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AN INDUSTRIAL SOLAR BREEDER PROJECT USING CONCENTRATOR
PHOTOVOLTAICS

Final Report for June 1, 1978—February 28, 1979

By
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August 1979

Work Performed Under Contract No. ET-78-C-04-5310

Solarex Corporation
Rockville, Maryland

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U.S. Department of Energy

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Solar Energy

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For the Period June 1, 1978 to February 28, 1979

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Executive Summary

ABSTRACT

The Solarex Corporation has proposed to construct a concentrating photovoltaic system of 200 kW_e peak output as the energy source for a solar cell production line. This project will demonstrate the Solar Breeder concept, whereby a photovoltaic factory quickly becomes energy-independent, supplying its own needs and also making a net energy contribution to society.

Solarex has constructed and operated a prototype linear-focus concentrating photovoltaic system during Phase I of this program. This prototype incorporates techniques and components developed during this program and through experience gained during the design and exercise of previous Solarex prototypes. This system represents the fourth generation of Solarex tracking concentrator prototypes, and includes:

- Solarex concentrator solar cells of high conversion efficiency;
- high-reflectance sagged-glass mirrors using second-surface-deposited Ag as the reflector;
- a cell protection/power assurance scheme based on shunt diodes;
- actively cooled solar receivers;
- a simple, reliable, yet highly accurate two-axis tracking system;
- a Windworks/Gemini inverter;
- electrical energy storage comprising lead-calcium batteries;
- a microprocessor-based data acquisition and logging system.

This system has demonstrated the feasibility of constructing and operating hybrid concentrating energy systems of considerable efficiency, and has enhanced the viability of serving the proposed Phase II load -- a solar cell production line -- and other industrial loads by such systems. This prototype and its predecessors have provided the setting for a broad examination of the multiple and interdependent variables impacting the suitability of such systems for industrial use, including the evaluation and development of components and techniques. Improvements obtained during development have included desensitization of receivers to minor illumination non-uniformities, and a 36% improvement in trough (receiver/reflector) conversion efficiency. Trough efficiency exceeding 10% has been achieved, and it is clear that this figure is still well below that achievable by a fully optimized system.

Operation of the prototype has provided a body of "hands-on" experience and data upon which to base the detailed design of the full-scale optimized system which Solarex has proposed to construct during Phase II. In addition, extensive computer simulation and mathematical modeling have been performed to match the energy output of the proposed system to the requirements of the cell production line.

In summary, Phase I activities have confirmed the viability of such systems as potential energy sources for industrial loads. The Phase II system would provide opportunity for further system optimization in addition to the benefits inherent in building and operating a system of such scale.

INTRODUCTION

The purpose of this program is to demonstrate the use of a concentrating photovoltaic system to provide the energy for operating a silicon solar cell production facility, i.e., to demonstrate a Solar Breeder.

Solarex has proposed to conduct the first real test of the solar breeder concept by building and operating a 200 kW_e (peak) concentrating photovoltaic system based on the prototype and system design developed during Phase I. This system will provide all of the electrical and thermal energy required to operate a solar cell production line. This demonstration would be conducted at the Solarex Rockville facility, with the photovoltaic array located over the company parking lot and on an otherwise unusable flood plain.

Phase I of this program included a comprehensive analysis of the application, prototype fabrication and evaluation, system design and specification, and a detailed plan for Phases II and III. A number of prototype tracking concentrator solar collectors were constructed and operated. Extensive system analysis was performed to design the Phase II system as a stand-alone power supply for a solar cell production line. Finally a detailed system fabrication proposal for Phase II and an operation and evaluation plan for Phase III were completed. These proposals included technical, management and cost plans for the fabrication and exercise of the proposed system.

PROTOTYPE DEVELOPMENT AND TESTING

Solarex designed and constructed a prototype system that incorporated the latest developments in reflector design and materials, cells, receivers, and tracking systems. Two collector quads of 4 troughs each were used in the prototype. The unit incorporates the following features:

- (1) sagged-glass mirrors for high reflectance and durability;
- (2) single-plane mounting of large photovoltaic cells for low-cost receiver assembly;
- (3) 51° rim angle for more normal incidence of solar radiation from the reflector's rim area onto the cells and thereby better absorption and efficiency;
- (4) two-axis tracking to maximize daily solar energy collected, combined with the excellent wind stability of a tilting frame;
- (5) a 20-to-1 concentration ratio;
- (6) large silicon concentrator cells specially designed for this concentrator;
- (7) the use of a bypass diode in parallel with each series unit, which minimizes the effects of end shadowing or partial shadowing of a cell string.

During the course of the program the efficiency of the system was improved. Initial experiments with planar cells in series strings resulted in a trough efficiency of 9.05% at 28°C. The

use of high-efficiency textured cells with parallel-series inter-connection resulted in a trough efficiency of 10.3% at 28°C. This latter cell/receiver prototype configuration has shown that very respectable efficiencies can be achieved from such a concentrator system.

The remainder of the prototype system included:

- 20 kWh lead-calcium battery storage
- A solid-state 8 kW "Gemini" line-commutated inverter with peak power tracking
- a microcomputer-based data acquisition and control system adapted from heating, ventilating, and air conditioning (HVAC) applications.

During Phase I this system was exercised; the results served as a basis for the Phase II design.

SYSTEMS ANALYSIS AND DESIGN CONSIDERATIONS FOR PHASE II SYSTEM

An analysis utilizing computer modeling was conducted to define the characteristics of the cell processing line selected as the Breeder Line for this program. Model parameters included process definition, equipment energy consumption, and space conditioning loads. Process energy consumption was found to average 350 kWh/day; this load would be supplied by a self-commutated inverter, with space conditioning loads served from the house bus, into which excess array power would be fed by a line-commutated inverter.

Operation of the array indicated by the preceding analysis was also computer-simulated, examining the effects of variations in:

- array field slope,
- frame rotation and tilt angle limits,
- spacing of frames,
- spacing of troughs, and
- row orientation.

The results of this analysis and the test results obtained from the prototype array enabled the design and sizing of the array for Phase II. An array with a total aperture of approximately 2000 square meters was chosen. The proposed array would consist of 640 troughs in 160 frames with a nominal peak output of 200 kW_e. This array is expected to produce a yearly average output of 598 kWh/day.

The electrical system designed for Phase II includes:

- 200 kW peak-electrical-power solar array;
- 2000 kWh storage battery (storage sufficient to operate the production line for 5 days);
- a DC-to-DC converter which maintains the array load at the peak power point;
- a self-commutated inverter to provide the AC power to the solar breeder production facility;
- a line-commutated inverter to provide AC power to the auxiliary load during periods of high insolation;

- a power management system that controls the operation of the power conditioning system and records the data from the various system sensors;
- system switchgear that has the capability of isolating parts of the array, each battery string, power conditioning components and loads.

PHASE II PLANS AND COMPONENT SPECIFICATIONS

Phase II plans have been formulated to specify the fabrication, installation and checkout of a 200 kW concentrating photovoltaic system. The considerations in formulation of this plan included:

- cost-effectiveness of the proposed approach;
- close control and monitoring of technical, quality, assurance, schedule and cost parameters;
- provisions for early detection of problems impacting project workflow and timely application of corrective feedback.

As part of the Phase I effort all of the components to be used in the Phase II system were identified. The various components are described below.

Solar Cells

The cell has a 5 cm x 4.3 cm active area with dual interconnecting bars along the sides. These cells have been fabricated using single-crystal, p-type, boron-doped, (100) oriented

silicon wafers. The front surface is textured for increased light trapping. The gridline pattern is applied by photolithographic methods. The bulk of the current-carrying metallization is applied by electroplating silver to the required thickness. Solarex's patented tantalum oxide antireflective coating provides excellent optical matching with overcoating and encapsulants.

Receiver Design

Solarex has chosen the unique receiver design approach of paralleling adjacent cells along the linear receiver. Although this technique enhances receiver output over time, field wiring losses increase and cable economics worsen as the number of cells paralleled in a receiver string is increased. For this application, a cost-effective balance between flux area integration and cabling losses is reached at two parallel cells.

The cells are arranged with their ohmic contact pads parallel to the length of the string, and with 1mm spacing between cells. The interconnects, composed of OFHC copper, are soldered at the top of each pair of adjacent cells and to the bottom of the next cell pair. The center of each interconnect contains stress-relief pleats in order to compensate for thermal expansion. The cell string is then mounted onto the receiver tube by means of a thermally conductive, electrically insulating adhesive developed for operation under high solar concentrations (e.g. up to 100X).

Each solar cell is bonded to a coverslide of microsheet glass on its active surface by means of a specialized silicone rubber adhesive which optically matches the antireflective coating, eliminating selective losses occurring within the slide/silicone rubber/cell interface.

The cell string is protected against reverse electrical breakdown due to shadowing by means of diodes placed across each two-cell unit; this placement frequency also insures that minimum power is lost during the short periods of receiver end shadowing. The diodes are connected to the cell interconnects by means of tinned copper ribbons. Both cell interconnects and diodes are encapsulated with silicone rubber to protect them against impact and moisture.

Concentrating Collector

The basic unit of the photovoltaic array is a quad, which consists essentially of a large frame which carries four mirror-receiver assemblies. The four mirror-receiver assemblies track the sun's motion from east to west. The quad frame tracks the sun's elevation by pivoting around its lower (southern) edge, resulting in true two-axis tracking.

Pipes in the quad frame and rotary fluid couplings allow coolant to be pumped through the receiver for active cell cooling. Coolant temperature, pressure, and flow rate sensors provide signals to the Energy Management System. In case of severe weather, e.g., hail, the EMS can override the analog tracking loop and slew all mirror troughs to a protected position.

The tracking concentrator assembly is a modification of a tracker which has been extensively tested and deployed as a component of solar thermal systems. Required modifications have been quite minor; Phase I operation and testing indicate that the changes have had no adverse impact on the assembly's capabilities, reliability, or capacity to tolerate stress.

The unit is operational in winds up to 35 mph, and may be moved to 'stow' position in winds as high as 40 mph. It will tolerate winds of 100 mph in any position without damage, and will operate with a snow/ice loading of up to 10 lb/ft².

Reflectors

Each photovoltaic array contains four parabolic cylindrical reflective troughs formed by 12 mirrors each. Each trough has an active area for solar radiation of 3.2m by 1.0m. The mirrors are held in place by a metallic frame which tracks the sun, causing the mirrors to focus solar energy onto the receiver. These mirrors are already fully developed, having been employed for years in large numbers in thermal concentration systems. These systems have been field-tested in a wide variety of climates, displaying excellent weatherability and negligible performance degradation over many years of use.

Power Conditioning Equipment

There are three basic elements to the power conditioning system; a Delta Electronics maximum-power-point tracker with DC-to-DC conversion for interfacing the photovoltaic array with the

battery storage; a Delta Electronics self-commutated three-phase inverter to power the production line, and a Windworks line-commutated inverter for providing power to the lighting and HVAC. These manufacturers are presently supplying this equipment for photovoltaic applications.

System Control

System control functions will be handled by the central Energy Management System (EMS). Procurement and installation of this system would be performed by team member Radix II, Inc. which has extensive experience in similar energy management systems in numerous applications. All EMS components are well-developed "off-the-shelf" items, with which Radix II is thoroughly familiar.

Energy Storage

A bank of lead-acid storage cells will be provided to supply operating energy during periods of low insolation. The proposed battery bank will consist of 864 lead-calcium cells, each capable of 3 kWh storage. The cells chosen are manufactured by C&D Batteries Division, their Model #2X4Q160-23. These large cells will be grouped in voltage modules with 12 cells per module. A total of 72 modules will have a storage capacity of 2.6 MWh; the large capacity per module minimizes electrical interconnection and cabling.

Each module will be approximately 35 inches high and occupy 55 inches by 18 inches of floor space; each will weigh approximately 3800 pounds. Due to their size and weight, it will not

be practical to stack the modules. The modules will be arranged in 8 rows of 9 modules each. All cells in a row will be connected in series, producing approximately 230 volts; the 8 rows will be connected in parallel.

CONCLUSIONS

Solarex's prior experience with prototype concentrating collectors enabled construction of a Phase 1 prototype which incorporated both innovative and well-tested components and techniques. Operation of the prototype verified its reliability and efficiency, but simultaneously demonstrated that its best observed trough conversion efficiency (10.3%) may be further optimized with additional development. Exercising the prototype also provided sufficient experience and data to enable cost-effective design of a 200 kW_e Solar Breeder system and to project its performance with considerable confidence.

This full-scale system would satisfy all the process-equipment electrical requirements of the Breeder production line and most of the area's HVAC and lighting load. It is expected that operating the system would demonstrate an energy payback period considerably reduced from the 3.8 years calculated during the effort detailed in ERDA/JPL Report 954606, "Energy Requirement for the Production of Silicon Solar Arrays."

1. Introduction

This final report summarizes the work performed by the Solarex Corporation on Contract ET-78-C-04-5310, Phase I of "An Industrial Solar Breeder Project Using Concentrator Photovoltaics." Phase I included a comprehensive analysis of the application, prototype fabrication and evaluation, system design and specification, and a detailed plan for Phases II and III. A number of prototype tracking concentrator solar collectors were constructed and operated. An iterative development process led to a collector/receiver combination with a electrical conversion efficiency of 10.3%. This prototype incorporated textured silicon concentrator solar cells with over 15% conversion efficiency, a specialized shunt-diode-protected interconnect scheme, and a highly reliable two-axis tracking system.

Extensive system analysis was performed to design the Phase II concentrator system. This system was designed to function as a stand-alone power supply for a solar cell production line. Therefore such factors as energy storage capacity, production facility downtime, and the disposition of excess energy were addressed. The proposed Phase II system could serve as a prototype not only for a stand-alone solar breeder facility, but for a variety of manufacturing loads.

Phase I was broken down into six Tasks as described below. Figure 1-1 shows a milestone chart detailing the program schedule as it was performed.

PRDA-35 SOLAREX INDUSTRIAL PHOTOVOLTAIC BREEDER PROJECT
PHASE I SCHEDULE BY MONTHS

Figure 1-1

TASK 1: SYSTEM ANALYSIS

The purpose of this task was to perform a system analysis of the proposed concept for a concentrating photovoltaic system. This included an analysis of the application, and resulted in projected cost and performance of the system. The analysis included key subsystems: solar concentrator and tracking system; receiver, including solar cells and heat exchanger; power conditioning equipment; energy storage system; and overall system controls.

TASK 2: COMPONENT DEVELOPMENT AND SPECIFICATIONS

The purpose of this task was to evaluate the components to be used in the Phase II system. The primary vehicles for component evaluation were a series of small operating prototypes. The final prototype included all key elements of the full-scale system, with two tracking concentrating collector units ("quads") comprising four troughs each. During the course of prototype development, various improvements in optical design, receiver design, and solar cells were incorporated. The initial trough exhibited an efficiency of only 7.6%; optimized troughs have now exhibited 10.3% conversion efficiencies.

A small (8 kW) Gemini line-commutated inverter was used to load the system. Power output has been monitored under various operating conditions in order to optimize final system parameters.

The results obtained during this prototype phase have been employed to design the Phase II system and to estimate its performance.

TASK 3: SYSTEM DESIGN

The purpose of this task was to design the photovoltaic system and installation, based upon the results of Tasks 1 and 2. This task culminated in working drawings and component specifications sufficiently complete that procurement, fabrication and installation of the system could proceed immediately if a decision is made to enter Phase II. Key elements in this design included:

- a. design of the structure used to support the tracking collectors.
- b. a site layout which details the placement and nature of all site modifications.
- c. precise specification of the tracking systems and solar receivers.
- d. specification of the electrical and thermal storage facilities.
- e. specification of the inverters and other power-conditioning equipment.
- f. specification of the Power Management System components, including all sensors, switches and valves.
- g. specification of all interconnecting hardware, including connectors, wire, pipe, and other miscellaneous items.

The results of this task were used as a basis for completion of Task 4--System Fabrication Proposal.

TASK 4: SYSTEM FABRICATION PROPOSAL

The purpose of this task was to prepare a detailed technical and management proposal and a detailed cost proposal for Phase II. This included a description of the system defined in Task 3 and a schedule for system fabrication. The technical proposal was submitted to DOE on January 31, 1979, and the cost proposal was submitted on February 28, 1979.

TASK 5: OPERATION AND EVALUATION PLAN

The purpose of this task was to define the plan for system operation and data collection and analysis during Phase III. This included a description of the data to be collected and the analysis to be performed. Analysis of the performance of the photovoltaic system in Phase III will include such characteristics as overall system efficiency, change in efficiency as a function of time, and reliability. Indirect aspects to be evaluated will include energy payback time of the cells and impact on manufacturing productivity. The technical and management proposal for Phase III was submitted to DOE along with the Phase II proposal on January 31, 1979; the Phase III cost proposal was submitted on February 28, 1979.

TASK 6: REPORTING

The purpose of this task was to communicate significant progress and results to DOE. This task was performed per the instructions in the contract.

The work performed by Solarex during the course of the contract is detailed in this report. Section 2 describes the development of the prototype system, describes this system in detail, and

discusses the results obtained from this system. Section 3 includes a detailed discussion of all the analyses performed during this program, encompassing the systems analysis performed to match the load to the system, the design considerations studied for the Phase I prototype system, the component design considerations investigated for incorporation in the Phase II plan, and descriptions of the components and system chosen for Phase II. Section 4 is a detailed technical and management plan prepared for the construction of the system during Phase II. Section 5 contains specification for all of the components incorporated in the Phase II system. Finally, Section 6 describes the plan developed for the operation and evaluation of the Phase II system during Phase III.

2. Prototype Development and Testing

2.1 Introduction

Solarex developed a prototype photovoltaic concentrating system as part of the Phase I development contract. Construction of the prototype enabled Solarex to identify and solve many practical design, assembly, test and optimization problems at the prototype stage rather than at a later, more costly stage. Solarex designed and constructed a prototype system that incorporated the latest developments in reflector design and materials, cells, receiver and tracking systems.

The Solarex PRDA prototype system was designed to utilize the same basic design and hardware as would be used later in the Phase II full-size 200 kW system. Two collector "quads" of 4 troughs each were used in the prototype. Each quad produces nominally a kilowatt of electrical peak power, tracking the sun in two axes. A 20 kWh lead-calcium battery storage bank was included in the prototype system, as was a solid-state inverter for power conditioning. The inverter selected jointly with Windworks was an 8 kW "Gemini" line-commutated inverter which uses DC power from the photovoltaic system to provide AC power to loads connected into the Solarex building wiring. This inverter can utilize a built-in peak power tracker to operate directly from the collectors and can also operate from parallel connection with the battery bank and collectors.

The prototype collector design was reached as a result of an evolutionary development program in which the solar concentrator,

the receiver, the photovoltaic cells and their receiver mounting received the principal design and development effort.

2.2 Prototype Development History

2.2.1 General

The development of the PRDA prototype discussed herein resulted from an in-house Solarex program started in 1977 when Solarex constructed its first 2-axis-tracking pedestal-mounted photovoltaic collector. The development and refinement of the 4th-generation prototype for the Phase I PRDA, which is improved in nearly every parameter, continues as this final report is being written. System efficiency was increased during both the Solarex prototype development efforts and in the PRDA program. Many practical design, assembly and operational problems have been identified and solved. This section describes three collector systems installed by Solarex before the Phase I PRDA efforts, as well as the Phase I prototype.

2.2.2 First Generation Solarex Prototype

The pedestal-mounted first generation Solarex prototype was constructed in 1977. This concentrator system was adopted from a solar-thermal system which utilized a 180° reflector trough focusing at the center of its top plane.

The overall efficiency of this photovoltaic concentrator was considered to be too low, and the cost of mounting small photovoltaic cells on both sides of a vee receiver (to reduce the angle of incidence) too high to achieve system goals. Further, the reflectance of the anodized aluminum reflector surfaces deteriorated

unacceptably after a few months exposure to the dust, dirt and atmosphere in the Rockville area. The characteristics of this first-generation photovoltaic concentrator are shown in Table 2-1.

2.2.3 Second Generation Solarex Prototype

The second generation Solarex-funded prototype used a single receiver plane for mounting larger cells (thereby reducing assembly cost) and a smaller rim angle*, 60° instead of 90° (Fig. 2-1). This second-generation prototype increased the incidence angle of solar radiation reflected from near the rim of the mirror onto a flat receiver. Further, the reflector material was changed to a 3M product--FEK 244--with higher and more durable reflectance (see Fig. 2-2) than anodized aluminum. However, it was concluded that tracking perturbation by wind was a serious drawback of a pedestal-mounted collector, and that a larger-area collector unit was necessary to decrease overall system costs.

2.2.4 Third Generation Solarex Prototype

The third generation Solarex-funded concentrator prototype (hereafter called a quad) is shown along with the first two types in Figure 2-3. The quad consists of 4 east-west-tracking trough-type collectors mounted in a tilted frame facing South. The tilt angle of this third-generation single-axis-tracking prototype was capable of manual adjustment only. The prototype incorporated sagged-glass second-surface-silvered mirrors that had been precision-made to focus on a 2-plane receiver, with a rim angle of 90°.

*Note: rim angle is defined as half the angle subtended by the arc of the parabolic trough.

Table 2-1. Description of First 4 Generations of Solarex Concentrating Photovoltaic Reflector-Receivers

Generation	Receiver Reflecting Material	Reflector Rim Angle	Receiver Cell Mounting Planes	Solar Tracking Axes	Reflector Troughs	Mounting Configuration
1	Anodized Aluminum	90°	2	2	2	Pedestal
2	FEK-244 & Aluminum	60°	1	2	2	Pedestal
3	Sagged Glass & Silver	90°	2	1 E-W only	4	Quad
4 (PRDA)	Sagged Glass & Silver	51°	1	2	4	Quad

a. V-trough (dual-plane) receiver mounted in early collector with 90° rim angle.

b. Single-plane receiver employs large cells, is more economically assembled than dual-plane.

c. Optimized single-plane receiver in operation in final Phase I prototype.

Fig. 2-1. Single- and Dual-plane Receiver Configurations.

a. FEK-244 material (collector on right) maintained reflectivity better than electropolished aluminum (left collector) as demonstrated by clarity of reflected image.

b. Receiver image viewed in aluminum reflector shows loss of reflectivity.

c. FEK maintained reflectance, is dependent on substrate for optical precision.

Fig. 2-2. Reflectance Comparison, Second-generation Prototype

Fig. 2-3. Solarex Concentrating Collector Prototypes

a. Solarex's Rockville concentrating collector test site with frame- and pedestal-mounted trackers. These early prototypes provided a basis for evaluating reflective surfaces, alternative rim angles, receiver configurations, tracking schemes, and durability under environmental stress.

b. Third-generation prototype employed sagged-glass mirrors and single-axis tracking.

c. Second generation displays two rim angles, receiver configurations, and surfaces. FEK (right) sheds snow better than Al (left).

This collector had been originally developed for a solar thermal application but was employed to evaluate the efficacy of silver as the reflector surface and the durability of sagged glass. The silver reflector performance was excellent, the sturdy mounting arrangement greatly improved focus stability, and the sagged glass was also kept quite clean by rainfall. However, it was decided that two-axis tracking has a definite advantage for photovoltaic collectors, by eliminating daily end shadowing.

2.2.5 Fourth-Generation (PRDA Contract) System

The characteristics of the fourth-generation concentrating photovoltaic system as constructed for Phase I of the PRDA is shown in Fig. 2-4. This unit incorporates all the desired features exercised in the three Solarex-funded earlier prototypes:

- (1) sagged-glass mirrors for high reflectance and durability;
- (2) single-plane mounting of large photovoltaic cells for low-cost receiver assembly;
- (3) 51° rim angle for more normal incidence of solar radiation from the reflector's rim area onto the cells and thereby better absorption and efficiency; and
- (4) two-axis tracking to maximize daily solar energy collected , combined with the excellent wind stability of a tilting frame.

As can be seen in Figure 2-4, the PRDA prototype employs a simple galvanized pipe frame as a support structure, which is in turn mounted on galvanized pipes set in concrete footings. Each quad of collectors has its own tracking motors, electronics and

sun sensor cells. The east-west tracking drive employs a reduction motor for ruggedness and a rack-and-pinion coupling of the four troughs. Coolant coupling is through rotary seals at both ends of the troughs which also form the hubs of the east-west drive gears. Tilt of the troughs in the quad employs separate sensing and a worm-reduction motor with a sprocket drive which climbs chains affixed to the vertical (pivoted) pipe frame. The frame containing the four collectors is extruded aluminum with channels for the coolant piping and drive mounting.

2.3 Description of the PRDA Prototype System

2.3.1 General Overall Description

The PRDA prototype solar photovoltaic concentrating system consists of two solar concentrating assemblies (quads) and their associated two-axis solar tracking system, batteries, a Windworks/Gemini line-commutating inverter which includes a maximum power point tracker, a cooling system plus a complete data recording and acquisition system (Fig. 2-5). The prototype installation shown in Fig. 2-4 is located in front of the Solarex parking lot. The system schematic drawing is shown in Figure 2-6. Descriptions of the major sub-systems follow with reference to both the photographs of the prototype and the schematic drawing of the electrical, instrumentation and data acquisition systems.

2.3.2 Prototype Site Plan

The Solarex PRDA-35 prototype is installed at the company headquarters, 1335 Piccard Drive, Rockville, Maryland. The two quads, the cooling system and the shed which contains the electrical junction

Fig. 2-4. Phase I Prototype System

2-6a

a. View from southeast corner of Phase I prototype system shows collectors, control, data, and power lines, and shed. Solarex building housing Breeder Line shown background right.

b. Prototype array comprises two quads of four troughs each. Test equipment trailer at left.

c. Troughs are gang-driven by a DC motor via a sliding gear rack.

a. Analog input lines, PROM-based microcomputer, output relays, and control panel in shed adjacent to array.

b. Equipment shed houses junction boxes, shunts, power wiring terminals, microcomputer, and other data acquisition equipment.

c. Instrumentation in prototype control center includes voltmeters, ammeters, accumulative ampere-hour and watt-hour meters

d. Data logger/microprocessor and wall-mounted Gemini inverter.

Fig. 2-5. Data Acquisition and Control System

boxes and the instrumentation inputs are located in front of the company parking lot as shown in Figure No. 2-4. Each quad consists of four collectors with an area of 3 square meters each, providing an active area of 12m^2 for each of the two quads. Both quads are oriented 20° East of due south.

Computer analyses indicate that the orientation will have little or no effect on the seasonal or annual energy output of the concentrating solar collectors. The shed in the corner is about 6' on each side. The pump, the expansion tank and the heat exchanger for the cooling system are located about 5' to the south of the quad farthest from the existing building. Electrical cables to the shed and cooling system pipes are underground, while overhead lines cross the parking lot entrance to the main building.

The data logging equipment, the power conditioner and the batteries are located in the Solarex building.

2.3.3 Quad: Solar Concentrating Photovoltaic Converter

The concentrating collector system designed by Solarex for the prototype is shown in Figure No. 2-4. Each of the eight collectors track the sun in azimuth from East to West. The entire frame which supports the reflectors tilts up and down to track the sun's elevation. DC motors are utilized for tracking power.

The prototype was the forerunner of the system proposed for Phase II and incorporated many, but not all, of the same features. The prototype includes the following:

1. sagged-glass parabolic reflector with silver back surface which has high reflectance, is easily cleaned and does not degrade in reflectance appreciably with time,
2. A 20-to-1 concentration ratio,
3. large silicon concentrator solar cells specifically designed for this concentrator,
4. the use of bypass diodes in parallel with each series cell which minimizes the effects of end-shadowing or other shadowing of the cell strings,
5. A high-stability concentrator support frame and system design which tracks well in winds up to 35 MPH and can survive in winds up to 100 MPH.

2.3.4 Quad Frame and Base Assembly

The four parabolic troughs are mounted in a rectangular frame structure fabricated from aluminum extrusions. The trough drive gear rack drive mechanism, sun sensor, tracking system electronic control box, and thermostat coolant exit temperature control are all mounted on the frame. The coolant piping is contained in the frame extrusions at the top and bottom of the collector array. The array frame assembly is supported at each corner, and in the middle, by galvanized pipes. These pipes are mounted onto a pivoting connector attached to structural base pipes running parallel to the ground on three sides and the middle. The structural base piping is fastened to short pipes set in concrete.

2.3.5 Electric Power Collection Network

As shown in Fig. 2-6, the Breeder prototype system schematic, the four receivers in quad 1 (farthest from the Solarex building) are connected in a parallel-series configuration. The receivers in quad 1 are in parallel-wired pairs, with the pairs wired in series. The receivers themselves have their cells connected in series, 60 per receiver.

The series-parallel connection of receivers was used because quad 1 is connected in series with quad 2. Each of the receivers of quad 2 are connected in series with one another. However, adjacent pairs of cells on the receivers of quad 2 are connected in parallel, with a bypass diode in parallel with each pair. Because the individual cells on the receivers of quad 1 are connected in series with one another, it was necessary to parallel those receivers to match the current of quad 2.

The two quads in the prototype are connected through several disconnect switches, a current shunt, diode, and overhead power lines to the Gemini inverter and the storage batteries as shown in Fig. 2-6. The Gemini inverter is electrically isolated from the electric utility network ground by means of an isolating transformer as shown in the figure. AC and DC watt-hour meters are connected as shown to measure the flow of energy to and from the batteries and to the load network. Twenty Delco Model 1200 maintenance-free batteries are used in the prototype as the electrical energy storage system, with a capacity of approximately 20 kWh.

2.3.6 Sensors and Data Logging

The data acquisition and logging system (Fig. 2-5) has platinum

resistor temperature sensors at the output of each receiver coolant line, and a current shunt and voltage pickoff line for each receiver. These all feed appropriate signal conditioning amplifiers or dividers, which in turn input to analog-to-digital converters. The remainder of the data process chain is handled digitally by the microprocessor in the building and the satellite multiplexing unit in the shed. The data logging system for the prototype was built by Radix II, Inc.

2.4 Cells

The concentrator cells fabricated in Phase I for use in seven of the eight receivers were conventional, non-textured cells of 25.5 cm² active area. The cell processing sequence and a sample cell are shown in Fig. 2-7. After cover-sliding, the average cell efficiency at 15 X AM1 and 28°C was measured to be 13.8%. The I-V characteristics are shown in Fig. 2-8.

One receiver of the system contained specially fabricated textured cells. The processing sequence for the fabrication of these cells was essentially that of the non-textured cells with the additional step being texturing of the silicon before formation of the p-n junction. Untextured Corning #0211 microsheet cover slides with magnesium fluoride coating to enhance absorption are attached to the cells. After cover-sliding, the average cell efficiency at 15 X AM1 and 28°C was measured to be 15.8%. The I-V characteristics are seen in Fig. 2-9. The textured cells, on average, are almost 15% more efficient than the non-textured cells. The higher efficiency is due to a 15% increase in current brought about by lower reflectance and altered light paths that result in

Fig. 2-7
CONCENTRATOR CELL PROCESSING

Fig. 2-8 Breeder PRDA (non-textured) @ 15XAM1, 28°C

Fig. 2-9 Breeder PRDA (textured) @ 15X AML, 28°C
2-13

FORM 11142

the generation of minority carriers closer to the n+-p front junction.

The temperature coefficient of the open-circuit voltage at AM1 has been measured to be $-2.13 \text{ mV}/^{\circ}\text{C}$. At $15 \times \text{AM1}$ the coefficient is $-1.9 \text{ mV}/^{\circ}\text{C}$. Since the change (loss) in efficiency is primarily due to the decrease of V_{OC} with temperature, it is calculated that the percentage change in the efficiency with temperature is $\sim -0.29\%/^{\circ}\text{C}$. Consequently, for a cell operating temperature of 55°C , the efficiencies of the non-textured and textured cells would be 12.6% and 14.6%, respectively.

2.5 Adhesive Evaluation

Because of the different thermal expansion coefficients of silicon and aluminum, it is necessary to use thermally conducting adhesives that are mechanically pliable to cement cells to aluminum receivers. Also, the adhesives must be electrically isolating. A number of adhesives have been evaluated for their thermal properties by the following technique:

Samples consisting of a $2 \text{ cm} \times 2 \text{ cm} \times 0.025 \text{ cm}$ concentrator cell and a $2 \text{ cm} \times 2 \text{ cm} \times 3 \text{ cm}$ aluminum block joined by an adhesive layer of a known thickness were prepared. A thermocouple was inserted into a small hole in the aluminum block near the cell-adhesive-aluminum block interface in order to measure the block temperature. The temperature of the solar cell was measured using the open-circuit voltage of the cell. The cell mounted on the block was exposed to $20 \times \text{AM1}$ illumination, and the temperature difference between the cell and the block was calculated.

The Solarex-proprietary adhesive used in the receivers showed a temperature drop per unit thickness of approximately $-0.6^{\circ}\text{C}/\text{mil}$. Since a thickness of ~ 8 mils provides the necessary electrical isolation, the cell temperature will be only $\sim 5^{\circ}\text{C}$ warmer than the aluminum at the interface. This has been demonstrated on a number of samples.

2.6 Receiver Development

During the prototype development Solarex constructed eight receivers and evaluated their performance in the eight mirror troughs of the two collector quads. The receivers fabricated for the prototype exercise employed three types of interconnection and cell construction. The first, which was employed for all four troughs in the first quad, had all sixty cells on each receiver connected in series (individually diode-protected) and employed smooth-surface Solarex concentrator solar cells as described above in this report. After adjustment of the collector to focus on the receiver, simultaneous measurement of the incident direct-beam sunlight was made with a calibrated Eppley pyrhelimeter and the receiver I-V curve was plotted with a four-terminal measurement. Figure 2-10 is a representative I-V curve obtained in December 1978 with cleaned mirrors at 25°C coolant temperature with 902 W/m^2 incident on the collector. The receiver output is 285W at 32.5V, representing a conversion efficiency for the trough of 9.05%. At a 55°C operating temperature the conversion efficiency would be 8.3%, correcting for the measured power reduction with temperature per cell of 0.29%/°C.

Connection of all four troughs of the first quad in series to produce a 120V unit resulted in the performance shown in the I-V curve of Figure 2-11 for January 1979 with 905 W/m^2 incident and 22°C coolant temperature at the receiver outlets. This represents an overall efficiency of 8.41% for the quad, which would be 7.6% at 55°C operating temperature. Comparison of the I-V curve for the 4-receiver series connection in Figure 2-11 with that of the single

Fig. 2-10 Output Curve of Receiver 2

Fig. 2-11 Output Curve of Quad 1.

receiver in Figure 2-10 shows that there is some localized current mismatch which lowers the fill factor of the 240-cell series string.

The second type of receiver/cell/interconnection permutation employed smooth-surface cells with adjacent cells paralleled to provide 10 cm of receiver length per collection unit. This 2-parallel/30-series configuration was employed to increase the integrating area per series current unit, to alleviate current non-uniformities and shunt diode bypassing due to minor focus variations along the receivers. Figure 2-12 shows the sort of "staircasing" of the receiver I-V curve which can happen between tracking corrections for full series-connection cell strings on receivers as the light beam nears the edges of the cells. Small focus irregularities then result in variations of I_{sc} along the cell string, which turns on the shunt diodes of the less-illuminated cells in the string to pass the current level of the better-illuminated series cells. Paralleling every two cells halves the current difference per series current-generating unit and allows halving the width of the "stairstep" in the receiver's I-V curve and staying closer to the full-illumination peak power value. Measurements showed the improvement, but the inclement weather in Rockville during January and February 1979 precluded the production of complete comparative I-V curves under varied tracking situations for this report.

The third type of receiver employed in the prototype utilized high-efficiency textured concentrator cells interconnected in the 2-parallel/30-series configuration. One such receiver was built and installed in one trough of the second quad collector in February 1979. Figure 2-13 is a representative I-V curve for the textured-cell

receiver measured with 963 W/m^2 incident and a coolant exit temperature of 28°C , which shows 330W peak power output, or 10.3% overall conversion efficiency. At 55°C operating temperature the overall conversion efficiency would be 9.5%.

This latter cell/receiver prototype configuration has shown that very respectable efficiencies can be achieved from such a concentrator system with incorporation of the improvements realized during Phase I prototype development.

2.7 Prototype Thermal System

The thermal system is illustrated in the Prototype Thermal System Block Diagram, Fig. 2-14. As shown in this figure, the motor-driven pump supplies coolant under pressure to the manifolds in the extruded frames at the bottom of the four receivers in each quad. The coolant flows upward through each receiver into the upper or discharge manifold inside the upper frame and thence back to the heat exchanger and the expansion tank. Flowmeters measure the coolant flow rate through each quad and individual temperature sensors measure the temperature of the coolant exiting each receiver. The coolant heat exchanger has a thermostatically controlled fan to augment air flow over the heat exchanger coils as necessary in the summer.

Prototype thermal system test results are limited because collector and photovoltaic receiver efficiencies and related aspects of the prototype had higher priority. However, the coolant exit temperature variation with air temperature and wind velocity was observed.

Receiver 5

Cells: 60 in series;
individually diode-
protected.

Insolation: 910 W/m^2

T_{coolant} : 24°C

Fig. 2-12 "Staircase" effect displayed by series-wired receiver between tracking corrections

Fig. 2-13 Output Curve of Receiver 6

Figure 2-14. Prototype Thermal System Block Diagram

This variation will be greatly reduced later with additional insulation. During the winter, coolant exit temperatures varied from 18°C to 35°C. However, during the early spring months, when the outside air temperature reached 16°C, the exit temperature of the coolant reached 60°C without the heat exchanger.

2.8 Gemini Inverter

The Gemini synchronous line-commutated inverter converts variable-voltage DC power into AC at standard line voltages and frequencies synchronized with the local electric utility. The power available from the DC sources (the batteries and the concentrating photovoltaic array) is consumed by AC loads in the Solarex plant.

The principal advantage of using a line-commutated inverter in the PRDA prototype is that it does not require a specifically sized load, as would a stand-alone self-commutated inverter. Although the full-size system proposed for Phase II would be stand-alone, it was not feasible to separate a small load for the prototype in Phase I. Therefore, the Gemini line-commutated unit was selected to pump available DC power into the Solarex building distribution system. An 8kW size was picked as a convenient level for familiarization with reasonably large power levels during the prototype phase, yet small enough to be efficient when driven directly by the two quads in the peak-power-tracking mode.

The efficiency of an 8 kW Gemini inverter versus line current is shown in Fig. 2-15. Its efficiency is very respectable at the nominal 20 amperes from the two quads at peak operation, and still near 90% at 5 amperes. The inverter has a fixed-voltage operating

mode as well as a peak-power-tracking mode selectable. Inclusion of an inductor to limit current surges allowed operation from the battery bank as well as directly from the array, which provided experience in employing the inverter as a high-power shunt regulator for the battery bank.

Fig. 2-15. Gemini Inverter Efficiency

A commutator that uses line voltage must disconnect when the 60-cycle power is interrupted, lest the thyristors effectively cause a short at the DC source and the utility's power lines have DC voltages applied to them. Both the AC and DC sides of the Gemini inverter are fused to protect the system from damaging overloads.

Since the utility service is tied to ground, it was also important that the inverter be isolated by a transformer to avoid a common-

ground fault condition for the DC and AC parts of the system.

2.9 Data Acquisition and Control System

The prototype Data Acquisition and Control system is based on the Radix II R515 CPU which has been adapted from heating, ventilating and air conditioning (HVAC) applications. This is a two-part distributive system having a satellite (i.e., Field Interface Device, or FID) serially interfaced to a main console unit as shown in Figures 2-5d. The Field Interface Device is the primary functional unit of the total system. The FID is supported by a PROM-based program that requires no user/programmer intervention to bring the system into service. Upon startup--either by powering up the system or by initializing via a control/interrupt switch on the front panel (Fig. 2-5a)--the FID immediately begins operation.

Figure 2-16 summarizes the PROM-based program flowchart as it is presently realized. In general, the FID polls 48 multiplexed channels performing A/D conversions in real time and transferring these data into one of two data arrays used to perform a continuous time-weighted average of the data. The main console microcomputer periodically interrupts the FID for output or inputs to update its control parameter settings. All updates are input via the console keyboard. The console microcomputer supports a PROM-based interpreter language termed RPL/1, which is a combination of integer Basic, Pascal, and Assembler. Programs that are encoded into the system are restricted to 8K RAM for the program and 3K RAM for data arrays. Appendix 1 shows a sample listing of the reporting program presently in use. This program provides for several different modes

of reporting and capability to read/write data and programs from a digital cassette tape.

Figure 2-16. FROM-based Program, Summary Flowchart

3. Systems Analysis and Design Considerations for Phase II

3.1 Introduction

This section describes the systems analysis performed by Solarex during Phase I of the Photovoltaic Concentrator Applications Experiment and the results of this analysis. These results guided the design and construction of the Phase I prototype and the final design of the Phase II system.

The objectives of the Phase I program were to conduct analyses enabling design of an efficient concentrating photovoltaic system which would power a solar cell production line, and to design, build and optimize the performance of a 2.5 kW system prototype. The overall program objectives are to demonstrate the use of a concentrating photovoltaic system as the source of power for a photovoltaic cell production facility, and to demonstrate the solar breeder concept.

3.2 The Industrial Solar Breeder Concept

The industrial solar breeder concept refers to the use of energy produced by photovoltaic cells to provide energy for the manufacture of more photovoltaic cells. This concept has been thoroughly studied at Solarex under a JPL contract and is reported in Ref. 1. This earlier study modeled the operation of a solar

Reference 1: Energy Requirement for the Production of Silicon Solar Arrays, Final Report, Dec. 1977
ERDA/JPL 954606, Solarex Report SX/111/4

breeder, a facility manufacturing photovoltaics using electricity generated by an array of photovoltaics. The model considers variations in insolation as simulated by the SOLMET tapes. It includes electrical energy storage in batteries as well as energy storage in the form of in-process solar cell inventory. Figure 3-1 shows the basic concept. Figure 3-2 shows further details of the concept and includes the direct energy coming into the factory via the photovoltaic array, the energy in the incoming materials, and the energy in the manufacturing equipment which effects production capacity and has a given lifetime. Figure 3-3 shows how the various forms of energy flowing into the factory are distributed among each of the manufacturing processes.

The analyses conducted in this initial breeder feasibility study (Ref. 1) concluded that, based on 1977 technology for nonconcentrating tilted flat-plate photovoltaic panels, the total energy required for the manufacture of cells would be paid back in 6.4 years of operation. A similar analysis based upon projections of a 20X concentrator system predicted an energy payback time of 3.8 years. This means that after 3.8 years of operation the concentrator system has paid back the energy required for its fabrication. Any future energy collected from the array can then be employed to produce additional solar arrays without taxing existing energy sources. This is the concept of the solar breeder, using solar energy to produce arrays that can produce more solar energy.

Fig. 3-1 BREEDER MODEL CONSISTING OF UP TO NINE PROCESS STEPS.

Fig.3-2 CHARACTERIZING PARAMETERS OF A PROCESS STEP.

FIG. 3-3 PANEL PRODUCTION SEQUENCE AND ENERGIES

3.3 Description of the Load

Solarex chose to design a concentrator photovoltaic array to provide all of the electrical and thermal power required to run a solar cell production line. A small production line located on the second floor of the Solarex building was chosen as the load. This load could be easily isolated from the remainder of the building load and therefore be operated in a stand-alone mode, with all of its electrical and thermal power supplied by the photovoltaic concentrator system.

3.4 Proposed Site

The site proposed for installation of the system is the Solarex facility in Rockville, Maryland, approximately 15 minutes north of Washington, D.C., and adjacent to Interstate 270. The array would be located over the facility's parking area and an undevelopable flood plain on the 5.4 acre site, making optimum use of available land. A preliminary layout of the site is shown in Figure 3-4. This property is owned by Solarex.

3.5 System Elements

The following system elements were proposed in the initial Phase I proposal:

1. A 20:1 concentrating two-axis tracking collector with receiver.
2. An electrical energy storage system, size to be determined.
3. A power conditioning system, rating and type to be determined.

Figure 3-4

Site Plan
3-7

4. A thermal energy transfer and storage system, type and size to be determined.

3.6 System Design

Given the specified site, load, and system elements, a detailed system design was performed to determine the specifics of a system to meet the requirements of this program. This analysis was based upon the load requirements, the land availability, and the expected array performance as determined from the Phase I prototype array. The results were used to determine the size and configuration of the proposed Phase II system.

3.6.1 Photovoltaic Cell Production Process: Energy Requirements

The system's stand-alone design necessitated thorough modeling and analysis of the production line's energy requirements in order to determine the size and output required of the photovoltaic array. Modeling and analysis was also used to develop a load management strategy that could be used during Phase III operation.

The facility to be powered is a Solarex solar cell manufacturing line used for the production of high-efficiency concentrator and non-concentrator cells. The production facility occupies 183 m² and is illustrated in Figure 3-5. The process flow used to fabricate the solar cells is shown in Figure 3-6. After specifying the equipment required for operation of the line, a survey of the power requirements of each piece was performed. Time averages of the power usage were taken from chart recordings of power meters connected to the equipment. This information was

Fig. 3-5 Floor Plan of Solar Breeder Manufacturing Line

Fig. 3-6 Process Flow

used to determine start-up energy and operating power requirements for each piece of equipment. This information, as well as an estimate of the maximum wafer through-put for each step, is shown in Table 3-1. The initial steps are capable of twice the throughput of the final steps. This allows a load management strategy of stockpiling wafers after the initial steps and varying the hours of operation of the initial steps.

The solar cell production line requires power for heating, cooling, and lighting in addition to its equipment power. The values for these loads were derived from the nameplate ratings of the cooling and lighting equipment. These loads were much larger than the expected output of an array sized for the land available.

The production facility at Solarex typically is in use for 2 8-hour shifts per day for a 5-day week. Using this operational requirement the process equipment has a daily requirement of 350 kWh. This value has been averaged over 7 days and is independent of the time of the year.

A preliminary estimate of the array size indicated that a 200 kW-peak-output array could be constructed on the available land. As will be described later, an array of this size would, with storage, be capable of acting as a stand-alone supply for the processing equipment load--350 kWh per day. There would, however, be excess power generated during periods of high insolation. It was decided that the excess power should be used to meet part of the HVAC and lighting demands. Therefore the proposed system would utilize a

Table 3-1 Solar Breeder Electrical Loads

PROCESS STEP	Equipment	Start-up Energy (kWh)	Operating Power (kW)	Maximum Through-put (Wafers/hour)
ETCH	Heated Tank	4.	3.	200
DIFFUSE	Furnace Tube	6.	8.	200
AL EVAP.	Two Filament Vacuum Evaporators	4. + 4.	2.4 + 2.4	200
ALLOY	Furnace Tube	6.	8.	200
BACK CONTACT	One Filament Vacuum Evaporators	4.	2.4	100
PHOTOLITH	Oven & Spinner	0.3	2.	100
FRONT CONTACT	One Filament Vacuum Evaporator	4.	2.4	100
SILVER PLATE	Plating Tank	0.	0.2	100
AR-COAT	Two e-Beam Vacuum Evaporators	4. + 4.	1.6 + 1.6	100
Total Inverter Load:			34.kW	

stand-alone self-commutated inverter to supply the process equipment and a line-commutated inverter to supply the HVAC and lighting loads.

3.6.2 Array Performance

A computer model was developed to simulate the operation of the array field and optimize array field geometry, battery storage, and inverter sizes. The input data for this simulation is the direct-normal radiation for the period 1970-1974 obtained from the Washington, D.C. SOLMET Tape.

To estimate the expected output of the array that is designed for Phase II, a series of computer calculations have been performed. The computer program calculate the sun's position each hour and then derives the elevation and east-west orientation angles which yield the highest output from an isolated trough. These angles are then used to calculate shadowing caused by adjacent troughs and rows of frames. The array output is then calculated for various time periods. Variations in:

- array field slope
- frame rotation or tilt angle limit
- spacing of frames
- spacing of troughs
- row orientation

were all examined during the system design analysis.

3.6.2.1 Array Slope Angle

Increasing the slope of the array decreases the shadowing due to frame rows and therefore increase yearly array output. This effect is most pronounced in the winter when the energy collection is most critical. The limit on the tilt angle is not a function of array performance but rather a function of cost and architectural desirability. Our limit was chosen on the basis of the height of the present Solarex building. No part of the array would be higher than this limit. Under this condition the highest allowable slope is 6° ; therefore a 6° slope angle was chosen for the array.

3.6.2.2 Quad Frame Tilt Angle Limits

Another factor examined was the range of tilt angle required for optimum power production. Table 3-2 shows the annual energy collected by quads utilizing 180° ($+90^\circ$ to -90°) and 65° ($+15^\circ$ to 80°) tilt angle ranges. This table also shows the effect of various frame and trough fill factors or spacings as described later.

The numbers in the matrices of Tables 3-2a and 3-2b represent the proportion of energy collected over a year relative to the energy that would be collected by a totally unshadowed frame. The proportions in Tables 3-2c and 3-2d represent the annual energy collected per unit of land area relative to the energy collectible under ideal (but unachievable) conditions: 100% fill factor and no shadowing.

This table indicates that there is little gain in energy, only about 1.5%, by having the frame sweep a full 180 degrees.

Annual Energy Collected Per Quad Frame

180° Range

-90° to +90° TILT

TROUGH FILL FACTOR	FRAME FILL FACTOR			
	FRAME	FILL	FACTOR	
	.4	.6	.8	1.0
.6	.94	.91	.84	.73
.8	.89	.85	.79	.69
1.0	.79	.77	.70	.61

(a)

65° Range

+15° to +80° TILT

TROUGH FILL FACTOR	FRAME FILL FACTOR			
	FRAME	FILL	FACTOR	
	.4	.6	.8	1.0
.6	.92	.89	.83	.72
.8	.87	.84	.80	.68
1.0	.78	.75	.69	.60

(b)

Annual Energy Collected Per Unit of Land Area

180° Range

-90° to +90° TILT

TROUGH FILL FACTOR	FRAME FILL FACTOR			
	FRAME	FILL	FACTOR	
	.4	.6	.8	1.0
.6	.23	.33	.40	.44
.8	.29	.41	.50	.55
1.0	.32	.45	.56	.61

(c)

65° Range

+15° to +80° TILT

TROUGH FILL FACTOR	FRAME FILL FACTOR			
	FRAME	FILL	FACTOR	
	.4	.6	.8	1.0
.6	.22	.32	.40	.43
.8	.28	.41	.49	.54
1.0	.31	.45	.55	.60

(d)

Table 3-2 Geometrical Considerations for
Collector Field Layout

This is because the extreme backward tilt (-90°) is needed only in the summer during early morning and late afternoon, when output is small because direct-normal insolation is low. The same applies for the extreme forward tilt, greater than 80 degrees, which is only needed in the winter during early morning and late afternoon. The Phase II system has been designed to tilt from $+15^\circ$ to $+80^\circ$, which results in reduced cost, increased reliability and little loss of collected energy compared to a wider-tracking system.

3.6.2.3 Trough and Frame Fill Factors

The term "trough fill factor" is the trough width divided by the distance between equivalent points of two adjacent troughs. "Frame fill factor" refers to the array row spacing. The product of these two fill factors equals the fraction of site land area shadowed by the array when the sun is at the zenith.

As a general rule, high fill factors are desirable since they indicate high energy collection per frame or unit of land. However, as trough fill factor increases, losses due to shadowing also increase, resulting in decreased annual output. Table 3-2 demonstrates the effect of both trough and frame fill factors on a) the annual energy collected per quad frame and b) the annual energy collected per unit of land area. The choice of a particular fill factor is then a function of land cost, array cost and finally energy needs. If the output per dollar invested in land and the photovoltaic system were maximized, row and trough spacing would be such that there would be little or no shadowing of the reflectors at any time

of the year. Even though the Solarex Rockville facility is located in an area where land costs are high -- about \$1.70 per square foot -- the cost of the complete photovoltaic system per square foot of active reflector area is more than 10 times as much as the land cost. Therefore, our economic goal should be to maximize the system output per dollar invested considering all costs, not just per square foot of land. Minimizing the initial capital investment per unit output as measured in peak kilowatts or per annual kWh is the really important criterion that will enable photovoltaics to compete successfully with other energy sources.

The application under study in this program was a stand-alone power system designed to provide all of the energy requirements of a solar breeder factory. One of the most critical factors in the design is the array output during the worst season of the year. Therefore the trough fill factor was chosen as the maximum fill factor at which there was negligible loss due to trough shadowing during the months of November, December and January. The computer analysis indicated that a fill factor of 0.7 fulfilled this requirement, so the Phase II array was designed using a trough fill factor of 0.7.

The frame fill factor or row spacing also depends on system requirements. Figure 3-6a shows the expected energy output per trough and per area as a function of frame fill factor for both the yearly average and the winter average. In the three months of lowest insolation (November, December, and January) an increase

Fig. 3-6a Row Spacing Influence on Array Energy Output

in row packing is almost exactly compensated by an increase in shadowing, as shown in Figure 3-6a, "Winter Average."

The energy per area is of greatest importance in the winter when insolation is comparatively low. Yet, by the flatness of the Energy/Area curve in Figure 3-6a it can be seen that the energy per unit area in winter is nearly constant for any row spacing above approximately 0.45.

An additional consideration in selecting the frame fill factor is the minimum voltage required to drive the Power Conditioning System. The computer program assumes that the power loss is proportional to the shadowing. For the case of end shadowing this proportionality is roughly obtained by the use of shunt diodes. However, there is a certain additional loss since the shadowing not only eliminates the voltage of the shadowed cell, but also causes the current to flow through a shunt diode which induces a drop of 0.7 volts. In order to minimize the effect of reduced voltage and power loss due to shadowing during the winter months, the row spacing or frame fill factor was chosen to eliminate end showing between 10:30 am and 1:30 pm on the day of the year when the sun is at its lowest zenith, December 21st. Therefore a frame fill factor of 0.46 was chosen for the system.

3.6.2.4 Mean Array Azimuth Angle

While it is advantageous to point the field directly southward, our parking lot is oriented 20° east of south. Savings in construction time and improved esthetics would result if the array

was aligned with the parking lot. The relative energy per frame and per area was calculated for both orientations. Table 3-3 shows the result of these calculations. As can be seen from the table, there is less than 1% difference between the two orientations. Therefore the Phase II plan calls for the parking lot array to be aligned 20° east of south, in line with the parking lot and the building.

	20°E	S
Relative Energy/Frame, Annual	.86	.86
Relative Energy/Frame, Winter	.85	.84
Relative Energy/Area, Annual	.32	.32
Relative Energy/Area, Winter	.31	.31

Table 3-3

3.6.2.5 Array Output Simulation

With the various alignment and fill factors determined the performance of arrays of various sizes can be simulated. Figure 3-7 shows the effects of shadowing on array performance. The design has maximized the array output for the winter months. The losses at the other times of the year must be tolerated to maximize winter output.

The computer program determines array output, both peak and integrated over time for an array of given aperture and efficiency using the various fill factors and tilt angles previously determined. The results of Phase I testing indicated that the troughs could operate at 10% efficiency, so this value was used in all subsequent

Typical Insolation, Clear Day

Array Energy
Received vs
Clear Day
Insolation

TYPICAL INSOLATION, CLEAR DAY

Fig.3-7

TYPICAL INSOLATION, CLEAR DAY

calculations. Since power delivered to the load must match the load requirements, the efficiency of the entire system must be determined before the array size can be finalized.

3.6.3 Electrical System

The proposed electrical system is shown in Figure 3-8. It consists of a photovoltaic concentrator array feeding power through a 232 VDC bus to a 40 kW self-commutated inverter, powering the Solar Breeder Line. Also fed by the array, a 100 kW line-commutated inverter is connected to the central house bus, where it provides power to off-set the Solar Breeder's HVAC and lighting loads. The tracking and coolant control systems are powered from the DC bus, considered to be the uninterruptible point in the system. A minicomputer Energy Management System controls operation of the system and continually monitors operation of the system. The battery bank provides energy storage for both system tracking and operation of the Solar Breeder Facility. The various components and the rationale for their choice will be addressed elsewhere. The efficiency of each of the various steps in the power conditioning process were identified from information and available literature as:

● DC-to-DC peak-power tracker	96%
● battery cycle efficiency	90%
● inverter efficiency	85%

Therefore the power conditioning system is 73.4% efficient.

BLOCK DIAGRAM

Fig. 3-8 Photovoltaic Electrical System

3.6.4 System Performance and Size

The array has been sized to provide the energy necessary to operate the Solar Breeder production facility during the period of least insolation, the winter. Although the production line operates only five days per week, insolation is of course, collected over the full week. Therefore, energy collection calculations have been performed using average weekly winter insolation.

Using the efficiencies of the various subsystems as listed in Section 3.6.3, shadowing losses from section 3.6.2, load characteristics from section 3.6.1, and parasitic power losses due to tracking and cooling pumps, a total array aperture of approximately 2000 square meters was found to be required. This requirement is met by the proposed array of 640 troughs in 160 quad frames, with an aperture of 2048 square meters and nominal peak output of 200 kW. The proposed array is shown in Figure 3-9.

The expected electrical output of this array has been calculated for the three insolation seasons. Output and load for an average day during each season is shown in Figure 3-10. This figure expresses both energy generated and load on a daily basis, resulting in the area under the load curve exceeding that under the generation curve. Again, it must be remembered that energy collection functions over a 7-day week, while load exists on weekdays only. It should also be noted that the loads represented in this figure have been

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			SHEET OF

3-24a

Fig. 3.10a

DAILY GENERATION AND LOAD
MAY, JUNE, JULY; AVERAGE OF ALL DAYS

Fig. 3.10b

DAILY GENERATION AND LOAD
FEB., MAR., APR./AUG., SEPT., OCT.; AVERAGE OF ALL DAYS

Fig. 3.10c

DAILY GENERATION AND LOAD
NOV., DEC., JAN.; AVERAGE OF ALL DAYS

Daily
Power and Load
Breakdown

divided by the efficiencies of the power conditioning system to allow accurate comparison of energy generated and consumed.

To calculate the total yearly energy that the system would supply to the load, the peak power, 200 kW, was multiplied by the average annual insolation in the Rockville area: 3.4 kWh/m²/day. The product was then adjusted to account for the system's loss due to shadowing (12% annual average), leaving array output at 598 kWh/day.

Tracking and coolant pumping requirements average 50 kWh/day. Subtracting this and taking the efficiency (73.4%) of the power conditioning system into account results in a total energy delivered to the load of 401 kWh/day or 2805 kWh/week or 146 MWh/year.

3.6.5 Electrical Energy Storage Optimization

One of the most important design criteria of a stand-alone system is its storage capability. Various types of storage were considered including electrical, mechanical and intrinsic (stocking of in-process wafers). Because of space limitations at the site and the applicational (rather than experimental) nature of this project, it was decided to design the system for a combination of electrical (battery) storage and intrinsic (wafer) storage.

A computer program was developed to compare various battery and storage sizes. Figure 3-11 shows the results of this calculation. The cost of the particular storage combinations were based on a battery cost of \$140 per kWh and an

Trade-off Between Battery Storage and Intrinsic Energy As COST
 (BOLDFACE) and Wafers/Year Produced. (Numbers in Parentheses are
 Average Days/Year of Shut-down Due to Insufficient Available Energy)

Figure 3-11 Intrinsic vs Battery Energy Storage Trade-off

inventory cost of \$5.00 per stored wafer. The two sets of interconnecting curves are explained as follows:

- The bold curves represent lines of equal cost.
- The lighter curves represent lines of equal yearly wafer output in thousands. The numbers in parentheses are the average number of days in one year that the line will be shut down due to insufficient available energy.

It is our desire to have sufficient electrical storage available for a series of experiments during Phase III to study the effects of wafer storage and process line down-time. Therefore, a 2600 kWh storage system was chosen. This represents energy storage sufficient for five days of operation of the processing line. This battery size would be sufficient to limit the down time to less than two weeks per year without excessive intrinsic storage. However, it gives us the flexibility to operate over a large range of intrinsic storage without suffering severe curtailment of production.

3.6.6 Thermal System Design

Calculations were performed to estimate cell operating temperatures for the design of the Phase II system. The calculations were correlated with the measured power output and temperature of the Phase I prototype array. The general

procedure was to:

- 1) Estimate the heat loads to the coolant for assumed temperatures and environmental conditions.
- 2) Calculate the cell and receiver temperatures in terms of coolant temperature over a range of coolant flow rates from 0.5 gpm to 5.0 gpm.
- 3) Check the estimate of step 1 with the results from step 2 and if necessary iterate the process. This iteration includes re-evaluating fluid properties based on the temperatures found in step 2.

In all of these calculations the coolant was assumed to be 50% H₂O and 50% ethylene glycol.

Two cases were examined, comprising two combinations of assumed cell-to-ambient temperature differential and wind velocity:

- a) $\Delta T = 10^{\circ}\text{C}$; still air ("summer")
- b) $\Delta T = 40^{\circ}\text{C}$; 30 mph ("winter")

The results are shown in Figure 3-12. It is clear that a high coolant flow rate is needed to maintain an acceptable cell temperature during summer operation. In particular, for a cell temperature of 50°C and an inlet temperature of 30°C , a flow rate of approximately 2.8 gpm per receiver is needed.

Figure 3-12

At low flow rates, the average cell temperature is high due to the large increase in fluid temperature from inlet to outlet, which is reflected in a high receiver temperature at the outlet. In addition, low coolant velocity gives poor heat

transfer from receiver's wall to coolant, requiring a large wall-to-fluid temperature difference. Although flow rate may be increased, the relatively large cross-sectional area of the receiver -- and therefore, long conductive path -- greatly inhibits heat transfer.

Excessive flow rates would be required to reduce the cell-to-fluid temperature differential below 15°C . An alternative approach, one which will be adopted in Phase II receivers, is to augment the heat transfer surface with internal fins. The wall-to-fluid temperature differential is then minimized, not only because of the increased heat-transfer area, but also because the conduction paths are considerably reduced. Average receiver temperature is then governed by fluid temperature increase and the required flow rate can be chosen accordingly.

3.7 Design of Components

While a preliminary system had been designed for the Phase I proposal, many of the components had not been designed in detail. Several of the proposed components were rejected for this program due to information gathered between the preparation of the proposal and the start of the contract. Prime among these was the concentrating collector itself. The remainder of Section 3.7 describes the component develop-

ment activities which led to the present prototype configuration and the hardware and configuration proposed for the Phase II system.

3.7.1 Concentrating Collector

As described in Section 2, Solarex determined before the start of this contract that the collector system originally proposed for Phase I would not satisfy the requirements of this program. Therefore, a design analysis and search for a more appropriate solar collector was initiated.

3.7.1.1 Optical Design

Many concentrator systems that have been proposed for use in photovoltaics have one or more of the following disadvantages:

- V-trough receivers with cells mounted on both sides of the trough center line. Such receivers are extremely labor-intensive, since they utilize cells of comparatively small area, require numerous wiring and interconnection operations, and necessitate considerable handling (with the inevitable breakage) of cells. In addition, a gap is required between cell rows at the apex of the V to assure electrical isolation. This gap is located at an area of typically high illumination and causes a substantial decrease from potential system efficiency.

- Short-focal-length concentrators. Optical accuracy for such a concentrator is quite critical, particularly for the sections of the mirror near the rim, which see the receiver as a small target.
- Large rim angles*. Mirrors with large rim angles require extreme optical accuracy near their rim, and exhibit high reflection losses due to the acute angle of incidence of light on the cell surface.

Solarex has performed extensive calculations to determine the optimum rim angle. For a nominal cell width of 5 cm and a collector width of 100 cm, the allowable slope error was calculated for a set of sequentially decreasing angles. As shown in Figure 3-13, larger slope errors are allowable in the central section of a large-rim-angle mirror, with allowable error dropping rapidly toward the rim. However, although exhibiting significantly less allowable slope error in the central section, a small-rim-angle mirror exhibits a more gradual decline approaching the rim. It is evident from this analysis that a smaller-rim-angle mirror provides greater tolerance of slope error near the edges, where it is most needed. In addition, because the light from a smaller-rim-angle mirror strikes the receiver closer to the normal than

* Rim angle is defined as half the angle subtended by the arc of the parabolic trough.

Figure 3-13 Maximum Allowable Mirror Slope Error Analysis

Figure 3-14 Collector Optical Design

light from a large-angle mirror, losses due to reflection from the cell at the receiver are reduced. Therefore, it is necessary to achieve a balance between slope error at the edge and focal length. To this end, a rim angle of 51° was selected, as shown in Figure 3-14.

A collector of relatively small rim angle enables use of a single-plane receiver rather than one of V-trough design. Such a receiver -- covered with a single string of cells -- is far less expensive to construct and assures that the areas of highest illumination will be active photovoltaic area.

Receiver development is fully described in Section 2, cell design in Section 5.2.1.

3.7.1.2 Reflectors

During the course of the program various reflector materials were investigated including aluminum, FEK, sagged glass with silver backing, and foam glass with silver backing. Tests of reflectance, both initial and after weathering (described in Section 2) led to the choice of 1/8-inch sagged glass with a silver layer deposited on the back followed by a protective coating. These mirrors exhibit an AML-weighted average reflectance of 90% in the $0.4\text{ }\mu\text{m}$ -to- $1.1\text{ }\mu\text{m}$ range of the solar spectrum, and form a parabolic trough with a 51° rim angle. Each trough measures 43 inches wide by 10.5 feet long, comprising 12 mirror segments, 6 on each side of the center-line.

The mirror segments are held in place by two aluminum extrusions, one at the base of the collector, the other at the edge. Plastic pads are placed on the edges of each mirror segment, then fitted into slots in the extrusion. This arrangement firmly holds the mirrors while allowing for thermal expansion and contraction. The combined extrusion and mirror assembly is held in place by trapezoidal end-plates (see Figure 3-15).

3.7.1.3 Collector Support Structure

In our initial work with concentrator systems, it became obvious that a sturdy structure was needed to achieve and maintain the required tracking accuracy under cumulative environmental effects, including high wind conditions. Many single-axis trackers (including one tested during this program, described in Section 2) offer such ruggedness, but produce significantly less output than dual-axis trackers. The system meeting all Solarex requirements would feature dual-axis tracking, be rugged yet lightweight, and reliable yet inexpensive.

The collector which best meets these criteria -- and which is specified for the Phase II system -- is illustrated in Figures 3-16 and 3-17. A group of four reflector troughs is supported in an aluminum frame of rectangular cross-section. This "quad" is supported at six points. The quad assembly base is constructed of galvanized pipe and is fitted with pivots at its southern edge, which engages fittings attached to the

Fig.3-16 Quad Unit, Solarex Prototype Collector

lower rail of the quad frame (see Figure 3-17). The frame pivots along its southern edge to track sun elevation. The upper rail of the quad frame is supported by a pivoting frame, the three upright members of which are fitted with fixed chains accepting spur-cut pinion gears driven by the elevation motor.

3.7.1.4 Mechanical Tracking System

A two-axis tracking system was chosen to obtain maximum energy from the array. East-west tracking is accomplished by simultaneous rotation of all four troughs in each frame. The east-west tracking motor, mounted between the two center collector troughs, rotates a shaft extending from top to bottom of the frame. Both ends of the shaft are fitted with pinion gears which engage racks mounted on rollers along the top and bottom of each trough.

To accomplish elevation tracking the whole frame assembly is pivoted about its lower end, and the upper end is elevated on the three pivoted support poles arranged along the back of the quad frame. Elevation movement is provided by a motor driving spur-cut pinion gears which engage chains fixed to the pivoted support poles.

3.7.1.5 Electrical Tracking Control

Because of the need for very accurate tracking control, it was decided to employ sensor tracking rather than to attempt to use a clock drive. The sensing system consists of two

independent sets of small matched solar cells equipped with shadowing baffles. One baffle-equipped cell set (or "sun sensor") senses east-west accuracy; the other sensor detects any error in frame elevation.

The elevation sensor comprises:

- two tilted outboard cells which detect diffuse illumination and initiate frame movement toward the source;
- two flat inboard cells mounted next to the shadowing baffle. As long as one of these cells are shadowed by the baffle, pair output is unbalanced. When the frame is perfectly aimed the baffle casts no shadow; pair output is fully balanced, causing cessation of tracking motion.

An east-west sensor is mounted on one receiver of each frame, and comprises:

- two upward-facing cells which sense diffuse light and initiate east-west movement;
- two downward-facing cells on the outboard portion of the receiver which intercept the edges of the light pattern from the trough mirrors. When the output of these cells is balanced, the collector pattern is optimally centered on the receiver and tracking motion ceases.

3.7.2 Power Conditioning and Switchgear

The photovoltaic power system requires a power conditioning system to maximize the power delivered to the load and to provide the load with the appropriate form of power. The system designed to do this was shown in Figure 3-8. The DC-to-DC converter maintains the array load at the peak power point and down-converts to the DC bus voltage. The purpose of this unit is to extract available power from the array by providing more efficient coupling to the DC bus.

Figure 3-18 shows the array voltage-current relationship and the battery/storage voltage window. Without a maximum power tracker, the battery/storage window would have to be selected such that its upper limit did not exceed by more than 5% the voltage at peak power for the lowest array output voltage (highest cell operating temperature). Otherwise the array could not drive appreciable power into the power conditioning system when the battery was near full charge, resulting in a major energy loss throughout the year. On the other hand, with a peak power voltage near the top of the battery window, substantial system power would be lost when the battery was discharged and at a low operating voltage. For example, for an array peak power voltage of 275 volts and a battery voltage of 190 volts, approximately 25% of the photovoltaic power would be thrown away.

Fig. 3-18 Array Output Voltage-Current Relationship and Battery/Inverter Operating Window

Switching battery cells or array sections in and out of series strings was considered as a way to optimize operating voltages, but was rejected because of such problems as difficulty in maintaining battery equalization, increased array and switchgear costs, and the fact that the voltage match would still be imprecise.

These problems are all eliminated by a maximum power tracker, which allows the array to operate at its optimum point and deliver maximum power to the power conditioning system at all times. This feature is a very important advantage for a stand-alone system. Once the thermal storage is raised to its design temperature, 25°C in our case, the cells can be operated at a much lower temperature, raising the array output voltage and power output. The resulting increase in energy output partially compensates for the reduced winter insolation, and smooths annual output variations. Thus, by using a maximum power tracker a constant load can be provided on a stand-alone basis with a smaller array.

The disadvantages of this approach are the efficiency loss and the cost. However, for a stand-alone load the efficiency loss, 5-10%, is more than offset by the smaller array needed to sustain the load, even though the net energy output on an annual basis is increased only slightly. Further, we have compared the cost of the peak power of a larger array, elimination of the tracker, and narrowing the battery voltage

window, which would result in a smaller charge capacity for a given battery bank. The use of a peak power tracker was found to be the most cost-effective approach.

The primary DC-to-AC inverter is a self-commutated unit, supplying 3-phase 480V power for the stand-alone Breeder Manufacturing Line. The power quality and regulation requirements for the manufacturing equipment, primarily small motors and heaters, have been reviewed and are easily satisfied. Other inverters were also considered, including the Westinghouse 50 kW unit, Type AVI-503A, developed under contract to Sandia specifically for photovoltaic applications. While this unit offers potential low cost and high inversion efficiency, it was rejected because of the long delivery time -- 10 months ARO -- and the high non-recurring cost, \$233,578, quoted to us by Westinghouse. A DC-to-AC motor-generator set was also considered but rejected as being less applicable to most photovoltaic applications than a solid-state unit.

At certain times more energy will be available than can be used by the stand-alone system. Rather than dump this power we will use it by feeding power directly into the house bus with a secondary 100 kW line-commutated inverter manufactured by Windworks. Power from this 480-volt, 3-phase unit will compensate for the power required for HVAC and lighting of the Breeder Manufacturing Facility. In reviewing the building load, it is anticipated that power will never be delivered back to the utility. Approaches other than a line-commutated

inverter were considered, including solid-state and rotary self-commutated systems. These were rejected because of higher cost and added complexity of maintaining the proper phase relationship with the utility.

An overall drawing of the proposed system switchgear is shown in Figure 3-19. The equipment illustrated has the capability of isolating any subarray, either array sub-field, any piece of power conditioning equipment, and each battery series string. A switch parallels the maximum-power-tracking DC-to-DC converter in order to operate the system in case of converter failure, or to evaluate system performance without the converter during Phase III. A manual transfer switch would allow connection of the utility to the stand-alone load in the case of an emergency, such as component failure, and during the periodic system power interruptions expected during the construction and debug phase.

3.7.3 Battery Storage Subsystem

The analysis of the capacity of the battery storage system for Phase II was described in Section 3.6.5 . Various storage systems were considered. Nickel-cadmium batteries were rejected as uneconomical. Other battery manufacturers were considered, but C & D was selected on the basis of past and projected performance, available technical information, and desire on their part to optimize characteristics for

Figure 3-19 System Switchgear

photovoltaics. Several hydraulic storage systems were considered and rejected because of estimated installed cost at the Solarex Piccard Drive facility.

The battery subsystem would consist of 8 series strings of 9 C & D 12-cell batteries each, providing a total electrical storage of 2.6 MWh. These would be operated from 1.75 volts to 2.45 volts per cell, for a nominal system voltage of 189 to 265 volts. At least once per month, the system voltage would be raised to 2.55 volts per cell to provide system equalization and electrolyte mixing through overcharging and resulting high gas evolution. Specific gravity of each cell would be checked monthly in order to monitor battery condition. The system would be housed in a well-ventilated enclosure and all electrical fixtures (including fans and lights) would be of explosion-proof construction in order to minimize the explosion hazard.

3.7.4 Energy Management System (EMS)

As part of the Phase I program, Solarex has designed an Energy Management System for use in Phase II. The proposed Energy Management System comprises a functionally decentralized data acquisition and control network. This approach yields characteristically high system throughput because of its capability of performing data acquisition and data compression in a distributive fashion, in turn increasing the system operating reliability by introducing redundancy at several levels of operation. This overall approach has been adopted

by most heating, ventilating, and air conditioning (HVAC) energy system designers, and is considered to have substantially greater overall operating reliability than systems which limit control and data management functions to a centralized point. In addition, it has been demonstrated that such a system can provide significant cost savings.

One of the most salient features of the Solarex EMS, shown in Figure 3-20, is that both sensing and signal conditioning are distributed. The signal conditioners, or signal transmitter (ST), are small phase-locked-loop current sources, which have self-contained, self-compensating operational amplifier circuitry designed to counteract biases associated with a particular sensing device's functional anomalies. Another advantage of distributive signal conditioning over analog measurement is that line noise and shielding requirements are minimized because the transmitted signal is sufficiently large (± 5 VDC) to eliminate the Type I or Type II measurement errors associated with a low signal-to-noise ratio.

The signal transmitter analog outputs are routed to submultiplexing units and digitized using multislope integrating type A-to-D converters having 12-bit accuracy. The data acquired from the various input sensors will be buffered in one of four satellite microprocessor units associated with its respective segment of the solar array field. Data acquired by the satellite microprocessors will in turn feed machine-amenable digitally coded information to the central minicomputer via a digital

communication multiplexer (DCM) through a direct memory access (DMA) port, thus eliminating the need for cycle-stealing by the minicomputer's processor (CPU) in order to service the digital multiplexer. The application of distributive computing by the satellite processors allows added truncation in time. This is because the data is being collected in parallel by each satellite. The satellite processors would also be equipped with resident PROM-based software to continue intelligent monitoring and perform rudimentary failsafe control of the arrays and power conditioning units in the event the minicomputer fails.

The network of sense inputs to be utilized in the proposed system would contain nine classes of information deemed relevant to efficient system performance monitoring:

- Current of each series string of cells
- Inlet and outlet manifold temperatures of each tracking system
- Flow rate measurement placed proximal to associated control components
- Battery current
- Battery voltages
- DC power usage for tracking and thermal system drive
- AC power output of inverters
- AC power consumed by breeder facility
- Temperature of the thermal storage tank

Functions requiring control, as depicted in Figure 3-21, are relegated to those subsystems necessary for maximizing the energy system's operation and protection. These major control functions are as follows:

- array detracking
- self-commutated inverter turn off/on
- line-commutated inverter turn off/on
- system coolant pump speed control
- process water, battery heat, cooling tower heat exchanger loop valve controls
- monthly battery electrolyte destratification cycling

The EMS Minicomputer will function in two basic modes during daylight operation. In foreground operation, the foreground process will continuously apprehend information transferred from the background sector in order to perform real-time diagnostic calculations and to invoke the appropriate controls. Additional foreground operation will provide the facility of allowing the user to query the system for a specific set of graphic or tabular information about the ongoing system operation. In the event of major control operations, as in the case of switching the inverters into or out of the system circuit, a printed output of the operation and the time it occurred will be generated for a permanent record. These control occurrences will also be written to high-speed disk for further analysis after daylight hours. In the background

Figure 3-21
Major Control Functions
3-53

operation mode the central EMS minicomputer will be continuously engaged in polling its satellite interface devices. The requisite functions associated with the background operation would take place independently of commands generated in foreground. In addition, the background processor will average input data and write it in disk memory. Access of critical nature for failure mode diagnosis will be linked between foreground and background environments in real time to allow for rapid execution of control and/or failure mode protection schemes, prioritized as a function of time and the criticality of the overall system's status. Other interruptions will be clocked by the processor at relatively slower rates associated with the onset rates of failure conditions.

Secondary in priority to failure mode protection, diagnosis, and control are those measurement and control functions which are continuous operations, such as varying coolant pump motor speeds, operating valves in the thermal system, operating the line-commutated inverter, and monitoring system performance status. In addition, from input data on the battery storage level and the load demand profile of the Breeder manufacturing line, the EMS controls the operations of the self-commutated inverter switchgear to power the Breeder line, or provide warning of impending shutdown. These functions are depicted schematically in Figure 3-21.

3.8 Collector Array Field

The proposed Phase II collector array field would consist of 160 quads, divided into two subfields as shown in Figure 3-9. The first field would consist of 84 quads, covering the Solarex parking lot, sloping upward 6° and oriented 20° E of South. The other subfield would be level, oriented due South, and located partially over a flood plain unsuitable for buildings but usable for array support. The parking lot land serves two functions and the flood plain land cannot be used for either buildings or a parking lot.

The array field is divided into 20 subarrays comprising series strings of 4 quads each, as shown schematically in Figure 3-22. Each subarray is center-tapped, producing an array voltage above ground at peak power, worst-case average cell temperature 55°C , of + 145 volts and -145 volts. At the ungrounded end of each string a manual circuit breaker/disconnect switch, blocking diode and Hall-effect current sensor are connected in a junction box used to join to the feeder cables. The wire sizes of the feeders are designed to provide a worst-case field wiring loss of less than 2%. Each of the two subfields can be disconnected independently at breakers located within the System Control Room.

Temperature monitoring is done at the output of each collector system; this is to assure that a localized coolant loss, caused by a coolant leak or blockage, can immediately be detected and the appropriate quad defocused. The inlet

TYPICAL SUBARRAY (4 Quads in Series)

SYSTEM ELECTRICAL DIAGRAM

FIGURE 3-22 Electrical Interconnection

temperature and flow rates are also monitored at the end of the collector subfields, at the end of each collector row, and at the middle of the subfield over the parking lot. This will allow adjusting flow conditions to equalize temperatures throughout the system.

Other array interconnection configurations were also evaluated. A nominal 480-volt system was rejected because of safety (well over 600 volts maximum open-circuit voltage), and because failure of one quad would electrically eliminate 1 of 20 subarrays, or 5% of the total system power. The configuration selected produces low wiring loss, a voltage compatible with the battery and inverter operating windows, and a modularity of construction which minimizes wiring labor costs.

3.9 Thermal System

The thermal energy system designed for the Phase II array would consist of four primary fluid loops:

- (1) solar concentrator loop
- (2) storage/heat rejection loop
- (3) space heat loop
- (4) water preheat loop

Loop interconnections are shown schematically in Figure 3-23. A description of each loop follows.

3.9.1 Solar Collector Loop

A non-freezing working fluid is circulated through the collector receiver by a variable-speed D.C. pump. As the level

Ⓟ Pump

Bypass Valve

TS Temperature Switch

Figure 3-23 Thermal System Block Diagram

of solar radiation received increases, the flow rate in the collector loop will increase proportionally, thereby removing thermal energy in approximate proportion to its absorption.

This arrangement has many benefits:

- temperature of solar cells will be controlled
- power used to transport the thermal energy will be minimized
- direct current can be used with minimal conditioning and without inversion to alternating current

Conventional base-mounted centrifugal pumps will be employed. Flow rate will range between 75 and 350 gpm depending on thermal energy available. Average cell operating temperature will range from 25°C in winter to 55°C in summer.

The collector loop fluid will consist of a 50:50 mixture of ethylene glycol or propylene glycol and water and appropriate corrosion inhibitors for the aluminum receivers. Fluid expansion compensation will be accomplished with a diaphragm-type expansion tank which prevents the working fluid from contact with either air or metal, thereby greatly reducing potential corrosion problems.

The thermal energy in the collector loop is transferred to the storage/heat rejection loop by means of a plate-type heat exchanger with 621.6 ft² of heat transfer area. The high efficiency of this type of heat exchanger makes it well suited to our application.

Its high heat-transfer coefficient results in low surface area requirements and relatively low cost for the performance provided. The design also allows the flexibility to increase capacity by the addition of more heat transfer plates on the support frame. Standard material of construction is stainless steel which has excellent corrosion resistance in this application.

3.9.2 Storage/Heat Rejection Loop

To maintain the collector loop temperature within the design parameters (30-60°C), it is necessary to dissipate the collected energy. This is accomplished in two ways:

- (1) by dissipation of energy through a cooling tower, and
- (2) by supplying thermal loads, such as space and process heating.

Whenever there is circulation in the collector loop there is also circulation in the storage/heat rejection loop, containing water which is circulated through the plate heat exchanger. The loop circulation pump is variable-speed and is regulated in consort with the collector loop pump. To achieve the desired system performance the cooling tower flow-rate is about 1.25 times that of the array. Flow within this loop is directed to energy storage or the cooling tower depending on the loop temperature. A temperature sensor

directs all flow to the cooling tower when loop temperature is above its set point to keep the collector loop coolant temperature in the 30° - 60°C range. At lower temperatures a valve diverts flow to the insulated storage tank.

An ejector-type cooling tower was selected for its compatibility with the variable-flow pumping system. There are no fans, motors or wiring needed for this type of tower. Compared to the wet deck/fan type, installation is simpler, and noise and vibration levels are lower, all of which translates into high reliability, long life and very low maintenance costs. The tower selected has a nominal heat rejection capacity of 160 tons. The thermal storage tank is an above-ground 20,000 gallon steel water tank, whose maximum temperature will be limited to 50°C throughout the year.

3.9.3. Space Heat Loop

Hot water from the thermal storage tank will be circulated through conventional radiators inside the system control center during winter to optimize battery efficiency. The thermal storage tank is sized to store heat sufficient for five days of control center space heating

3.9.4 Process Water Loop

Energy from the thermal storage tank will be transferred to the water in the process water tank by an integral heat exchanger whenever its temperature drops more than 5°C below that of the thermal storage. This transfer will be terminated when the storage tank temperature drops below that required to provide adequate control center space heating.

Approximately 11,000 gallons of process water per day are consumed at Solarex.

Thermal energy from the photovoltaic array will be able to provide between 5 and 10 million BTU per day to the combined process and space heat loads.

3.10 Environmental Assessment

During Phase I Solarex conducted an environmental assessment of the impact of both the Phase I prototype systems and of the proposed Phase II system.

No significant environmental effects were noted as a result of the operation of the prototype systems constructed during Phase I. As with all photovoltaic systems, the prototypes are emission-free, essentially noiseless, and require no environmental disruption (e.g., mining) for provision of fuel.

Furthermore, unlike the constituents of some photovoltaic cells, silicon is not poisonous and has no negative environ-

mental effects. Should this system be damaged, fragments of cells and receivers would require no unusual precautions or extraordinary cleanup procedures.

The power system proposed for construction during Phase II is about 80 times larger than the prototype, however, so environmental considerations were not dismissed merely by virtue of favorable Phase I experience and the intrinsic environmental compatibility of silicon photovoltaics. Specific considerations addressed during Phase I appear in the following sections.

3.10.1 Land Use

Because of their comparatively low energy density, photovoltaics require more land per kilowatt of peak output than most other sources of electric power. The proposed installation demonstrates two techniques for minimizing the impact of photovoltaic land requirements:

- approximately half of the collector array is mounted above the Solarex parking lot, so that no additional land is required;
- the remainder of the array extends into the flood plain of a stream, occupying land with very few other practical (or legal) uses.

3.10.2 Water Use

Solarex presently uses considerable quantities of water to wash cells after various processing steps. The only means of reducing water consumption is by heating it, thus increasing

its ability to dissolve contaminants. Thermal energy collected by the array will be used to heat this water, an option not previously available to the company since the only on-site energy source -- utility-generated electricity -- is quite expensive.

3.10.3 Impact on Life Forms

The site of the proposed installation is a portion of a designated light industrial park, zoned for uses compatible with this project. Now basically rural and suburban in nature, the general area is rapidly building up, with all the environmental changes that accompany such a transition. The impact of the proposed installation will be similar to that of a typical mid-sized construction project, with some loss of animal habitat and scrub vegetation. This project will destroy no unique habitats or resources of great value.

3.10.4 Optical Consideration

Solarex has considered the potential danger presented by the project's large mirrored surface and resulting reflections. In addition, it is recognized that the collectors present a hazard to humans or animals that approach the collector focal line. It appears that the installation will be quite safe because:

- access will be controlled by a security fence, preventing children and the curious from approaching the focal line of any trough;
- past the focal line, light rays reflecting from the mirrors diverge rapidly, presenting nothing worse than an annoying flash at a distance of twenty feet. At greater distances this flash is insignificant. In any case, such flashes pose no threat to air traffic, since the site is not on or near the approach pattern of any airport.

3.10.5 Climatological Considerations

The cooling tower included in the system is of modest size, and will have no impact whatsoever on local climate. At full thermal capacity, which should occur on only a few days each year, the tower will dissipate approximately 5 million BTUs per hour.

4. Phase II, Fabrication and Installation:

Technical and Management Plan

4.1 Introduction

An important component of the work to be performed during Phase I was the development of detailed technical and management plans for the conduct of Phases II and III. This section details the technical and management plan to be activated if Phase II of this project is authorized.

4.2 Overall Plan for Procurement, Manufacturing, and Checkout Procedures

Phase II plans specify the fabrication, installation and checkout of a 200 kW(e) concentrating photovoltaic system powering a solar cell production facility. Major management considerations in program execution include:

- cost effectiveness of the proposed approach;
- project incorporation of close control and monitoring of technical, quality, scheduling, and cost parameters;
- incorporation of provisions for early detection of problems impacting project workflow and timely application of corrective feedback.

These considerations are reflected throughout the specific procurement, manufacturing, and assembly plans as outlined in this report and in the PERT chart included as Figure 4-1. They are particularly evident in the concept of "pilot" items and lots, which provide for early detection of workflow perturbations and quick corrective action. For example, the general plan calls

for the following schedule of completed quads (4-trough assemblies) made ready for installation in the power field:

Month	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>	<u>11</u>
Completed Quads	1	9	25	30	35	30	30

Extraordinary effort and attention will be focused on the completion of the pilot quad in month 5, and only slightly less on the 9 quads to be completed in month 6. This hardware will be minutely scrutinized, integrated with other subsystems, and tested in a timely manner, providing feedback that will eliminate detected defects from subsequent hardware.

4.3 Key Planning Tool: The PERT Chart

The PERT chart, Figure 4-1, is the key tool in planning and execution of the Phase II Technical and Management Plan. The PERT chart shows all of the task elements and hardware flows required to build system components, assemble the system, check it out, and complete the objectives of the Phase II program. Each task element is shown on the chart with time plotted in a linear manner from left to right and all of the events and their interrelationships shown in network form.

The PERT chart is a dynamic project management tool in this program. The data and the times estimated to be required for the completion and/or delivery of each subsystem, significant hardware item, or project element are updated at least once a week. Within a day's time this information is made available to the Solarex project manager, the General Contractor, the principal subcontractors and, if so desired, DOE. At the weekly project coordination and program review meeting the PERT chart

is the chief instrument for informing the project manager of the status of the project and for identifying any corrective action required to keep the project on schedule. A related management tool, PERT-Cost, can also be used to keep track of the financial status of the project with regard to the tasks that have been completed and the hardware that has been delivered, checked and installed.

4.4 Major Tasks and Division of Responsibility

The project may be divided into five major tasks:

1. construction of the power system
2. installation of the power system
3. modification of the photovoltaic factory
4. connection of the power system to the factory
5. instrumentation of the factory and power system and integration with a data acquisition system to gather critical performance information for evaluation and analysis

This effort will be organized and conducted by the management of Solarex Corporation, which will be responsible for all project activities. Functional responsibility may be conceived as being divided into three areas, with:

- the Solarex Manufacturing Department responsible for solar cell and receiver fabrication;
- the Solarex Systems Department responsible for procurement of key electrical system components;
- the General Contractor--supported by electrical, plumbing, and construction contractors--responsible for construction

of collector assemblies, field and building modifications, and installation and interconnection of components.

4.5 Solar Cells and Receivers

Solar cells and receivers for this program will be fabricated at the Solarex Rockville facility using technology and designs developed and proven during Phase I of this program. Fabrication will be begun immediately upon contract initiation. Prompt initiation of cell fabrication is required for this project to meet schedule. This will include tooling for receiver production, which tooling will permit building up to 140 receivers per month, the maximum production rate specified for this program. Like the rest of the program, the tooling build-up will be controlled so that the first unit may be checked out before commitment to large numbers of tools or fixtures.

As shown in the PERT chart, Figure 4-1, three hundred 16%-efficient cells will be available by the middle of the third month and will be incorporated into the four solar receivers which will be required for the pilot quad. With 70 cells per receiver, each quad will require 4×70 or 280 solar cells. However, in anticipation of some breakage during receiver construction, lots of 300 cells per array will be supplied initially. Should the margin for breakage prove overly generous, it will be reduced or eliminated later in the program in order to avoid excess cell production. The cell lots fabricated will correspond to the receiver production schedule which, in turn, will correspond to the array assembly schedule as shown in the

PERT chart.

The receivers will be checked out and tested electrically and mechanically before delivery to the General Contractor for assembly into arrays. Assembly of the quads on the supporting structure will be described later. Finished quads will be delivered to the field site for installation.

4.6 Key Electrical System Components

The Solarex Systems Department will be responsible for procuring the key components of the electrical system and certifying their performance. These components will then be provided to the General Contractor for mechanical and electrical integration into the system. These components include the batteries, power conditioning system, data acquisition and control system. Fully defined and using off-the-shelf components, they nonetheless are sufficiently critical to the success of the program to warrant special provisions for their procurement.

The PERT chart, Fig. 4-1, shows these components ordered on contract initiation and delivered, inspected, and ready for installation by the end of the fourth month. This schedule has been verified with the suppliers, and is fully acceptable to them. One month is provided for installation of these components in the system control building.

The battery procurement and delivery schedule is slightly accelerated with respect to other system electrical components, due primarily to battery availability and the desirability of spreading out major installation tasks. They are scheduled to

be received, inspected, and ready for installation by the end of the third month, with installation in the battery bay of the system control building complete by the end of the fourth month.

4.7 Selection and Responsibilities of the General Contractor

4.7.1 General

The program General Contractor will be selected by bid procedure from qualified local firms who are fully familiar with all applicable building and electrical codes. The General Contractor will provide major support to Solarex, and will lead electrical, plumbing, and structural subcontractors in the accomplishment of three parallel tasks as indicated in the PERT chart: (1) fabrication and installation of the quads on support structure; (2) solar array field installation including wiring and plumbing; and (3) modifications to the Solarex factory.

The hardware involved in the tasks of the General Contractor is well-defined; the Contractor's primary challenge will not involve hardware, but efficiency in assembly and installation. When difficult or specialized techniques, e.g., optical alignment of troughs and receivers, are required, Solarex will provide close support to the General Contractor. Final field checkout of each quad will be performed by Solarex personnel with the General Contractor's support.

4.7.2 Fabrication of the Array Quads

Construction of the array components will begin immediately on contract initiation, and will utilize "pilot-item" and feedback techniques described previously. Additional key elements:

of this program task will be:

- the immediate release of purchase orders for array components;
- the development of tooling, fixtures, and detailed procedures for rapid assembly of quads. Examples of tooling and fixtures are described in Section 4.8.

Several concentrating collector designs were evaluated by Solarex during Phase I; the present design was chosen, in large part, because of its design simplicity and ease of fabrication. The array quads can be completely constructed including wiring, plumbing, receiver installation and alignment, and fitting of sensors before delivery to the site. This preassembled approach allows the majority of fabrication work to proceed indoors, minimizes the effect of inclement weather, and will permit the project to proceed rapidly.

Several suppliers of the sagged-glass mirrors have been identified and delivery schedules have been checked out. Similar investigations into supply of all other major components indicate that the General Contractor will encounter no problems in meeting the desired delivery schedule.

For example, the final 54 mirrors will be delivered 2 1/2 months after order. Inspection of these mirrors will have already been conducted at the mirror manufacturer to insure mold design and product quality. It will be noted that, since 12 mirrors are required per trough, 4 x 12 or 48 mirrors are needed per quad; the additional 6 mirrors represent spares. Again,

as in the case of the cells, these spares will be closely monitored. If unnecessary, they will be cut back or eliminated from future deliveries.

4.7.3 Solar Array Field Modification

In parallel with quad construction, the solar array field sites will be surveyed and prepared for installation. It is expected that steel for the "over-the-parking-area" site will be delivered 30 days after order. The system control building will be constructed by the end of the third month and the field completely plumbed and wired, ready for the first quad installation, by the end of month 5.

4.7.4 Building Modifications

The General Contractor will also accomplish the requisite modifications to the Solarex Rockville facility in parallel with the activities mentioned previously. Building modifications are minor, composing primarily:

- addition of supply wiring from array and modification of existing circuits to permit isolation and monitoring of solarized production line;
- modification of plumbing to accomodate thermal input from system (for process-water heating);
- relocation of some production equipment and installation of temperature and power sensors.

These modifications are scheduled for completion by the end of the fourth month.

4.8 Discussion of Overall Plan Quality Control Procedures

4.8.1 General

It is vital to this program's success that extensive, yet cost-effective controls be applied to program elements. While inspection and testing of all system components and subassemblies before delivery would be ideal, it cannot be cost-effective. Therefore, we propose a program that will insure a high degree of control and reliability, yet maintain cost-effectiveness. This quality control plan will focus maximum attention on the more critical components and less on others. The most critical elements of this system, as determined from Phase I experience, include solar cells, receivers, and reflectors. For example, the QC program for the solar cells includes the following:

- In-process inspection and testing;
- Electrical testing and sorting of all cells at 20X;
- Provision for inspection and testing by DOE personnel for conformance with program specifications.

In addition to the above, sample lots of cells and completed receivers will be furnished to the customer on a regular basis for verification. Particular emphasis will be placed on Solarex's evaluation of the first, or "pilot" lot. It is expected that the customer will also subject the pilot lot to intensive inspection and testing, since it will serve as the basis for standardization of all succeeding cells for this project.

As shown in Table 4-1, it is anticipated that Solarex will be responsible for similarly intensive inspection and testing of pilot lots of components of lesser priority, and for their standardization and compliance with specifications. Such a program will assure that components meet program specifications

	Inspection & Test of Pilot Lot		Solarex In-process Quality Control		Inspection and Testing of Completed Component for Conformance to Specifications	
	by Solarex	by Customer	on Sample basis ⁽¹⁾	100%	at Pt. of Manufacture	at Project Receiving
Concentrator cells	X	X		X	X	
Other receiver components (diodes, encapsulant, adhesive, extrusions, fittings, etc.)	X			X	X	X
Completed receivers	X	X		X	X	
Sagged glass mirror sections	X		X			X
Sun sensors	X			X	X	
Tracking drive motors	X		X			X
Other quad ⁽²⁾ components (frames, pipe, gears, wire, fittings, etc.)	X					X
Completed quads, including trough/receiver alignment, wiring, drive hardware, plumbing, and mounted sensors	X	X		X	X	
Storage batteries	X	X	X			X
Inverters					X	X
Data acquisition hardware					X	X
Structural steel	X					X
Thermal system components (pumps, storage tank, heat exchangers, pipe, cooling tower, fittings)						X

NOTES: (1) Indicated in-process quality control procedures will be performed by Solarex personnel, and will be in addition to, and in verification of, in-process control which will be required of all suppliers and subcontractors.

(2) For purposes of this program, a quad comprises 4 gang-mounted troughs with receivers and other associated tracking, thermal, and electrical hardware.

TABLE 4-1. PROCUREMENT AND QUALITY ASSURANCE PROCEDURES FOR MAJOR COMPONENTS

before tooling and production processes are finalized and commitment is made to the complete Phase II delivery requirement. It should also be emphasized that Solarex will provide the customer with ready access to key facilities for the purposes of pilot-lot and other acceptance-testing operations.

4.8.2 Electronic Subassemblies

It is Solarex's experience that the most effective technique for quality assurance of state-of-the-art electronic equipment is in-plant inspection and testing for conformance to program specifications before shipment. Such a procedure assures prompt discovery of malfunctioning or otherwise defective equipment and expeditious repair or replacement. The more sophisticated electronic subassemblies, e.g., data acquisition hardware and power conditioning equipment, will therefore be inspected and tested by Solarex at point of manufacture.

4.8.3 Array Quads

A vital project milestone is the assembly, installation, and checkout of the first quad, including concentrator troughs and solar receivers, tracking and thermal control equipment, and output wiring. Provision will be made to expedite completion of the first quad so that timely feedback can be incorporated in further hardware production and testing.

Since the basic quad design has been extensively tested during Phase I, no significant problems are expected. Expeditious completion of the pilot unit will, however, give added

confidence to project management, provide a basis for standardization and calibration procedures, and reveal technical, procedural, or material problems early enough to permit corrective action without major schedule disruption. Major coordination between Solarex and the customer is planned to ensure the establishment and application of uniform standards and calibration techniques. These standards and techniques and others established by Solarex will be applied to the output of all suppliers and subcontractors.

Dimensional control of arrays will be ensured by the use of a jig or fixture which will accurately reflect the dimensions and general conformation of quad support structures.

4.8.4 Quad Support Structures

Rapid and cost-effective construction of quad support structures will be enabled, even before delivery of quad frames, by the use of carefully constructed mechanical simulators. One example of such a simulator is a quad mock-up. Essentially a mirror image of the jig referred to in Section 4.8.3, it will reflect quad dimensions exactly, enabling accurate installation of support structures. Similar mechanical simulators will provide cost-effective control of general construction conformation and array field configuration, spacing and orientation.

4.8.5 Component Delivery, Inspection, and Conformance Testing

All components will be inspected and tested for conformance to procurement specifications on receipt at Solarex. In addition, as indicated in Table 4-1, specific key components will also be inspected and tested at point of manufacture.

A detailed delivery schedule will be developed for all components, materials, and software; project control will maintain daily cognizance of delivery status, and acceptability of delivered items for project incorporation.

Such major construction areas as site preparation and array field installation will be performed by the General Contractor. Solarex will insure the performance of the General Contractor and insure the integration and cooperation of all subcontractors contributing to this effort.

4.9 Project Management

This program will be managed by John V. Goldsmith of Solar-ex Corporation. Mr. Goldsmith will provide executive direction for all program activities, and will bear primary responsibility for program planning, budgeting, and scheduling; progress monitoring, program control, and reporting.

The program will be initiated with a detailed plan that sets forth the objectives, the schedule, and the budget for each of the participants. They, in turn, will convert the overall requirements for each of their respective groups into detailed task descriptions, detailed schedules, and budgets and task assignments, and will submit their plans to the Program Manager for approval. Then a comprehensive reporting and milestone schedule illustrating the task integration will be developed for implementation.

Program management will be facilitated by employment of a computer-assisted Program Evaluation and Review Technique (PERT). All tasks and subtasks will be both charted and recorded in com-

puter files. All milestone tasks and critical tasks (i.e., those which require on-time accomplishment to prevent major program schedule disruption) will be defined and highlighted. Both computer and chart-form (PERT) data will be updated at least weekly, allowing immediate identification of problem areas.

A portion of program monies will be reserved as a contingency fund, which monies will be applied to those critical tasks which threaten to disrupt schedule integration or achievement of program goals. Four-digit account numbers compatible with Solarex's computerized accounting system will be established for the program, in which all expenditures, categorized by the same work breakdown structure used to define program tasks and subtasks, will be accumulated. Subcontractor and team-member expenditures will be reported weekly to Solarex, which will verify all claims before processing for payment. Strict cost control will be accomplished by requiring prior approval by the Project Manager of all expenditures for labor or material. Costs will be reported and billed to the customer monthly in whatever depth of detail is required.

4.10 Communications and Control

The Program Control function will be established at the Solarex Rockville facility. Weekly progress reports via TWX or telex will be required of all participants.

A three-day start-up review will be presented to all participants. Integrated task assignments, budgets, and schedules will be discussed and verified at this meeting, which will

include all team members, consultants, the General Contractor, and all subcontractors. Succeeding meetings for review of progress, updating of PERT chart and program, and adjustments to task load, budget, and schedule, will be scheduled (A) weekly with team members and General Contractor and (B) every two weeks with the complete program group.

All contracts issued by Solarex Corporation shall include clauses permitting termination for reasons of non-performance, and shall also include provisions for liquidated damages as compensation for delays and/or increased expenses incurred as a result of subcontractor non-performance. The Program Manager or his designee will conduct monthly inspections at the facilities of major suppliers, the General Contractor, and subcontractors for the purpose of verifying progress as reported by TWX, examining hardware in manufacture, and coordinating subcontracted tasks.

5. Component Specifications

5.1 Introduction

The components specified for the Phase II system are described in this section. They have been selected based on pre-award experience, experience gained during the construction and operation of Phase I prototypes, and the systems analyses described in Section 3.

5.2 Photovoltaic Cells

5.2.1 Cell Selection and Design

For this linear-focus concentrator system Solarex has designed a linear concentrator cell from a generic class of design rules developed for Sandia Laboratories under the Concentrator Solar Cell Manufacturing Development Program (Contract #05-6391). Details of the design considerations and calculations are included in the Task I, Interim Report, Report No. SX/117/1 and the Final Report No. SX/117/F for that contract. The cell size was determined by the optical concentrating system, the availability of standard silicon wafer sizes, and the need to maximize cell length along the focal line to minimize array assembly labor.

The cells have interconnection buses on two opposing edges to provide redundant interconnection and to reduce the current path length in the gridline metallization. The active area is 5 cm wide with 0.25 cm-wide pads along both edges. 4.3 cm in length, this cell can be made within a round wafer sliced from a commonly available 3-inch diameter ingot. Figure 5-1 shows the details of the cell geometry.

5-2

FIGURE 5-1

ALL LINE WIDTH 0.0005,"
HORIZONTAL CENTER TO
CENTER 77 SPACED AT 0.026"

		UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE:		CONTRACT NO.		SOLAREX CORPORATION 1335 PICCARD DRIVE ROCKVILLE, MD 20850 □ 301 948 0202	
		FRACTIONS DECIMALS ANGLES		APPROVALS	DATE	SOLAREX COLLECTOR CELL	
		± .XX ± ±		DRAWN D. LEBOWITZ	9-15-78		
		± .XXX ±		CHECKED J.H.W.	9-15-78		
		MATERIAL					
		FINISH					
NEXT ASSY		USED ON				SIZE A	CODE IDENT NO. R D
APPLICATION		DO NOT SCALE DRAWING				DRAWING NO. 0093	
				SCALE 2X		SHEET OF	

Solarex concentrator cells are $n^+ - p - p^+$ type cells employing gaseous diffusion for junction formation and Al p^+ formation. The gridline metallization pattern is generated by photolithography. The metallization is Ti-Pd-Ag, with the bulk of the current-carrying material consisting of electroplated silver. The n^+ sheet resistance, metallization resistance, and bulk resistance are all minimized under processing and efficiency constraints as outlined in the referenced reports. Textured-surface cells are proposed for this application in order to improve the cell efficiency by increasing both the percentage of light absorbed by the cell and the minority-carrier collection efficiency. These cells are designed to meet all of the cell specifications set forth in JPL Document #5-34-2-1, "Silicon Solar Cell Performance, Environmental Test and Inspection Requirements," Rev. B.

Since the solar cells designed for this program are generically similar to the cells designed and fabricated for Sandia, the component development is well-documented. Thousands of cells have been fabricated for this effort, the Sandia program, and other government and commercial orders. Component performance and durability is well-documented, with cell performances as defined in the Cell Specification predicted from Phase I data.

All of the solar cells will be fabricated by the Solarex Corporation. The number of cells required for this program, approximately 45,000 can be produced over a 6-month period, commencing within a few weeks of the start date of a contract. Up to 4,000 cell starts a week can be scheduled to produce the required number of cells.

5.2.2 Cell Type Specifications

- n on p with Al p^+
- Silicon: Boron-doped, single crystal CZ, p-type, 100 orientation, with resistivity between 0.2 and 0.6 ohm-cm.
- Pyramid textured surface
- Contact material: Front and back contracts Ti-Pd-Ag (both solderable and weldable).
- Antireflective Coating: Durable high-index tantalum oxide (Ta_2O_5).
- Contact Thickness: No less than 15 μm of silver in the interconnect attachment areas on both front and back of cell.

5.2.3 Performance Specifications

- Power Output: Lot minimum average 4.7 watts at 15 suns uniform illumination at 28°C (15.7% efficiency)
- Temperature Coefficient: Less than 0.35%/°C decrease in maximum power at 15X concentration.
- Less than 10% loss in output power due to off-axis illumination non-uniformity of up to 60 suns (same total area integral).

5.2.4 Environmental Characteristics

- Thermal Cycling: Cells withstand more than 250 cycles from 150°C to -180°C.
- Temperature-humidity Storage: Cells withstand storage at 90% relative humidity and 75°C for 30 days.

- Contact Integrity: Cells accept welded and soldered tabs both before and after thermal cycling and temperature-humidity storage.

5.3 Solar Receiver

This specification pertains to the solar receiver, that part of the system which contains the photovoltaic cell string and thus carries out the energy conversion. It consists of a coolant-carrying hollow aluminum extrusion with the solar cell string and all necessary electrical parts such as diodes, interconnects, etc., mounted on it. The Solarex receiver specified is a well-developed device since it shares the technology of the design developed for the MCCC project. Receivers for MCCC were subjected to extensive tests--with excellent results--both at Solarex and at Honeywell. Solarex's tests have been documented in the Solarex Document SOLQ-CR-378 A which has been submitted to TEAM, Inc. of Virginia.

The receiver is highly resistant to impact, with solar cells protected by means of coverslides and electrical connections fully encapsulated for corrosion prevention. The receivers will be built by Solarex using production techniques developed during the performance of several concentrator programs. Plans exist already for large-volume production of concentrator receivers for the MCCC project; the same logistics will be used to manufacture the required 640 receivers within this project's four-month time frame.

5.3.1 Receiver Specifications

(A) Receiver

Length, overall	3.2 meters
Width, overall	89 mm
Cross section	Shaped to accept cell string, coolant, diodes, interconnects and wires for encapsulation
Nominal Operating Voltage	18 Volts
Maximum Operating Current	20 Amps
Number of Solar Cells	70
Supplier	Solarex Corporation

(B) Subcomponents

1. Receiver tube

(a) material	Al 6063-T52
(b) surface finish	anodized
(c) flow ports	3/4" threaded (2)
(d) cell surface width	1.96"
(e) supplier	Solarex

2. Solar Cell

See 5-2

3. Coverslide

(a) material	0.02" Microsheet
(b) thickness	0.018" to 0.024"
(c) size	4.28 cm x 4.58 cm
(d) supplier	J. Melvin Freed, Inc.

4. Cell Interconnect

(a) material	OFHC Copper
(b) surface	tinned
(c) thickness	0.005"
(d) configuration	Center accordion
(e) effective length	7.0 cm
(f) effective width	1.1 cm
(g) supplier	Wyngard Stamping Co.

5. Diode

(a) material	silicon
(b) crystallinity	single crystal, CZ
(c) base dopant (p-dopant)	boron
(d) base resistivity	1 Ω cm
(e) n-dopant	phosphorus
(f) thickness, nominal	0.03 cm
(g) size	1 cm x 1 cm
(h) metallization	Trimet ^R
(i) reverse breakdown voltage, min	12 V
(j) leakage current, max at 10V	10mA
(k) supplier	Solarex

6. Diode Interconnection

(a) material	tinned OFHC copper
(b) thickness	0.004"
(c) width	0.125"
(d) length	As required
(e) supplier	Wyngard Stamping Company

7. Output Pad
 - (a) material Fiberglass-reinforced Teflon cloth, copper clad
 - (b) size, nominal 1 cm x 1 cm
 - (c) thickness, nominal 1/16"
 - (d) clad thickness 0.002"
 - (e) supplier Fluorglas
8. Output Wires
 - (a) wire size #12AWG
 - (b) insulation silicone rubber
 - (c) length (min) 3 ft.
 - (d) conductor material copper tinned
 - (e) supplier Belden, 33312
9. Cell Mounting Adhesive
 - (a) thickness 0.005", nominal
 - (b) thermal conductivity $0.003 \frac{\text{cal}}{\text{sec cm } ^\circ\text{C}}$
 - (c) supplier Solarex
10. Cover Slide Adhesive
 - (a) transmittance (AM1) 99%
 - (b) supplier Dow Corning

5.4 Reflectors

Each photovoltaic array contains four parabolic cylindrical reflective troughs formed by 12 mirrors each (shown in Figure 5-2). Each trough has an active area for solar radiation of 3.2 m by 1.0 m. The mirrors are held in place by a metallic frame which tracks the sun, causing the mirrors to focus solar energy onto the receiver. These mirrors are already fully developed, having been employed for years in large numbers in thermal concentration systems. These systems have been field-tested in a wide variety of climates, displaying excellent weatherability and negligible performance degradation over many years of use. Their specular reflectance is illustrated in Figure 5-3. Typically 90% over the silicon absorption band, it is practically immune to long-term degradation. Surface dust accumulation is periodically removed by washing if natural rainfall does not suffice.

The mirrors may be procured from: Polisolar, Bern, Switzerland; or Schott Glass, N.Y., N.Y. in quantities of 8500 over a five-month period.

Parabolic shape according to
 $x^2 = 2200y$

PARABOLIC MIRROR
 Figure 5-2

Figure 5-3 MIRROR REFLECTANCE VS. WAVELENGTH

5.4.1 Mirror Specifications

(a)	Material	sagged glass
(b)	Thickness	3 mm
(c)	Mirror Type	second surface
(d)	Shape of Second Surface	parabolic cylinder
(e)	Equation of Para- bola	$x^2 = 2200 y$
(f)	Focal Length	550 mm
(g)	Mirror Layer	silver, copper backing and protective lacquer
(h)	Mirror Edges	sealed with protective lacquer
(i)	Mirror Length along Opt. Axis	$528 \text{ mm} \pm 0.5 \text{ mm}$
(j)	Mirror Full Aperture Width	551 mm
(k)	Supplier	Polisolar, Schott

5.5 Concentrating Collector

The basic unit of the photovoltaic array is a quad, which consists essentially of a large frame which carries four mirror-receiver assemblies. The four mirror-receiver assemblies track the sun's motion from east to west. The quad frame tracks the sun's elevation by pivoting around its lower (southern) edge. Operation of this true two-axis tracking system is more fully described in Sections 2 and 3.

Pipes in the quad frame and rotary fluid couplings allow coolant to be pumped through the receiver for active cell cooling. Coolant temperature, pressure, and flow rate sensors provide signals to the Energy Management System. In case of severe weather, e.g., hail, the EMS can override the analog tracking loop and slew all mirror troughs to a protected position.

The tracking concentrator assembly described above is not a new device, but a modification of a tracker which has been extensively tested and deployed as a component of solar thermal systems. Modifications required have been quite minor; Phase I operation and testing indicate that the changes have had no adverse impact on the assembly's capabilities, reliability, or capacity to tolerate stress.

The unit is operational in winds up to 35 mph, and may be moved to 'stow' position in winds as high as 40 mph. It will tolerate winds of 100 mph in any position without damage, and will operate with a snow/ice loading of up to 10 lb/ft².

Quad assemblies will be procured either from Solar Collector Corporation (a subsidiary of the Solarex Corporation) or from Polisolar, Bern, Switzerland. It is probable that the program's delivery and installation schedule will require procurement from both sources.

5.5.1 Concentrator Quad Specifications

(A) Dimensional Parameters

Width	5.6 m
Depth	3.5 m
Height, nominal	4.0 m

(B) Electrical Parameters

Voltage at operating point, nominal	72 Volts @ 20X, 55°C
Current at operating point, nominal	16 Amps, @ 20X, 55°C

(C) Thermal Parameters

Cell operating temperature	55°C, max
Fluid flow	2 gal/min
Cooling fluid	50/50 Water Glycol

(D) Tracking

Number of axes	two
Control	analog with sun sensors CPU override capability

5.6 Power Conditioning Equipment

There are three basic elements to the power conditioning system; a Delta Electronics maximum-power-point tracker with DC-to-DC conversion for interfacing the photovoltaic array with the battery storage; a Delta Electronics self-commutated three-phase inverter to power the production line, and a Windworks line-commutated inverter for providing power to the lighting and HVAC. These manufacturers are presently supplying this equipment for photovoltaic applications. Specifications for the three units follow in the subsequent subsections. All three units can be delivered within 120 days ARO, and are fully developed items already manufactured for other customers.

5.6.1 Maximum Power Tracker

Rating	200 KVA
Efficiency at rated power	95%
Input voltage range	210-500V
Output voltage range	190V to 275V
Minimum voltage differential	10V (preferred) 2V minimum
Series chopper & filter automatic array power point tracking supplier	Delta Electronics Irvine, California

5.6.2 Self-Commutated Inverter

Input

Voltage Range	190-275VDC
Current Range	0-250A

Output

Voltage	480V, 3Ø
Rating	62.5kVA, 0.8PF
P.F. Limits	<u>0.5 lag, 0.5 lead</u>
Voltage Regulation	± 1%
Output Quality	Under 3% T.H.D.
Phase Angle	120° ± 1° balanced load
Frequency	60Hz ± 0.05Hz
Overload Capacity	125% for 10 minutes 150% for 10 seconds
Efficiency	93% full rating 88% half rating
MTBF	<u>Over 8,000 hours</u>
Operating temp. range	-10°C to 45°C
Supplier	Delta Electronics Irvine, California

5.6.3 Line-Commutated Inverter

Input

Voltage Range	190-275VDC
Current Range	400A, 1000A peak

Output

Voltage	480V, 3Ø
Rating	100kVA

Output Quality	2% THD
Motor Starting Capacity	1hp/kW
Overload Capacity	200% for 2. minutes
Efficiency	85% full load 84% 3/4 load 83% 1/2 load 78% 1/4 load
Model #	PCV-1000
Supplier	Windworks, Inc. Mukwonago, Wisc.

5.7 System Control

System control functions will be handled by the central Energy Management System (EMS). Procurement and installation of this system would be performed by team member Radix II, Inc. which has extensive experience in similar energy management systems in numerous applications. All EMS components are well-developed "off-the-shelf" items, with which Radix II is thoroughly familiar. The entire diverse set of EMS components would be delivered and installed within 6 months ARO. A summary listing of the components of the EMS follows:

<u>Supplier</u>	<u>Item</u>
Digital Equipment Corp.	Model 1134 minicomputer, 128K 16-bit word capacity
Digital Equipment Corp.	TU-10, 800 bpi 9-track tape unit and controller
Digital Equipment Corp.	AAV-11A real-time clock
Digital Equipment Corp.	Digital communication multiplexer and DMA controller

<u>Supplier</u>	<u>Item</u>
Calcomp	Trident model multiplatter disk memory with 50 M-byte capacity and DMA controller
Centronics	Line printer, 300 line/min capacity and interface controller
Tektronics	4006 model graphics terminal and 4031 hard copy unit.
Radix II	Satellite microprocessors (field interface devices) (4 each)
Radix II	Signal transmitters (approx. 500 ea.)
Various	Hall-effect current sensors, temperature sensors, etc.
Various	Switchgear and valving (see succeeding sections)

5.8 Switchgear

The switchgear employed for circuit breakers, manual disconnect of main power lines and electromagnetic switching controlled by the central EMS is off-the-shelf hardware available from several manufacturers. Solarex has consulted with Holec of Utrecht, The Netherlands during the Phase I period concerning switchgear for this application. Holec has decades of experience in all aspects of designing, manufacturing, and installing electrical power handling systems from the component level through electrification projects. Holec manufactures both DC and AC switchgear for all of the needs of this application, with reliability in the tens of millions of operations.

The following switchgear would be procured during Phase II from Holec, with their assistance:

Field circuit breakers for 4-array groups	Type B-32-a
Half-field switchgear	Type GMC-414
Peak power tracker disconnect, battery disconnect, and array disconnect	Type RAS-12P
Inverter input switches	Type GMC-415
Inverter output switches (manual)	Type Dumeco
Inverter output switches (control)	Type GMC-415

All of this switchgear is deliverable within 60 days ARO.

5.9 Energy Storage

A bank of lead-acid storage cells will be provided to supply operating energy during periods of low insolation. The proposed battery bank will consist of 864 lead-calcium cells, each capable of 3kWh storage. The cells chosen are manufactured by C&D Batteries Division, their Model #2X4Q160-23. These large cells will be grouped in voltage modules with 12 cells per module. A total of 72 modules will have a storage capacity of 2.6MWh; the large capacity per module minimizes electrical interconnection and cabling.

Each module will be approximately 35 inches high and occupy 55 inches by 18 inches of floor space; each will weigh approximately 3800 pounds. Due to their size and weight, it will not be practical to stack the modules. The modules will be arranged in 8 rows of 9 modules each. All cells in a row will be connected in series, producing approximately 230 volts; the 8 rows will be connected in parallel.

From a number of battery firms contacted during the Phase I efforts, Solarex has selected C&D Batteries of Plymouth Meeting, Pennsylvania. C&D has considerable experience in cycling-type batteries for photovoltaic application, and we feel their 'Q-line,' long-life lead-calcium cells are the best available for an application of this type. C&D has a good consulting staff and an excellent track record in photovoltaic storage applications, some in concert with Solarex photovoltaic systems.

Both the charging current and maximum voltage will be controlled which will tend to alleviate the release of hydrogen. However, as a safety measure, hydrogen detection will be employed in conjunction with an exhaust system. The storage room will be heated by the thermal output from the array to keep battery operation at peak efficiency.

5.10 Thermal System

The thermal system described in Section 3-8 has numerous components, which are specified in detail in Table 5-1. These components include piping, pumps, valves, cooling tower, heat exchangers, and storage tanks, all of which are off-the-shelf items.

Specific testing for durability or performance for the large components was not within the scope of the small prototype in the Phase I effort. However, all are items whose performance, reliability, and longevity has been field-proven in numerous applications.

Table 5-1 THERMAL SYSTEM SPECIFICATIONS

COMPONENT	SPECIFICATIONS	EXPECTED SOURCES	DELIVERY SCHEDULE
COOLING TOWER	Ejector Cooling Tower Model J1205-B Nominal Rating: 160 tons Flowrate: 450 gpm Design pressure: 75 psi	Baltimore Aircoil Company	6 - 8 Weeks
ARRAY TO COOLING TOWER HEAT EXCHANGER	Plate and Frame Heat Exchanger Superchanger Model 6-HP-156 Design Pressure: 75 psi Design Temperature: 120° C Plate Material: Stainless Steel Number of Plates: 156 Surface Area: 621.6 sq. ft. Weight: 2150 lbs.	Tranter, Inc.	4 - 6 Weeks
ARRAY CIRCULATING PUMP	350 gpm @ 45 ft. Head 5 hp centrifugal pump 1725 rpm	Pacific Pumping Company Gelber Pump Co.	8-10 Weeks
D.C. MOTOR FOR ARRAY PUMP	5 hp Shunt Wound D.C. Motor Model 1810-AT 1750 rpm	Powertron Corp.	8 - 10 Weeks
COOLING TOWER PUMP	450 gpm @ 150 ft. Head 15hp Centrifugal Pump 1750 rpm	Gelber Pumps LaBour Pumps	8 - 10 Weeks

Table 5.1 continued

D.C. MOTOR FOR COOLING TOWER PUMP	15 hp Shunt Wound D.C. Motor Model 253-AT 1750 rpm 240 V	Powertron Corp.	8 -10 Weeks
THERMAL STORAGE TO HEAT EXCHANGER PROCESS WATER LOOP PUMP	20 gpm @ 30 ft. head 1 hp Centrifugal Pump 1725 rpm	Gelber Pumps LaBour Pumps	2 - 3 Weeks
D.C. MOTOR FOR ABOVE PUMP	Model 4580 TEFC 1 hp 180 VDC, 2.8 Amps Rated Torque: 8 in-lbs 1725 rpm	Indiana General	4 - 6 Weeks
THERMAL STORAGE TO SYSTEM CONTROL CENTER LOOP PUMP	5 gpm @ 20 ft. Head 1/4 hp Centrifugal Pump	Gelber Pumps LaBour Pumps	3 - 4 Weeks
D.C. MOTOR FOR ABOVE PUMP	Model 4518 TENV 1/4 hp 180 VDC 2.8 Amps Rated Torque: 8 in-lbs 1725 rpm	Indiana General	4 - 6 Weeks
THERMAL STORAGE TANK	20,000 Gallon Capacity 10 ft. Diameter, 31 ft. Length 1/4" Thick Steel 6" Mylar-Wrapped Fiberglass Insulation	Buffalo Tank Division	8 - 12 Weeks

Table 5.1 continued

PROCESS WATER TANK	2000 Gallon Steel Tank 4" Mylar-Wrapped Fiberglass Insulation	Buffalo Tank Division	8 - 12 Weeks
EXPANSION TANK ON ARRAY LOOP	Amptrol Co.'s AX-450 Spherical Tank Acceptance Volume: 125 gallons Tank Volume: 250 gallons	Amptrol Company	6 - 8 Weeks
PIPING	4800 ft., 2" ID 1500 ft., 6" ID Black Galvanized Steel Pipe 1" Mylar-Wrapped Fiberglass Insulation	Anaconda Co.	6 - 8 Weeks
SOLENOID BYPASS VALVES	Two Temperature Controlled Three-Way Valves 6-inch Pipe Carbon Steel -20 to +400°C Temperature Setting	Foxboro	8 - 10 Weeks

6. Phase III, Operation and Evaluation Technical and Management Plan

6.1 General

Among Phase I tasks was the development of technical and management plans for the operation and evaluation of the system in Phase III. These plans are described in this section.

6.2 Phase II Purpose

The purpose of Phase III is to:

- operate the system for 1 year using both the Solarex and the independent DOE data acquisition systems,
- tabulate, evaluate and report this data with recommendations for improving the system,
- determine the operating performance and overall system efficiency including the annual net energy delivered in kWh considering tracking motor, inverter and other losses,
- recommend approaches to improving performance that would increase annual net energy delivered and and improve the peak watt per dollar average output,
- determine analytically from actual system operation the economic characteristics of the system; primarily from capital investment required in 1979 dollars per peak watt, and the system life-cycle costs per peak watt and per net annual kWh for 30 years.

6.3 Management Organization

The management organization is structured according to the

functions to be performed in Phase III. These functions are as follows:

1. Operate the system for 1 year, including maintenance and repair as required;
2. Record data on operation of the system and the resultant system performance;
3. Record the actual system reliability, power availability, and maintenance and evaluate the economic performance of the system using the Data Acquisition and Control system;
4. Compare the actual operating results with expected performance and efficiency predicted on the basis of solar insolation and temperature;
5. Provide monthly technical progress and financial reports as well as final technical and financial reports.

The Phase III Project Management Chart presented in Figure 6-1 shows an organization which is matched to the functions described above. The organization includes the Phase III Program Manager and branches which perform the following functions:

1. The Data Acquisition and Control System ; Supervises the DAC operation, programming and check out, including the program which computes the operational standards used for evaluating the actual daily data. This branch is responsible for the operation of both the Solarex and the DOE Uniform Data Acquisition Systems.

Figure 6-1
PHASE III PROGRAM MANAGEMENT CHART

2. Performance Analysis: Establishes the performance parameters and the analysis used as the basis for evaluating the overall performance of the system;
3. Economic Analysis: Includes the acquisition of economic data, analysis and the establishment of economic projections for system operation;
4. Reliability, Availability and Maintenance: Conducts analysis and to determine if the system is performing as predicted by the reliability, availability and maintenance simulation models;
5. System Operations: Operates the system and conducts the various maintenance operations and repairs.
6. Personnel and Social Impact: Evaluates the impact on employees (and their interaction) of the solar dependence of their working environment.

6.4 Operating Plan

The approach planned by Solarex to achieve the purposes outlined in the preceding section is shown in Figure 6-2, Phase III PERT Chart. Preparation for Phase III would take place during the time that the system is being installed and checked out so that the Data Acquisition and Control System is delivered, programmed, checked out and ready to start operation when Phase II is completed.

Phase III includes:

1. the appointment of the Phase III Program Manager
2. the implementation of Phase III team operations

Figure 6.2 PHASE III PERT CHART

3. the assignment of a Phase III project staff arrangement which differs from Phase II and requires the following specialists:

- a. a system engineering performance analyst
- b. an electrical system reliability, availability and maintainability engineer
- c. operating engineers and technicians
- d. system maintenance and repair technicians
- e. personnel specialist (part time)

4. Implementation of the Phase III operating mode for the Breeder production line, including Personnel Department involvement in scheduling operational flexibility, Production Engineering planning for manufacturing equipment utilization and provision for manufacturing equipment utilization and provision for pre-processed wafer stockpile storage modes.
5. Team member responsibilities in Phase III are as follows:
- Solarex - Project Management
 - System Operation and Data Collection
 - System Analysis; Electrical, Thermal and Economic
 - Sociological and Operations Analysis of Breeder Line

- Radix II
 - DAC and EMS Maintenance
 - Software Consultation and Support
- Windworks
 - Power conversion System; Consultation and Evaluation
- Mueller Associates
 - Thermal System; Consultation and Evaluation
- E. Cohn
 - Electrical Storage System; Consultation and Evaluation

6.5 Uniform Data Acquisition System for DOE

An independently operating data acquisition system could be provided by DOE to monitor the performance of the Solarex 200 kW concentrator photovoltaic system.

The uniform data requirements for the DOE Uniform Data Acquisition system are recognized as containing two parts:

- 1) transducer inputs from the solar array, power conditioning system, thermal system and a Class 1 meteorological station,
- 2) a method through which information classified as "soft data" can be generated. Pertaining to the transducer inputs Solarex is able to provide three optional avenues of meeting this requirement, pending decisions reached during negotiations for Phase II. Briefly, these options are as follows:

- Solarex provides duplicate tapes of the Solarex Energy

Management system data exclusive of the DOE computer data obtained from its Class 1 meteorological inputs.

- Solarex provides a serial interface between the Solarex Energy Management computer and the DOE onsite data acquisition computer to transmit raw data stored on high-speed disk file at periodic intervals
- Solarex provides DOE (on a CPFF basis) a complete parallel set of input sense line and acquisition strategy as previously described in Section 3.7.4 which will cover the full gamut of measures stipulated in the DOE document generated from the Phase 1 Contract Initiation Meeting.

In general, it is Solarex's contention that full duplication of transducer inputs is not cost-effective. If DOE should select either of the first two options stipulated above Solarex will assist in Phase II inspection of all software programs and data logging methods for verification as to the type and quantity information to be provided.

The system would be designed to meet all the Data Acquisition System requirements set forth in the description issued from the Photovoltaic Concentrator Applications Experiments Phase I Contract Initiation Meeting held June 1, 1978 at Sandia Laboratories by the DOE Albuquerque Operations Office. Solarex is proposing options to DOE for their Uniform Data Acquisition

System at this site, one that is completely responsive to all of the requirements of DOE but quite expensive, plus other approaches which would functionally provide virtually all of DOE's requirements but would be much more cost effective.

6.6 The Solarex Data Acquisition and Control System (DAC)

The Solarex DAC differs from the DOE system in that it includes a number of control functions and will definitely include the computer program which will generate the standard values against which the engineering performance of the system and its efficiency would be compared daily, as well as the reliability, availability, and maintenance operations and the economic performance of the system would be compared and summarized in each month's report. The Solarex system also will include the latest proven approach in sensor input which greatly reduces overall system cost, reduces pick-up noise effects and significantly improves the signal/noise ratio at the first stage of the DAC. The DAC also includes multiplexing functions which will greatly improve overall performance and decrease costs as compared to other systems which do not include these functions.

The Solarex data acquisition plan entails a set of interactive operations that will be integrated to function under partial control of the Solarex computer-based energy management system. Essentially, the foreground system package will comprise a set of reporting and system diagnostics and evaluation. In principle the computer will perform continuous online

data logging and statistical operations analysis of the system.

Information directly relevant to the overall system performance will be analyzed daily during off-times when the solar arrays are not engaged in active tracking. At night a series of performance evaluation analysis programs will be loaded via time-actuated batch processing into the minicomputer's memory which will generate reports of the systems operation for the day.

Samples of the types of evaluative analysis of the system performance that will be performed are:

- Graphical and printed output of energy output and consumption of the system for the day
- Comparison analysis of actual system operation versus the conceptual performance model, with performance normalized for temperature and other environmental and operational constraints.
- Failure mode analysis and system check-out alerting: This comprises the following functional information groups:
 1. Analysis, evaluation and reporting of control operation statistics. This includes frequency and duration of: Inverter on/off contact closures, storage status update, etc.

2. Thermal system function operations.

These generated reports will be the fundamental basis by which the data acquisition system manager will be able to expedite check-out or repairs on individual components.

Staff members delegated to perform maintenance on the system will be issued forms that will require on-site evaluation of the problem, and documentation of the type and nature of failure, probable causal factors, estimated time to repair the component, whether or not replacement is recommended or if an on-site repair can be made. These data are in turn rerouted to the Data Management supervisors and logged manually into the data management network. In compliance with the Uniform data requirement classified under soft data, the computer data acquisition system will serve as one evaluative source of input toward investigation and optimization of overall system operation in connection with the following subset of "soft" measurements required by DOE:

1. Scheduled and non-scheduled cleaning, maintenance, calibration and repair;
2. System down-time, and
3. Component and equipment failures

6.7 Performance Analysis

During Phase III, analyses will be conducted to compare the actual daily performance of the system against its projected performance. The Performance Analysis group of the

Phase III organization would develop equations and parametric performance values that take into account the variation in direct normal solar insolation as measured by a calibrated pyreheliometer, the receiver cell temperature, and the accuracy of the solar tracking system to determine the projected output of the receivers as compared to the output actually measured at various time intervals during the day. The input and output values of each receiver string and all the electrical and thermal system elements will be measured, the performance, efficiency and transfer characteristics of each significant element of the system will be evaluated and compared.

All out of performance range values will be calculated and graphed in print-outs from the mini-computer system. This approach of comparison against projected performance greatly simplifies the monitoring of system operation.

6.8 Reliability, Availability and Maintainability Analyses (RAM)

During Phase II a computer simulation model will be written and checked out which uses the best available sub-assembly and component data to generate the overall probable system MTBF and the associated standard deviation. The photovoltaic system is designed so that local mirror or receiver degradation will only have a relatively small effect on the overall output of the array. The model would simulate the probability of such small decreases in output versus time as well as other failures. The system is configured so as to minimize the impact on overall

system power output of both partial and complete component and sub-assembly failures.

The model would also estimate overall system availability versus full rated power output and fractional power ratios including the probability of failure of system elements and their Mean Time To Repair, MTTR, based on stated assumptions regarding the immediate availability of repair parts. When this RAM analysis is completed during the Phase II program, the results will be reviewed and inventory will be generated for those economically effective relatively high probability replacement parts that have lead times of more than 3 days and whose failure would reduce the output power of the array by more than 5 percent. Thus the Phase II RAM analyses will be used to order spare parts for the system to minimize the product of power loss and down time.

In addition, periodic measurements of changes in system components would be performed to predict both life and regular maintenance requirements. For example, mirror segments would be removed and measured for spectral reflectance changes, receivers would be removed and evaluated for individual characteristics, thermal components would be removed and evaluated for corrosion, etc.

6.9 Economic Analyses

The computer program developed during Phase II will have cost parameters and routines to compare both the initial capital investment and life cycle costs discounted to 1979 dollars.

The program will also take into account the probable failure rates of various system elements and the resultant impact on the daily net energy produced from the array. Thus the program will provide a baseline or reference capital investment plus monthly and annual life cycle cost to which the actual life cycle cost of the operating system can be compared.

The actual capital investment and the actual operating cost for the system will be calculated for each month of operation and the daily and monthly average for the project to date will be compared with the initially estimated costs. The model will be updated at periodic intervals so that at the end of the program the correlation between the estimated investment and annual life cycle costs will be improved, and the economic analysis program will be a more accurate tool to be used to predict the probable life cycle and/or operating cost of future projects.

6.10 Non-Technical Issues: Personnel and Social Impact

This project offers an excellent opportunity to study the effects of solar dependence on a manufacturing organization, including the psychological and sociological impact on personnel, the effects on productivity and manufacturing economics, and safety.

Solar dependence will require new flexibility of management and production workers, a flexibility mandated greatly by weather. Various steps are considered to optimize productivity, including the scheduling of energy-intensive processes during

periods of high insolation, the rescheduling of personnel to either alternate jobs or alternate work schedules (e.g., shorter work weeks during low insolation--longer work weeks during high insolation), and stockpiling cells processed through the most energy-intensive steps during periods of high insolation.

These solar-dependent adjustments will be documented in a log book along with the records of production, maintenance, safety, and personnel assignments. In addition to the log book, a management report will be prepared monthly. This report will include a summary of the monthly production, a discussion of any problems related to the production line, and a discussion of the effects of the solar dependence of the production line. The productivity of the production line will be compared with the productivity that would be expected from an equivalent production line utilizing utility power.

The solar dependence of the production line will have both psychological and sociological impact on the production personnel which will be reported in the log and reports previously mentioned. These employees will be required to vary their work schedule. Techniques under consideration include 1) a sliding work schedule so that employees have a shorter work week during the winter and longer work week during the summer; or 2) reassignment to alternate jobs during periods of low insolation. It is most likely that a combination of a sliding work schedule and job reassignment will be employed.

During short periods of low insolation, low-energy-requirement jobs such as maintenance, testing, forms and reports completion can be performed. However, during extended bad weather personnel may be required to work a short work week with the opportunity to make up lost time during high-insolation periods. Details of this sliding work schedule and its effects on the personnel involved will be recorded in the log book.

Appendix

```

LIST
1 GOTO 9
2 GOTO 9
3 GOTO 9
4 GOTO 9
5 GOTO 9
6 GOTO 9
7 E=1
8 X=#300A:K=0:J=42:GOSUB 300
9 @#3001=0:@#3002=0
10 LINK #20F8:H=@#1124:M=@#1125
15 LINK #20F8:N=@#1125:GOSUB 650:GOSUB 550
20 IF ((H<4) OR (H>21)) GOTO 15
25 IF(M=N) GOTO 15
30 IF(M>N) GOTO 40
31 IF(M=0) GOTO 41
35 Q=MOD(N,M):GOTO 45
40 IF(N=0) GOTO 35
41 Q=MOD(M,N)
45 IF(Q>2) GOTO 55
50 GOTO 15
55 GOSUB 200:GOSUB 400:X=#1201:Y=#300A:K=0:J=42:GOSUB 250
56 Z=#3269:X=Y:Y=#3061
57 IF(E=1) GOTO 59
58 GOSUB 370
59 GOSUB 250
60 X=#300A:Y=#301F:K=0:J=42:GOSUB 305:Y=#31BC:GOSUB 305
65 R=R+1:S=S+1
70 IF((@#3001=1) AND (R=15)) GOTO 120
75 IF((@#3001=2) AND (R=6)) GOTO 120
80 IF((@#3001=3) AND (R=3)) GOTO 120
85 IF((@#3001=4) AND (R=1)) GOTO 120
90 IF((N>57)OR(N<2)) GOTO 10
91 IF(S<30) GOTO 10
100 Y=#30B8:X=#31BC:K=0:J=42:T=S:GOSUB 830:X=Y
105 X=#300A:K=0:J=42:GOSUB 800:X=#30B8:J=42:GOSUB 800
110 R=0:S=0
115 GOTO 10
120 T=R:Y=#310F:X=#30B8:K=0:J=42:GOSUB 830:GOSUB 850
125 R=0
126 E=0
130 Y=#30B8:K=0:J=259:GOSUB 800
135 GOTO 90
200 @#1200=2:@#1201=2:@#1122=2:LINK #2088
201 IF(@#1123<>0)PRINT"OUTPUT ERROR"
202 LINK #2000:IF(@#1123<>0)PRINT "INPUT ERROR"
203 RETURN
250 FOR I=K TO J STEP 2
251 @ (Y+I)=@ (X+I):@ (Y+I+1)=@ (X+I+1)
252 NEXT I
253 RETURN
275 FOR I=K TO J STEP 2
276 A=@ (X+I)*256+@ (X+I+1)
277 B=@ (Y+I)*256+@ (Y+I+1)
278 A=A/B
279 @ (X+I)=A/256:@ (Y+I+1)=MOD(A,256)
280 NEXT I
281 RETURN
350 FOR I=1 TO 5
351 PRINT " "
352 NEXT I
353 RETURN
375 FOR I=1 TO 20
376 PRINT "***";
377 NEXT I
378 PRINT " "
379 RETURN
400 X=#1201
401 FOR I=0 TO 42 STEP 2
402 A=@ (X+I)*256+@ (X+I+1)
403 IF((I>0)AND(I<=13)) A=(A/4095)*100:GOTO 410
404 IF((I>=14)AND(I<=15)) A=(A/2048)*15:GOTO 410
405 IF((I>=16)AND(I<=23)) A=(A/102):GOTO 410
406 IF((I>=24)AND(I<=31)) A=(A/20):GOTO 410
407 IF((I>=32)AND(I<=34)) A=(A/102):GOTO 410
408 IF((I>=35)AND(I<=38)) A=(A*6)/10:GOTO 410
409 IF((I>=39)AND(I<=42)) A=(A/20)
410 NEXT I
411 RETURN
500 PRINT "TIME",H," ",N,"HOURS EST"
501 RETURN
550 IF((@#8033 AND S)<>8) GOTO 555
551 @#8035=0:PRINT"INPUT OPERATION MODE#":GOSUB 350
552 INPUT A:@#3001=A
553 PRINT "INPUT TAPE RECORDING MODE #":GOSUB 350
554 INPUT A:@#3002=A
555 RETURN
600 FOR I=K TO J STEP 2
601 A=@ (X+I)*256+@ (X+I+1)
602 PRINT Y," "
603 IF MOD(I,10) GOTO 605
604 PRINT " "
605 NEXT I
606 PRINT " "
607 RETURN
650 IF(@#3000>=253)@#3000=0
660 FOR I=0 TO 3
661 @ (#8002+I)=@#3000
662 @#3000=@#3000+1
663 NEXT I
664 RETURN
800 FOR I=K TO J STEP 2
801 @ (X+I)=@ (X+I+1)=0
802 NEXT I
803 RETURN
805 FOR I=K TO J STEP 2
807 A=@ (X+I)*256+@ (X+I+1)
808 B=@ (Y+I)*256+@ (Y+I+1)
810 B=A+B
814 @ (Y+I)=B/256:@ (Y+I+1)=MOD(B,256)
816 NEXT I
817 RETURN
830 FOR I=K TO J STEP 2
831 A=@ (Y+I)*256+@ (Y+I+1)
833 A=A/T
837 @ (X+I)=A/256:@ (X+I+1)=MOD(A,256)
838 NEXT I
839 RETURN
850 IF((@#3001<=0) OR (@#3001>4)) RETURN
851 GOSUB 375:GOSUB 500:PR" VOLTAGES":K=24:J=21:GOSUB 500
852 PR"CURRENTS":K=16:J=23:GOSUB 500:PR"TEMPERATURES"
853 K=0:J=10:GOSUB 600:PR"FLOWRATE":K=14:J=15
854 GOSUB 600:Y=X+16:X=X+25:K=0:J=7:Z=#300A
855 GOSUB 275
856 PR"POWER OUTPUT":X=Z
857 GOSUB 600
858 GOSUB 375
859 GOSUB 350
860 RETURN
870 FOR I=K TO J STEP 2
871 A=@ (X+I)*256+@ (X+I+1)
872 B=@ (Y+I)*256+@ (Y+I+1)
873 IF(A>B) GOTO 876
874 IF(B=0) GOTO 878:A=A*10:A=A/B
875 @ (Z+10+B)=@ (Z+10+B)+1
876 IF(A=0) GOTO 878:B=B*10:B=B/A
877 @ (Z+10+B)=@ (Z+10+B)+1
878 NEXT I
879 RETURN
910 PR"HOURLY REPOINT"
912 GOSUB 850:GOSUB 950
913 RETURN
950 PR" FREQUENCY OF TIME VARIATIONS":B=#3269
951 FOR I=1 TO 2
952 IF(I=1) PR" +BINS FROM 0% - 100%":GOTO 954
953 PR" -BINS FROM 0% - 100%"
954 FOR L=0 TO 9
955 B=B+J
956 A=@B
957 PRINT A," ";
958 IF MOD(L,10) GOTO 960
959 PRINT " "
960 NEXT L
961 PRINT " "
962 NEXT I
963 RETURN

```