam at 540°C (1000°F) and up to 14 MPa (2000 psi) pressure. On completion of these conceptual designs, contracts for one Brayton and one Rankine receiver will be continued through final design and the fabrication of a prototype unit. These receivers will be installed on the Test Bed Concentrator with the 15 kWe engines from the Lewis Research Center work at the Solar Thermal Test Site (STTS). A test program will fully characterize their operation technically and economically. Special attention will be paid to installation, operation and maintenance costs, areas in which empirical data is largely missing.

As the technology develops, higher performance types of receivers such as the second generation types from the ASTT project will be developed in a similar fashion. Figure 5-1 shows this progression and the current five-year schedule for development.

D. CONTRACTING PROGRESS

Early in the fiscal year, preparations were begun to issue Requests for Proposal (RFP) for the conceptual design of both steam Rankine and air Brayton receivers. Initial work concentrated on the production of Statements of Work (SOW) and on producing both procurement plans. By December of 1977, both documents were completed.

The salient features of the SOWs included: 1) a parametric analysis of the receiver(s) proposed by the vendor; 2) a final conceptual design; 3) examination of important interface requirements with other subsystems; 4) estimation of costs to produce the receiver as a function of quantity; 5) submission of a Phase II proposal to complete a production design and fabricate one prototype unit; and 6) to adequately report and document the entire project. It was intended to let three contracts each for the Rankine and Brayton systems which would be narrowed down to one each for the Phase II effort.

Concurrent with these activities, a notice of the procurement action was prepared for publication in the Commerce Business Daily (CBD) and a suitable bidder's list was collected. The original bidder list consisted of 44 companies known to be interested in solar thermal work.

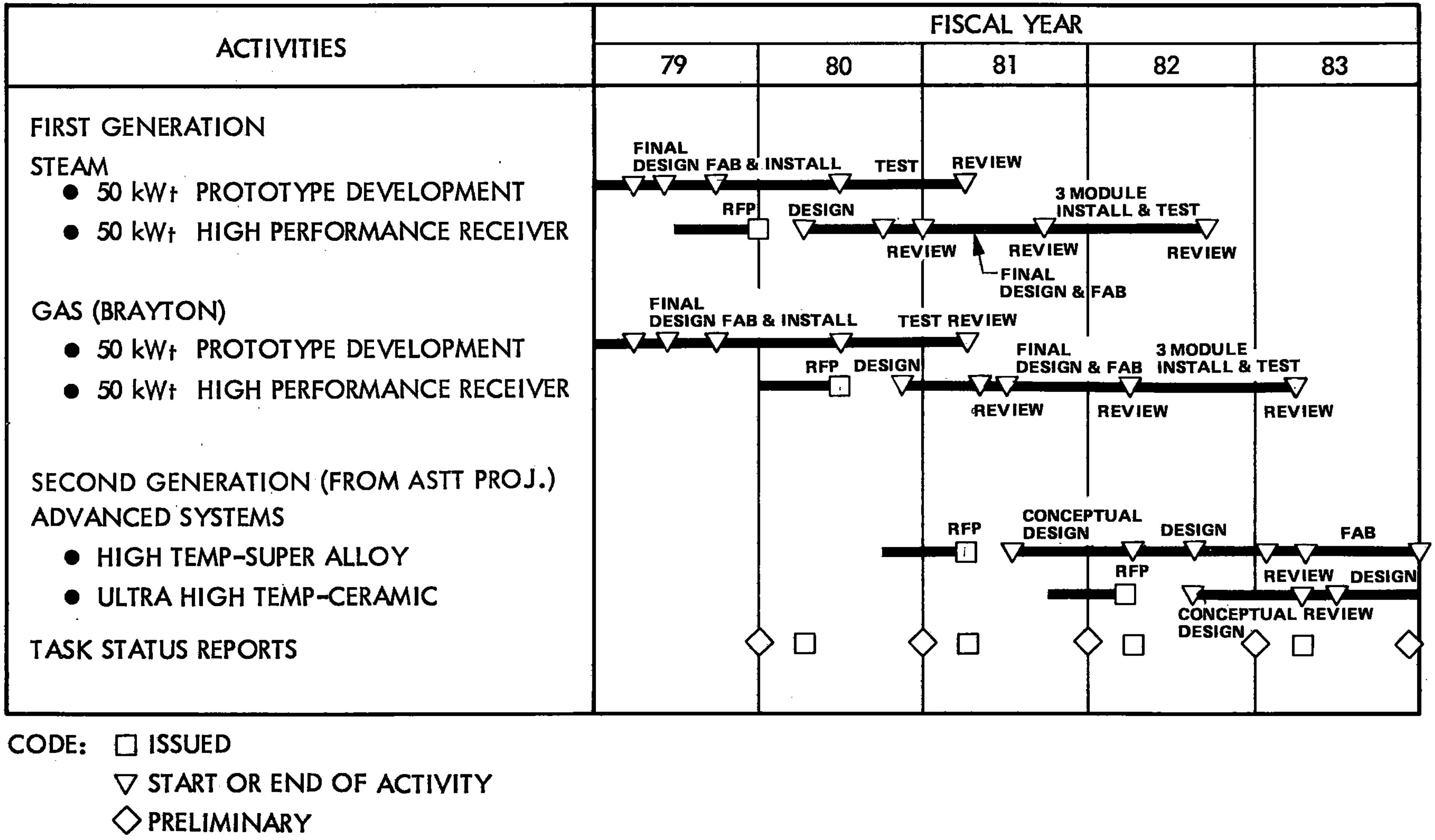


Figure 5-1. Five-Year Receiver Development Milestones

After a thorough internal review at DOE Headquarters and at JPL, the notice was published in the CBD. About 40 responses to this notice were received. In addition, several companies which had not responded to the notice requested inclusion on the bidders list so that when the RFP's were issued in February, a total of 76 were sent out.

The proposal return date was March 3, 1977. During the proposal production period, several addenda in response to questions by the potential vendors were issued. On the return date, nine proposals were submitted, five for the Brayton and four for the Rankine systems.

Two proposal review teams, one for Brayton, one for Rankine, had been organized and were prepared to begin the review as soon as the proposals were logged-in. Each team was made up of technical and contracts experts drawn not only from the PFDR technology project but from various other JPL groups to insure a wide range of expertise and experience. Initial reviews were completed within two weeks.

On comparing these early review reports, it was evident that there was a wide spread in the quality of the proposals. The Brayton proposals were in general all very good but the Rankine proposals had an extremely wide breadth ranging from excellent to unacceptable. The Project, on reviewing this information, coupled with a developing programmatic emphasis on systems having the greatest long term potential, elected to amend the Procurement Plan to issue four Brayton and two Rankine conceptual design contracts rather than the original three and three.

After all information had been collected and final evaluations completed, the names of the successful potential vendors were announced. They were: For the Brayton system: 1) Garrett AiResearch, Los Angeles, CA; 2) Sanders Associates, Nashua, N.H.; 3) Boeing Engineering and Construction, Seattle, Washington; and 4) Dynatherm Corporation; Cockeysville, MD. For the Rankine system: 1) Fairchild Stratos, Manhattan Beach, CA; and 2) Garrett AiResearch, Los Angeles, CA. The Brayton contracts all began on July 6, 1978 and the Rankine contracts on July 27, 1978.

All of the receivers proposed by the contractors were cylindrical cavities but varied greatly in design concept. Since some of the contractors elected to examine more than one conceptual design, a total of 12 designs was looked at initially. These are listed in Table 5-2. The various basic conceptual designs are outlined in Figures 5-2 and 5-3. Each contractor completed a Task 1 parametric (see Table 5-3) design study in September, 1978 after which, they began their final conceptual design and costing tasks. These will be complete early in Fiscal Year 1979. By the end of the second quarter, the contracts to complete a final design and fabricate a prototype receiver will be given to two of these companies.

Table 5-2. Proposed Receiver Designs

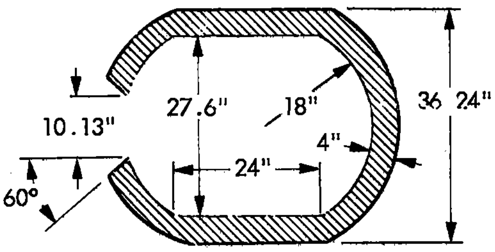
Brayton Receivers - 1500°F - Open Cycle Air

1. Garrett AiResearch, Los Angeles, CA
    - a) Plate fin
    - b) Tubular-1 pass
    - c) Tubular-2 pass
2. Boeing Eng. & Const., Seattle, Washington
    - a) Conical
    - b) Tubular
3. Sanders Associates, Nashua, N. Hamp.
    - a) Ceramic core
    - b) Tubular
4. Dynatherm Corp., Cockeysville, MD
    - a) Heat pipe
    - b) Tubular

Rankine Steam Receivers - 1000-1200°F Steam

1. Garrett, Los Angeles, CA
    - a) Tubular
    - b) Tubular w/steam drum
2. Fairchild Stratos, Manhattan Beach, CA
    - a) Coil

GARRETT PLATE FIN DESIGN



CAPACITY: 62 kWth

WEIGHT: 325 lbs WITH INSULATION

MATERIAL: HASTELLOY

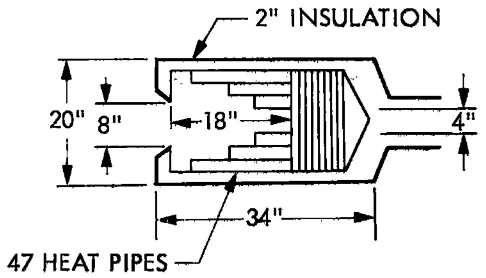
INSULATION: MIN-K 2000

STORAGE TYPE: INTEGRAL OR SEPARATE MOLTEN SALT (NaCl)

WEIGHT OF STORAGE: 325 lbs

THERMAL EFFICIENCY: 84%

DYNATHERM CORP.



CAPACITY: 100 kWth

WEIGHT: 700 lbs INCLUDING STORAGE

MATERIAL: STAINLESS STEEL OR SUPERALLOY

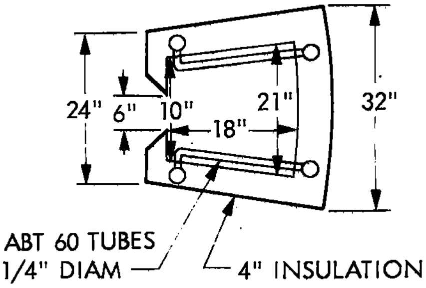
INSULATION: NOT SPECIFIED

STORAGE TYPE: INTEGRAL MOLTEN SALT (LiF/NaF/MgF)

WEIGHT OF STORAGE: INCLUDED IN ABOVE

THERMAL EFFICIENCY: 95%

BOEING ENG AND CONST.



CAPACITY: 90 kWth

WEIGHT: 300 lbs

MATERIAL: INCONEL 617

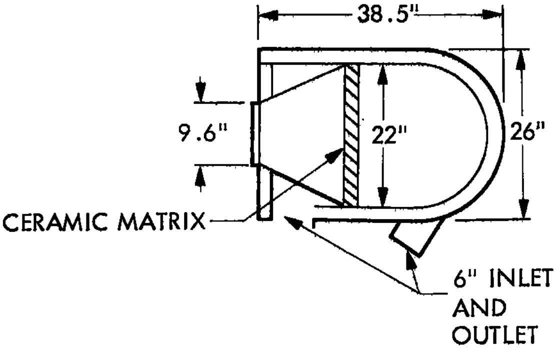
INSULATION: KAOWOOL BLANKET AND BLOCK

STORAGE TYPE: ① SENSIBLE HEAT IN REFRACTORY SPHERES OR
② BATTERY

WEIGHT OF STORAGE: ① 1000 lbs
② 50 lbs

THERMAL EFFICIENCY: 87.4% (NOT COUNTING SPILLAGE)
77.8% WITH 11% SPILLAGE

SANDERS ASSOCIATES



CAPACITY: 80 kWth

WEIGHT: 150 lbs

MATERIAL: STAINLESS STEEL

INSULATION: THERMO 12

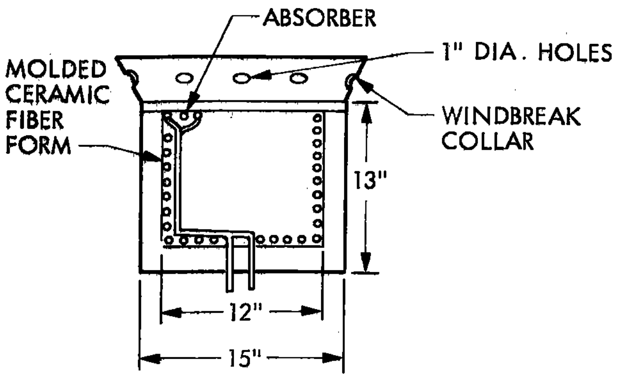
STORAGE TYPE: SEPARATE SENSIBLE HEAT IN REFRACTORY BLOCKS

WEIGHT OF STORAGE: 300 lbs

THERMAL EFFICIENCY: 86%

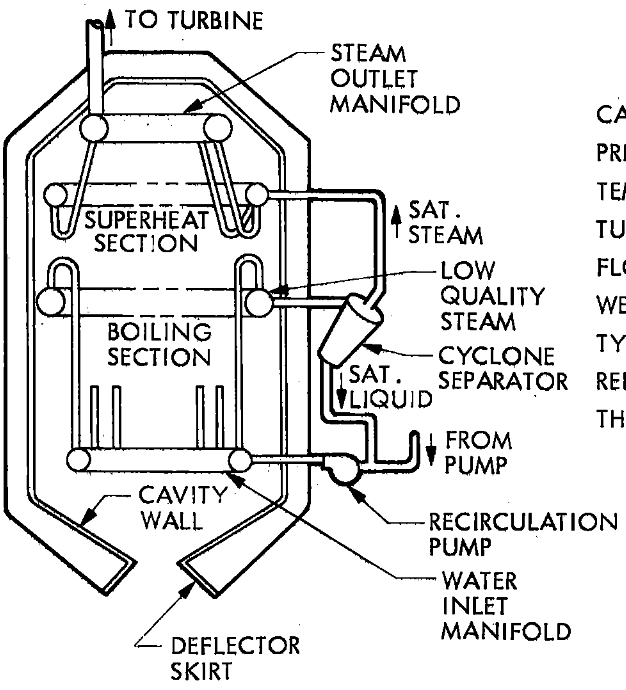
Figure 5-2. Proposed Brayton Receiver Designs

FAIRCHILD STRATOS



CAPACITY: 90 kWth
PRESSURE: 1500 psi
TEMPERATURE: 1200°F
TUBE MATERIAL: STAINLESS STEEL
FLOW RATE: 2.5 lbs/hr kWth
WEIGHT: 75 lbs
TYPE: ONCE THROUGH TO SUPERHEAT
REHEAT CAPABILITY: WITH MINOR MODS
THERMAL EFFICIENCY: 80-90%

GARRETT AIRESEARCH



CAPACITY: 50-90 kWth
PRESSURE: 1500 psi
TEMPERATURE: 1200°F
TUBE MATERIAL: STAINLESS STEEL
FLOW RATE: 2.5 lbs/hr kWth
WEIGHT: 200 lbs
TYPE: SEPARATE BOILER/SUPERHEATER
REHEAT CAPABILITY: WITH MINOR MODS
THERMAL EFFICIENCY: 80-90%

Figure 5-3. Proposed Steam Receiver Designs

Table 5-3. Variables for the Parametric Analyses

I. For the Open Cycle Air Brayton Systems:

a) Peak Thermal Power Input (I_o) - 50, 90, 150 kWt
b) Fluid Outlet Temperature (T_o) - 1000, 1300, 1500, 1600°F
c) Fluid Inlet Temperature (T_I) - 800, 1000, 1100, 1200°F
d) Fluid Flow Rates (F) - 0, 0.004, 0.008, 0.012, 0.016 #/sec/kWt
e) Fluid Inlet Pressure (P_{in}) - 30, 45, 60, 75 psig

Dependent variables to be calculated include but are not limited to:

f) Efficiency (η) - %
g) Pressure Drop (ΔP) - psi (not to exceed 5% of P_{in})
h) Maximum Cavity Temperature (T_{max}) - °F

II. For the Steam Rankine Systems:

Baseline

a) Peak Thermal Power Input (I_o) - 30, 80, 130 kWt
b) Fluid Outlet Temperature (T_o) - 1000, 1300°F
c) Fluid Outlet Pressure (P_o) - 500, 1250, 2000 psi
d) Fluid Flow Rate (F) - 2, 3 #/hr/kWt
e) Fluid Inlet Temp - 100, 400°F

Advanced

f) Baseline plus reheat - T_{in} = 550°F, Pres. = 250psi

Dependent variables to be calcuated include but are not limited to:

g) Thermal efficiency (η) - %

$$\text{Where: } \eta = \frac{\text{Heat energy into fluid}}{\text{Solar heat energy into cavity}}$$

h) Pressure drop (ΔP) - psi
j) Maximum Cavity Temp (T_{max}) - °F

F. IN-HOUSE PROGRESS

Along with the contractors' development of the conceptual receiver designs, a vigorous support program is being pursued in-house. This effort was established to insure that the technical, managerial, and cost benefits to be gained from the outside contracts are maximized.

A receiver design program was begun early in the year to provide information and data for the contract preparation. Both steam Rankine and air Brayton receivers were designed. Work included preparation of a fluid flow, heat transfer parametric analysis which was utilized to establish preliminary configurations. Materials selection was made after a stress analysis and structural design were completed. Capacities and sizes were varied to envelop possible PFDR modules. From these, the variables specified to be studied in Task 1 effort of the RFP were established.

Through the Design Team, overall technical coordination was established and is being maintained. Interfaces with the systems, concentrator, power conversion unit, manufacturing and test and evaluation groups were organized about mid-year. Frequent meetings were held, as often as weekly when needed, to insure that each element of the total effort was adequately coordinated.

The organization and methodology utilized by the Design Team was established to coordinate and communicate. It is not a problem solving group but attempts to detect, define and clarify Project requirements. Problems and necessary studies are assigned to knowledgeable sub-groups made up of Project and support personnel as required. Some of the principal activities of the Team are the development of all system requirements for the early hardware experiments. This has considerable impact on the receiver development program since the precursor concentrator and Omnium-G systems will produce the earliest empirical data on energy distribution into the receiver cavities. This also will offer the first opportunity to operate and test the instrumentation being developed to map the energy distribution at a concentrator focus.

Receiver design is greatly influenced by the geometrical distribution of the solar energy on the cavity interior surfaces. To better understand the distribution of energy at the focus of a concentrator, a Flux Mapper was designed to measure the concentrated energy in three dimensions. Figure 5-4 shows an overall view of the apparatus.

The development of the Flux Mapper is planned for two phases, the first (Mark I) to produce a system adequate for mapping the energy from the precursor and Omnium-G concentrators, the second (Mark II) to be expanded in size and data collection capability for future systems such as the Test Bed Concentrator and Low Cost Concentrator.

The construction of the Flux Mapper will utilize the lightest possible hardware to insure that it can be mounted on a variety of concentrators without affecting its balance. It will be of the "X-Y"

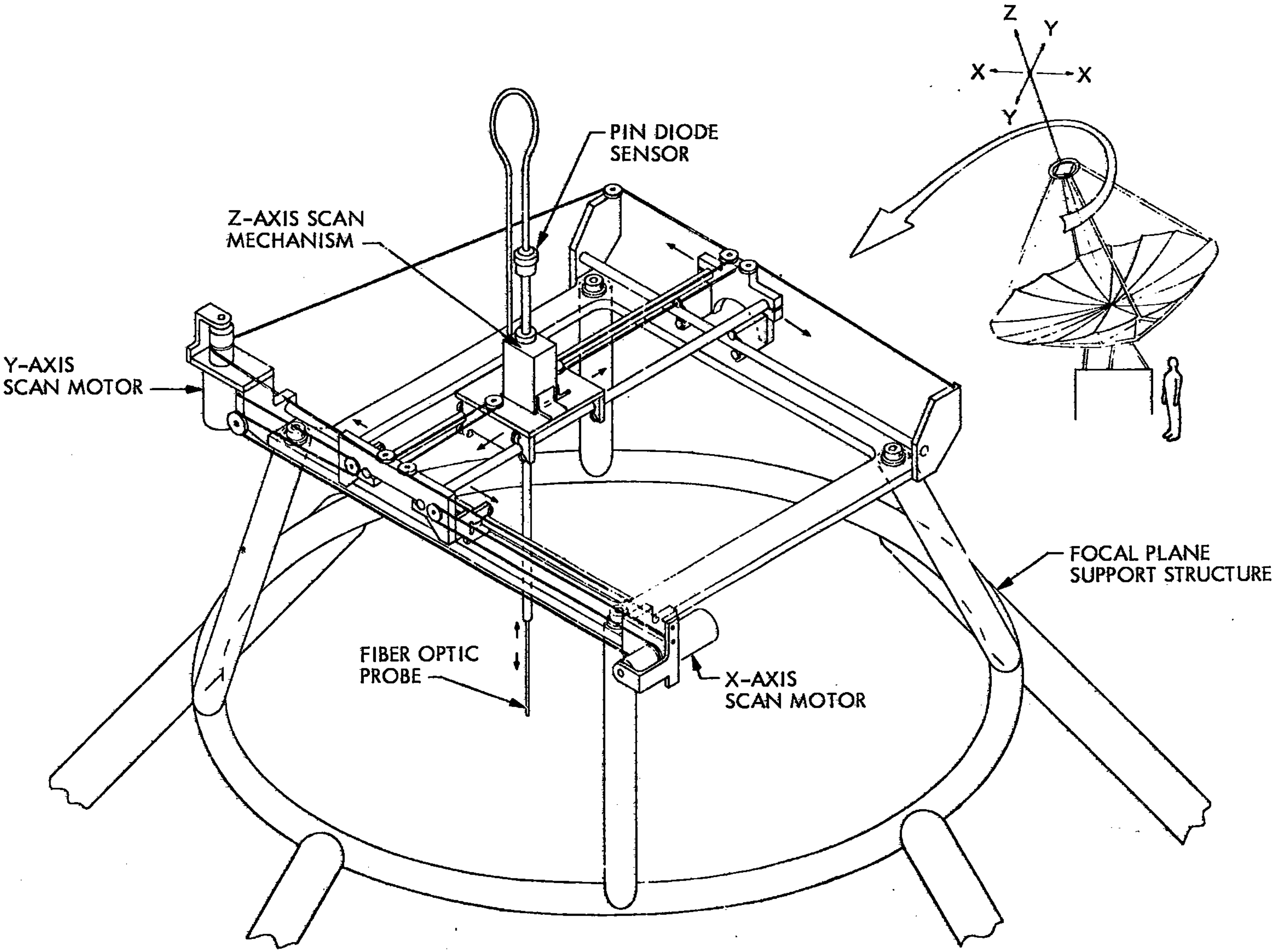


Figure 5-4. Solar Flux Mapper

scan type with a settable sensor along the Z-axis. It will have a cable drive for the "X-Y" scan portion and a rack and pinion drive for the Z-axis. It will be located at a distance of approximately 18 to 24 inches beyond the prime focus to avoid the high energy environment and will have a minimum of local heat shielding. All surfaces will be bright finish to minimize heat absorption.

The sensor will be a fast PIN diode type with absolute input reduced by an area ratio reduction through the use of fiber optics. The fibers will be area distributed throughout a sensing area of approximately one eighth inch diameter and have an irradiance attentuation of approximately 1000:1 to operate in concentration ratios of approximately 10000:1. The maximum expected image irradiance would be less than 1000 watts/cm^2.

The scan control will be operated with programmed stepping motors allowing a variable scan rate. Programming of the scanner will allow any type of pattern to be accomplished. Only simple programming is planned for Phase 1.

The Mark II version will be much the same in basic concept. The same sensor, PIN diode, will be utilized and the same mechanical drives. Differences are that the scanning distances will be larger to accommodate the larger focal zones expected. In addition, the data acquisition system will be improved to give a digital output suitable to be integrated with the computerized facility system which will be available at the STTS later.

The design and fabrication of the Mark I system was completed during the last fiscal quarter of the year. The Mark II system will be available about mid-FY 1979.

Another part of the in-house support program is the development of a suitable model of the receiver subsystem to permit computer simulation. Work on the model was begun about mid-year and will continue into the next fiscal year. The purpose of the model is twofold. It will serve as a development tool to optimize receiver efficiency by the better understanding of cavity dynamics and heat exchanger fluid flow. Its second use will be to help standardize the review of all receiver designs especially in the monitoring of outside design contracts.

Other activities during the year were mainly of a support nature. Liaison work during the formative months was particularly heavy. Within the Project, lines of communication with all other subsystems and support activities were established early in the year and are being maintained on a permanent basis. This has included the development of a close working relationship with Lewis Research Center personnel via telephone and datafax in addition to our monthly Design Team and review of written reports as well as attendance at major design reviews. For example, receiver task personnel attended the DOE Solar Thermal Central Power Systems Semi-Annual Reviews in San Diego, California in March and in Dallas, Texas in September.

SECTION VI

POWER CONVERSION DEVELOPMENT

A. INTRODUCTION

As part of the DOE/NASA Solar Thermal program, investigations of dispersed solar/electric power systems are being conducted by JPL and NASA-LeRC. Conceptual design studies are being generated on each of the major components and systems to determine the economics of Rankine and Brayton solar power systems. Such systems are characterized by a single point-focusing paraboloidal concentrator, matching receiver, at the focal point and a power conversion unit. Figure 6-1 shows an artist's view of a typical small Brayton cycle power conversion unit (15 kWe) mounted on top of a receiver that is, in turn, supported at the concentrator focal point.

Following the conceptual design studies it is expected that selected design configurations will be chosen for each conversion cycle followed by a design, fabrication, and test phase. This is illustrated in the schedule shown in Figure 6-2 for the steam Rankine cycle engine. A similar schedule was prepared for the Brayton cycle engine; however, that portion of the project was transferred to the Advanced Solar Thermal Technology Project by direction of DOE/SOLAR in May 1978.

B. OBJECTIVES

Within the overall joint DOE/NASA Solar Thermal program, LeRC specific objectives are to investigate the technical and economic characteristics of a variety of candidate small Rankine and Brayton power conversion systems. Such systems shall be suitable for use with single, point-focus solar concentrators and receivers. During the course of the investigation the estimated performance and projected life cycle costs thus determined will assist in determining which of the systems are economically viable and where they are competitive in future energy markets.

The specific objective of the power conversion technology task is to establish the technology readiness of efficient and cost-effective subsystems to convert thermal energy into electrical energy. The targets for the first generation power conversion subsystems are conversion efficiency of 25%-35% by 1982 and for the second generation 35%-45% by 1985. The Modification-0 conversion subsystems are for use with the Test Bed Concentrators (TBC), the Modification-1 subsystems are for the Low-Cost Concentrators which will be available later than the TBCs and may be a different size than the TBCs. Target efficiency for Modification-0 is at the low end of the range of first generation targets while that for Modification-1 is at the high end of the range for the first generation targets. If engines of high efficiency can be mass produced it is hoped that the mass-produced cost could be targeted around $60-$75 per electric kilowatt.

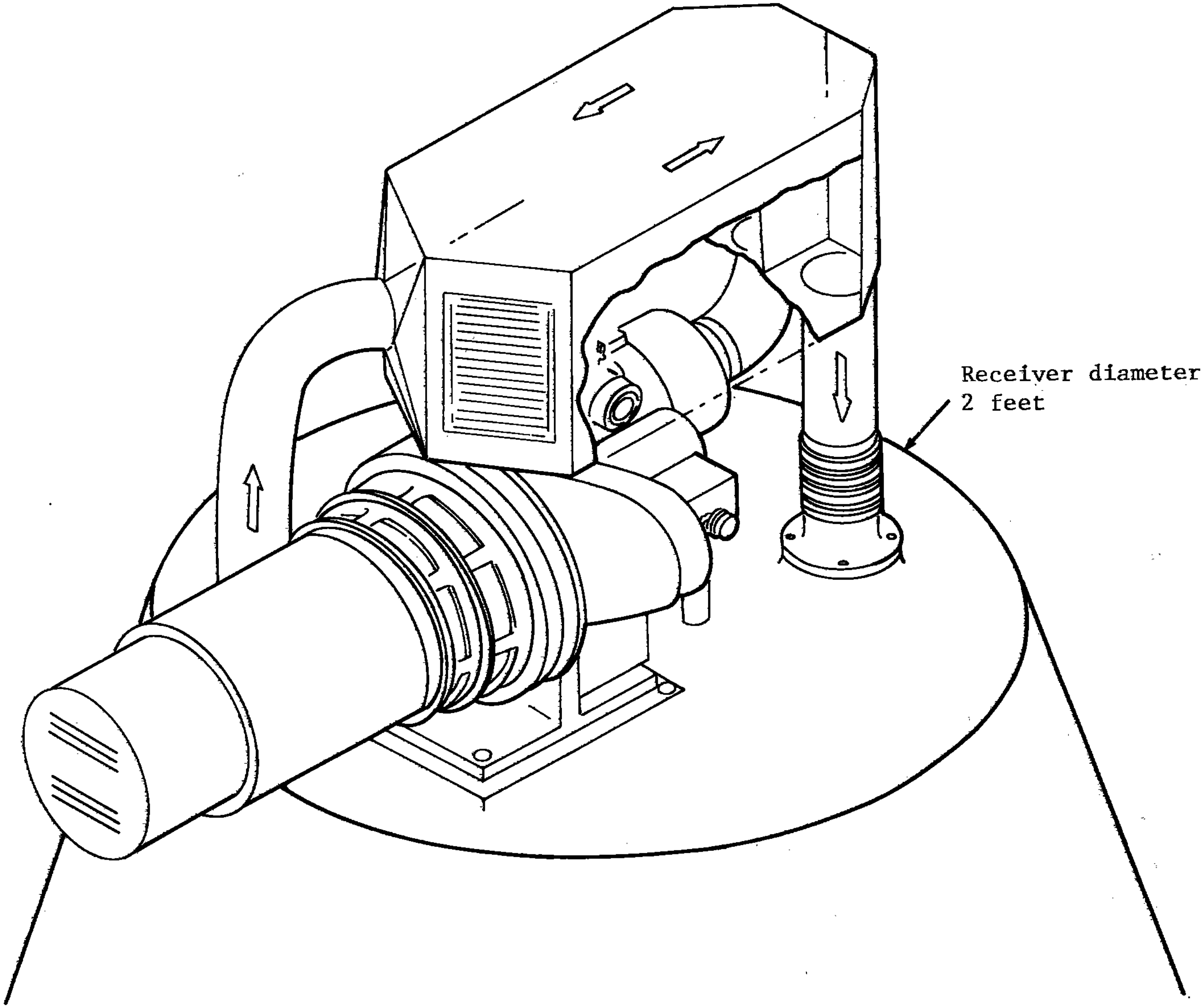


Figure 6-1. Solar Brayton Engine Generator Set ,

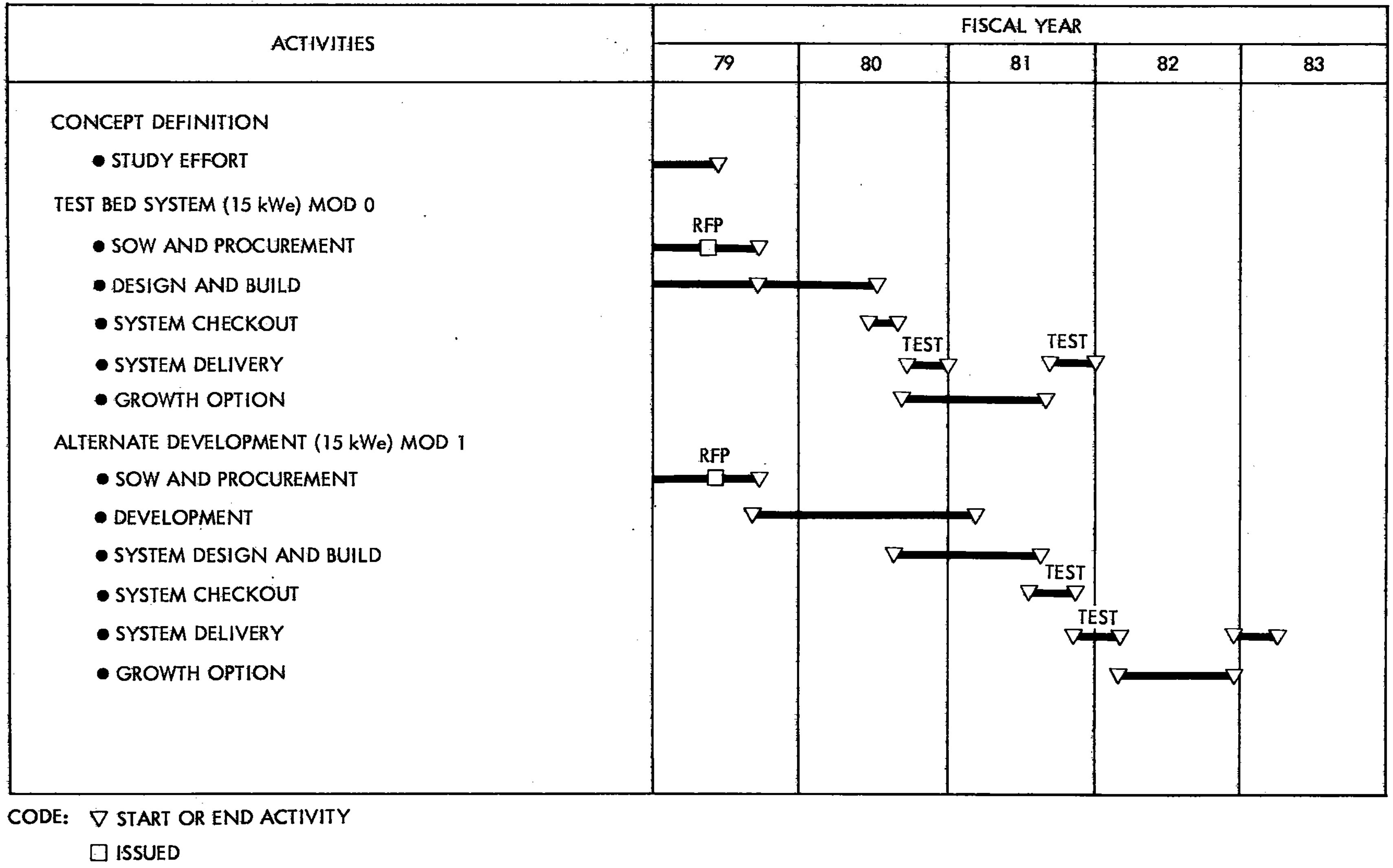


Figure 6-2. Five-Year Steam Rankine Power Conversion Schedule

C. APPROACH

1. Determination of the State-of-the-Art

From an in-depth expertise in power generation and conversion systems in the aircraft, space power, utility and automotive fields, the LeRC has charted a number of Rankine and Brayton solar thermal systems as the basis for studies and experimental investigations of performance.

2. In-House Engine Cycle Analyses

In the LeRC approach to investigation of the candidate power conversion systems,a balanced effort of in-house analyses is maintained to support and direct effort contracted with industry. A number of in-house Brayton cycle and Rankine cycle computer programs and modifications of them are used in this analytical support activity. As power conversion system and component test data become available, they will be correlated with the appropriate predicted performance analysis and the disparities, if any, resolved.

3. Conceptual Design Studies Test Hardware

As noted in the above paragraph,the LeRC in-house program is being complemented by contracted effort with industry. The first in the contract series will be a contract to provide a concept definition study of small (15 kWe: an approximate value, used throughout this report) Brayton cycle and steam Rankine cycle engines for dispersed solar electric power systems. As a result of the contractors performance and cost studies,DOE will select one or more engines for each cycle to be designed and fabricated under contract with industry for subsequent testing.

The 5-year schedule shown in Figure 6-2 illustrates the sequence of activities to be followed for the development of the steam Rankine 15 kWe engine. A similar schedule will be followed for the Brayton cycle engine which was transferred to the Advanced Solar Thermal Technology Project.

D. STATE-OF-THE-ART

1. State-of-the-Art of Small Brayton Engines

At this time there are several small Brayton engines which, when modified, would be near-term candidates for solar thermal power. These small engines are presently used in military generator sets for tactical use in the field. They are diesel-fuel powered, open cycle unregenerated Brayton units driving a constant speed generator through a gear box. Figure 6-3 shows a representative gas turbine and a complete assembly of such a machine. For reasons of "battlefield mobility" the military generator sets are not regenerated, hence modification of such engines in general will require the removal of the fuel system and combustor. Also, the solar thermal Brayton engine will require the addition of a recuperator to attain acceptable efficiencies.

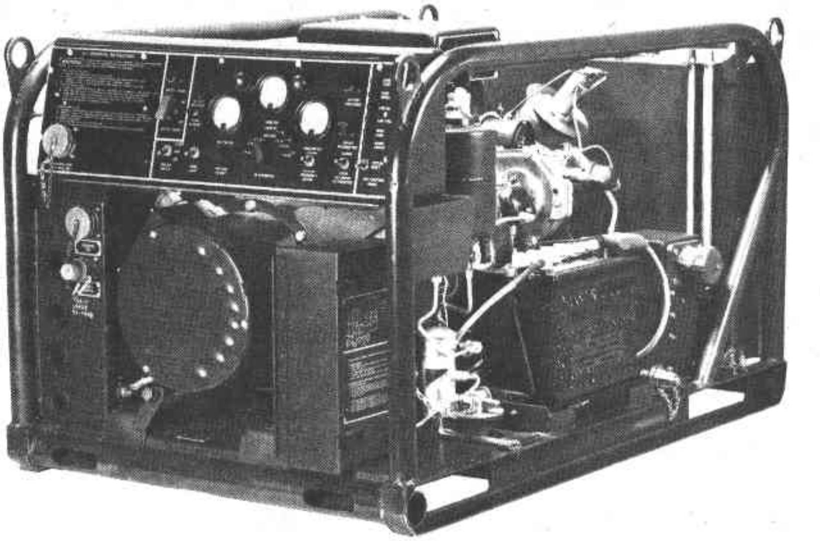


Figure 6-3. Gas Turbine and Complete Generator Set

Considerable research and development has been expended by NASA on the small closed Brayton cycle engines for auxiliary power in space. A 10 to 15 kWe unit and a 1.2 kWe unit are typical of this class. They were designed for use with radioisotope energy sources but could run on a variety of energy sources such as solar and a nuclear reactor. Table 6-1 lists known Brayton cycle engines in the 10 to 100 kWe size and with compressor pressure ratios of 2 to 3.

2. State-of-the-Art of Small Steam Rankine Engine

The state-of-the-art in steam Rankine systems currently is very much a function of system size. The largest systems for use in utility power plants have been developed with multistage turbines utilizing a reheat cycle and multiple feedwater heaters for maximum conversion efficiency. Power conversion efficiencies in excess of 40% are now being realized in 300-500 MWe utility plants with initial steam conditions of 2400 psia and 1000°F. In contrast, the very small turbines rated at 30-50 kWe in the industrial field are the single-stage type using low cost materials which limit the maximum steam conditions to 600 psia and 750°F. These small systems operate on a simple cycle without reheat or feedwater heaters and their power conversion efficiency is accordingly quite low. Figure 6-4 illustrates the performance available in commercial steam-electric systems over a wide size range.

Historically, the performance gap between the large and the smaller systems results from a combination of technical and economic factors. In the past, low fuel prices have dictated minimum capital cost rather than improved performance as the market criteria for small systems. From a technical viewpoint, friction effects and other loss characteristics work in favor of the larger systems. There is, however, considerable promise for improvement of small systems where economics justify the effort. Development efforts on the California steam car are currently targeted for 30% efficiency using reheat/ feedwater heating and steam temperatures up to 1300°F. The solar thermal-electric application may achieve similar performance from a smaller engine due to freedom from the variable speed automotive drive cycle and the constraint of mounting the condenser behind an automobile grill.

E. CONTRACTORS PROGRESS

1. Brayton Conceptual Design Studies - Contract

As discussed in Section C, Approach, procurement activites are underway with industry to proceed with conceptual design studies for small Brayton cycle power conversion systems to establish their economic viability and efficiency. As a result of current competitive procurement the LeRC has negotiated with Garrett AiResearch Manufacturing Company of Arizona (AiR) to study three configurations:

(1) Brayton Baseline Open Cycle

(2) Brayton Baseline Closed Cycle

Table 6-1. Summary Status Brayton Cycle Engines (0-100 kWe)

Company	Cycle, Regen./Recup.	Size kW	Turbine Inlet Temperature °F	Engine Eff, %	Regen./Recup. Effectiveness	Status
Garrett	Open	30	1400	10.7		Commercial aircraft
	Open	45	1400	10.0		Derivative production
	Open	60	1400	9.8		Derivative production
	Open	100	1400	12.6		Derivative production
	Closed, Recup.	10	1650	28.0	0.85	Developmental - built & tested
	Closed, Recup.	30	1550	25.0	0.88	Developmental - built & tested
Williams Research	Open	26	1600	8.6		APU - production
	Open	51	1600	10.2		APU - production
	Open	88	1400	13.7		APU - production
	Open, Regen.	90	1800	24.4	0.90	Automotive - developmental
Solar	Open	10	1300	7.5		T-G set - production
	Open	47	1700	10.8		APU - production
	Open	60	1700	11.5		APU - production
	Open	70	1700	11.8		APU - production
	Open	97	1700	10.2		APU - production
Chrysler	Open, Regen.	70	1900	26.4	0.88	Automotive - developmental
	Open, Regen.	100	1850	21.7	0.88	Automotive - developmental

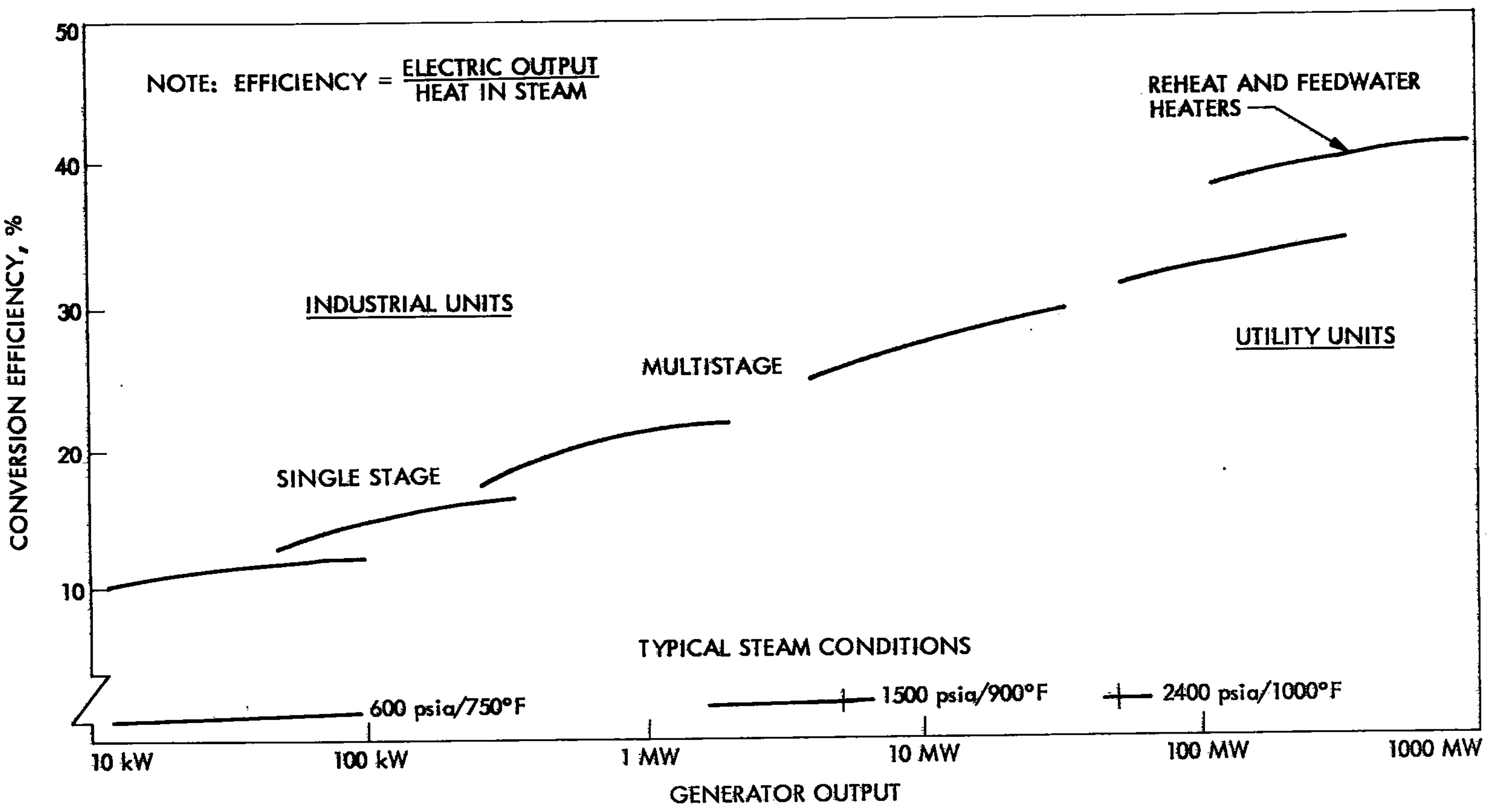


Figure 6-4. State-of-the-Art Performance of Commercial Steam-Electric Systems

(3) Brayton Alternate Open Cycle

The Brayton engine/generator set for this study will consist of a turbocompressor, gear box, generator, recuperator, and associated coolers, piping and controls. The purpose of the study is to consider ways of increasing efficiency, for example, by increasing recuperator effectiveness. Availability and development risk differentiates between the baseline and alternate categories. Baseline configurations are modifications of production units available for testing by calendar year 1980, while alternate configurations are those that require additional modification (i.e., improved performance, life) and will be available for test by calendar year 1982.

The contract effort will be performed under the following tasks for each of the three configurations:

(1) Open Cycle Brayton-Modification 0

(2) *Closed cycle Brayton-Modification 0

(3) *Open cycle Brayton-Modification 1

Task 1. Parametric Performance Analyses

The contractor will determine the design and off-design performance of a variety of Brayton units over a range of values of the major variables:

(1) Power level, 10 to 20 kWe

(2) Turbine inlet temperature, 650 to 815°C

(3) Recuperator Effectiveness, 0 to 0.95
(Note that 0 is used as a reference only)

(4) Cycle loss pressure ratio, 3 to 7%

(5) Shaft speed of Generator, 1800 to Turbine speed

Task 2. Conceptual Designs

The contractor will prepare design data packages on three NASA selected designs in sufficient detail to provide a basis from which realistic cost estimates can be made.

Task 3. Interface Requirements

The contractor will identify physical and operational interfaces with the balance of the system and assure that the power conversion system designs are compatible with the complete solar thermal system.

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*Contract effort was initiated in September. Contractor results in each of these categories will be reported in the next Technical Report.

Task 5. Reporting

The contractor will prepare a technical schedule, financial monthly reports, schedule periodic technical briefings, and a Final Report.

2. Conceptual Design Studies for Small Steam Rankine Engine - Contracts

In FY 1978 the steam Rankine effort conducted under contract centered on initiation of industry participation in a concept definition study to identify what small engine improvements can be expected for solar thermal-electric applications. A statement-of-work for the study was structured with an initial parametric analysis task to estimate performance sensitivity to temperature in the 800-1500°F range and sensitivity to size in the 5 to 100 kWe range. From the parametric results a design point, nominally at the 15 kWe power level, will be selected for a conceptual design task. The conceptual design effort will include layout and cross-section drawings, a weight and envelope estimate, and a more definitive estimate of power conversion subsystem efficiency over the solar duty cycle. In subsequent tasks the design will be evaluated for interface limitations, production costs, life characteristics, and maintenance requirements in a solar application.

The concept definition RFP was issued in April indicating response options of test-bed (Mod 0) and/or alternate (Mod 1) engine categories. Performance targets of >20% and >30% were established for the two categories. The RFP identified the Government plan for multiple awards with one award as a small business set aside. In the May response a total of twelve proposals were received with nine of these being from small business. An extensive proposal evaluation effort was completed in June and negotiations initiated with three firms. Contract awards were made in September for three parallel six-month studies:

Sundstrand Energy Systems - Mod 0 Category Turbine

**Foster-Miller Associates - Mod 1 Category Turbine

**Jay Carter Enterprises - Mod 0 Category Recuperator

In concept definition studies, the Mod 1 category concepts include reheat. Further, in each of the Mod 0 studies a reheat configuration will be investigated as a growth option. Figure 6-5 is an example parametric plot of performance potential for 15 kWe reheat engine. Completion of the concept definition studies for both Mod 0 and Mod 1 systems will provide data for a FY 1979 decision by DOE on hardware systems.

Task 4. Assessment of Production Implementation

The contractor will estimate production costs of the selected engine concepts and determine their life cycle costs and service life.

**Small business

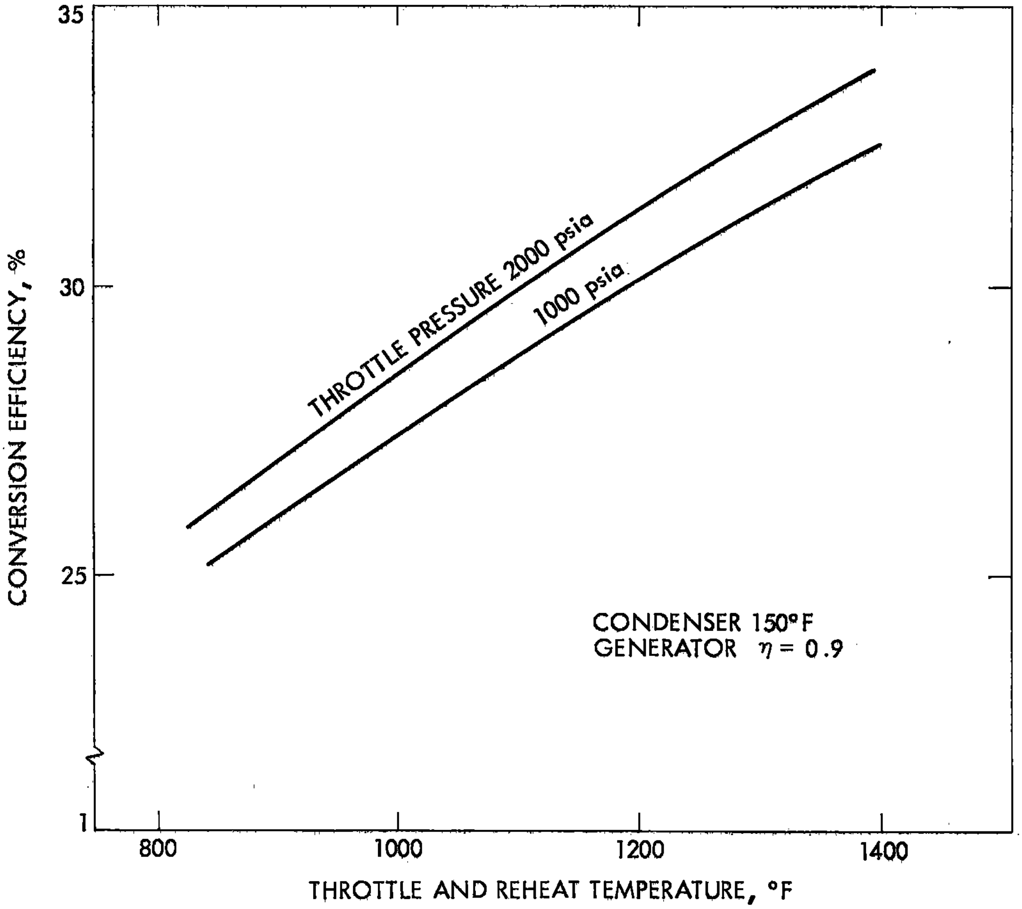


Figure 6-5. Parametric Performance Potential for 15 kWe Steam Rankine Reheat System

F. IN-HOUSE PROGRESS

1. A Cycle State Point Investigation-Brayton

Using in-house generated multi-purpose Brayton cycle computer codes, system net cycle efficiency was computed as a function of a variety of component parameters applicable to solar thermal systems. These included compressor inlet temperature, compressor pressure ratio, turbine inlet temperature, recuperator effectiveness, loss pressure ratio, and working fluid. Table 6-2 lists these parameters and their respective values. Both open and closed cycles were investigated. The open cycles have an atmospheric compressor inlet pressure, whereas the closed cycles are not bound by this constraint. Those analyses further assumed that the following parameters had the nominal fixed values shown.

Turbine polytropic efficiency, η_T = 0.86

Compressor polytropic efficiency, η_C = 0.82

Net generator output power, kWe = 15.0

Gear box efficiency, 0.96

Generator efficiency, 0.96 = 0.903 combined

Mechanical efficiency, 0.98
(bearing losses)

Further, the analyses assumed no compressor intercooling, no turbine reheat, and no bleed air for turbine cooling. Figures 6-6 and 6-7 show, respectively, closed and open cycle schematics of typical Brayton solar power units. The cycle state points shown in the figures were obtained from system design point performance computations using the fixed values above and the following values of Table 6-2 parameters:

Compressor inlet temperature = 80°F

Compressor pressure ratio = 2.50

Turbine temperature = 1500°F

Recuperator effectiveness = 0.95

Loss Pressure Ratio = 0.92

Working fluid = air

Two sets of system performance data were selected from the computer runs and are shown in Figure 6-8. Net system efficiency is plotted against compressor pressure ratio for two values of compressor inlet temperature, 80°F and 120°F, Figure 6-8 A and B, respectively, and for three values of turbine inlet temperature, 1200°F, 1500°F, and 2000°F. At a 1500°F turbine inlet

Table 6-2. System Net Cycle Efficiency/Parameters

Parameter	Values
Compressor inlet temperature, ^{o}F	80, 120
Compressor pressure ratio	1.5 to 5.0
Turbine inlet temperature, ^{o}F	1200, 1500, 2000
Recuperator effectiveness, E	0.85, 0.90, 0.95
Loss pressure ratio	0.90, 0.92, 0.94, 0.96
Working fluid	air, inert gas

temperature an increase of 40°F in compressor inlet temperature causes a 3 percentage point drop in net system efficiency at the design point shown in Figure 6-8A. This points out the efficiency gains to be made in cooling compressor inlet flow. Further gains in system efficiency can be made by increasing turbine inlet temperature beyond 1500°F; however, it is not yet known whether this will be practical due to the very high costs of high strength materials and attendant high costs of fabrication of the turbine, solar receiver, and concentrator.

2. Off-Design Performance-Brayton

The off-design or part-power operation was investigated for both closed and open cycle Brayton engines. The part power operation of closed cycle engines using air or an inert gas is achieved by changing the system inventory, thus dropping cycle pressure level. This pressure change occurs while holding a constant turbine inlet temperature (T.I.T.). Since the rotating components remain near their design point the closed cycle efficiency remains high at low power levels. Part power operation of the open cycle can be accomplished either by varying speed at constant T.I.T. or by varying T.I.T. at constant speed. The more efficient operation is to vary speed and hold T.I.T. constant. This is shown in Figure 6-9 where part power characteristics of a 10 kWe Brayton engine have been computed by Garrett AiResearch for open and closed cycles and for two methods of engine control. The open cycle performance is equal to the closed cycle performance when T.I.T. is kept constant and the speed permitted to vary. This mode of control also permits a wider range of power variation since, as shown in Figure 6-10, engine operation moves along a ridge of high efficiency, and parallel to the compressor surge line. If control of the open cycle, however, were to be restricted to operation along the 100% constant speed line ($N/\sqrt{\theta_{DES}}$) as shown in Figure 6-10 the variation in power would be limited by the surge line on the left and the choked flow regime on the right. Using the

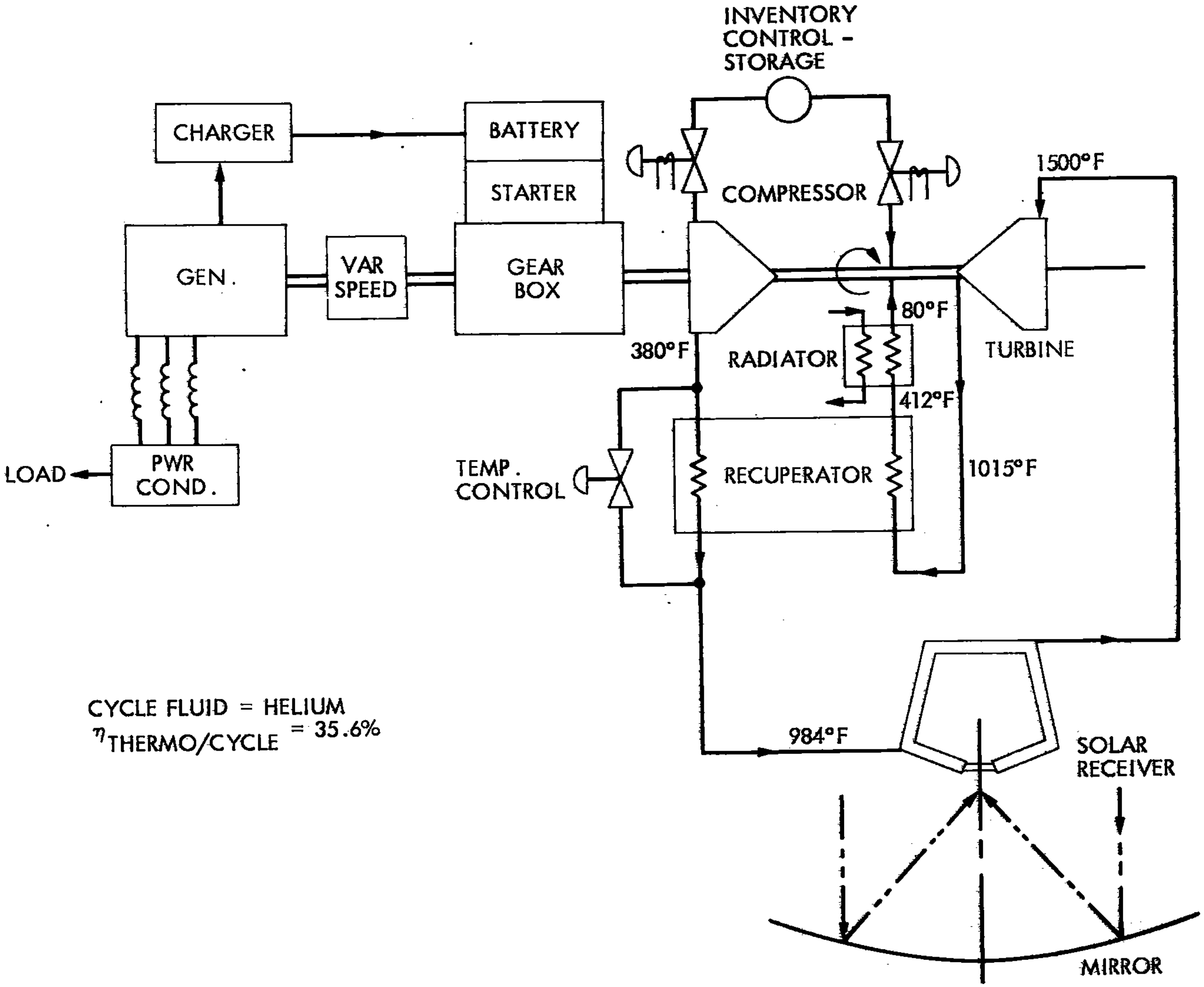


Figure 6-6. 15 kWe Brayton Solar Power Unit Schematic Closed Cycle

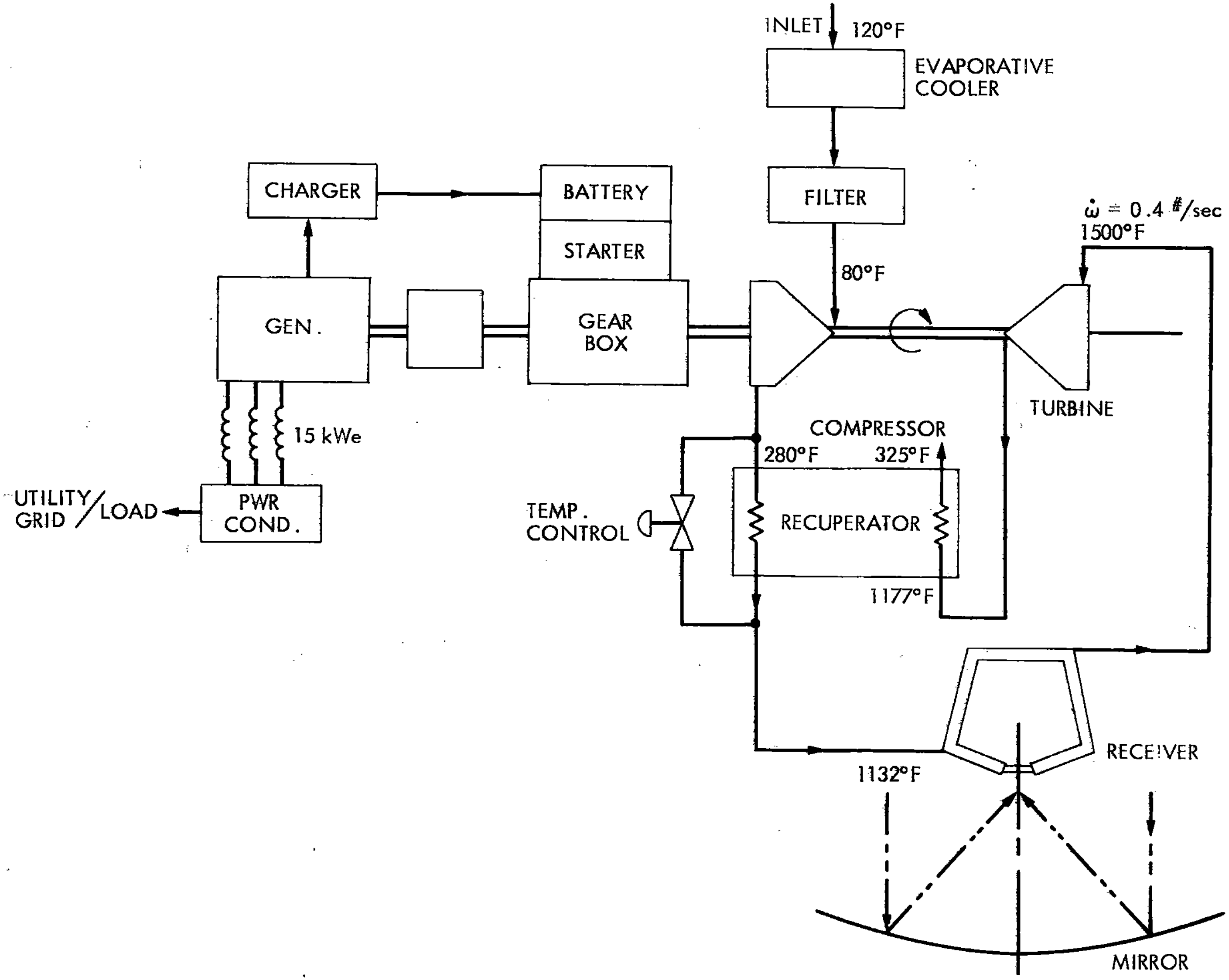


Figure 6-7. 15 kWe Brayton Solar Power Unit Schematic Open Cycle

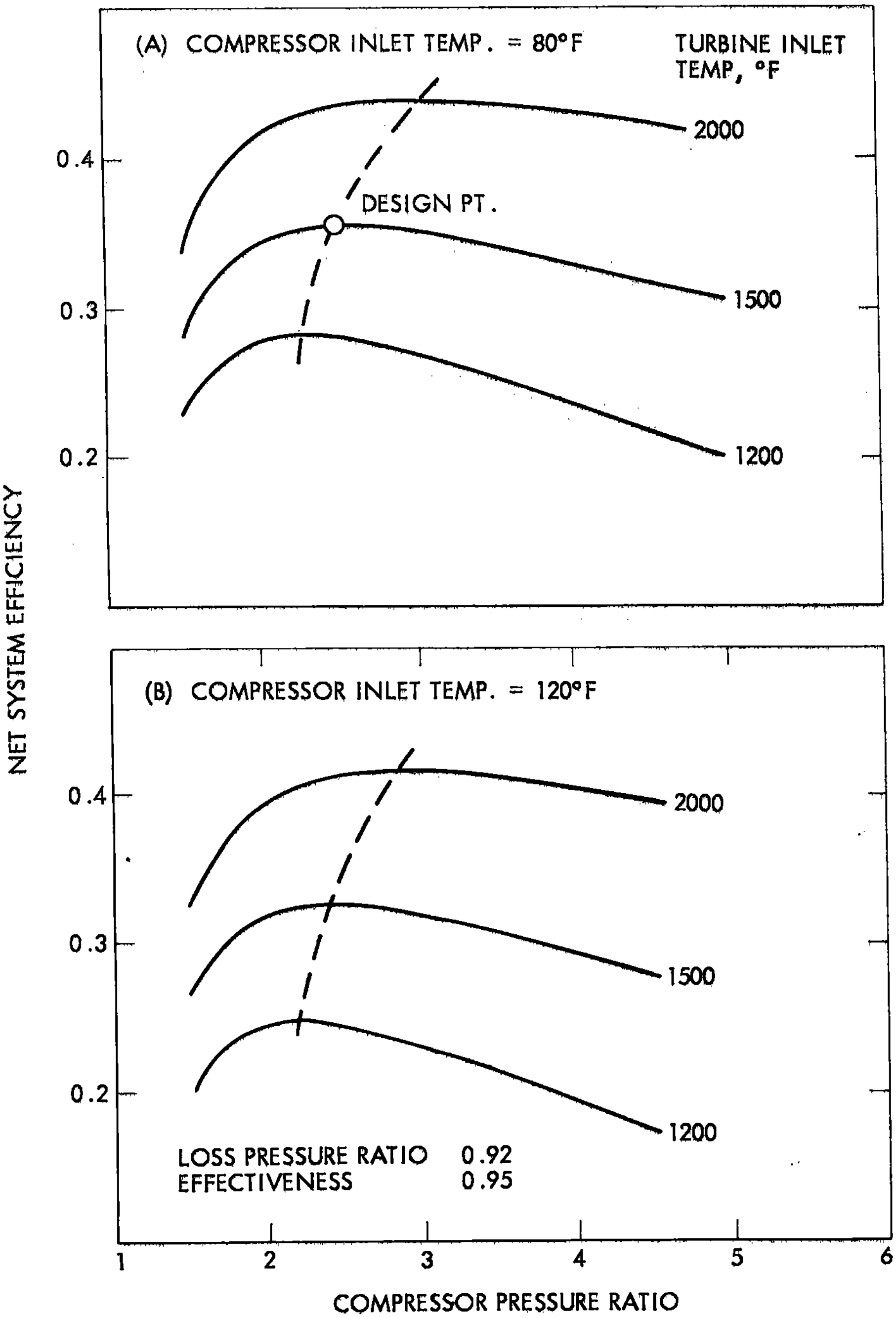


Figure 6-8. Net Subsystem Efficiency vs Compressor Pressure Ratio

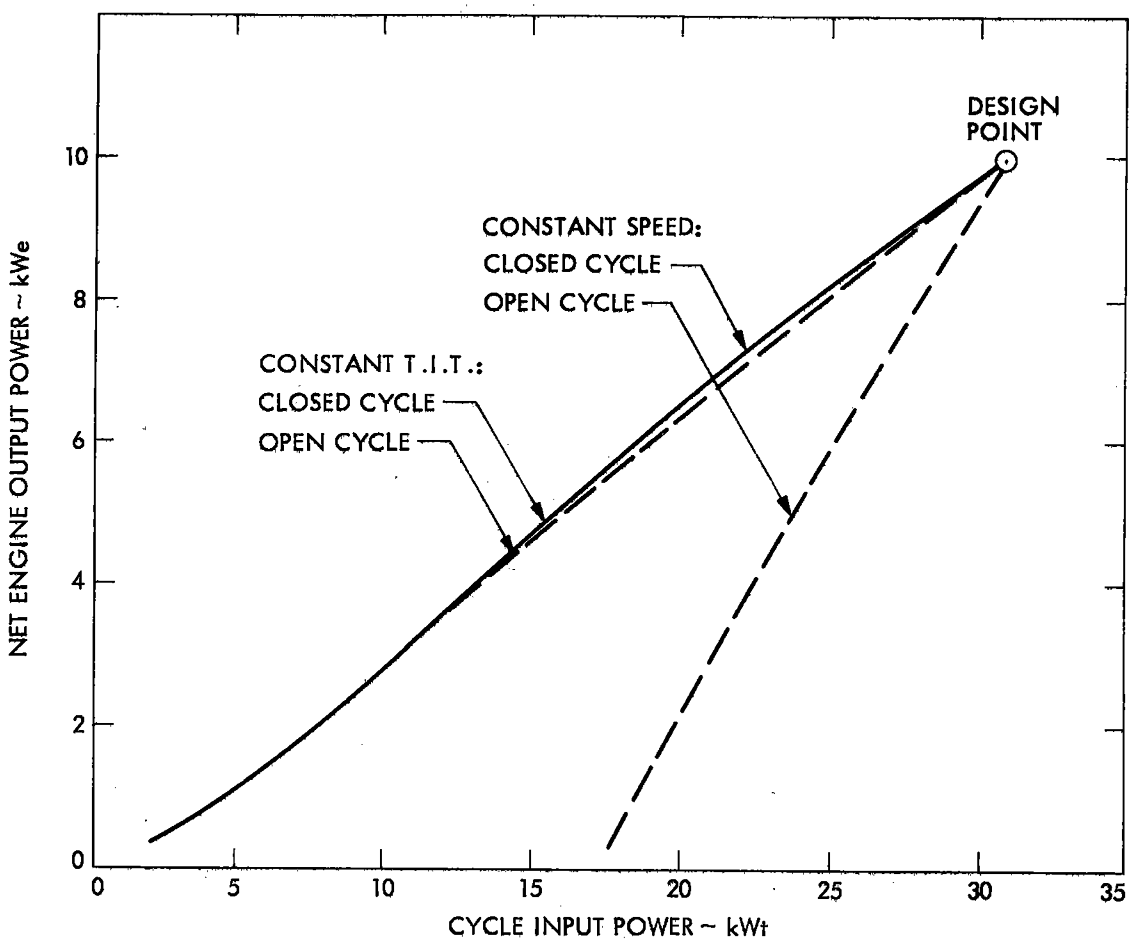


Figure 6-9. Brayton Engine Part Power Characteristics; Open vs Closed Cycle

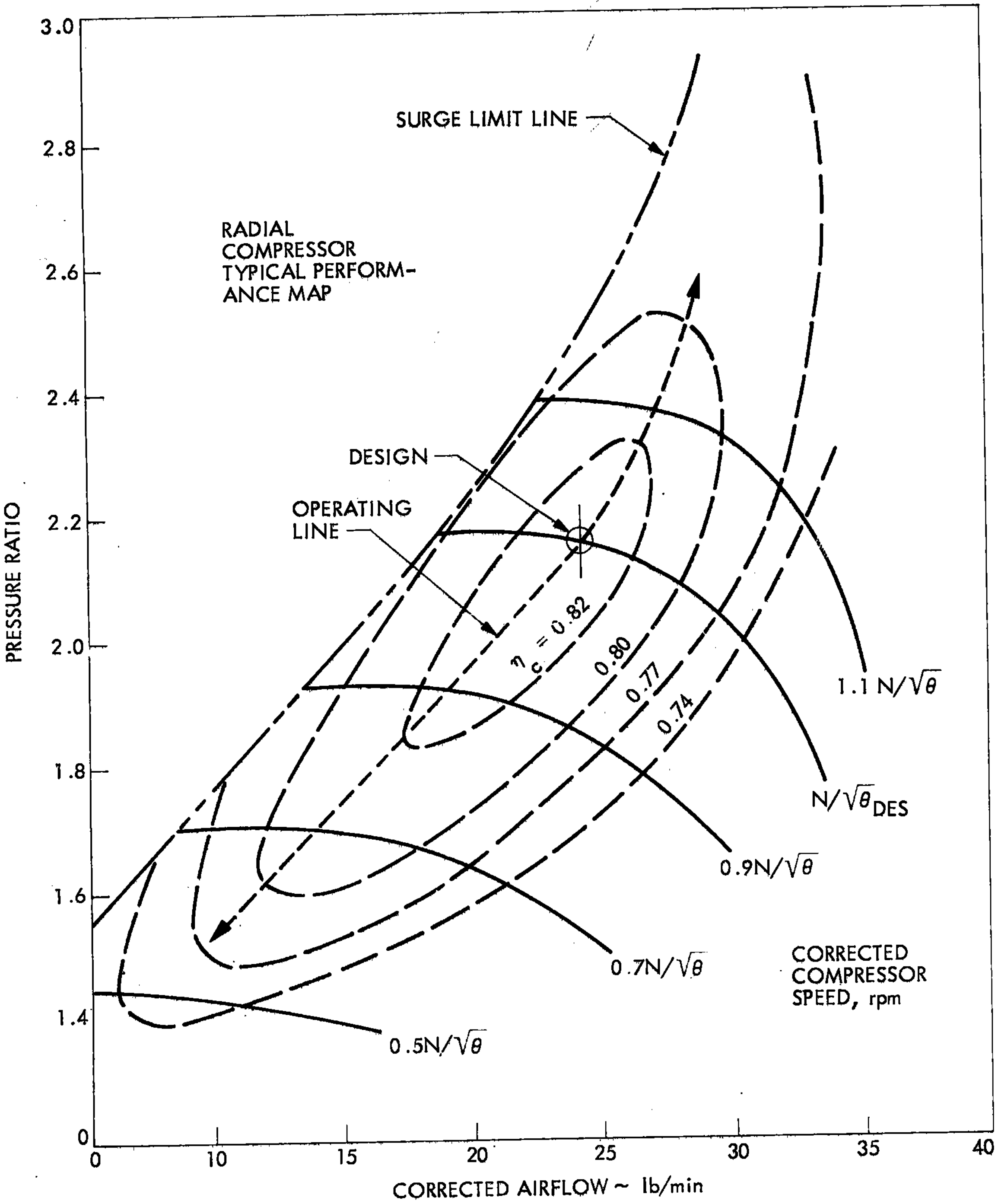


Figure 6-10. Typical Performance Map - Radial Compressor

performance characteristics of a 10 kWe open cycle Brayton engine the energy conversion effectiveness of the engine using a constant T.I.T. control was calculated to be 18 percent better than when engine speed was held constant. Energy conversion effectiveness is defined as the ratio of electrical energy generated per year to the solar energy available per year. Since the optimum engine control requires a variable engine speed several means will be investigated to convert the resulting variable frequency output to a usable constant 60 Hz a/c with inverter/rectifiers and variable speed ratio drives.

3. Performance Improvements with Water Injection-Brayton

An in-house preliminary analysis was conducted to investigate the potential improvements in performance with water injection into the cycle. Two levels of relative humidity at the compressor discharge were examined. Table 6-3 presents a summary of the resulting improvements in efficiency and net specific power and compares them with the basic design point values (dry engine).

Increasing the relative humidity to 50% at the compressor discharge results in a 5.6 percent increase in overall thermal efficiency and 16.4 percent increase in specific power. Increasing the relative humidity to 90% and increasing the compressor pressure ratio from 2.5 to 4.0, the efficiency and specific power improvements over the base case increase by 7.9 and 75 percent, respectively. In the latter case a flow of about 0.028 pounds of water per second (~100#/hr or ~12 gallon/hr) is required for water injection. Increases in efficiency and specific power would permit corresponding reductions in receiver and mirror size to achieve a desired fixed power.

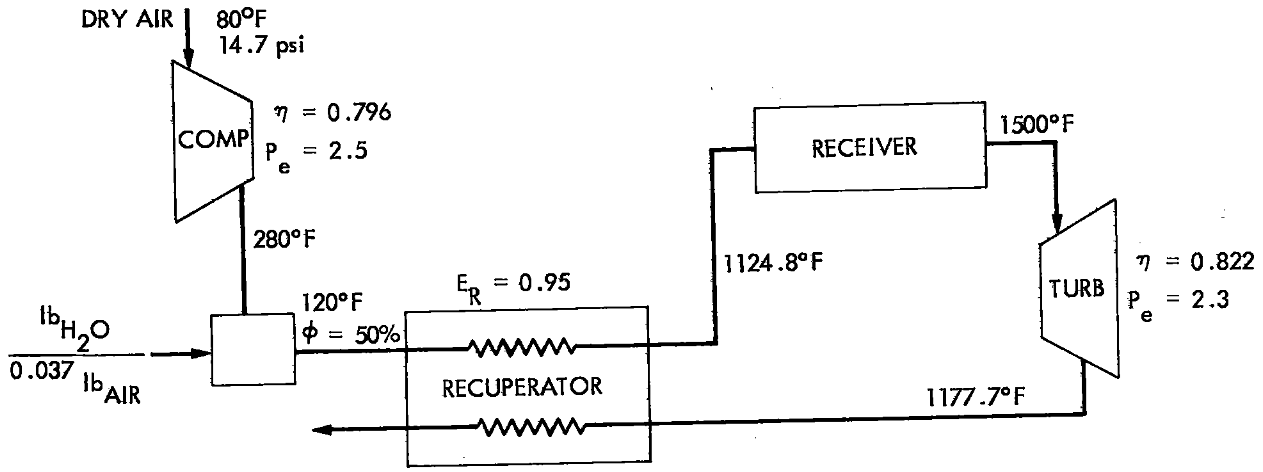
4. Preliminary Cycle State Point Investigation-Rankine

In-house activities during FY 1978 proceeded in parallel and in support of the program's contracted efforts. A significant part of the effort involved survey activities to accurately define the state-of-the-art and thus establish the starting point for funded contract efforts. The state-of-the-art investigations included extensive review of the EPA/ERDA automotive Rankine program as the most current major effort to advance the technology of small steam engines. Knowledge gained was used to develop preliminary performance estimates and envelope and weight estimates for potential solar thermal-electric engines. Specific preliminary point design estimates at 15 kWe (Figure 6-11) and 60 kWe were provided to the systems engineering group at JPL for their overall systems studies.

5. Off-Design Analysis - Rankine

Off-design performance was also studied and results (Figure 6-12) were provided to JPL.

Table 6-3. Open Cycle Design Point with Humidification of Compressor Exit Flow



PERFORMANCE COMPARISON

CYCLE CONDITIONS	$\frac{lb_{H_2O}}{lb_{AIR}}$	REL HUMID ϕ AT RECUP INLET	THERMO. EFFICIENCY	% INCREASE	NET SPECIFIC POWER (BTU/lb OF AIR)	% INCREASE
BASIC: SOLAR BRAYTON DESIGN POINT $P_R = 2.5$, $T_{T\Sigma} = 1500°F$ $E_R = 0.95$	0	0	39.3%	-	39.1	-
I SOLAR BRAYTON DESIGN POINT WITH HUMIDIFICATION (SEE SCHEMATIC)	0.037	50%	41.5%	5.6	45.5	16.4
II SOLAR BRAYTON $P_R = 4.0$, $T_{T\Sigma} = 1500°F$ $E_R = 0.85$ WITH HUMIDIFICATION	0.0714	90%	42.4%	7.9	68.6	75.4

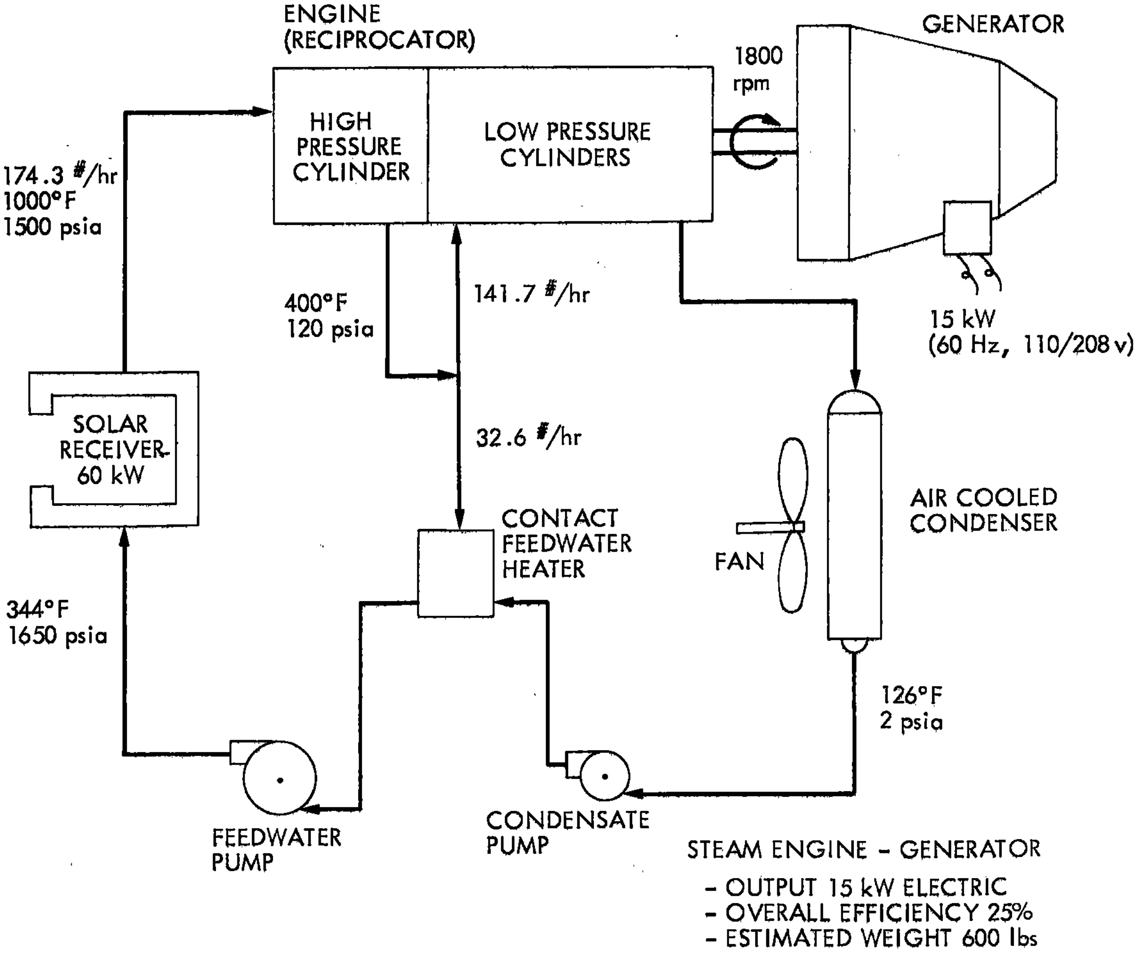


Figure 6-11. Preliminary 15 kWe Schematic Prpared by LeRC for Systems Engineering Studies

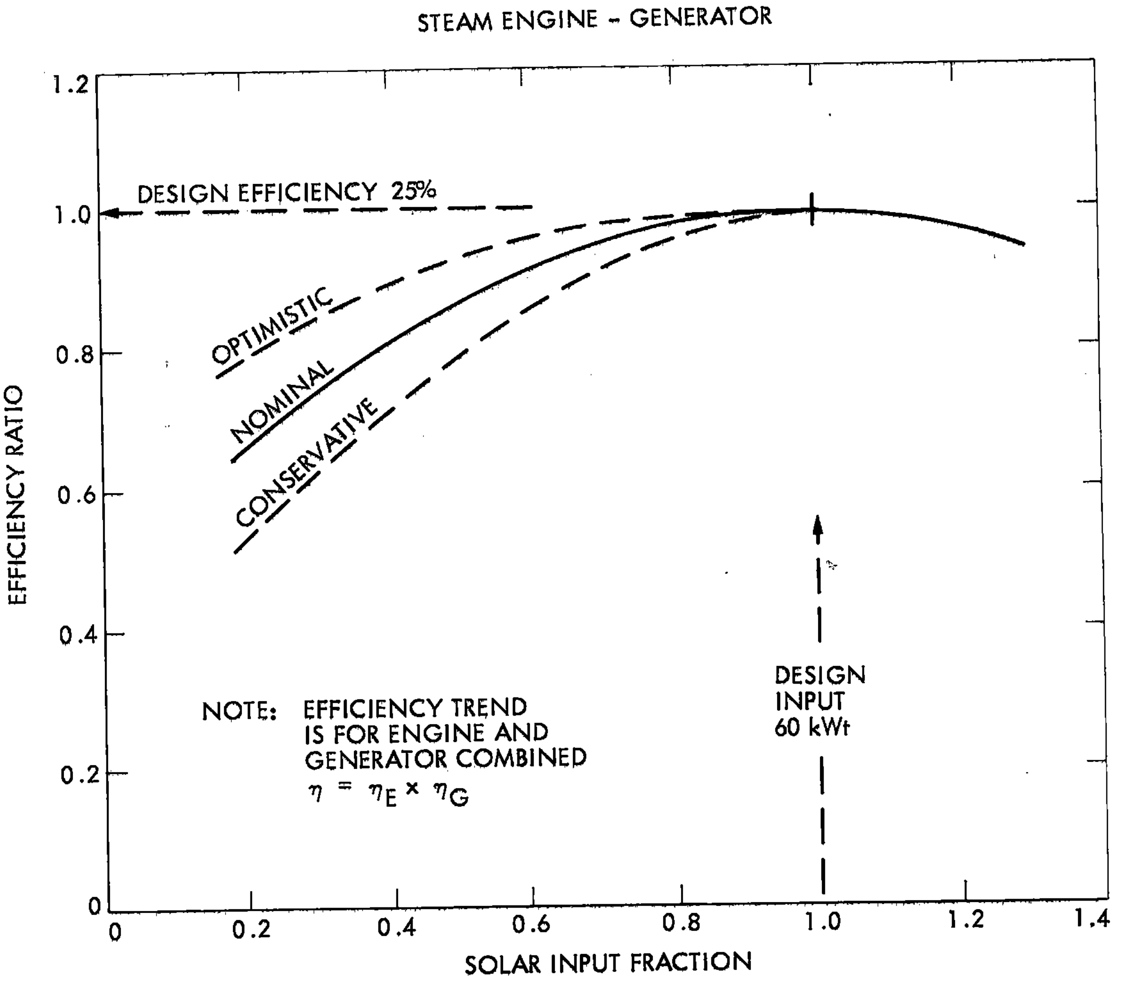


Figure 6-12. Off-Design Power Conversion Efficiency Estimate Prepared by LeRC for Systems Engineering Studies

6. Performance Evaluation Testing - Brayton

a. In-House. In support of performance testing of the complete solar thermal power system at STTS a schedule of power conversion system instrumentation has been prepared and furnished to the JPL Test and Evaluation Task. Table 6-4 lists each parameter to be measured together with the experimental range anticipated and the maximum number of channels estimated to be required. Figure 6-13 shows a schematic of the instrumentation stations.

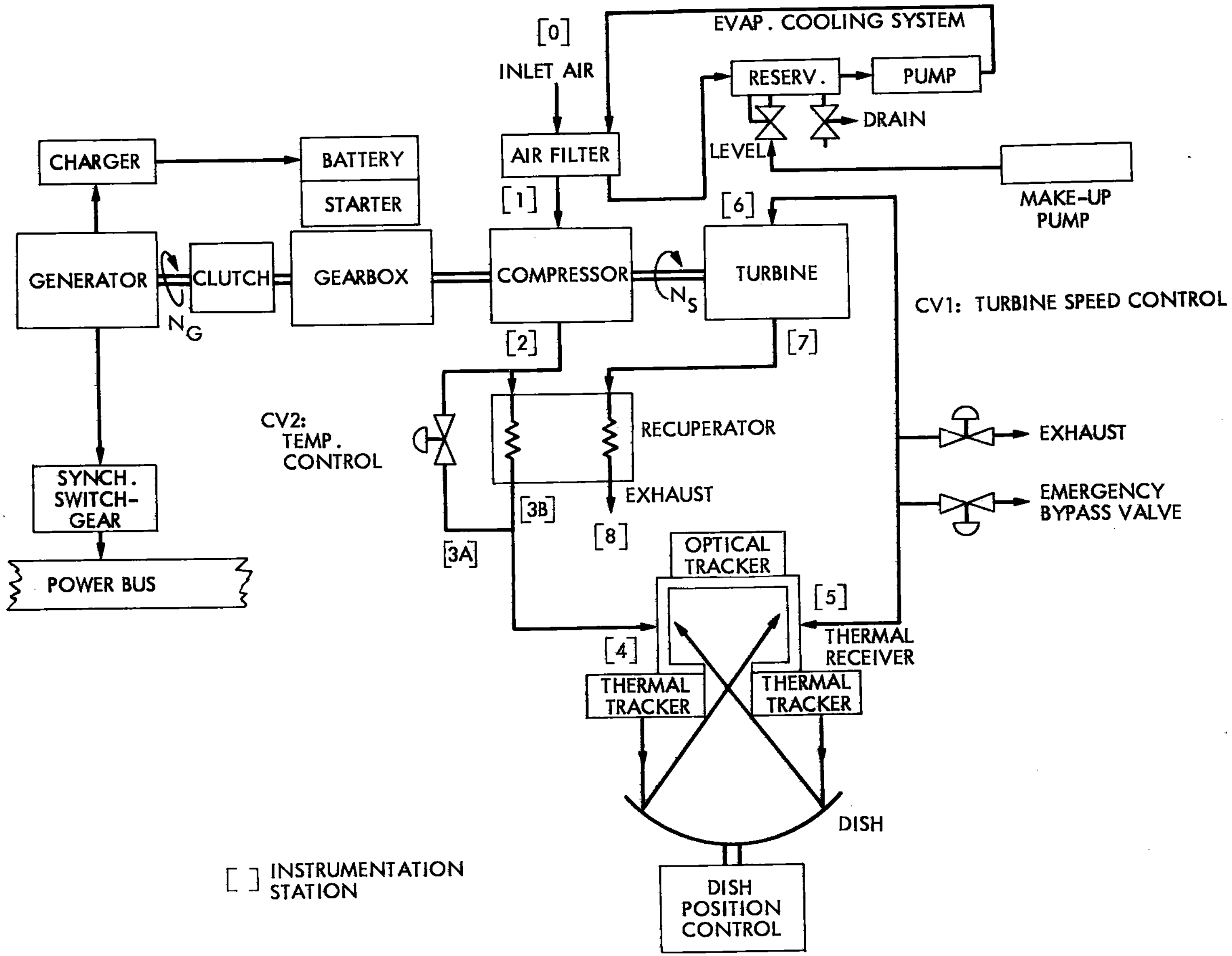


Figure 6-13. 15 kWe Solar Power Unit Schematic Diagram

SECTION VII

MANUFACTURING DEVELOPMENT

A. INTRODUCTION

In most cases, cost analysis studies of solar energy components made in the past have not been sufficiently detailed to yield results from which accurate economic decisions could be made. In general, the earlier analyses did not adequately address the following details:

(1) Manufacturing process to produce parts.

(2) Time required per operation for each part.

(3) Tooling required to produce parts, subassemblies and final assemblies.

(4) Capital equipment required to manufacture parts.

Therefore, it was necessary that an active and ongoing cost analysis and manufacturing development task be established to assist in insuring that high performance, low-cost PFDR solar energy components are available in the mid 1980's.

B. OBJECTIVE

The principal objective of this task is to assist in the development of PFDR products having high solar energy performance that can be manufactured in high volume at a low unit cost. Efforts to accomplish the objective of this task are focused on (1) the development of credible cost numbers for PFDR concentrators, receivers and power conversion systems, (2) development of tooling and determination of capital equipment requirements to produce solar energy modules, and (3) detailed studies of the possible use of automation techniques in the production of PFDR products for cost reduction.

C. APPROACH

The five year schedule, Figure 7-1, shows the three major thrusts of the Manufacturing Development Task.

(1) Mass Production Cost Studies. This activity addresses the applicability of the various components, subsystems and systems production design to high volume mass production, with the resultant low cost of manufacturing the various system components. An existing state-of-the-art PFDR total system, the Omnium-G, was selected and is being cost analyzed to establish a "baseline" to which all subsequent components, subsystems and systems can be compared for cost and performance. This study is cost analyzing

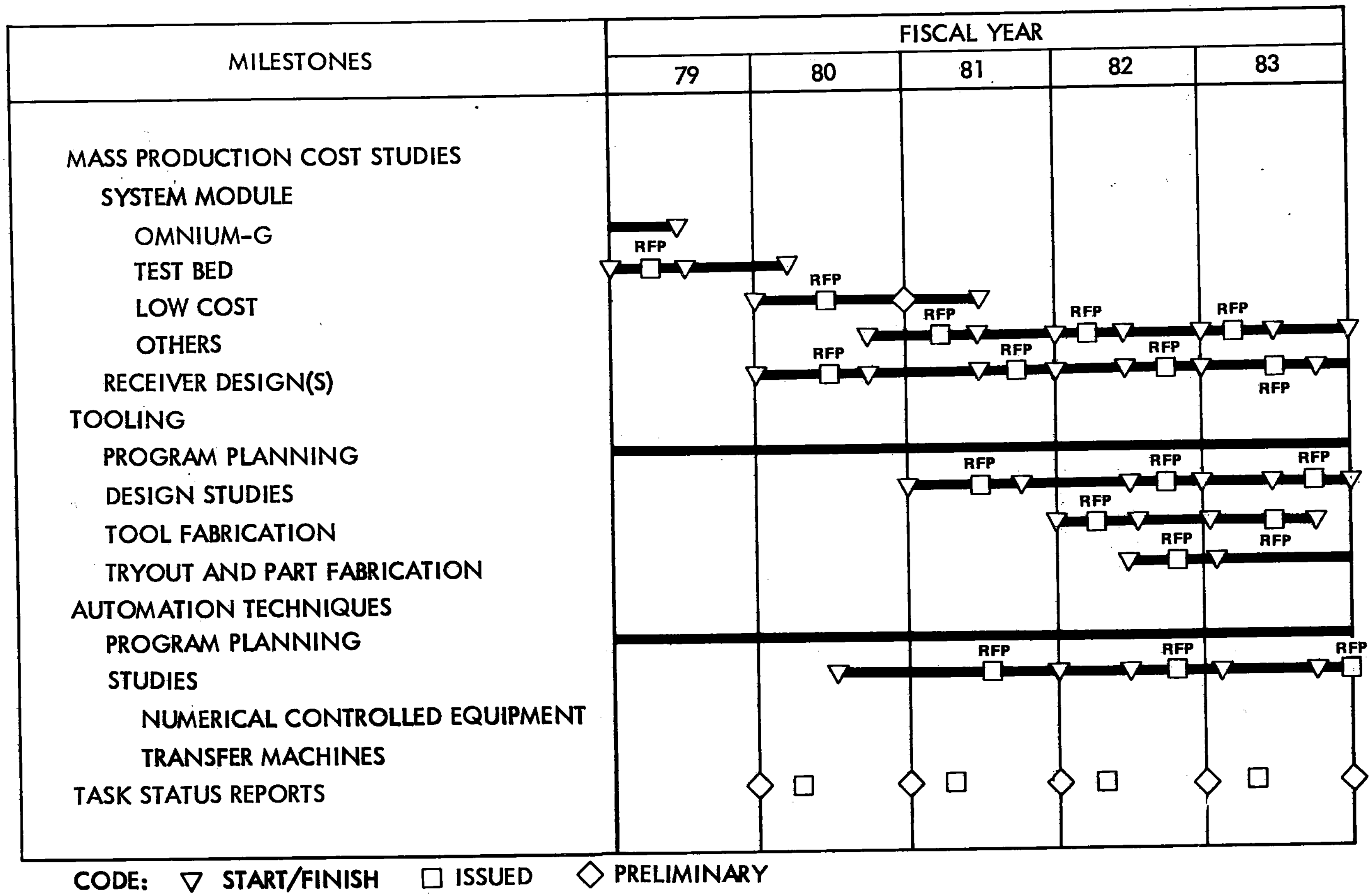


Figure 7-1. Five-Year Manufacturing Development Milestones

the "baseline" module in production quantities ranging from 100 to 1,000,000 units per year. This is the first step in establishing an active and ongoing cost analysis and tool development program to assist in insuring that high performance, low-cost, point-focusing solar subsystems are available in the mid 1980's.

The "baseline" system cost analysis includes the following criteria:

(a) Establish engineering parts list.

(b) Obtain raw material costs.

(c) Determine part manufacturing process.

(d) Estimate labor hours to produce part.

(e) Estimate assembly labor hours.

(f) Estimate tooling costs and amortization rate.

(g) Estimate capital equipment cost and amortization rate.

(h) Perform value analyses where applicable.

As new and varied designs of point-focusing subsystems become available, they will be cost analyzed, using the criteria noted above and compared to the "baseline" for cost and performance. RFP's will be issued to industry to accomplish these objectives in FY 1979-1982. The resulting estimated costs are to be compared with cost goals to determine if a given subsystem/system is (1) acceptable, (2) should be abandoned, or (3) reconfigured.

(2) <u>Tooling</u>. Detailed studies will be executed to determine the exact nature of the tools required to produce each part, component or assembly. RFP's to industry will solicit assistance in tool design, fabrication and tool tryout.

(3) <u>Automation Techniques</u>. The third and final thrust is to determine if the use of automation techniques can substantially reduce the cost of point-focusing solar energy components. RFP's will be prepared to solicit industry participation in the design and selection of numerically controlled equipment and transfer machines that may be used in the mass production of point-focusing solar energy components.

D. PROGRESS

During FY 1978, an existing state-of-the-art PFDR total module, commercially available from Omnium-G, was selected for cost analysis and will serve as a "baseline" to which all subsequent parabolic dish concentrators can be compared. Parts lists are being prepared for each of the major components and/or assemblies and have been completed for the receiver assembly, concentrator (including support), azimuth and elevation controls, and electronic controls. The balance of the parts lists will be compiled in FY 1979.

In order to effectively estimate costs, capital equipment and tooling requirements for the components in the Omnium-G module, it is necessary that drawings, sketches, and specifications be analyzed.

Preliminary studies have been made on estimates of cost, tooling, and capital equipment requirements for the receiver, concentrator, azimuth and elevation controls, and the electronic controls.

All of the estimates cover production quantities ranging from 100 to 1,000,000 units per year.

Preliminary studies were made relative to planning the programs for tooling and automation techniques.

SECTION VIII

SYSTEMS ENGINEERING

A. INTRODUCTION

The objective of the PFDR Technology Project is to develop technology and mass production techniques that will become available in the early 1980's for applications experiments utilizing low-cost, long-life, and reliable solar thermal power systems. The Systems Engineering Task was established in October of 1977 to help implement this objective. Systems Engineering defines and analyzes candidate system configurations, coordinates the establishment of subsystem interfaces and functional requirements for the subsystems, provides direct support to the other tasks, and establishes and monitors performance and cost targets. The power conversion subsystem candidates for first generation systems are steam Rankine and gas Brayton.

In an effort of this nature, there is the traditional dichotomy that finds its parallel in the "chicken or egg" problem. That is, systems engineering needs to know the subsystem requirements, which necessarily are vague in the early stage, but subsystems needs to know the capabilities of systems engineering that, too, are not well developed. This has led to a natural evolution of the role of systems engineering during FY 1978. This role has developed into several major activity thrusts that are described briefly herein. Other changes have occurred as well. Activities in the sector of industrial engineering have been channeled into a new task, i.e., Manufacturing Development, separate but complementary to Systems Engineering. In addition, the recognized need for early "hands-on" experience with hardware has led to a new thrust that centers on evaluation of the commerical (Omnium-G) module. It is hoped that experience with this unit will provide information leading to improved next generation hardware as well as confirmation of analytical design tools.

The technical progress included in this report for FY 1978 is intended to portray an illustrative overview rather than an in-depth description. More detailed and comprehensive technical results have been, and will be, presented in separate reports, symposia presentations, and journal papers.

The methodology and analysis tools for assessing candidate systems were developed in FY 1978, and will be refined, broadened, and improved to meet anticipated needs in the future. Simplifications were introduced to enable a timely approach to achieve early results. Candidate PFDR systems in the nominal range of 15 kWe output were examined initially with regard only to performance and capital cost, and thermal/electrical storage was not considered. Other Thermal Power Systems Projects have conducted general studies on power plants using different solar technologies. In contrast, in the PFDR activities, emphasis was placed on more detailed analysis and simulation of single-dish modules. This was done to come to a clearer understanding of performance tradeoffs for competing candidates. Sample results are presented herein.

Currently, the leading candidates for baseline systems utilize the steam Rankine and the open-cycle air Brayton engines. The steam Rankine systems under consideration are in the range of 1000°F to 1100°F and the Brayton systems are evaluated at 1500°F. Power conversion systems may be dish-mounted in the case of single-dish modules, or ground-based in the case of multiple-dish systems. Sensitivity analyses have been performed, e.g., variations in concentrator cost and quality, and power conversion cost and efficiency, as a precursor to future optimization and tradeoff studies. Periodic technology assessments will be made in the future to determine optimal systems that should be accorded development impetus. Systems Engineering will lead these assessments to arrive at pertinent recommendations regarding selective technology development of specific systems. Future budget limitations may force a decision to select either the gas Brayton or the steam Rankine power conversion candidates before actual hardware is produced. Systems Engineering will develop screening methods to prepare for this anticipated decision using all available information obtained from contracted studies.

B. OBJECTIVES

The objectives of this task are to provide a systems approach to the individual subsystem development efforts, to integrate the subsystems, and to assure that goals accountability is maintained. Major subtasks to accomplish these objectives are:

(1) To lead and support the design team which will integrate the development of the concentrator, receiver and power conversion subsystems.

(2) To perform systems analysis leading to a clearer definition of technology systems appropriate for development.

(3) To establish and monitor technical performance and cost targets for the several subsystems comprising point-focusing technology.

C. APPROACH

1. Methodology

Systems Engineering has been organized along lines that address the objectives set forth above. Systems Engineering activities have four major thrusts to meet the objectives.

The first and largest thrust is the design team activity. Systems Engineering leads this team which includes members from the subsystem tasks. The design team establishes the subsystem interfaces and the functional and technical design requirements for each subsystem. The System Engineering effort integrates the development of the concentrator, receiver, and power conversion subsystems, including system module operating controls, and assures that tradeoffs are properly performed such that system optimization is achieved.

The second thrust of Systems Engineering is the system definition studies. These studies first are used to determine functional requirements and then to define and characterize the candidate distributed receiver technology systems. The systems are catalogued with consideration given to current technology status and the anticipated degree of development difficulty in terms of time and resources to develop the technology to the point of readiness for applications projects, and to projected commercial cost/performance. Cost and performance results are used to rank the systems. Sensitivity analysis is used as an indicator for optimizing systems. Several different (generic) kinds of distributed receiver systems will be examined and rank-ordered during the course of these definition studies. The candidate systems are based on point- focusing, two-axis tracking concentrators using either gas Brayton or steam Rankine power conversion.

It is not yet possible to perform optimization studies on candidate systems because sufficient technical and cost data is lacking. Nominal values of system parameters such as power level (15 kWe) and peak temperature have been selected based on available information, but they have neither been fixed nor optimized. Clearly, tradeoff studies will be required to determine the optimal values of all subsystem and system design points. It is anticipated that concentrator cost and characteristics will have a major influence on the overall system designs. Much information will become available in FY 1979 through the subsystem contractors and will be used as inputs for tradeoff studies.

Preliminary screening of system concepts has, to date, been accomplished using quasi-steady state analysis. However, the transient behavior of solar power systems will be critical for matching subsystem components, and for understanding dynamic response and establishing controls strategy. Transient system behavior is an important aspect of start-up, shutdown, and performance during varying cloud cover. An analysis of transient behavior will be initiated in FY 1979. Consideration will be given as well to requirements for thermal storage and thermal power utilization (in addition to electric power).

The third thrust is to establish cost and performance target goals. This activity was initiated in FY 1978 and preliminary targets were developed. Results from previous applications studies provided conventional (non-solar) costs projected to the time of solar commercialization (approximately 1990), and were used as a reference. This information was used as input to help establish preliminary subsystem cost and performance targets. Both the general results of the definition studies, which will have identified the attractive systems, and the specific sensitivity analyses, will be used to develop and allocate cost and performance targets for each major subsystem.

A fourth thrust is use of a commercial module as a means toward early evaluation of hardware. In addition to performance data, early hardware evaluation will provide early hands-on test experience, and insight concerning operation and maintenance as well as safety procedures. It may help, as well, to provide early confirmation of analytical tools. An initial effort will be directed towards the evaluation of the Omnium-G module. The test and evaluation results derived from that effort will provide most of the experience needed in forthcoming test and evaluation activities, beginning with the Test Bed Concentrator, and will be utilized as a pathfinder to that end. The emphasis towards early hardware evaluation extends to power conversion subsystems as well. The commercial module presents an opportunity to test and evaluate a different engine, having higher performance than the standard engine of the Omnium-G module.

2. Schedule

The five-year schedule for Systems Engineering is shown in Figure 7-1. Milestones for the four thrusts are established to coordinate with overall PFDR Technology Project plans.

The design team will be a focus for activities interrelating all subsystems and the other PFDR Tasks; its activities reveal pertinent subjects for future systems definition studies as well as needs for cost and performance goals. Overall coordination of the test and evaluation effort on the Omnium-G module was assigned to Systems Engineering because that commercial module is a complete system. Nevertheless, all the other PFDR Task areas have defined roles and an intimate participation in that effort. The test results will be transmitted to the Tasks responsible for concentrators, receivers, and power conversion subsystem development.

D. PROGRESS

Progress is discussed with reference to the four thrusts of the Systems Engineering task. The results presented are intended to provide an overview rather than an in-depth treatment of the technical accomplishments.

1. Design Team

Design team activities remained informal throughout FY 1978 until the month of June when Systems Engineering initiated the formation of the first design team. Nevertheless, considerable ad hoc interfacing did occur of necessity prior to June 1978 between task personnel of the subsystems and systems areas. This occurred naturally through co-consultation arising from subsystem RFP preparation, proposal review, and contract awards. Systems Engineering personnel participated in all of these activities and will continue in this capacity in the future.

Systems Engineering leads the design team, which ultimately will produce subsystem interfaces, subsystem/system functional requirements, and design point specifications. A principal role of the

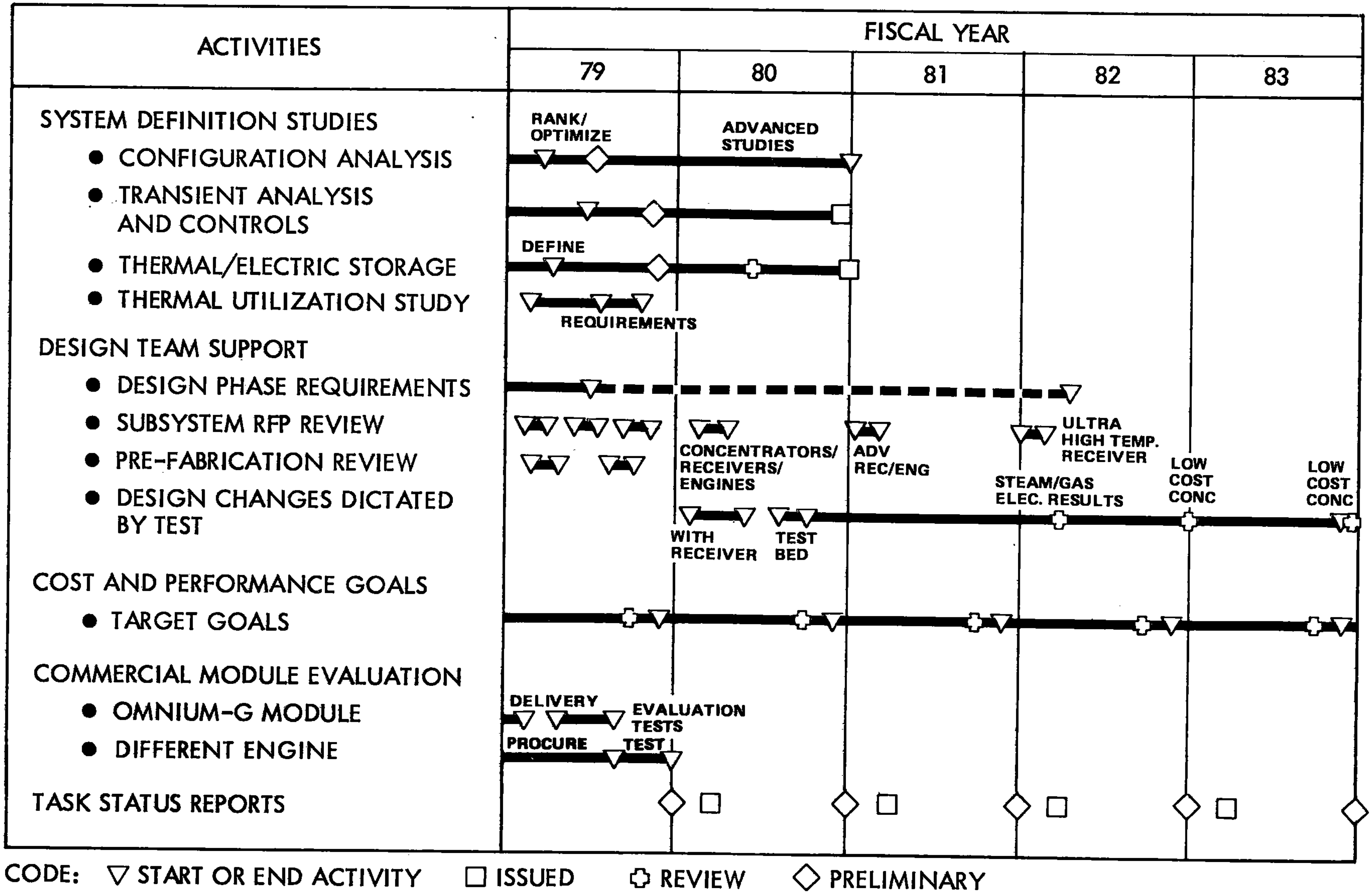


Figure 8-1. Five-Year Systems Engineering Milestones

design team is to define problems related to the subsystem areas themselves, subsystem interfaces, and problems related to future hardware test and evaluation operations.

The design team met regularly throughout the last quarter of FY 1978 and included LeRC personnel (in the Power Conversion Task) on a periodic basis. In addition to establishing short-range goals, the principal design team accomplishments were to (a) create a detailed list of desirable/necessary tests at both the subsystem and system level for the Ominium-G module, (b) establish a general list of all subsystem interfaces, (c) produce an integrated PFDR milestone chart as an aid to planning future design team activities and, (d) review receiver contractor presentations on their respective parametric studies of steam and gas receivers in order to support the selection of design point specifications for the preliminary design phase.

2. Systems Definition

Systems Definition activities were initiated in December 1977. The first objectives were development of computer programs and identification and simulation of candidate systems.

a. Development of Analyses and Computer Programs. An optics computer program was developed to determine the effect of optical surface properties of a paraboloidal dish on the thermal power delivered to a receiver. The analysis was based on cone optics. The concentrator surface is subdivided into many small elements which individually reflect incident solar energy toward the focal spot. Imperfection in individual mirror elements causes the solar image to be enlarged. The superimposed resultant solar image has a high-intensity central core surrounded by a fringe area. Figure 8-2 illustrates a representative flux distribution at the focal plane as a function of surface slope error, σ_s. Note that the peak flux decreases and the distribution broadens as dish quality decreases. Preliminary results of the study were presented at the Second AIAA/ASME Thermophysics and Heat Transfer Conference in Palo Alto, CA, May 24-26, 1978, Paper No. AIAA 78-903. This paper was titled "Thermal Optical Surface Properties and High Temperature Solar Energy Conversion."

A system simulation computer program has been developed in joint effort with the Advanced Solar Thermal Technology and the Small Power Systems Applications Projects. The approach used in developing this computer program is based on optimizing the sizes of the collector and storage subsystems to achieve minimum energy cost (in mills/kWe-hr) for any capacity factor. The program consists of three related but independent programs. The collector field program evaluates the collectors and the thermal energy transport system performance for specified conditions of insolation and meterology over any given period of time. The power program determines the performance of a given power plant for various collector and storage sizes under specified engine part-load conditions. The economics program determines the minimum energy cost envelope for the plant for any range of capacity factors. The program has a modular structure which enables the user to analyze any solar power system. The program

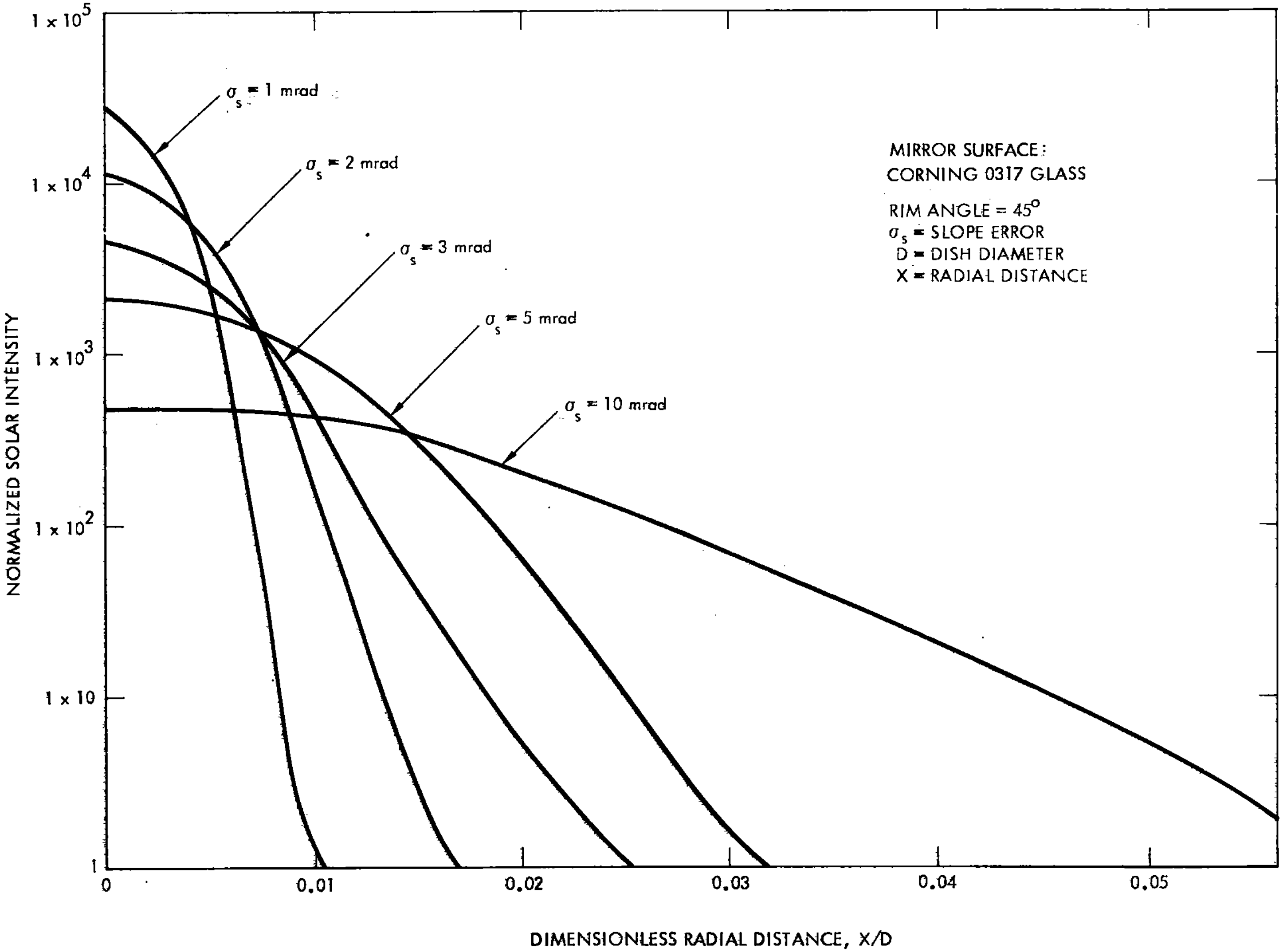


Figure 8-2. Theoretical Focal Plane Flux Distribution

structure is shown in Figure 8-3. Typical results for a sample case of a dish-Brayton system with battery storage are shown in Figure 8-4.

A general tradeoff relationship for concentrator quality, receiver temperature and power conversion efficiency has been established. Representative annual electric energy production rate versus engine effectivity, e, expressed as a percent of Carnot efficiency, is illustrated in Figure 8-5 for two possible Brayton receiver temperatures. In this case Figure 8-5 indicates that higher annual energy production occurs for high receiver temperature when the slope error is small, and vice versa. Figure 8-5 is an early result obtained using Inyokern insolation data, and is shown for illustrative purposes. The preliminary results were included in a paper entitled, "Thermal Performance Tradeoffs for Point Focusing Solar Collectors," presented at the 13th IECEC, San Diego, California, August 20-25, 1978.

b. Identification and Simulation of Candidate Systems. A preliminary selection of five candidate configurations was identified: (1) dish Brayton open cycle, (2) dish steam Rankine cycle, (3) dish Brayton closed cycle, (5) multiple-dish steam modular arrangements, and (5) a Cassegrainian concentrator with steam Rankine or Brayton cycle power conversion. Schematic diagrams of Configurations No. 1 and No. 2 are shown in Figure 8-6 and 8-7, respectively. Preliminary analysis of these two configurations using Inyokern insolation data was completed to demonstrate the established methodology. The two configurations then were rerun using Barstow insolation data. A sensitivity analysis was performed varying concentrator slope error and power conversion efficiency; a wide range of cost and performance values were explored to encompass the current PFDR target values. A draft report entitled, "A Preliminary Assessment of Small Rankine and Brayton Point-Focusing Solar Modules" was completed in September of 1978. It is anticipated that a final report on this work will be published early in FY 1979.

It is to be noted that the full computer simulation (described in section 2.a. above) is not required for the current studies on module configurations. Current studies do not consider energy storage and, because only capital costs are used, the economics program is decoupled from the performance programs.

In the analysis justified capital investments were computed based on a range of energy cost targets and system energy production rates. These justified capital investments can be viewed as a relative "figure of merit," which reflects the project subsystem cost targets for different energy cost scenarios. Representative results are presented in Figure 8-8 for the total system cost of the baseline Rankine and Brayton systems and for an energy cost target of 50 mills/kWe-hr using single-dish modules.

Note that the corresponding hardware cost targets (including concentrators, receivers, and power conversion units) range from 100 to 200\$/m^2 depending upon the concentrator quality, system configuration selection and power conversion efficiency. For convenience in comparing systems of different size, or power output, the capital investment has been normalized by dividing the total system

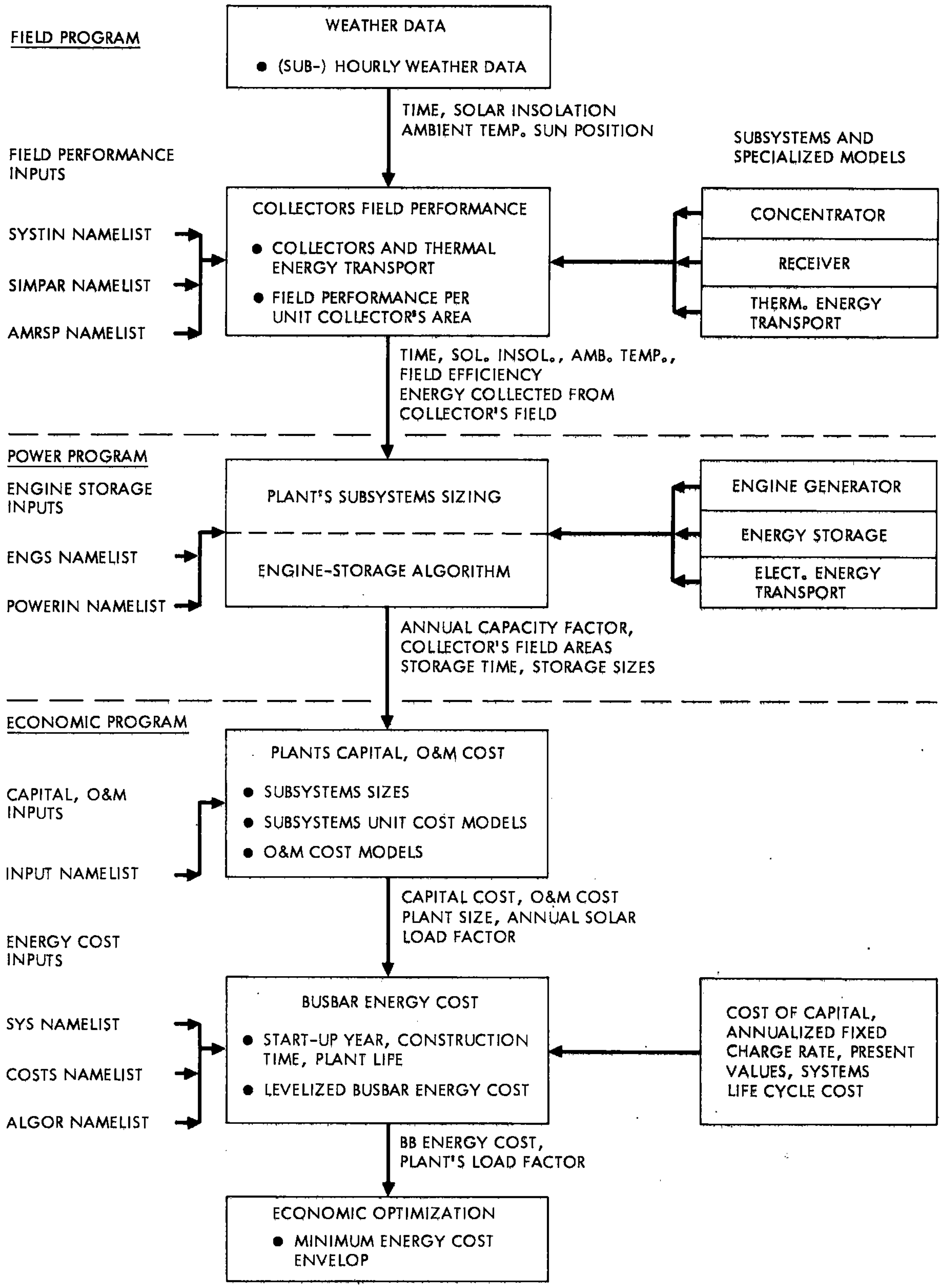


Figure 8-3. Computer Program Structure: Solar Power Plant Energy Cost

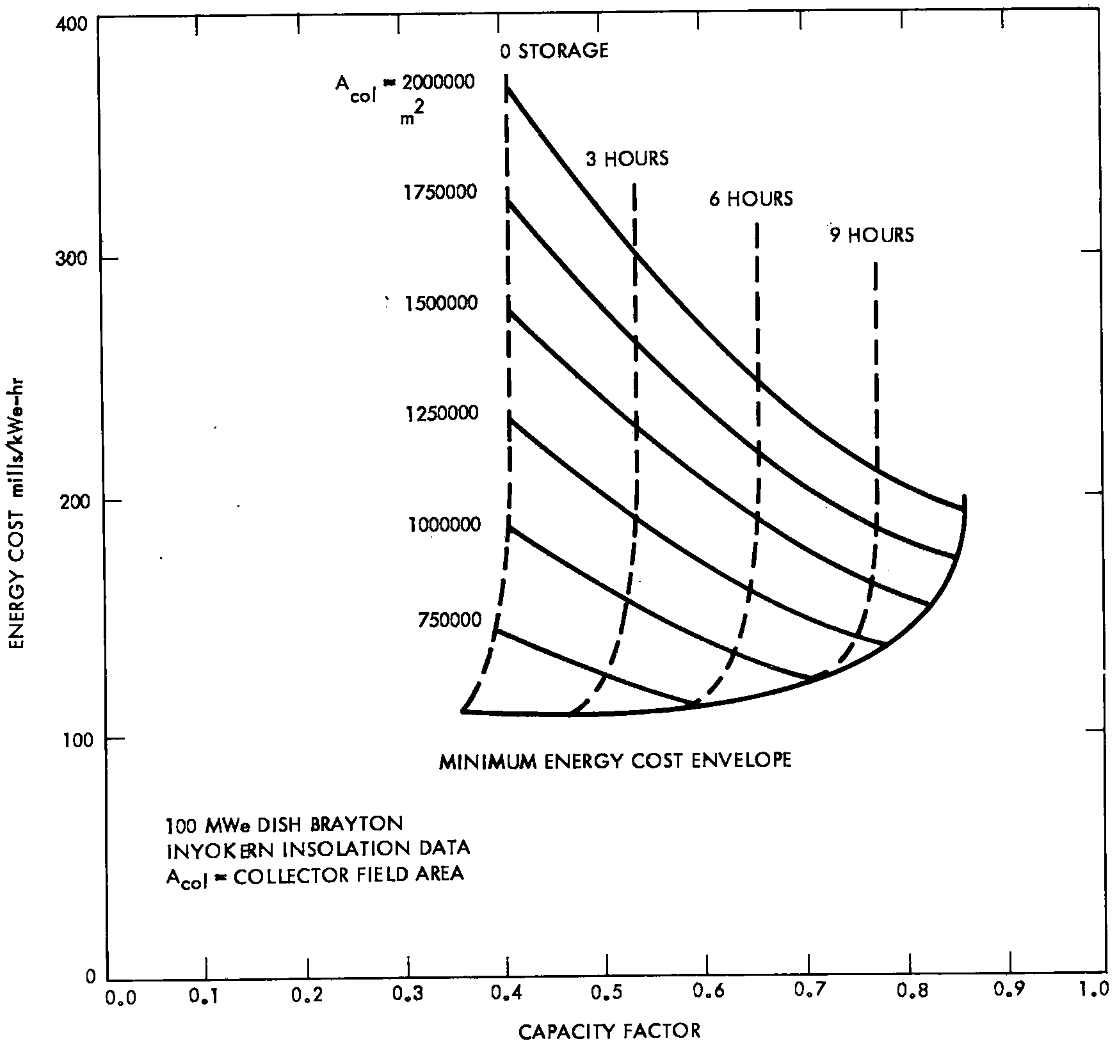


Figure 8-4. Point-Focusing Brayton Engine Computer Simulation: Sample Case

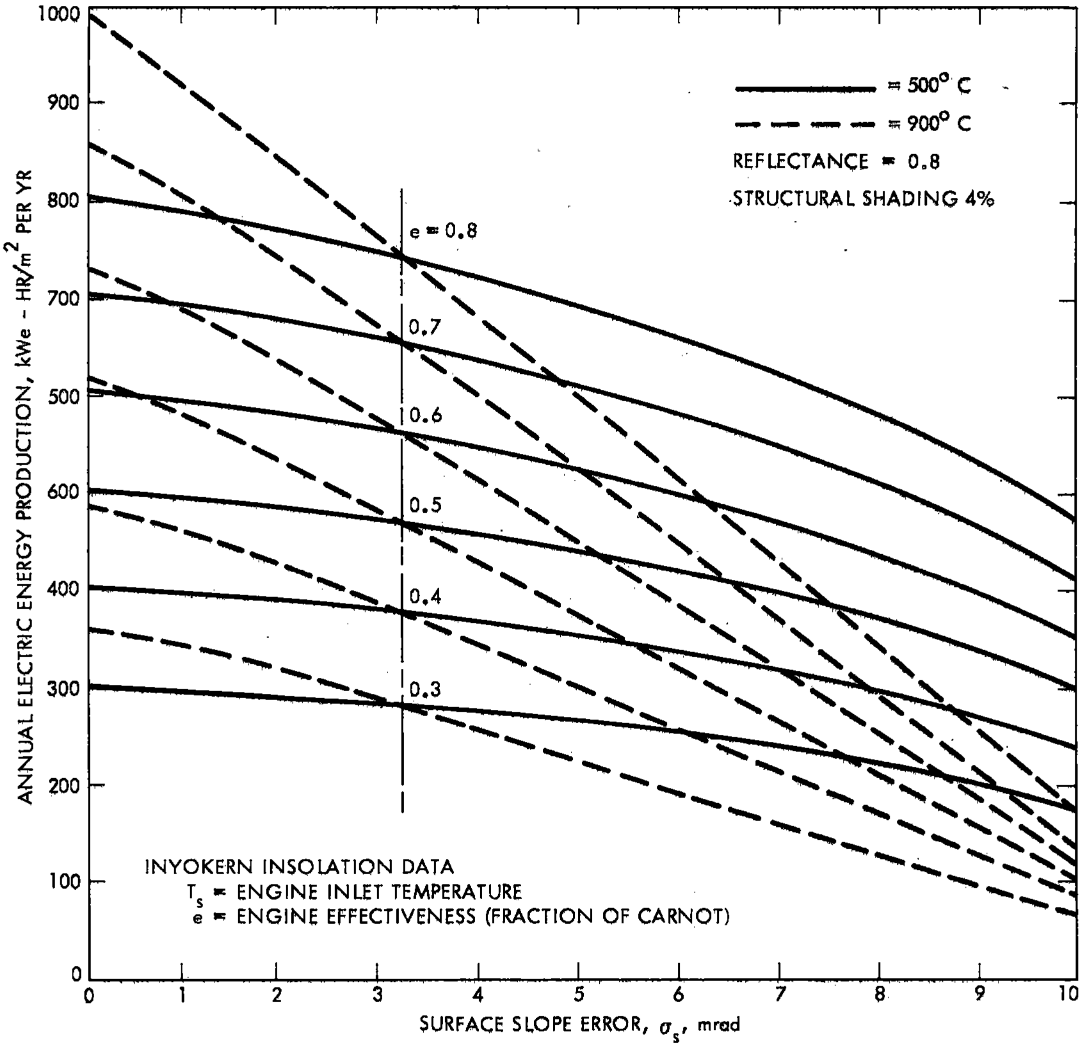


Figure 8-5. Annual Electric Energy Production Rate Versus Engine Effectiveness

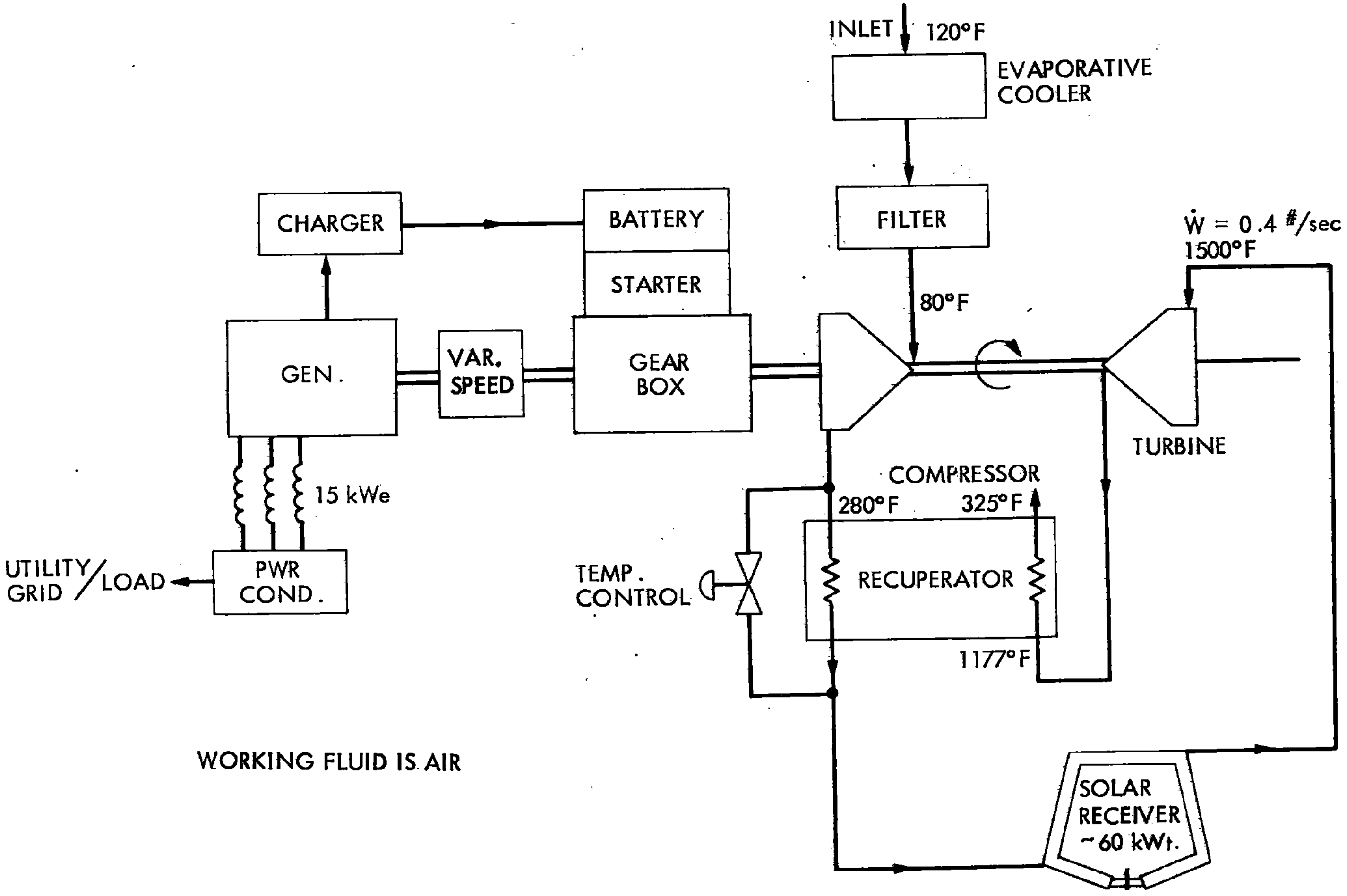


Figure 8-6. 15-kWe Brayton Solar Power Unit Schematic

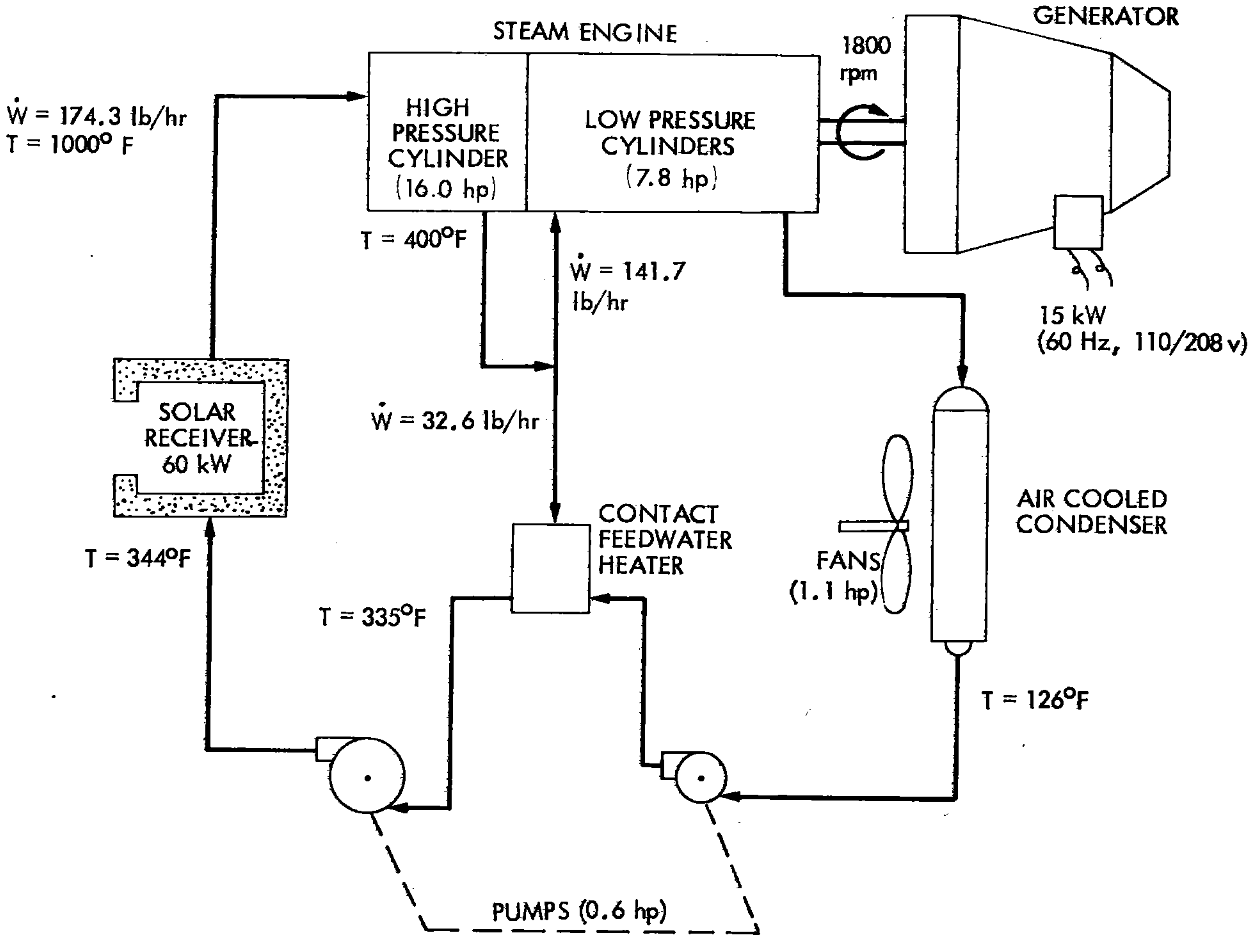


Figure 8-7. 15-kWe Steam Rankine Power Unit Schematic

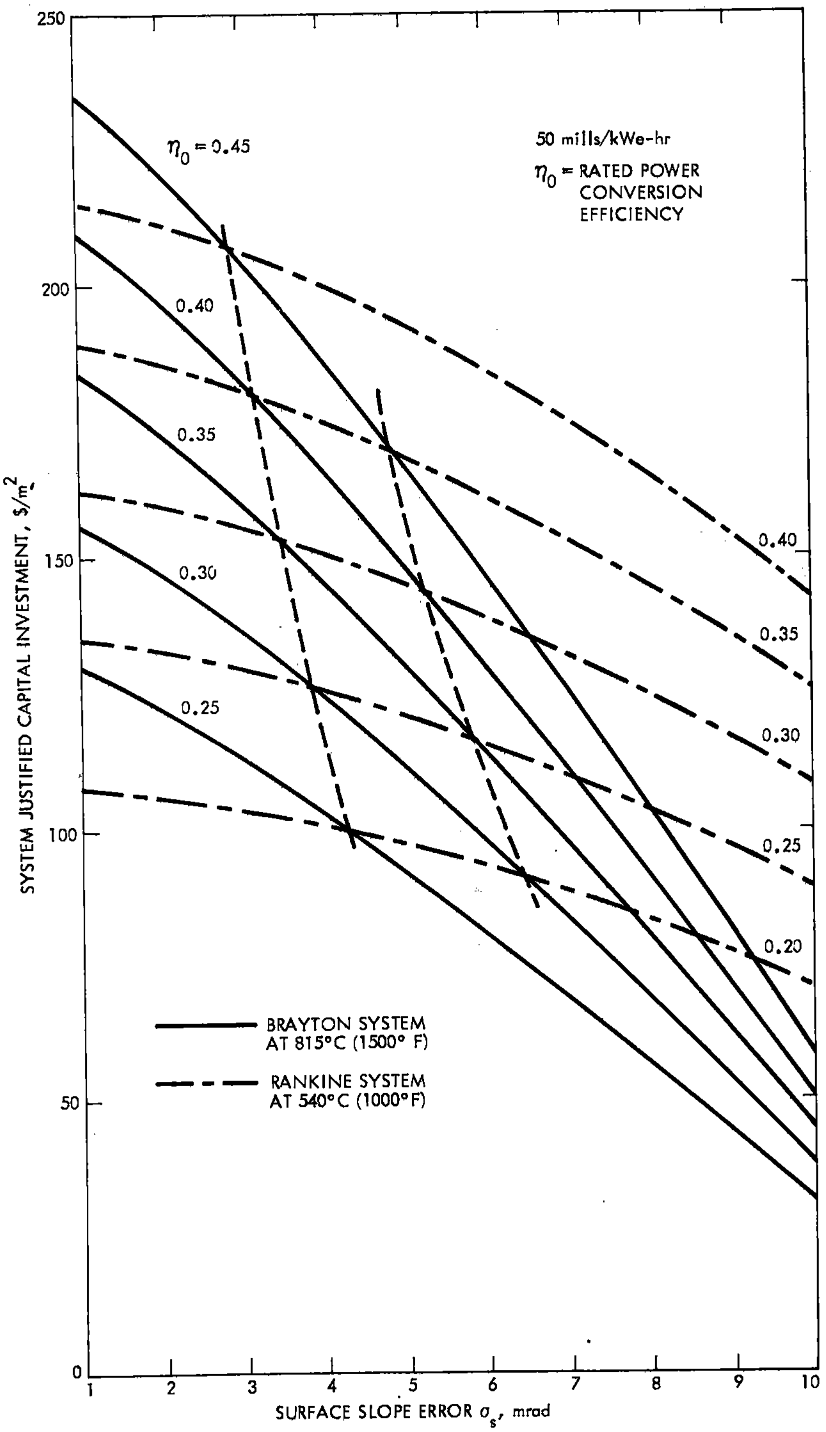


Figure 8-8. Justified Capital Investment of Representative Rankine & Brayton Systems for an Energy Cost Target of 50 mills/kWe-hr

cost by the concentrator area. Generally speaking, concentrators with larger surface errors should be used with Rankine systems, which have a lower power conversion efficiency compared to the higher temperature Brayton systems. Rankine systems, however, are less sensitive to concentrator quality. High quality concentrators (3 mrad, or better) are more compatible with Brayton systems at higher temperatures. The two, steep dashed lines in Figure 8-8 indicate the equal performance boundaries for the two systems when the Brayton efficiency is 5 percentage points and 10 percentage points higher respectively than the Rankine system.

Figure 8-9 shows the relationship between energy cost and capital investment. Rated power conversion efficiency was used as a parameter to illustrate the effect that increasing power conversion performance has on lowering the energy cost per capital investment, for a representative solar Brayton system.

c. Modules of Four Dishes. Emphasis has been placed on the single dish studies called Configurations 1, 2 and 3. These were the first applications of the computer program to point-focusing collectors. The energy costs predicted will not be significantly higher if a cluster of these dishes are connected electrically. It is generally realized that the same cluster of dishes might be more cost-effective if a larger, more efficient heat engine was used to service the entire cluster. The larger engine is expected to be more efficient and perhaps cost less per kilowatt output. A fluid transport system is needed, however, to connect the receiver with the more efficient engine, which, probably, would be ground mounted. There is the real possibility that the thermal loss from a well designed transport system, and the cost of such an added subsystem, might nullify the expected gain in engine performance. LeRC has recommended that the 60 kWe power conversion system be assumed to be 27.5% efficient; this compares with a 25% efficiency for the 15 kWe engine used in Configuration No. 2. In the case of steam Rankine systems, higher efficiency may be achieved using superheat and reheat between expander stages.

If land cost is neglected, dishes in the cluster of dishes electrically connected can be spaced so that shadowing of one by another is not a problem. As mentioned earlier, thermal loss from the transport pipes must be minimized and their lengths must be as short as possible, consistent with the shadowing problem. A four-dish system is large enough to work out this tradeoff and the methods will be applicable to larger systems.

Although multiple-dish modules have not yet been analyzed in detail certain preparatory support work has been accomplished. The shadowing problem has been examined for a diamond configuration of four dishes and equations have been developed from graphical data to enable computer simulation of the associated losses. The thermal pipeline transport losses have been explored in some detail for steam Rankine systems. Transport losses vary inversely with dish diameter because pipe lengths are proportional to the dish diameter, whereas the solar input varies with the diameter squared. A typical result is shown in Figure 8-10, which indicates the effect of latitude and, thus,

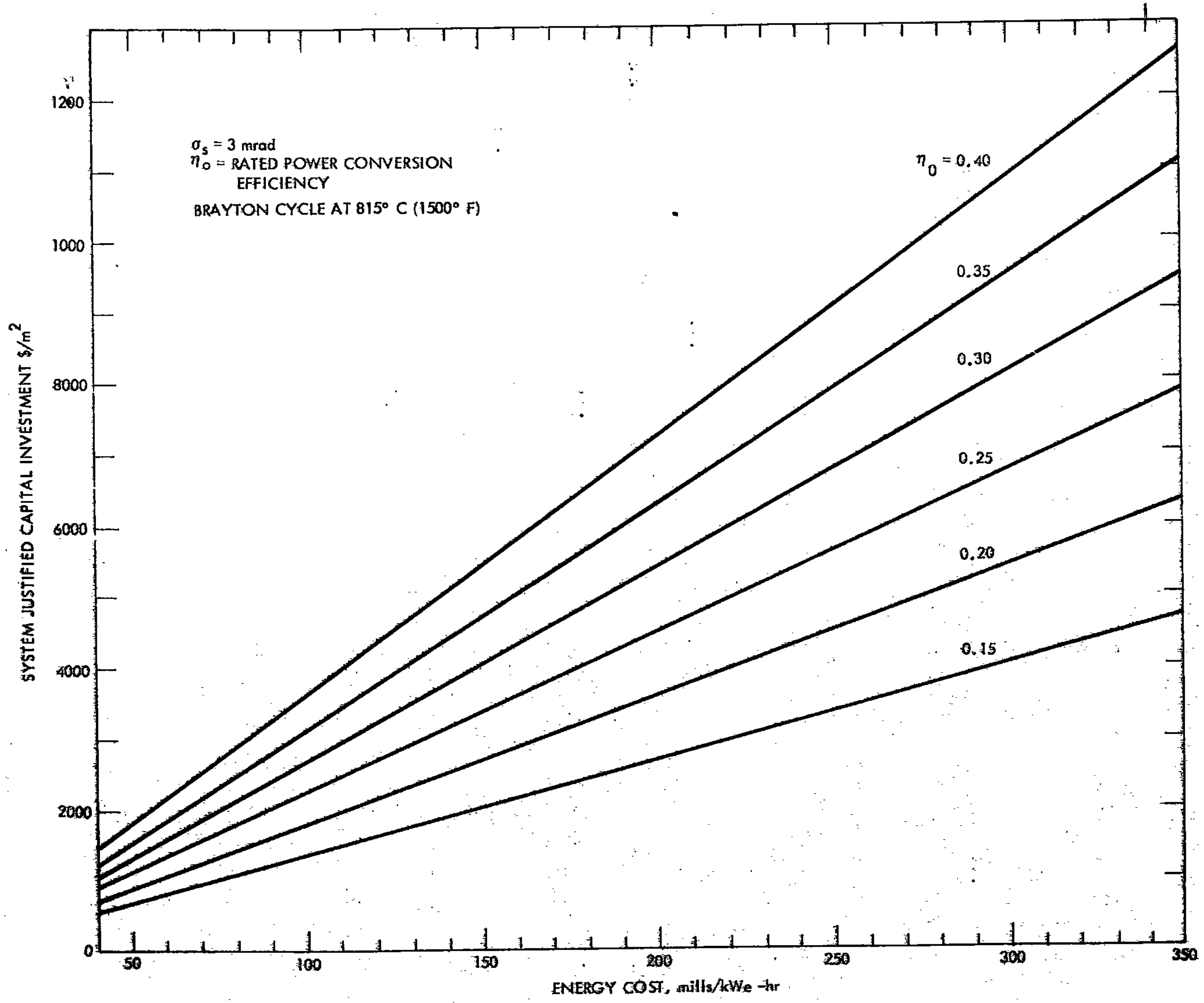


Figure 8-9. Energy Cost Versus System Capital-Investment for a Brayton System with a 3-mrad Concentrator

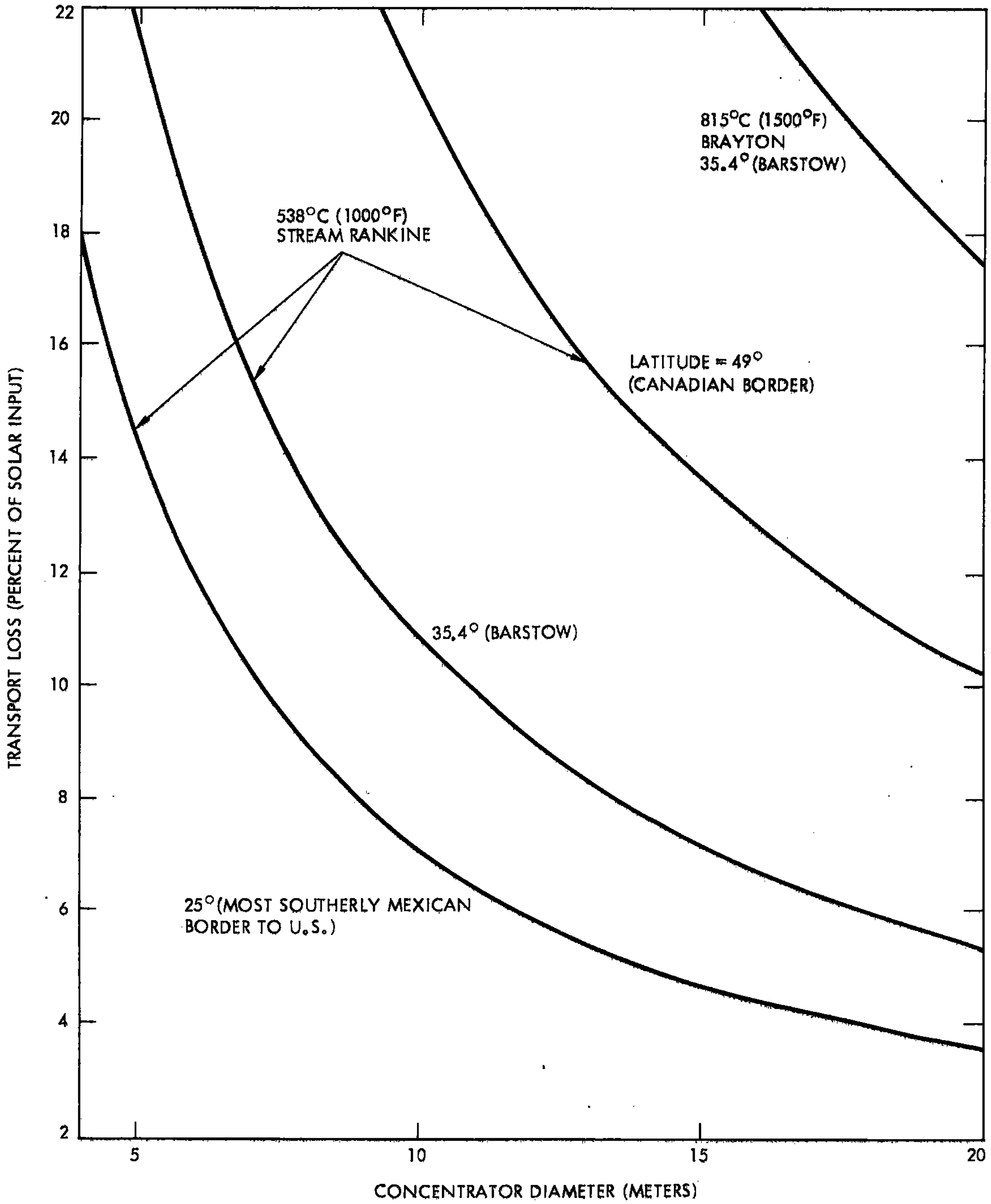


Figure 8-10. Transport Losses for a Four-dish Module as a Function of Concentrator Diameter for Several Latitudes

site location. The Brayton system (upper righthand corner, Figure 8-10) has a transport loss approximately three times greater than the Rankine system. This is due mainly to the higher operating temperature.

Early indications are that once-through steam Rankine systems can be improved by utilizing one of the dishes, in a four-dish cluster, to provide superheat. If the remaining dishes in the cluster produce saturated steam only, the lower temperatures will result in reduced transport losses. This type of cluster system offers potential cost savings in that only the superheat dish need have high optical quality. Of course, dish-cluster modules also are of interest in that the modular concept offers growth potential to fields of larger output.

d. Transient Analysis. Dynamic simulation activity was initiated in late FY 1978. In the first phase of the investigation, emphasis was placed on developing the necessary methodology and establishing viable approaches for this difficult problem. Transient thermal analysis of an open-cycle air receiver (Brayton system) currently is under investigation. Following this, an internal review will be conducted to examine the methodology and to evaluate the proposed approach prior to initiating the second phase of effort.

3. Cost and Performance Targets

An ongoing objective is to establish, monitor, and update system and subsystem cost and performance targets. This activity was initiated in FY 1978. Table 8-1 shows the preliminary cost and performance targets established for the PFDR subsystems for the years 1982 and 1985. The 1985 targets are consistent with an energy cost target in the range 50 to 60 mills/kWe-hr. This list lacks the level of detail needed to run computer simulations for specific candidate configurations such as the 15 kWe steam Rankine and Brayton systems. The initial estimates must be used with caution because they do not delineate module size (capacity), system operating temperature, or mass production rate. Additionally, they do not specifically relate quality and cost, e.g., concentrator quality versus cost.

An alternate approach is to vary cost and performance in a sensitivity analysis that spans the range of the current target values, including energy cost. Then, observations from the data can be made by assuming selected combinations of subsystem cost and performance without recourse to rigid target values. This adopted approach was utilized in the work described in Section D-2b, Page 8-10 of the present report, as reflected in Figures 8-8 and 8-9.

The target values listed in Table 8-1 will be reviewed and updated periodically (Figure 8-1) as information is generated by the Manufacturing and Development Task and other PFDR tasks, and from information obtained from subsystem contractors and industry. The analysis approach adopted by Systems Engineering will provide the discrimination necessary to select optimal PFDR systems in the future when practical/realistic cost and performance values approach the target values.

Table 8-1. Current PFDR Subsystem Cost and Performance Targets

Subsystem	Targets for FY	1982	1985
Concentrators	Cost in mass production	\$100-150/m^2	\$70-100/m^2
	Reflector efficiency	90%	92%
Receivers and Energy Transport	Cost in mass production	\$30/kWe	\$20/kWe
	Efficiency	80%	85%
Power Conversion	Cost in mass production	\$75/kWe	\$60/kWe
	Efficiency	25%-35%	35%-45%

4. Commercial Module

This new thrust was initiated in May of 1978. It was established that the Omnium-G module was the only point-focusing, two-axis tracking, solar thermal power system available in the commercial market. PFDR personnel visited the Omnium-G Company in May and September of 1978 in an effort to gather as much technical information on the module as possible. A procurement action was initiated in the latter part of June and a purchase order was issued in September. Delivery of the concentrator/tracker portion of the module is expected in December of 1978 and the remainder of the system in February of 1979. Two spare concentrator petals and a spare receiver also were ordered for purposes of separate laboratory testing, and for backup.

The Omnium-G module utilizes a 6 m diameter dish consisting of 18 separate reflector petals staggered to reduce wind loading, and has a 4 m focal length. The receiver has a molten aluminum bath that provides about 20 minutes of thermal storage reserve. The power conversion subsystem utilizes a low-performance reciprocating steam engine. The module is reputed to incorporate automatic startup and shutdown, and automatic sun tracking. Both electrical and thermal output can be provided. According to company literature the module will produce 7.5 kWe at steady state (and peak insolation at Anaheim, CA) and a nominal 30,000 BTU thermal output in addition. Thermal output is stored in a 500 gal insulated container and can be used, for example, to heat domestic hot water. Peak electric power output for short periods is estimated by company officials to be 10 kWe.

A main goal will be to establish the (now uncertain) performance of the Omnium-G system module. This will be accomplished at the Point-

Focusing Solar Test Site, Edwards Test Station, Edwards Air Force Base. The PFSTS is the responsibility of the Test and Evaluation Task and is managed and operated by JPL personnel. Systems Engineering has responsibility for procurement of the module and overall coordination of the evaluation effort. Test operations and scheduling will be provided by the Test and Evaluation task with consultation from the design team. Tests will be performed first at the subsystem level and then will proceed through a complete system test. Throughout the testing period the subsystem task areas will remain cognizant of their respective subsystems. Aside from early hardware performance data, it is anticipated that other benefits will accrue: (a) early "hands-on" hardware experience, (b) training of Test and Evaluation personnel in test operation and procedures, (c) experience in operating and maintenance, and safety procedures, and (d) verification of analytical design tools.

Methods for upgrading the performance of the Omnium-G module were considered. Performance improvement could be accomplished by replacing the standard engine with a different, higher performance engine. In consultation with LeRC personnel, several candidate engines and associated companies have been identified. Other questions will have impact; for example, it is not yet known whether a new receiver and transport system will be required. In August of 1978, System Engineering initiated a feasibility study to determine whether the technical and programmatic restraints imposed by an engine change could be accommodated within the PFDR schedule and available resources. Preliminary indications are that a complete replacement power module will cost more than has been budgeted for this purpose. There are uncertainties in the FY 1979 budget, but this effort probably will be funded if technical feasibility is established and schedule constraints can be met.

5. Other Activities

a. Papers Presented. L. Wen, "Thermal Optical Surface Properties and High Temperature Solar Energy Conversion," at the AIAA/ASME Conference in Palo Alto, California, May 24, 1978.

L. Wen, "Thermal Performance Tradeoffs for Point Focusing Solar Collectors," 13th IECEC in San Diego, CA, August 1978.

b. Study. An internal study was conducted on the field-modulated alternator. Past problems, such as low efficiency, have been overcome. The field-modulated alternator is an essentially high rpm device, suitable especially to Brayton engines; gear boxes are not needed. The device offers the potential of high efficiency, low weight, high reliability and durability, and low unit cost.

SECTION IX

TEST AND EVALUATION

A. INTRODUCTION

A necessary step in the development of concentrators, receivers, power conversion systems, related subsystems and components is their test and evaluation. The information gathered from these evaluations will lead to improved systems with a resultant reduction in cost, and greater efficiency.

Existing solar-thermal test facilities provide the capability for test and evaluation of components and subsystems for dispersed power systems with working fluid temperatures of up to 600°F. Point-focusing distributed receiver systems, however, will operate at working fluid temperatures between 600°F and 2,500°F. Therefore, a test site is being established to enable testing to be performed at these higher temperatures.

This section of the report presents the design approach and status of the task to provide a dedicated Point-Focusing Distributed Receiver (PFDR) technology Point-Focusing Solar Test Site (PFSTS).

B. OBJECTIVES

The objectives of this task are (1) to provide the required PFDR PFSTS capability at a minimum cost, (2) to perform testing and evaluation of point-focusing distributed receiver subsystems and system modules at working fluid temperatures between 600°F and 2500°F, and (3) to determine operations and maintenance parameters and data to support early commercialization of point-focusing systems.

C. APPROACH

1. Methodology

After intensive study of the alternatives available for providing the necessary test capability for the PFDR Technology Project, it became quite clear that two key parameters must be used in test site selection. These were: (1) An adequate, cost effective test site must be established within the budget allocation, and (2) Operational readiness of the test site was a major concern since a full-scale testing capability must be provided to support collector testing in early FY 1979.

The conclusion reached from this study was that the most cost effective way to establish a test site within schedule restrictions was to utilize existing JPL facilities. One JPL facility was immediately available for use by TPS Projects, which would satisfy near and far term test site requirements. This JPL facility is Edwards Test Station (ETS), located on Edwards Air Force Base, near Lancaster, California.

Accordingly, Building E-9 and the area immediately adjacent to it at ETS has been committed in support of this task. This site has been designated the Point Focusing Solar Test Site (PFSTS). An additional area for future expanded testing requirements has also been set aside at ETS. An Environmental Assessment was submitted to the Edwards Air Force Base Environmental Protection Committee detailing the PFDR technology program and goals. The Committee evaluated the submittal and issued an Environmental Assessment Certificate which allows JPL to proceed with the solar thermal test and evaluation activity. The next step was to obtain NASA approval for making minor modifications to the ETS facility. This approval was obtained, for FY 1978, from the local NASA office in December, 1977, and from NASA Headquarters in January, 1978.

2. Schedule

The PFDR Technology Project, Test and Evaluation (T&E) Task schedule for FY 1979 through FY 1983 is shown in Figure 9-1. The schedule indicates the major milestones and completion dates.

D. PROGRESS

1. Preliminary Design of the Data Acquisition System

Testing of the Test Bed Concentrator, receiver, and converter (CRC) modules will be conducted at JPL's Edwards Test Station at the PFSTS. To obtain the required data formatted for efficient analysis, during performance testing of the CRC modules, a computer automated Data Gathering and Processing (DGAP) system was designed by the Test and Evaluation task group.

DGAP equipment is required to periodically make parametric measurements, display the data in real time, monitor and record data on mass storage. The necessity of a computer processor system is dictated by the large volume of data to be processed, the need for real-time analysis of critical parameters, the requirement for graphical respresentation and off-line data analysis with higher mathematical functions, and the requirement for efficient system flexibility to support a wide range of testing. Figure 9-2 shows a block diagram of the major components of the overall system.

The raw analytical data from the CRC modules are channeled through remote interface circuitry in the field to a front-end processor in the Test Operations Center (Building E-9). The front-end processor multiplexes and converts the measured data into a format acceptable to the computer. An experimenter console is provided with real-time display of the acquired data. Low level mathematical data massaging is performed at the Test Operations Center, such as conversion to engineering units and simple waveform graphics. Finally, the data are recorded on magnetic tape reels for off-line analysis.

Relaying of the data to the Test Evaluation Center at JPL is via physical transportation of the magnetic tape reels, or via telephone

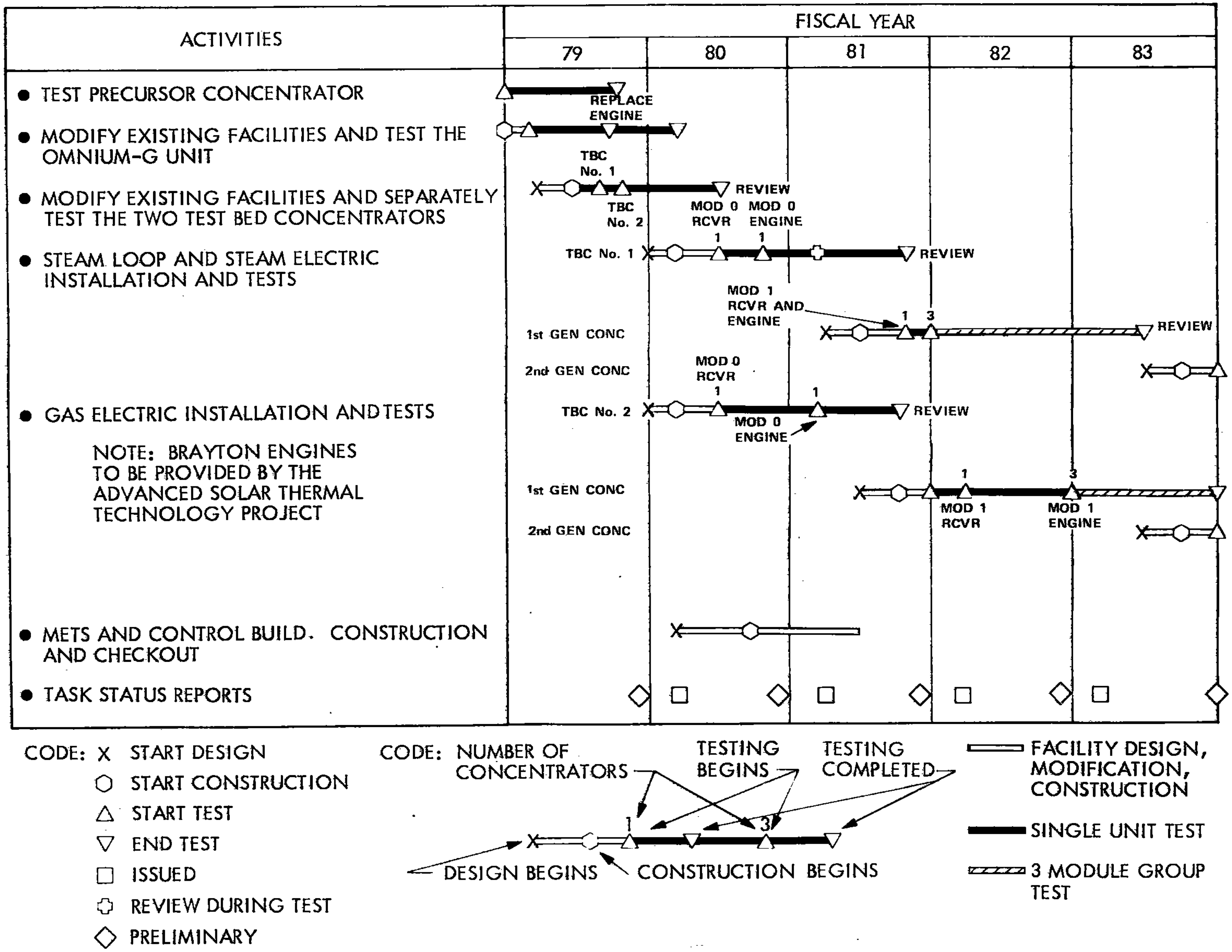


Figure 9-1. Five-Year Subsystem/System Test and Evaluation Schedule

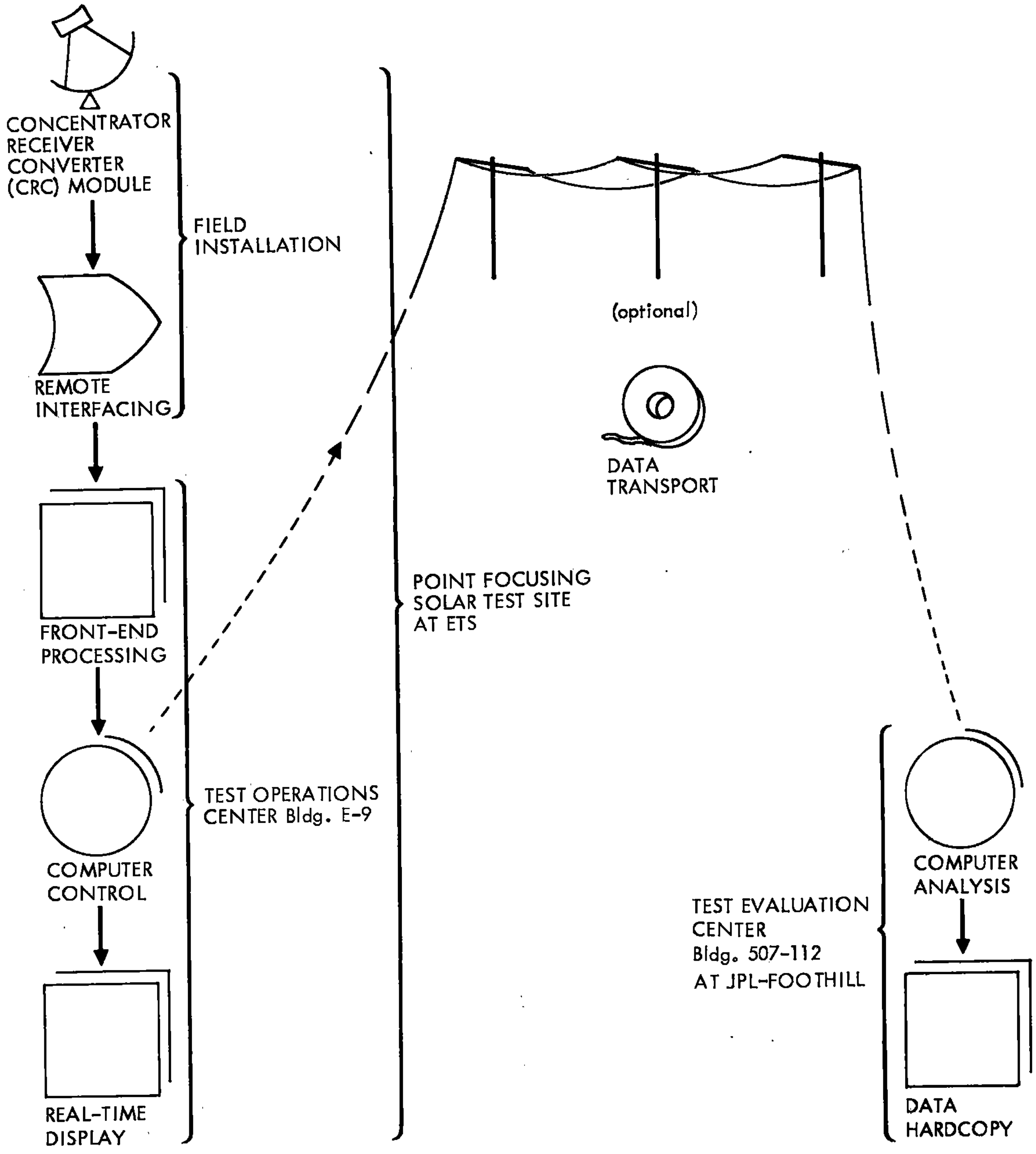


Figure 9-2. Data Acquisition Concept

communication. High level data reduction and analysis is then performed at the discretion or need of the experimenter. Report quality hardcopy of desired data and calculations is also provided. The location of the Test and Evaluation Center will be physically close to its users to facilitate interactions and reduce turn-around time. In addition to evaluation of test data acquired at the PFSTS, the Test Evaluation Center is used to develop the software necessary at the Test Operations Center.

2. Data Gathering and Processing Equipment Requirement Analysis

The testing schedule is shown in the milestone chart of Figure 9-3. The equipment necessary for the Precursor and Omnium-G module testing is shown in Figure 9-4.

For the Precursor Concentrator, the major sensors include thermocouples at the cold water calorimeter, a flux mapper to characterize the focal point flux, and a pyrheliometer mounted adjacent to the Concentrator. Analog signals are scanned and converted to engineering units by a data logger, and stored on magnetic tape via a PDP-11/10 minicomputer. Tabular printout of the measured parameters is provided at the printer, while disks and consoles support the minicomputer operation.

For the Omnium-G module, the following additional items are added. A link to the meteorological subsystem allows for real-time display and storage of meteorological data. An analog input interface to the minicomputer processes data from the flux mapper while a digital interface processes data from azimuth and elevation encoders. Finally, an Omnium-G module support equipment panel is incorporated to remotely monitor and control concentrator operation. The minicomputer is capable of monitoring the operational status of the CRC and to automatically execute system level commands.

During Omnium-G module testing, a PDP-1134A minicomputer at the Test and Evaluation Center will be used to reduce CRC test data, generate hardcopy printouts, and to develop software programs. The minicomputer is supported with operator terminals, extended memory, disks, magnetic tape, and a printer/plotter.

3. Preliminary Design of Control Room Electronics

The electronic DGAP equipment is divided into subsystems. The remote interfacing and front-end processing are included in the interface subsystem. Meteorological or weather and insolation data are monitored by the meteorological subsystem (MSS). The interface subsystem and weather data are processed by the computer subsystem. Display of the data is a subset of the experimenter subsystem. Finally, all other hardware supporting the above and/or the CRC modules is grouped as the operations support equipment (OSE).

The Interface Subsystem consists of remote interface electronics such as junction-boxes and conditioning circuits, a "communications highway," to transfer measurements from the field to the Test Operations Center (Building E-9), and front-end processing equipment,

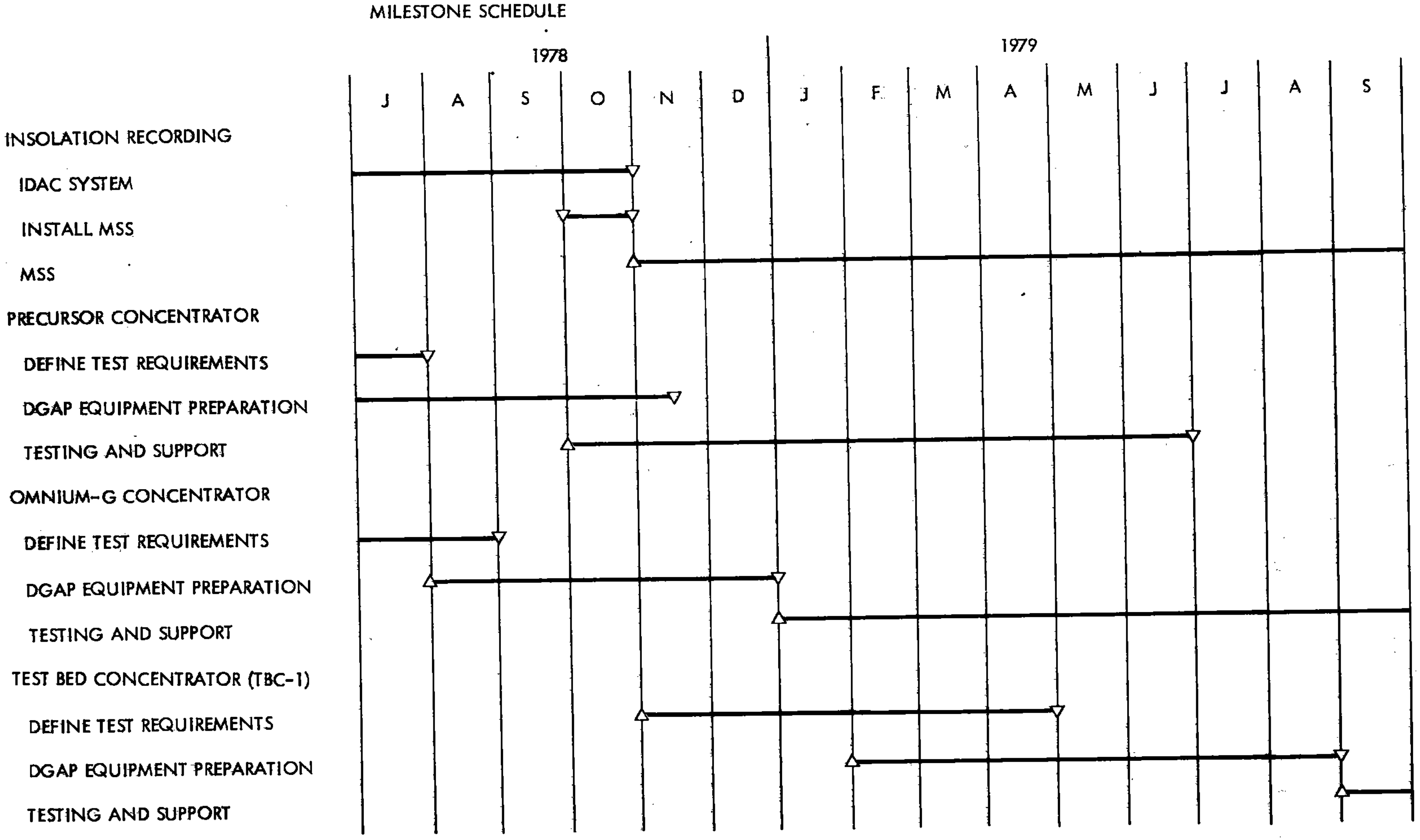


Figure 9-3. Near Future Test and Evaluation Milestone Schedule

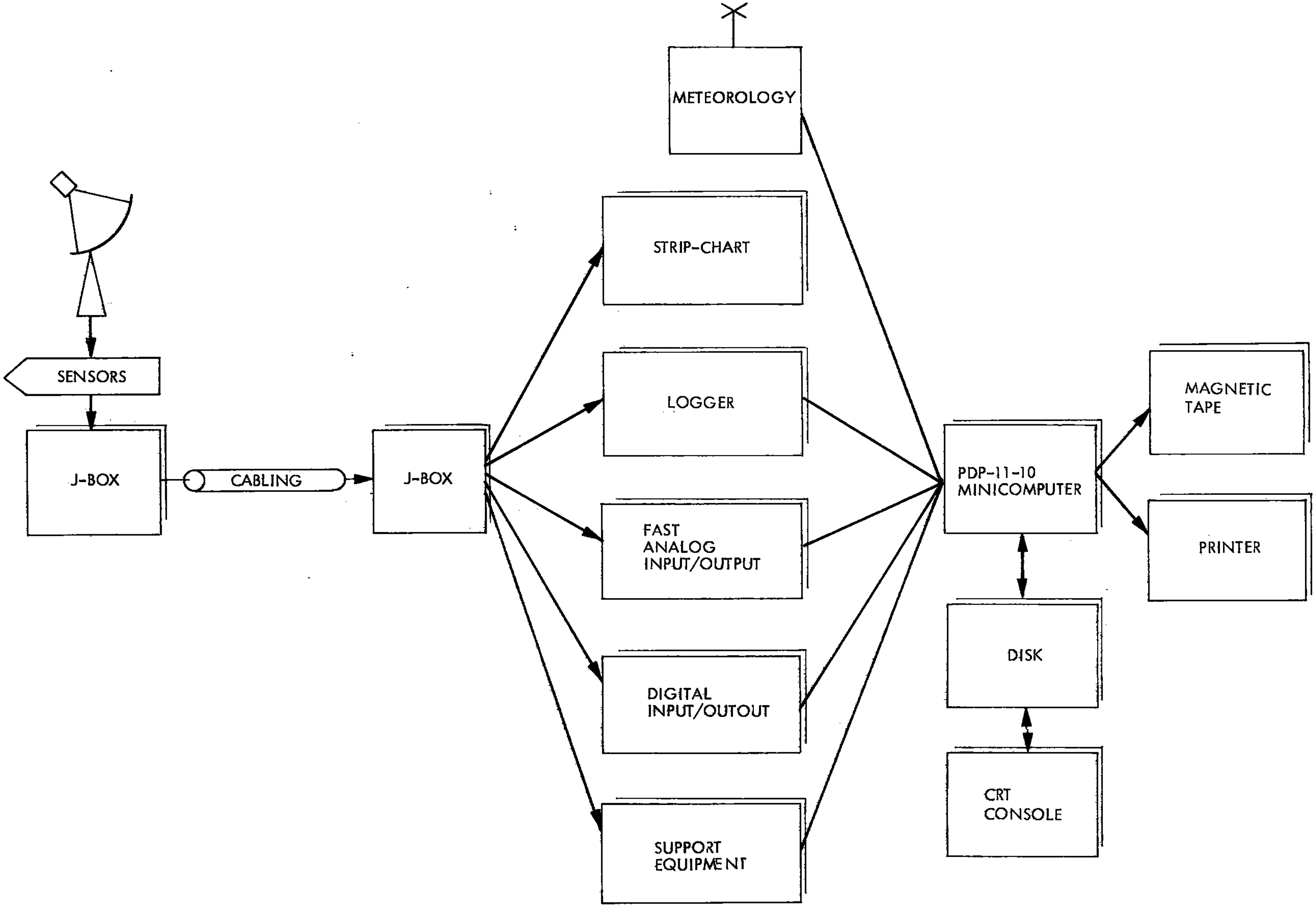


Figure 9-4. Data Gathering and Processing Configuration for Precursor and Omnium-G Concentrators

including multiplexers, digital and analog input/output controllers, etc. For most analog signals, a commercial data logger is utilized.

To correlate CRC performance with ambient conditions, the meteorological measurements are recorded periodically. These include insolation, wind speed, wind direction, ambient air temperature, humidity, and inversion temperature (ΔT). Signals from meteorological sensors in the field are channeled to an analog logger. The logger dumps the accumulated data onto a magnetic tape recorder for permanent storage. The subsequent tape reels are transported to the Test and Evaluation Center for data reduction and hardcopy. The Meteorological Subsystem operates in a stand-alone manner continuously for 24 hours a day, 7 days a week.

4. Preliminary Test Requirements

Test requirements for the Precursor Concentrator and Omnium-G module have been compiled.

The test requirements for the Precursor are primarily:

(1) Thermal performance of single and multiple mirror facets using a cold water calorimeter.

(2) Flux mapping of the fireball.

(3) Investigating mirror alignment techniques.

The requirements for the Omnium-G module are summarized in Table 9-1.

Considerable effort has been spent in gathering test requirements for the Test Bed Concentrators. These are essentially an extension of the test requirements for the Precursor Concentrator and Omnium-G module. The requirements will be expanded further in preparation for Test Bed Concentrator testing in FY 1979.

5. Data Logger

The data acquisition subsystem for the PFDR technology program utilizes a microprocessor controlled (smart) data logger as a front end to the minicomputer. Together they provide the basic data gathering and processing capability needed at the PFSTS.

Three Acurex Autodata Nine data loggers have been ordered and received. One is being installed at the ETS Building E-22 facility, to acquire weather data and insolation measurements. This unit includes a crystal clock and clock keep-alive battery option. The remaining two loggers are located at the PFSTS Building E-9. These two loggers will support the precursor concentrator and Omnium-G module solar powered electric generator system tests.

Table 9-1. Test Requirements for Omnium-G Module

Concentrator	Receiver	Power Conversion Rankine
Reflectivity measurements	Focal spot location	Engine performance
Alignment techniques	Off sun focal point	Engine efficiency
Concentration ratio	"Normal" tests (thermal)	Condenser performance
Tracker physical characteristics	Whole day	Pump performance
Moon track	Sunset operations	Pump efficiency
Solar tracking error	Sunrise operations	Off-nominal performance
Cold water calorimeter tests	Transient operations	Generator performance
Flux map	Varying meteorological conditions	
Off axis tests		
On sun tests		

6. Insolation Measurement Program

Insolation measurements were begun in October 1977 at ETS, Building E-22. This facility is approximately 500 feet from the PFSTS. Measurements being taken and recorded include:

(1) Direct component of radiation, using two pyrheliometers.

(2) Total sky radiation, using a pyranometer.

(3) Wind speed.

(4) Wind direction.

(5) Inversion temperature (commonly expressed as ΔT).

(6) Humidity
(7) Temperature
} These measurements will begin in FY 1979.

7. Point-Focusing Solar Test Site - Modifications

Utilization of the existing JPL facility (ETS) resulted in minimal modifications to develop the PFSTS. An existing building (E-9) is used as the control room and will house all the necessary electronic equipment used to monitor and control the concentrators, receivers and power conversion units under test. All necessary electrical power already exists in the control room, so the only modifications required will be cable ducts to provide power, command, and signal lines between the control room and the units under test in the field. External to the building, minor grading will be required to provide a flat surface for the concrete pads upon which the concentrators will be mounted. Trenching for the power and signal lines for each collector will also be required.

The cable ducts, concrete pad and necessary power and signal lines have all been installed for the Precursor Concentrator. The only additional utility service necessary for the Precursor Concentrator is domestic water and this has also been provided. An existing grounding grid at ETS will be utilized by the PFSTS to provide the necessary earth ground for instrumentation and lightning protection. This ground grid is now in place for the control room and the Precursor Concentrator.

8. Point-Focusing Solar Test Site - Utilization Plan

A plan for the utilization of the PFSTS has been prepared. This is shown in the site plan in Figure 9-5. The first unit to be tested will be the Precursor Concentrator, followed by the Omnium-G unit and later by the Test Bed concentrators. All of this testing will be initiated in FY 1979, although extensive preparations have taken place in FY 1978. Building E-9 is the control room and will be the nerve center controlling all activities at the PFSTS.

Although not funded by the PFDR technology project, an area has been set aside in support of the Advanced Solar Thermal Technology Branch (ASTT) Project immediately to the north of E-9. A three meter concentrator is shown to the south of E-21 which is also part of the ASTT Project. The PFSTS thus takes advantage of the synergism involved in combining two projects. This will result in considerable cost savings to TPS Projects, because the PFDR and ASTT projects can use the same test personnel and support facilities, instead of providing for them separately.

9. Point-Focusing Solar Test Site - Survey and Soil Investigation

One of the first activities undertaken at the PFSTS at Edwards Test Station was a site survey and soil investigation. The site survey disclosed no unusual problems and the results will be kept on file to be used for positioning of the concrete pads for the various concentrators.

The soil investigation was accomplished for the purpose of exploring soil conditions. This was done by drilling two exploration borings at the PFSTS (where the Omnium-G module unit and the test-bed

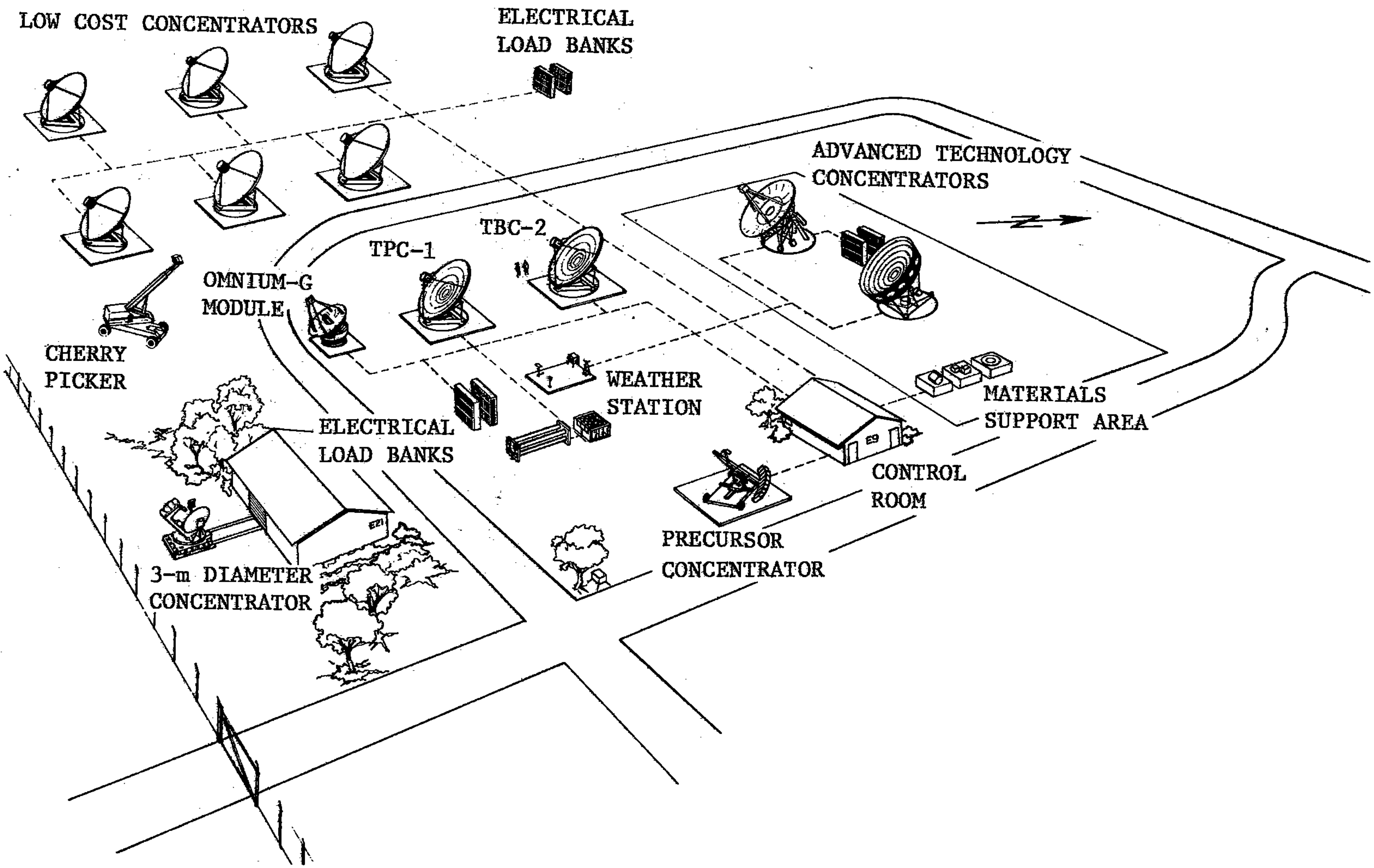


Figure 9-5. PFSTS for PFDR, ASTT and SPSA Projects

concentrators will be located) and by performing direct shear tests and consolidation tests on representative undisturbed samples of the soils obtained from the borings. The two borings were drilled to depths of 20 and 24 feet below the existing grade, using 20 inch diameter, bucket-type drilling equipment.

Existing fill soils were not encountered within the exploration borings. The natural soils consist of silty sand with some lesser deposits of clay and claylike sand. Deposits of caliche were encountered within the natural soils. The upper two to four feet of the natural soils are only moderately firm. Below the two to four foot depth, the natural soils are firm. Based upon the test results, the allowable bearing value is estimated to be 1,200 pounds per square foot for the soils within the upper four feet. Below the four-foot depth, the allowable bearing value would be on the order of 5,000 pounds per square foot.

10. Shading Analysis for Solar Collectors

A numerical study was conducted to evaluate the shading impact of trees and buildings on the collectors situated at the PFSTS.

To avoid shading of the collector situated in front, the centers of the collector pedestals must be separated by at least 31 m. The calculation was based on (a) 15 m diameter collectors with a pivot point 8 m above ground, (b) north-south alignment, and (c) shading at the winter solstice.

The preliminary calculations show no significant shading to the collectors during the conventional 8-hour work shift.

11. Quality Assurance

The present plan for Quality Assurance (QA) coverage is to inspect electronic equipment using "best commercial practices" as the inspection criteria. The criteria are based on a mutual agreement between the T&E team and the QA representative.

12. Preliminary Safety Aspects of Testing Thermal Power Systems at the PFSTS

As testing progresses from the Precursor Concentrator test phase to the Test Bed Concentrator test phase, the safety aspects for the PFSTS will become more involved. Initially, fairly simple safety requirements are needed, while the ensuing phases will require more elaborate, and stricter safety requirements.

The following safety documents will be used for all phases of testing:

(1) JPL Safety Practices (applicable portions).

(2) State of California Title 8 Industrial Safety Orders.

(3) ASME Boiler Code.

13. Transient Protection and Noise Reduction

High energy electrical transients can destroy sensitive electronic equipment if protection from these transients is inadequate. The two most prevalent sources of electrical transients are power main load switching, and lightning strikes. While these transients cannot be eliminated, they can be suppressed or bypassed to a point where they no longer pose a serious problem.

Transients riding on the power main, as seen at a conventional wall outlet, will frequently reach hundreds of volts and occasionally reach several thousand volts. These transients can couple into an electronic system and cause failures, component degradation, or erratic operation. Circuitry for reducing problems from transients has been included in the design to minimize the possibility of problems in the PFDR electronic equipment at the PFSTS. The design incorporates good grounding techniques, the use of isolation transformers, and three-electrode gas filled surge arrestors across the power main.

14. Preliminary Design Review

A test and evaluation preliminary design review was held on April 3, 1978, at JPL. The preliminary design review covered in detail all areas of the test and evaluation task. The major categories covered by the review included:

(1) System Definition

(2) Design Requirements

(3) Test Requirements

(4) System Description

(5) Initial Installation

(6) Projected Growth

All action items and concerns resulting from the review were responded to and closed out.

15. Operations and Maintenance Parameters

Development of Operations and Maintenance parameters and data to support early commercialization of point-focusing systems will begin in early FY 1979.