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Thermal Power Systems Point-Focusing Distributed Receiver Technology Project

Annual Technical Report

Fiscal Year 1978

Volume I: Executive Summary

Prepared for
U. S. Department of Energy
by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

(JPL PUBLICATION 79-1)

Artist's Concept of a Point-Focusing Parabolic Concentrator

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ABSTRACT

Thermal or electrical power from the sun's radiated energy through Point-Focusing Distributed Receiver Technology is the goal of this project. The energy thus produced must be technically, as well as economically, competitive with other energy sources. This project is to support the industrial development of the required technology to achieve the above stated goal. Solar energy is concentrated by either a reflecting surface or a lense to a receiver where it is transferred to a working liquid or gas. Receiver temperatures are in the 1000° - 2000°F range. Conceptual design studies are expected to identify power conversion units with a viable place in the solar energy future. Rankine and Brayton cycle engines are currently under investigation. This report details JPL accomplishments with point-focusing technology in FY 1978.

FOREWORD

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

This Executive Summary presents the results of activities conducted by the Jet Propulsion Laboratory during Fiscal Year '78 in support of this DOE Branch. Specifically, it discusses the Point-Focusing Distributed Receiver (PFDR) Technology Project.

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

This Summary, formerly published as JPL Internal Document 5104-26, covers the accomplishments during the first year of the project and is intended as a means of briefly describing them to industry and universities.

CONTENTS

SECTION I

INTRODUCTION

The Point Focusing Distributed Receiver (PFDR) Technology Project is concerned with small solar-thermal power systems for providing thermal and/or electrical power. The goal of this Project is to support the industrial development of point-focusing distributed receiver technology which will provide the most favorable life-cycle costs per unit of useful energy produced.

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

Table I. Preliminary Cost and Performance Targets

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

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

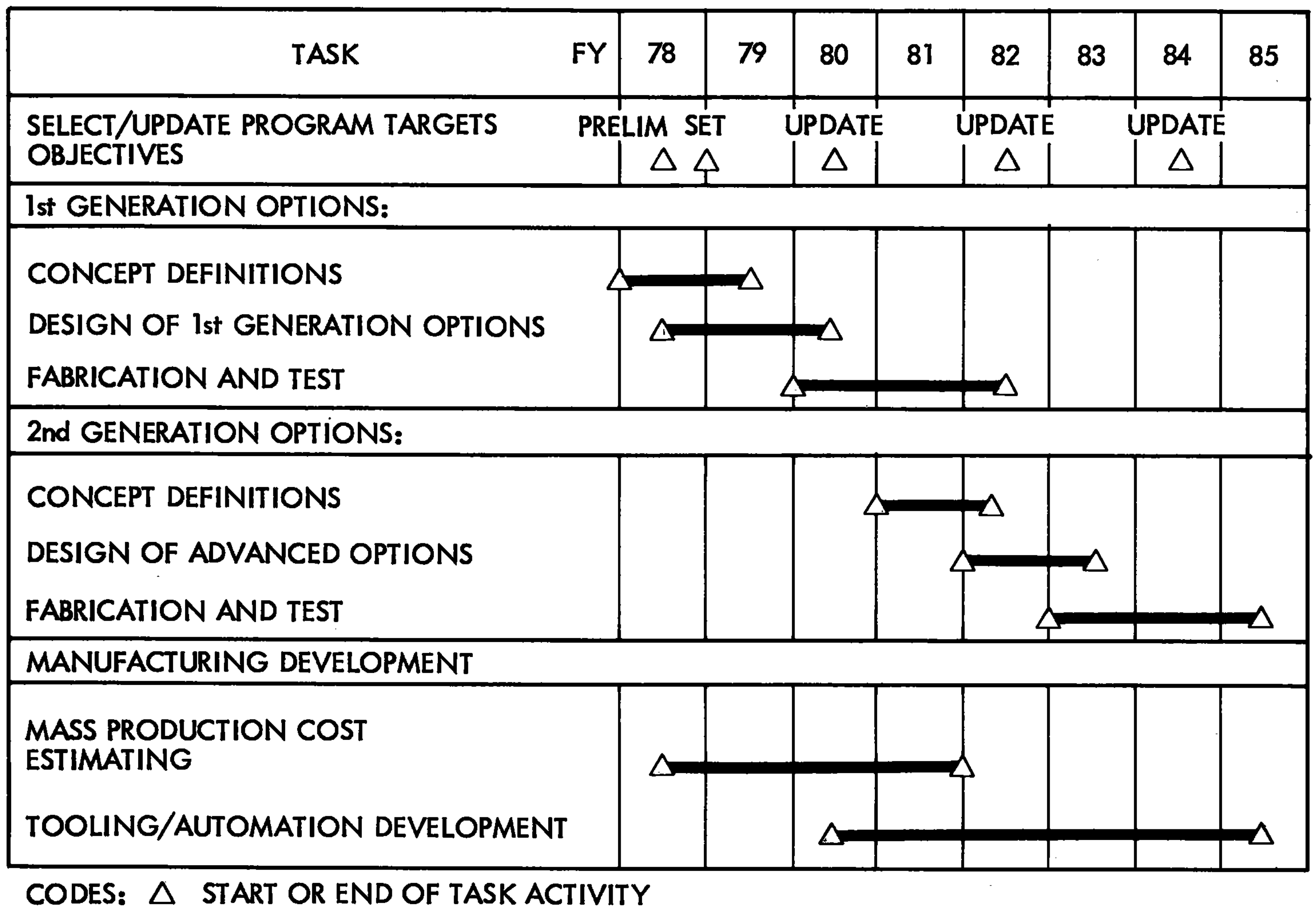

Figure 1. Overall Schedule of Subsystem Development

SECTION II

TECHNICAL APPROACH

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

The Project is divided into seven tasks, Table II summarizes the major objectives of each task. A summary of major project milestones through FY 1983 is given in Figure 2.

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

The major test periods are shown in Figure 3. It should be noted that concentrator, receiver and power conversion units assembled together make up an individual module for electric power generation. Testing of Test-Bed Concentrator No. 1 will begin in the latter portion of FY 1979. After test and evaluation the initial steam receiver will be installed on it and tested. The steam power conversion unit will then be added to the assembly and tested. This process will be used with Test-Bed Concentrator No. 2 for the gas Brayton and also for the first modification of both steam and Brayton modules.

After individual modules have been developed and tested, modules in a group of approximately three will be assembled and tested as shown in the lower part of Figure 3. The prime purpose of these tests will be to determine interactions among the modules on a small scale.

It is planned to make periodic assessments of the technology to determine which configurations should be pursued in the following time period. These assessments will be led by the Systems Engineering task area and will include inputs from both systems and each subsystems area. Examples of assessment results will be recommendations for the type of subsystem, steam Rankine versus advanced cycle engines, and the temperature and power levels for each subsystem.

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

Table II. Project Objectives by Task

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

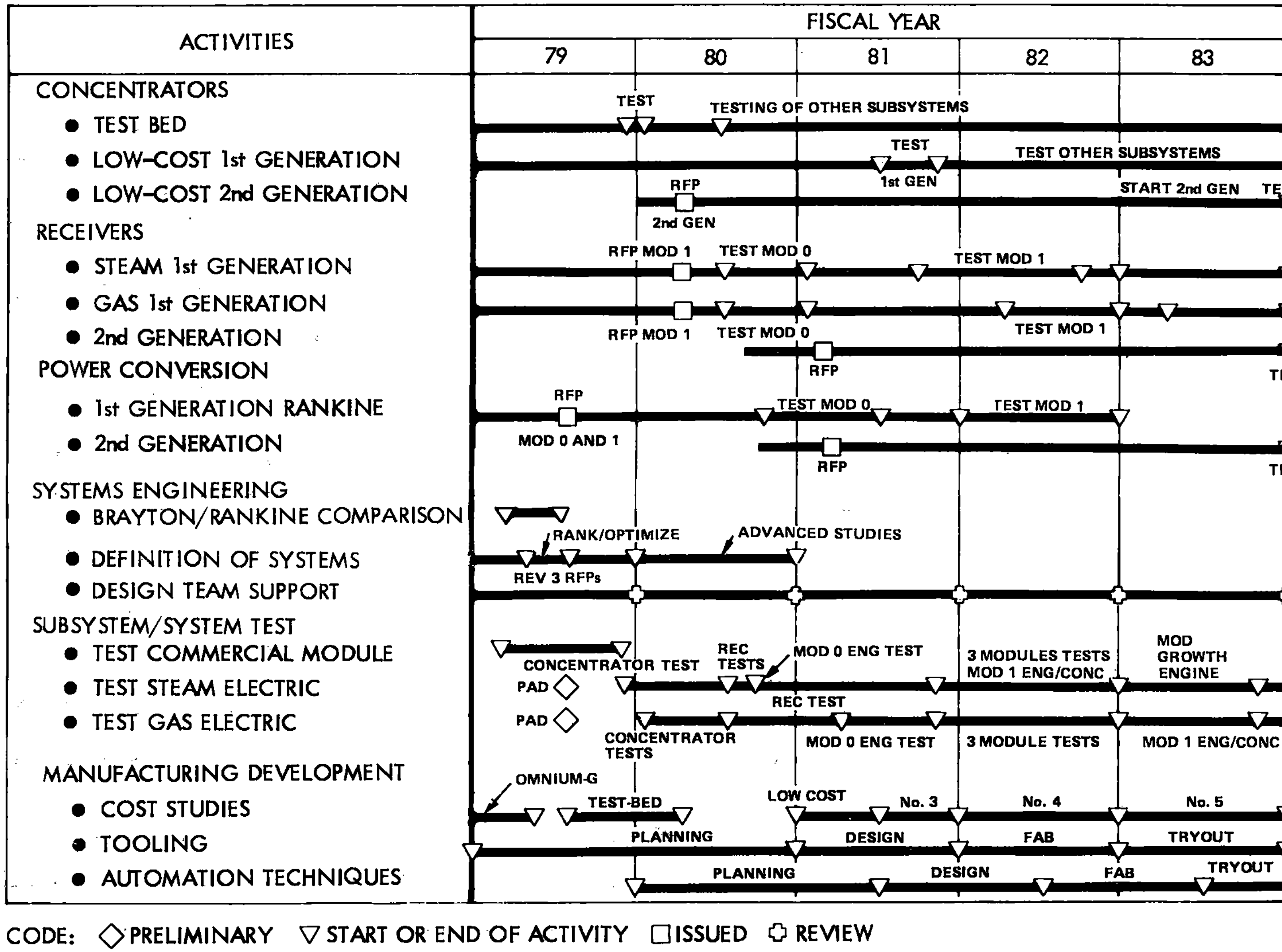

Figure 2, Summary Five-Year Schedule

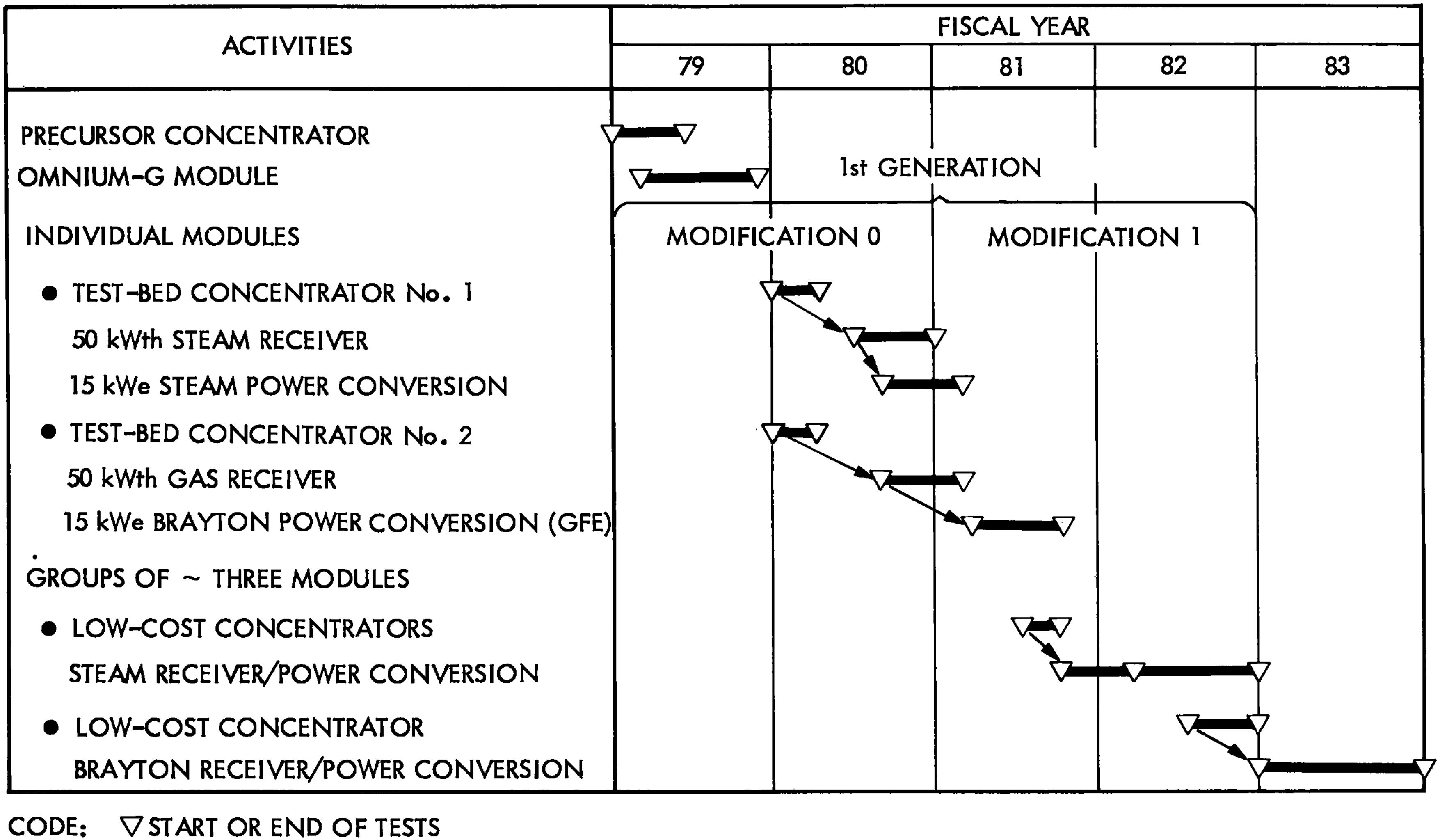

Figure 3. Five-Year Subsystem Test Periods

SECTION III

TECHNOLOGY INFORMATION DISSEMINATION

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

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

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

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

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

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

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

(2) Presentations at scientific, technical, and trade conferences representative of the three communities.

(3) Publication of an annual Technical Progress Report.

(4) Publication of leaflets and brochures.

SECTION IV

CONCENTRATOR DEVELOPMENT TASK

The Concentrator Development Task activities are directed toward developing high temperature Point-Focusing Concentrator technology with a major emphasis on low-cost in large quantity production. This approach is motivated by the fact that the concentrator comprises more than half of the cost of a solar thermal module. The implementation of this task is primarily through contracts with industry.

The Task consists of three thrusts, (1) an early test program, (2) a first generation Low-Cost Concentrator and (3) second generation concentrators. Compatible tasks are underway for the development of receivers and power conversion subsystems using steam Rankine and air Brayton cycles for the first generation; the Stirling cycle will be considered for the second generation.

Early test capability and experience will be obtained with a Precursor Concentrator and through the evaluation testing of an Omnium-G module. The Precursor Concentrator is a simulation of a portion of a concentrator utilizing mirror facets for the reflecting surface. This tool is used to evaluate mirror performance and alignment techniques.

Another effort leading to early test capability is the Test Bed Concentrator (TBC). The TBC shown in Figure 4 is a microwave antenna design modified to accommodate the requirements of solar tracking and support of the receiver/power conversion package at the focal point. Spherical mirror facets, developed by JPL, will be supplied for use as the reflector surface. Two such units are being supplied by E-Systems Inc., Dallas, TX with first delivery at the end of FY 1979.

The mirror facets for the TBC are based on a development effort at JPL. They are made by bonding a second surface mirror to a spherically contoured block of Foamglas* and coating the substrate with a protective sealer and painting it white. Supports for the facet may be embedded in the substrate or preferably bonded to the edges. An investigative effort was carried out to select the combination of materials to use for the fabrication of the facet. In addition an environmental and a severe temperature - humidity cycling test was used to screen the materials and demonstrate the mechanical integrity of the materials combination. Workability was an important criterion in the selection effort. Other tests were conducted with ice balls, to simulate hail, impacting the facet surface. The adequacy of the design was verified through Foamglas strength characterization tests, shear and peel tests, and facets subjected to simulated design wind loads. A technique for quick acceptance testing of the mirror quality has also been developed.

The first generation Low-Cost Concentrator effort was initiated in FY 1978. Phase I includes the concept development and preliminary

* ® Pittsburgh Corning Corporation

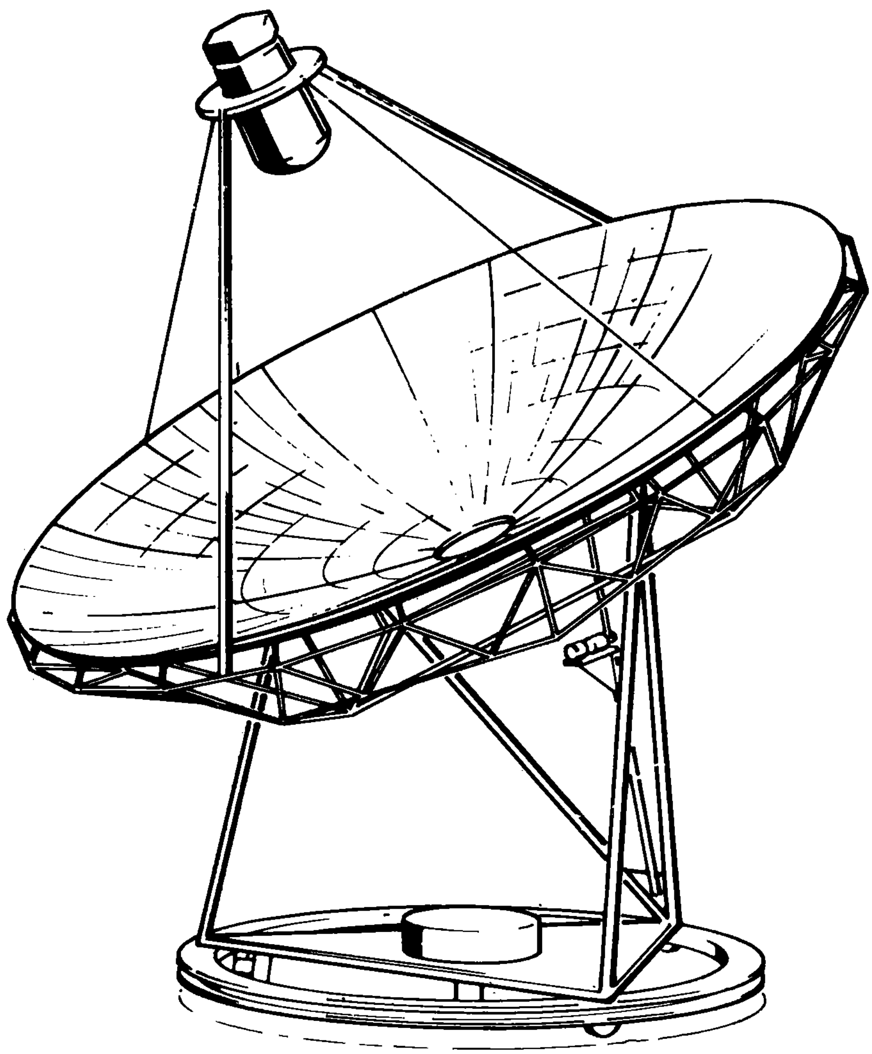

Figure 4. Test Bed Concentrator

design of a parabolodial concentrator to provide receiver temperatures in the 1200 to 1700°F range. The cost target for the first generation concentrator is $100-150/m^2$.

Twelve responses to the low-cost concentrator procurement solicitation were received subsequent to a notice in the Commerce Business Daily and issuance of the Request for Proposals; seven were from small business. Contracts were awarded for the initial phase to Acurex Corporation, Mountain View, CA; Boeing Engineering and Construction Company, Seattle, WA; and the General Electric Company, Space Division, Philadelphia, PA. See Figure 5 for their concept illustrations. It is planned that one contractor, selected from these three, will continue with the design, fabrication and installation of several concentrators at the JPL Point-Focusing Solar Test Site. Testing of the concentrators will begin in FY 1981.

The Task Development plans call for initiation of effort on the second generation concentrators in FY 1980. The design concept to be developed is expected to result from the DOE Advanced Solar Thermal Technology Project. It is anticipated that this effort will begin with a study of how the concentrators will be built in mass production. These concentrators have a cost target of $70-100/m^2$.

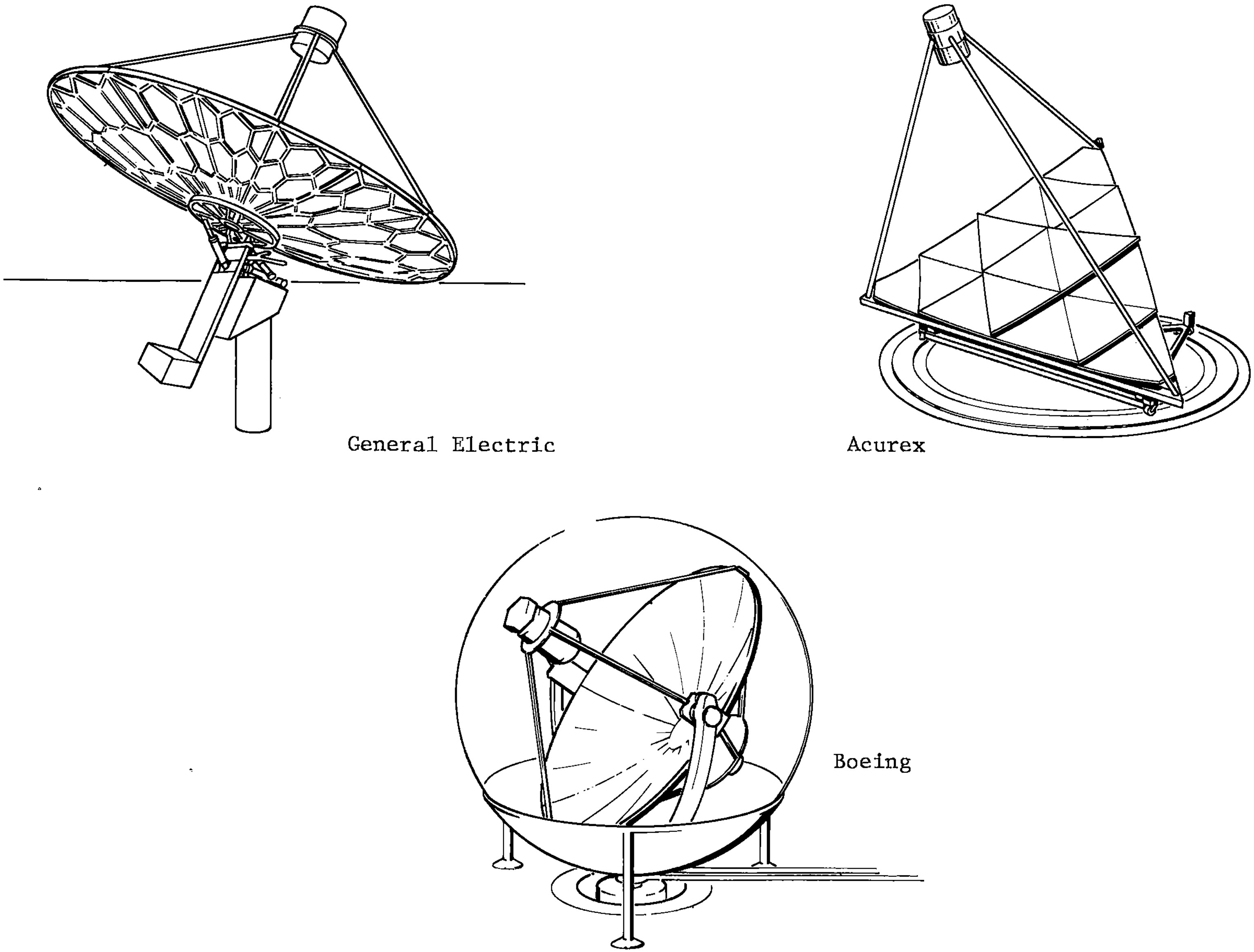

Figure 5. Low Cost Concentrator Concepts

SECTION V

RECEIVER DEVELOPMENT

The goal of the Receiver Development Task is to design and fabricate efficient, cost effective solar thermal receivers relying heavily on the capabilities of industry. Annual activities in achieving this goal fell into three principal areas: planning and in-house development, contracting and support tasks.

Early in the year, parametric heat and mass flow analyses were made in-house resulting in the preliminary design of several possible receiver configurations. These, together with systems, structural and materials inputs, were used to assess the current state-of-the-art and serve as guides in preparing for outside procurements. Two basic types of receivers resulted. The first was a steam receiver, once through to superheat, operating at about 540°C (1000°F) to 650°C (1200°F) at pressures up to about 14 MPa (2000 psi). The second type receiver was for an open cycle, air system with a turbine inlet temperature of about 820°C (1500°F).

Notices were placed in the Commerce Business Daily of the impending procurements and about 75 RFP packages were sent out. Both Requests for Proposals were for a Phase I Conceptual Design by several contractors which would be followed by single Phase II contracts to complete the design and fabricate a prototype of each type receiver.

Nine proposals were received, five for the air Brayton design, four for the steam. After a thorough proposal review cycle, six contracts were awarded: four for Brayton receivers and two for steam receivers. The contractors selected for the Brayton work were: 1) Garrett AiResearch, Los Angeles, CA; 2) Sanders Associates, Nashua, NH; 3) Dynatherm Corp., Cockeysville, MD; and 4) Boeing Engineering and Construction Company, Seattle, WA. Their concepts are shown in Figure 6. For the steam receivers, 1) Garrett AiResearch, Los Angeles, CA; and 2) Fairchild Stratos, Manhattan Beach, CA., were selected. Samples of their initial concept drawings are shown in Figure 7.

Each contractor had the initial task of doing a parametric analysis over a range of operating variables specified by JPL to insure adequate versatility. In early September, the four Brayton contractors made their presentations and the two steam contractors later in the month. All contracts are continuing into the next fiscal year. Plans call for a contract completion in early January 1979, and initiation of Phase II Final Design and Prototype Fabrication at the start of the third quarter of FY 1979.

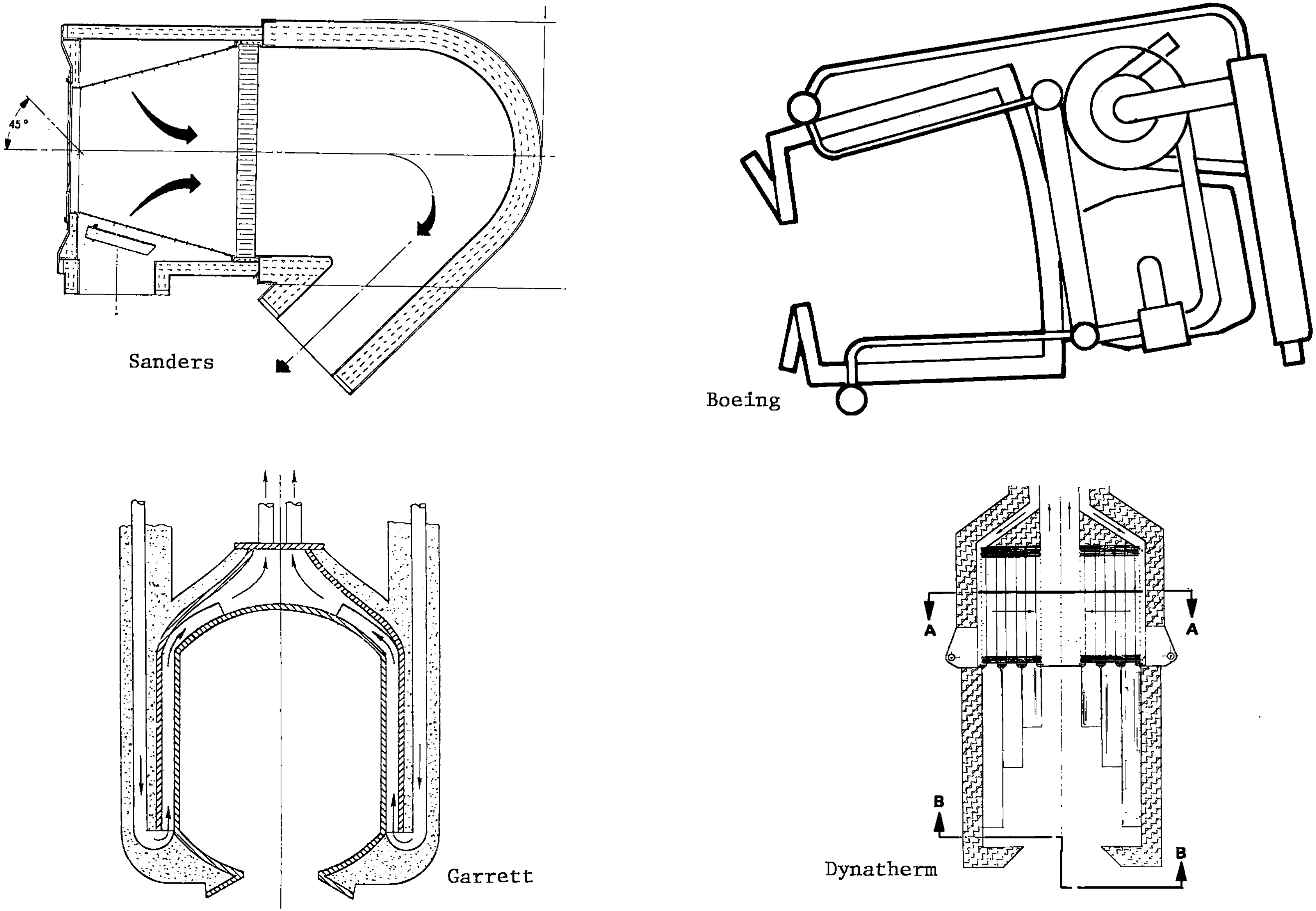

Figure 6. Brayton Gas Receiver Concepts

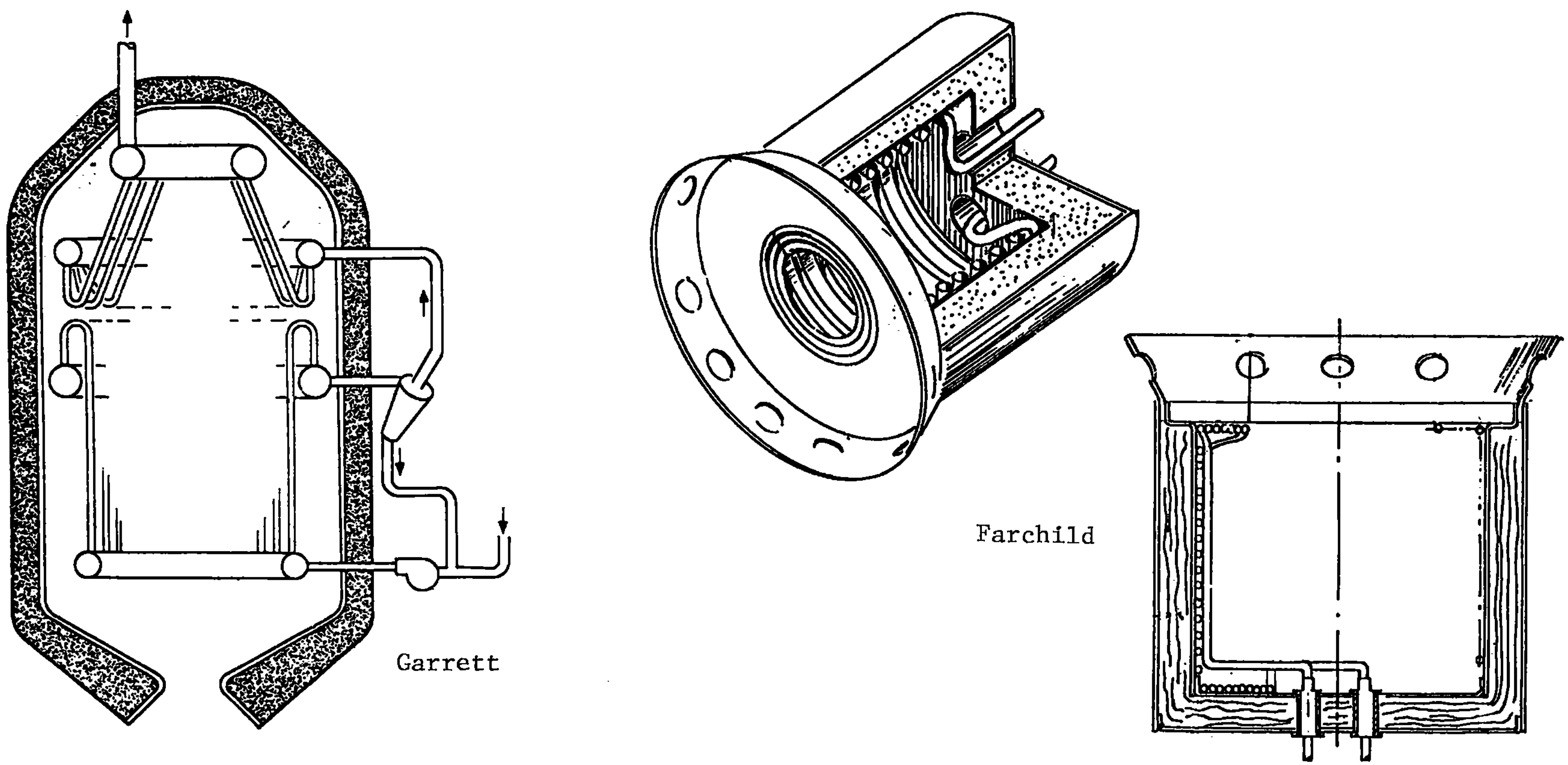

Figure 7. Steam Receiver Concepts

A flux mapping apparatus was developed to measure the intensity and geometry of focused solar radiation. The prototype device was completed in September of 1978 to support the testing of early hardware, such as the Precursor Concentrator mirror and the Omnium-G module.

Other support activities included the continuing development of a system model to help understand receiver dynamics by computer simulation. This activity will continue into the next fiscal year.

Second generation receivers are expected to be for Stirling and higher-temperature Brayton engines.

SECTION VI

POWER CONVERSION DEVELOPMENT

In support of the PFDR Project's goal of developing the necessary point-focusing dish technology for application in small solar-thermal power systems, the LeRC has provided in-house and contracting efforts towards the development of efficient power conversion units. In the technology development area key issues are efficiency, cost, and reliability which are of special interest to the engine. Because the heat engine is subject to high temperatures and pressures, and since it contains most of the moving parts, its reliability is critical to the overall system reliability. This is an important consideration as reliability is critical to small dispersed power systems if they are to compete for the electric power generation market. A highly efficient power conversion unit reduces the area required for the solar concentrator, which is the major cost item. The engine is also a significant part of the total capital cost and must be considered in the tradeoff between cost and efficiency. These factors were considered for both in-house and contracts efforts in FY 1978 to adapt existing small (15 kWe) engines with conversion efficiencies targeted at 25-35% by 1982 and 35-45% by 1985.

The thermodynamic cycles considered for the first generation were the gas Brayton and the steam Rankine because, for these cycles, considerable technology is available to provide the power conversion efficiency required in the early time frame of 1980-1982. In previous systems studies performed by JPL the diameter for a dish concentrator was provisionally selected to be a nominal 10 meters. Using target efficiencies a dish of this size could produce a nominal 15 kWe output. Therefore, the nominal engine size selected for the first phase in-house studies and the contractual concept definition studies was 15 kWe for the power conversion units. The following contracts were initiated in FY 1978 to conduct these studies:

The Garrett Corporation, AiResearch Manufacturing Co. Phoenix, AZ.	Brayton Open Cycle (Baseline) Brayton Closed Cycle (Baseline) Brayton Open Cycle (Alternate)
Sundstrand Energy Systems, Rockford, IL	- Rankine Turbine (Baseline)
Foster-Miller Associates Waltham, MA	- Rankine Reciprocator (Alternate)
Jay Carter Enterprises Burkburnett, TX	- Rankine Reciprocator (Baseline)

These studies are to be concluded in 6 months with reports prepared following the study phase. The steam Rankine cycle power conversion concepts are shown in Figure 8. An artist's conception of a typical small Brayton cycle power conversion unit is shown in Figure 9. The information from these studies will be made available for the design and fabrication phase that follows which will be based on competitive procurement.

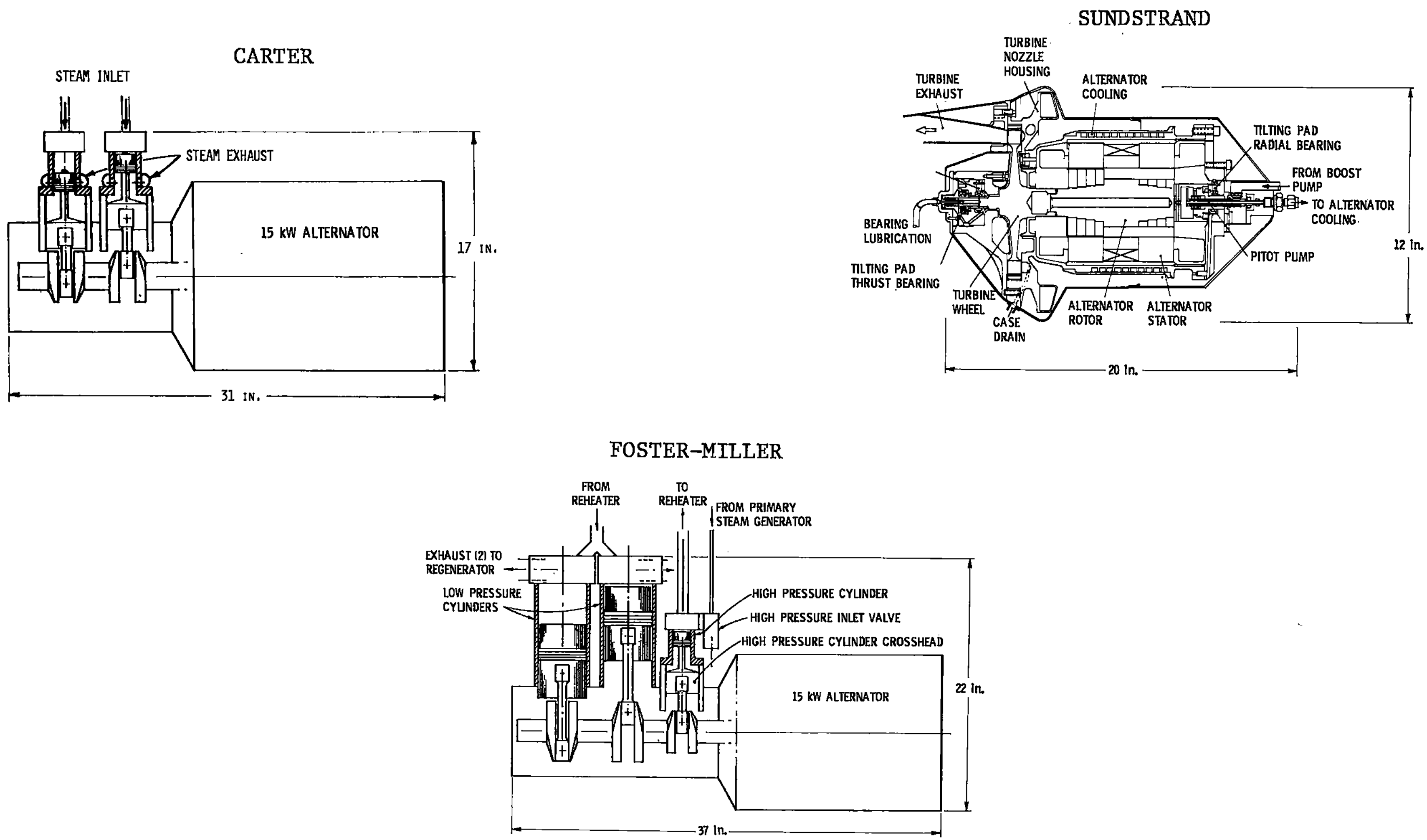

Figure 8. Steam Rankine Engine Concepts

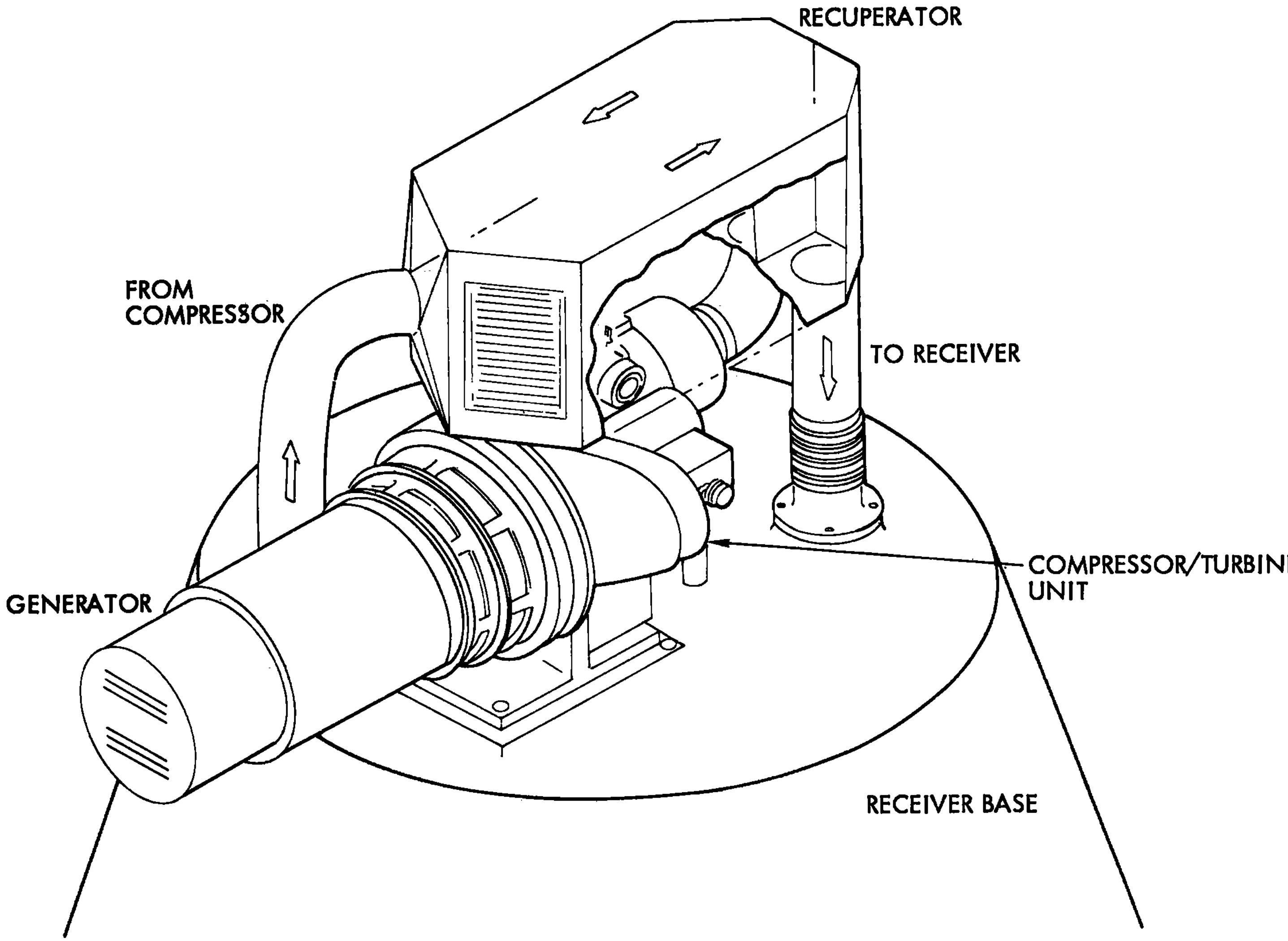

Figure 9. Concept of a Solar Brayton Engine Generator Set
Mounted on a Receiver Base

The in-house effort during FY 1978 consisted of establishing the state-of-the-art performance for small steam Rankine and Brayton cycle engines, performing preliminary cycle calculations to establish point design estimates at 15 kWe and in determining off-design performance capability for both the Rankine and the Brayton engines. The results of this effort are that for small (1-100 kWe) engines off-the-shelf, the state-of-the-art engine cycle efficiencies to shaft are as follows:

Steam Rankine Reciprocating ($\sim 1000^{o}F$)	20% or less
Steam Rankine Turbine ($\sim 1000^{o}F$)	10% or less
Open Gas Brayton (non-recuperated) ($\sim 1500^{o}F$)	13% or less
Closed Gas Brayton ($\sim 1500^{o}F$)	25% or less

The responses to the RFP for the concept definition study phase indicate that the engines for the first generation (Mod 0 and Mod 1) will be substantial improvements over what exists as off-the-shelf engines today. Namely the Rankine power conversion units will be improved to about 20-25% with turbines and about 30-35% with reciprocators. The Brayton power conversion units will be improved to about 30-35% for both the open and closed cycle designs with recuperation.

The in-house studies on each of the cycles indicate that performance is affected less by maintaining a constant temperature level and reducing the mass flow rate for reduced heat input rather than by trying to maintain constant speed. This then puts the burden on the generator to follow speed changes. It appears that for a 50 percent reduction in insolation the efficiency of the steam Rankine conversion unit would be approximately 85% of full power at constant steam temperature. For a high speed turbine Brayton conversion unit the decrease in performance could be as much as 50% unless properly designed to maximize performance for the annual solar input. This and other design features will be the concern of the contracted and in-house efforts which will continue into FY 1979.

Engines to be considered for the second generation include those based on Stirling and high-temperature Brayton cycles.

SECTION VII

SYSTEMS ENGINEERING

With one exception (Omnium-G), point-focusing, two-axis tracking systems for solar thermal power conversion do not exist today. Progress in FY 1978 toward identification and development of the types of systems needed included the following:

1. A list of candidate system configurations and their variations was established for preliminary cost/ performance tradeoff for selection of the most productive areas for further development and analysis.

2. A preliminary analysis was initiated for five of those configurations: No. 1 - Dish Brayton open cycle, No. 2 - Dish steam Rankine cycle, No. 3 - Dish Brayton closed cycle, No. 4 - Multiple dish steam modular arrangements, and No. 5. - a Cassegrainian concentrator with steam Rankine or Brayton cycle power conversion.

Analysis of configurations No. 1, No. 2, and No. 3 was completed and a draft report on that work was issued in September of 1978. It is anticipated that the final report entitled, "A Preliminary Assessment of Small Rankine and Brayton Point-Focusing Solar Modules" will be published early in FY 1979. Detailed analysis of several multiple dish configurations will be initiated in FY 1979. Preliminary work on configuration No. 5 was completed.

Cost/performance targets were developed for the three subsystem areas for 1982 and 1985; these targets will be refined further as information is generated by the Manufacturing Development and other Tasks.

Review of subsystem Requests for Proposals from the system's point of view was provided to assure system functional compatibility. In addition, Systems Engineering participated on the receiver review team, established in August, 1978, to review and to approve design points based on the results from the contractor parametric studies performed earlier for steam Rankine and gas Brayton receivers.

In keeping with a new emphasis towards early hardware evaluation, a purchase order was placed for a commercial point-focusing solar power system module (Omnium-G). Planning for test operations was begun and will continue into early FY 1979. In addition, a feasibility study was initiated to examine and evaluate the interfacing of a different steam engine with the Omnium-G collector.

Systems Engineering leads the design team, which will produce subsystem interfaces, interface control documents, system configurations, subsystem/system functional requirements and design point specifications. A principal role of the design team is to define problems related to the subsystems themselves, and problems related to future hardware test and evaluation operations.

SECTION VIII

TEST AND EVALUATION

The Test and Evaluation task during FY 1978 was to establish a Point-Focusing Distributed Receiver technology (PFDR) Point Focusing Solar Test Site (PFSTS), shown in Figure 10, at JPL's Edwards Test Station (ETS) located on Edwards Air Force Base near Lancaster, California. This existing high desert facility offers ideal weather conditions for solar power systems, sufficient area to accommodate future growth, housing for the PFSTS Operations Center, and site security.

A Data Gathering and Processing (DGAP) system was designed and implemented to provide data acquisition, display, and recording at the test operations center and for high level data reduction and analysis at the Test and Evaluation Center located at JPL in Pasadena. An insolation measurement and recording program was implemented beginning October 1977 at ETS. Measurements include the direct component of radiation, total sky radiation, wind speed, wind direction, and thermal gradient. Humidity temperature and barometric pressure measurements will begin in early FY 1979.

Utilization of the ETS facility resulted in minimal modifications to develop the PFSTS. Minor changes to Building E9 to accommodate the PFSTS Operations Center were implemented, and a concrete pad poured for the Precursor Concentrator. Plans were completed for a concrete pad, trenching, installation of cable ducts, power and signal lines to support the Omnium-G system.

Hardware compatibility tests were successfully conducted to verify the performance and interfacing between the weather data scanner (data logger), digital tape recorder and the playback of recorded data into the DGAP computer for data processing.

Safety aspects of the PFSTS have been reviewed and safety plans implemented to protect personnel and equipment.

All preparations were completed for the Precursor Concentrator tests scheduled to commence in October 1978. Preparations for the Omnium-G tests are on schedule with the first testing scheduled for January, 1978.

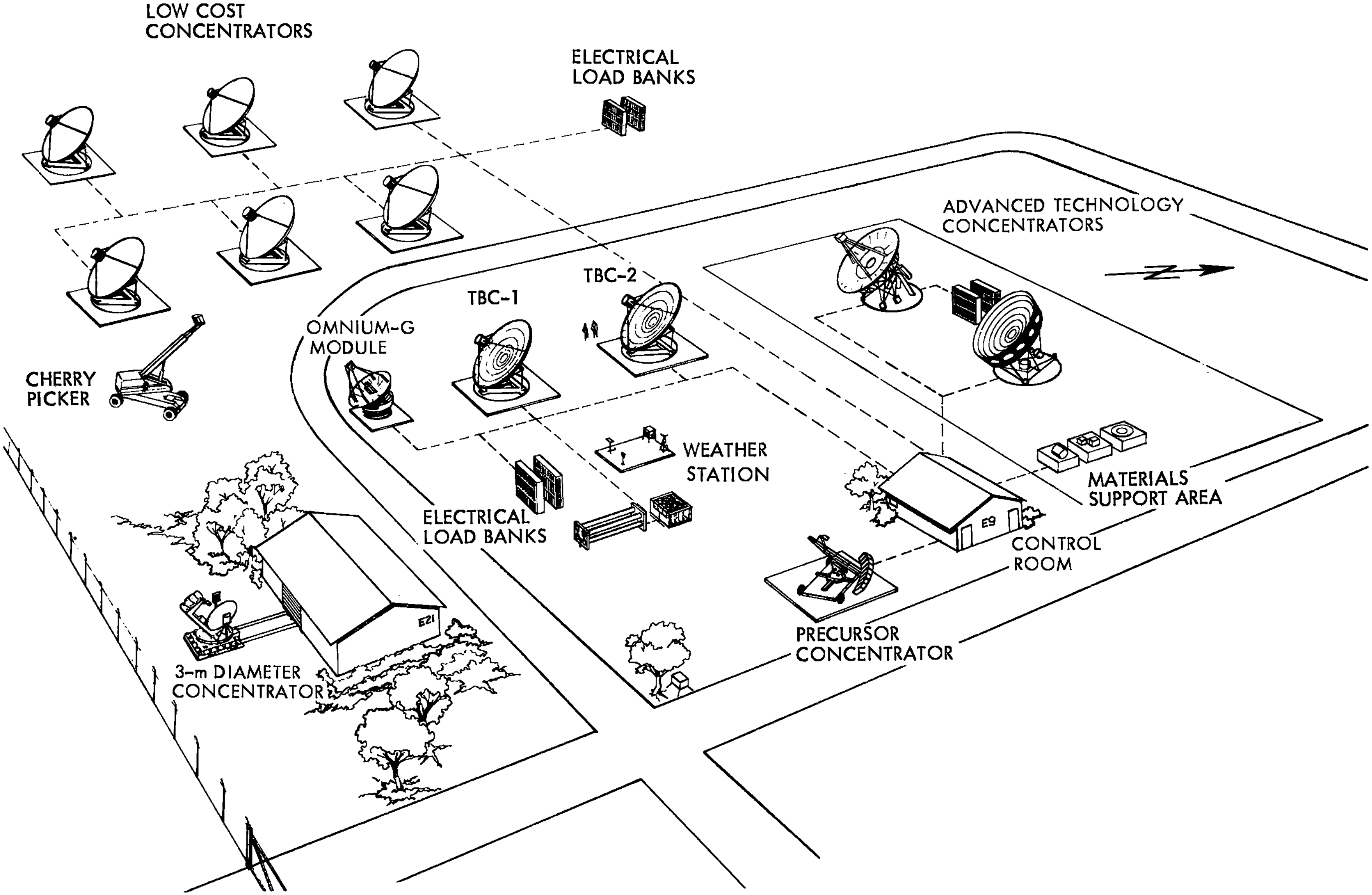

Figure 10 Point-Focusing Solar Test Site

SECTION IX

MANUFACTURING DEVELOPMENT

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

(1) Manufacturing process to produce part.

(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 program be established to assist in ensuring that high performance, low cost PFDR solar energy components are available in the mid 1980's.

The Manufacturing Development Task is making mass production cost studies of Point-Focusing Distributed Receiver components. A state-of-the-art PFDR total system, namely the Omnium-G, has been selected for cost analysis and will serve as the "baseline" to which other components, subsystems and systems can be compared for cost and performance. All systems are being cost analyzed for production quantities ranging from 100 to 1,000,000 units per year.

Preliminary studies have been completed for planning the programs for tooling and automation techniques.