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Solar Thermal Power Systems  
Point-Focusing  
Distributed Receiver Technology Project  
NASA-CR 159715

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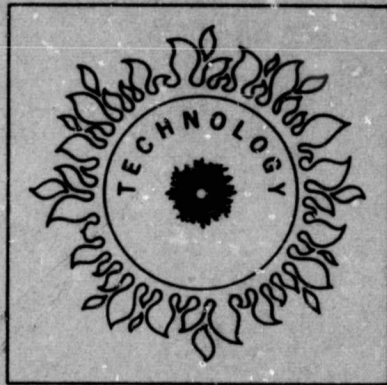
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# Annual Technical Report

Fiscal Year 1979

Volume II: Detailed Report



April 1, 1980

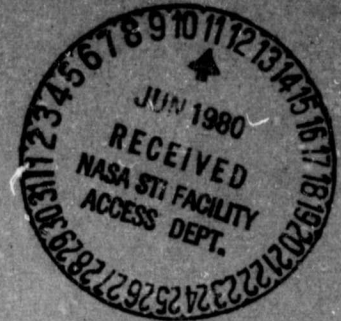
Prepared for  
U.S. Department of Energy  
Through an agreement with  
National Aeronautics and Space Administration  
by

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

and

NASA Lewis Research Center  
Cleveland, Ohio

(JPL PUBLICATION 79-112, VOLUME II)



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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.

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develop low-cost solar thermal and electric power plants.

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## ABSTRACT

This report details accomplishments of the Point-Focusing Distributed Receiver Technology Project during Fiscal Year 1979.

The objective of this Project is to produce thermal and electrical power from the sun's radiated energy by means of Point-Focusing Distributed Receiver (PFDR) technology. A specific goal of this effort is to develop industrial capability and system designs which will enable power produced by PFDR technology to be economically competitive with other energy sources.

Present studies involve designs of modular units that collect and concentrate solar energy via highly reflective, parabolic-shaped dishes. The concentrated energy is then converted to heat in a working fluid, such as hot gas. In modules designed to produce heat for industrial applications, a flexible line conveys the heated fluid from the module to a heat transfer network. In modules designed to produce electricity, the fluid carries the heat directly to an engine in a power conversion unit located at the focus of the concentrator. The engine is mechanically linked to an electric generator. A Brayton-cycle engine is currently being developed as the most promising electrical energy converter to meet near-future needs.

## FOREWORD

The Distributed Receiver 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 parabolic dish systems.

This report presents the results of activities conducted by the Jet Propulsion Laboratory during FY 1979 in support of this DOE Section. Specifically, it discusses the Point-Focusing Distributed Receiver (PFDR) Technology Project.

The PFDR Technology Project was initiated in August 1977 by 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 leading the development of point-focusing technology for use in applications projects.

This Technical Report covers the accomplishments during FY 1979, the second year of the Project. It is intended as a means of publishing results produced to date and disseminating this information to industry and universities. If additional information is needed or if the reader wishes to discuss any items, please contact Dr. John W. Lucas, Assistant Thermal Power Systems Manager for PFDR Technology, at Jet Propulsion Laboratory, FTS 792-9368, 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 part of the Thermal Power Systems (TPS) organization at JPL. TPS is an element 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 and provide thermal power for rural communities and farms, municipal customers and industrial users by means 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. As shown in Figure 1-2, 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 organic Rankine, the gas Brayton (open and closed cycle), and the Stirling. For thermal power production, the power conversion unit is replaced by the energy transport network, also shown in Figure 1-2.

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 15 meters. 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 aperture 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 1-3 indicates how several modules might be arranged to deliver electricity to a transmission grid. Many other arrangements are possible.

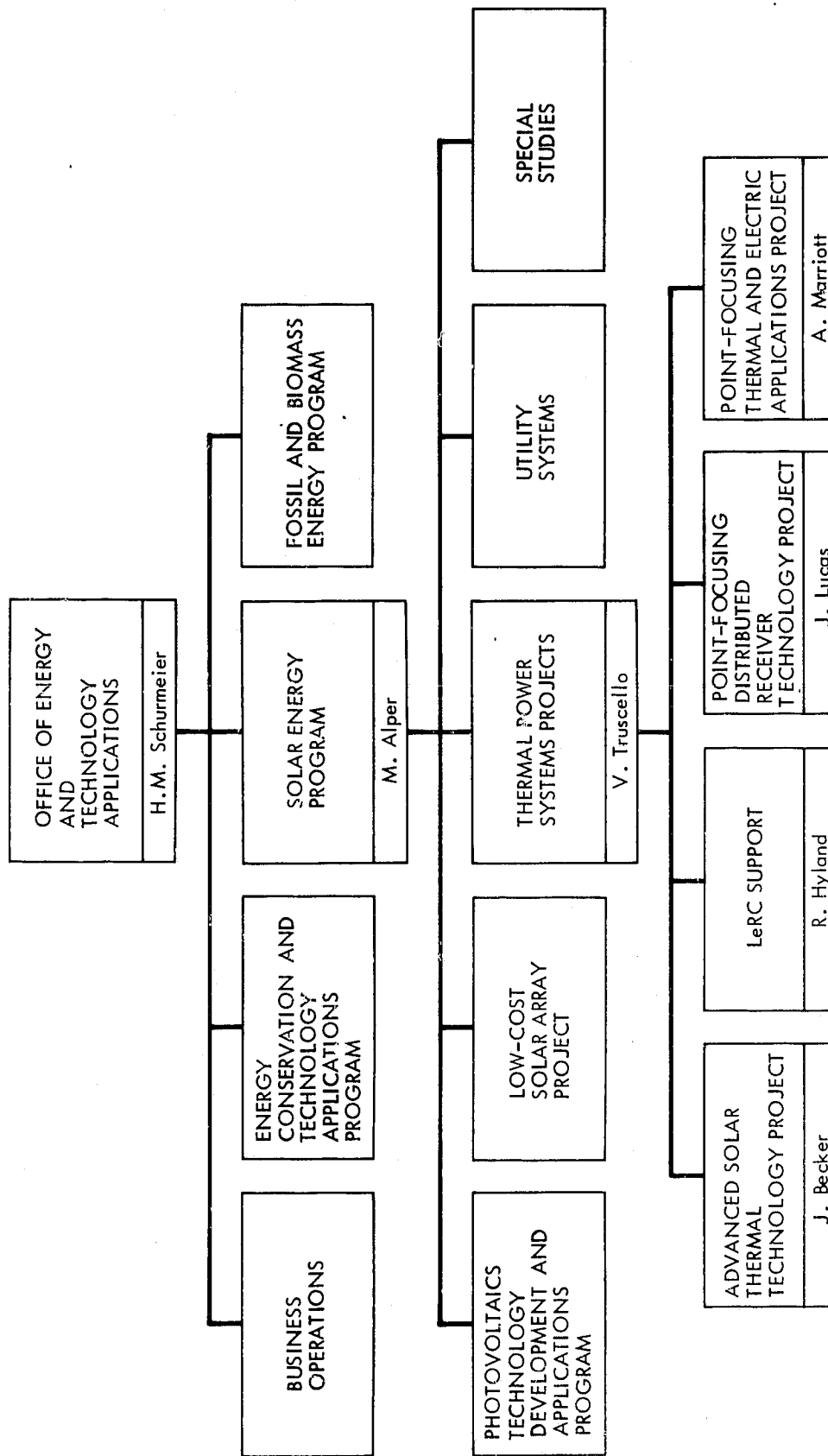


Figure 1-1. Thermal Power Systems Projects Organization Structure

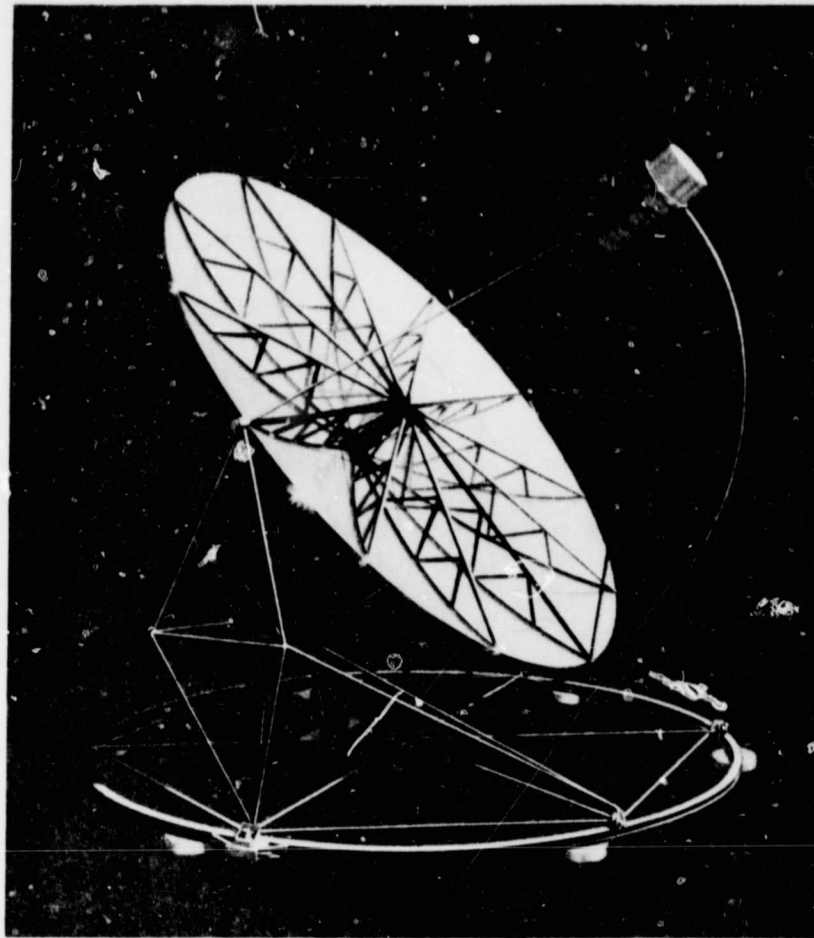


Figure 1-2. Typical PFDR Parabolic Dish Module

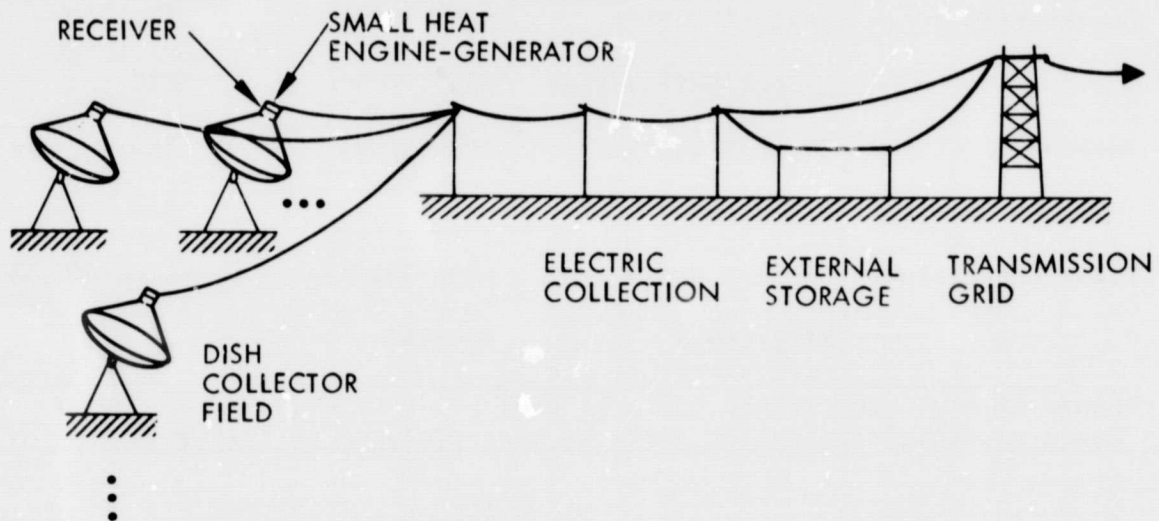


Figure 1-3. Parabolic Dish -- Electric Transport

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The goal of the Point-Focusing Distributed Receiver Technology Project is to develop the technology within industry for cost-effective, environmentally benign, point-focusing distributed receiver systems for electric and thermal applications. The preliminary cost and performance targets for electric power are shown in Table 1-1; targets for thermal power are being prepared. The cost targets will be achieved by industry employing new designs and mass production techniques for the major subsystems. For concentrators and receivers it is expected that the reduction arising from mass production, relative to costs of prototypes fabricated in very limited quantities, will be a factor of five; for power conversion units the reduction factor is expected to be a factor of ten.

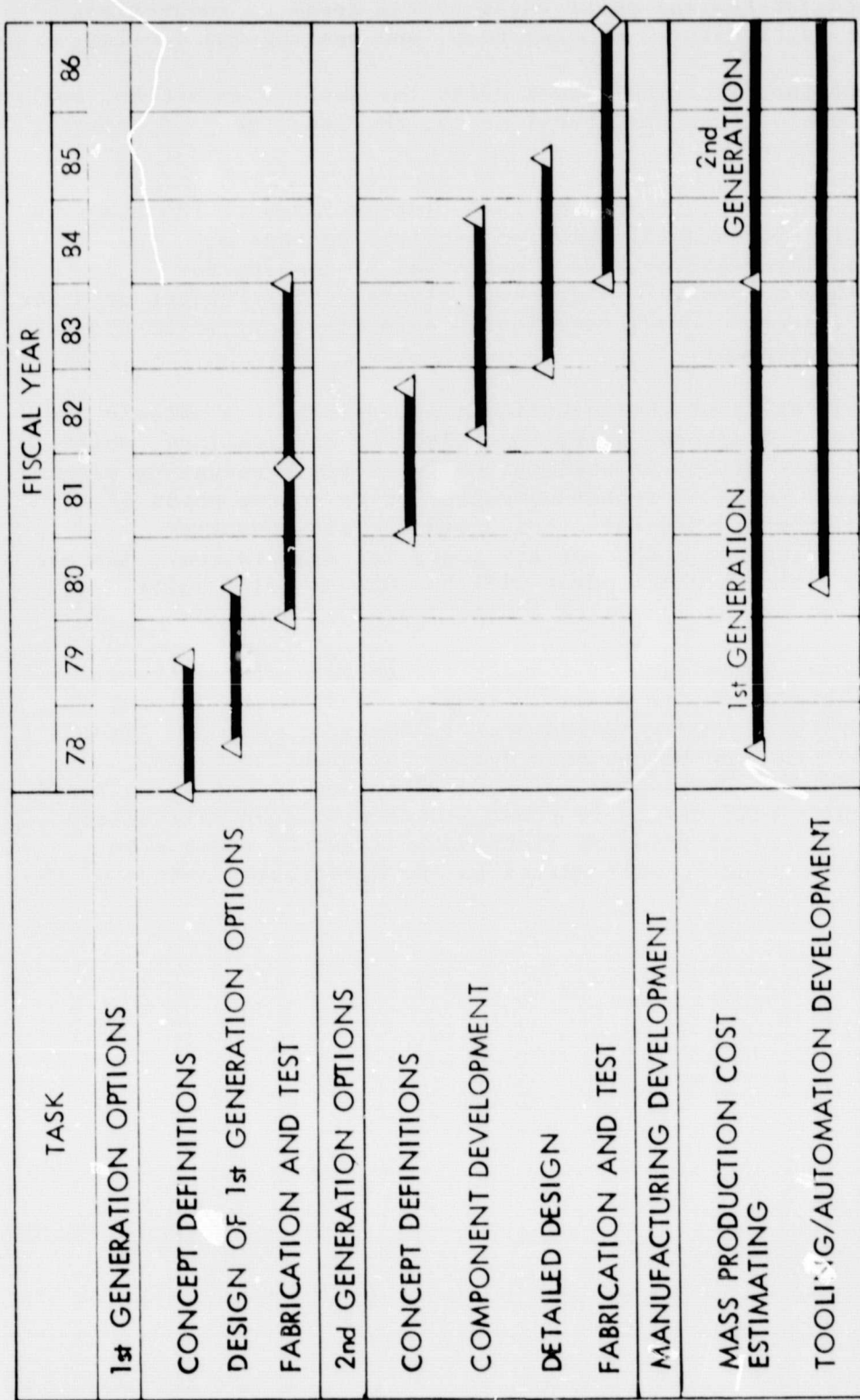
The major activity of the Project is to direct the development by industrial firms of the major subsystems listed in Table 1-1. The first generation subsystems are to be completed in FY 1982, as shown in Figure 1-4, to meet the associated performance targets. The costs shown in Table 1-1 should be interpreted as the costs that would result if the indicated mass-production levels were achieved. The second generation is to be completed in FY 1986 for the corresponding targets. The parallel effort to reduce mass-production costs is shown at the bottom of Figure 1-4.

Funding information for FY 1979 is provided in the Solar Thermal Power Systems Program Summary (DOE/CS-0145).

Table 1-1. Preliminary Cost and Performance Targets for Electric Power

Subsystem	Target Item	1982	1986
		First Generation (1978 \$)	Second Generation (1978 \$)
Concentrators	Capital Cost*	\$100-150/m <sup>2</sup>	\$70-100/m <sup>2</sup>
	Mirror Reflectance	78%	92%
Receivers	Capital Cost*	\$40-60/kWe	\$20-40/kWe
	Efficiency	82%	85%
Power Conversion	Capital Cost*	\$200-350/kWe	\$100-200/kWe
	Efficiency	25-35%	35-45%

\*Range of first-generation costs if mass-produced at 5,000-25,000/yr.  
 Range of second-generation costs if mass-produced at 10,000-1,000,000/yr.



CODES: △ START OR END OF ACTIVITY  
 ◇ VERIFIED MODULE AVAILABLE

Figure 1-4. Overall Schedule of Subsystem Development



## B. JUSTIFICATION

Markets for thermal power exist in the areas of industrial process heat, agricultural process heat, and heating and cooling.

Markets for electrical power exist for small communities, small utilities, remote locations, rural users, the Department of Defense and foreign countries.

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 based on modular units will result in power plants with good reliability. In addition, the point-focusing distributed receiver power plant offers a concept that is well suited to the distributed nature of the solar resource.

## SECTION II

### TECHNICAL APPROACH

#### A. GENERAL

The large majority of the requirements of this Project are met by contracts to industry and universities. JPL maintains a staff to manage the Project and has developed a base of technical expertise to coordinate, monitor, direct and support, as required, the activities under contract. In those instances where independent analyses are deemed desirable by DOE, JPL provides the resources and management to conduct such studies.

The seven tasks of the Project are as follows:

- (1) Project Management
- (2) Systems Engineering
- (3) Concentrator Development
- (4) Receiver and Heat Transport Network 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

A summary of major Project milestones through FY 1986 is given in Figure 2-1. 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. It should be noted that the concentrator, receiver and power conversion units assembled together comprise an individual module for electric power generation.

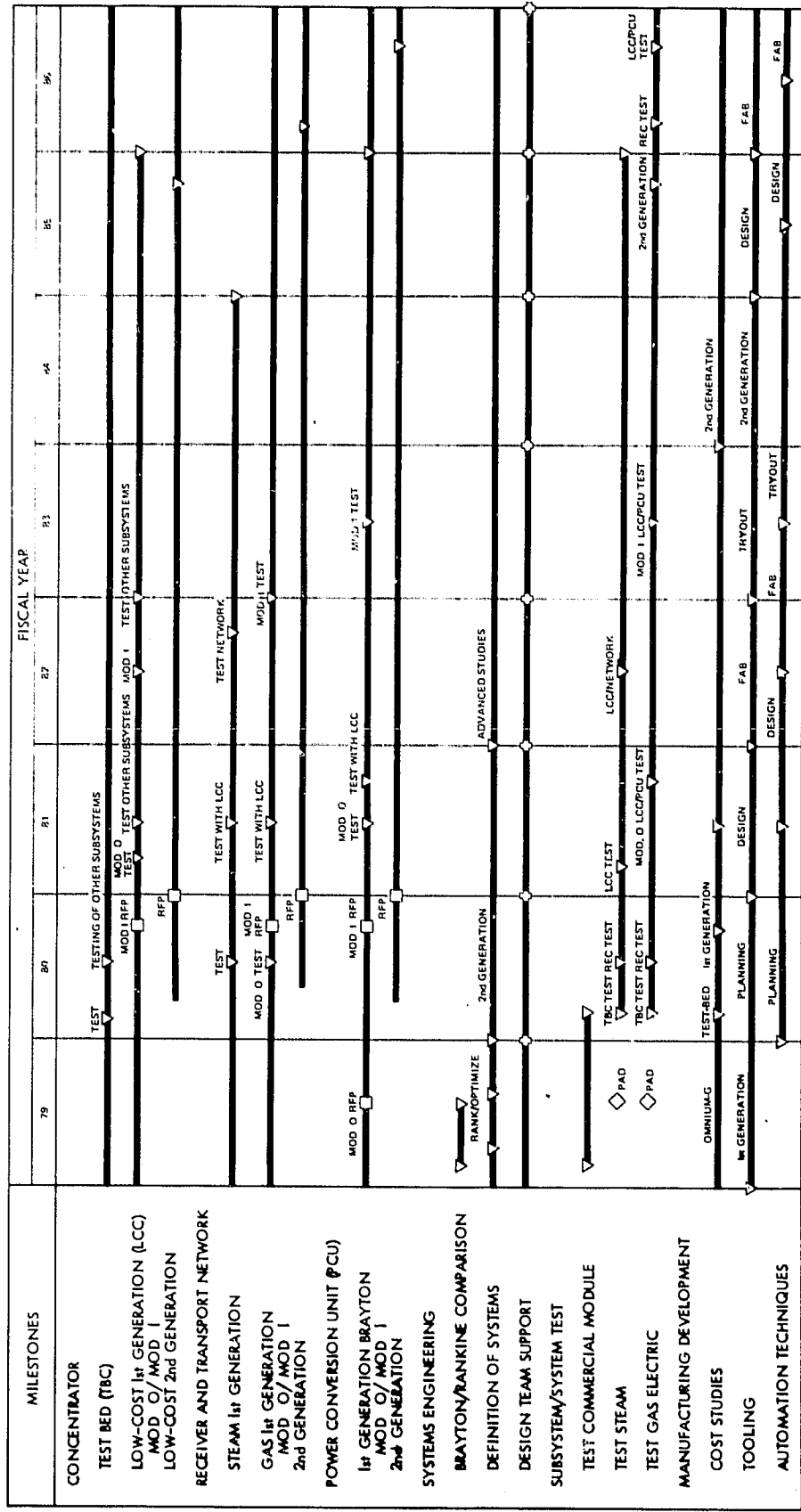
The major test periods are shown in Figure 2-2. Continuation of testing of the Omnium-G system module\* is shown in the upper portion of the figure. Testing of Test-Bed Concentrator No. 1 will begin in

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\*Heliodyne<sup>tm</sup> MTC-25 manufactured by the Omnium-G Company.

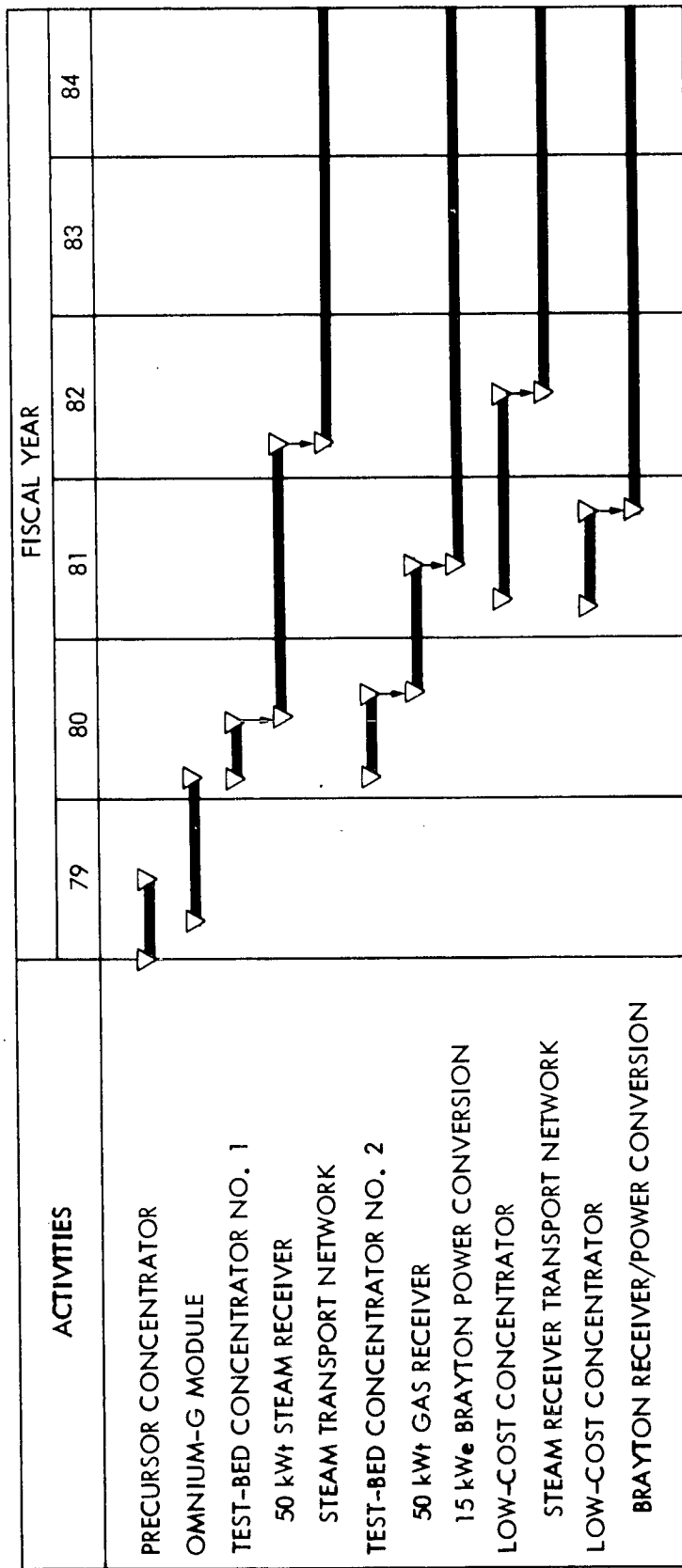
Table 2-1. Project Objectives by Task Area

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 plan.
Systems Engineering	<p>Lead and provide support to design team.</p> <p>Define and analyze system configurations.</p> <p>Establish and monitor system and subsystem performance/cost targets.</p>
Concentrator Development	<p>Develop point-focusing concentrators to provide sufficient energy for steam Rankine, gas Brayton, and future advanced cycles such as the Stirling.</p> <p>Optimize designs for low cost in large quantity production.</p>
Receiver and Heat Transport Network Development	<p>Develop cost-effective receivers to provide superheated steam and gas.</p> <p>Develop cost-effective heat transport networks.</p>
Power Conversion	<p>Provide efficient, cost-effective power conversion.</p> <p>Provide Brayton engines initially, and advanced Brayton and Stirling engines following early development by the Advanced Solar Thermal Technology Project.</p>
Test and Evaluation	<p>Provide a test site at minimum cost.</p> <p>Perform testing and evaluation of point-focusing distributed receiver subsystem modules.</p>
Manufacturing Development	<p>Estimate mass-production costs of subsystems.</p> <p>Develop tooling for mass production.</p> <p>Develop associated automation techniques.</p>



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Figure 2-1. Milestone Summary



CODE: ▽ START OR END OF TESTS

Figure 2-2. First-Generation Subsystem Test Periods

early FY 1980. After test and evaluation, the steam receiver will be installed on it and tested. The steam transport network will then be added to the assembly and tested. Following testing of Test-Bed Concentrator No. 2, the air receiver will be installed on it and tested. The air-Brayton power conversion unit will then be mounted on the receiver and the module tested. Testing will be carried out at the JPL Point-Focusing Solar Test Site (PFSTS)\*, at Edwards Test Station near Lancaster, California.

After modules based on the Test-Bed Concentrator have been developed and tested, modules based on the Low Cost Concentrator will be assembled and tested as scheduled in the lower part of Figure 2-2. In addition to the Low Cost Concentrator, these modules will consist of steam- and air-Brayton receivers, along with their respective steam transport networks and 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.

Periodic assessments of the technology are planned to assist in the determination of which configurations should be pursued in subsequent time periods. These assessments will be based upon criteria approved by the Department of Energy and will include inputs from both systems and each subsystem area. Anticipated assessment results include recommendations for the type of subsystem, and the temperature and power levels for each subsystem.

Initial work encompassed both steam-Rankine and air-Brayton subsystems. Due to future year funding constraints it was necessary during FY 1979 to select either steam Rankine or air Brayton for further effort. The latter was selected and the Brayton activity, then in the Advanced Solar Thermal Technology Project, was transferred to the PFDR Technology Project. As progress continues, work on advanced types may be added while effort on earlier ones may be completed or terminated.

\*In early FY 1980 the name was changed to Parabolic Dish Test Site.

## 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. Studies on the advancement of technology have shown that the time from laboratory to marketplace is generally from 20 to 50 years, and sometimes even longer, unless there is some special stimulation to catalyze the process. There is a national need to establish options for new energy sources as rapidly as possible; therefore, a plan for accelerating the technology transfer process is a major component of this Project.

The effort to accelerate the transfer process includes 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 and participation with the communities of interest will be a major effort.

At present, the supplier community of solar energy industries is 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 emphasize 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.
- (3) Providing computer codes to industry and universities.

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

(5) Exchange fellowships between industry and government.

A list of current PFDR technical papers is included in this Section.



TECHNICAL INFORMATION PAPERS

- A Preliminary Assessment of Small Steam Rankine and Brayton Point-Focusing Solar Modules, E. J. Roschke, et al, DOE/JPL 1060-16, (JPL Publication 79-21), March 1979.
- Comparative Study of Solar Optics for Paraboloidal Concentrators, L. Wen, L. Huang, P. Poon and W. Carley, 1979 ASME Winter Annual Meeting (79-WA/Sol-8) New York, New York, December 2-7, 1979.
- Efficiency of Dispersed Solar Power Modules, H. Steele, AIChE 86th National Meeting, Houston, Texas, April 1-5, 1979.
- Heat and Electricity from the Sun Using Parabolic Dish Collector Systems, V. C. Truscello and A. N. Williams, AIAA Utilization of Space Technology Conference, Los Angeles, California, November 15, 1979.
- Parabolic Dish Technology for Industrial Process Heat Applications, J. W. Lucas, Solar Industrial Process Heat Conference, Oakland, California, October 31-November 2, 1979.
- Point-Focusing Dishes, J. W. Lucas, DOE Advanced Solar Thermal Technology Semiannual Review, Long Beach, California, June 19-21, 1979.
- Point-Focusing Distributed Receiver Technology Project, Annual Technical Report - Vols. I and II, J. Lucas, DOE/JPL 1060-7; Volume I: Executive Summary, September, 1978, and Volume II: Detailed Report, Fiscal Year 1978; (JPL Publication 79-1); February 15, 1979.
- Solar Parabolic Dish Thermal Power Systems Technology and Applications, J. W. Lucas and A. T. Marriott, 14th IECEC, Boston, Massachusetts, August 5-10, 1979.
- Solar Thermal Power Systems Point-Focusing Distributed Receiver (PFDR) Technology: A Project Description, J. W. Lucas, E. J. Roschke, AIAA Conference on Solar Energy (78-1771) Phoenix, Arizona, November 27-29, 1978.

## SECTION IV

### CONCENTRATOR DEVELOPMENT

#### A. INTRODUCTION

Solar concentrators currently under development 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 at some other location on the module or on the ground. The thermal energy is also suitable for process heat applications. The point-focusing concentrator is considered an attractive form of solar energy collection because of its modularity, high efficiency, and ability to provide quality thermal energy in the 260°-1370°C (500°-2500°F) range.

The solar energy is focused by a highly reflective, parabolic-shaped dish that automatically tracks the sun by means of two axes incorporated into the support structure, which also contains associated controls, sensors and drives. In addition to the dish and tracking devices, the concentrator includes the support structure for the receiver/power conversion package located at the focal point.

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

Concentrator development under this task is implemented primarily through industry, via contract for design, fabrication and installation at the PFSTS. Integration of the modules as well as testing and evaluation, will be accomplished by JPL.

#### B. OBJECTIVE

The objective of this task is to develop high-operating temperature, point-focusing concentrators which will meet low-cost goals when manufactured in large quantities using mass-production techniques. These concentrators will be used in application experiments to demonstrate the viability and availability of PFDR technology. The task objective is being 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.

Cost and performance targets are shown in Table 4-1.

Table 4-1. Concentrator Cost and Performance Targets

Target	1982 First Generation (1978 \$)	1986 Second Generation (1978 \$)
Capital Cost in Mass Production*	\$100-150/m <sup>2</sup>	\$70-100/m <sup>2</sup>
Mirror Reflectance	78%	92%

\*Range of first-generation costs if mass-produced at 5,000-25,000/yr.  
Range of second-generation costs if mass-produced at 10,000-1,000,000/yr.

### C. APPROACH

The task objectives have been approached by a development effort having three primary thrusts. The first entailed acquisition of concentrators to be used in an early testing program. These included a Precursor Concentrator and two Test-Bed Concentrators (TBCs). The Omnium-G concentrator\* obtained via the Systems Engineering Task was also part of this test activity (see Section VIII). The Test-Bed Concentrators' performance parameters will be well characterized by tests. This information will provide a data base for point-focusing concentrator performance. Additionally, the TBCs will be used at the test site for testing of other subsystems.

A mirror facet development activity was undertaken in support of the Test-Bed Concentrator. This work was an extension of an earlier activity at JPL which developed a second-surface mirror bonded to a Foamglas\*\* substrate.

The second thrust involves development of the first-generation, low-cost paraboloidal concentrator to ensure efficient operation in the 540°-815°C (1000°-1500°F) range and to meet a mass-produced cost target of \$100-150/m<sup>2</sup>. Three contracts were implemented for the preliminary design phase. One of the three Phase I contractors was selected by a competitive procurement to implement a combined effort of detail design, fabrication, installation and checkout at the PFSTS.

The third thrust, to be initiated in FY 1980, will be the development of a second generation of Low-Cost Concentrators. Among the candidates for these second-generation concentrators are those design concepts evolving from the work of the Advanced Solar Thermal

\*Heliodyne<sup>™</sup> Model MTC-25 manufactured by the Omnium-G Company.

\*\*<sup>®</sup> Pittsburgh Corning Corporation

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Technology Project. The second-generation concentrators will have a mass-produced cost target of \$70-100/m<sup>2</sup>.

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

#### D. ACCOMPLISHMENTS

During FY 1979, significant progress was made in two areas: the acquisition and early testing of concentrators, and the development of first-generation concentrators. In accordance with the Concentrator Development Task schedule, development of second-generation Low-Cost Concentrators will be initiated in FY 1980.

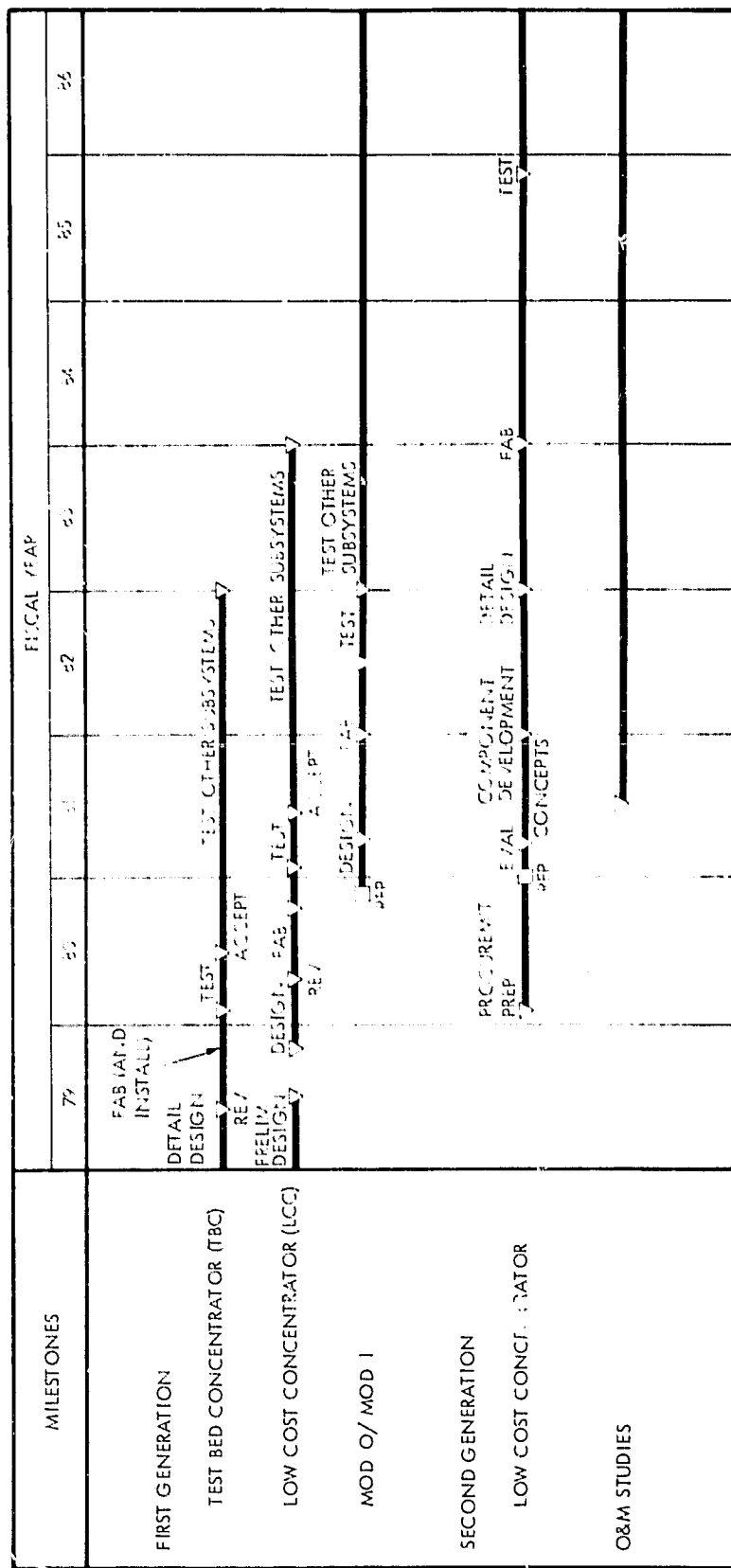
In the first area, the Precursor Concentrator, designed to simulate a section of a full-size reflector, was completed and employed in a variety of tests requiring the solar source. A flat-plate cold-water calorimeter was designed, fabricated and used in evaluation testing of the Omnium-G concentrator. The dominant activity in this early hardware area was the design, fabrication and installation of two Test-Bed Concentrators by E-Systems, Inc. A parallel activity was the assembly of JPL-developed mirror facets to be used for the TBC reflector surfaces. Techniques were developed to evaluate the optical characteristics and to align the mirrors after installation. Also, a cold-water cavity calorimeter was designed to be used in evaluation of the thermal performance of the TBCs.

In the second area, the development of first-generation Low-Cost Concentrators was initiated. Phase I studies for the definition of design parameters and preliminary design were completed by Acurex Corp., Boeing Engineering and Construction Co., and General Electric Co. (For titles of the final reports from these contractor studies see References 4-1 through 4-3.) An RFP was issued for Phase II/III, the detail, design, fabrication and installation of three units. This contract was awarded to General Electric, and work began in August, 1979. In addition, concentrator performance analyses were completed for the evaluation of the Low-Cost and Omnium-G concentrators, and for prediction of TBC performance.

The remainder of this section details the above accomplishments.

##### 1. Precursor Concentrator

The Precursor Concentrator installed at the PFSTS is shown in Figure 4-2. The JPL-developed reflector facets are second-surface, silvered mirrors bonded to spherically-contoured Foamglas substrates. The base support is an Hour Angle-Declination Antenna Mount. A cold-water calorimeter was modified for use with the unit. The Precursor is a tool to be used for tests requiring a modest solar image concentration. It was used to evaluate mirror performance, a flux-mapper device and candidate aperture plate materials for use with the cold-water calorimeter developed for testing of the Omnium-G module.



▽ START OR END OF ACTIVITY    □ ISSUED

Figure 4-1. Concentrator Development Milestone Schedule



Figure 4-2. Precursor Concentrator

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Possible future uses of the Precursor include: evaluation of mirror performance degradation caused by dust and film accumulation, and testing of segments of various reflector configurations mounted on the mirror support arm.

## 2. Cold-Water Calorimeter

A cold-water calorimeter was designed and fabricated for evaluating the thermal performance of the six-meter diameter Omnium-G concentrator. The calorimeter, a heat exchanger, was mounted near the focal plane of the concentrator. Incident concentrated solar energy was measured in steady-state conditions by measuring the temperature rise at a known water flow rate. The quality of the concentrator can be assessed by measuring the amount of energy which passes through various sizes of circular aperture plate openings mounted at the focal plane.

A flat-plate design was selected for this application and was sized for a 25 kWt load. Low operating temperatures allow convective and re-radiation heat losses to be disregarded; they were calculated at less than one-half percent. A parallel flow across the plate allowed operation with low head loss -- a requirement imposed by the water supply available at the test site. Implementation of the parallel flow was accomplished by milling channels in a copper plate and furnace brazing a cover plate to it, forming flow passages through the plate assembly. Manifolds brazed onto the plate assembly used standard 38.1 mm (1 1/2 in) pipe fittings to accommodate plumbing for the tests (see Figures 4-3, 4-4).

Parallel flow into a common manifold required attention to temperature stratification effects. Thorough mixing of the water is essential before it reaches the exit temperature probe. Mixing tests indicated a ten-diameter exit extension to be adequate.

The aperture plates were machined from 355.6 mm (14 in) square pieces of 19.05 mm (3/4 in) thick transite. The material's test life is adequate to withstand several tests. Apertures of various sizes are mounted in a frame at the focal plane and the calorimeter is mounted 76.2-152.4 mm (3-6 in) behind the focal plane in order to maximize the image size on the plane surface of the heat exchanger. A geometric computer program (SPOT) was written to properly locate the calorimeter behind the focal plane. Figures 4-5 shows the calorimeter/frame mounted on the concentrator quadripod, and Figure 4-6 the same with 177.8 mm (7 in) diameter aperture plate.

## 3. Test-Bed Concentrator

The Test-Bed Concentrator (see Figure 4-7) was developed as an early testing device to obtain concentrator performance data and to test several types of receiver/power conversion subsystems. The TBCs were developed from an existing microwave antenna design which was modified (a) to accommodate the JPL-developed mirror facets as the

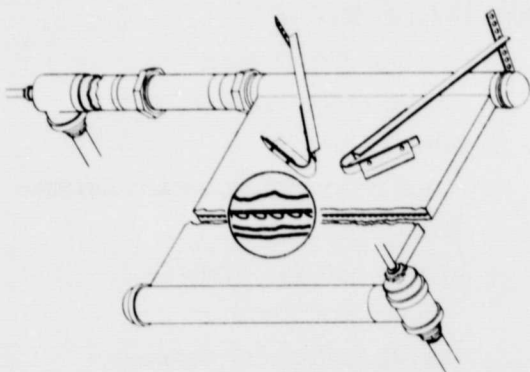


Figure 4-3. Cross-section of Flat-Plate Calorimeter

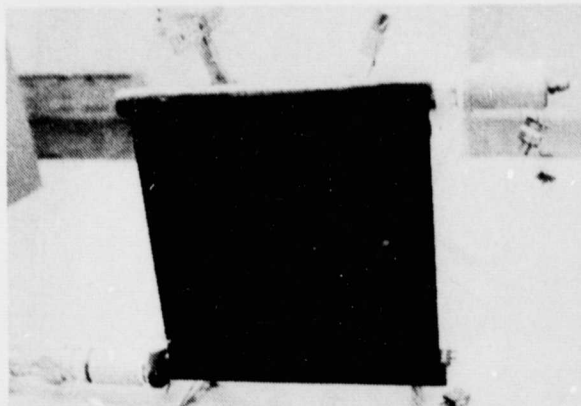


Figure 4-4. Flat-Plate Cold-Water Calorimeter

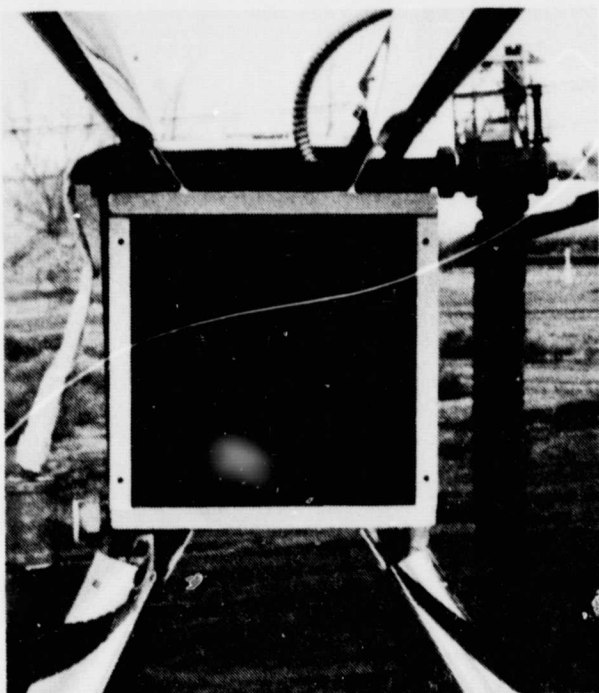


Figure 4-5. Calorimeter and Aperture Plate Support Frame Mounted on Quadripod

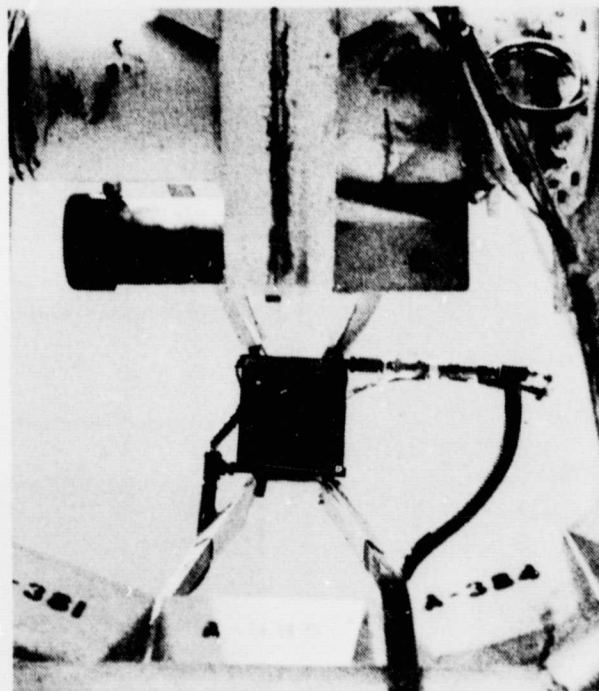
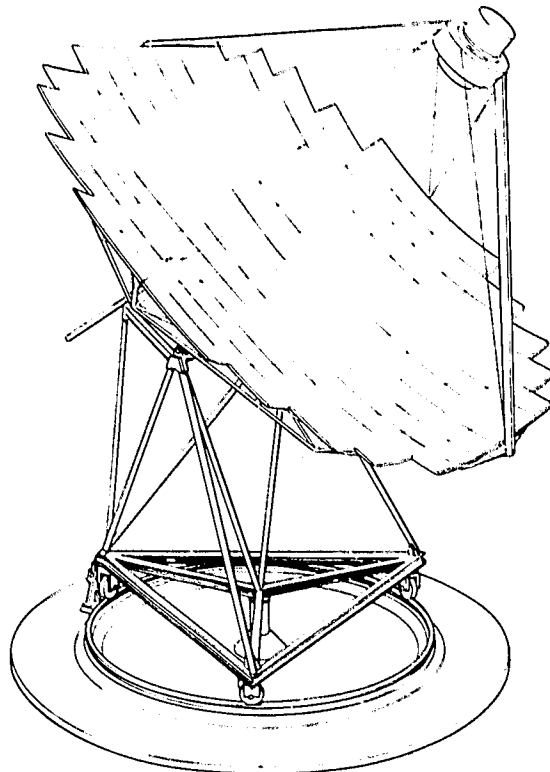


Figure 4-6. Calorimeter with 177.8 mm (7 in.) Aperture Plate Mounted on Quadripod (with mixing test extension)

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REFLECTOR: NOMINAL 11-METER DIAMETER  
 OUTPUT: 70 kWth at 800 W/m<sup>2</sup> INSOLATION

MIRROR FACETS: 224

- o SECOND-SURFACE GLASS
- o NOMINAL SIZE: 60.96 cm x 71.12 cm  
(24 in x 28 in)
- o THREE REGIONS OF NOMINALLY DIFFERENT RADIi OF CURVATURE:  
1320 cm, 1574.8 cm, 1610.4 cm  
(520 in, 620 in, 634 in)
- o INITIAL REFLECTIVITY: 95% MAX
- o SLOPE ERROR: 1 mrad

FOCAL LENGTH 6.6 METERS (21.65 ft)

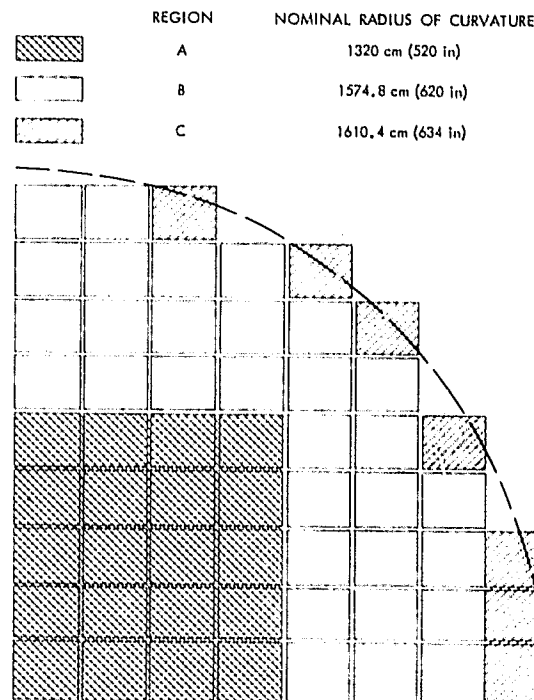
PARABOLOIDAL MOUNTING STRUCTURE:  $f/d = 0.6$

DESIGN WEIGHT AT FOCUS: 504.4 kg (1100 lbs)

TRACKING ERROR: 1 mrad

Figure 4-7a. Test Bed Concentrator

Figure 4-7b. TBC Specifications



TBC FACET LAYOUT  
 (ONE QUADRANT)

Figure 4-8. Mirror-Facet Layout

reflector surface, (b) to provide solar tracking and high-rate slew speeds, and (c) to support the receiver/power conversion package at the focal point.

A contract for two Test-Bed Concentrators was initiated in mid-September of 1978 with E-Systems, Inc. whereby their existing microwave antennas were modified to meet the requirements for a solar concentrator. The completed design modifications were accepted in April of 1979. Fabrication, trial assembly, and delivery of parts to the test site was completed by mid-August, at which time final assembly and installation was started.

A standard 13-meter diameter microwave antenna was redesigned to a nominally 11-meter diameter reflector for the solar concentrator adaptation. The  $f/D$  was changed from 0.37 to 0.6 to provide better solar concentrator characteristics. A series of parallel, parabolic-shaped tubes were placed on the face of a typical dish support structure for mounting the mirror facets. An alidade designed for larger dishes was scaled down to fit the solar concentrator. The alidade provides the solar concentrator with continuous travel for solar tracking and also allows it to be pointed north for maintenance and repair functions.

The reflector layout utilizes three regions of different radii of curvature mirror facets. This provides better performance than can be achieved by using a single radius of curvature, and yet keeps mirror fabrication, assembly, and the number of required spares reasonable. (See Figure 4-8.)

The mirror facets were designed to attach to the parabolic tubes through the use of a flexure-bracket clamped to the tube. Three flexures are used to mount each mirror facet. Half of the flexure is bonded to the mirror facet and the other half is attached to the brackets. A field joint between the two parts of the flexure has slotted holes to provide for individual facet alignment and adjustment requirements.

At the focal point there is a toroidal ring to which the receiver/generator subsystems will attach. The ring is mounted using a bipod design with eight guy rods for stability. The bipod-ring system is designed to support a receiver subsystem of up to 504.4 kg (1100 lbs). The deflections due to this weight at the focal point are included in the overall error analysis, and are compensated for in the tracking and control subsystem.

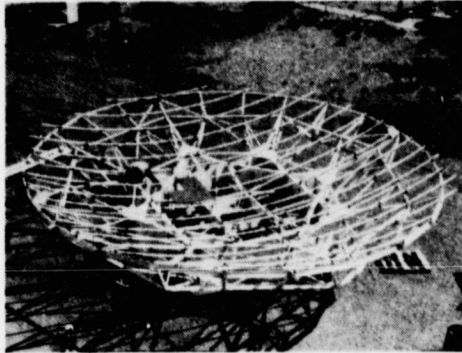
The structure, including the alidade, is a bolted design. This approach was employed so that the concentrator structure could be fabricated and trial-assembled at a steel fabrication shop and then disassembled, shipped to the PFSTS and reassembled using nuts and bolts with only a minimum of field welding. During the reassembly process continuous alignment checks were made to ensure that the final structure assumed the proper shape. Each of the piece parts were match-marked prior to disassembly at the factory so that the field assembly could be done correctly and with a minimum of alignment problems. Figure 4-9 shows the TBCs in various stages of installation at the PFSTS.



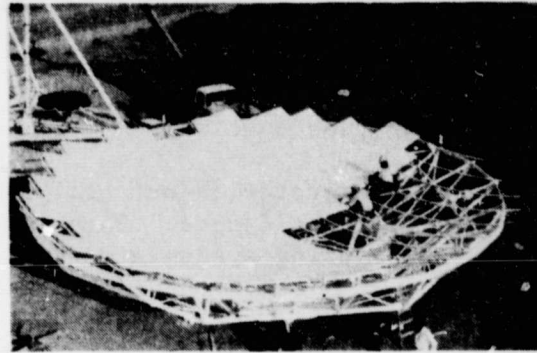
4-9a. Initial Field Assembly



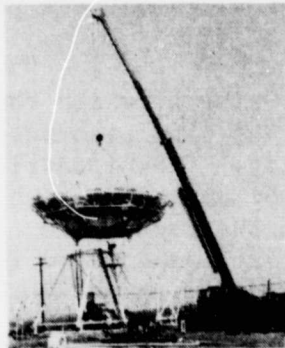
4-9b. Alidade



4-9c. Reflector Structure with Mirror Support Tubes



4-9d. Mirror Facet Installation



4-9e. Reflector Being Placed on Alidade



4-9f. Assembled Test-Bed Concentrators

Figure 4-9. Various Stages of TBC Assembly/Installation

Installation and checkout by E-Systems was nearly completed by the end of the fiscal year. Alignment of the mirror facets will follow and tests to characterize the concentrator performance will begin early in FY 1980.

#### 4. Mirror Facet Development and Assembly

At the close of FY 1978, development tests of candidate materials to be used for the TBC mirror facet had not been completed. Facets subjected to a severe humidity-cyclic temperature test had shown evidence of degradation in the form of speckling. This was attributed to the adhesive system used to bond the mirror to the substrate, aggravated by the moisture penetrating the edge to wet the mirror substrate interface. Laboratory tests had shown that a system having a near neutral pH caused the least mirror degradation.

To confirm this laboratory result, eight facets were fabricated using the different adhesive systems. Only half of the facets were edge sealed. All were subjected to the cyclic environmental test shown in Figure 4-10. Evaluation of the speckling degradation of the mirrors and consideration of previous experience at JPL, led to the decision to use Furane 9427 with the Dow Epoxy Resin 332 as the adhesive system. This was no longer a Furane standard commercial item, but it was purchased by special order. The facets bonded with the same resin but using the hardner, Epicure with ClBA-GELG4 064 accelerator showed very minor mirror degradation.

A short test program was also conducted to evaluate the sensitivity of Foamglas strength to freeze-thaw cycles at a 95% humidity environment. Samples were tested both uncoated and coated with Pittcote 404/Chemglaze. It was concluded that the coating greatly increased the freeze-thaw resistance of Foamglas and that the sealant must be carefully applied to preclude the presence of pinholes in the coating through which water might penetrate.

The materials selected for construction of the TBC mirror facets are listed in Table 4-2. The Foamglas substrates were procured from Pittsburgh Corning which used its standard commercial process for the special production run. The mirrors were procured from the Corning Glass Works, who subcontracted the silvering process to Falconer Plate Glass. The substrate blocks were made using special molds.

Mirrors with three silvering configurations were purchased and will be evaluated on the TBCs. Most mirrors were cut to size and silvered, but some were silvered and then cut and some have a 4.83 mm (3/16 in) silk screen protective edge seal.

These materials were shipped to JPL on the same non-commercial carrier truck to ensure minimum damage from handling and the road environment. Precautions notwithstanding, flaws were present in the materials and significant damage occurred in shipping. The suppliers replaced all material not meeting specification.

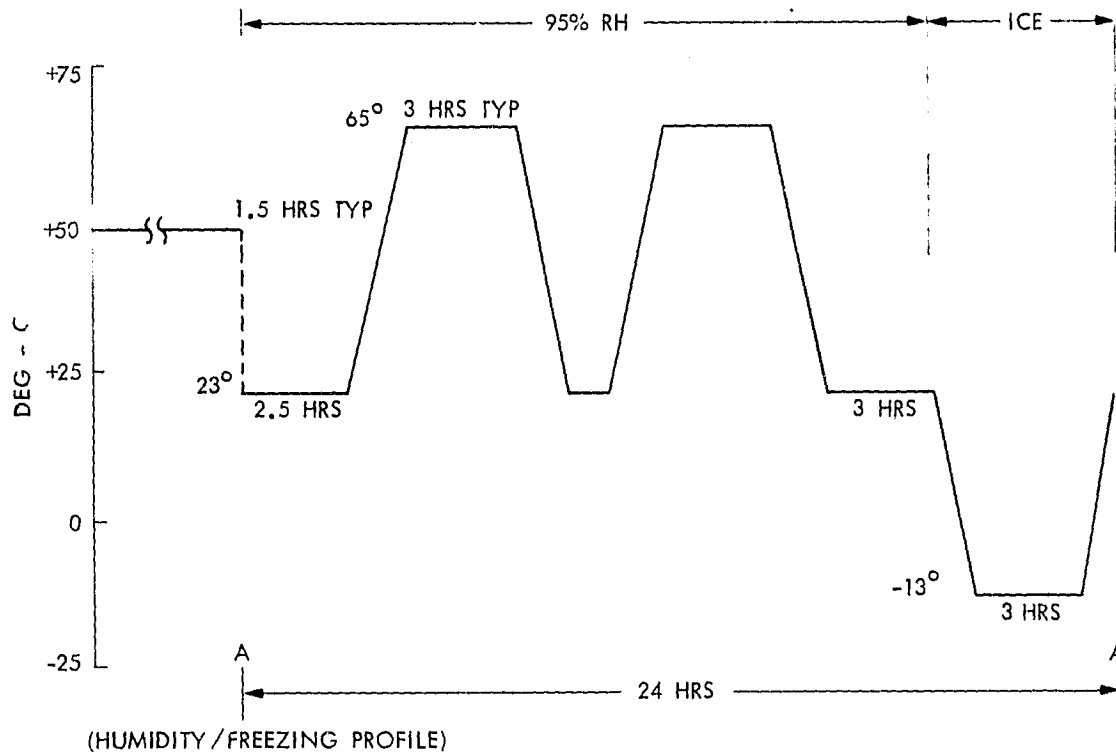


Figure 4-10. Environmental Test Cycle

The epoxy hardener, 9427, was supplied as a special order from Furane Plastics. A small number of mirrors were assembled using Epicure 855, with an accelerator, as the epoxy resin catalyst for evaluation on the TBCs.

Tooling for the mirror assembly was arranged to produce groups of ten facets daily. The typical flow for the assembly starts with trimming the substrate to size. Rough-grinding to a nominal radius of curvature of 1524 cm (600 in) was accomplished using a fly cutter tool on a milling machine (Figure 4-11a). The final radius of curvature was obtained by a hand-grinding operation on a master spherical mold covered with 120 grit abrasive paper (Figure 4-11b).

The back surface of the mirror was cleaned in preparation for bonding. A very thin layer of adhesive was applied to the painted back surface using a paint roller (Figure 4-11c). The mirror is placed on the contoured surface of the substrate (Figure 4-11d) and vacuum bagged and cured for eight hours (Figure 4-11e). After cure, the facet was inspected and a serial number and date written on the mirror face with a diamond pencil.

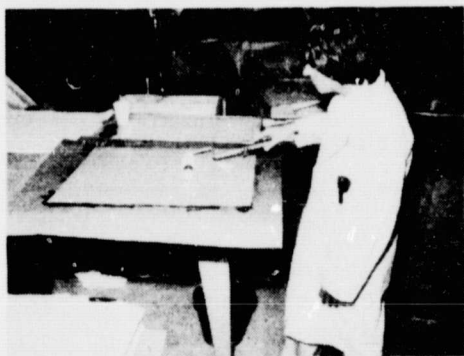
Before proceeding with assembly, the optical characteristics of each facet were measured and compared to the acceptance criteria. The focal length and slope error were measured in an optical tunnel



4-11a. Machine-Grinding



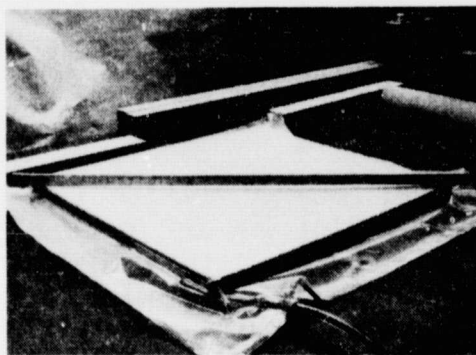
4-11b. Hand-Grinding



4-11c. Adhesive Application



4-11d. Placement on Substrate



4-11e. Vacuum Bagging

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Figure 4-11. Mirror Facet Assembly

Table 4-2. Materials Selected for TBC Mirror Facets

Substrate	60.96 cm x 71.12 cm x 5.1 cm (24 in x 28 in x 2 in) Foamglas High Load Bearing 136.17 kg/m <sup>3</sup> (8.5 lbs/ft <sup>3</sup> density) - Pittsburgh Corning
Mirror	60.33 cm x 70.41 cm x .15 cm (23-3/4 in x 27-3/4 in x 0.058 in) Corning Glass Code 0317 - Silvered by Falconer
Mirror Adhesive	DER 332 - Dow Epoxy Resin 9427 Hardener-Furane Plastics
Support Tabs	0.032 Aluminum with 5.1 cm x 7.6 cm (2 in x 3 in) contact area with Foamglas
Support Tab Adhesive	PC-88 two-part adhesive - Pittsburgh Corning
Mirror Edge Seal	Vulkem 116 Urethane Sealant - NAMECO
Foamglas Sealant	Pittcote 404 Acrylic Latex - Pittsburgh Corning
Paint	Chemglaze 11 A276 White Polyurethane

assembled for this purpose. The technique used for slope error acceptance tests is described in the PFDR Technology Project's Annual Technical Report for FY 1978. Essentially, discs, whose diameters represent one through six minutes of slope error, are inserted into the center of the light beam reflected from the mirror. Each disc will block the light reflected from all points on the mirror with slope errors less than that for which the disc is sized. A photocell was used to measure the amount of light passing around the disc; this was compared to the acceptance criteria.

It was difficult to obtain high sensitivity in measurement of the focal length. Many mirrors were checked by measurement to the location of the smallest image using the sun and the moon as the light source. Tests using the moon gave good results, but the image using the sun was too bright to be used.

Reflectance measurements were made at five positions on each facet to give an initial reference value for use in later degradation and cleaning tests. Figure 4-12 shows the reflectometer equipment.

The mirror supports, consisting of three flexure tabs, were bonded to the substrate using a fixture for accurately locating the tabs relative to the mirror surface. Set-up time for the adhesive permitted bonding of tabs on two facets per day in each of ten fixtures (Figure 4-13).

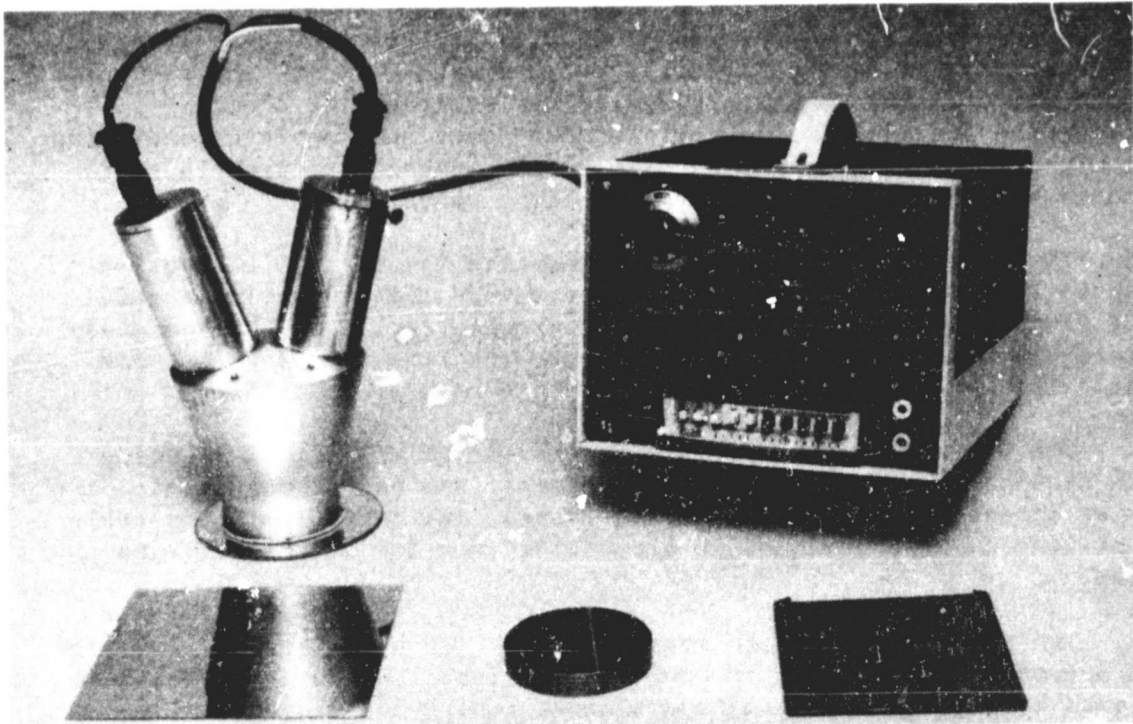


Figure 4-12. Reflectometer Equipment

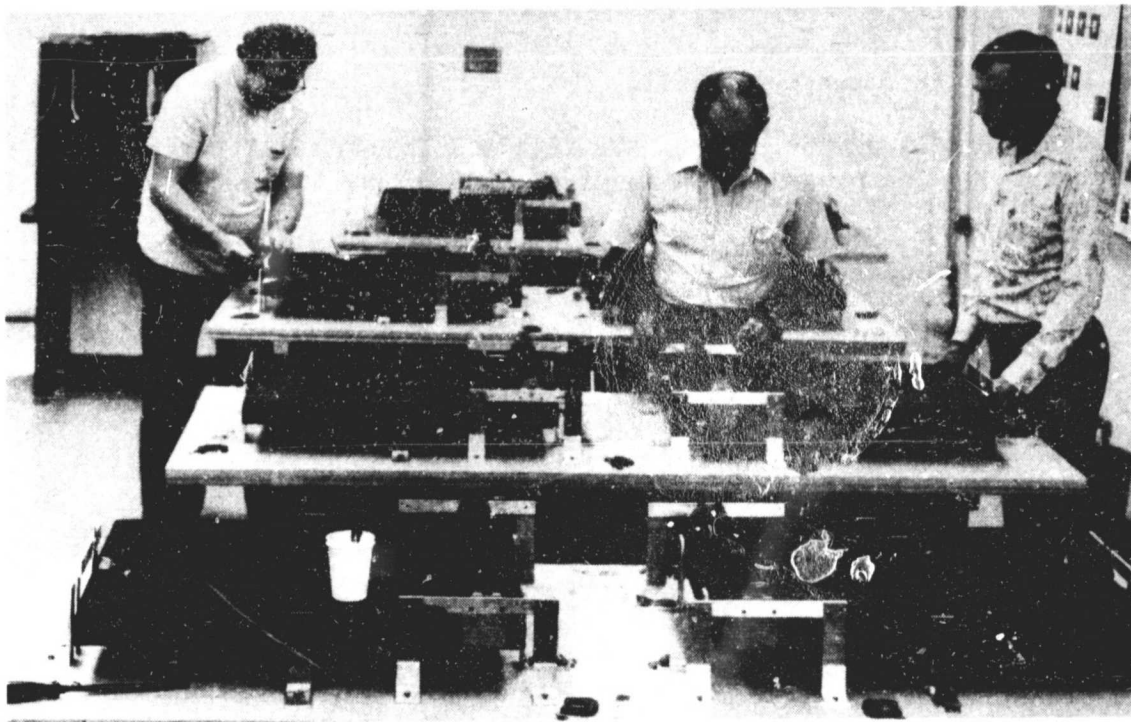


Figure 4-13. Bonding of Mirror Facet Supports



After a 24-hour cure of the tab bonding adhesive, substrate corners were rounded and the mirror was cleaned in preparation for application of the sealant along the interface between the substrate and the edge of the mirror. The Vulkem 116 sealer was applied with a syringe, forcing the sealer into the cells at the joint and completely covering the mirror edge (Figure 4-14). The excess on the mirror surface was removed and seal allowed to cure for eight hours.

The final step in the assembly process was to seal the entire exposed Foamglas with PC 404. Two coats were applied, being careful to fill the open cells, to prevent water penetration to the Foamglas through pinholes in the seal. An eight-hour cure was used for each coat. The surface was then painted with a coat of Chemglaze.

The mirror on each completed facet was given a final cleaning with alcohol and a commercial glass cleaner and the facet serial number stenciled on the back of the facet. Two facets, of comparable focal length, were packaged in a cardboard box for shipment to the PFSTS.

The mirror facets were mounted on the TBC by E-Systems, Inc. and JPL personnel at the time of concentrator installation. They will be aligned by a technique utilizing a light source located on a hill 5.8 km (3.6 miles) away from PFSTS. Each individual facet will be adjusted to image the collimated light from this source onto a target mounted at the focal plane. Covers have been made for each facet and only the one being aligned will be uncovered to ensure obtaining an unambiguous image at the target. The equipment to be used at the light source is shown in Figure 4-15.

## 5. Optical Performance Analysis

The optical performance of the Test Bed Concentrator has been investigated. The prominent features of the TBC are reviewed as follows:

- Substructure: 45° rim angle paraboloidal dish.
- Rectangular facets: 228, 60.96 cm x 71.12 cm (24 in x 28 in) each.
- Single radius of curvature for all facets: 1585 cm (624 in).
- Concentrator focal length is set to be equal to the focal length of the substructure.
- Facet slope error (excluding alignment error and structural deflection) was assessed to have a 0.5 milliradian standard deviation for a "typical" facet.

The optical performance of the TBC was simulated assuming all facets are identical to the measured sample. The error budget for structural deflection (due to gravity and wind) was estimated by



Figure 4-14. Application of Edge Seal

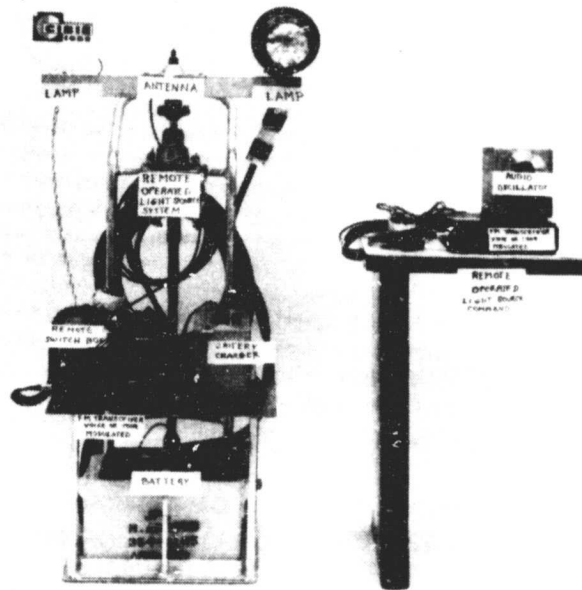


Figure 4-15. Light Source Equipment

E-Systems Inc., to have a standard deviation of approximately 0.5 milliradian. A total slope error (standard deviation) of 1 milliradian is considered representative for the TBC at this time. The flux distribution and intercept factor at the concentrator target plane are shown in Figures 4-16 and 4-17. A flux distribution mapping of a cylindrical cavity,  $D = 60.96$  cm (24 in),  $L = 91.44$  cm (36 in), is shown in Figure 4-18.

## 6. Low-Cost Concentrator

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

A three-phased procurement was initiated in FY 1978 to design, develop, fabricate and install paraboloidal point-focusing concentrators capable of providing high thermal flux to a receiver operating at 815°C (1500°F). The receiver supplies thermal energy to power a Brayton engine/generator in a solar thermal electric test module.

Three contractors (Acurex Corp., Boeing Engineering and Construction Co., and General Electric Space Division) participated in the Phase I effort. Each conducted a six-week parameter optimization study (funded in FY 1978) of their individual concentrator concepts to maximize the predicted kWt/\$. The remainder of Phase I (funded in FY 1979) was a 16-week effort generating a preliminary design, based upon the selected parameters, and an assessment of mass-production costs. A delay in FY 1979 funding availability shifted the Phase I completion date to March 1979.

The preliminary designs generated in Phase I are shown in Figures 4-19, 4-20, and 4-21.

- (1) Acurex. The Acurex design is based upon a "Faceted Compressed Paraboloidal Reflector." The concentrator reflector is comprised of 33 triangular, individually alignable, reflective panels of seven panel types. The panels are arranged in a truncated triangular array (a triangle with the three points removed) composed of three nested paraboloids with a common focus. The reduced height of the nested configuration is expected to reduce wind drag when in the survival stow position; the triangular shape reduces wind drag during operation. The concentrator is stowed during high winds with the axis pointed to the zenith. The concentrator is positioned overnight, when winds allow, looking at the east horizon to aid in preventing dirt build-up and dew formation on the reflective surface. The effective surface area is 102

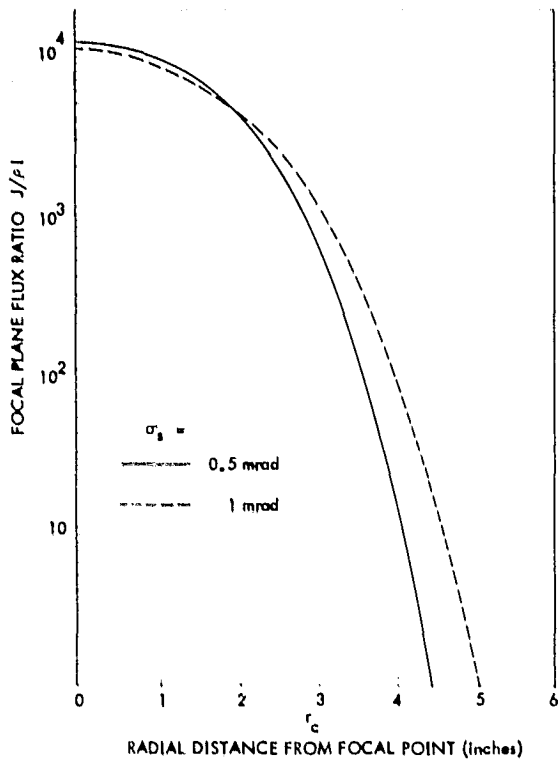


Figure 4-16. TBC Focal-Plane Flux Distribution

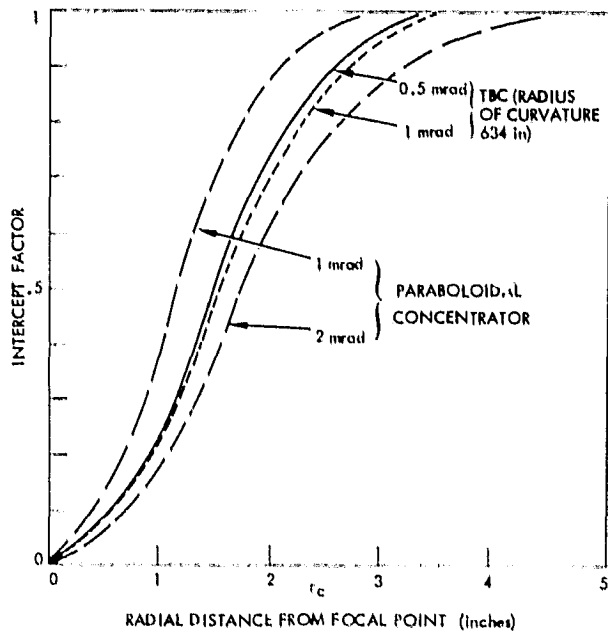


Figure 4-17. TBC Intercept Factor Variation

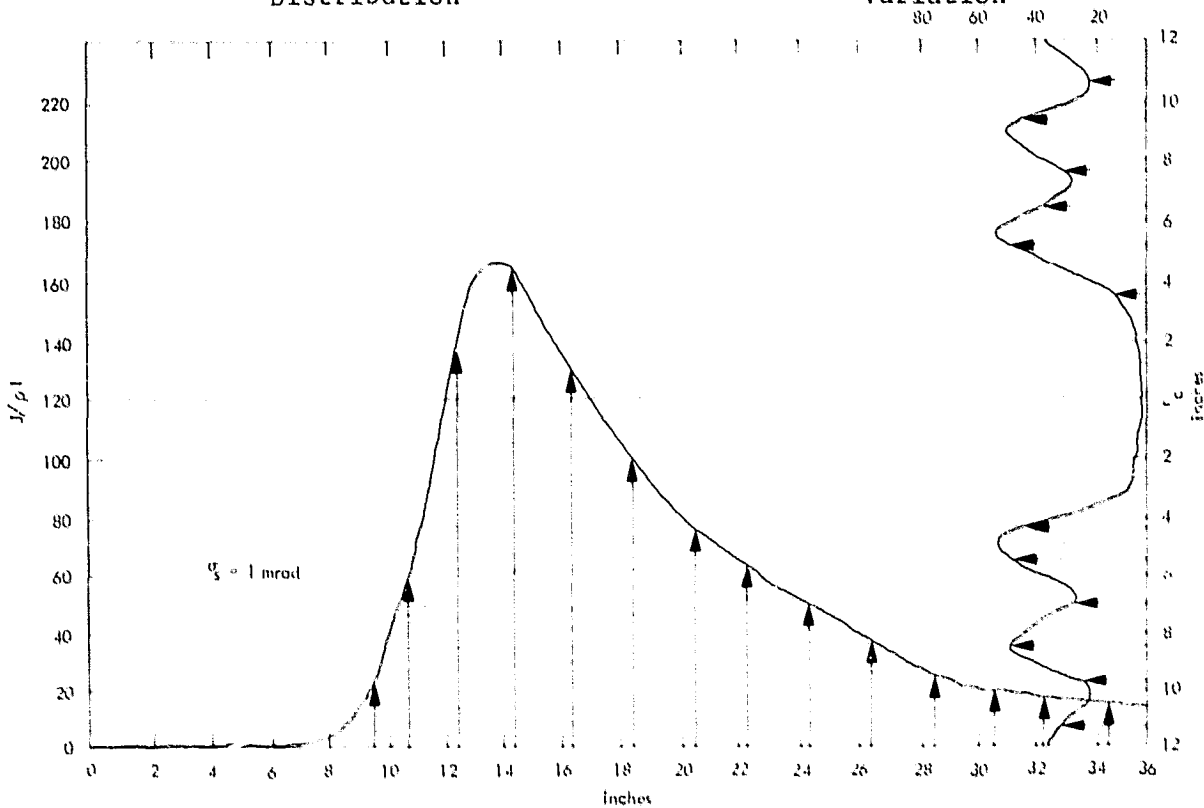


Figure 4-18. TBC Flux Distribution in Cavity Receiver

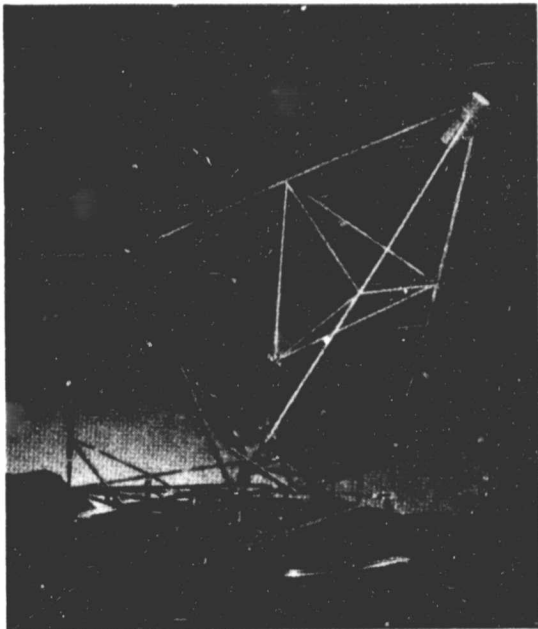


Figure 4-19. Acurex Low-Cost Concentrator Preliminary Design

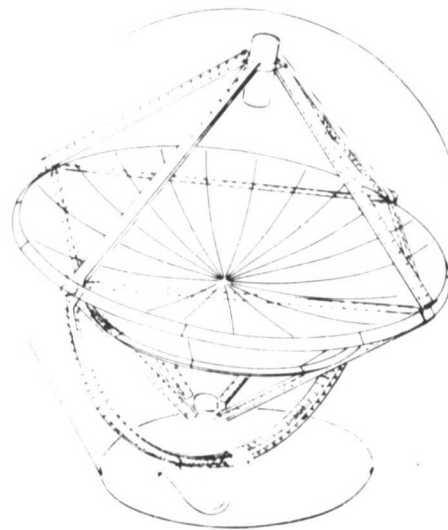


Figure 4-20. Boeing Low-Cost Concentrator Preliminary Design

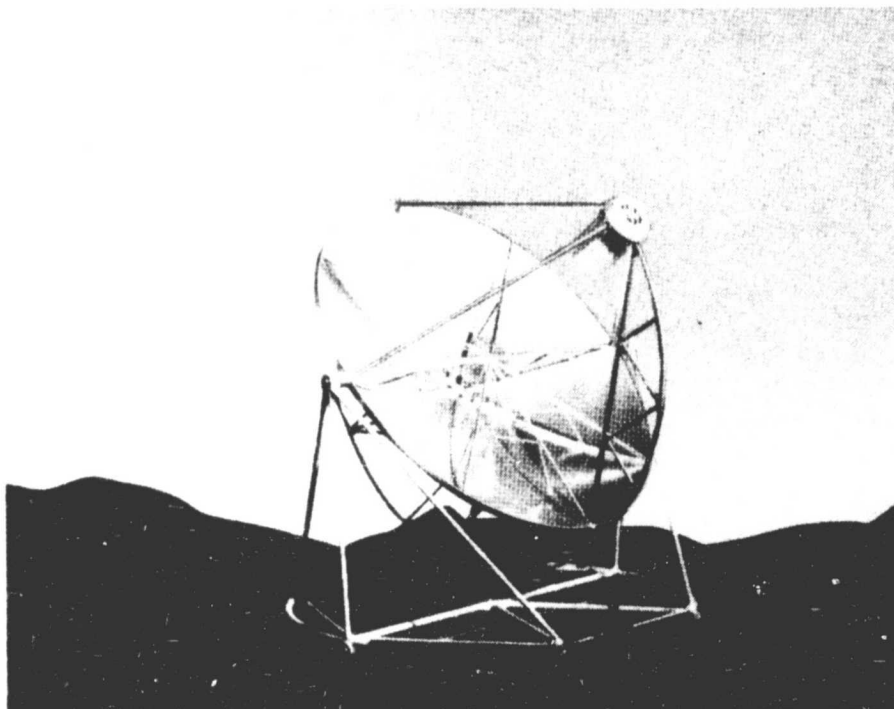


Figure 4-21. General Electric Low-Cost Concentrator Preliminary Design (Selected for Phase II/III)

square meters, equivalent to a 11.4 meter diameter paraboloid.

The reflective surface is a mosaic of back-silvered thin glass mirrors which are bonded to a sheet molding compound, glass fiber-polyester resin substrate. The panel substrate has an integrally molded isogrid ribbing on the back for support. The reflective panels are each supported on a spaceframe tubular truss-work by three adjustable links to permit alignment after installation. The receiver/engine is supported at the reflector focus by a tripod structure mounted on the spaceframe. The panels are predicted to have a reflectance of 0.95 when new. The surface slope error of the reflector is estimated to be less than 1 milliradian.

The concentrator axes are in an azimuth and elevation configuration. The elevation axis is a pair of hinge points at the lower edge of the triangular array with elevation motion implemented by a double-acting, single-stage hydraulic cylinder. Emergency stow is accomplished in one minute, using hydraulic fluid stored in an accumulator. The azimuth rotation is provided by the triangular base which turns around a central pintle bearing that rides on three wheels on a raised track resting on six piers. The rotational drive is a hydraulic rack-and-pinion rotary actuator located at the central pintle bearing. The reflector loads are reacted at the two elevation hinge points located on the base near track wheels and the bearing at the lower end of the hydraulic cylinder at the pintle. The hydraulic components are mounted on the base structure and rotate with it. Vertical lifting restraint is provided by the central bearing.

The solar-tracking system developed by Acurex uses a microcomputer, combined with positional feedback potentiometers, to provide coarse synthetic tracking within  $5^\circ$  of the sun's true position and an active, shadowband sun-sensor to control the system to within  $0.2^\circ$ . The system performance is estimated to be 64.3 kWt (net) under the design conditions (800 W/m<sup>2</sup> insolation and 925°C (1700°F) receiver cavity temperature).

- (2) Boeing. The Boeing design is based upon a "Pneumatically Stabilized Film Membrane Reflector." The reflector is a 13-meter diameter, first-surface, metallized plastic film which is maintained in its paraboloidal contour by a small pressure differential across the film. The film membrane is fabricated in a nearly parabolic shape and edge-supported on a conical frustrum ring of honeycomb-core-sandwich construction. The back of the frustrum is closed by another membrane, allowing a slight

vacuum to be maintained within the frustrum. The reflector, receiver and engine, gimbals, and drives are all enclosed in a 14.7-meter diameter inflated plastic bubble. The enclosure provides environmental protection for the reflector and structure. Air supplied to maintain pressure within the bubble is filtered. Therefore, the reflective surface should not require periodic cleaning. The exterior surface of the bubble itself will require washing.

The gibal configuration is elevation over azimuth, somewhat like a toy gyroscope. The elevation axis is a pair of bearings on a yoke, pivoting the reflector at opposed points on the edge. The yoke rotates in azimuth at a single bearing on the foundation. The enclosure intercepts the environmental loads, allowing minimal weight structures. Air to the receiver and exhaust air from the Brayton engine are manifolded to the ambient air outside of the enclosure by ducts.

The solar-tracking system designed by Boeing employs controller-generated sun predictions for coarse solar tracking and sun sensors for fine control of  $\pm 2$  milliradians. The system utilizes electric stepper motors with speed reducers. The system performance is estimated to be 71 kWt (net).

- (3) General Electric. The General Electric design is based upon the "Plastic Injection Molded Reflector". The reflector is comprised of 24 panels arranged in three concentric rows forming a seven-meter diameter circular reflector with a single paraboloidal surface. The reflector is stowed when not in use with the axis pointed at the nadir, to give reduced wind drag loadings and to aid in keeping the reflective surface clean of dirt and dew. The surface area is 38.5 square meters. The reflector and receiver/engine are counterbalanced by a concrete weight to minimize the drive load requirements.

The reflective surface is a second-surface, aluminized, polyester film bonded to a Reaction Injection Molded glass-fiber, epoxy-resin substrate. The substrate has integrally molded ribbing on the back for stiffness. The reflective panels are supported at the radial edges by eight radial aluminum trusses and circumferentially by bolting to the adjacent panel. The radial trusses and reflective panels are accurately positioned at assembly to avoid individual alignment after the reflector is mounted on the base. The receiver/engine is supported by a quadripod which carries the loads to the aluminum radial members. The panels are predicted to have a reflectance of 0.82 when new and the reflector to have a surface slope error of less than 2 milliradians.

The concentrator axes are in an azimuth and elevation configuration. The elevation axis is a pair of pivots located at the rim of the reflector, supported by tripods from the circular platform base. The azimuth motion is around a central bearing which rides on six wheels on a raised track that rests on 12 piers. Both elevation and azimuth drives employ capstan-driven cables, attached to large radius channels. The large radius of action permits the use of small electric motors and gear boxes, with high angular resolution. The elevation drive gives 30°-per-minute emergency defocus movement. The six azimuth wheels provide vertical restraint to prevent lifting off of the track.

The solar-tracking system developed by General Electric employs a microcomputer on each concentrator which uses solar ephemeris data generated by a central computer, compared with positional feedback potentiometer, to provide synthetic tracking within 1° of the sun's true position, and an active fiberoptics sun sensor system to control the system to within 1/8°.

The system performance is estimated to be 20.4 kWt (net) under the design conditions.

In April 1979, following the completion of Phase I, an RFP was issued to the three Phase I contractors for proposals for Phase II/III. This Phase includes the detail design and fabrication of three prototype LCC units, as well as an assessment of the implication of mass production. Boeing determined that the candidate plastic material for the enclosure would not be available in the 18-month contract period and declined to submit a proposal.

General Electric was selected for Phase II/III and a 16-month contract was executed in August 1979. The concentrator is sized at 11-meter diameter with a thermal performance of 56 kWt (at 800 W/m<sup>2</sup> insolation) into the receiver aperture. However, larger sizes are being studied. The reflective surface to be used is an aluminum coated plastic, covered with a polyester film. The substrate for the prototype hardware, a fiberglass-epoxy material system, will be formed by Resin Transfer Molding rather than Reaction Injection Molding which requires more expensive tooling and is still under development. An investigation of glass mirrors as an alternative surface will be also undertaken.

## 7. Heliostat Modification Feasibility Study

The concept of modifying the central receiver heliostat design to a point-focusing concentrator was reviewed by Martin Marietta and McDonnell Douglas. A short presentation by each company was made to JPL. Subsequently an RFP was issued for a feasibility study of this



adaptation in two sizes ranging from 50 to 120 square meters. The design for the smaller size will emphasize maximum utilization of current heliostat hardware while the other design will extend heliostat technology to a larger size which may be optimal for a point-focusing concentrator. It is planned that this study will start early in FY 1980.

#### 8. Low-Cost Concentrator Analyses

In support of the evaluations of Low-Cost Concentrator concept development, a study was conducted to review different analytical methods for computing the flux distribution at the focal plane of a paraboloidal concentrator. Various methodologies employ differing assumptions concerning the definition of optical parameters. These parameters include solar irradiance distribution (limb darkening and circumsolar), reflector-surface specular spreading, surface-slope error and concentrator pointing inaccuracy. The results obtained by the various methodologies were compared and evaluated (see Reference 4-4).

## SECTION V

### RECEIVER AND HEAT TRANSPORT NETWORK DEVELOPMENT

#### A. INTRODUCTION

The solar receiver at the focal point of each PFDR module converts the radiant solar flux into useful heat. Together with the heat transport network, an entire system is brought together which is capable of generating electricity or supplying heat for industrial processes. Therefore, cost-effective, efficient receivers and heat transport networks are essential to an economical, effectual system.

Industry plays a central role in the development of receivers and heat transport networks. Contracts have been awarded for the final design and prototype fabrication of both steam and gas receivers. Later a contract to design and fabricate heat transport networks will be let. This equipment will become part of a module designed to produce an efficient, cost-effective prototype system for future wide-scale energy production in support of national goals to reduce the use of fossil fuels in the electric utility and process heat industries.

#### B. OBJECTIVES

The fundamental objective of the Receiver Development Task is to provide efficient, cost-effective equipment. The scope of the task has been broadened during FY 1979 to include the heat transport subsystems ancillary to the solar collectors. In addition, as improved technical and cost information has been developed, cost and performance targets have been reviewed to insure the use of the most up-to-date information. Current cost and performance targets are shown in Table 5-1.

Cost and performance goals for the heat transport network will be forthcoming in FY 1980. As with the receivers, these targets are being set within a context of maximum total system efficiency rather than single component efficiency. Functional specifications, e.g., temperature/pressure ranges, allowable heat loss, and the like, are being developed to encompass a wide range of applications.

#### C. APPROACH

The initial six Phase I receiver contracts were narrowed to two. These contracts, one for a steam and one for a gas receiver, are now in Phase II which includes final design, prototype fabrication, bench testing, and delivery to the PFSTS. Details of these contracts will be found in Section D below.

As the program matured, several technical changes and additions were made to insure optimal progress. The heat transport subsystem,

Table 5-1. Receiver Development Targets

Target for FY	1982	1986
Cost in Mass Production	\$40-60/kWe	\$20-40/kWe
Efficiency	82%	85%

including both the flexible attachments at each module and the interconnecting piping between modules, was integrated with the receiver area. All systems were modified to use fossil fuel in addition to solar heat. This was done to encourage early deployment of this technology by insuring maximum use of the equipment as well as to obviate the development of energy storage subsystems for early systems. It should be emphasized that the goal of these solar systems has not been changed but that these temporary modifications were made to increase testing and acceptance of the technology.

Technical advances will be incorporated into the development as they become available. Figure 5-1 shows how these will be integrated into the current milestone schedule.

#### D. CONTRACTOR PROGRESS

At the start of this fiscal year, six Phase I receiver contracts were in progress, two for steam Rankine systems and four for open-cycle air Brayton systems. The contractors for air Brayton receivers were Dynatherm Corp., Boeing Engineering and Construction Company, Sanders Associates and Garrett AiResearch Manufacturing Company of California. The steam receiver contractors were Fairchild Stratos and Garrett AiResearch. (For final reports from these contractor studies see References 5-1 through 5-6.) The output of Phase I was to produce conceptual receiver designs with 10-minute buffer storage, a complete parametric analysis, initial production costing and a proposal for a final design including the fabrication of prototype equipment.

Early in the year, the contractors were given a suitable design point to size and direct the final design. A Phase II RFP and Statement-of-Work including evaluation criteria and requirements was prepared for release. Early in December, the six contractors made final Phase I presentations. The proposed designs are shown in Figures 5-2 through 5-7. Figure 5-2 shows the Garrett AiResearch gas receiver. The receiver cavity, 508 mm (20 in) in diameter by 711.2 mm (28 in) deep, consists of an Inconel, plate-fin matrix heat exchanger with ceramic back plate and aperture. The aperture is about 254 mm (10 in) in diameter. The buffer thermal storage assembly contains a phase-change salt to give it a 10-minute capacity. The Boeing Engineering and Construction design is shown in Figure 5-3. The

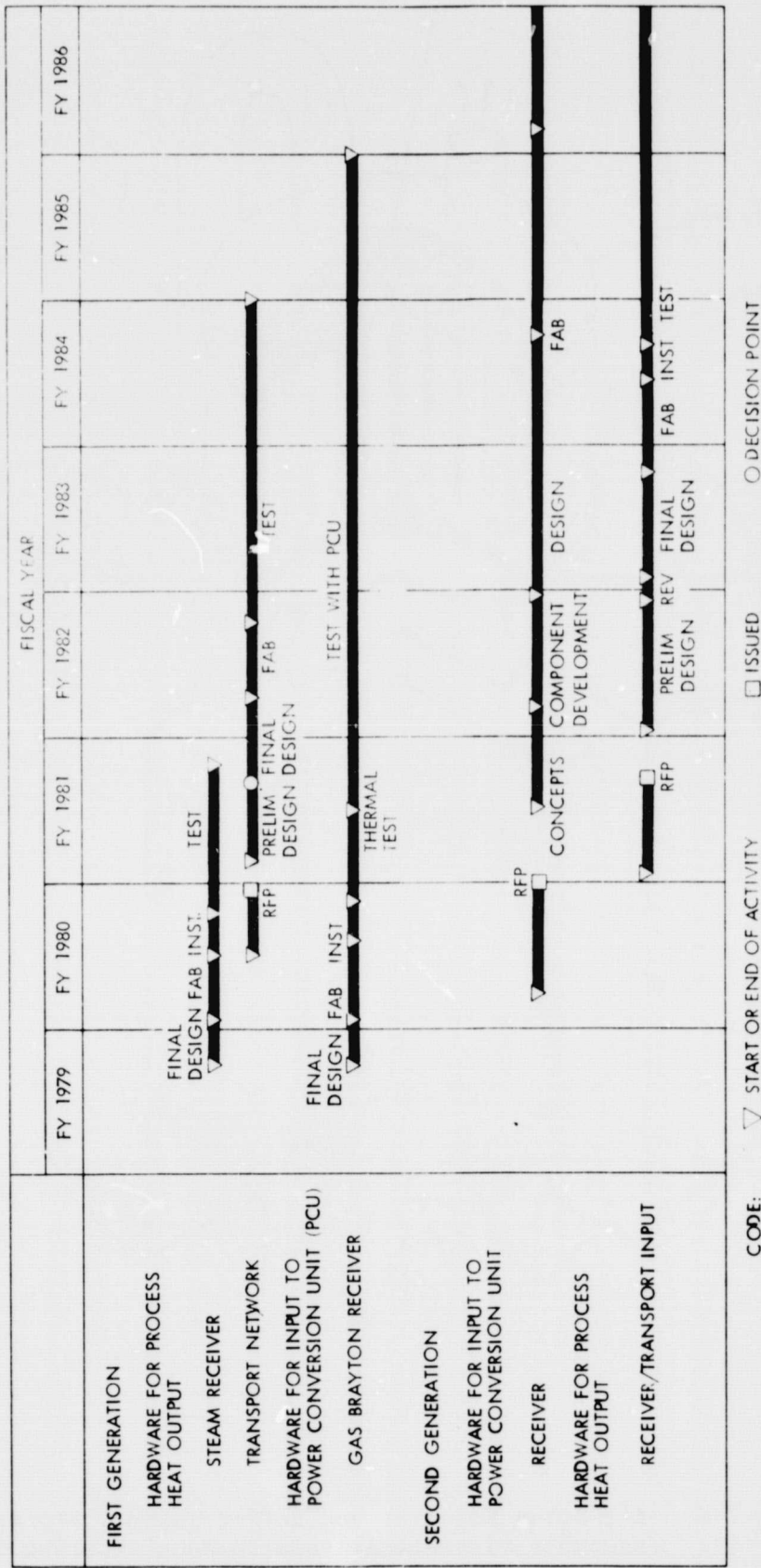


Figure 5-1. Receiver and Heat Transport Network Development Milestone Schedule

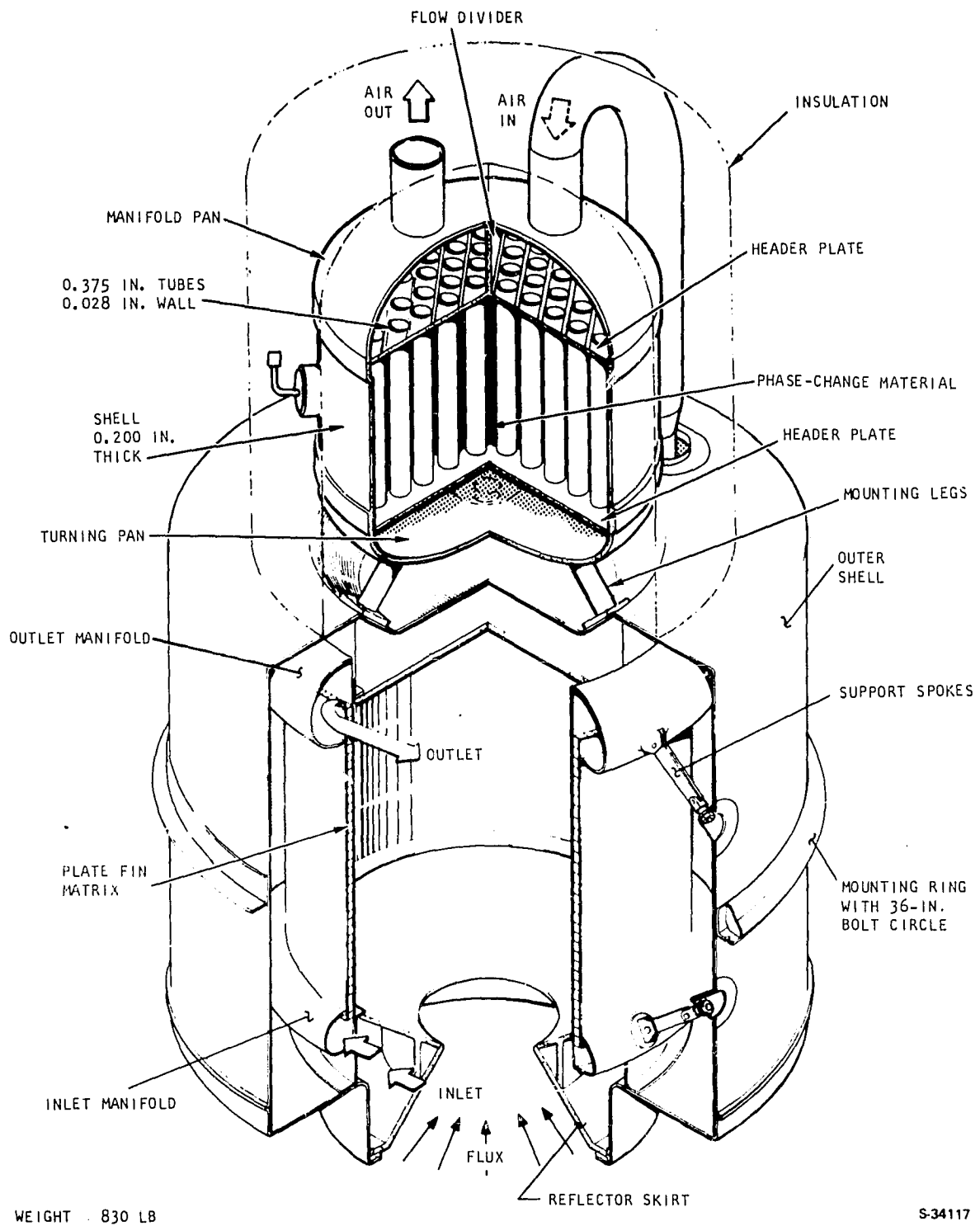
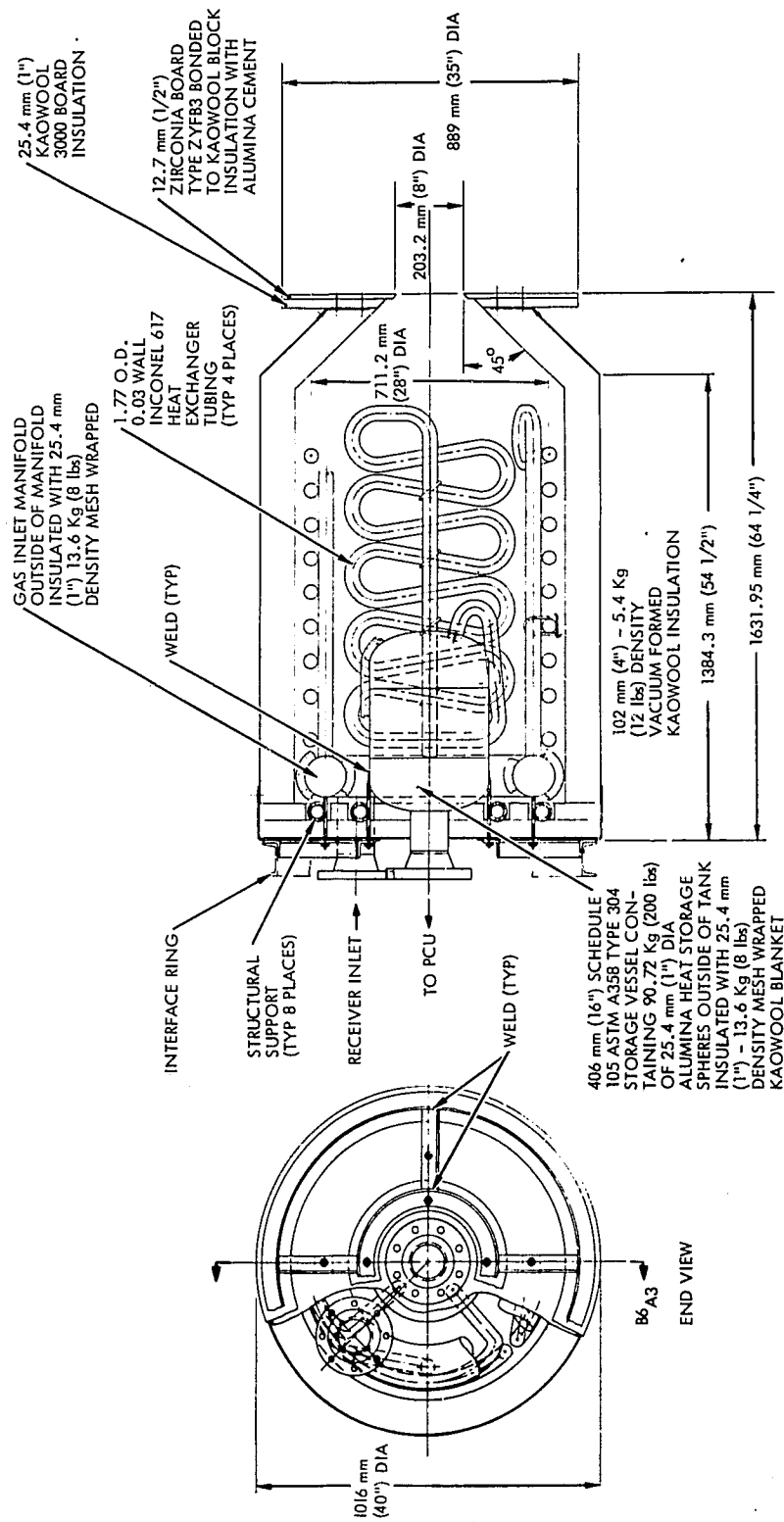


Figure 5-2. Air Solar Receiver and Buffer Thermal Storage Assembly (Garrett AiResearch Manufacturing Co.)



SECTION B6

Figure 5-3. Air-Brayton Solar Receiver and Storage Assembly (Boeing Corp.)

four flat heat exchanger arrays are fabricated of Inconel tubing. The 812.8 mm (32 in) diameter by 1117.6 mm (44 in) deep cavity is lined with Kaowool insulation. Buffer storage is provided within the cavity by placing about 90.72 kg (200 lbs) of alumina spheres within a stainless-steel pressure vessel. Dynatherm Corp. designed the receiver shown in Figure 5-4. The receiver cavity is formed by 18 separate, stainless-steel, sodium heat pipe, heat exchangers and is 457.2 mm (18 in) in diameter and about 762 mm (30 in) deep. Buffer storage is provided by placing sealed tubes of phase-change salts within the heat pipes. The fourth gas receiver, shown in Figure 5-5, was designed by Sanders Associates. It consists of a 558.8 mm (22 in) diameter ceramic honeycomb on which the concentrated sunlight falls after entering through a 190.5 mm (7 1/2 in) diameter quartz window. The gas stream enters peripherally and flows through the heated honeycomb. An integral, phase-change, salt-buffer storage unit with valving to distribute the flow is also shown in Figure 5-5. Figure 5-6 shows the Fairchild Stratos design for a steam Rankine receiver. The 425.45 mm (16 3/4 in) diameter by 711.2 mm (28 in) deep cavity wall is formed of a single 6.35 mm (1/4 in), inside diameter, Incoloy tube approximately 45.72 m (150 ft) in length. The reheat section, forming the back wall of the cavity, is fabricated of 30 tubes, 1.803 mm (0.071 in) inside diameter, in parallel. A magnesium-lithium eutectic in a multi-tube heat exchanger configuration provides the 10-minute buffer storage. Another steam Rankine receiver design by Garrett AiResearch is shown in Figure 5-7. This is a parallel-tube, recirculation-type boiler with separate superheat section. Reheat can be added to the superheat tubes. A salt fusion storage unit was designed to meet the buffer storage requirement. After review of these designs, the RFP for Phase II, final design and prototype production, was released in December 1979.

In January 1979, the six proposals were received. The four proposals for the Phase II air Brayton program were reviewed immediately. The two proposals for the steam Rankine systems were held pending a thorough review of the entire steam program necessitated by fiscal constraints. These two entered the review cycle about two weeks later when it was decided that the need for steam receivers for industrial process heat was essential even though the development of small, high-efficiency steam engines had to be delayed due to funding limitations.

After a technical, cost/price, and management review, Garrett AiResearch was selected to continue with both the steam and air receivers. The Phase II contract for the open-cycle air Brayton receiver was awarded in May and for the steam Rankine receiver in June.

Several important changes in the program influenced the design progress between Phase I and Phase II. Among the most important was the stipulation that all systems must accommodate hybrid operation with fossil fuel. This allowed the 10-minute buffer storage requirement to be relaxed to the inherent storage of the receiver mass. In addition, the requirement to produce industrial process heat was emphasized to insure receiver compatibility with a variety of systems.

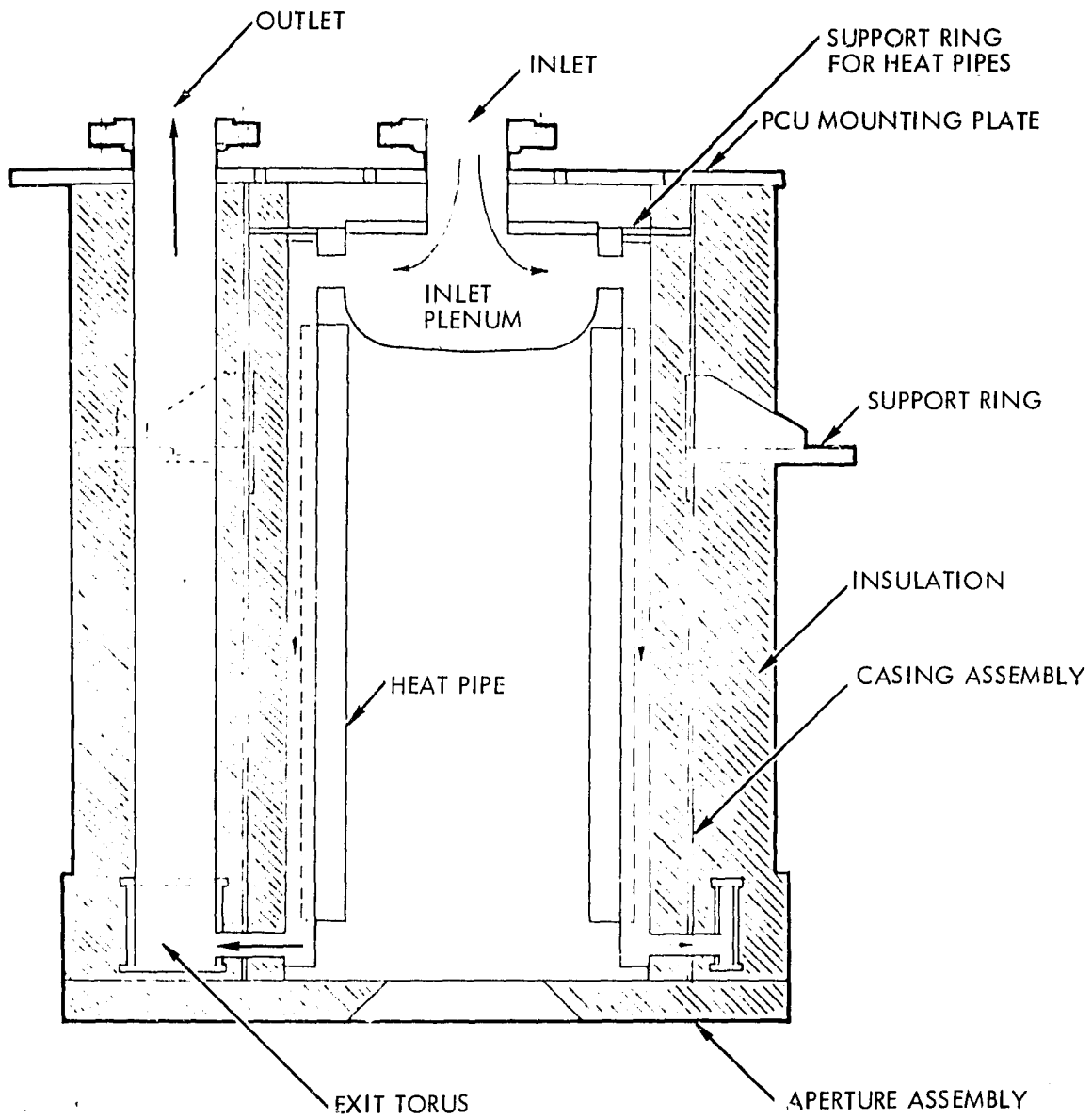
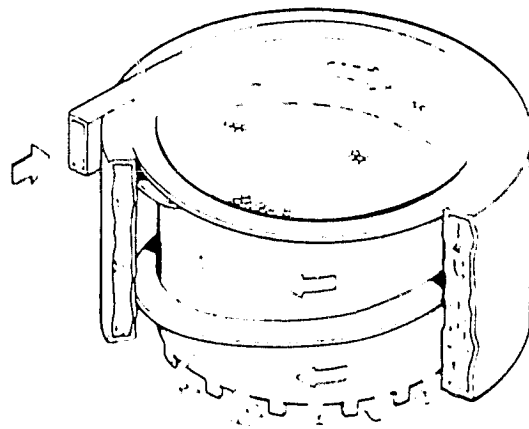
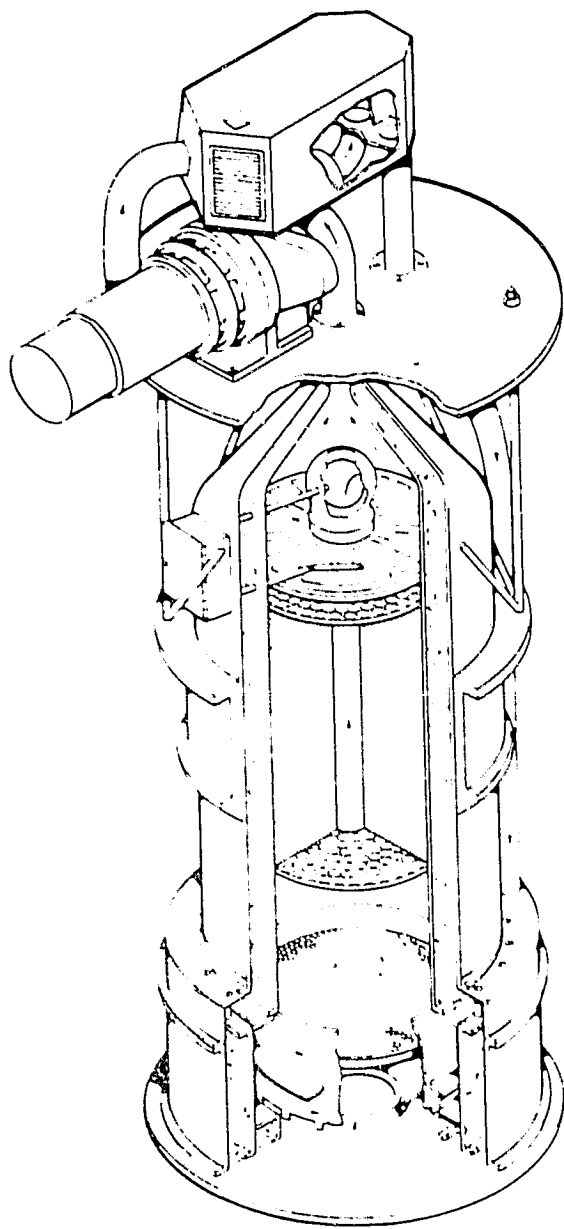


Figure 5-4. Air Solar Receiver (Dynatherm Corp.)

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RECEIVER INLET SCROLL

Figure 5-5. Air Solar Receiver (Sanders Associates)  
(A power conversion unit is shown mounted  
on top of the receiver)

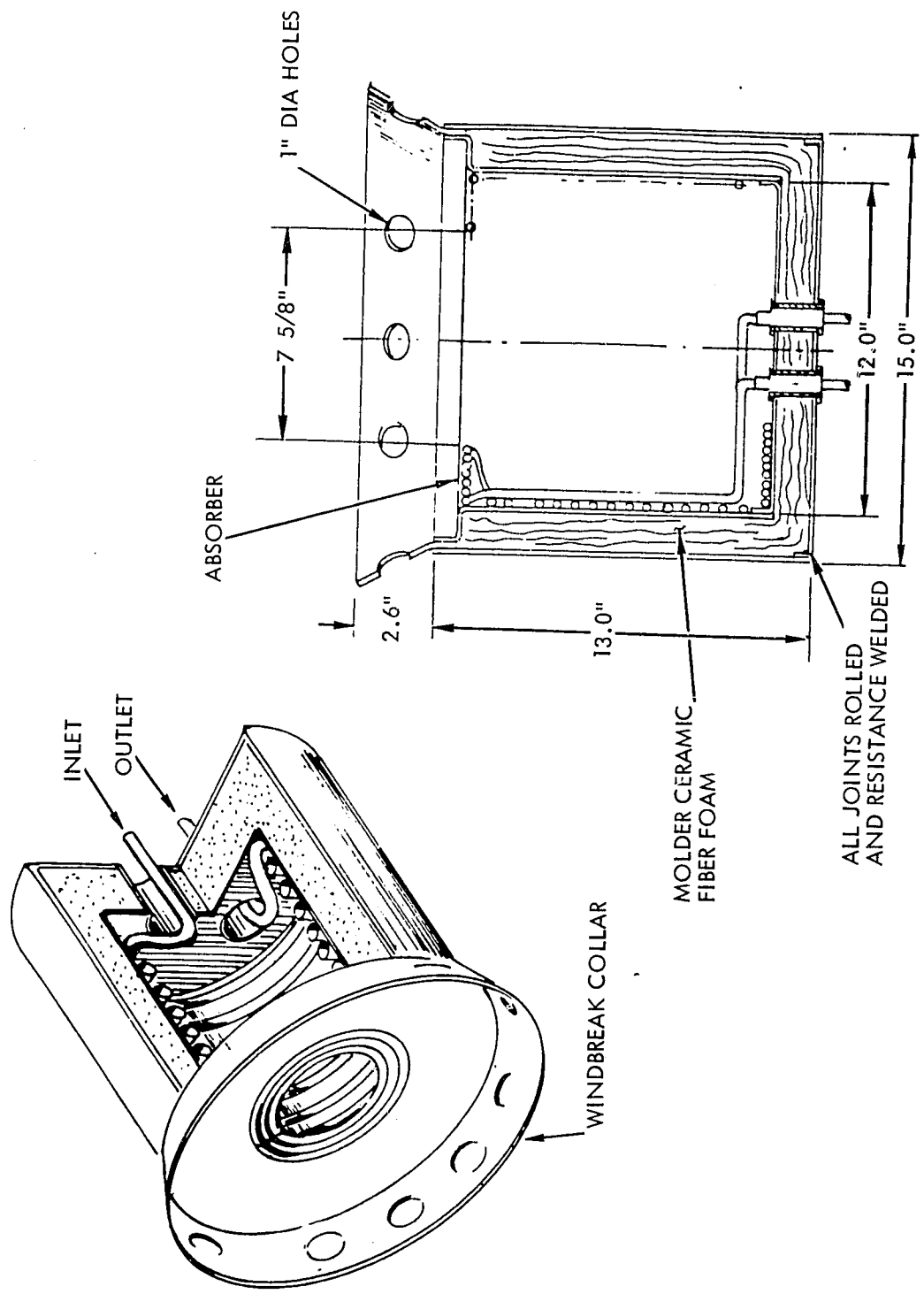


Figure 5-6. Steam Solar Receiver (Fairchild-Stratos Division)

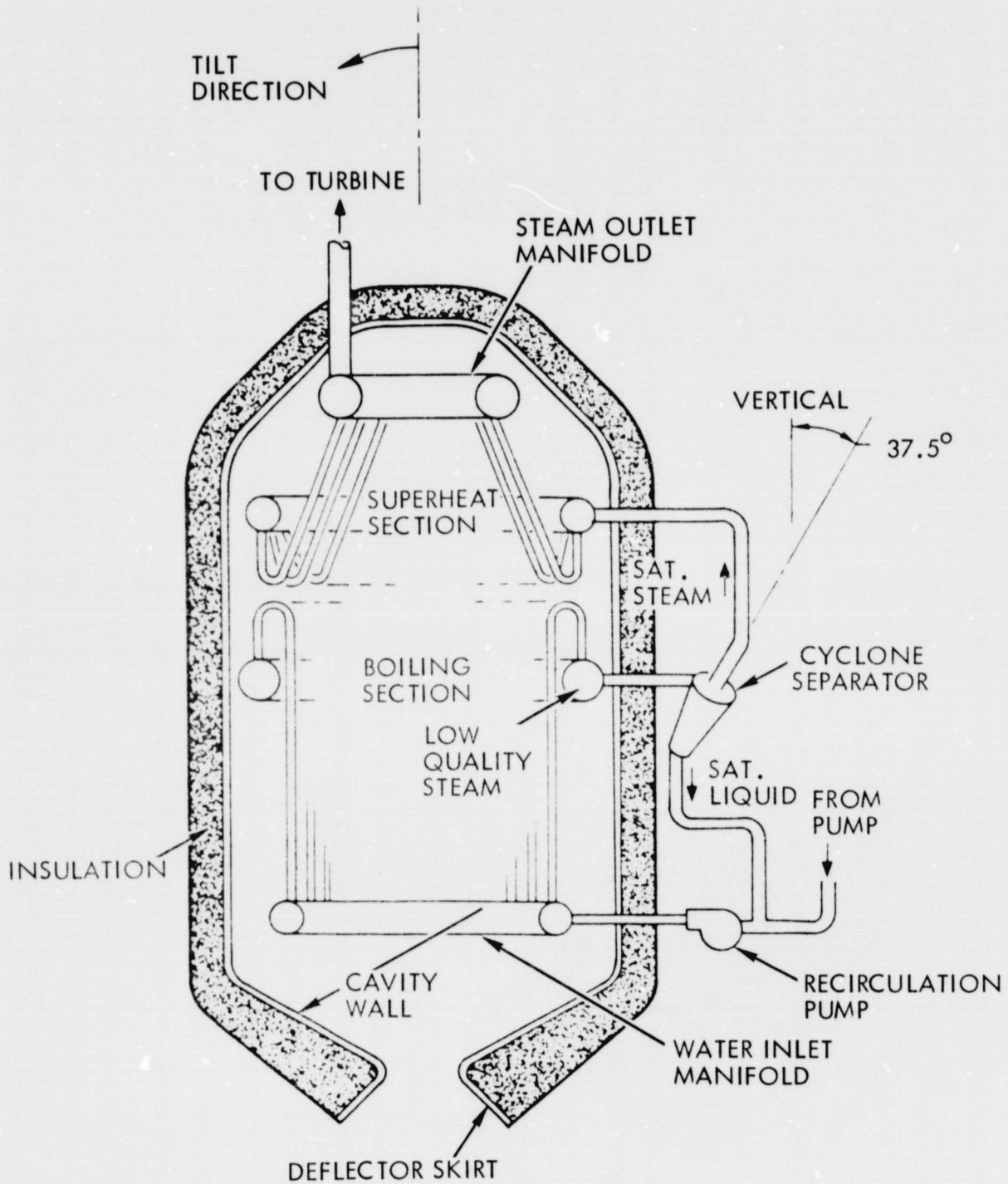


Figure 5-7. Parallel Tube Recirculation Receiver Concept  
(Garrett AiResearch Manufacturing Co.)

In August, a Preliminary Design Review for each receiver was conducted by Garrett AiResearch. The preferred designs which meet all of the functional specifications, and some of the more important design features, are shown in Figures 5-8 and 5-9. Final design of each receiver was started in late August. Prior to the fabrication stage, Critical Design Reviews were scheduled, in September for the air Brayton receiver, and October for the steam Rankine receiver.

Heat transport networks are an important element in producing cost-effective, distributed receiver systems. An efficient heat transport system is essential not only for the production of electricity, but especially in utilizing module output for industrial process heat. Preparation of an RFP package will be completed in FY 1980. The Statement-of-Work will include the following:

- (1) Systems analysis task to establish candidate transport systems.
- (2) Component characterization to assess currently available components.
- (3) Systems optimization review to insure lowest possible costs.
- (4) Prototype production to test key elements at the PFSTS.
- (5) Operations and maintenance optimization.
- (6) Production cost estimates.

The RFP will be released in late FY 1980 for a contract start in early FY 1981.

#### E. IN-HOUSE PROGRESS

While receiver development is primarily contracted to industry, a strong in-house support effort was pursued to insure timely, cost-effective management of the task. This support included: continued development of the flux mapper, support for Omnium-G testing program, an analytical receiver model program, and program support tasks.

The Mark I Flux Mapper, shown mounted on the Omnium-G concentrator in Figure 5-10, was completed late in the first quarter of FY 1979. It was shipped to the PFSTS in January and mounted on the Precursor Concentrator. Test and calibration runs were completed between late January and early February 1979. After several revisions to the software, preparations were made to mount the Flux Mapper on the Omnium-G system in March. Delayed somewhat due to particularly windy weather, first flux maps of the concentrated sunlight were made in April. The Omnium-G system was reconfigured (with new petals) and additional flux maps were produced in May. The Flux Mapper functioned

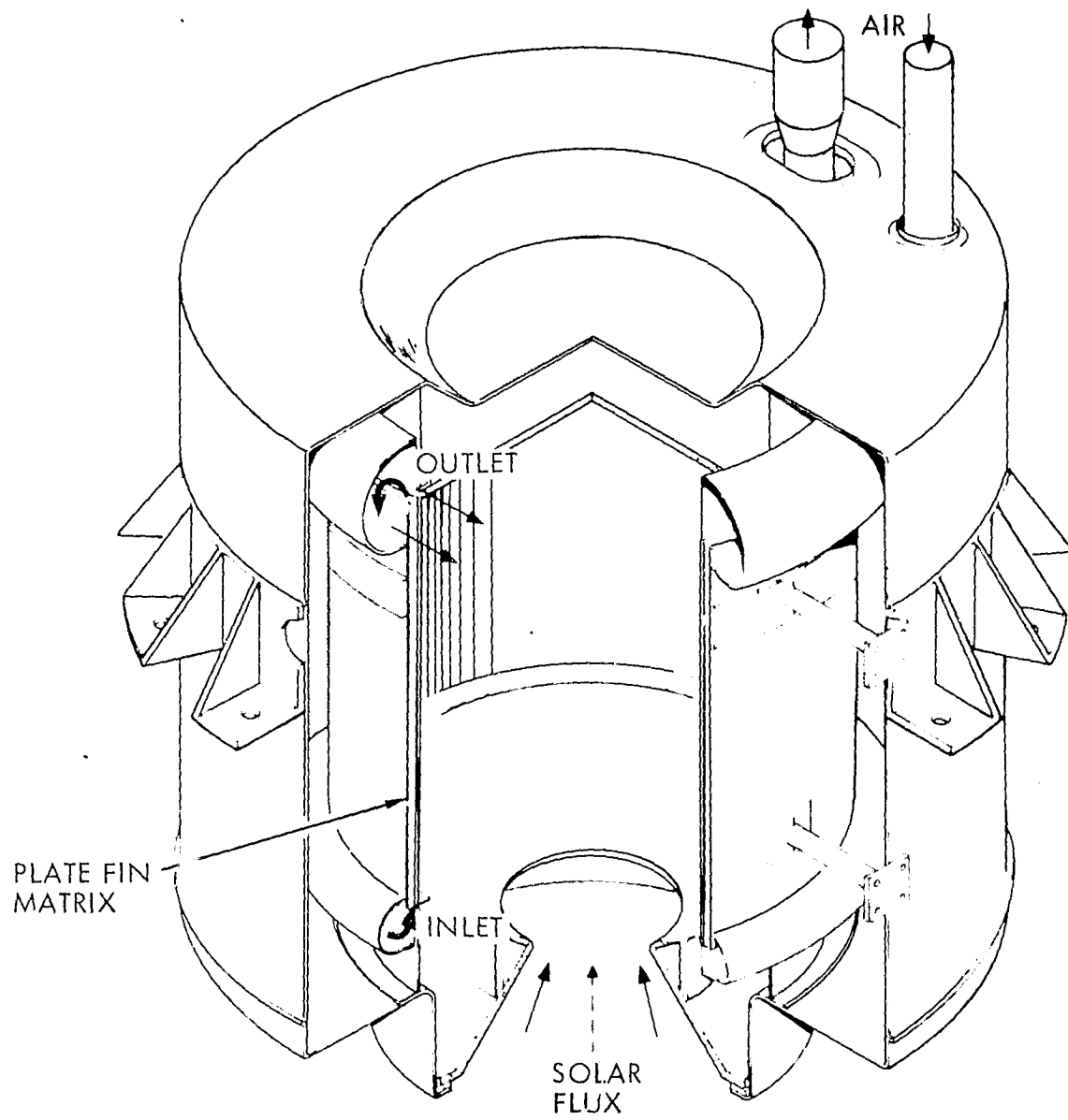


Figure 5-8. Air-Brayton Solar Receiver (Garrett AiResearch Manufacturing Co.)

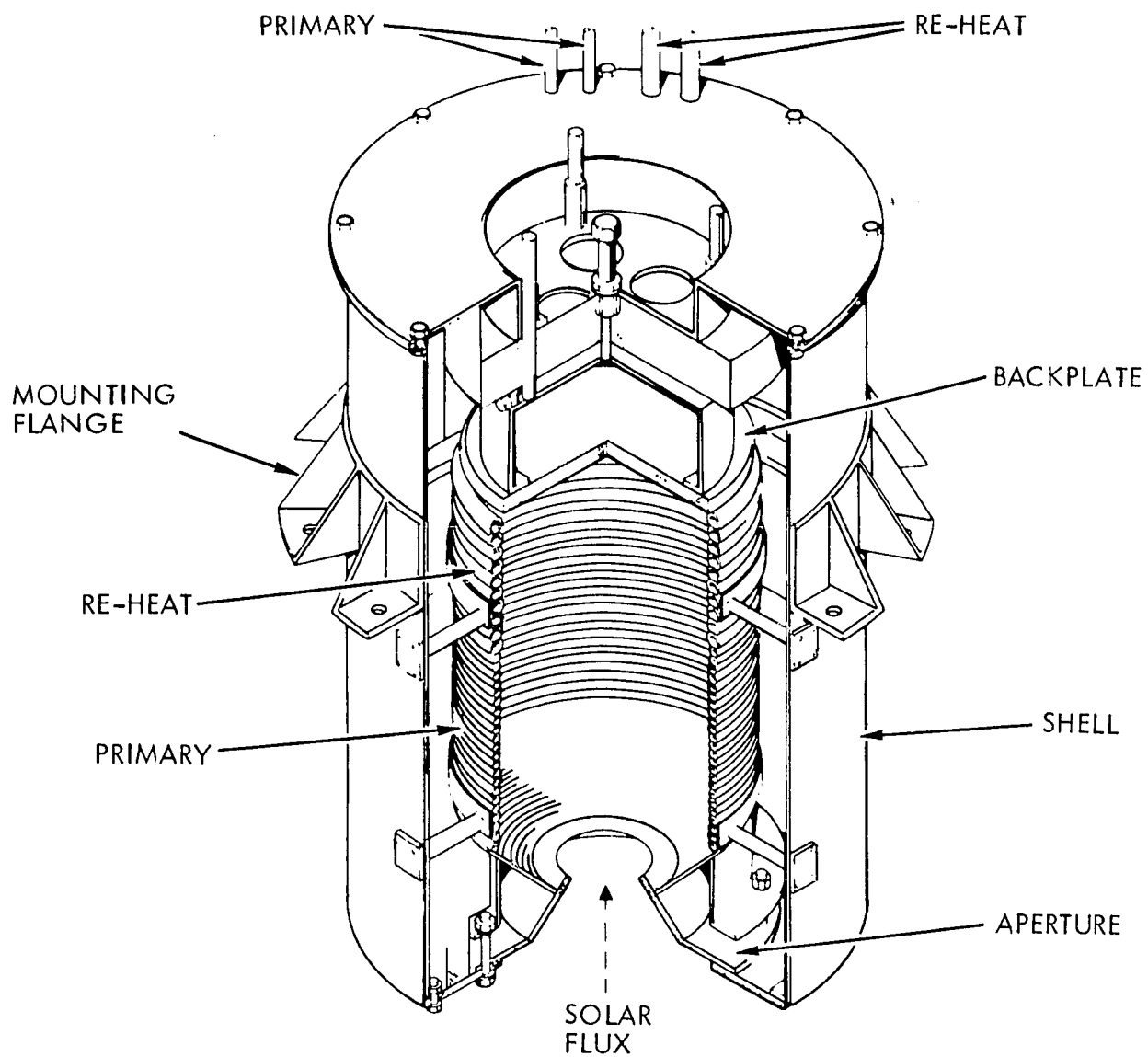


Figure 5-9. Steam Solar Receiver (Garrett AiResearch Manufacturing Co.)

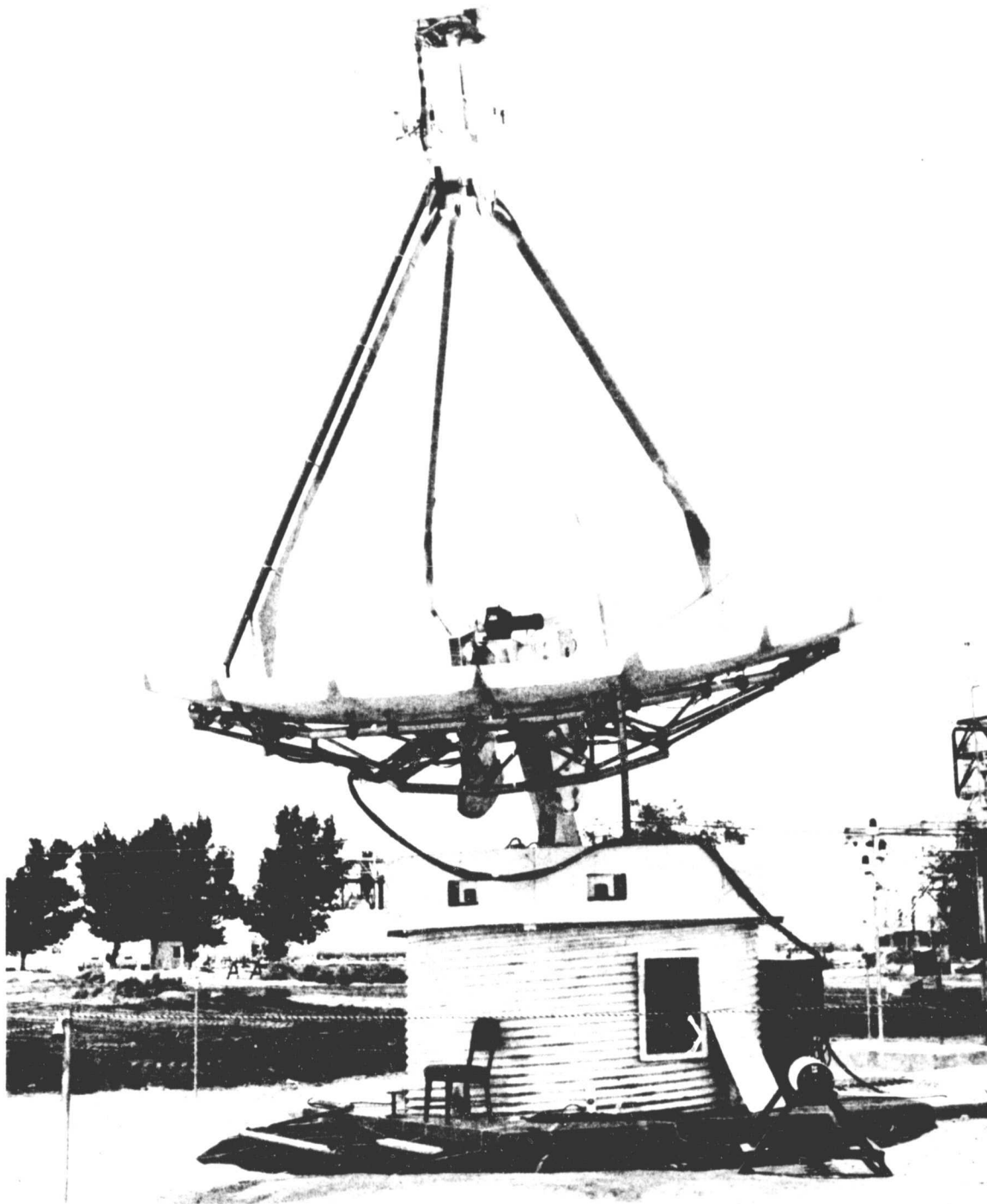


Figure 5-10. Flux Mapper Mounted on Concentrator

as predicted. Typical data is shown in Figure 5-11. When integrated, the Flux Mapper data agreed very well with calorimeter data taken on the Omnim-G system. This comparison is shown in Figure 5-12. As a further check on the accuracy, a Kendall absolute cavity radiometer suitable for operation at high intensities was fabricated to mount on the Flux Mapper. Data reduction and comparison to earlier data is expected early in FY 1980. The Flux Mapper was used to help characterize the performance of the Omnim-G system. Additional support to this activity included test planning, data analysis, receiver thermal analysis, calorimeter comparison and other tests. In addition to further improvements to the operating system, the Flux Mapper is being readied to mount on the Test-Bed Concentrator early in the next year.

The development of an in-house computer simulation model for receivers was extended by analyzing the suitability of available computer programs to development needs. An existing program, HEAP, was determined to be suitable if specialized input, output, and data management features were added. This modification of the HEAP program was begun about mid-year and will continue into the next fiscal year.



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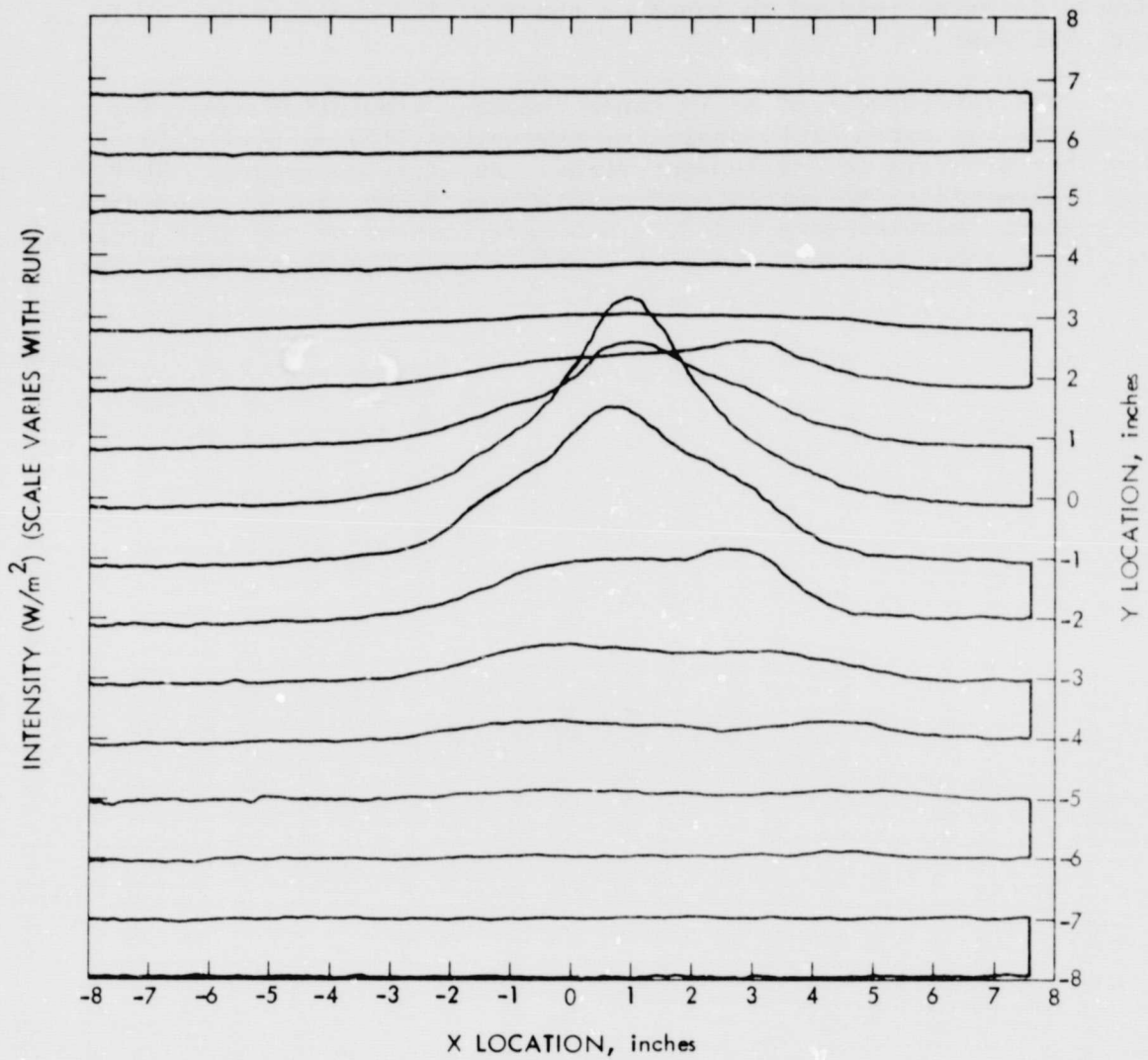


Figure 5-11. Typical Flux Mapper Data

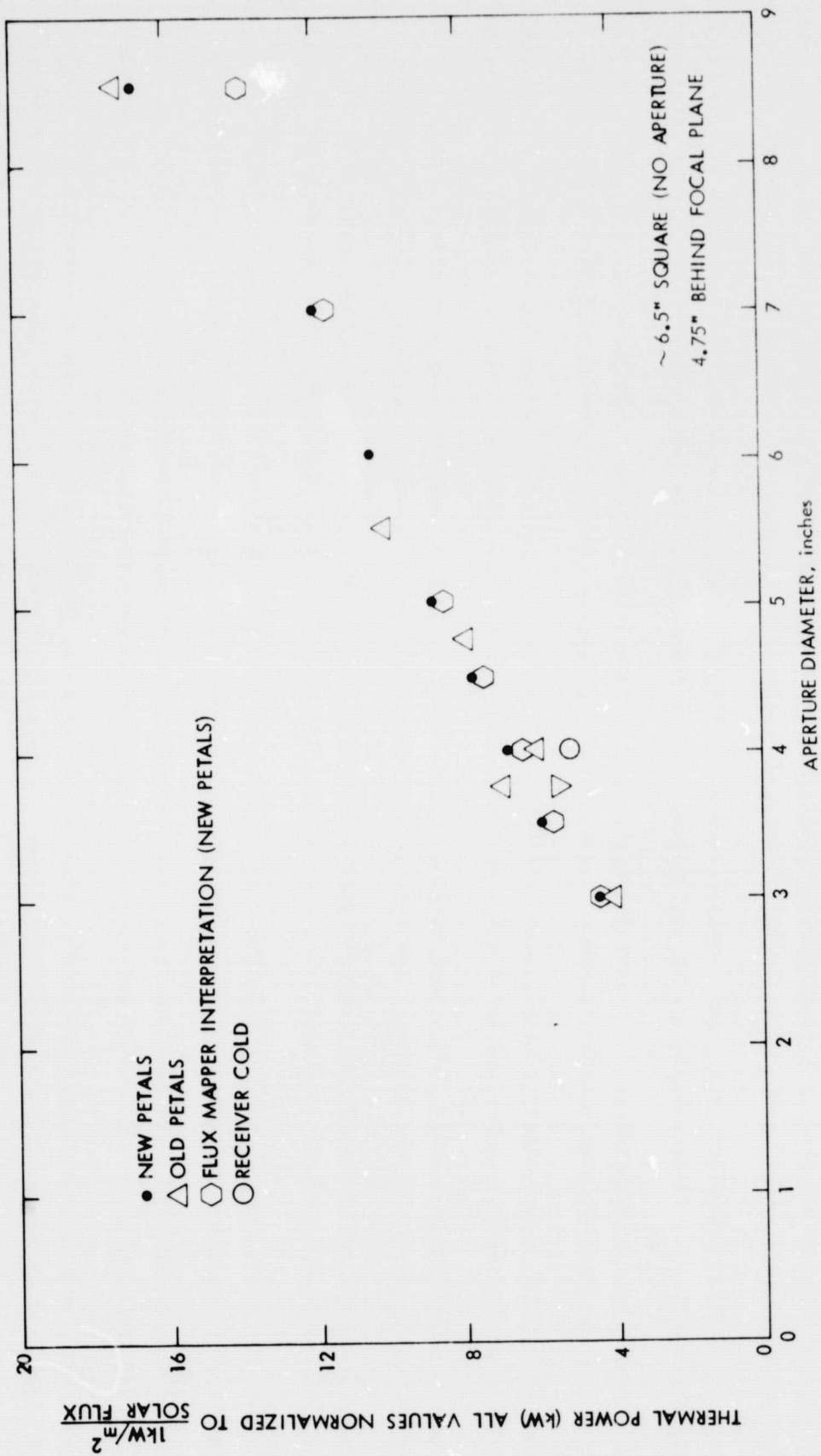


Figure 5-12. Comparison of Flux Mapper and Calorimeter Data Obtained from the Omnium-G Module

## SECTION VI

### POWER CONVERSION DEVELOPMENT

#### A. INTRODUCTION

As part of the DOE/NASA Solar Thermal Power Program, investigations of dispersed solar-electric power systems are being conducted by NASA-Lewis Research Center (LeRC) for JPL. These systems are characterized by a point-focusing, parabolic-shaped concentrator, with a receiver mounted at the focal point and a heat engine and generator set. Figure 6-1 shows an artist's view of a Brayton open-cycle power conversion unit, with recuperator, mounted at the back of a receiver. All of these components would be supported by the concentrator assembly. The focal point is located in the receiver.

The first part of these investigations entailed conceptual design studies of the major components and systems to determine potential performance, and to select receivers for the system. The two candidate power conversion cycles considered ready for technology development were the Rankine cycle and the Brayton cycle. Multiple contracts were awarded for conceptual design in September, 1978. A design, fabrication and test phase was entered following completion of the conceptual design studies and evaluation phase. This is illustrated in the schedule shown in Figure 6-2. The power conversion units selected for the later phase will be tested with appropriate concentrators and receivers produced by the other tasks in the PFDR Technology Project.

#### B. OBJECTIVES

The specific objectives of LeRC are to investigate the technical and economic characteristics of a variety of candidate small power conversion systems. These systems will be suitable for use with single, point-focusing solar concentrators and receivers. During the course of the investigation, the estimated performance and projected life-cycle costs will assist in determining which of the systems are economically viable and where they would be most competitive in future energy markets.

The specific objective of the Power Conversion Development 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 efficiencies of 25%-35% by 1982 and for the second generation, 35%-45% by 1986. The conversion subsystems will be tested initially on the Test-Bed Concentrators, and then on the Low-Cost Concentrators. If engines of high efficiency are mass produced, it is hoped that the mass-produced cost could be targeted at \$200-350/kWe for the first generation and \$100-200/kWe for the second generation.

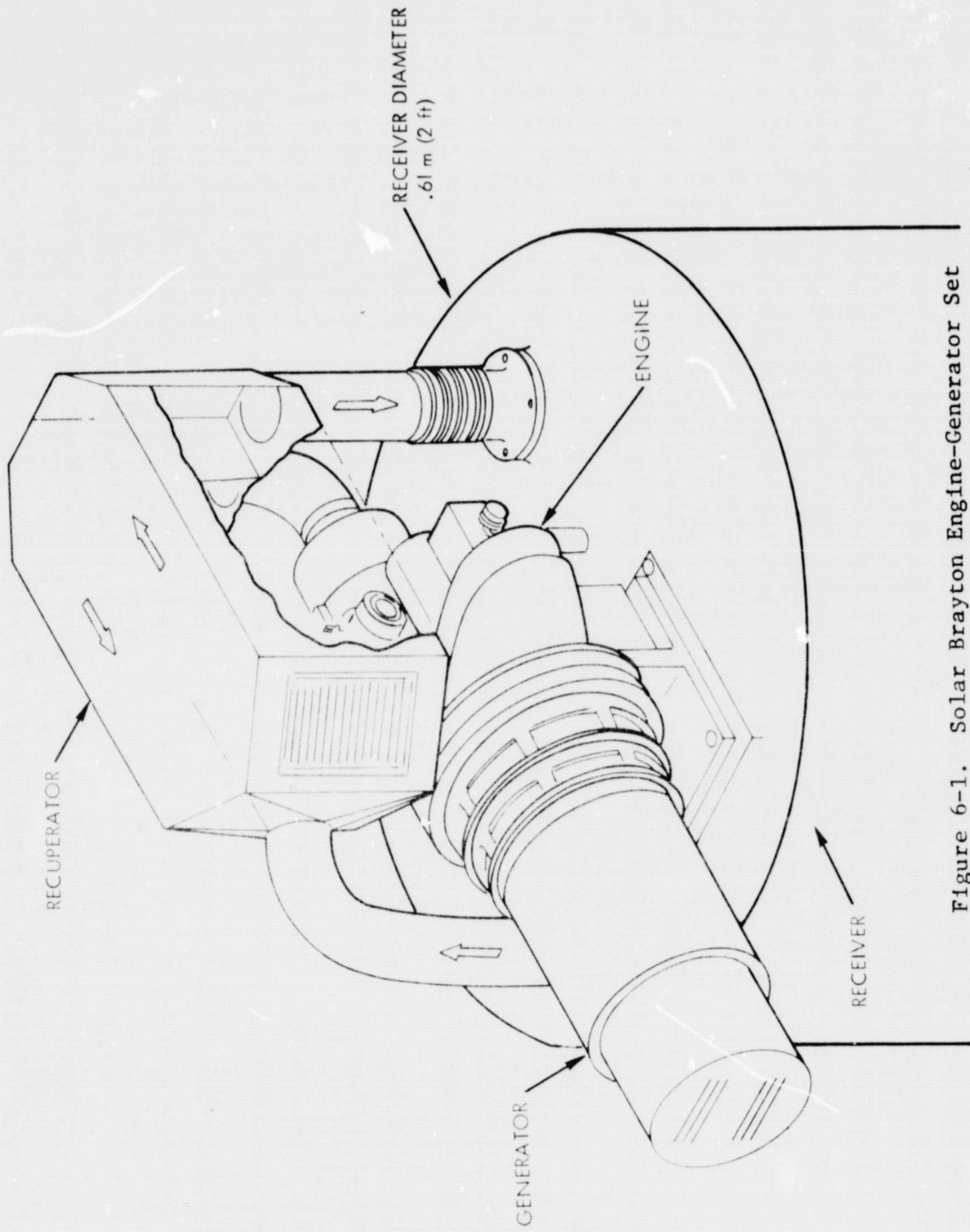


Figure 6-1. Solar Brayton Engine-Generator Set  
(Garrett AResearch Manufacturing Company)

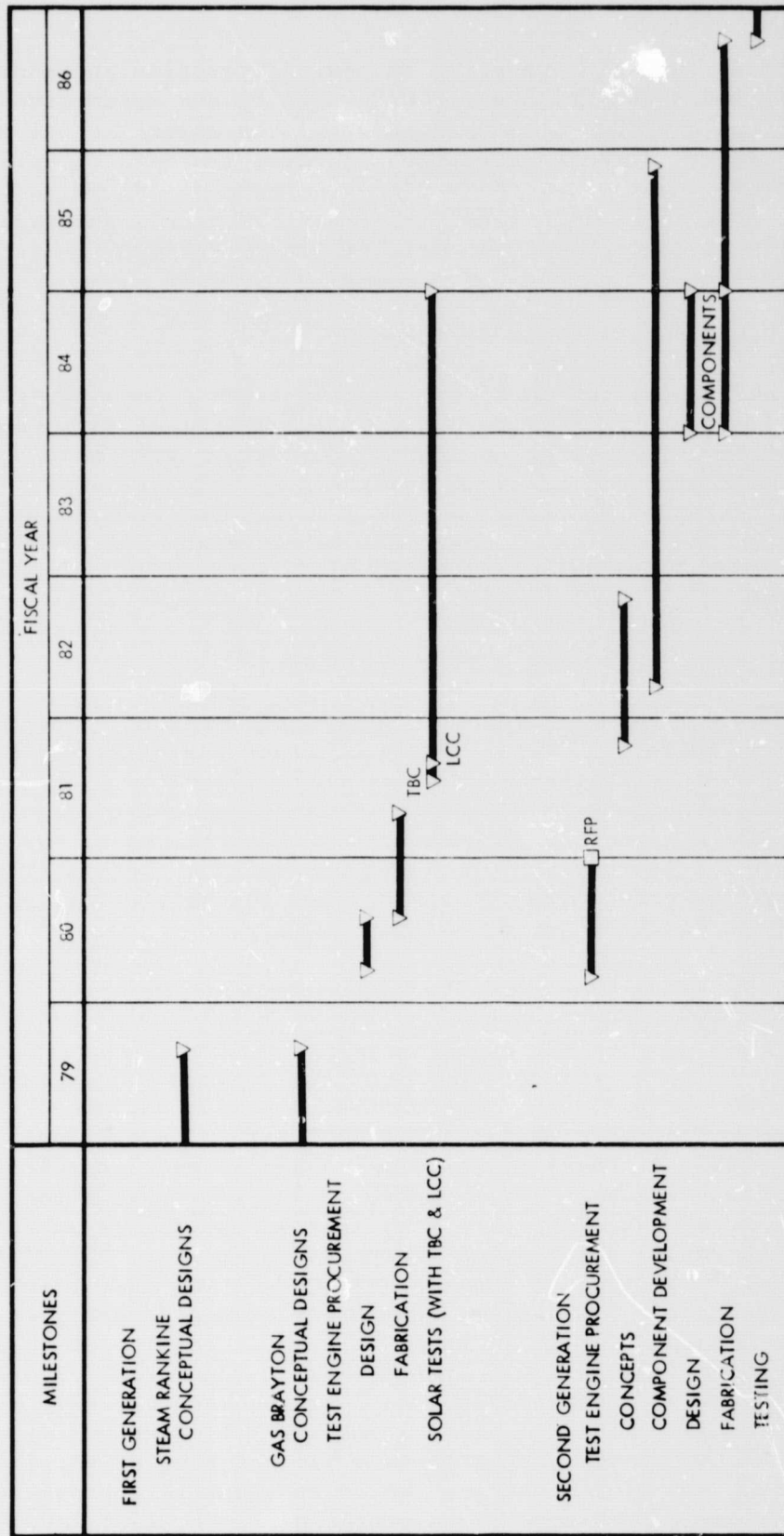


Figure 6-2. Power Conversion Development Milestone Schedule

## 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, LeRC selected a number of Rankine and Brayton solar thermal systems as the basis for studies and experimental investigations of performance for the first generation. A "Handbook of Data on Engine Components for Solar Thermal Applications" (DOE/NASA/1060-78/1) was published in 1979 by the Advanced Solar Thermal Technology Project.

### 2. In-House Engine Cycle Analyses

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

### 3. Contractor Conceptual Design Studies

The LeRC in-house program is being complemented by contracted efforts with industry. First in the contract series were contracts to provide concept definition studies of small (15 kWe: an approximate value, used throughout this section) Brayton-cycle and steam Rankine-cycle engines for dispersed solar-electric power systems. As a result of the contractors' performance and cost studies, DOE selected one Brayton engine to be designed and fabricated under contract with industry for subsequent testing.

## D. CONTRACTOR ACCOMPLISHMENTS

Table 6-1 list design conditions and performance characteristics obtained from the engine studies conducted by the various contractors. The efficiencies cited in Table 6-1 correspond to engines at various stages of development and at rated conditions which differ for each engine. For example, the type of engine used to derive the steam Rankine engine efficiencies is further advanced than that used to derive the Brayton engine efficiencies. Therefore these efficiencies should not be compared directly. The last column of Table 6-1 partially illustrates the effect of engine designs at off-design conditions. It is based on a solar insolation curve over a year with reduced power input to the engine. An effect of off-design performance can be observed since each engine used the same annual insolation curve. Although all systems were relatively constant in performance, the steam Rankine systems had the best off-design performance. All of the designs showed substantial improvements over the off-the-shelf performances reported in "Handbook of Data on Engine Components for Solar Thermal Applications."

Table 6-1. Solar Engine Conditions and Performance Characteristics

POWER CONVERSION UNIT/COMPANY	WORKING FLUID	THERMAL POWER (kW)	INLET CONDITIONS		MASS FLOW (LB/HR)	ENGINE	EFFICIENCY			
			TEMP. (°C)	PRESS. (MPa)			ELECTRICAL GENERATION*	PCU	ANNUAL CONVERSION	
STEAM RANKINE:										
2 STAGE TURBINE										
SUNDSTRAND	STEAM (REHEAT)	80	732	4.137	179	.31	.87	.27		.26
COMPOUND RECIPROCIATOR										
J. CARTER	STEAM (REHEAT)	80	676	17.237	175	.33	.92	.31		.29
OPPOSED 2 CYC RECIPROCIATOR										
FOSTER-MILLER	STEAM (REHEAT)	80	700	12.066	136	.36	.92	.33		.32
BRAYTON:										
OPEN: GTP 36-51	AIR	72.7	815	.258	2226	.30	.80	.23		.22
AIRESEARCH										
CLOSED: PFE (MOD)	AIR	72.7	815	.331	2443	.30	.80	.24		.22
AIRESEARCH										
OPEN: ADV (BRU)	AIR	72.7	815	.269	2141	.32	.84	.28		.27
AIRESEARCH										

\*FOR RANKINE TURBINE SYSTEMS THIS INCLUDES CONVERSION OF HIGH FREQUENCY AC TO 60 Hz, 3φ FOR RANKINE RECIPROCIATOR SYSTEMS, THE GENERATOR DELIVERS 60 Hz, 3φ. FOR BRAYTON SYSTEMS, GEARBOX AND CONVERSION OF HIGH FREQUENCY AC TO 60 Hz, 3φ IS INCLUDED AS NEEDED.



1. Brayton Conceptual Design Studies

Procurement activities were initiated with industry to proceed with conceptual design studies to establish the economic viability and efficiency of small Brayton-cycle power conversion systems. As a result of competitive procurement, LeRC awarded a contract to Garrett AiResearch Manufacturing Company of Arizona in September 1978 to complete a study of three configurations:

- (1) Brayton Baseline Open Cycle
- (2) Brayton Baseline Closed Cycle
- (3) Brayton Alternate Open Cycle

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

The contract effort has performed the following tasks for each of the three configurations.

a. Task 1: Parametric Performance Analyses. The contractor, Garrett AiResearch, determined the design and off-design performance of several Brayton units which they had designed previously for various non-solar applications. These included three open-cycle engine designs:

- (1) a 9.5 kW engine designed for the American Gas Association (AGA)
- (2) a 19.8 kW engine designed for Pacific Fruit Express (PFE)
- (3) a 30 kW engine designed for military application, the Gas Turbine Power Plant (GTP) 36-51

and one closed-cycle design: the 30 kW Closed-Cycle Power System (CCPS-40).

The performance characteristics were determined over a range of values of these major variables:

- (1) Power level: 10 to 20 kW<sub>e</sub>
- (2) Turbine inlet temperature: 650° to 815°C  
(1200°-1500°F)

- (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 rpm to turbine speed (65,000 rpm)

b. Task 2: Conceptual Designs. The contractor prepared detailed design data packages on three NASA-selected designs. The parametric results of Task 1 and the requirement to use existing hardware resulted in the components selected by AiResearch to match the power level (72.7 kW) of the Test-Bed Concentrator. The components selected for each of the three Brayton configurations are presented in Table 6-2. These design packages provided a basis from which realistic cost estimates were made.

Table 6-2. Selected Components for Brayton-Cycle Power Conversion Unit Configurations

	<u>Open Cycle 1980 Test</u>	<u>Closed Cycle 1980 Test</u>	<u>Open Cycle 1982 Test</u>
Turbocompressor	GTP 36-51	Pacific Fruit Express	Scaled Brayton Rotating Unit
Recuperator	(Plate-Fin Sized to Match Design Power)		
Alternator	400 Hz	400 Hz	Permanent Magnet (PMA)
Gear Box (rpm)	63,000/8,000	60,000/8,000	None
Efficiency at 60 Hz	25%	24.2%	26%

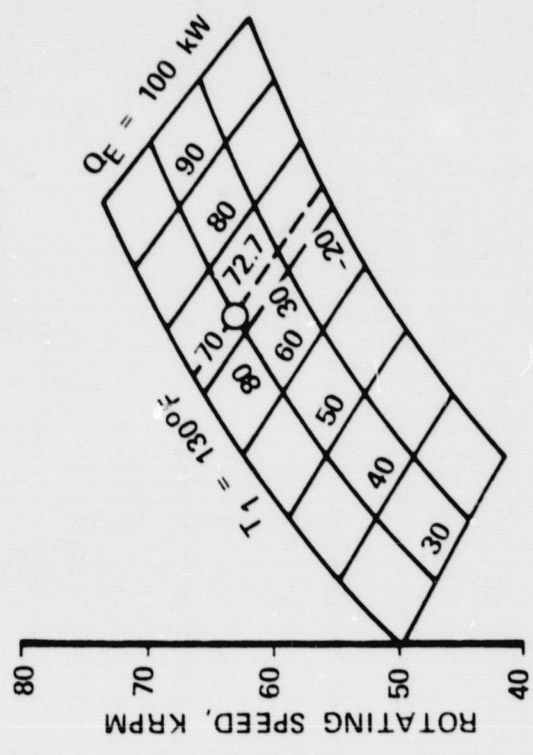
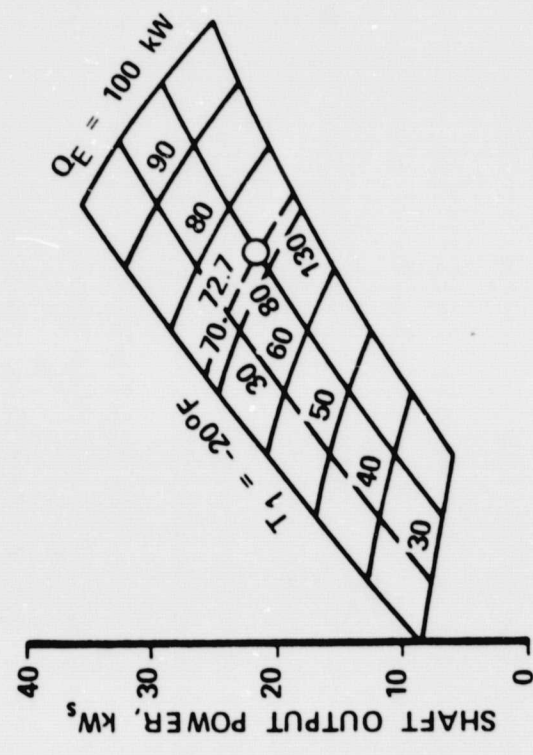
c. Task 3: Interface Requirements. The contractor identified physical and operational interfaces with the balance of the system to assure compatibility of power conversion system designs with complete solar thermal systems. Performance maps were generated for each configuration assuming operation in the pure solar mode, that is, without any provisions for augmenting the solar input with liquid or gaseous fuels. The GTP 36-51 open-cycle engine configuration was selected for Phase II design. Figure 6-3 shows a typical performance map on the GTP 36-51 at sea level for the full range of design and off-design solar insolation ( $Q_E$ ) and compressor inlet temperatures ( $T_I$ ). Layouts of the three engine configurations were made in Task 2. However, only the baseline open-cycle configuration will be discussed in detail. For information on the closed-cycle and alternate open-cycle configurations please see References 6-1 through 6-3. Figure 6-4 shows the GTP 36-51 engine assembly and its mounting arrangement on the cylindrical receiver. With only minor exceptions, the engine fits within the nominal .9 m (3 ft) diameter shadow of the receiver, in order to minimize reduction of useful concentrator area.

The baseline open-cycle Brayton engine/generator set consists of the following components:

- (1) A radial flow turbine and compressor assembly running on oil bearings. This is the power section of the contractor's model GTP 36-51 engine.
- (2) A 400 Hz, 8000 rpm electrical generator.
- (3) A gear box from the contractor's production engines to reduce the high turbine shaft speed to the required range of generator speeds.
- (4) A high effectiveness, pure counterflow, plate-fin recuperator.
- (5) An engine control system which holds turbine inlet temperature constant at 815°C (1500°F) over a range of solar thermal power input from 30 to 72.7 kW. Inputs below 30 kW require the unit to run at a constant speed and a reduced turbine inlet temperature to avoid recuperator overtemperature above 700°C (1300°F).

The total estimated weight for this engine/generator configuration was 345 kg (760 lbs) which would be mounted to the receiver and supported along with the receiver at the focal point.

Although the system was initially configured for solar thermal operation only, a modification to the engine, including a new combustor, allows the system to perform in a hybrid or fossil-fuel augmented mode.



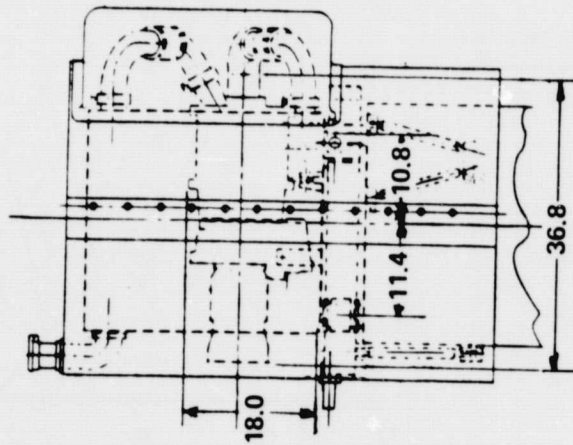
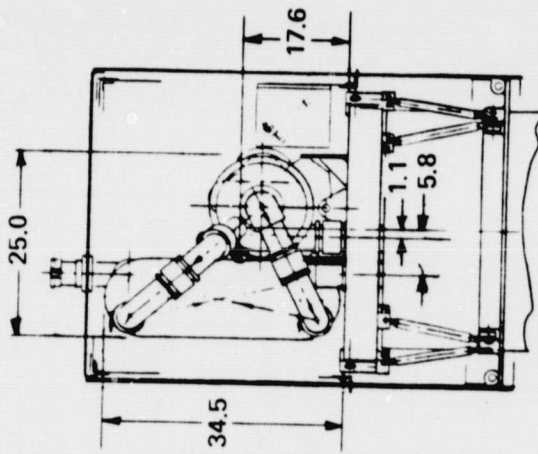
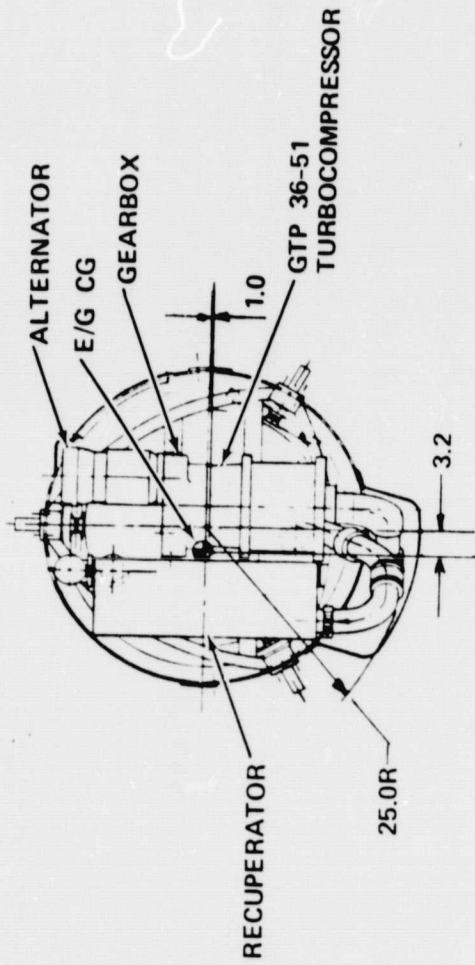
$$kW_e = \eta_g * kW_s$$

$$\eta_g = 0.933$$

○ HYBRID ENGINE DESIGN POINT

Note: Constant Inlet Temperature of 1500°F (815°C).

Figure 6-3. Performance Map of the GTP 36-51 Engine at Sea Level  
(Garrett AiResearch Manufacturing Company)



Note:  
Dimensions are in inches.

Figure 6-4. Baseline Open-Cycle GTP 36-51 Engine Assembly and Mounting Arrangement on Receiver

d. Task 4: Assessment of Production Implementation.

The contractor estimated the production costs of several engine concepts as a function of production rate. Maintenance considerations to achieve long life and reduce life-cycle costs were included. The production model, shown in Figure 6-5, is identified as Production Configuration Five (PC-5); it represents the fifth configuration of the baseline GTP 36-51. It includes internal electrical power conditioning for DC output. Table 6-3 shows a cost breakdown for this optimized production configuration estimated on the basis of 10,000 units per year and 1978 dollars. Table 6-4 presents the normalized unit cost of the PC-5 in various production quantities. Minimal maintenance costs are projected for the PC-5, since the turbomachine does not require a lubrication system or a gearbox. The permanent magnet alternator is driven at turbine speeds contributing to a fairly lightweight power system. (See References 6-1 through 6-3 for contractor cost estimates of other engine concepts.)

e. Task 5: Reporting. A final report of Garrett AiResearch's Brayton Conceptual Design Study is expected to be released for distribution in late CY 1979.

2. Steam Rankine Conceptual Design Studies

The steam Rankine contract effort was initiated in late FY 1978 for a concept definition study to identify expected improvements in small engines for solar thermal-electrical applications. An SOW for the study was structured with an initial parametric analysis task to estimate performance sensitivity to temperature in the 425°-815°C (800°-1500°F) range. From the parametric results a design point, nominally at the 15 kWe power level, was selected for a conceptual design task. The conceptual design effort included 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. Subsequent tasks evaluated the design for interface limitations, production costs, life characteristics, and maintenance requirements in solar applications.

A concept definition RFP was issued in April 1978 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. Contract awards were made in September for three, parallel, six-month studies:

- (1) Sundstrand Energy Systems - Mod 0 Category Turbine
- (2) Foster-Miller Associates - Mod 1 Category Reciprocator
- (3) Jay Carter Enterprises - Mod 0 Category Reciprocator

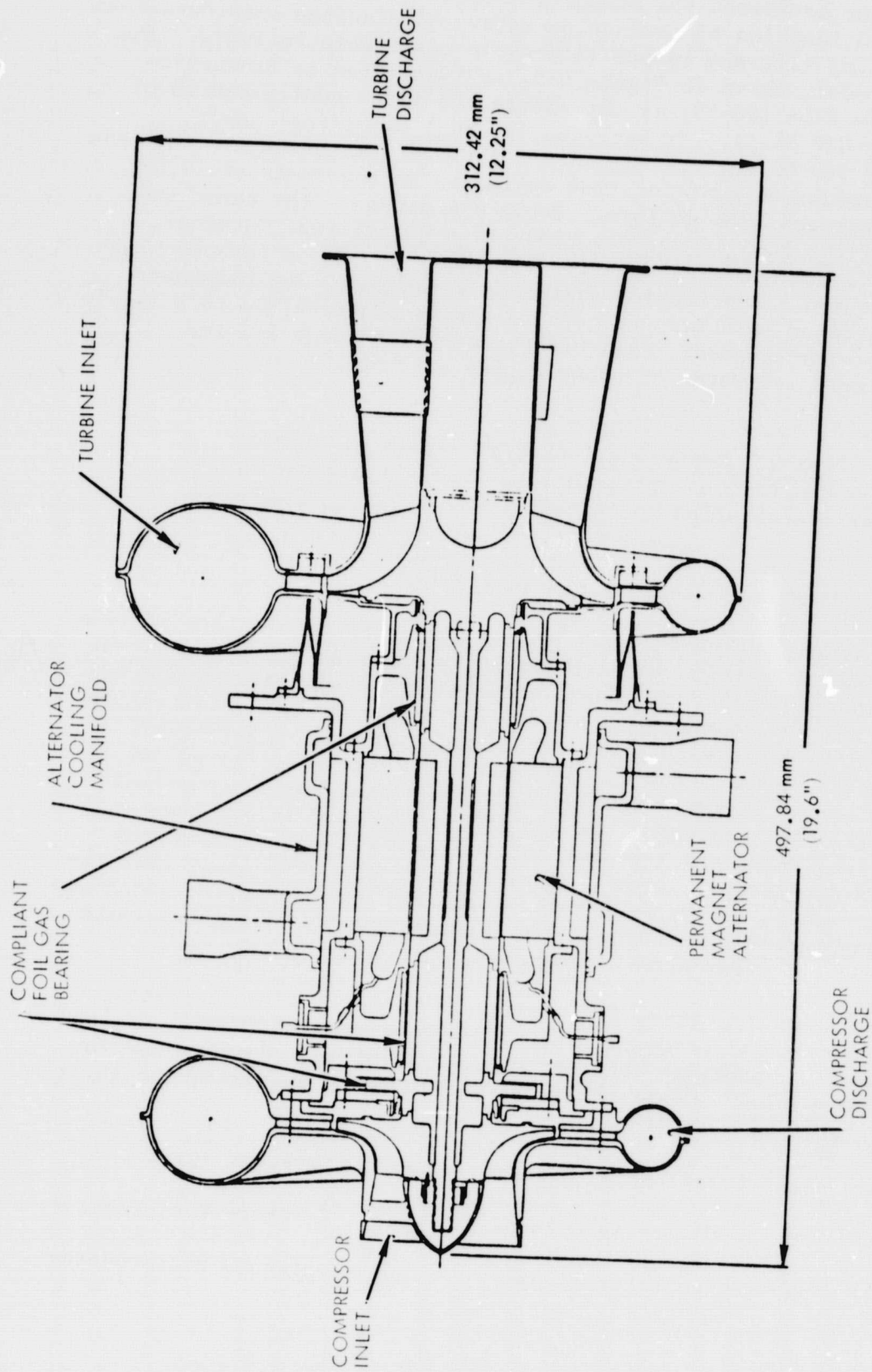


Figure 6-5. Turbomachinery for Engine Generator Model PC-5  
 (Garrett AiResearch Manufacturing Company)

Table 6-3. Cost Estimate for Production Configuration Five (PC-5)

	Material \$	Labor Hrs	Markup On Labor And Material	Estimated Purchase Price \$
Turbocompressor	217	7.5	1.937	885
Generator	302	14.2	1.937	1462
Recuperator	497	12.6	1.937	1743
Other Parts	35	2.7	1.937	235
Bellows, Ducting, Filter Insulation, Structure and Enclosure				
Controls And Accessories				
Sensors, Hardness etc.				
Control Module				250
Fuel Pump And Metering				
Rectifier				450
Electronic Start Power Supply				100
Assembly and Test		2.0	1.937	124
(1) 1978 Dollars		Total		\$5249
Production Rate 10,000/yr				
Labor \$32/hr				

Table 6-4. Normalized Unit Cost of PC-5 in Selected Production Quantities

Production Rate Units/Year	Normalized Unit Cost*
100	3.75
1,000	1.80
10,000	1.00* (Base)
100,000	0.85
1,000,000	0.71



In concept definition studies, the Mod 1 category concepts specifically included reheat. Further, in each of the Mod 0 studies a reheat configuration was investigated as a growth option. The concept definition studies for both Mod 0 and Mod 1 systems were to provide data for an FY 1979 decision by DOE on hardware systems for testing.

The tasks to be performed by each contractor were similar to those shown in the Brayton studies: Parametric Analyses, Conceptual Designs, Interface Requirements, Implementation Assessment and Reporting. In Task 1, the parametric ranges of interest were:

- (1) Net electric power output - 5 kWe to 100 kWe
- (2) Inlet steam temperature - 450°C to 815°C (830°-1500°F)
- (3) Inlet steam pressure -  $6.89 \times 10^6$  -  $17.23 \times 10^6$  N/m<sup>2</sup>  
(1000 - 2500 psia)
- (4) Condensing temperature - 38.3°C - 148.9°C  
(101°-300.2°F)

Each of the three contractors completed the technical tasks and prepared final reports. These reports were reviewed and will be prepared for distribution. Following is a brief overview of each concept. More detailed results can be found in the final reports (References 6-1 through 6-3).

a. Steam Rankine Turbine System -- Sundstrand Energy Systems. The concept proposed by Sundstrand in the baseline category was a single-stage turbine. This concept, which was used in an organic Rankine previously built and operated by Sundstrand for remote communication systems, was reconfigured for the steam application and resulted in an engine efficiency of 23% at inlet steam conditions of 730°C (1350°F) and  $6.41 \times 10^6$  N/m<sup>2</sup> (930 psia). Although this condition met the minimum design requirement of 20% engine efficiency, it was decided to evaluate the design for the growth potential which was part of the Implementation Assessment task. As a result, the single-stage turbine with one steam pass through an admission arc of 0.15 was redesigned to provide for reheat and a second pass across the single-stage turbine which would now appear, in effect, as a two-stage turbine. This turbine, with homopolar alternator, is illustrated in Figure 6-6. This configuration, at full power (80 kWt) with steam conditions of 730°C (1350°F) for both passes and  $4.14 \times 10^6$  N/m<sup>2</sup> (600 psia) on first stage and approximately  $1.40 \times 10^3$  N/m<sup>2</sup> (20 psia) on the second stage, results in an overall engine efficiency of 27% assuming an alternator efficiency of 93%. The final expansion is to a pressure of  $12.4 \times 10^3$  N/m<sup>2</sup> (1.8 psia), or less than atmospheric, with a condensing temperature of 50°C (120°F). The system as proposed by Sundstrand, including the condenser, regenerator, combined rotating unit and condenser fan, is shown in Figure 6-7. The estimated total weight for this system was 217 kg (478 lbs), not including structural or mounting supports.

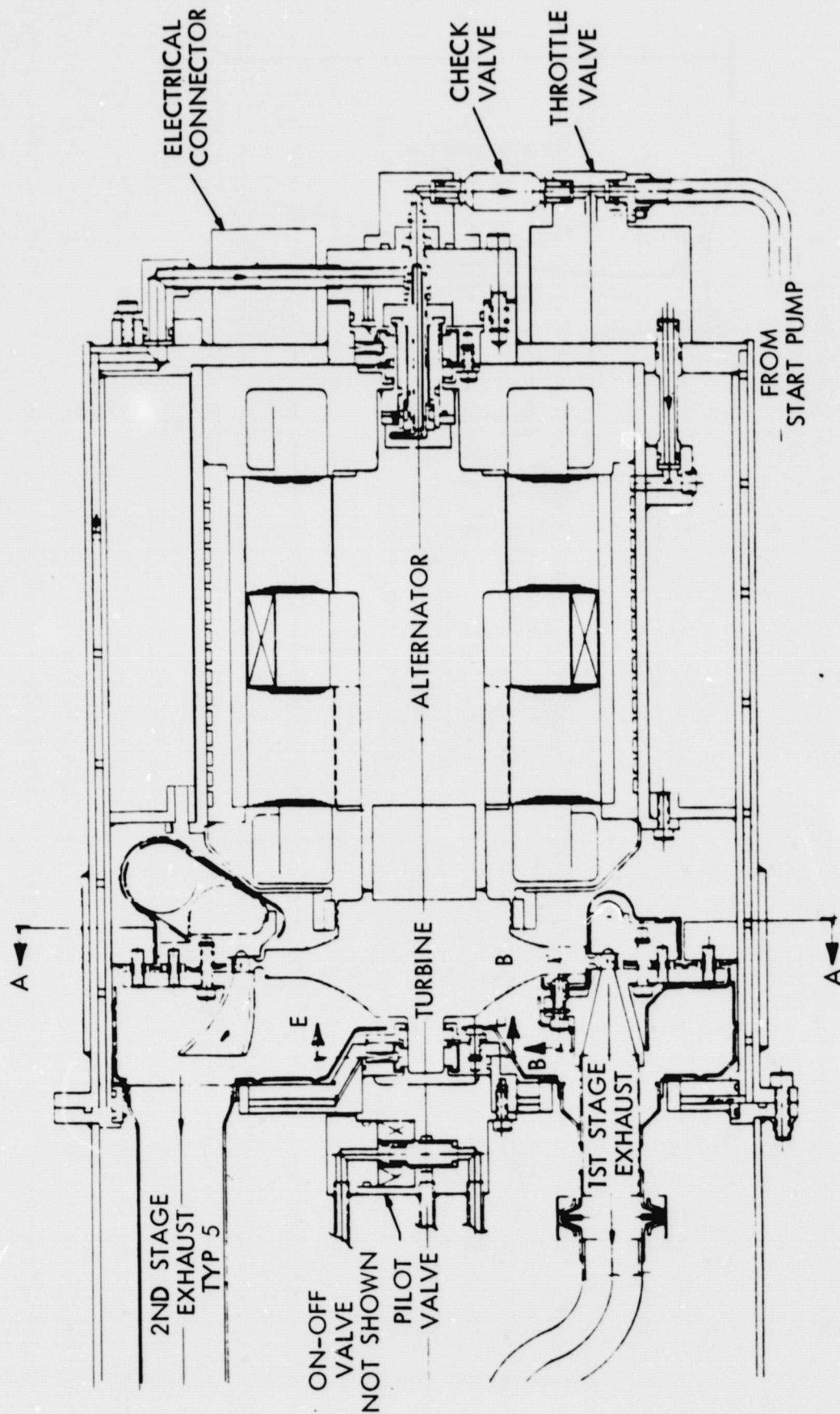


Figure 6-6. Combined Rotating Unit  
(Sundstrand Energy Systems)

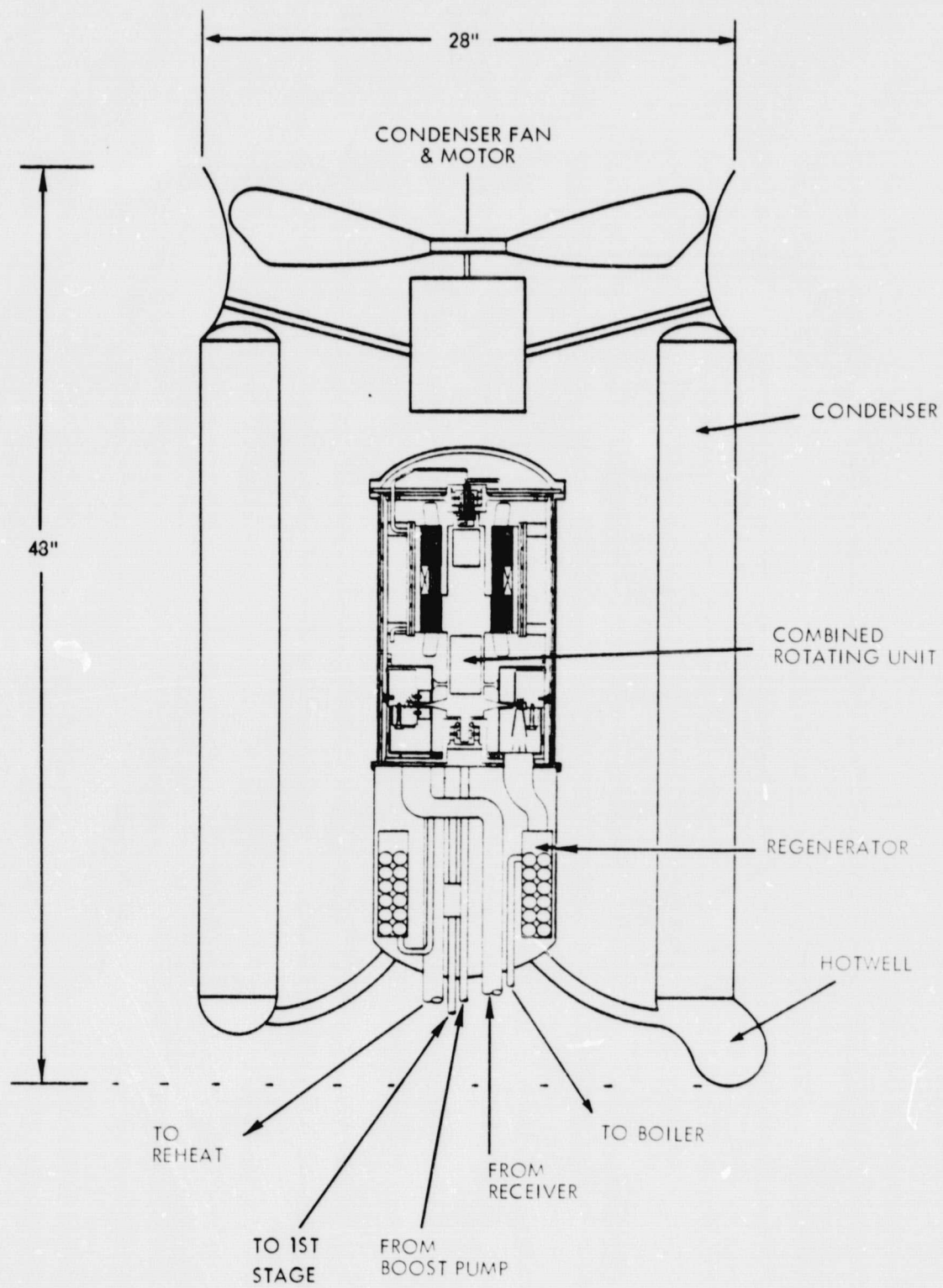


Figure 6-7. Two-Stage Steam System - 22 kW  
(Sundstrand Energy Systems)

The proposed scheme for operation of the system (Figure 6-7) involves maintaining the turbine inlet temperature at a constant value with a flow control valve. The speed would vary with power level. The alternator speed would be controlled by an alternator field and a load that absorbs all power. A savings can be made in performance efficiency, especially at low power level, by providing a variable fan speed for the condenser.

A preliminary cost estimate was made for the two-stage steam system on the basis of various production rates and facilities. The estimated costs for an engine manufactured at a low production rate of 100 units per year in an existing facility is \$35,000. At a higher production rate, nominally of 100,000 units per year, in a new facility, the costs could be reduced to approximately \$8,000 per unit.

b. Steam Rankine Reciprocator (Mod 0) -- Jay Carter Enterprises. The other conceptual design selected for the baseline steam system (Mod 0) was a reciprocating expander modified from an experimental piston engine for an automotive application. This concept as proposed in the simple-cycle mode would, for a thermal input of 80 kW and a design point steam condition of 675°C (1250°F) and  $17.2 \times 10^6 \text{ N/m}^2$  (2500 psia), produce an engine efficiency of 26%. The engine, shown in Figure 6-8 with a generator, is basically a single-cylinder, uniflow (i.e., flow in at top and exhaust at bottom), simple-cycle engine connected to a crankshaft. For balancing purposes, two counter-rotating balance shafts are driven via belts from the crankshaft.

As in the turbine design concept, reheat was considered for a growth version of the engine. In this version, as seen in Figure 6-9, a second cylinder is employed for the reheat cycle. For this design, the two cylinders are properly sized for a high pressure side and a low pressure reheat side. The overall engine efficiency was calculated at 30% for a thermal input of 80 kW, design point steam conditions of 675°C (1250°F) inlet steam temperature, with  $17.2 \times 10^6 \text{ N/m}^2$  (2500 psia) on the high pressure cylinder and  $140 \times 10^3 \text{ N/m}^2$  (600 psia) on the low pressure cylinder, exhaust to atmospheric conditions, and a condensing temperature of 100°C (212°F).

The compound reheat, two-cylinder concept with condenser, generator and pumps has a total estimated system weight of 600 kg (1323 lbs).

The control scheme for operation of this system is similar to that used by Sundstrand and is similar to a temperature and water control developed by Jay Carter Enterprises for their steam car development. The control scheme maintains constant temperatures by mass flow control (i.e., adding water or exhausting steam).

An accumulator in the system helps prime it for start-up. The generator is brought on the utility line when its speed matches or exceeds line frequency. It is dropped when revolutions per minute are

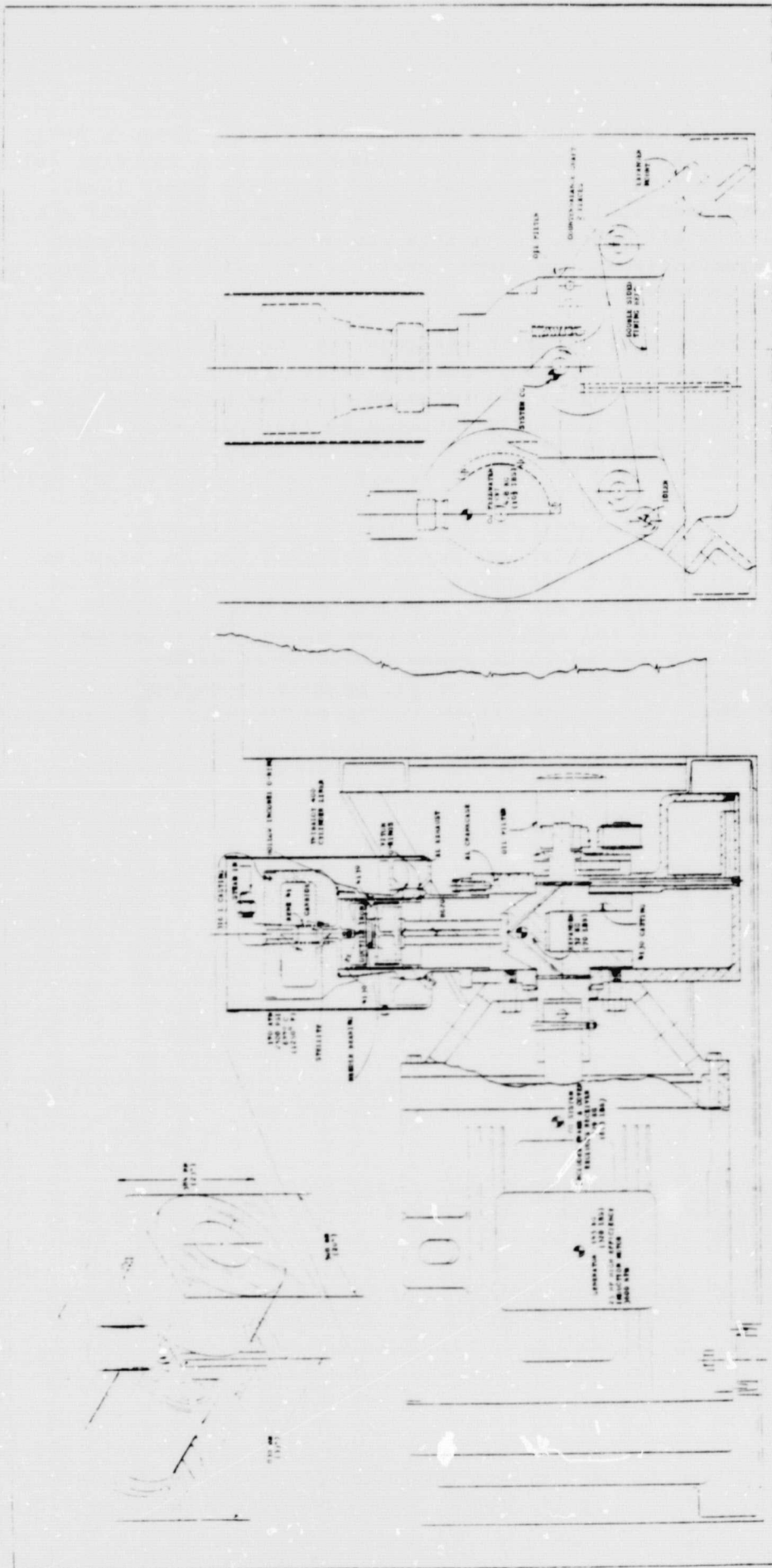


Figure 6-8. Simple-Cycle Concept - Layout of Dish-Mounted Components (Jay Carter Enterprises)

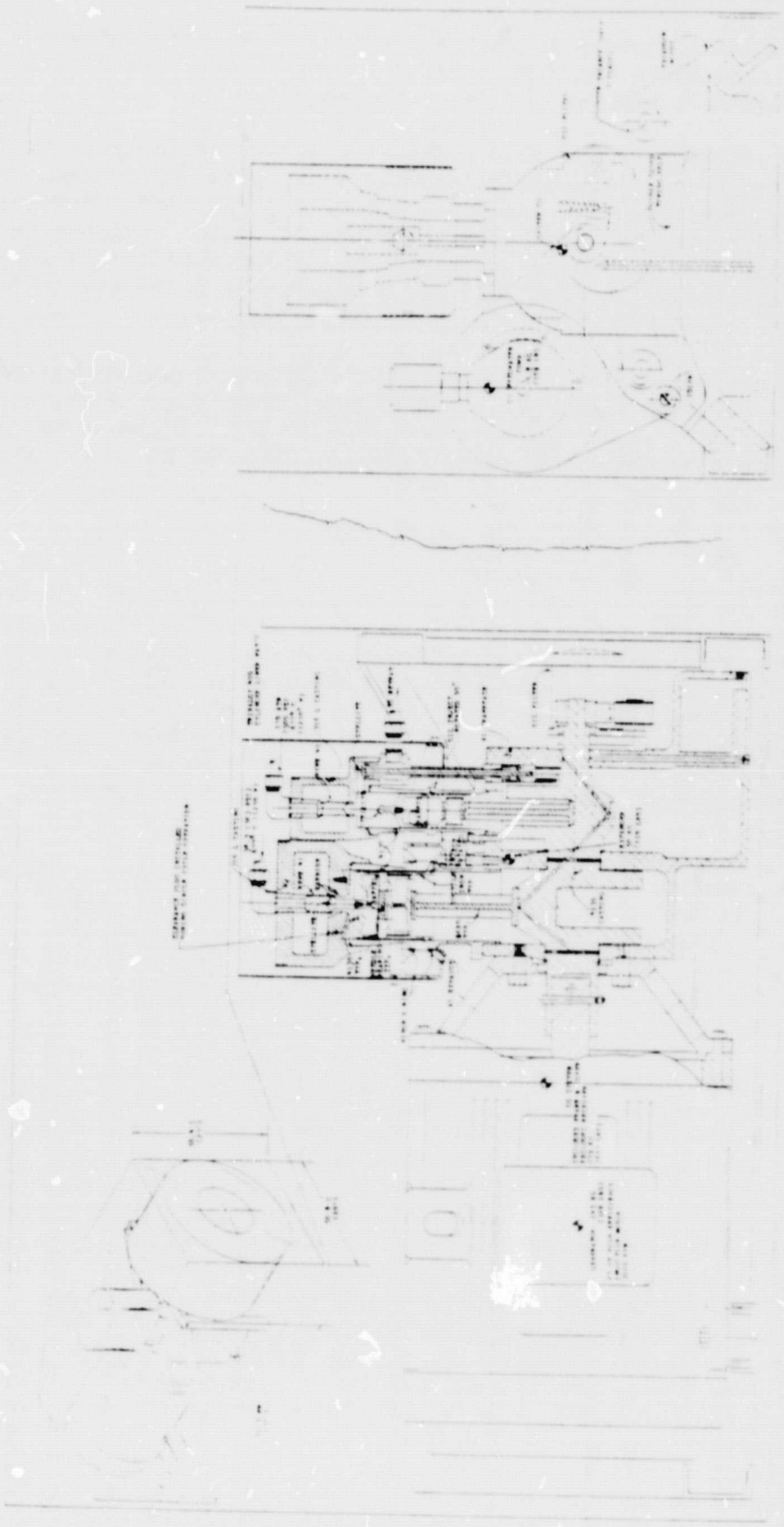


Figure 6-9. Compound Reheat Cycle Concept - Layout of Dish-Mounted Components (Jay Carter Enterprises)

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less than line frequency so that the generator will not motor. Overspeed conditions would be handled by throttle and safety valves to bypass steam to condenser and lower temperatures.

As indicated by the contractor, the simple-cycle expander is similar to a two-cycle, internal combustion engine and no new technology development is necessary for mass production. However, at these temperatures and pressures, development of the compound reheat expander would be necessary and could be accomplished in six steps from the simple cycle, with only the low-pressure cylinder, to final temperature and pressure with both cylinders active.

The estimated costs for a manufactured engine at high-production rates were based on costs per pound of comparable engines (i.e., diesel generator, small tractors and automobile). These costs ranged from \$13,000 (100 units per year) to \$3300 (100,000 units per year).

c. Steam Rankine Reciprocator (Mod 1) with Reheat -- Foster-Miller Associates. Approximately a two-year development would be needed for Mod 1 to arrive at the level of performance required for solar testing. In this category Foster-Miller performed a conceptual design of a reciprocating, two-cylinder, compound steam engine following a parametric study and selection of a design point. The design point conditions specified for the two-cylinder, opposed, compound engine with reheat were: inlet steam at 700°C (1290°F) and  $12.1 \times 10^6 \text{ N/m}^2$  (1750 psia), reheat at 700°C (1290°F), and a condensing temperature of 100°C (212°F) for a power input of 80 kWt.

The power conversion concept shown in Figure 6-10 includes expander, alternator condenser, cooling tower and pumps. The two-cylinder reciprocator steam engine is shown in Figure 6-11. The calculated performance for the power conversion system at the design point conditions was 33%, including an induction generator with an efficiency of 92%.

The two-cylinder, opposed concept with counterflow, which was selected over uniflow due to its higher mechanical efficiencies, was sized to produce approximately 20 kWe. The high-pressure cylinder has a bore of 4.3 cm, with a displacement of 100 cm<sup>3</sup>. The inlet pressure is  $12 \times 10^6 \text{ N/m}^2$  (1750 psia). The low-pressure cylinder or reheat cylinder has a bore of 14.9 cm and a displacement of 1179 cm<sup>3</sup> for an inlet pressure of  $1.1 \times 10^6 \text{ N/m}^2$  (160 psia). This low-pressure stage exhausts to essentially atmospheric conditions. The condensing temperature is 100°C (212°F). The single-throw crank mounted between the opposing cylinder provides the drive for the alternator without a gearbox. A rotation speed of 1800 rpm was selected as a compromise between the lower speeds preferred for valve sequencing and the higher speeds suitable to the weight and size of the alternator. Because of the high temperature (700°C, 1290°F), the lubricating system is an important and difficult component. The design technique applied to the concept was to employ carbon rings with lubricating properties. Some evidence indicated that the carbon

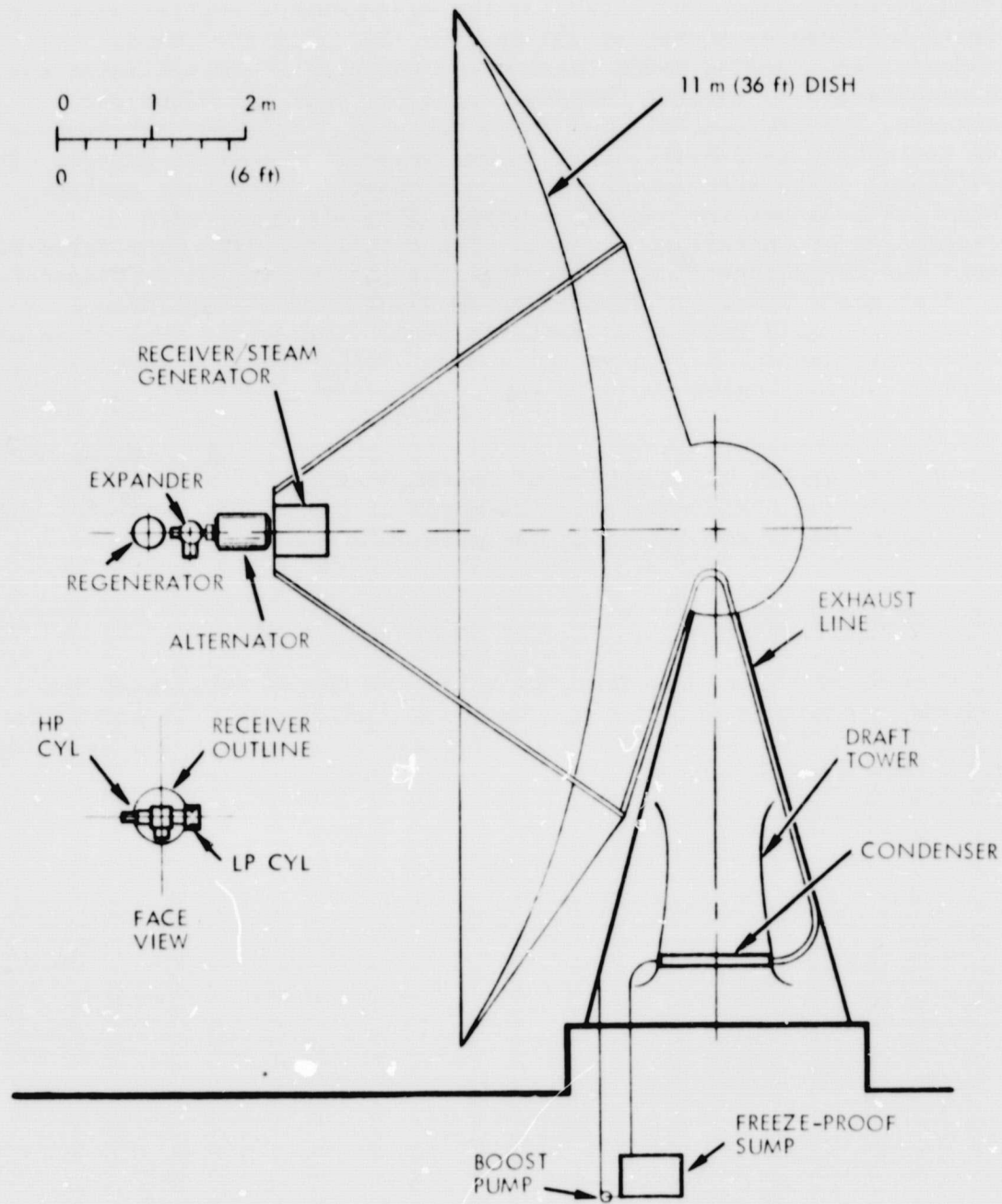


Figure 6-10. Solar Rankine Engine/Alternator with Collector/Receiver (Foster-Miller Associates)



rings could provide long life with low friction. As a back-up to the approach, a labyrinth seal system was suggested. These concepts would require some development to assure that lubrication and life could be provided with minimal power loss.

The proposed system was divided into dish-mounted equipment and off-dish equipment. The weight of the dish-mounted portion shown in Figure 6-12 was estimated at 230 kg (507 lbs) with the pumps, condenser and cooling tower located off the dish. The estimated cost to manufacture in several thousand units per year was \$2000 per expander, cut-off control, and feedwater pump. This did not include the generator, condenser, draft stack, frames, or central system. The additional costs were estimated at approximately \$1000 per system. These costs do not include any payback, G&A, shipping, site preparation or installation costs. The contractor also considered O&M costs for the expander and determined that if the engine were operated by solar power only, for approximately 3300 hours a year, normal maintenance could be handled once per year. This would include an oil change, tightening of joints, and general inspection. A general overhaul of the engine would be performed every other year.

The control of the system is handled primarily by altering mass flow to the system via a series of solenoid-activated valves, water boost pumps and thermocouples. The speed of the engine/generator when grid connected is controlled by the grid on any 60 Hz reference.

#### E. IN-HOUSE PROGRESS

In-house effort was directed primarily toward evaluating the various concepts as proposed by the above contractors. In particular, an in-house effort was directed towards assisting Sundstrand on design of the gas bearings and evaluating several configurations.

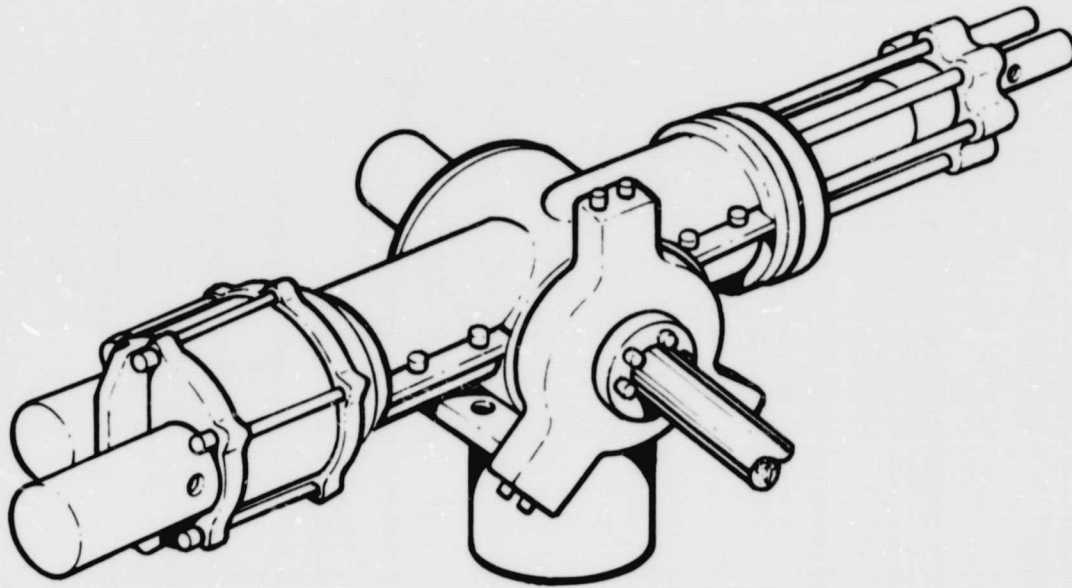
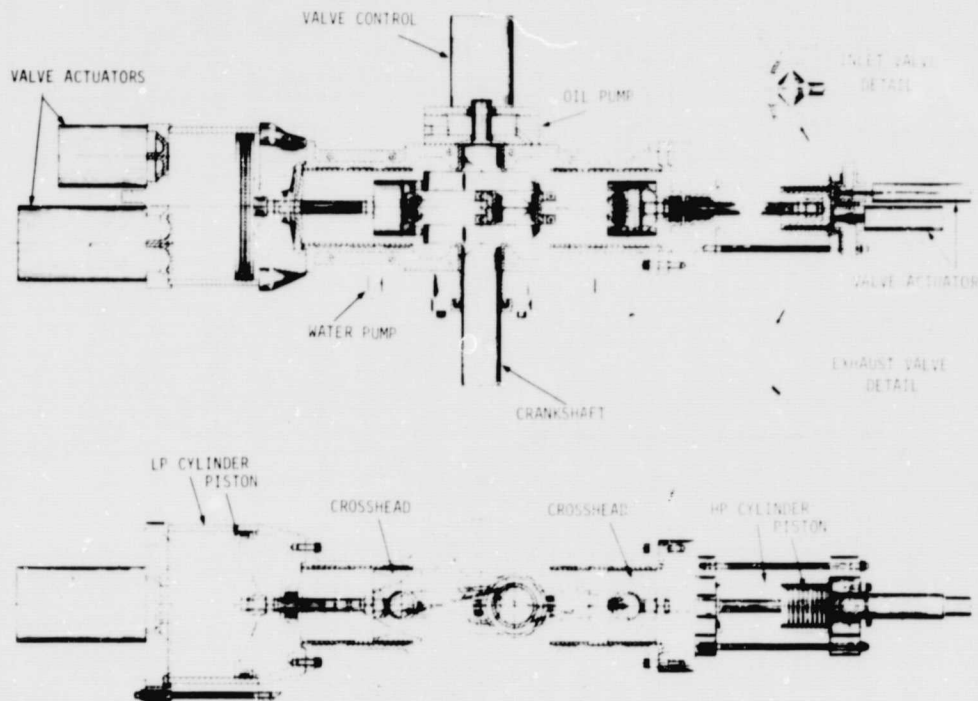


Figure 6-11a. Compact Steam Engine-Design Exterior  
(Foster-Miller Associates)



EXPANDER - SECTION VIEWS

Figure 6-11b. Cross-Section Views of Expander  
(Foster-Miller Associates)

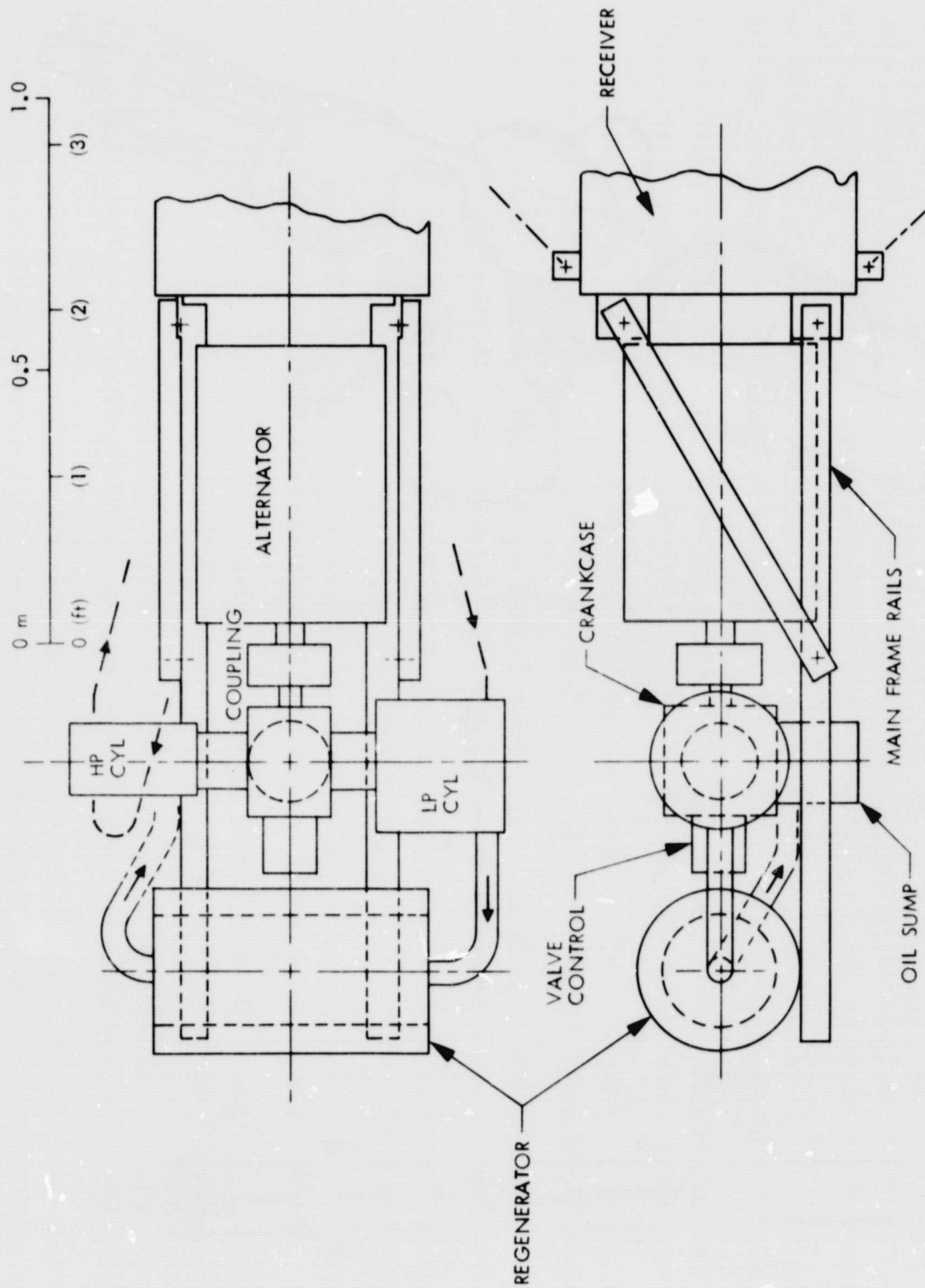


Figure 6-12. Solar Rankine Engine - Mounting on Receiver  
(Foster-Miller Associates)

## SECTION VII

### MANUFACTURING DEVELOPMENT

#### A. INTRODUCTION

In most cases, previous cost-analysis studies of solar energy components, 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

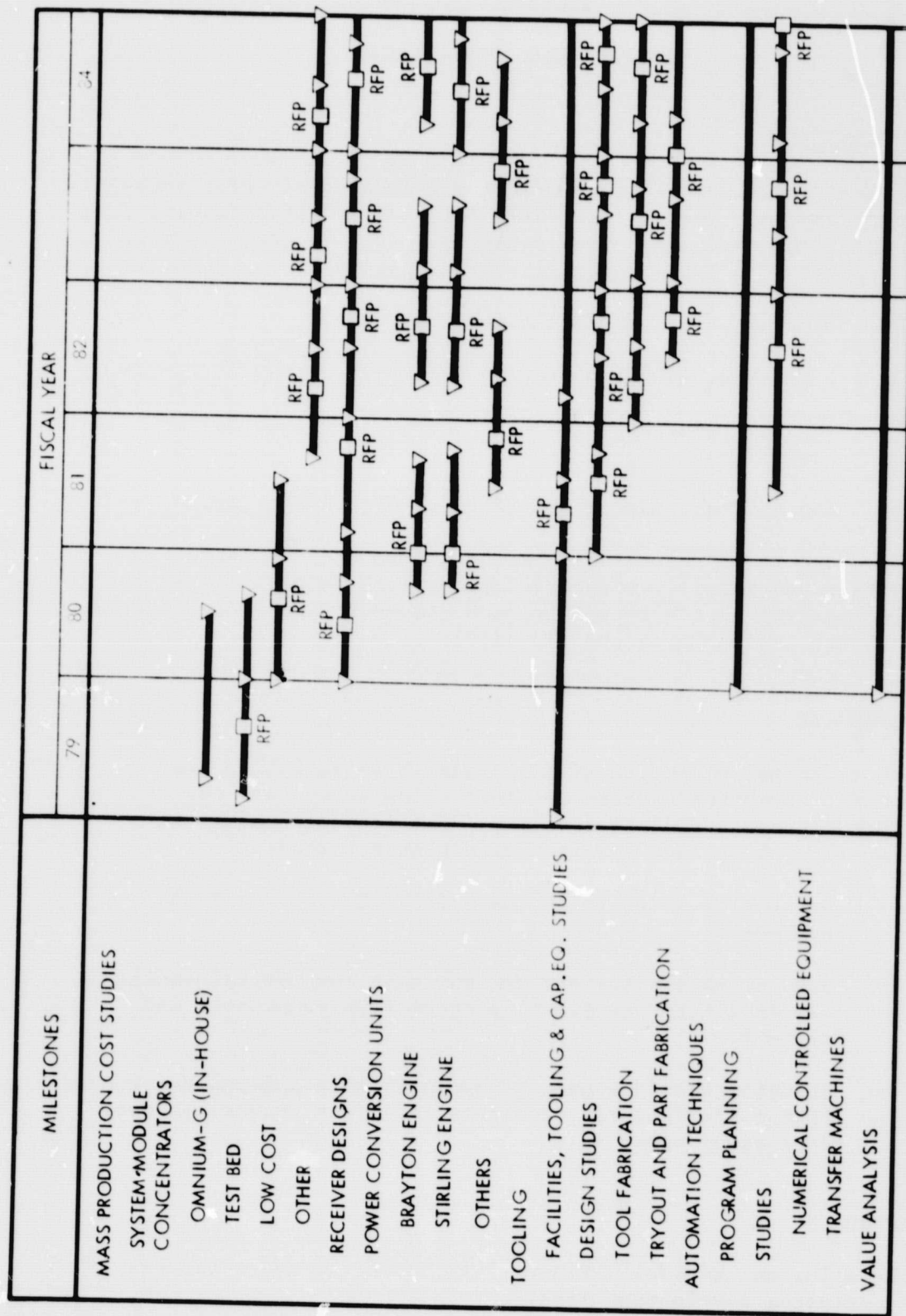
The principal objective of this task is to assist in the development of high-performance point-focusing subsystems that can be manufactured in high-production volumes at a low-unit cost. To accomplish this objective, efforts are directed toward:

- (1) Developing independent costs of PFDR components and systems.
- (2) Developing tooling and design costs for capital equipment and facilities needed to produce PFDR components and systems.
- (3) Studying possible uses of automation techniques to produce PFDR concentrators, receivers and power conversion units at a lower cost.

#### C. APPROACH

The milestone schedule, Figure 7-1, shows the 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 designs to high-volume mass production,



CODE: ▽ START OR END OF ACTIVITY    □ ISSUED    ◇ PRELIMINARY

Figure 7-1. Manufacturing Development Milestone Schedule

with the resultant low cost of manufacturing the various system components. A baseline PFDR system was cost-analyzed to which all other components, subsystems and systems can be compared for cost and performance. This study cost-analyzed the baseline module in production quantities ranging from 100 to 100,000 units per year. The baseline system cost analysis includes the following elements:

- (a) Engineering parts list
- (b) Raw material/purchased items cost
- (c) Part manufacturing process
- (d) Labor hours to produce each part
- (e) Labor hours to assemble components and system

As new and varied designs of point-focusing subsystems become available, they will be cost-analyzed using the elements listed above and compared to the baseline for cost and performance.

RFP's are being issued to industry to accomplish these costing objectives. Detailed cost estimates of power conversion units were conducted for production quantities ranging from 1000 to 400,000 units per year. The resulting estimated costs are to be compared with cost goals to determine if a given subsystem/system should be pursued, abandoned, or reconfigured.

- (2) Tooling. Detailed studies were executed to determine the exact nature of the tools required to produce each part, component or assembly under consideration. RFP's to industry solicited assistance in tool design, fabrication and tool tryout. A preliminary study was made of tooling, capital equipment and facilities required to produce a complete PFDR system and components in quantities ranging from 5000 to 100,000 units per year.
- (3) Automation Techniques. Studies were conducted to determine if the use of automation techniques can substantially reduce the cost of point-focusing solar energy components. RFP's will be prepared, when required, 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 PFDR solar energy components.

#### D. PROGRESS

During FY 1979 an existing state-of-the-art PFDR total module, commercially available from the Omnium-G Company was cost-analyzed for production quantities ranging from 100 to 100,000 units per year. Parts lists were prepared for all components. Engineering drawings were prepared for over 70% of the parts and components used in the complete system. Raw material costs and the labor hours required to produce parts and assemblies were estimated. The results of this study are shown in Table 7-1.

In another effort, preliminary study of tooling, capital equipment and facilities required to produce PFDR components in production quantities ranging from 5000 to 100,000 units per year was completed. The study did not cover the costs of operation or maintenance. No provision was made for storage. The system used for this study had the following characteristics:

- (1) Concentrator:
  - Parabolic Dish - 15.2 m (50 ft) diameter
  - Cellular Glass Gores
  - Second-Surface Glass Mirrors
  - Azimuth and Elevation Control
  - Aperture area - 186 m<sup>2</sup> (2,000 ft<sup>2</sup>)
- (2) Receiver: Steam Type
- (3) Power Conversion Unit: Steam Rankine

The study did not include the costs of the foundation or field erection. The preliminary results of this study are shown in Table 7-2.

A contract was awarded to Pioneer Engineering and Manufacturing Company to perform a cost analysis of the Test-Bed Concentrator in selected annual production volumes. Additionally, Pioneer will recommend design changes to reduce production costs.

Table 7-1. Cost of Omnium-C 7500 System in Selected Annual Production Volumes

	COST \$/MODULE			COST \$/METER <sup>2</sup>		
	QUANTITY MANUFACTURED/ YEAR			QUANTITY MANUFACTURED/ YEAR		
	100	25,000	100,000	100	25,000	100,000
CONCENTRATOR	8219	6162	4384	291	218	155
RECEIVER	493	371	259	17	13	9
POWER CART (INCLUDES STEAM ENGINE)	4307	3228	1959	153	115	70
TOTAL SYSTEM/MODULE	13,019	9761	6602	461	346	234

Table 7-2. Cost of Tooling, Capital Equipment and Facilities Required to Produce PFDR Systems in Selected Production Quantities

	ANNUAL PRODUCTION QUANTITY				
	100,000	50,000	25,000	10,000	5,000
	COST (\$K)				
CAPITAL EQUIPMENT & TOOLING	170,161	87,420	47,110	20,605	11,686
BUILDING & LAND	326,414	231,110	147,595	66,755	39,760
MISC. EQUIPMENT	1,500	810	580	315	160
ENGINE PLANT	200,000	150,000	110,000	75,000	--
TOTAL	698,075	469,340	305,195	162,775	51,606
CONTINGENCY FOR CHANGES - 10 YEARS	200,000	100,000	75,000	50,000	15,000
GRAND TOTAL	898,075	569,340	380,195	212,775	66,606



SECTION VIII  
SYSTEMS ENGINEERING

A. INTRODUCTION

The Systems Engineering Task defines and analyzes candidate system configurations, coordinates establishment and maintenance of subsystem interfaces and functional requirements, establishes and monitors performance and cost targets, leads the Design Team, establishes system test requirements, and performs special system studies.

B. OBJECTIVES

The objectives of this task are to:

- (1) Provide the project with a systems approach to subsystems and development efforts
- (2) Integrate the subsystems
- (3) Establish system test objectives
- (4) Establish success criteria for project-developed and commercial point-focusing systems
- (5) Assure that goals accountability is maintained.

Major subtasks to accomplish these objectives are:

- Lead and support the Design Team which integrates the development of design criteria for key subsystems: concentrators, receivers, transport networks and power conversion units.
- Provide analyses leading to a clearer system/subsystem definition of systems that appear viable for technology development.
- Develop technical requirements for system operation including thermal/electric storage, process heat, and associated control strategy.
- Establish, monitor, and maintain performance/cost targets for the subsystems that will lead to competitive energy-producing systems.
- Prepare and maintain system test plans specifying system requirements and success criteria for testing developed and commercial systems at the PFSTS.

### C. APPROACH

Systems Engineering has organized five major thrusts to accomplish the objectives set forth above.

The first and largest thrust is the Design Team activity. Systems Engineering leads this team which includes members from each of the subsystem tasks as well as other appropriate participants. The Design Team establishes and maintains the functional and technical design requirements and the system interfaces for each subsystem. The System Engineering effort integrates the development of the concentrator, receiver, transport network, and power conversion subsystems, including module operating controls, and assures that trade-offs are properly performed to achieve system optimization. The Design Team reviews the system test plans to verify that systems/subsystems are adequately tested and that trade-offs are properly performed.

The second thrust of Systems Engineering is the system definition studies. These studies 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:

- (1) Current technology status
- (2) Anticipated degree of difficulty in terms of the time and resources needed to develop the technology to the point of readiness for applications projects
- (3) Projected commercial cost/performance.

In addition cost and performance results are used to rank the systems. Sensitivity analysis is used as an indicator towards optimizing systems. Several different (generic) kinds of distributed receiver systems were examined and rank-ordered during the course of these definition studies. The candidate systems for the first generation were point-focusing, two-axis tracking concentrators using gas Brayton and steam Rankine power conversion.

Optimization studies have been performed on candidate systems; however, additional technical and cost data are required. Nominal values of system parameters such as power level and peak temperature have been selected based on available design information, but they are neither fixed nor optimized. Continued trade-off studies will be required to determine the optimal values of all subsystem and system design points. Information from subsystem contractors will be used to upgrade trade-off studies.

The transient behavior of solar power systems is critical for matching subsystem components, and for understanding dynamic response and establishing controls strategy. Transient system behavior is an important aspect of start-up, shut-down, and performance during

varying cloud cover. Analyses of transient behavior have been initiated and will continue through FY 1980. Studies of thermal storage and thermal power utilization were initiated during FY 1979 and will be expanded during FY 1980.

The third thrust is to establish and maintain cost and performance target goals. This activity was initiated in FY 1978 and continued in FY 1979. Results from initial studies were upgraded with new data and cost projections provided throughout FY 1979. The preliminary subsystem cost and performance targets developed in FY 1978 were updated to reflect the latest data from contractors. The targets are being periodically upgraded as more detailed data becomes available.

A fourth thrust involved use of the solar-powered electrical module from the Omnium-G Company for early testing at the PFSTS. The purpose of these subsystem/systems tests was to evaluate the commercial module and provide early hands-on test experience at the PFSTS prior to the delivery of the Test-Bed Concentrator. The module was used to provide early confirmation of analytical tools and test equipment planned for use in later PFSTS tests. A report on the Omnium-G module testing is included in Subsection D.

Systems test, the fifth thrust, included preparation of the test plans for the Omnium-G system. In FY 1980, systems test plans will be expanded to include the TBC.

A milestone schedule for Systems Engineering is shown in Figure 8-1.

D. PROGRESS

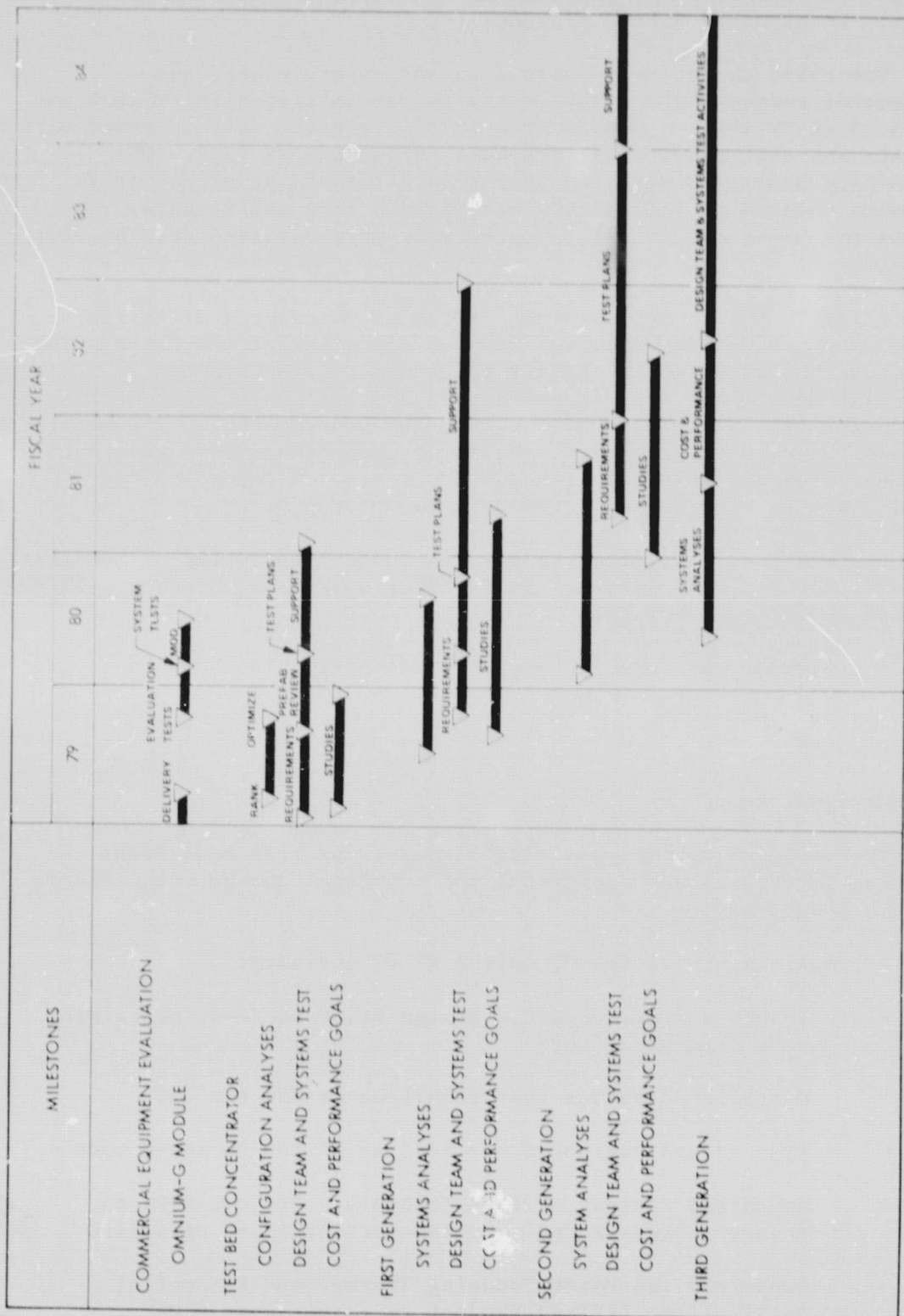
1. Design Team

The Design Team (DT) was established in FY 1978 to define subsystem interfaces and functional and technical design requirements for each subsystem.

Accomplishments of the DT during FY 79 included:

- Issued and maintained a Design Point Document containing subsystem parameters
- Established system test requirements for the TBC
- Planned and monitored the testing of the Omnium-G module
- Supported reviews of PFDR Technology Project RFPs to assure subsystem design parameters could be satisfied
- Supported the Point-Focusing Thermal and Electrical Applications (PFTEA) Project to assure that PFDR subsystems are viable options for PFTEA

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Figure 8-1. Systems Engineering Milestone Schedule

## Systems Definition/Analysis

a. Process Heat Survey. A survey was made to identify the potential contributions of solar energy to the process heat market in the 425°-815°C (800°-1500°F) range. This range was selected to maximize the advantages of point-focusing technology which can generate higher temperatures than those obtainable with single-axis tracking systems. The upper limit temperature of 815°C was chosen to be compatible with the near-term Brayton engine technology.

According to 1971 data, the industrial sector consumed 20 quads (1 quad =  $10^{15}$  BTU) of the total U.S. energy consumption of 69 quads (17 quads for electricity, 18 quads for transportation, and 14 quads for household/commercial consumption). Of these 20 quads, (see Figure 8-2), 8.2 quads took the form of process steam, 5.6 quads were indirect process heat (such as air), and 6.2 quads were for feed stock and electric drive. Hence, 13.8 quads of the industrial energy requirement are used for process heat or process steam. Table 8-1 lists the U.S. process heat consumption by temperature range.

Table 8-2 lists candidates for application in the 425°-815°C (800°-1500°F) range with the terminal application temperatures, excluding preheating, and amount of thermal energy consumed by the application. A significant number of the applications are in the petroleum industry. Processes such as mineral drying and lime calcining are also likely candidates.

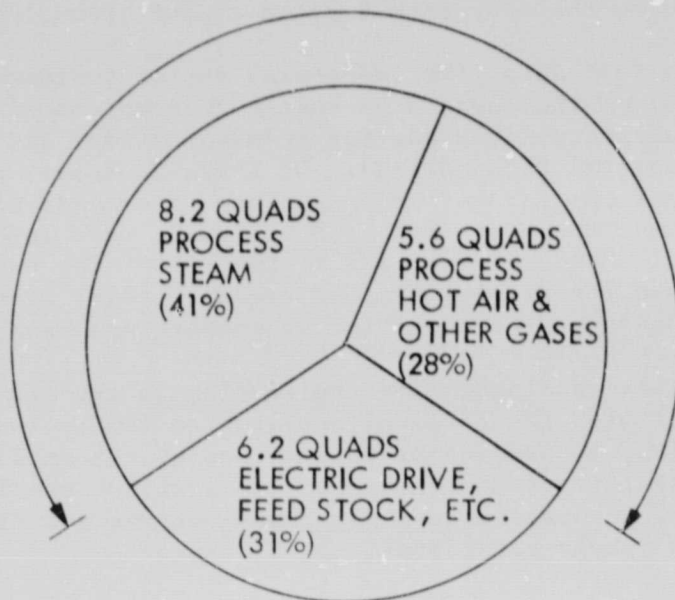
Three key issues envisioned for PFDR process heat applications are: (1) the cost and performance optimization potential of thermal transport, (2) the optimization of dish size (larger sizes tend to minimize transport requirements), and (3) the impact and potential of hybrid operation, e.g., the use of fossil fuel to augment or displace solar energy during periods of non-solar availability.

It was recommended that the PFTEA Project undertake a detailed, long-range study of the applicability of PFDR technology to process heat generation. The full range of temperature applications anticipated for first- and second-generation PFDR systems applicable to PFTEA would be included in this study. More detailed information on the use of solar thermal energy to provide industrial process heat may be found in References 8-1 through 8-4.

b. Concentrator Shading Methodology and Field Layout Analysis. In conjunction with collector field layout studies, a methodology (Ref. 8-5 and 8-6) was developed for evaluating shading of a paraboloidal concentrator from adjacent concentrators in a collector field. The methodology considers solar declination angle, local surface azimuth, collector field arrangement, collector size and geographical location (longitude, latitude). The algorithm developed is briefly described in the following paragraph.

Figure 8-2. Industrial Sector Energy Consumption

TOTAL INDUSTRIAL CONSUMPTION = 20 QUADS  
 PROCESS HEAT CONSUMPTION = 14 QUADS  
 (69% OF TOTAL CONSUMPTION)



(1971 DATA)

Table 8-1. Process Heat Consumption in the United States

Below 175°C (350°F)	22%
Above 175°C (350°F)	78%
175°-425°C (350°-800°F)	18%
425°-815°C (800°-1500°F)	10%
815°-2595°C (1500°-4700°F)	50%

Table 8-2. Process Heat - Candidates for Thermal Energy Development

Process	Temperature of Application		10 <sup>12</sup> BTU/Yr
	(°C)	(°F)	
Prime Candidates			
Petroleum Refining			
Olefins	650	(1200)	124
Catalytic Cracking	605	(1125)	447
Thermal Applications	540	(1010)	154
Catalytic Reforming	495	(925)	498
Delayed Coking	480	(900)	225
Vacuum Distillation	425	(800)	183
Secondary Candidates			
Glass Containers	650	(1200)	13
Minerals, Drying	590	(1100)	6
Cane Sugar Refining	400-595	(750-1110)	4
Wet Corn Milking, Fiber Dry	540	(1000)	3
Lime Calcining	540	(1000)	3
Flat Glass Annealing	500	(930)	6

Paraboloidal dish concentrators cast elliptical shadows. The interplay between these shadows is the concern of this shading algorithm. The dimensions of the elliptical shadow depend solely upon the dish diameter and solar altitude angle (elevation angle above horizon). The major axis of the ellipse shadow is directly proportional to the dish diameter and inversely proportional to the trigonometric sine of the elevation angle. The orientation of the ellipse is solved by calculation of the local surface azimuth angle. The major axis of the ellipse shadow lines up with the surface azimuth angle. Once the dimensions and orientation of the ellipse shadows are determined, the computer is instructed to find any intersections between shadows. If there are intersections, the intercepted area is evaluated and the shading factor determined.

Collector field arrangement is generally determined by the system optimization criteria which may be affected by many technical and economic factors. However, a basic constraint is that there should be sufficient clearance between concentrators to avoid mechanical interference during installation, operation and maintenance. The minimum separation distance between concentrators to allow for passage of servicing trucks is one example of the above constraint.

Three major conclusions were drawn from this shading study:

- (1) It appears that a diamond field arrangement is slightly better than an equivalent rectangular pattern with the same packing density.
- (2) It does not appear that there is an aspect ratio (EW/NS spacing) that optimizes the field layout for a given packing factor (a contrary argument is presented in References 8-5 and 8-6).
- (3) Field layout optimization is a complex trade-off process which must consider many relevant factors such as transport loss/cost and power conversion efficiency versus size/temperature. For example, the Shenandoah project emphasized a total energy system. The field layout was optimized for maximum power per field area rather than a more cost-effective system.

### 3. Solar Brayton Dynamic Simulation

A dynamic simulation model was developed for simulating the transient performance of a point-focusing solar Brayton system in order to establish subsystems interfaces in the transient mode. Although the model (Figure 8-3) was developed for transient performance, steady-state operations are easily produced by switching to a non-dynamic mode. The system's steady off-design performance is a byproduct of the system's transient performance analysis.



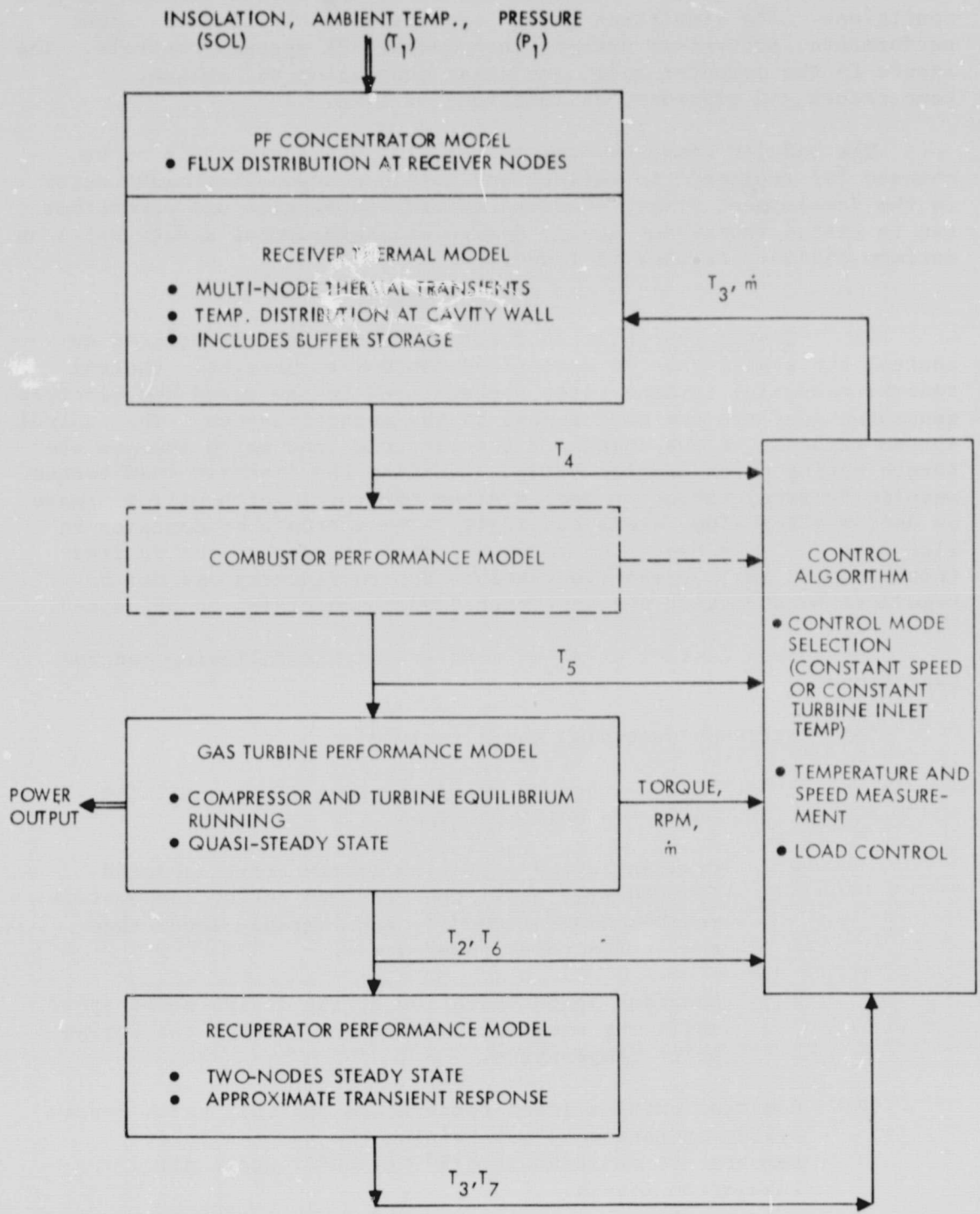


Figure 8-3. Solar/Hybrid Brayton System Dynamic Simulation Model

a. System Simulation. System transient performance is simulated with the Solar Brayton Dynamics computer program which simulates system dynamic behavior under varying insolation and ambient conditions. The simulation model consists of subsystems transient performance, subsystems dynamic interfaces, and systems controls. The inputs to the computer model are solar insolation and ambient temperature and pressure, as functions of time.

The modular computer program permits subsystem models to be changed (or replaced) to reflect any design changes that might occur in the development stage. Various control strategies and algorithms can be tested throughout system design and development stages until an optimum control strategy is found.

b. System Controls. A feedback controller was devised to control the system through prescribed control strategies. Control sensors measuring turbine inlet temperature, engine speed and electric generator load are the main inputs to the control system. The control system response is the change of the electric load which changes the torque acting on the engine rotor. Changing the electric load torque results in accelerating or decelerating the rotor which will increase or decrease the flow rate accordingly. The increase or decrease in flow rate cools or heats the receiver until it reaches the desired temperature. Small speed fluctuations due to disturbances can be regulated by adjusting the generator load to maintain the set speed.

The system control strategy consists of the following control operations:

(1) Start-up controls, which include:

- "Cold" start-up using starting motor until the engine is self-sustained.
- Constant speed operation at the starting speed (54,000 rpm) until the receiver outlet temperature reaches 650°C (1200°F), considerably lower than the design point temperature.
- Constant speed operation at the design point speed until the receiver temperature reaches the design point temperature.

(2) Constant turbine inlet temperature controls which govern system operation by maintaining the turbine inlet temperature constant at 815°C (1500°F) under all insolation levels.

c. Simulation Results.

1) Transient Analysis. The simulation results presented in

Figure 8-4 show the response time of the system and the controls to variations in operating conditions. The receiver outlet temperature (turbine inlet temperature), receiver inlet temperature and engine speed are shown as functions of time.

2) System Part-Load Characteristics. Receiver efficiency and the recuperator limiting temperature affect the system's part-load performance. The receiver efficiency decreases as the operating temperature increases. As a result of the different temperature and part-load efficiency trends of both the receiver and engine, system efficiency has the following characteristics (Figure 8-5): (1) slow decrease at moderate part loads and sharp decline at low part loads; (2) higher turbine inlet temperature (T.I.T.) or receiver outlet temperature results in higher system efficiencies at higher part-load operations and lower system efficiencies at lower part-load operations, i.e., higher T.I.T. and lower T.I.T. curves switch at lower part-load operation.

3) Recuperator Effect. For part-load constant T.I.T. operations, as the heat input decreases the recuperator inlet temperature (hot side) increases. This limiting of the recuperator inlet temperature forces the turbine to work at lower temperatures at part loads. Figure 8-6 presents the recuperator limiting temperature curves superimposed on the T.I.T. curves. This shows that the recuperator inlet temperature limit could constrain turbine operation.

d. Conclusions.

1) Transient Analysis.

- In the solar only mode, constant turbine inlet temperature control strategy is unstable when the system experiences large fluctuations in solar insolation, particularly when the insolation suddenly increases. The strategy is stable for small insolation fluctuations.
- For systems transient performance, constant speed operations are slower and more stable than constant turbine inlet temperature operations. However, system efficiency is much higher for the latter.
- A compromise between system stability and system efficiency suggests that a control strategy be used consisting of both controls. That is, constant turbine inlet temperature control strategy be used for the normal operations with small fluctuations in insolation, while constant speed control strategy be used for start-up and whenever the system experiences instabilities. Such a controller is being investigated. An optimal controller which maximizes the system's output while maintaining its stability can be developed through the simulation studies.

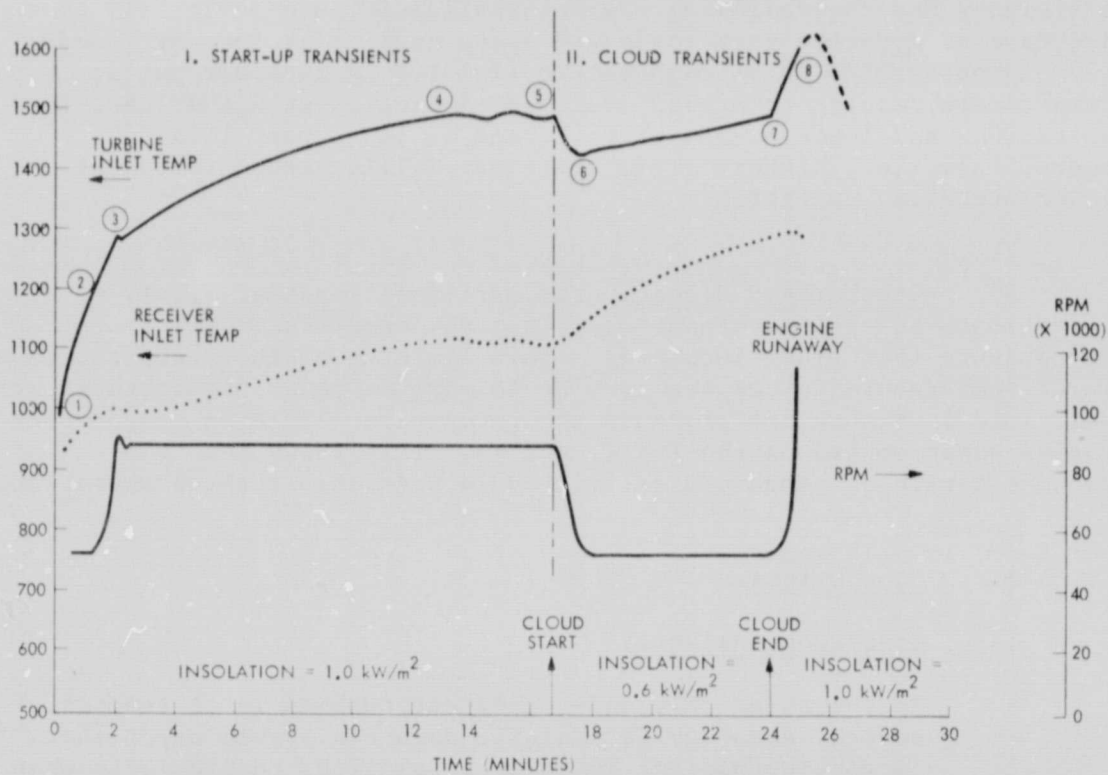


Figure 8-4. Receiver and Turbine Inlet Temperatures as a Function of Time in Transient Operation

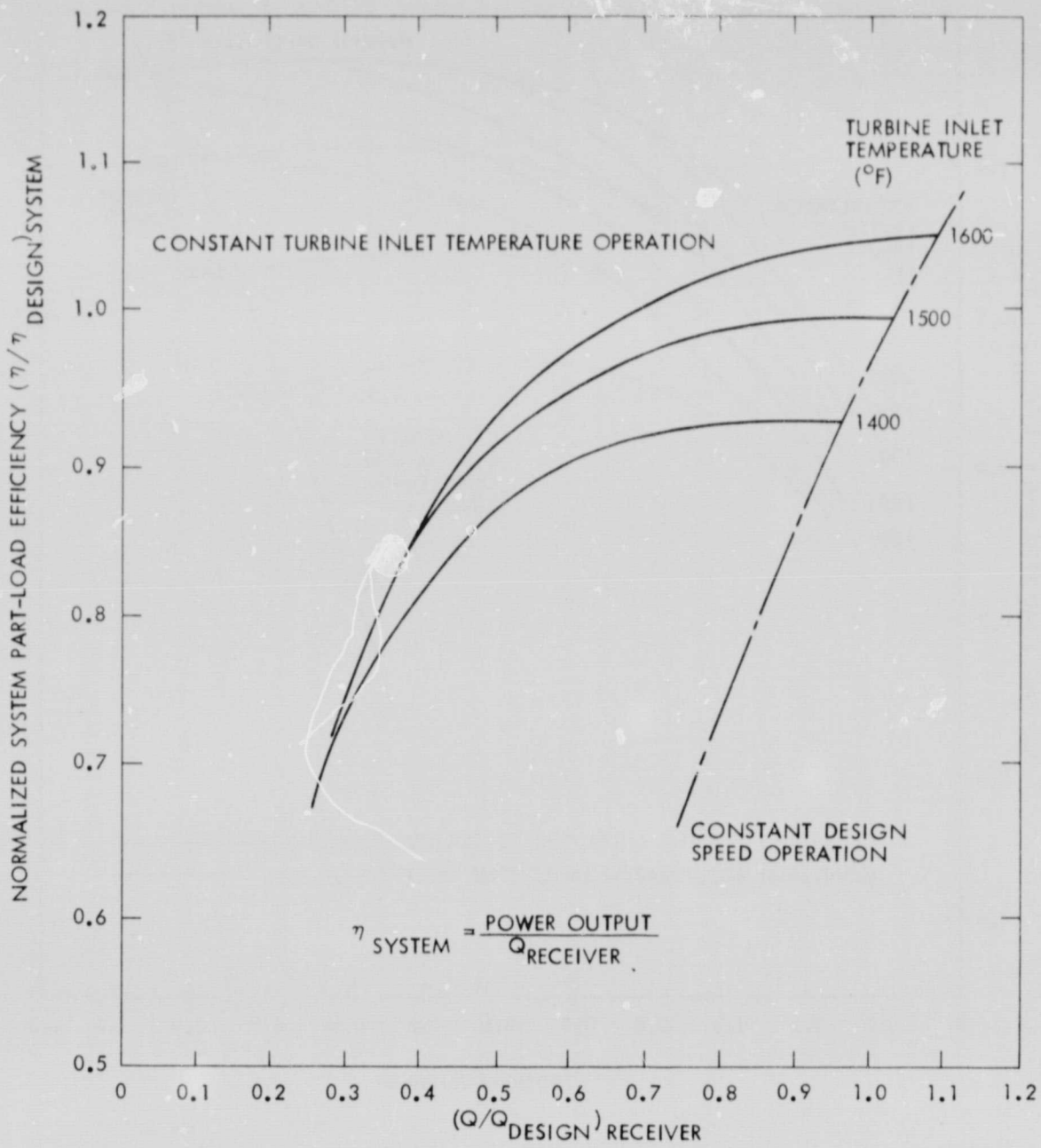


Figure 8-5. System Part-Load Efficiency

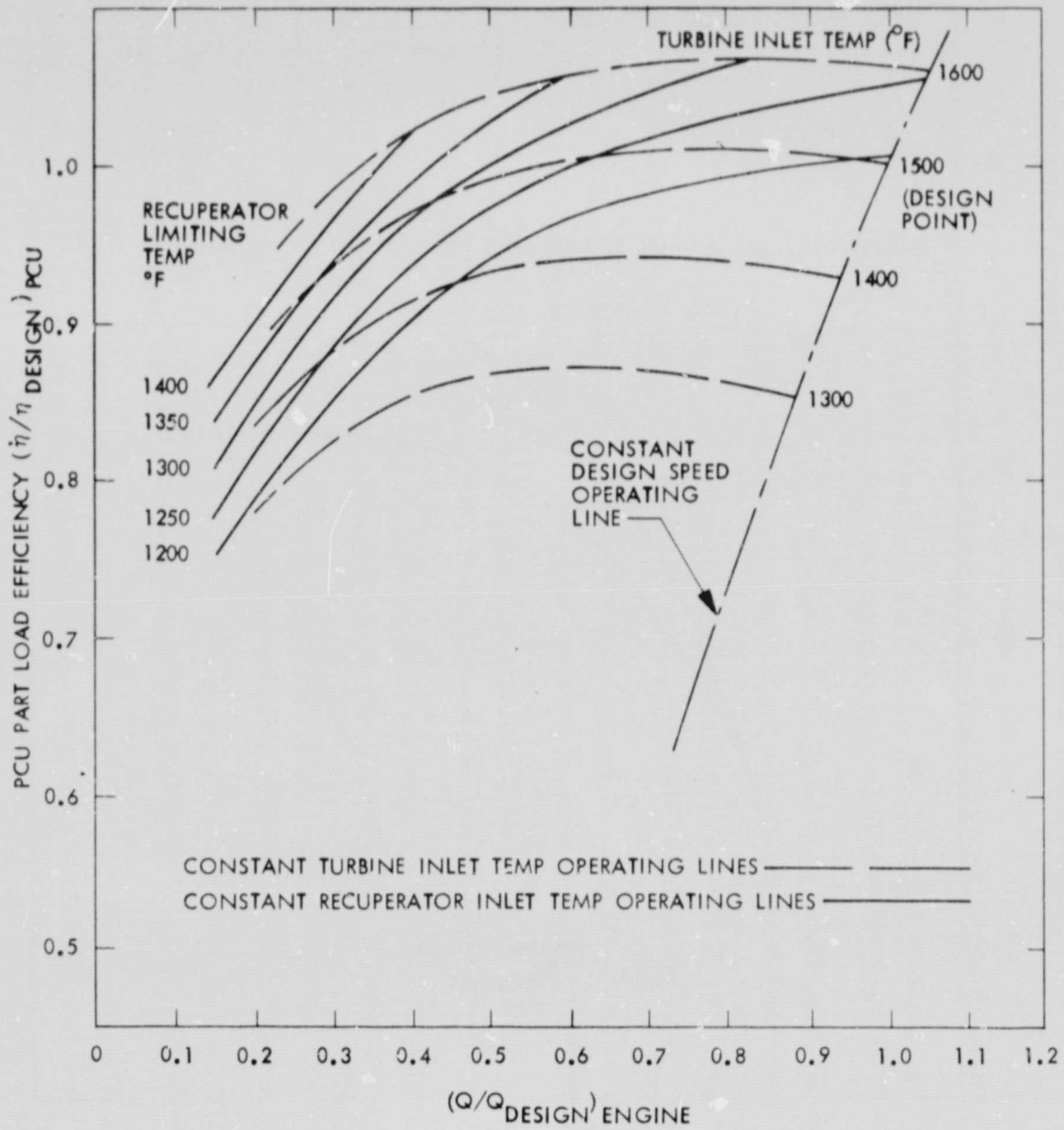


Figure 8-6. PCU Part-Load Efficiency Due to Recuperator Limiting Temperature

- Even with the use of a stable controller, spikes in the receiver outlet temperature are unavoidable unless buffer storage is used in the receiver in the solar-only mode. In this case buffer storage will cover the spike duration (between 2-4 minutes) rather than covering the cloud duration.

2) Part-Load Analysis.

- For the solar-only mode of operation, increasing the turbine inlet temperature to improve engine efficiency does not necessarily increase overall system efficiency. The slight increase in system efficiency at high part loads is offset by a slight decrease at low (and moderate) part-load operations. Maintaining the turbine inlet temperature at 815°C (1500°F), and even decreasing it to 760° (1400°F) at lower part loads, should be considered for the LCC operation.
- Part-load engine operations increase the recuperator inlet temperature. A higher temperature recuperator is required for low capacity concentrators.

4. Omnium-G Test Program

The tests of the Omnium-G module performed at the Point-Focusing Solar Test Site included mechanical checkouts, optical alignments, and thermal power tests. A photograph of the Omnium-G module is presented in Figure 9-3 of Section IX, "Test and Evaluation."

a. Mechanical Checkouts. The mechanical checkouts were initiated soon after the enclosure and mirror support structure were installed. First tracker performance was tested in late 1978. Tracker on-sun testing was performed without the mirror elements installed to evaluate tracker electronics and mechanical drive performance.

Following the mirror installation and alignment, boresighting operations were performed by Omnium-G personnel to position the hot spot (or region of maximum intensity) approximately at the focal point. The hot spot could be positioned on the geometric center, or be swallowed (projected) through the aperture of the converter (receiver). Visual evaluation of the spot location while on sun, followed by slewing off sun, then mechanically repositioning the sun sensor relative to the concentrator, was the method used by both Omnium-G and JPL personnel to perform the boresighting operation. This operation is required prior to performing any new experiment.

b. Optical Alignments. Optical alignment operations were performed following the initial installation of the mirror elements as a verification of correct alignment, and following a complete exchange of the mirror array. The initial method used to align the elements is shown in Figure 8-7. All alignment operations were conducted at night to eliminate hazards to personnel from sun concentration. Satisfactory alignment was accomplished by adjusting individual mirror elements until full illumination of each surface was observed. Verification operations were conducted. (See Figure 8-8.) An alternate method was performed following the mirror segment change-over. The major difference in this alignment procedure was that the lamp was located about 5.8 km (3.6 miles) from the collector as compared to 365 m (1200 ft) in the initial alignment.

c. Thermal Performance. Thermal performance of the system was determined; the results and test details will be presented in a final report to be published in FY 1980. Following is a discussion of the devices used to evaluate thermal performance: the flat-plate calorimeter, the flux mapper and the Omnium-G converter (receiver), and a brief description of tests performed.

1) Flat-plate Calorimeter. The flat-plate calorimeter (see Figures 4-3 through 4-6 of Section IV, "Concentrator Development") consists of a 356 mm x 356 mm x 9.5 mm (14 in x 14 in x 3/8 in) copper plate constructed for parallel water flow. This device was located 102 mm (4 in) behind the nominal focal plane (away from the mirror). An aperture support structure was mounted to hold the transite aperture plates which were positioned at the focal plane. Instrumentation included a turbine-type flowmeter, water manifold inlet and outlet thermocouple probes and surface thermocouples on the front and rear surface of the absorber plate. Figure 8-9 is a schematic diagram showing the calorimeter and instrumentation. The principal parameters of interest were flowrate, aperture size and flow mixing tube lengths (which were varied in the tests). Water was supplied at facility pressure (about 60 psig) and the differential temperature from the water inlet to the water outlet was held to a maximum of 11°C (20°F) to minimize thermal losses.

Three calorimeter test-series were performed using essentially the same experimental technique. The first two series, conducted with the original set of mirror petals, employed aperture plates with a thickness of 9.5 mm (3/8 in). The third series of tests were conducted with 19 mm (3/4 in) thick aperture plates to reduce material spalling around the aperture; this series was performed following exchange of the mirror petals. Aperture size was varied in all three series of tests.

2) Flux Mapper. The second thermal performance evaluation conducted with the Omnium-G system was the flux mapper test series. This device (see Figure 5-10 of Section V, "Receiver and Heat Transport Network Development") utilized a water-cooled probe which



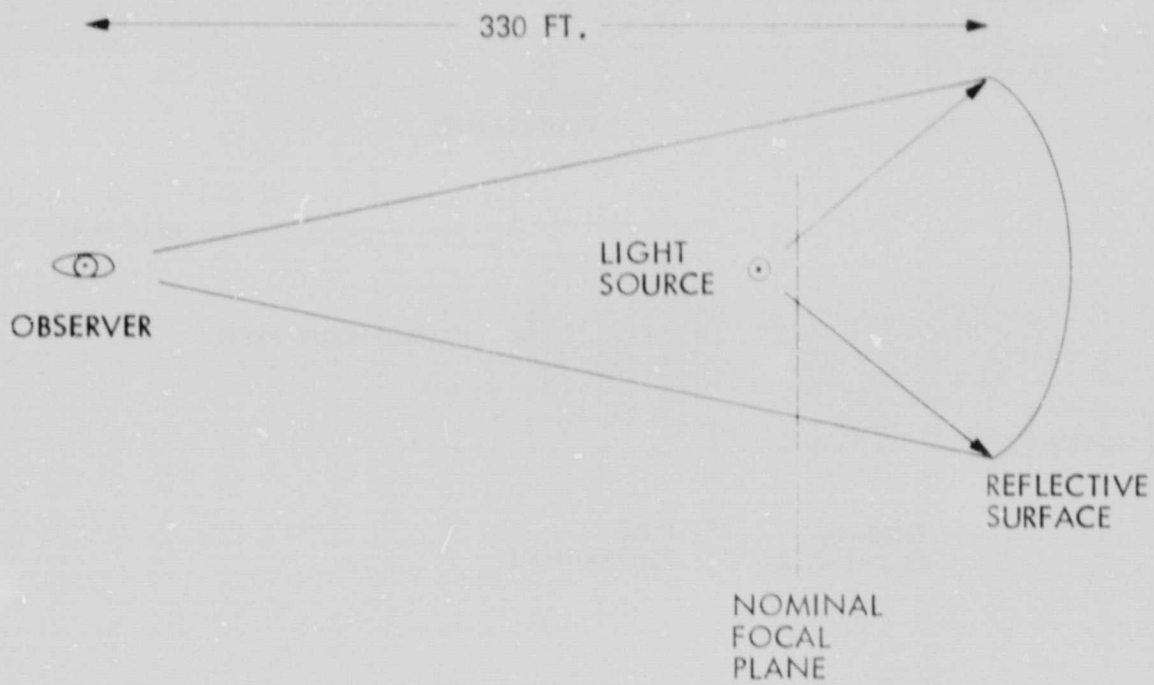


Figure 8-7. Initial Alignment Configuration

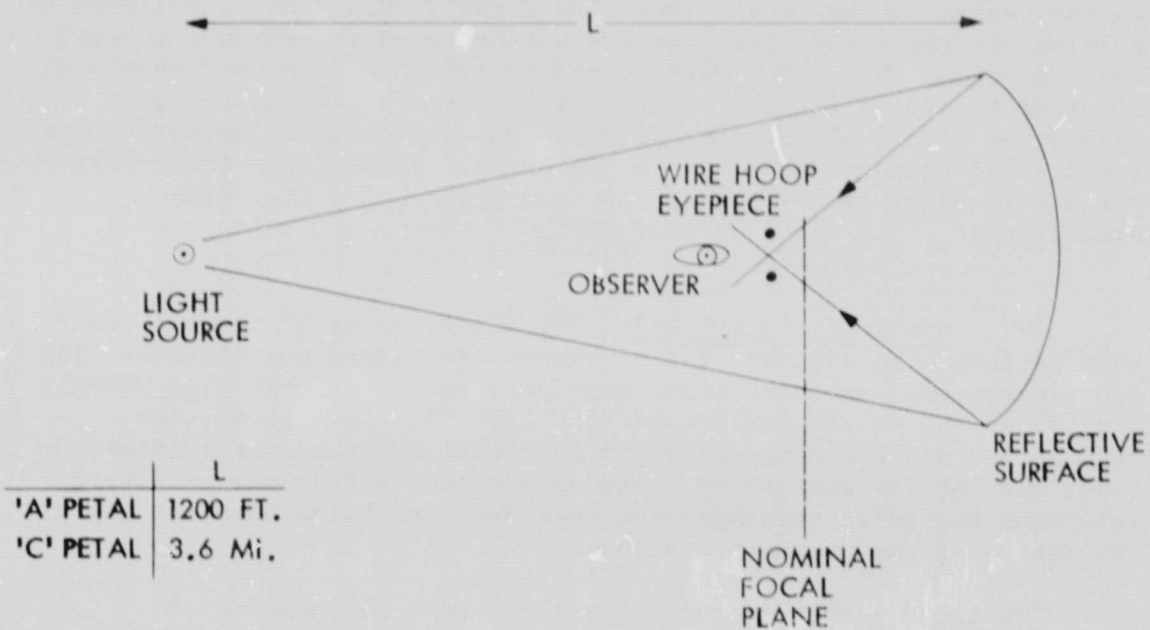


Figure 8-8. Improved Alignment Configuration

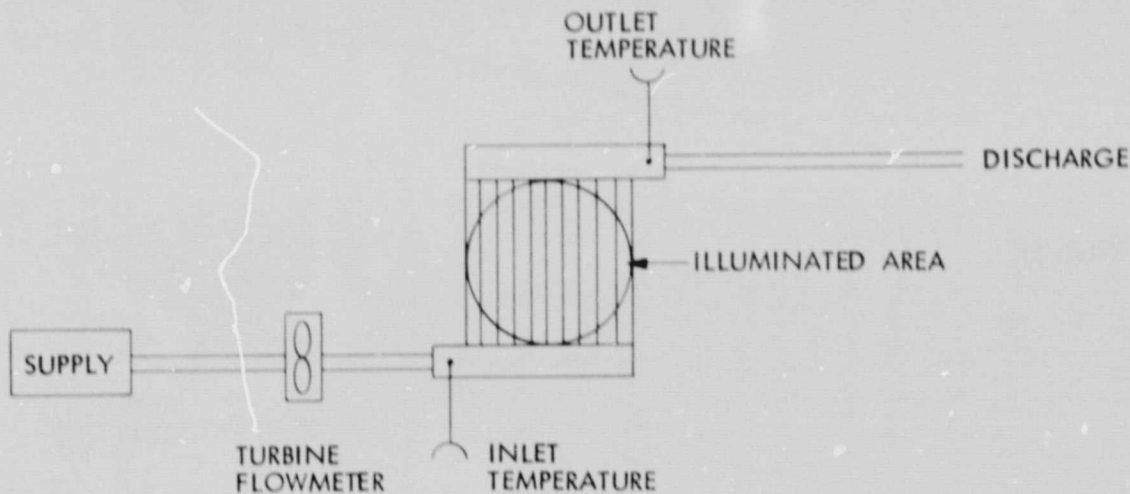


Figure 8-9. Flat-Plate Calorimeter Schematic Diagram

was moved about the X, Y, and Z axes to measure the solar flux density in the region of the focal plane. An X and Y scan raster, followed by a change in the Z (or focal) axis position, produced various spatial cross-sections which then were reconstructed into a three-dimensional model of the focal region. All controls for the flux mapper were programmed into a microprocessor which was also used to gather, store and process the data acquired by the probe. Output from the processor was displayed on an X-Y plotter or line printer for real time evaluation.

3) Converter (Receiver). The final series of thermal tests were performed to evaluate the converter (receiver) performance. The low-temperature converter tests were performed with open-loop water flow at an outlet temperature of 95°C (200°F). This particular test series was performed prior to the petal exchange for information only, and not for evaluation. The second test series was performed following the petal exchange; the test data are being used for overall evaluation of the Omnium-G system.

The third series of converter tests were performed with high-temperature water. For this series, all of the Omnium-G hardware including the feed-water reservoir, feed-water pumps, and transport lines were installed.

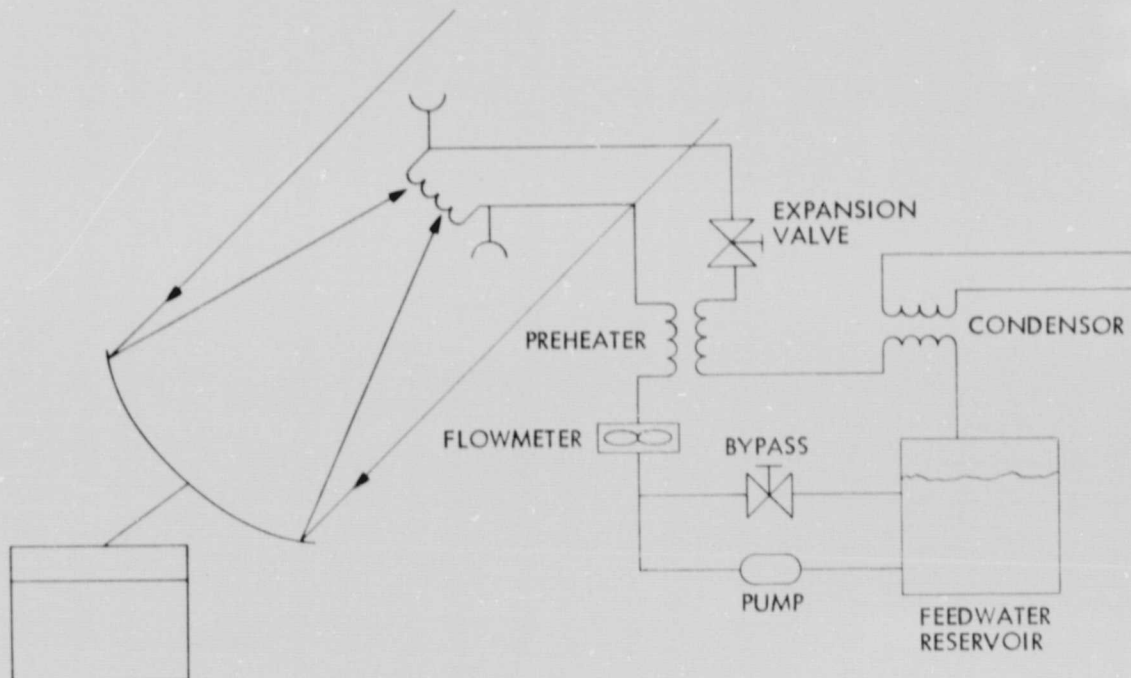


Figure 8-10. Converter Thermal Performance Test Schematic Diagram

The schematic diagram, Figure 8-10, shows an additional manual valve which was used in place of the steam engine to maintain a positive pressure on the converter so that saturated water existed at the converter water outlet. The high temperature water was allowed to flash to steam across the added expansion valve, flow into the condenser, and return to the feedwater reservoir. Good control of the back pressure on the converter was demonstrated, and two different temperature levels were achieved.

d. Problems. Some difficulty in meeting the module testing schedule occurred because of the time required for preparations prior to performing the experiments and occasional delayed support from the Omnium-G Company. The major contributor to schedule delay was the Company's decision to replace the original array of "A-mold" petals for the improved "C-mold" petals. DOE concurred with this change. Problems related to test operations, hardware, and weather also contributed to delays in schedule.

e. Plans. Preparations are now underway to install the steam engine and complete system performance testing of the Omnium-G module.

## SECTION IX

### TEST AND EVALUATION

#### A. INTRODUCTION

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

Several 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 315°C (600°F). Point-focusing distributed receiver systems, however, operate at working fluid temperatures between 315°C (600°F) and 1370°C (2500°F). Therefore, a test site was established to enable testing to be performed at these higher temperatures.

This section of the report presents the status of the Test and Evaluation (T&E) effort to provide and implement a Point-Focusing Solar Test Site (PFSTS)\* for PFDR technology.

#### B. OBJECTIVES

The objectives of the T&E task are to:

- (1) Provide the required PFDR PFSTS capability at a minimum cost.
- (2) Perform testing and evaluation of PFDR subsystems and system modules at working fluid temperatures between 315°C (600°F) and 1370°C (2500°F).
- (3) Determine operations and maintenance parameters and data to support early commercialization of point-focusing systems.

#### C. APPROACH

The existing JPL Edwards Test Station (ETS), near Lancaster, California was modified to develop the PFSTS. An existing building (E-9) has been used as the control room to house all the necessary electronic equipment used to monitor and control the solar concentrators, receivers, and power conversion units under test. Only minimal modifications, external to the control room, have been required.

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\*In early FY 1980 the name was changed to Parabolic Dish Test Site.

A formal design review which included instrumentation, software, control, and safety, was presented in June 1979 for the PFSTS facility to conduct Test-Bed Concentrator testing.

The test schedule for the PFSTS, shown in Figure 9-1, indicates test periods for the respective hardware items.

Figure 9-2 illustrates the interrelationship between the solar concentrator/receiver/power converter (CRC) under test and the PFSTS control and monitoring instrumentation, support equipment, site support facilities, and the data acquisition and processing system.

#### D. PROGRESS

##### 1. Solar Module Testing Operations

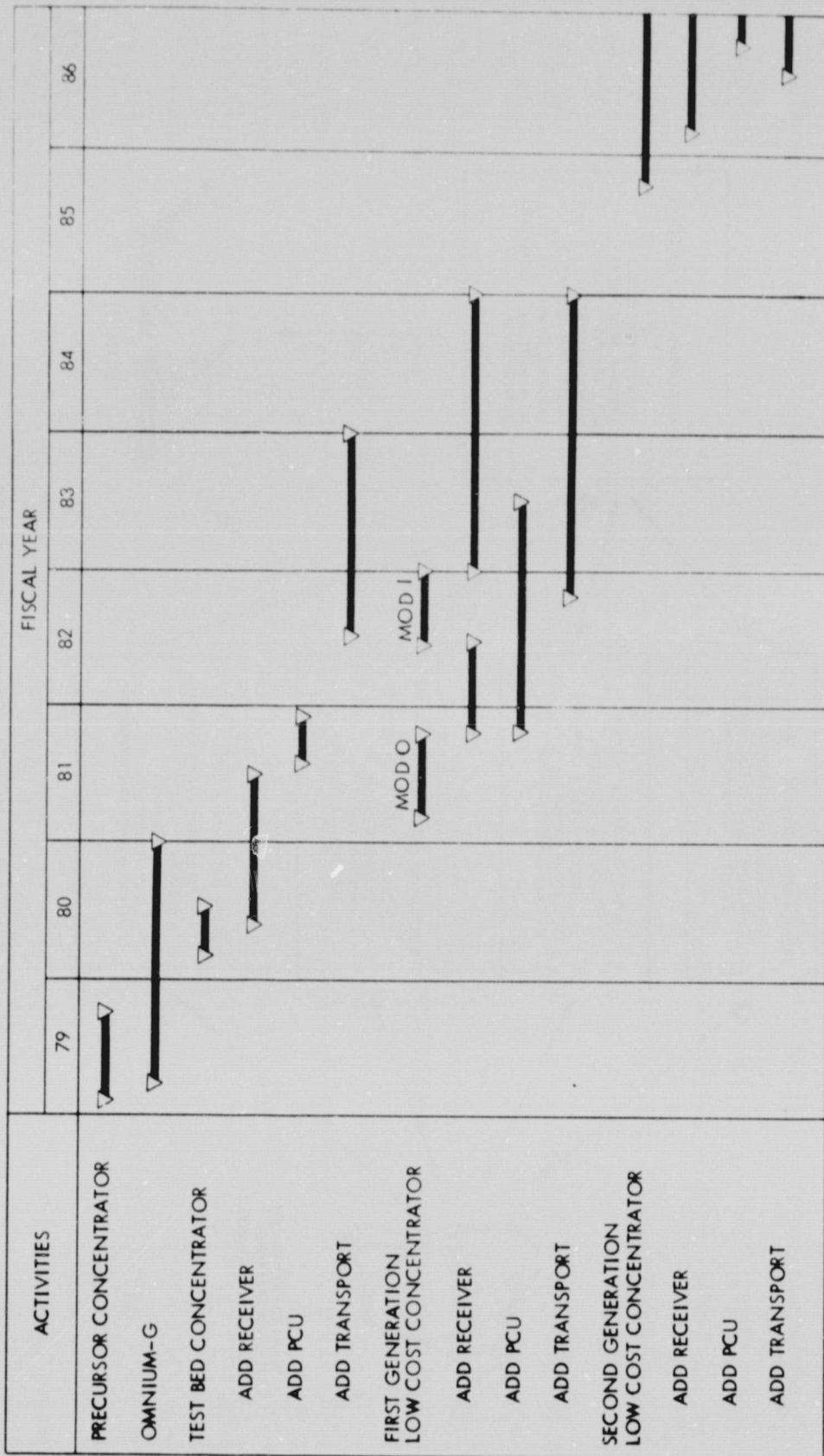
a. Test Protocol. A "Protocol for Testing Solar Energy Conversion Equipment" at the PFSTS was prepared and released in October 1978. A revised draft was issued in August 1979. This document presents a guideline by which to plan, conduct, and report on performance testing of solar concentrators, receivers, and power conversion modules. The guideline is currently in effect.

b. Precursor Concentrator Tests. All facility support equipment necessary for the operation of the Precursor Concentrator was installed or constructed in place. Planned testing utilizing the Precursor has been completed. Hemispherical mirror facets, similar to those manufactured for the TBCs were installed on the Precursor. Optical tests of mirror quality were performed by assembling up to eight 60.96 cm x 71.12 cm (24 in. x 28 in.) mirror facets on the Precursor mount. Calorimeter testing was performed using both a coiled-tube and flat-plate calorimeter. The flux mapper which measures the sun's concentrated flux density was first tested using the Precursor as a test bed.

c. Omnium-G Tests. The instrumentation and power cable ducts, concrete pad, and necessary power and instrumentation lines were installed for the Omnium-G module. The concentrator is a six-meter, two-dimensional, solar-imaging parabolic reflector. The reflective surface is a thin sheet of anodized aluminum with foam backing for support. The six-meter dish consists of eighteen "pie"-shaped petals assembled on a structural, aluminum-pipe back-up structure.

The test and evaluation phase included the following tests at the PFSTS:

- Tracker Mechanical Checkout
- Concentrator Mechanical Checkout
- Mirror Segment Alignment



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Figure 9-1. PFSTS Test Schedule

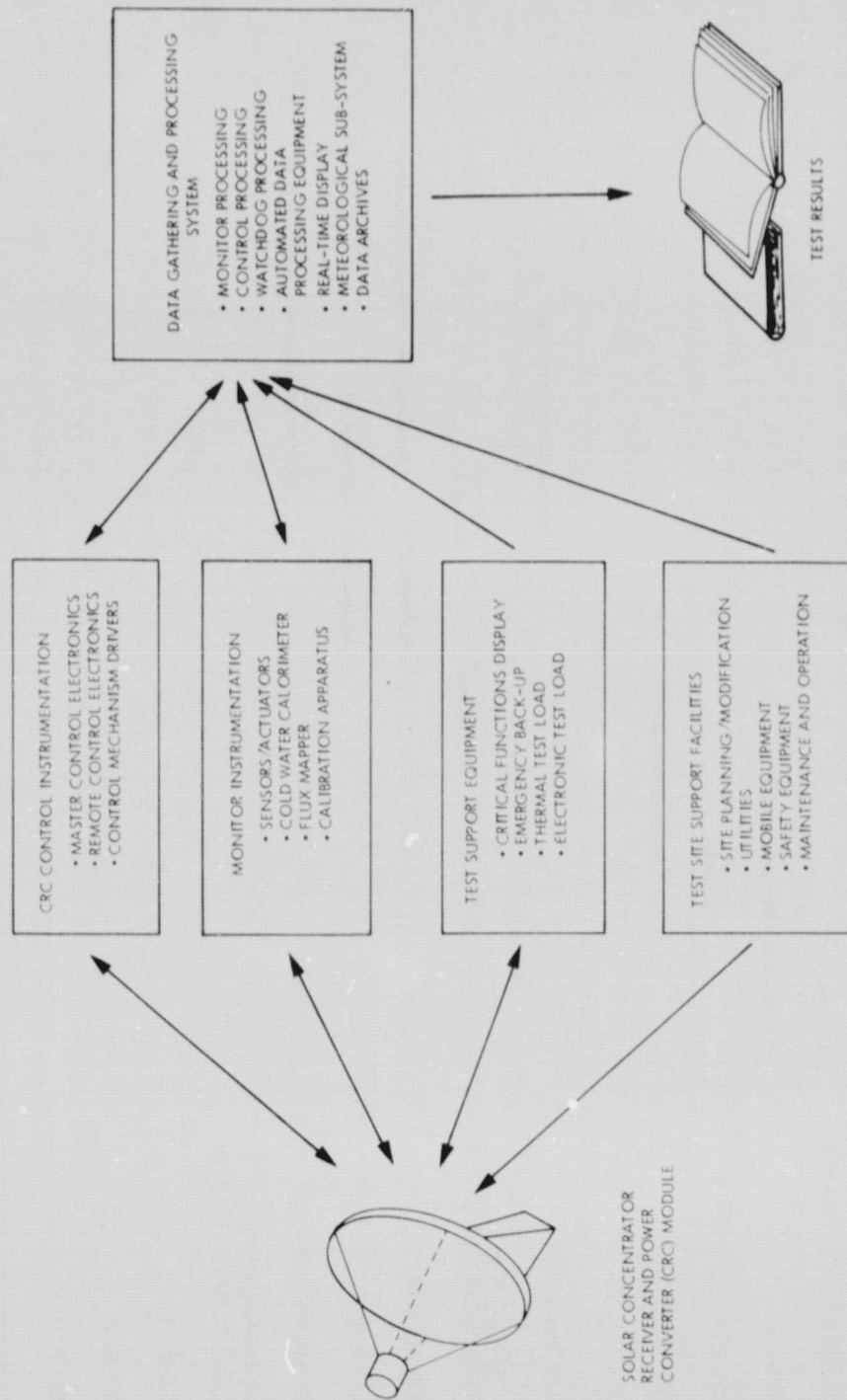


Figure 9-2. Solar Module Testing Logistics

- Solar Tracking Error
- Moonlight Focal Point Location
- Reflectance (18 Panels)
- Flux Mapper
- Cold Water Calorimeter
- Receiver Thermal Performance
- System Proof and Leak Test
- Power Conversion Performance

In the future the concentrator may be used as a test bed for the test and evaluation of receivers, engines, etc. A photograph of the Omnium-G module is shown in Figure 9-3.

d. Test Bed Concentrator Installation. The instrumentation and power cable ducts, concrete pads, water and air lines were installed for the TBCs. The two concentrators are each 11-meter, two-dimensional solar-imaging parabolic antenna fabricated by E-Systems, Inc. Attached to each concentrator are 224 spherical mirror facets. Construction of the two concentrators was near completion at the end of the fiscal year. A photograph of the TBCs during construction is shown in Figure 9-4.

e. Site Safety. As testing progressed from the Precursor Concentrator to the Test-Bed Concentrator phase, the safety aspects for the PFSTS became more numerous. Initially, fairly simple safety requirements sufficed, but as solar flux densities increased, stricter safety requirements were implemented. Table 9-1 lists the governing safety documents and main points of the PFSTS safety practices. No significant safety problems were encountered and none resulted in lost time in test operations.

## 2. Module Control Instrumentation

The critical design criteria for the control of a solar CRC were established and dictated the necessity for the following basic features:

- Remote Control and Monitoring
- Closed-Loop Sun-Sensor Control (Automatic Track Mode)
- Manual Operation
- Back-up Azimuth and Elevation Controls and Power Source





Figure 9-3. Omnim-G Concentrator at PFSTS

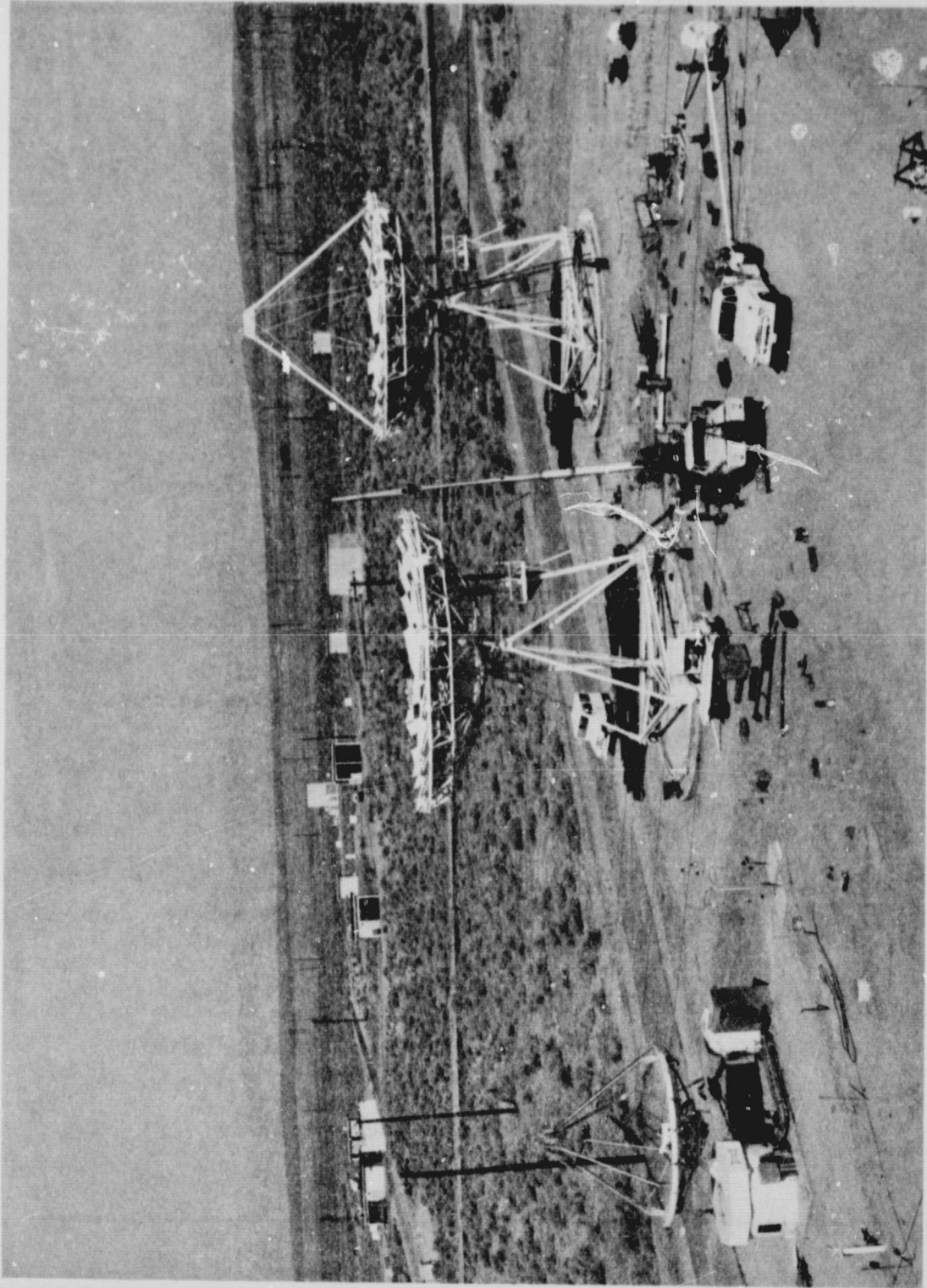


Figure 9-4. TBC Construction

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Table 9-1. Site Safety at the PFSTS

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GOVERNING DOCUMENTS

- PFSTS Safety Practices
- Safety Review - New Operations
- JPL Safety Manual
- ETS Safety Manual
- Division 34 Safety Practices
- ASME Boiler Code
- National Electric Code

MAIN POINTS

- (1) A "Control Area" shall be outlined by a yellow and black striped rope at no less than two times the concentrator's focal length from the mirror surface.
  - (2) Critical operating parameters shall be remotely monitored and displayed in the control room.
  - (3) An emergency override procedure shall be implemented if a safe operating limit is exceeded or such an occurrence is anticipated.
  - (4) A red-green light warning system shall be implemented at each control area except at the Precursor.
  - (5) The site manager, or assistant site manager, shall supervise all operations on site during any activity at PFSTS.
  - (6) Written test procedures shall be prepared and approved by the site manager and ETS safety coordinator prior to start of testing activity.
  - (7) Hard hats are required in the control area.
  - (8) Dark goggles and hard hats are required within or adjacent to the control area.
  - (9) The "buddy system" shall be used during operations.
-

a. Omnium-G Module. The Omnium-G module was supplied with all of its controls and monitors housed within the concentrator's mounting base enclosure. No facilities were provided by the manufacturer for remote controls or monitors. A Remote Control Transfer Switch assembly and associated interfacing circuitry were designed and integrated into the Omnium-G module. Control and monitor lines were situated in conduits between the Omnium-G module and the control building (E9). A concentrator control panel was designed, fabricated and installed in the operator's console in the control building. This panel provides the capability to transfer elevation and azimuth drive from the closed-loop, sun-sensor mode to manual control. In the manual mode either axis may be slewed in the direction desired. The slew rate is controlled by the selection of either a 12 or 24 volt power source. The source used for remote-controlled manual slewing of the concentrator is a back-up (emergency) power source consisting of automotive-type batteries. These batteries are located at the concentrator site.

b. Test-Bed Concentrator Module. The TBC is furnished with a remote control panel which is installed in the operator's console in the control building. This control panel provides for selecting closed-loop, sun-sensor tracking, manual control, or tracking from sun position data that is stored within its own solid-state memory and processed by a microprocessor.

A back-up (emergency) control panel and power source was being fabricated at the end of the fiscal year to provide azimuth and elevation control in the event of a facility power or electronics failure. This is required to minimize structural damage which could occur if concentrated solar energy were allowed to dwell on an unprotected structure - a condition which could occur as the sun moves in relation to the structure when the concentrator is not tracking. The back-up power source will consist of fifteen 12-volt automotive batteries.

### 3. Module Monitor Instrumentation and Electrical Loads

a. Omnium-G Module. The Omnium-G module was instrumented to provide several real-time monitoring functions remotely at the operator's console in the control building. Isolation amplifiers were added to provide low impedance outputs from the high impedance sun-sensor outputs. Both the azimuth and elevation sun-sensor cell balance signals are cabled to the operator console meters. Status lights indicate "Sun Acquisition" and tracker "Loop Open." Digital panel meters display the receiver temperature, receiver output pressure, and feed-water flow rate on a Critical Functions panel.

The Omnium-G alternator output is cabled to an electrical load bank. This load was designed and fabricated to provide a three-phase 120/208 volt, 60 Hz, 16 KVA resistive load. The load may be adjusted from 0 to 16 KVA in 100 VA steps. The load is instrumented with voltage and current sensors for each phase plus three-phase watts and

frequency sensors. The frequency and power are displayed in real time by digital panel meters at the operator's console. The load was sized to be functional for larger CRCs than the Omnium-G module and is planned to be used with the TBCs.

The data logger (described in Subsection 5) scans all Omnium-G sensors. It is programmed with limit levels on all critical channels. The status of these limit monitors are indicated by visual and audible alarms on an Alarm Monitor panel located in the operator's console.

b. Test Bed Concentrator Module. The control panel furnished with the TBC includes several monitors. The concentrator position indicators display the azimuth and elevation position to a resolution of  $0.01^\circ$ . Limit switch indicators show when the concentrator has reached an axis limit. Sun acquisition and tracking status are displayed. A fault indicator is illuminated during a drive motor overload, SCR controller power loss, main power breaker trip, loss of sun track, or open interlock.

A data logger with programmed limits and an Alarm Monitor panel will be employed during TBC testing as described above for the Omnium-G module.

#### 4. Experimentation Equipment

In-field interface electronics at the module are required to obtain parametric measurements of the solar module under test. Instrumentation used for the Precursor and Omnium-G concentrators are identified here. Similar ones are being installed for TBC testing.

a. Sensors. For Precursor and Omnium-G concentrator testing, sensors included type "K" and "T" thermocouples, type "E"  $\Delta T$  thermopile probes, turbine flow meters, and strain-gauge type pressure transducers. Sensors used on the meteorological subsystem are presented below.

b. Cold-Water Calorimeter. A flat-plate cold-water calorimeter was designed in-house and used to measure the integrated thermal flux at the concentrator's focal point. A calorimeter description is given in Section IV of this report.

c. Flux Mapper. To map the relative solar intensities about the focal point, a JPL-designed flux mapper was used. Section V of this report describes the instrument.

d. Instrument Calibration. To ascertain acceptable data quality, two levels of calibration were performed. First, each sensor was calibrated to obtain conversion factors between the raw measurement parameter and the respective engineering unit. Second, an end-to-end calibration check was performed. The sensors were subjected to known conditions and the final results were processed by the computer and compared with expected values.

## 5. Data Gathering and Processing Hardware

The basic design for the system to monitor, process, and record experimental measurements was presented in the FY 1978 Annual Technical Report. The data gathering and processing (DGAP) concept is summarized in Figure 9-5. A block diagram of the hardware is shown in Figure 9-6.

a. Front-End Processing. Analog signals from the sensors are routed to and scanned by Acurex Autodata-Nine data loggers. One logger is dedicated to each concentrator. Scanning of the signals was typically at a rate of 24 readings per second. The analog measurements were digitized and serially fed to the minicomputer system. On critical signals, alarm limit set points were programmed into the logger. In the event of an alarm condition, a message is transmitted to the computer and an acoustic alarm activated.

For TBC testing, measurements from the flux mapper will also be processed by the mini-computer. A separate data input port to the computer is being built to handle the faster data rates from the flux mapper.

During overcast periods, the TBC tracks the sun via azimuth/elevation coordinate data stored in semiconductor memory within the concentrator's control unit. These data must be updated daily. A special link has been designed to the supervisory computer so that it may calculate and load the coordinate data. The associated software is now being developed.

b. Watchdog Processor. One of the major concerns during test activities is safety to personnel and equipment. During TBC operation, an independent micro-processor is being considered to constantly monitor critical parameters such as collector pointing accuracy, temperatures, and pressures. In the event of a critical alarm situation, the watchdog processor will slew the concentrator away from the sun, conduct an orderly shut-down of equipment, and notify the attending operator of the cause.

c. Automated Data Processing Equipment. All DGAP activities are centralized in the automated data processing equipment (ADPE) which consists of a mini-computer and related peripherals. The

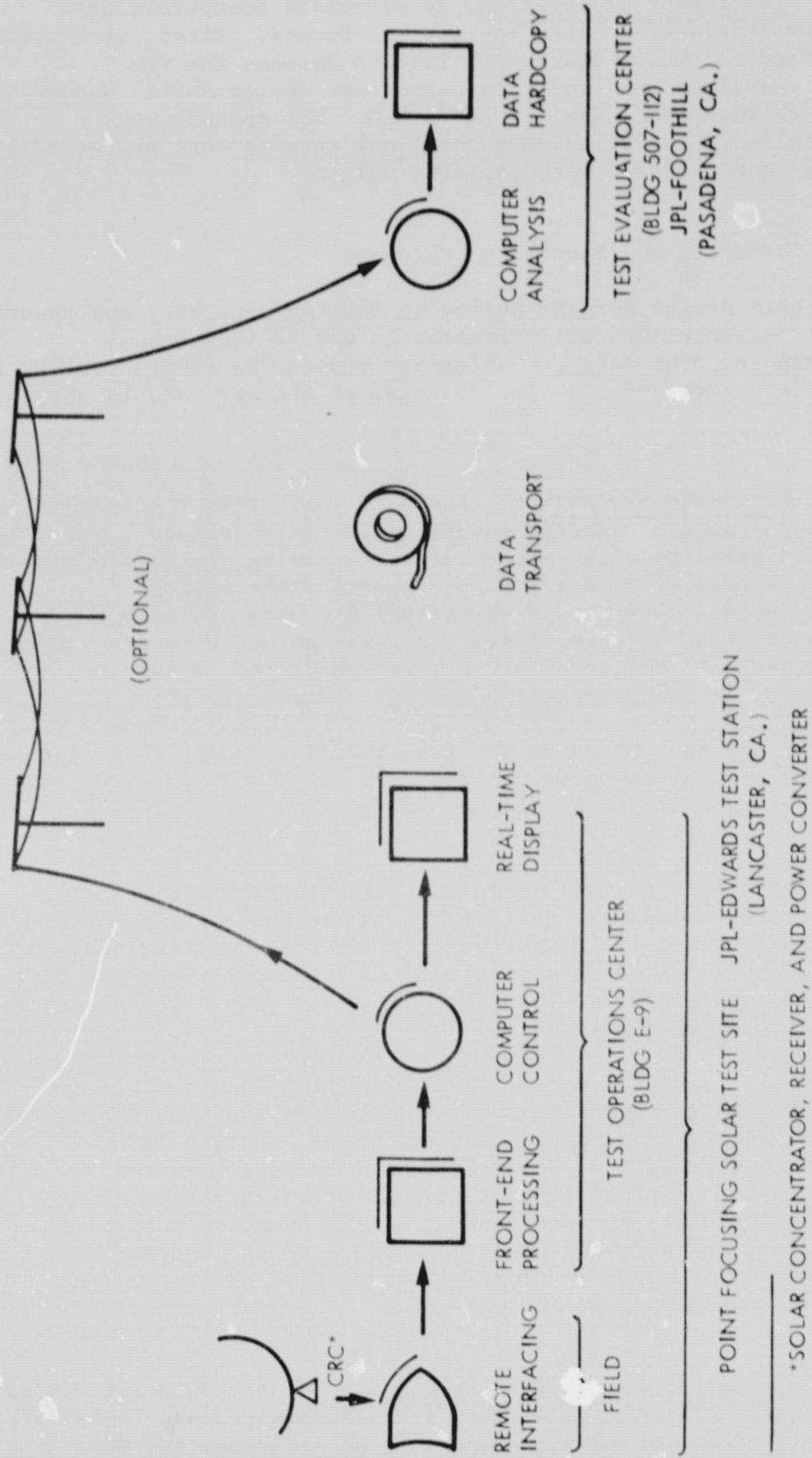
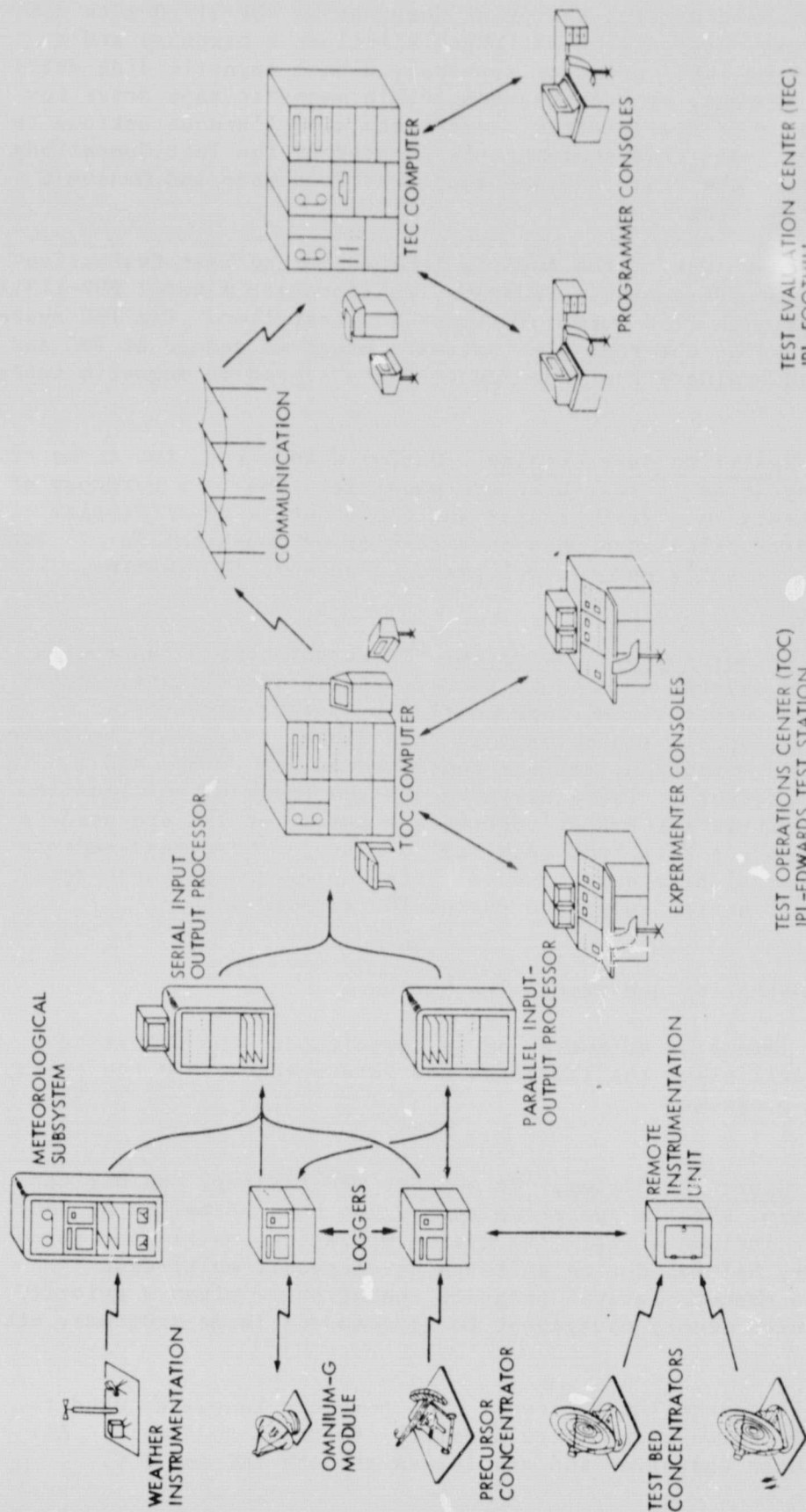


Figure 9-5. Data Gathering and Processing System Concept



TEST EVALUATION CENTER (TEC)  
JPL-FOOTHILL

TEST OPERATIONS CENTER (TOC)  
JPL-EDWARDS TEST STATION

Figure 9-6. Data Gathering and Processing System Hardware



mini-computer is a Digital Equipment Corporation PDP-11/10 with 28K words of memory. Supporting peripherals include a hardcopy and a cathode-ray tube (CRT) operator terminal, a dual magnetic disk drive for program storage, an industry-compatible magnetic tape drive for data storage, a printer/plotter device, and miscellaneous options to the processor. All this equipment is located at the Test Operations Center (TOC) in the PFSTS and has supported Precursor and Omnium-G concentrator testing.

A duplicate set of the ADPE is located in the Test Evaluation Center (TEC) at JPL-Foothill Pasadena, California. A model PDP-1134A mini-computer with 124K words of memory was installed. The TEC system is used to develop the real-time software programs needed at TOC and to reduce and evaluate the experimental data stored on magnetic tapes.

d. Real-Time Data Display. During a test run, two forms of data representation in real-time are possible. One is a hardcopy of the measurements on a fast printer and the other is a CRT display of measured and/or calculated data in a tabular or graphical form. Both methods are currently under development to support TBC testing.

e. Meteorological Subsystem. To support PFSTS testing, a stand-alone subsystem is used to record meteorological data. For compatibility purposes, the same model data logger used for concentrator testing is also used to scan direct and total insolation, wind speed and direction, ambient temperature, dew point, and atmospheric pressure. These measurements are recorded on magnetic tape at one-minute intervals. Software programs at TEC are used to reduce one month's data from each reel of tape. These measurements also provide real-time environmental data during concentrator tests via an RS 232C serial interface to the TOC computer.

## 6. Data Gathering and Processing Software

Three levels of software can be classified: the operating system and utilities, the languages and interpreters, and the custom application programs.

a. Operating System. To support TBC testing, the Digital Equipment Corp. RSX-11M operating system has been installed at TEC. Its features include a real-time system operation, multi-user support which is very helpful during software development, multi-task operation to execute several programs concurrently given a priority index, extended memory management to accommodate large programs, etc.

b. Language Interpreters. The computer languages used to develop DGAP software are Macro assembly, Fortran, and Basic. All three have been installed and are in use at both TEC and TOC.

c. Custom Application Programs. The software programs written in-house to gather and process solar module test data are grouped by the module that they support. They include:

- (1) Meteorological Subsystem Application Programs
- (2) Precursor Concentrator Application Programs
- (3) Omnimium-G Application Programs
- (4) Test-Bed Concentrator Application Programs

## 7. Data Reduction and Computer Support

a. Data Analysis Support. The computer system at TEC has also supported post-test activities. Additional software programs have been written to reduce particular magnetic tapes and to aide the data analysts. These program functions include: performing special calculations, data averaging, and obtaining statistical means.

b. Data Archives. A data library has been initiated at TEC for orderly storage and retrieval of test data and description. The archive is categorized into each solar module operated at the PFSTS. Information cataloged includes module description, general test plan, associated table of parameters, list and description of the test runs, data for each test run, and documentation on test results and analysis. Each test run includes the data recorded on magnetic tape, a brief description of the test activities, and a hardcopy of the data which has been disseminated.

c. Software Maintenance. The impromptu nature and the complexity of large scale test activities requires the DGAP software to be (1) continuously ready for use yet adaptable to last-minute changes without disruption to test schedules, and (2) extremely reliable. Such responsibility requires a workable, systematic approach to (1) modifying errors in both operating system and application software, (2) incorporating changes and enhancements from test to test, and (3) inventorying the various iterations of each program with associated programs and with the applicable test data files. Special data sheet forms have been drafted and a master index of all DGAP software is maintained to help coordinate software maintenance tasks.

## 8. Test Site Activities

a. Site Configuration. The present configuration of the PFSTS consists of the Control Room (building E9), Precursor Concentrator, Omnimium-G Concentrator module, Test-Bed Concentrators 1 and 2, remote instrumentation housings at the Omnimium-G and TBCs modules, and an electric load bank. The PFSTS is shown in an artist

sketch (Figure 9-7). Also shown is the placement of future Low Cost Concentrators and advanced technology concentrators. All instrumentation cabling and utilities are installed for existing concentrators.

b. Mobile Equipment. A two-man, 60-foot, self-propelled aerial lift was procured to facilitate assembly, maintenance, mirror cleaning, checkout, and instrumentation installation on the solar concentrators. All functions are hydraulically powered including wheel drive. Its lifting capability ranges from 227 kg (500 lbs) fully extended horizontally to 454 kg (1000 lbs) when in a vertical position.

Also available on a shared basis with the Edwards Test Station are a 5,080 kg (5 ton), 4.9 m (16 ft) crane, fork lifts, various trucks and automobiles.

c. Safety Equipment. Each concentrator is encircled by a yellow and black safety rope, and access gate. Rigid control of access to the area enclosed by the above safety rope is maintained at the PFSTS. Red-yellow-green warning light towers are placed at each operating concentrator to display the hazard status. Safety helmets and dark glasses are available at the site and must be worn within the restricted area. Eye wash and shower facilities have been installed near the battery rack at the Omnium-G site.

d. Operation and Maintenance. One of the tasks of the PFDR project is to identify and cost the O&M activities of a solar electric power plant composed of various point-focusing collector modules. The task is being conducted in two phases. First, a list of O&M parameters and their relevance to operating costs is compiled from public literature, technical reports and in-house experience with the PFSTS. Second, each O&M parameter is quantized based upon maintenance work and failure modes encountered during test activities at PFSTS and upon mathematical algorithms used to extrapolate from a test site environment to an industrial power plant operation.

Operation and maintenance parameters considered are categorized into (1) solar module optics; thermal, mechanical, electrical, and control electronics (2) site and building maintenance, utilities, and mobile equipment (3) operating and preventive maintenance manpower and trades (4) unscheduled emergencies and failure modes.

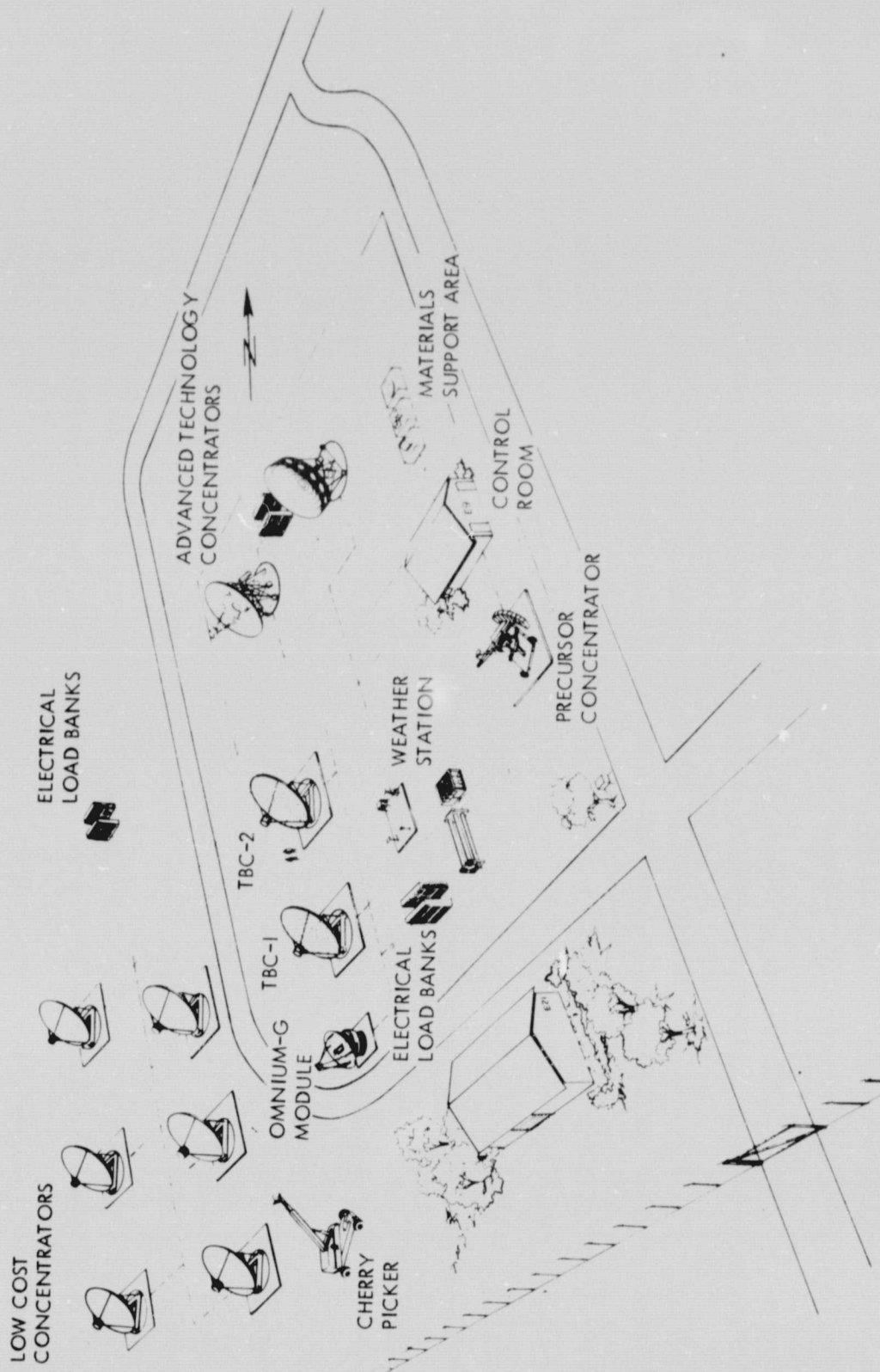


Figure 9-7. Point-Focusing Solar Test Site

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