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Sun Valley Photovoltaic Power Project

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Phase 1 — Final Report (June 1, 1978 to February 28, 1979)

Frank R. Goodman, Jr.
Los Angeles Department of Water and Power

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SUN VALLEY PHOTOVOLTAIC POWER PROJECT

FINAL REPORT ON PHASE ONE

1 JUNE 1978 -- 28 FEBRUARY 1979

FRANK R. GOODMAN, JR.

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FOREWORD

This report describes the work performed under Contract ET-78-C-04-4281 between the United States Department of Energy and the Los Angeles Department of Water and Power. The author wishes to acknowledge major contributions to the work upon which this report is based by N. J. Grossman and D. A. Laurie of Spectrolab, Inc. Additional contributions were made by D. B. Bauer, A. Kanov, and J. L. Perry of the Los Angeles Department of Water and Power.

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ABSTRACT

An application experiment was devised for fabrication, installation, operation, and evaluation of a concentrating photovoltaic system for direct conversion of sunlight to electricity. If the experiment is performed, the photovoltaic system will be connected to an electric motor load and to an electric utility system. Provisions will be made to allow the motor load to be supplied with power from either the photovoltaic system or the utility system. When the demand of the motor load is low, the photovoltaic system will deliver excess power to the utility system for use elsewhere. Thus, the experimental installation has been designed with sufficient flexibility to enable several modes of operation to be evaluated. This type of application is a typical example of on-site power generation at an individual load center involving two-way energy exchange with the adjacent utility system. Because a growing market for photovoltaic systems in this type of application is expected in the 1980's, the experiment will provide needed information in a timely manner. The experiment was carefully planned to identify and resolve technical and institutional problems that may be encountered with this new form of supplying electricity.

The experiment was devised jointly by the Los Angeles Department of Water and Power (LADWP) and its subcontractor, Spectrolab, Inc. LADWP will furnish a site and operate the equipment after installation. The subcontractor will manufacture and furnish a concentrating photovoltaic array with a power rating of approximately 200 kilowatts at one kilowatt per square meter of insolation. Other required equipment will be purchased to specification from appropriate suppliers. The photovoltaic system represents a state-of-the-art design at the time this report was prepared. However, minor design improvements may be made prior to and during system installation. All phases

of fabrication, installation and operation will be documented through formal reports. The results of the experiment will contribute to the goals of the National Photovoltaic Conversion Program. Actual performance of the experiment is contingent upon receipt of funding from the United States Department of Energy.

CHAPTER 1

INTRODUCTION

This report summarizes work performed to devise a utility interactive application experiment involving an array of photovoltaic concentrators. A detailed description of this work is given in subsequent chapters. In reading this report it should be kept in mind that the experiment has not actually been performed. The experiment is described as though it will be performed eventually based upon the hypothesis that funding will be provided by the United States Department of Energy (DOE), which may or may not be the case depending on the outcome of a variety of DOE programmatic matters. The experiment is intended to be highly instrumental in contributing to the goals of the National Photovoltaic Conversion Program being sponsored by DOE. Performance of the experiment by the Los Angeles Department of Water and Power (LADWP) would be in accordance with LADWP's goal of developing new sources of energy to assure an adequate future supply of electricity for its customers.

If the experiment is performed, LADWP will field test an array of photovoltaic concentrator devices under controlled conditions. Spectrolab, a well-established manufacturer of photovoltaic equipment, will serve as a subcontractor to LADWP. The experimental installation has been jointly designed by both organizations. Spectrolab will produce and supply the photovoltaic array. LADWP will install and operate the experimental equipment. An artist's conception of the installed project facilities is provided in Figure 1.1. The selected site is located in Sun Valley, a community in the northeast portion of the City of Los Angeles. This site receives good insolation throughout the year and is in close proximity to Spectrolab. The site is on land already owned by LADWP adjacent to the Valley Generating Station, a large fossil-fueled generating

Figure 1.1. ARTIST'S CONCEPTION OF SUN VALLEY PHOTOVOLTAIC POWER PROJECT

facility. The experimental installation will be known as the Sun Valley Photovoltaic Power Project.

The photovoltaic array has been designed for a peak output of approximately 200 kilowatts under optimal sunlight conditions. The design enables use of the array output in several ways. The array will be connected to LADWP's electrical distribution system and to an electric motor load. The electric motor load will consist of seven fan motors on one of the cooling towers for the Valley Generating Station. During periods in which the array produces more power than the demand of the motors, the excess power will be impressed into LADWP'S distribution system for use elsewhere. When the demand of the motors is greater than the array output, the distribution system will supply the difference. Thus, the installation is a representative example of an on-site individual load center (ILC) application of a photovoltaic array with capacity backup from an electric utility. A market for this type of application is expected to develop in the 1980's, and performance of the experiment would produce information pertaining to the operational considerations in a timely manner. Three additional unique features of the planned installation are noteworthy. First, when the array supplies power to the cooling fan motors, it displaces the need for power from the fossil-fueled generating units for this purpose. Thus, the net power deliverable from the units to the utility system for use by customers is increased. Therefore, in this mode the photovoltaic array acts in a hybrid manner to augment the output of the conventional generating plant. Second, the fan motors could be disconnected entirely, allowing all array power output to be delivered into the utility distribution system. This operational mode would simulate one module of a central-station photovoltaic power plant. Central-station photovoltaic array applications are not expected until sometime after the penetration into

ILC applications. The National Photovoltaic Conversion Program has a goal of making central-station applications realizable in the 1990's. Third, during a utility system outage the photovoltaic system can continue to supply power to the electric motor load by use of an emergency stand-alone mode of operation. In summary, this experimental installation will produce relevant operational experience and other necessary information regarding future applications of photovoltaic systems.

The installation will provide a mechanism for addressing various experimental issues, both technical and institutional, and thereby enable maximum information to be obtained in a single application experiment. The experimental installation will help identify preferred sites and applications for future widespread deployment of photovoltaic systems. Operation, safety, and maintenance requirements will be identified. Performance of individual components in the photovoltaic array will be assessed. Overall performance of the photovoltaic system and technical problems associated with integrating a photovoltaic system into a larger system, such as an electric utility system, will be assessed. An attempt will be made to identify the preferred owners, operators, and users of photovoltaic systems in various applications. For example, the benefits of ownership of an ILC photovoltaic installation by a utility versus a utility customer will be studied. Attention will be given to desirable financial incentives and to constraints arising from building and zoning codes for widespread deployment of ILC photovoltaic arrays. The suitability of various rate structures for utility customers with on-site ILC photovoltaic arrays will be studied. The installation, operation, and maintenance costs will be monitored to help establish future cost objectives for photovoltaic equipment in various applications. Finally, a significant amount of favorable public visibility for the project

and the National Photovoltaic Conversion Program is desirable. The contrast of a photovoltaic installation alongside of a conventional generating facility will allow some unique opportunities in this regard.

The Sun Valley Photovoltaic Power Project, as conceived by LADWP, will utilize 20 Spectrolab photovoltaic concentrator subsystems, each rated in excess of 10 kilowatts of peak electrical power generating capability. This peak power rating is based on a standard test environment having an ambient air temperature of 28°C, wind speed of one meter per second, and direct normal insolation of one kilowatt per square meter. Each of these subsystems can be viewed as an independent power generating unit. The performance characteristics of each subsystem are representative of the performance characteristics of all 20 subsystems.

Each subsystem utilizes two-axis tracking and is comprised of 40 concentrator units supported by a common structure. Each concentrator unit uses two-stage optical concentration consisting of a linear parabolic trough primary mirror and a compound elliptical secondary mirror. The optics are designed to provide an overall effective clear aperture of 131.7 square meters per subsystem. The concentrator units are mounted on a low-profile steel truss framework which rotates in azimuth and is supported on a circular concrete track. The azimuth solar tracking is driven by one of four wheels which ride on the concrete track. In the center of the concrete track is a pintle bearing which transmits wind-induced shear loads to the ground. The elevation solar tracking is driven by four electrical linear actuators with parallel and series linkages to move all of the 40 concentrator units in unison. A solar tracking control system is used for the two-axis tracking of the sun. This control system includes logic for such functions as night-time return from west to east, offset tracking in the event of overheating

2

of solar cells, and catch-up provisions to minimize loss of power generation after periods of low insolation. Each concentrator unit utilizes single-crystal silicon photovoltaic cells and is passively cooled. Waste heat is convectively and radiatively transferred to the ambient air without the need for a fluid transport system. The nominal peak power rating of each concentrator subsystem is approximately 10.4 kilowatts based upon projected performance with planned modifications to a prototype design.

The actual power output at any particular instant of time depends on weather conditions on the one hand and system reliability and integrity on the other. Although system output is sensitive to seasonal and diurnal insolation cycles, the two-axis tracking system, as used in this design, maximizes the amount of available incident solar energy converted to electricity. The system efficiency is dependent on many factors, including those associated with optics, encapsulation, and photovoltaic cells. These factors are reviewed in Chapter 2. The efficiency of the silicon cells varies significantly with their operating temperature which is a function of insolation level, wind velocity, and ambient air temperature. High air temperatures and high insolation levels, together with low wind velocities, lead to higher cell temperatures and lower system efficiency. However, hourly computerized analyses based on two years of simulated weather data for Sun Valley, California, show that high cell temperatures, above 90°C, occur less than 1.6 percent of the time. These temperature characteristics are achieved through the use of purely passive cooling. The system is expected to produce approximately 487,500 kilowatt-hours of electrical energy annually, allowing for losses in the power conditioning apparatus.

The selected application will enable experience to be gained which is relevant to several possible photovoltaic array applications. The use of

the array to power the fan motors will provide information on the suitability of photovoltaic arrays for powering other electric motor loads, such as water pump motors. In general, some of the experience gained will be relevant to on-site applications of photovoltaic arrays for powering electrical loads of all types; i.e., to ILC applications. The provision for two-way power flow between the array-load combination and the utility distribution system will enable the investigation of suitable electric rate schemes for future ILC applications. Furthermore, because the photovoltaic system will be able to supply power to the distribution system and because it can enhance the steam plant output when it powers the fan motors, experience will be gained in use of photovoltaic arrays for central-station generation of electricity, either by themselves or in a hybrid combination with conventional generation. Finally, as noted earlier, the dramatic contrast of a photovoltaic array alongside of a conventional fossil-fueled generating station will enable significant benefit to be obtained in the area of public exposure to photovoltaic conversion as a potential future energy source. The fact that the project will be sited in a densely populated urban environment will ensure a large number of visitors.

The experimental project entails about a four-year effort. The work is divided into three phases. Phase 1, which consisted of a nine-month effort to devise the plans for Phases 2 and 3 and to produce a detailed design of the experimental photovoltaic system, was concluded on February 28, 1979. This report is the formal documentation of the work performed in Phase 1. DOE's decision to fund Phases 2 and 3 is to be based on performance in Phase 1 and other selection criteria. Phase 2 will consist of the fabrication and installation of the experimental photovoltaic system over approximately a one-year period. Phase 3 will consist of a test period with a duration of

one to two years for operating and evaluating the experimental photovoltaic system. The primary objectives during Phase 2 of the program will be:

1. To fabricate and install the photovoltaic system in accordance with the design and performance specifications produced in Phase 1.
2. To test the system for satisfactory performance and make adjustments if necessary.
3. To prepare formal reports as required by DOE.

The primary objectives during Phase 3 of the program will be:

1. To operate the experimental photovoltaic system for a test period of sufficient duration (e.g., two years) to acquire data necessary for complete evaluation.
2. To use experimental data in conjunction with analytical tools to address various experimental issues, both technical and institutional, and thereby establish information and guidelines which will advance the goals of the National Photovoltaic Conversion Program.
3. To prepare an operation and maintenance manual for the photovoltaic system.
4. To prepare formal reports as required by DOE.

The application will be highly suitable for meeting project objectives and for furthering the objectives of the National Photovoltaic Conversion Program. Having selected a site and ILC load which are owned by LADWP has facilitated activities in Phase 1, because only LADWP and Spectrolab were involved. Similarly, activities in Phase 2 will be facilitated. The suitability of the selected application to identify and resolve technical and institutional problems, as desired in Phase 3, is discussed in Chapter 5.

In summary, the project site, experimental application, and system design were carefully selected to allow many technical and institutional issues to be studied in a single project and thereby enhance the chances of a successful experiment. Furthermore, the proposed project was carefully planned to produce information that will reinforce the long-range objectives for using photovoltaic systems for meeting our Nation's energy needs.

CHAPTER 2

CONCEPTUAL SYSTEM DESIGN AND ANALYSIS

2.1 System Conceptual Design

2.1.1 Site and Application Characteristics

The site is located at the Valley Generating Station which is one of the four LADWP designed, built, owned, and operated fossil-fueled steam-electric generating plants located in the Los Angeles Basin. The plant is located in the northeast portion of the City of Los Angeles in the community of Sun Valley and covers approximately 155 acres. The steam-electric generating plant consists of four turbine-generator units with a combined total output of 550 megawatts. The plant was built between 1951 and 1955 and the last unit was on line in 1956. The ground at the site consists of sands and gravel with some boulders, silts, and clay and is very level. The use of the plant area is shared by several divisions of LADWP, with the major portion being occupied by steam plant equipment. The site designated for the project is approximately four acres in the northeast corner of the plant area and is now vacant. (See Figures 2.1 and 2.2.)

The tallest structures in the project area are cooling towers with a stack height of 70 feet, approximately 1100 feet south of the project area. The next tallest structures are fuel oil storage tanks, which are 48 feet high and located approximately 600 feet southwest of the project area. The electric output of the photovoltaic system will be used to supply power to several induced-draft fan motors on a cooling tower. These motors are 480-volt, two-speed type, rated 40 and 10 horsepower, and there are seven motors on the tower. Hence, a motor load of variable size will be available for determining the suitability of photovoltaic arrays for powering industrial motor loads.

Figure 2.1. OVERVIEW OF VALLEY GENERATING STATION WITH PROJECT SITE IN RIGHT FOREGROUND

Figure 2.2. SITE DETAILS AT VALLEY GENERATING STATION

Top left: A close-up of the proposed site.

Top right: The cooling tower in the right foreground will be powered by the photovoltaic system.

Bottom: Entry to the site is secured by a guard post.

The selected cooling tower is one of a pair of redwood towers used to cool the turbine exhaust steam of the Unit 2 turbine, rated at 100 megawatts. The energy consumed by these fan motors and all other motors in the plant represents approximately eight percent of the plant output. The use of the photovoltaic array will effectively lower this station service percentage and correspondingly raise the net plant output.

The installation of the project will result in no significant changes in the operation of the existing facilities at the Valley Generating Station. The cooling tower fan motor controls will be arranged so that when the photovoltaic array is producing no power, the system will be normal; i.e., the fan motors will be remotely controlled from the unit's control room and powered by the utility distribution system (i.e., the so-called station service). When the array is producing power, the fan motors will be powered by the photovoltaic array and utility station service in parallel. When the array output exceeds the demand of the motors, the excess power will be delivered into the LADWP's distribution system for use elsewhere. In summary, the photovoltaic array not only will supply power to an electric motor load, but also will augment the power output of the Valley Generating Station.

2.1.2 Description of Photovoltaic System

A block diagram of the photovoltaic electric power system is provided in Figure 2.3. This subsection contains a general description of the role of the major components illustrated in this block diagram. A detailed discussion of the components is given in Chapter 3. Furthermore, the block diagram and discussion herein do not address the on-site data acquisition system which is independent of the intended application of the photovoltaic system, which is to supply power to an electric motor load. The on-site data acquisition system which is a mechanism for monitoring performance of the photovoltaic system is discussed in Chapter 5.

Figure 2.3. BLOCK DIAGRAM OF THE PHOTOVOLTAIC ELECTRIC POWER SYSTEM

which is a mechanism for monitoring performance of the photovoltaic system is discussed in Chapter 5.

The photovoltaic system consists of an array of photovoltaic concentrator devices which produce a DC electrical power output. This output is conditioned by an inverter to provide 480-volt, 60-hertz, three-phase AC power. The power conditioning system contains a control circuit for peak array power tracking. The function of this control circuit is to keep the inverter operating at the knee or maximum power point of the current-voltage characteristic of the photovoltaic array. The AC electrical power output of the power conditioning system can be used to drive an electric motor load or can be fed into the adjacent utility distribution system for use elsewhere.

The array of photovoltaic concentrator devices is designed to produce approximately 200 kilowatts of peak electrical power output. The system consists of 20 photovoltaic subsystems, each of which produces approximately 10 kilowatts of electrical power output. A subsystem consists of a rotary carousel capable of azimuth solar tracking. An array of 40 elevation-solar-tracking photovoltaic concentrator units are positioned on the carousel. A photograph of a prototype subsystem is shown in Figure 2.4 wherein only four of the normal 40 concentrator units have been installed. Each unit consists of a two-stage concentrator having a parabolic trough primary mirror and compound elliptical secondary mirror. Single-crystal silicon photovoltaic cells are positioned at the focal point of the secondary concentrator. Consequently, there are 800 (20 times 40) individual two-axis tracking concentrator units in the overall system.

A power supply is required to drive the tracking mechanisms. The baseline system design calls for use of the adjacent electric utility distribution system for providing the required tracking power. For a truly stand-alone capability, meaning operation completely independent of the utility system, an

Figure 2.4. PARTIALLY ASSEMBLED PROTOTYPE SUBSYSTEM

uninterruptible power supply would be required for providing the tracking power. It is felt that use of an uninterruptible power supply for this purpose could easily be demonstrated; and hence, inclusion of this capability in the design was not done to keep the project cost from becoming excessive. If an uninterruptible power supply were provided as a system component, it would charge itself from the utility system during periods of normal operation wherein the tracking power is also supplied by the utility system. In emergency contingencies for which utility service is unavailable, the tracking power needed by the photovoltaic system would be supplied by the uninterruptible power supply. Without this capability, the tracking will stop in an emergency situation where utility service is unavailable.

On the other hand, it was decided to demonstrate stand-alone capability for the power conditioning system. Hence, the power conditioning system is capable of two modes of operation, namely, parallel operation with the utility distribution system and stand-alone load operation independent of the utility system. The power conditioning system and other switchgear will be housed in an equipment building which will also serve as a visitor facility. This building will be a low-cost design having air conditioning as needed to keep the equipment operating in a tolerable temperature range.

Spectrolab is well qualified to provide concentrating photovoltaic systems, including cells and modules, as a result of a great deal of research and development work in the photovoltaic area in general and concentrator development in particular. Spectrolab has designed the photovoltaic subsystem and evaluated the expected performance of the overall system, excluding the effect of the power conditioning system. LADWP has selected a design and a supplier for the power conditioning system and has evaluated the overall expected system performance. The decision by LADWP to team with Spectrolab to devise the application experiment was made prior to beginning Phase 1 of the project.

2.2 System Performance Analysis

The system performance analysis was done using Aerospace Corporation weather tapes compiled for Riverside, California, for the years 1962 and 1963. The 1962 and 1963 data is representative of a ten-year data base for Riverside and provides hourly data for total horizontal insolation, ambient air temperature, and wind velocity. Riverside data was used because of its completeness and because a complete data set for Sun Valley is not available. Partial data sets for the Los Angeles area available from several sources were used to assure that there was no gross error in the assumption that the Riverside data would simulate conditions at Sun Valley. The direct normal insolation values required by Spectrolab's computer code for system simulation were derived analytically from the total horizontal insolation data using an established methodology.

Average monthly wind velocities and ambient air temperatures for each hour of the day are presented in Tables 2.1 and 2.2, respectively. The average hourly direct normal insolation as computed from Riverside data using the algorithm is tabulated in Table 2.3. The calculated values for direct normal insolation are approximately 15 percent lower than the estimated values on the Aerospace Corporation weather tape.

The projected performance characteristics of the 10 kilowatt subsystem are based upon initial prototype performance data and certain design changes which will improve the optical performance. The various efficiency factors making up the overall subsystem efficiency are tabulated in Table 2.4. The efficiency factor values projected for the subsystem are presented along with those determined from experimental evaluation of a prototype concentrator unit. Also, the original values perceived at the beginning of the design work

TABLE 2.1
CALCULATED WIND SPEED RESULTS

Hourly Averages By Month

In Meters Per Second

<u>HOUR</u>	<u>JAN</u>	<u>FEB</u>	<u>MAR</u>	<u>APR</u>	<u>MAY</u>	<u>JUN</u>	<u>JUL</u>	<u>AUG</u>	<u>SEP</u>	<u>OCT</u>	<u>NOV</u>	<u>DEC</u>	<u>YEARLY MEAN</u>
1	1.6	0.7	0.4	0.3	1.0	0.7	0.5	0.5	0.6	0.5	0.4	0.2	0.6
2	1.3	0.8	0.5	0.4	1.1	0.7	0.4	0.2	0.4	0.5	0.4	0.3	0.6
3	1.6	1.2	0.4	0.5	0.9	0.7	0.4	0.1	0.2	0.3	0.3	0.4	0.6
4	1.1	1.0	0.5	0.4	1.1	0.6	0.3	0.3	0.3	0.2	0.3	0.5	0.5
5	1.0	0.9	0.4	0.3	1.0	0.5	0.2	0.1	0.3	0.4	0.2	0.4	0.5
6	1.5	1.1	0.6	0.5	0.8	0.3	0.4	0.3	0.2	0.2	0.3	0.5	0.6
7	1.4	1.0	0.3	0.5	1.0	0.4	0.4	0.1	0.2	0.3	0.3	0.4	0.5
8	1.7	1.1	0.4	0.5	0.9	0.5	0.2	0.1	0.3	0.5	0.5	0.5	0.6
9	1.4	1.4	0.6	0.5	1.1	0.7	0.2	0.3	0.6	0.5	0.4	0.4	0.7
10	1.7	1.9	1.2	0.9	1.4	1.0	0.6	0.5	0.8	0.6	0.7	0.6	1.0
11	2.2	2.7	1.2	1.3	1.7	1.3	1.5	0.8	0.9	0.8	0.7	1.2	1.4
12	2.2	2.3	1.1	1.5	2.4	2.0	2.7	2.6	1.9	1.2	0.8	1.3	1.8
13	2.7	2.6	1.8	2.3	2.9	2.9	3.3	3.7	2.7	2.4	1.6	1.7	2.5
14	3.2	3.0	2.3	3.0	3.2	3.4	3.9	4.2	3.7	3.4	2.6	2.9	3.2
15	3.9	3.1	2.6	3.5	3.9	3.8	4.4	5.0	4.4	4.0	3.0	3.9	3.8
16	4.4	2.8	3.3	3.8	4.6	4.9	5.0	5.7	5.2	4.2	4.1	4.1	4.4
17	3.8	3.0	3.6	4.5	5.0	5.2	5.5	6.2	5.4	4.7	4.2	3.9	4.6
18	3.8	3.0	3.5	4.7	5.4	5.1	5.9	6.1	5.0	4.3	2.9	2.2	4.3
19	2.7	2.4	2.4	3.6	4.6	4.3	5.2	5.0	4.0	2.4	1.8	1.7	3.3
20	1.7	1.6	1.7	1.9	3.1	3.3	3.8	3.5	2.3	1.4	1.1	1.3	2.3
21	1.8	1.3	0.9	1.0	2.1	1.9	2.5	2.2	1.3	1.0	0.9	0.9	1.5
22	1.6	1.2	0.9	0.7	1.7	1.4	1.7	1.3	0.9	0.7	0.7	1.1	1.2
23	1.3	0.8	0.9	0.5	1.6	0.8	1.2	1.0	0.5	0.7	0.5	0.9	0.9
24	1.3	0.9	0.4	0.4	1.3	0.8	0.7	0.5	0.5	0.8	0.6	0.6	0.7
DAILY MEAN	2.1	1.7	1.3	1.6	2.2	2.0	2.1	2.1	1.8	1.5	1.2	1.3	1.8

TABLE 2.2

CALCULATED AMBIENT TEMPERATURE RESULTS

Hourly Averages By Month

In Degrees Centigrade

<u>HOURL</u>	<u>JAN</u>	<u>FEB</u>	<u>MAR</u>	<u>APR</u>	<u>MAY</u>	<u>JUN</u>	<u>JUL</u>	<u>AUG</u>	<u>SEP</u>	<u>OCT</u>	<u>NOV</u>	<u>DEC</u>	<u>YEARLY MEAN</u>
1	7.4	7.8	7.3	10.9	11.2	14.2	17.0	18.3	16.0	10.9	7.5	4.8	11.1
2	6.6	7.4	6.5	10.2	10.8	13.6	16.3	17.4	15.1	10.2	7.2	4.0	10.5
3	6.5	6.9	5.9	9.7	10.0	13.1	15.6	16.4	14.6	9.5	6.0	3.5	9.8
4	5.8	6.8	5.8	9.2	9.8	12.7	14.8	15.5	13.9	8.9	5.7	3.3	9.4
5	5.6	6.4	5.4	8.8	9.4	12.2	14.3	15.0	13.0	8.4	5.5	2.7	8.9
6	5.1	6.1	4.9	8.2	9.2	12.1	13.9	14.6	12.8	8.3	5.1	2.5	8.6
7	5.1	5.9	4.7	8.7	9.9	13.1	15.2	15.1	12.7	8.0	4.5	2.6	8.3
8	5.2	5.7	5.4	11.0	11.7	15.2	17.5	18.0	14.7	9.3	5.2	2.2	10.1
9	6.0	6.9	7.5	14.4	14.2	18.3	21.1	22.3	18.4	12.3	7.5	4.0	12.8
10	8.4	8.8	10.1	18.3	16.5	20.8	24.6	26.7	22.6	16.5	11.3	8.0	16.1
11	11.4	10.3	12.3	20.9	18.9	23.4	27.5	29.8	25.6	20.2	14.7	12.1	19.0
12	14.2	11.5	14.1	23.0	20.6	25.4	29.9	32.5	28.3	22.9	17.8	15.6	21.4
13	15.8	12.9	15.3	24.4	21.9	26.7	31.3	33.8	29.9	24.4	19.3	18.2	22.9
14	16.8	13.5	15.8	25.3	22.9	28.0	32.3	34.4	31.0	24.9	20.2	19.3	23.8
15	17.2	13.5	16.4	25.7	23.4	28.5	32.9	34.6	31.3	25.1	20.9	19.0	24.1
16	17.0	13.6	16.4	25.7	23.0	28.5	32.4	34.3	30.6	24.7	20.4	18.5	23.8
17	16.3	13.4	15.8	24.5	22.3	27.5	31.3	33.1	29.5	23.6	19.0	16.9	22.8
18	14.4	12.4	14.5	22.7	20.8	25.7	29.6	31.2	27.5	21.1	15.9	13.7	20.8
19	12.8	10.8	12.5	19.9	18.8	23.6	27.4	28.3	24.4	18.4	13.9	11.5	18.5
20	11.4	9.9	11.0	17.2	16.8	21.2	24.7	25.3	22.1	16.8	12.5	10.4	16.6
21	10.6	9.3	9.8	15.5	14.8	19.1	22.2	23.2	20.1	15.3	11.2	9.2	15.1
22	9.3	8.7	9.1	14.1	13.6	17.3	20.5	21.8	18.5	13.6	10.0	7.9	13.7
23	8.7	8.2	8.4	12.7	13.0	16.1	19.3	20.5	17.4	12.5	9.1	7.2	12.8
24	7.4	7.8	7.4	11.9	11.9	15.2	18.0	19.2	16.6	11.5	8.2	6.2	11.8
DAILY MEAN	10.2	9.3	10.1	16.4	15.6	19.7	22.9	24.2	21.1	15.7	11.6	9.3	15.5

TABLE 2.3
CALCULATED DIRECT NORMAL INSOLATION RESULTS
Hourly Averages By Month
In Kilowatt-Hours Per Square Meter

<u>HOUR</u>	<u>JAN</u>	<u>FEB</u>	<u>MAR</u>	<u>APR</u>	<u>MAY</u>	<u>JUN</u>	<u>JUL</u>	<u>AUG</u>	<u>SEP</u>	<u>OCT</u>	<u>NOV</u>	<u>DEC</u>	<u>YEARLY MEAN</u>
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.032	0.087	0.030	0.078	0.045	0.0	0.0	0.0	0.0	0.023
7	0.0	0.004	0.059	0.205	0.289	0.284	0.328	0.360	0.259	0.044	0.0	0.0	0.153
8	0.006	0.119	0.438	0.478	0.417	0.427	0.560	0.665	0.500	0.347	0.208	0.082	0.355
9	0.221	0.305	0.584	0.564	0.486	0.469	0.639	0.763	0.592	0.556	0.464	0.433	0.508
10	0.529	0.482	0.562	0.613	0.561	0.488	0.731	0.786	0.662	0.637	0.590	0.656	0.609
11	0.661	0.506	0.574	0.675	0.612	0.581	0.758	0.800	0.718	0.701	0.604	0.698	0.659
12	0.712	0.464	0.595	0.718	0.660	0.656	0.800	0.821	0.812	0.762	0.651	0.729	0.700
13	0.707	0.490	0.616	0.758	0.716	0.704	0.798	0.803	0.838	0.762	0.722	0.743	0.723
14	0.698	0.416	0.585	0.753	0.718	0.733	0.804	0.819	0.819	0.763	0.718	0.731	0.715
15	0.644	0.412	0.539	0.776	0.684	0.739	0.790	0.814	0.802	0.764	0.726	0.692	0.700
16	0.327	0.296	0.515	0.691	0.685	0.740	0.784	0.808	0.771	0.647	0.575	0.491	0.613
17	0.030	0.172	0.378	0.565	0.622	0.745	0.756	0.729	0.603	0.379	0.307	0.315	0.468
18	0.0	0.026	0.224	0.350	0.524	0.608	0.604	0.495	0.397	0.139	0.0	0.0	0.282
19	0.0	0.0	0.0	0.045	0.355	0.252	0.429	0.226	0.0	0.0	0.0	0.0	0.110
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DAILY													
TOTAL	4.535	3.691	5.667	7.224	7.418	7.454	8.858	8.933	7.773	6.501	5.565	5.569	6.618

TABLE 2.4
EFFICIENCY FACTORS

EFFICIENCY FACTOR	ORIGINAL DESIGN	PROTOTYPE	PROJECTED 10 kW SUBSYSTEM
CELL EFFICIENCY AT 28°C	0.152		0.150
CELL MATCHING	0.98		0.98
CELL PACKING	0.975	0.973	0.973
	0.020-inch spacing 0.667-inch cell length	0.030-inch spacing 1.25-inch cell length	
WINDOW ENCAPSULATION		1.02	
WINDOW REFLECTION FACTOR	0.98	0.965	0.980
ANGLE OF INCIDENCE FACTOR		0.98	
OPTICAL TRANSFER			
PRIMARY	0.87	0.87	0.87
SECONDARY	0.965	0.895	0.85
	(50/50 split)	(75/25 split)	(60/40 split)
ENERGY DISTRIBUTION			
LONGITUDINAL (η_L)		0.944	0.985
LATERAL (η_F)	0.97	0.981	0.985
SYSTEM TEMPERATURE OPERATION FACTOR	0.796	0.74	0.748
TOTAL SYSTEM EFFICIENCY AT ENVIRONMENTAL TEST CONDITIONS (E.T.C.)	0.0899	0.0734	0.0791
TOTAL SYSTEM EFFICIENCY (CELL TEMPERATURE =28°C)	0.113	0.099	0.1055
UNIT OUTPUT POWER (PEAK) FOR ECA* = 3.29 M ² and E.T.C.	295 W	241 W	263 W

*ECA denotes Effective Clear
Aperture

are included for comparison. The major deviations from the original design were found to be in the area of the optics. A reduced optical transfer efficiency factor and reduced energy distribution factors were observed.

The optical transfer efficiency factor reduction for the prototype, as compared to the original design, was primarily due to the substitution of aluminized mylar for the silvered microsheet originally perceived for the secondary reflector. The substitution was due to cost and availability restraints. The secondary mirror of the prototype was well aligned with the primary reflection resulting in little spillage loss. Variations in line focus width on the cell string of the prototype caused nonuniform illumination of both individual cells and the entire string of cells. The nonuniform illumination of individual cells produces voltage losses and variations in illumination of the cell string leads to current limiting.

The projected efficiency factors for the subsystem are based on increased mirror quality to be achieved by using an aluminum honeycomb substrate for the primary mirror. An increase in thermal efficiency, as compared to the prototype, is projected based on the slotting of the cell substrate cooling fins according to the original design. The prototype was modified from the original design to expedite fabrication. The projected subsystem efficiency after incorporating planned changes is 7.9 percent. At this efficiency, the projected peak power output of the subsystem under standard environmental test conditions would be 10.4 kilowatts. These projections include a one-percent electrical distribution loss due to diode voltage drop, matching inaccuracies and line loss.

The simulated performance of a Spectrolab subsystem installed at Sun Valley has been analyzed using a Spectrolab-developed computer program named "TWOD". This program is a tool for investigating the performance char-

acteristics of a two-axis tracking photovoltaic concentrator system over an extended period of time, based on the projected weather conditions. The block diagram in Figure 2.5 depicts the information flow, the input data blocks, and the computational subroutines used in the program. The cell cooling and conversion subroutine is the heart of the program where the cell temperature is calculated for given environmental conditions. From the cell temperature, the cell efficiency and ultimately the power generated are calculated. The determination of cell temperature in this program is an iterative process based on the interaction between the energy generated, energy rejected by the heat sink, and resulting cell temperature. The input parameter values used for the simulation are consistent with the characteristics of the site under study and the planned system configuration. The simulation algorithm computes values for each hour of each day from the weather data tapes and then computes averages and output data for larger time bases. The simulation variables, performance equations, and parameter values used by TWOD are summarized in Tables 2.5, 2.6, and 2.7, respectively.

For analytical purposes a second algorithm was formulated to simulate a steady state at specified environmental conditions for given subsystem parameter values. For certain purposes it is desirable to predict cell temperatures and energy production under given environmental conditions. The steady-state algorithm was developed based on the cell cooling and conversion subroutine, allowing the user to specify insolation level, wind speed and ambient air temperature, as well as all the pertinent systems parameters and do performance computations for the selected conditions. This steady-state algorithm is particularly helpful when determining the electrical characteristics of the system under extreme weather conditions.

Figure 2.5. BLOCK DIAGRAM OF COMPUTER SIMULATION PROGRAM

TABLE 2.5
SIMULATION VARIABLES

Inputs

DN	direct normal insolation (kW/m^2)
T_A, T_A	ambient temperature ($^{\circ}\text{C}, ^{\circ}\text{K}$)
W	wind velocity (m/second)

Parameters

τ	optical transfer efficiency
α	cell absorptance
C	concentration ratio
a, b	convective heat loss coefficients
ϵ	emissivity of heat sink
σ	Stefan-Boltzman constant
S	ratio of radiative surface area of heat sink to cell area
K_B	heat transfer coefficient from cell back to support structure
EN	encapsulation transmission losses
PK	secondary packing factor
MA	cell matching efficiency
T_{ref}	cell reference temperature (e.g., 28°C)
UE	energy distribution factor
η_{ref}	cell efficiency at reference temperature (e.g., 28°C)
Δ	percentage decrease in cell efficiency per $^{\circ}\text{C}$
A	aperture area

TABLE 2.5 (Continued)

SIMULATION VARIABLES

Computed Values

Q	energy absorbed per unit of cell area (kW/m^2)
K_E	heat transfer coefficient from cell support structure to surroundings ($\text{kW/m}^2\text{-}^\circ\text{C}$)
$T_B, \bar{T}_B$	temperature of cell support structure ($^\circ\text{C}, ^\circ\text{K}$)
T_C	temperature of cell ($^\circ\text{C}$)
η	system efficiency
E	electrical output per unit of aperture area (kW/m^2)
ET	system electrical output (kW)
e	miscellaneous efficiency losses due to cell mismatch, encapsulation and packing

TABLE 2.6
PERFORMANCE EQUATIONS

Energy to be Dissipated by Heatsink

$$q = \tau \cdot \alpha \cdot C \cdot DN - C \cdot E$$

Electricity Generated

$$E = \eta \cdot DN$$

$$\eta = e \cdot \tau \cdot \eta_{\text{ref}} (1 - \Delta (T_c - T_{\text{ref}}))$$

$$e = MA \cdot PK \cdot EN \cdot UE$$

$$ET = A \cdot E$$

Cell Temperature

$$K'_E = a + b \cdot W + \epsilon \cdot \sigma \cdot S (\bar{T}_A + \bar{T}_B) (\bar{T}_A^2 + \bar{T}_B^2)$$

$$T_B = T_A + Q/K'_E$$

$$T_C = T_B + Q/K_B$$

TABLE 2.7
PARAMETER VALUES

$\tau = 0.784$	$S = 8.125$
$\alpha = 0.75$	$K_B = 3.0 \text{ kW/m}^2\text{-}^\circ\text{C}$
$C = 25.63$	$MA = 0.98$
$a = 0.158$	$PK = 0.973$
$b = 0.045$	$EN = 0.98$
$\epsilon = 0.8$	$T_{\text{ref}} = 28^\circ\text{C}$
	$UE = 0.970$
	$\eta_{\text{ref}} = 0.150 \text{ at } 28^\circ\text{C}$
	$\Delta = 0.0040$
	$A = 131.7 \text{ m}^2$

5

The results of the simulation show that average daily output of a subsystem at Sun Valley will be 72.6 kWh or 0.551 kWh/m². Because the average daily direct insolation on the 131.7 m² of effective array aperture area is 871.6 kWh, approximately 8.33 percent of this total available insolation is converted to electricity. The two-axis tracking system is designed to track the sun down to a solar altitude of 10°. To account for shading at solar altitudes below 20°, a somewhat conservative shading criterion has been used in the simulation. This criterion assumes 100 percent illumination at 20° solar altitude, decreasing to 50 percent at 10° solar altitude. The system is assumed not to operate at solar altitudes below 10°. To determine the penalty caused by shading using this criterion, the system performance was analyzed assuming that the system tracks to a zero-degree solar altitude without any shading. The average daily energy generated for this case was 78.9 kWh and represents a 9.05 percent efficiency of converting the total average daily direct normal insolation to electricity. Thus, the shading criterion used in this system simulation results in approximately a ten-percent reduction in electrical energy generation from the unobstructed nonshaded case. In the following paragraphs the terminal and electrical characteristics of the subsystem are reviewed for a hypothetical installation at Sun Valley.

The actual subsystem capability as related to the secondary absorber heat sink performance is highly dependent upon the photovoltaic cell temperature. Higher cell temperatures during operation result in lower cell efficiencies. The heat transfer characteristic of the secondary assembly is therefore crucial in obtaining efficient, economical, passively cooled concentrator units. The parameters utilized in the computer simulation program, and in the additional algorithm developed to establish performance of the system under fixed environmental conditions, have been derived from a combination of design data, results of prototype concentrator unit performance tests, and planned modifications.

The heat transfer parameters of the secondary absorber for operation in the standard environment, including the expected cell temperature, extrusion temperature, cell-to-ambient heat transfer coefficient, and heat sink parameter values, are listed in Table 2.8. The performance characteristics in the standard environment are used mainly for reference purposes. The actual subsystem capability, as related to the secondary absorber heat sink performance for a given location, can be demonstrated better by the average cell temperatures experienced. For Sun Valley, California, using the detailed hour-by-hour simulation, the average cell temperature was calculated to be 54.45°C . This reduction in cell temperature from standard environment test cell temperature is due to the fact that the average daytime weather conditions are considerably more favorable than the standard environment. The simulated conditions at Sun Valley are characterized by an average direct normal insolation of 652 W/m^2 , an average daily temperature of 20°C , and an average daytime wind velocity of 2.4 m/sec .

Simulated cell temperatures are shown in Table 2.9 for a heat sink configuration as expected on the units to be installed at Sun Valley. (Zeros indicate nonoperating periods.) These temperatures are averages for each hour over a 24-hour period for each month based on simulated Sun Valley, California, weather data. The highest value of 82.1°C is for August from 9:00 to 10:00 AM. Because of higher wind velocities in the afternoon, maximum temperatures tend to occur in the morning at this location. The subsystem is designed to operate at cell temperatures up to 100°C . At approximately 100°C cell temperature or 93°C extrusion surface temperature, a temperature sensor will provide an error signal to the tracking control electronics. The elevation drive will be actuated for a set period of time, equivalent to a 6° motion against the present direction of tracking, necessary to move the solar image off the absorber. The elevation drive will remain inhibited in

TABLE 2.8

HEAT TRANSFER PARAMETERS FOR SECONDARY ABSORBER

Input ValuesEnironmental Conditions

Insolation	1 kW/m ²
Wind Velocity	1 m/sec
Ambient Air Temperature	28°C

Heat Sink Parameters

Free Convection Factor	0.158
Forced Convection Factor	0.045
Cell Absorptivity	0.75
Heat Transfer (Cell to Extrusion)	3 kW/m ² -°C

Computed Values

Cell Temperature	90.7°C
Extrusion Temperature	86.4°C
Heat Transfer Coefficient K _e (Cell to Environment)	2565 kW/m ² -°C

TABLE 2.9

CALCULATED HOURLY AVERAGE PHOTOVOLTAIC CELL TEMPERATURES

By Month For System Operation In Sun Valley, California

Values In Degrees Centigrade

<u>TIME</u>	<u>JAN</u>	<u>FEB</u>	<u>MAR</u>	<u>APR</u>	<u>MAY</u>	<u>JUN</u>	<u>JUL</u>	<u>AUG</u>	<u>SEP</u>	<u>OCT</u>	<u>NOV</u>	<u>DEC</u>	<u>YEARLY MEAN</u>
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	28.35	30.57	34.86	39.91	42.24	52.04	0.0	0.0	0.0	35.88
7	0.0	20.89	37.84	46.88	40.99	46.70	59.27	68.01	52.07	31.58	0.0	0.0	46.94
8	21.12	28.58	50.21	55.40	48.38	50.99	68.09	77.36	61.45	53.52	41.27	36.37	49.69
9	41.23	40.31	48.56	59.83	53.53	53.74	74.81	81.19	68.35	61.61	52.22	53.73	57.55
10	51.72	39.88	51.49	63.03	56.35	59.97	72.04	82.11	73.77	67.25	55.29	57.72	61.03
11	56.16	39.95	53.42	66.23	57.11	62.49	69.53	74.44	74.15	72.27	62.20	61.97	62.64
12	55.04	41.38	52.77	65.21	58.29	60.96	68.34	69.29	72.54	65.13	63.30	63.22	61.41
13	53.77	37.90	48.17	62.36	57.87	61.79	67.14	68.93	67.75	59.37	59.00	56.06	58.46
14	48.17	34.96	44.38	62.34	53.87	60.61	65.25	66.31	64.22	58.63	57.03	50.15	55.62
15	33.55	29.18	41.50	56.34	50.63	57.61	62.51	63.79	60.39	52.87	45.24	39.41	49.61
16	0.0	26.07	34.00	47.29	46.08	55.47	59.07	58.47	51.95	37.35	0.0	0.0	47.88
17	0.0	0.0	0.0	37.92	39.83	48.56	50.87	48.34	42.74	0.0	0.0	0.0	45.67
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DAILY MEAN	45.37	35.25	46.27	55.64	49.46	54.48	63.07	66.70	64.55	56.67	54.44	52.33	54.45

this position until the cell temperature falls below a lower set point of approximately 90°C, after which normal operation will resume. According to Figure 2.6 which shows a distribution of simulated cell temperatures during sunlight hours for Sun Valley, the cell temperature would have never been higher than 100°C during the period simulated, and it would have been higher than 90°C for only 122 hours. The maximum cell temperature found using the simulation was 99°C. Combinations of low wind, high insolation and high ambient air temperatures resulting in high cell temperatures appear to occur infrequently at this location.

The cell circuit design for the concentrator unit has been configured to provide a system voltage of approximately 313 volts under standard environmental test conditions of 28°C ambient, 1000 W/m² insolation, and 1 m/sec wind. The concentrator subsystem consists of 40 concentrator units, each nominally rated at 250 W. Each unit contains 78 series-connected cells which will produce 8.30 amps at 31.67 volts for operation at the maximum power point, under the above-stated standard environmental test conditions. These numbers are based on tests performed on preproduction cells and can be considered good estimates of obtainable outputs by fully developed cells to be used on production units.

Table 2.10 gives concentrator unit output data for both standard environmental test conditions (cell temperature of 90.69°C) and standard test conditions (cell temperature of 28°C). Both sets of numbers are given as an aid to the reader, since the 28°C cell temperature number is so frequently used when stating photovoltaic system specifications. The subsystem is divided into four separate and electrically independent circuits. Each of these four circuits consists of 10 concentrator units connected in series. Each series string is electrically separated by blocking diodes to prevent losses during times of partial shading of the array. During operation at standard environmental test

Figure 2.6. HOURLY DISTRIBUTION OF PHOTOVOLTAIC CELL TEMPERATURES FOR SIMULATED CONDITIONS AT SUN VALLEY

TABLE 2.10
CONCENTRATOR UNIT SPECIFICATIONS AT STANDARD AND
ENVIRONMENTAL TEST CONDITIONS

	<u>Std. Test Conditions</u>	<u>Std. Environmental Test Conditions</u>
Concentration Ratio at AMI	19.13	19.13
Cell Temperature	28°C	90.69°C
Open-Circuit Voltage	50.87	39.57
Short-Circuit Current	8.84 amps	8.84 amps
Current at Maximum Power	8.25 amps	8.30 amps
Voltage at Maximum Power	40.63 volts	31.67 volts
Maximum Power	335.2 watts	262.9 watts

TABLE 2.11
PROJECTED SUBSYSTEM OPERATIONAL PARAMETERS
FOR SUN VALLEY

Environmental Parameters

Insolation (Mean)	652 W/m ²
Wind Velocity (Mean)	2.4 meter/sec
Ambient Air Temperature (Mean)	20°C

Subsystem Parameters

Cell Temperature	54.45°C
Power Output	72.59 kWh/day

conditions, the system will have a peak electrical power output of 10.40 kW at 313 volts. The projected operating parameter values are listed in Table 2.11. The values in both Tables 2.10 and 2.11 are projections based upon preproduction sample cells.

A current-voltage characteristic for the entire subsystem operating in the standard environment is shown in Figure 2.7. Performance data used to generate this curve was based on test results obtained on an assembled and encapsulated 39-cell half string using a pulsed solar simulator. In the standard test environment, the cell temperature is expected to be approximately 91°C , anticipating a cell irradiance level of 19.49 kW/m^2 , based on a geometrical concentration ratio of 25.63, an optical transfer efficiency of 0.784, and 97 percent transmission across the cell string encapsulation.

From the computer simulation it was found that a subsystem would produce 26,496 kWh/yr of electricity based on simulated weather data for Sun Valley, California. If the subsystem operated at its nominal rated capacity of 10 kW for 24 hours every day (where a 24 hour day can obviously be used only for analytical purposes), it would produce 87,600 kWh/yr; so its annual energy output is 30.25 percent of the energy that would be produced by a generating facility with 100 percent availability at its full rating.

The simulation program was used to calculate month-by-month hourly average electrical power output. The results for simulated Sun Valley weather data appear in Table 2.12. Typical daily profiles of power generated, cell temperatures, insolation levels, wind speed and ambient air temperatures are depicted in Figure 2.8. The fairly level power output over a good part of the day, following the profile of the direct normal insolation with some slight variations, is characteristic of two-axis tracking arrays. The sudden increase of power output at noon and the slight increase in the level of power

Figure 2. 7. PROJECTED CURRENT-VOLTAGE CHARACTERISTIC OF A 10kW SUBSYSTEM OPERATING AT 1000 W/m² INSOLATION, 28°C AMBIENT TEMPERATURE, AND A ONE METER-PER-SECOND WIND SPEED

TABLE 2.12

HOURLY AVERAGE ELECTRICAL POWER GENERATION IN KILOWATTS AND DAILY AVERAGE

ENERGY PRODUCTION IN KILOWATT-HOURS BY MONTH FOR A SUBSYSTEM

LOCATED IN SUN VALLEY, CALIFORNIA

<u>TIME</u>	<u>JAN</u>	<u>FEB</u>	<u>MAR</u>	<u>APR</u>	<u>MAY</u>	<u>JUN</u>	<u>JUL</u>	<u>AUG</u>	<u>SEP</u>	<u>OCT</u>	<u>NOV</u>	<u>DEC</u>	<u>YEARLY MEAN</u>
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	1.40	2.93	3.29	3.61	3.14	0.12	0.0	0.0	0.0	1.22
7	0.0	0.91	4.66	5.64	4.92	4.83	6.38	7.52	5.55	2.08	0.0	0.0	3.56
8	2.44	3.77	6.90	6.42	5.67	5.23	7.05	8.43	6.57	6.44	4.93	3.97	5.66
9	6.70	5.94	6.64	6.96	6.55	5.41	8.04	8.55	7.25	7.20	6.91	7.85	7.01
10	8.06	6.21	6.71	7.66	7.12	6.54	8.55	8.67	7.82	7.90	7.00	8.26	7.56
11	8.60	5.61	6.91	8.17	7.82	7.46	9.23	9.29	9.17	8.49	7.37	8.47	8.07
12	8.54	5.98	7.27	8.76	8.55	8.22	9.26	9.30	9.56	8.85	8.31	8.62	8.45
13	8.43	5.04	7.05	8.82	8.55	8.60	9.41	9.51	9.57	9.11	8.54	8.82	8.48
14	8.04	5.14	6.55	9.19	8.26	8.73	9.32	9.57	9.51	9.19	8.80	8.59	8.43
15	3.44	3.69	6.30	8.38	8.43	8.90	9.35	9.62	9.31	7.98	6.28	4.53	7.20
16	0.0	0.83	4.13	7.13	7.84	9.11	9.17	8.89	7.24	2.77	0.0	0.0	4.78
17	0.0	0.0	0.0	2.04	5.55	7.13	6.71	4.37	0.07	0.0	0.0	0.0	2.17
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DAILY													
ENERGY	54.26	43.11	63.13	80.58	82.18	83.47	96.09	96.87	81.74	70.02	58.14	59.11	72.59

Figure 2.8. TYPICAL SUMMER DAILY POWER GENERATION, CELL TEMPERATURE, INSOLATION, AMBIENT AIR TEMPERATURE, AND WIND SPEED PROFILES FOR SIMULATED CONDITIONS AT SUN VALLEY, CALIFORNIA

output in the afternoon, despite a gradual decrease in insolation for the same period, is related to the higher wind velocities at this location during the afternoon hours. The sharp drop in cell temperature, and thus increase in cell efficiency, is a direct function of the increased heat dissipation capacity of the passively cooled secondary extrusion, brought about by the normally prevailing wind conditions during the afternoon hours. Under these wind conditions, typical for this location, high cell temperatures will generally occur during the late morning hours. Temporary interruptions in power generation due to excess cell temperatures, as discussed earlier, are therefore most likely during this late morning period.

Dividing the average daily energy produced by the nominal rated output of 10 kW gives the equivalent hours per day that the subsystem operates at nominal rating. Thus, the subsystem would operate at a level that would be equivalent to the nominal rating for 4.31 hours per day in February and for 9.69 hours per day in August. On an annual basis, the average energy generated per day is 72.59 kWh or the equivalent of 7.26 hours per day at the nominal output. A chart of subsystem monthly energy production is given in Figure 2.9. The annual AC electrical energy delivered to the load is estimated to be 487,514 kWh. In computing this value the power conditioning system conversion efficiency was assumed to be constant at 92 percent. This approximation is reasonable because the efficiency varies between 92 percent and 93 percent from half load to full load, with the peak efficiency occurring at about three-fourths load. Furthermore, based upon discussions with the prospective supplier, the overall efficiency of the power conditioning system as a function of its power output is essentially independent of the influence of peak power tracking of the photovoltaic array output. A more rigorous hour-by-hour treatment is omitted here for brevity.

Figure 2. 9. SUBSYSTEM MONTHLY ENERGY PRODUCTION FOR SIMULATED CONDITIONS AT SUN VALLEY.

CHAPTER 3

COMPONENT SPECIFICATION

3.1 Photovoltaic Array

3.1.1 Introduction

The photovoltaic array will be composed of 20 Spectrolab photovoltaic subsystems, each having a peak rated electrical power generating capacity in excess of 10 kW. This peak power rating is based on a standard test environment having an ambient air temperature of 28°C , wind speed of one meter per second, and direct normal insolation of one kW/m^2 . Each of these subsystems can be viewed as an independent power generating unit. Hence, the output power of the photovoltaic array is approximately 20 times as great as that of a single subsystem.

Each subsystem utilizes two-axis tracking and is comprised of 40 identical concentrator units supported by a common structure. The concentrator units use two-stage optical concentration consisting of a linear parabolic trough primary mirror and a compound elliptical secondary mirror. The optics are designed to provide an overall effective clear aperture (ECA) of approximately 131.7 m^2 for a subsystem or 2634 m^2 for the system. The concentrator units are mounted on a low-profile steel truss framework which rotates in azimuth. The elevation tracking involves linkages which cause tilt movement of all 40 concentrator units in unison. A solar tracking control system is used for the two-axis tracking of the sun. This control system includes logic for such functions as nighttime return from west to east, tracking offset in the event of overheating of photovoltaic cells, and catch-up provisions to minimize loss of power generation after periods of low insolation.

Each concentrator unit utilizes silicon photovoltaic cells and is passively cooled. Waste heat is convectively and radiatively transferred to the ambient air without the need for a fluid transport system and its inherent power and maintenance requirements. In applications having a use for the waste thermal energy, an alternative actively cooled model can be used. High air temperatures and high insolation levels, together with low wind velocities, lead to higher cell temperatures and lower system efficiencies. Computer studies indicate good system efficiencies at most geographic locations in the United States.

The 200 kW nominal system is composed of 20 subsystems in parallel electrically. A temporary loss of power from one subsystem does not affect the output of the remaining subsystems. The system performance under standard environmental conditions is described in Table 3.1. The system power output is derated 1.5 percent from the algebraic sum for 20 subsystems to account for wiring losses in subsystem interconnections.

3.1.2 Subsystem Description

The 10 kW subsystem consists of an array of forty 250-watt concentrator units, mounted on a steel framework. The subsystem includes all equipment required for accurate two-axis solar tracking and a 131.7 m² array of parabolic cylindrical trough collectors and associated power conversion elements. The solar tracking mechanism consists of an azimuth-elevation drive assembly and a truss support and foundation.

A subsystem is designed as a broad cruciform array consisting of 40 concentrator units positioned in six rows. The front and rear rows each have four side-by-side concentrator units. The interior four rows each have eight side-by-side concentrator units. Each concentrator unit utilizes

TABLE 3.1
SYSTEM AND SUBSYSTEM OPERATING PARAMETERS

<u>Environmental Test Conditions</u>	<u>System</u>	<u>Subsystem</u>
Insolation	1.0 kW/m ²	1.0 kW/m ²
Wind Speed	1.0 m/sec	1.0 m/sec
Ambient Air Temperature	28°C	28°C
<u>Parameters</u>		
Number of Subsystems	20	1
Number of Concentrator Units	800	40
Aperture Area (Effective)	2634 m ²	131.7 m ²
Open-Circuit Voltage	386 volts	392 volts
Short-Circuit Current	707 amps	35.4 amps
Voltage at Maximum Power	308 volts	313 volts
Current at Maximum Power	664 amps	33.2 amps
Maximum Power	204.9 kW	10.4 kW

a two-element optical concentrator consisting of a linear parabolic primary mirror that focuses concentrated sunlight onto a compound elliptical secondary mirror. A schematic of a 250-watt concentrator unit is shown in Figure 3.1. The total geometric concentration ratio is 25.63. The concentrator units are mounted on the truss structure in an arrangement which minimizes gravity imbalances and wind torques on the axis drive trains. The design of this structure is intended to minimize foundation and drive train requirements and attendant drive system costs. Adjustment mechanisms are provided for independent alignment of each concentrator unit after assembly of the complete structure.

The single-crystal silicon cells employed in the subsystem are specifically designed for use in concentrated sunlight, and advanced aerospace

Figure 3.1. SCHEMATIC OF A 250-WATT CONCENTRATOR UNIT

cell manufacturing processes are utilized to achieve near maximum state-of-the-art conversion efficiency. The cells are rectangular in shape, closely packed, and thermally coupled to a high-efficiency heat sink for transferring waste heat to the surrounding air by convection and radiation. The subsystem is cooled entirely by passive means.

The truss structure rotates in azimuth and is supported on a circular concrete track with a diameter of 58.5 feet. The azimuth tracking is driven via one of the four wheels which ride on the concrete track. In the center of the concrete track is a pintle bearing which transmits wind-induced shear loads to the ground. The wheel and track arrangement provides adequate speed and travel range to track the sun in azimuth at any location in the continental United States, as well as an ability to catch up with the sun in about ten minutes after any period of nontracking because of low insolation.

The elevation drive consists of four linear actuators powered by a single electric motor which uses parallel and series linkages to drive all 40 concentrator units in unison. Both axial drives will use high-efficiency DC motors, and sun-seeking control circuitry will be exclusively solid-state. Consequently, these mechanisms will collectively consume an average power of less than 12 watts. All subsystem components are designed to survive in 40-meter-per-second winds in any axis orientation. With the exception of the reflective mirror surfaces, the subsystem is designed to have a minimum outdoor life expectancy of 20 years.

The solar tracking control system consists of the sensors, signal conditioning and logic required for two-axis tracking of the sun. The tracking sensor, which is mounted near the center of the truss structure, consists of an array of photocells geometrically arranged to provide insolation level and tracking error data. The tracking control uses simple on and off logic to eliminate the need for drive system control loops and modulated power

amplifiers. Movement about both axes will be done in approximately 0.7° increments, initiated whenever the direction in which the concentrator units are aimed lags the relative position of the sun by 0.4° . Additional system control logic is included for functions such as nighttime return from west to east and inhibition of tracking during periods of low insolation, overheating of photovoltaic cells, excess drive motor current in high winds, or axis motion beyond the desired travel limits. All subsystem control circuitry will be mounted in an enclosure with the tracking sensor. Manual slew controls for both axes will be provided at the perimeter of the truss structure.

Projected performance characteristics of a subsystem under standard environmental test conditions are presented in Table 3.1. A current-voltage characteristic for a subsystem is shown in Figure 2.7. The dependence of subsystem power output on direct normal insolation, wind speed, and ambient temperature is illustrated in Figures 3.2 through 3.4. The development of the 10 kW subsystem concept by Spectrolab is discussed in a recent report (1).

3.1.3 Concentrator Unit Description

Each 250-watt (nominal) concentrator unit consists of the concentrator optics, photovoltaic cell assembly, and the passive cooling provisions. The unit efficiency for converting solar insolation into electrical power is governed by the interaction of the optics, cell design, cell interconnections and laydown, and the ability of the system to dissipate waste heat to the surroundings. The concentrator unit is designed with amenability to mass production as a major consideration. Any unit can be interchanged with a replacement unit if necessary. System operating parameters under standard environmental test conditions are presented in Table 3.2. A photograph of a concentrator unit mounted on a test tracking fixture is shown in Figure 3.5.

Figure 3.2. SUBSYSTEM POWER OUTPUT VERSUS DIRECT NORMAL INSOLATION

Figure 3.3. SUBSYSTEM POWER OUTPUT VERSUS WIND SPEED

Figure 3.4. SUBSYSTEM POWER OUTPUT VERSUS AMBIENT TEMPERATURE

TABLE 3.2

UNIT OPERATING PARAMETERS AND SPECIFICATIONS

Environmental Test Conditions (ETC)

Insolation	1 kW/m ²
Wind Speed	1 m/sec.
Ambient Air Temperatures	28°C

Unit Specifications

Weight	170 lbs.
Aperture Area (Effective)	3.29 m ²
Concentration Ratio (Geometrical)	25.63
Clear Aperture Width	51 in.
Number of Cells	78
Cell Size	1.25 in. x 2.09 in.
String Length	99.54 in.
Cell Efficiency at 28°C	0.150
Cell Matching Factor	0.98
Cell Packing Factor	0.973
Encapsulation and Angle of Incidence Factor	0.980
Optical Transfer Factor	0.784
Energy Distribution Factor	0.970
Field of View (Elevation)	± 1.5°
Field of View (Azimuth)	± 1.5°

Unit Operating Conditions (ETC)

Cell Temperature	90.7°C
System Efficiency	0.0798
Open-Circuit Voltage	39.57 Volts
Short-Circuit Current	8.84 Amps
Voltage at Maximum Power	31.67 Volts
Current at Maximum Power	8.30 Amps
Maximum Power	262.9 Watts

Figure 3.5. CONCENTRATOR UNIT MOUNTED ON A TRACKING TEST FIXTURE

The unit design concept utilizes a two-element concentrator providing a geometrical concentration ratio of 25.63. The primary mirror and the secondary mirror are optically designed as an integral unit. A concentrator unit optical diagram is shown in Figure 3.6. The primary optical component is a parabolic trough with a 75° rim angle, 0.791 meter focal length, an effective clear aperture of 1.28 meters, and a physical length of 2.64 meters. The secondary mirror unit serves as the substrate and heat sink for the photovoltaic cell assemblies. The primary advantages of this optical system are related to the relatively large acceptance angle for collecting solar radiation. The system, as designed, has an acceptance angle of three degrees laterally across the parabolic trough and a significantly larger acceptance angle as measured longitudinally along the parabolic trough. The use of this two-element concentrator system in a two-axis tracking configuration allows cost reduction through low structural requirements for compliance under wind load, reduced optical quality requirements for the primary and secondary mirrors, and relaxed installation alignment tolerance between the secondary cell assembly and the primary mirror.

The parabolic trough primary mirror is designed to reduce distortions which would reflect incident radiation in the longitudinal direction of the mirror. Distortions of this type will grossly affect the system efficiency because they result in a lower illumination level on individual cells. Because the output of a series string of photovoltaic cells is for all practical purposes restrained by the characteristic performance of each of the individual cells making up the string, a reduced irradiance level on one cell in a series string will reduce the output performance of all cells in the string. The acceptance angle along the longitudinal length of the parabolic mirror is limited only by a reduction of system response as governed by the cosine of the angle between the

Figure 3. 6. CONCENTRATOR UNIT OPTICAL DIAGRAM

mirror's normal axis and that of the sun. With sufficient primary mirror length to completely illuminate the cell string for a given azimuth angle pointing error, tracking errors in azimuth will result in only small changes in system efficiency. The primary mirror length can accommodate an azimuth pointing error of ± 1.5 degrees.

The primary mirror is comprised of two 0.032-inch-thick sheets of 6061 T4 aluminum bonded with epoxy to the faces of one-inch-thick expanded hexagonal cell aluminum. The theoretical shape of the primary mirror trough is an off-axis segment of a parabola. This type of construction provides for a very rigid light structure. The reflective surface of the primary mirror is formed by bonding aluminized acrylic tape to the front aluminum sheet. The reflectivity of this tape in a solar spectrum at air mass one is approximately 0.88. Tape of this type provides a reasonable compromise between cost, performance, and longevity for the short term. The expected lifetime of the tape is estimated to be approximately five to seven years before replacement is needed. This choice is made on an interim basis recognizing that long-life glass front-surface mirrors may become available given the proper market incentive.

The secondary concentrator is formed by two separate elliptical mirrors which run the length of the cell assembly module. The secondary is schematically illustrated in Figure 3.7. The mirrors are fabricated using an extrusion process in which adequate mirror contours have been formed. Each side of the extruded aluminum trough forms a secondary mirror substrate and has an elliptical shape. The line foci of the ellipses are located at opposing edges of the primary mirror. Hence, incident radiation striking an edge of the primary mirror will be directed to an edge of a cell. Sunlight from either edge of the primary mirror is directed to the opposite edge of the cell string.

Figure 3.7. SCHEMATIC ILLUSTRATION OF SECONDARY CONCENTRATOR

Sunlight striking the primary mirror at intermediate positions will be directed to intermediate positions across the cell string. Approximately 60 percent of the radiation reflected from the primary mirror will strike the cell string without secondary reflections. This unique optical design configuration minimizes reflective losses and also provides nearly uniform distribution of radiation across the cell surface and a reasonable amount of insensitivity to deviations in absolute contour, alignment, and pointing accuracy of the overall system. The reflective surfaces on the secondary concentrator use a 3M #850 aluminized mylar adhesive tape. This material was chosen for its generally good reflectivity and its ability to withstand temperatures as high as 100°C. The aluminized acrylic tape used on the primary mirror cannot withstand these temperatures, even for very short periods of time.

3.1.4 Photovoltaic Cells and Absorber Module

The photovoltaic devices used in the 250-watt concentrator unit are N on P single-crystal silicon cells with back surface reflectors developed especially for use with concentrated sunlight. The cells are produced using advanced aerospace cell fabrication and processing techniques. Cell design and manufacturing processes were optimized to achieve high efficiency over the required operating range of 4 to 20 times the illumination under standard test conditions. The cell efficiency peaks at values greater than 15 percent for operation with 28°C cell temperature and between 10 and 15 times the illumination under standard test conditions. For concentrator cells, the correct selection of junction depth (and hence sheet resistance) and front contact configuration are important, because the

high current densities experienced under illumination by concentrated sunlight lead to a requirement for low overall series resistance in individual cells.

The cell width is 2.09 inches with two external ohmic contact bars running the length of the cell and a center ohmic contact bar parallel to the edge contacts. The center contact reduces series resistance and improves cell efficiency with a slight penalty for reduced active area. Narrow contact fingers running across the cell connect to these ohmic collectors. The external ohmic contact bars are located outside of the illuminated portion of the cell strings, whereas the center contact is not. The front and back contact material configuration consists of evaporated titanium, palladium and silver. The titanium provides the required adhesion characteristics; and the palladium acts as a buffer between the titanium and silver for galvanic protection required for a passive, humidity-resistant, contact configuration. The heavy silver outer layer provides the primary conduction path.

The design of cell interconnections and packaging for concentrator applications is more difficult than for flat-plate applications, particularly with respect to thermal considerations, current capacity, and ultraviolet exposure, which impose severe constraints on the cell module design. These design requirements include: performance integrity under moisture, thermal and mechanical stresses from the environment; minimizing the thermal impedance from the cell to the principal heat transfer structure (a finned aluminum extrusion); 1500-volt insulation to ground; and enabling a low-cost manufacturing concept to be applied to the fabrication of cell modules for integration into the concentrator units.

The basic module concept utilizes proven manufacturing techniques for providing the necessary interconnections between the cells and connections external to the module, as well as the means for protecting the cells in a

package that is thermally efficient and resistant to severe environmental stresses. Each concentrator unit has 78 series-connected photovoltaic cells. The cell interconnections are made with Kovar which has been plated first with silver, and then with solder. The cell string is bonded to the heat sink substrate using a silicone-mica dielectric adhesive with a high thermal conductivity. The cell string is then encapsulated in a silicone elastomer, which also serves to bond a protective glass cover pane to the cells and substrate. The ends of the module are terminated with commercially available weatherproof connectors. The encapsulated cell string configuration is illustrated in Figure 3.8. This technology was selected through substantial evaluation efforts at Spectrolab.

Cell cooling is accomplished using a sink type of heat exchanger designed for efficient transfer of energy by convection and radiation to the ambient air surroundings. The heat exchanger is integral with the secondary mirror and substrate of the cell module. This exchanger, of 6063-TS aluminum, is extruded with long trapezoidal longitudinal cooling fins. A large number of these longitudinal fins are saw-cut laterally across the extrusions to form rectangularly shaped pin fins. A hard anodized coating having a thickness of 0.0003 inches is applied to provide environmental protection, high thermal emissivity, and electrical insulation. Performance, to a large extent, depends upon the ability of the cooling system to maintain the cell temperature within a reasonable operating range. A sensor will feed an error signal to offset the tracking system if the cell substrate temperature exceeds 100°C . Enhancement of the passive cooling, which is dependent on heat exchanger geometry and orientation with respect to the earth's gravity field, wind, and ambient temperature, is accomplished in part by the use of high fins that are slotted to form

Figure 3.8. ABSORBER MODULE AND ENCAPSULATED CELL STRING CONFIGURATION

rectangular pins, as shown in Figure 3.9. Optimization of the heat exchanger design was accomplished using wind tunnel test data and computer simulations.

The absorber module is positioned slightly below the primary mirror focus by supporting arms made with the same rigid aluminum Hexcel composite material used in the primary mirror. The arms are permanently attached to the primary mirror with adhesive and mechanical fasteners, and the absorber module is bolted to the opposite ends of the arms. An aluminum sun shade is attached to the arms, above and parallel to the absorber module, to prevent additional heat load on the exchanger. The sun shade is lightweight, is shaped to minimize dust collection, and does not interfere with sun sensor operation. Doubler plates are epoxy bonded to the support arms for reinforcement. Bolts through the tracking structure pivot plates on the primary mirror into the doubler plates anchor the concentrator unit to the truss structure. Slots and oversized holes in the pivot plates allow for $\pm 1^\circ$ concentrator unit field alignment.

3.1.5 Electrical Circuitry

Each concentrator unit contains 78 photovoltaic cells connected in series. For the Sun Valley Photovoltaic Power Project, the concentrator units on each subsystem will be grouped into four electrically paralleled strings. Each string will contain ten series-connected concentrator units. Each concentrator subsystem interfaces with and supplies power to the outside load via a terminal box outside the carousel framework. This terminal box contains the main disconnect switch, which is electrically connected by wiring in rigid conduit (through the concrete track on which the carousel rides) to another box on the ground near the pintle bearing at the center of the carousel. This latter box provides a terminal for easy replacement of flexible welding cable (2/0 gauge) which connects this stationary box to a power junction box

Figure 3.9. PASSIVE COOLING SYSTEM FEATURES

attached to the rotating carousel. An eight-foot copper-coated rod driven into the soil provides a ground which is connected to the negative terminal in the stationary center box. The entire carousel frame is also grounded. Four pairs of leads enter the power junction box, one pair from each of the four parallel concentrator unit strings which each contain ten series-connected units, as shown in Figure 3.10. Each string consists of ten concentrator units and five boxes with the two end boxes providing the leads to the power junction box, as illustrated in Figure 3.11.

Wire sizes for all the primary current circuits, except short runs within the enclosed junction boxes, are determined by voltage drop requirements (less than 1 percent loss, including diodes, based on a system trade-off of power loss versus wire cost). The current carrying capabilities are much greater than if wiring were sized on a temperature-rise basis, and a very wide margin of safety results. Each series string can be isolated by switches which are at both ends of the string in junction boxes 1 and 5. In addition, there is a disconnect switch to cut off any subsystem from the power conditioning system and the rest of the photovoltaic system. These switches provide the capability to disconnect any defective string or subsystem and to isolate portions of the system to take measurements or for safety in working on it. Bypass diodes are used for protection from excessive voltages in any cases where cells in a series string are shaded. The diodes are physically located in the junction boxes and wired in parallel with the main current-carrying circuit. These bypass diodes serve the additional purpose of providing a current path around a concentrator unit in the event that an open-circuit occurs within the unit.

If at least two series strings are in parallel and one of these strings is partially or totally shaded, there would be a reverse current flow through the shaded string if a preventive measure was not taken. The needed

Figure 3.10. SUBSYSTEM ELECTRICAL SCHEMATIC

Figure 3.11. CONCENTRATOR UNIT STRING ELECTRICAL SCHEMATIC

measure is a blocking diode in series with each series string of ten concentrator units. Since this diode is always in the main current circuit, the voltage drop across it causes a loss of output power; the diode was selected for minimum voltage drop.

Each concentrator subsystem is protected from momentary surges, such as from nearby lightning strikes, by a transient suppressor in the power junction box. The suppressor is connected across the positive and negative power buses and has a nominal rating of 500 joules. In the event that the flexible lead between the ground box and power junction box were to be shorted, the high current in the system bus could flow into the subsystem if not prevented. To avoid damage from this occurrence, the disconnect box contains a fuse which is sized so that it will not react to subsystem current variations; but it will open circuit to prevent system current from surging into the subsystem.

An instrument box, installed adjacent to the tracking and control circuit box at the rear of each concentrator subsystem, has leads to every concentrator unit junction box. The instrument box provides connections to monitor:

1. Total concentrator subsystem voltage and current.
2. Current in any series string.
3. Voltage across one or more concentrator units in a series string.

A group of ground jacks are provided to permit the grounding of any portion of a series string to insure the safety of personnel while working on any part of the subsystem.

An AC power source (120 volts) will be provided for the subsystem by flexible cable to a point on the carousel near the pintle bearing. Leads are routed along the framework to the tracker controls at the rear of the subsystem. These controls have provisions for automatic or manual settings, with manual

control up/down, clockwise/counterclockwise, and stop. The tracking and control system uses DC motors (rated 90 volts) for the azimuth and elevation drives. This DC power is derived from the AC power source by silicon-controlled rectifiers. The electronics is provided with ± 15 DC volts for the analog circuits and +5 DC volts for the digital logic by conventional power supplies operating from the AC power source.

3.1.6 Mechanical Features

The major mechanical portions of the tracking system provide the necessary support and positioning drives necessary for efficient operation. The major components are the foundation, truss section, azimuth drive, and elevation drive. The foundation includes the circular concrete track and a center pier that supports the pintle bearing. The track transmits the wheel vertical loads and tractive forces to the ground and provides the level surface required for smooth azimuth rotation. The center pier provides restraint for the pintle bearing and transmits pintle shaft loads (which are primarily lateral loads due to wind) through the pintle bearing to the ground. The pintle pier is constructed of reinforced concrete and is composed of a large circular base section (8 feet in diameter, below ground level) and a smaller square pedestal (2 feet, 4 inches on a side) that extends up from the base to the level of the pintle bearing.

The truss structure is an intersecting network of 43 light open-web trusses that is cross-shaped in plan view. The cross shape of the truss structure is approximately 76 feet by 74.5 feet. Trusses vary in length from 14 to 45 feet and are all 3 feet in depth. Trusses intersect at right angles and are connected by gusset plates welded to one truss and bolted to the other. A bracket is bolted to the top of each truss intersection point, supporting the

concentrator modules by a pin through the bracket. Elevation actuators are supported by brackets that are located on the bottom. Careful attention has been given to production and installation considerations, such as utilization of prefabricated parts, oversized bolt holes, and standard part sizes. Large-scale production will permit weight and cost reduction through dedicated processes.

The azimuth drive system embodies some of the same principles employed for many years in the construction of large steerable structures, such as satellite-communication ground-terminal antennas. Standard commercial components are used wherever possible to insure that the equipment is both reliable and cost-effective. The operating specifications of the azimuth drive system are:

1. Motor speed:	1750 rpm	5. Gear motor ratio:	1505:1
2. Motor power:	0.5 hp	6. Wheel/track ratio:	44:1
3. Wheel diameter:	16 in.	7. Overall ratio:	66,220:1
4. Track diameter:	58 ft,
7.25 in.	8. Axis travel rate:	9.5°/minute
9. Travel limits:	70° to 290°		

The location of the support wheels and the size of the track result from optimization of the array grid configuration. The intersection of the primary longitudinal and transverse structural members provides four relatively firm points to which the wheel assemblies are attached. Much of the speed reduction ratio required between motor rotation and azimuth tracking is thereby automatically accomplished by virtue of the location of the wheels on a large radius. Each of the three idler wheel assemblies is a fully integrated commercial caster designed and built to withstand the anticipated loads. The drive wheel is also a commercial unit into which is pressed a shaft for direct coupling to

the drive. The wheel is supported on both sides by commercial self-aligning pillow blocks. All wheels are machined with tapered threads made of polyurethane, and the wheel axes are mounted to the structure in a canted position. This alignment places the theoretical apex at the track level elevation, thereby promoting scuff-free, low-friction rolling action. This design concept has been fully proven on numerous large steerable antennas.

The drive wheel is powered by a DC gear motor and reducer which are connected directly to the wheel axle with a flexible coupling. To minimize power requirements, a unique epicyclic device is utilized to provide the desired speed reduction. This device combines both a high ratio and a high efficiency and is of the type used on large antennas. The polyurethane wheel tread has excellent tractive properties. The drive is automatically controlled by the sun sensor that activates the system during the tracking cycle. It can be manually controlled by an override switch wired into the circuit.

Because the wheels primarily provide vertical support, horizontal or shear loads must be resisted by a separate pintle bearing located in the center of the structure. The bearing that serves this function also establishes the axis of rotation for azimuth tracking. This relatively compact assembly consists of a spindle secured to the structure and a self-aligning antifriction bearing cartridge fastened to a concrete pier. The spindle is axially restrained in the bearing and will resist nominal live loads in the vertical direction. Azimuth travel limits are electrically defined by a system of phototransistors and infrared light-emitting diodes located at the pintle bearing.

The elevation drive system must resist gravity and wind loads that vary over the entire range of travel. Pressure centers of wind loads vary; and in placement of the elevation axis, it is more cost-effective to design

the system to accommodate the loads than to minimize loads through extensive design analysis. Computer analysis of load distribution in the structural members for several configurations produced a drive system composed of a motor gearbox, four linear ball-screw actuators, and four lines of horizontal links that connect to the 40 units. Large-scale production will allow use of production techniques to reduce cost and weight. Functional characteristics of the elevation drive system are listed below:

1. Motor speed: 1750 rpm
2. Motor power: 0.5 hp
3. Gear motor ratio: 50:1
4. Actuator ratio: 6:1 (12.7 turns for 1 in. rise)
5. Overall ratio (average): 66,120:1
6. Axis travel rate (average): 9.5° /minute
7. Travel limits: 10° to 90°

The principal elements of the elevation drive system are the actuator assemblies, actuator links, drive links and pivot assemblies. There are a total of four actuator assemblies interconnected at their input shafts so that motion is imparted uniformly to all concentrator units. The actuators are located at the front row between adjacent cross rows of the array to minimize elevation pointing error resulting from structural compliance of the drive and actuator links. Of these actuators, only the center one is driven by the DC-powered gear motor coupled to it. The resulting power train provides uniform, synchronized motion transfer to the concentrator units.

A clevis arrangement at each end of the actuators provides the necessary pivoting action and permits a rigid connection between the structure and the actuator links. All actuators are aligned and their input shafts interconnected with flexible, floating shaft-type couplings. Torsional properties of

the couplings ensure synchronous movement of all concentrator units well within the required limits. All couplings used in the actuator assemblies are lubrication-free disk type. The actuator links are the main connecting members (one for each actuator) that transfer the loads from the drive links, through the actuators and into the structure. They consist of 3-inch by 5-inch rectangular steel tubing with three pivot points for bearings and pins. The bottom pivot engages a pin which also passes through the elevation bracket and the frames of two adjacent concentrator units. The upper pivot engages a pin that passes through the drive link as well as the frames of two adjacent units.

The actuators are commercial ball-screw-type jacks rated for 5 tons and designed for maximum efficiency. Inside the actuator, the ball screw passes through a captive ball nut which is rotated by a worm-driven gear set producing the linear motion required to rotate the units. The ball screw is protected from the elements by a flexing bellows at one end and a pipe at the other end. The actuators are grease packed and require relubrication only at relatively long intervals.

Optimization was carried out by computer analysis, which assisted in selecting the most efficient shape and cross-section. All drive links are fabricated of 2-inch square steel tubing. The design of the pivot assemblies is extremely important since they directly influence overall pointing error. Among the characteristics considered essential in the pivot assemblies are:

1. Controlled clearance (backlash).
2. Low cost.
3. Long-range dimensional stability.
4. Low maintenance requirements.

Each pivot assembly consists of a pin, bearings, cotter keys, and where applicable, a bracket to secure the pin to the structure or unit. The pins are made

of corrosion-resistant 0.75-inch-diameter steel ground bar stock. Positive retention is provided by a cotter key at each end, resulting in a design that is low in cost as well as easy to assemble.

Various alternative bearing types were considered. Among them were teflon- and nylon-lined bushings and numerous solid plastic types molded of a variety of thermosetting and thermoplastic materials. The selected bearing is a commercial, graphite-impregnated, sintered, bronze bushing that possesses the best combination of low cost, long-term reliability, and low maintenance. Unlike many of the commercial bearings that employ plastics, the bronze bearings exhibit superior properties and will not lose their tolerance due to cold flow from constant unidirectional loading. Lubrication is automatic and is provided by impregnating the bronze with graphite. This effectively provides a reservoir of lubricant possible only with the unique sintering process by which the bearing is made. To minimize cost, the bearings are used as purchased with no modification. The bearings effectively control lateral movement of the units while providing the close tolerances required to minimize pointing error resulting from bearing-to-pin radial clearance. Replacement of all pins and bearings is easily accomplished without disturbing connected equipment.

3.1.7 Control and Tracking Logic

The tracking and control system performs the function of keeping the optical axis of the solar concentrator array pointed directly at the sun whenever useful energy can be obtained from the system. The tracking and control system performs the array-positioning function automatically for system installations anywhere within the equivalent latitude boundaries of the contiguous United States. The control system positions the two axes of the array toward the mean sunrise angle prior to the start of the local solar day and begins tracking at

sunrise, or depending on atmospheric conditions, whenever the insolation level reaches a minimum usable threshold. The tracking and control system consists of a pair of electric drives (one for each axis), a tracking sensor that detects the array angular pointing error from the sun, tracking logic circuits that detect and control insolation and tracking error threshold levels, and operational logic and switching circuits.

The use of on-and-off tracking rather than continuous drive results in cost and complexity savings by eliminating the drive power amplifier. The use of relay and transistor drive power switching in conjunction with the error comparators allows tracking to within the required accuracy. Permanent magnet DC drive motors are used to control the structure motion. These drives are controlled by an on-and-off controller using relays and transistors. The relays are preset before current is turned on by the transistor. This prevents arcing and wearing of the relay contacts. The use of relays in conjunction with transistors ensures that there are no short-circuit paths due to faulty logic and allows simple shorting of the motor armature for dynamic braking. Proportional error sensing is accomplished by the use of a four-axis photocell feed in conjunction with a reference cell to produce a true error signal in volts per degree independent of insolation level. The photocells are operated in their short-circuit mode to ensure maximum linearity versus light level and to minimize output changes with temperature. The use of proportional error sensing allows the electronics to control the tracking error to within the desired accuracy for nearly full utilization of the sun's energy.

The control logic consists of safety limits, manual operation, wake-up and catch-up functions, low-insolation cutout, fine solar tracking, and overtemperature offset. The control logic is illustrated in block diagram form in Figure 3.12. The safety limits are composed of the azimuth encoder, the

Figure 3.12. CONTROL LOGIC BLOCK DIAGRAM

elevation position switches, and the control electronics. The purpose of the limits is to prevent array structure motion past the position set points. The logic is such that the safety limits override all other modes of operation. The manual mode of operation permits the positioning of the structure for such purposes as maintenance and cleaning. Operation is by means of switches on the control electronics board. The wake-up and catch-up functions will preposition the array to a fixed position at fixed times if the system is not automatically tracking at these times. In conjunction with the wide angle of the sun sensor, this logic provides complete coverage of the sun's position throughout the day in the event that cloud cover or low insolation levels interrupt the automatic tracking. The wake-up logic automatically prepositions the structure to the appropriate morning position and resets all the catch-up logic.

The low-insolation cutout inhibits automatic tracking whenever the insolation is below a preset level. When the insolation level is high enough for automatic tracking, the structure will catch up to the sun either because of the wide view angle of the sun sensor or by use of the catch-up logic. Fine solar tracking is accomplished by using the proportional error signals from the sun sensor and associated electronics. The reference photocell is used along with the two pairs of error photocells to generate a proportional error gradient independent of insolation level. This error signal is compared to fixed position set points, and the resultant comparison then drives the structure to a new position when the error builds up. The overtemperature offset logic is used to point the concentrator array ahead in elevation in the event of overheating. This position will assure the absence of reflected sun on the cells and heat sink assemblies. When the overtemperature condition ceases, the array will continue automatic tracking.

The tracking logic consists of an on-and-off servomechanism with the on state and off state controlled by a linear position error signal generated by the sun sensor and associated electronics. The linear position error is compared to fixed set points to determine if tracking motion is required at any given point in time. This scheme was chosen over a continuous-drive linear system to conserve power and to eliminate the expense of a power amplifier. Large offsets in either direction will drive the concentrator toward the zero error position. For instance, if the system is ten degrees behind the target, the forward drive will be on and the reverse drive will be off. The system will be driven toward the zero error position and then slightly beyond, at which time both the forward and reverse drives will be switched off. The relative position of the sun continues moving after the drives are switched off until the error is reduced to zero and then grows in the opposite direction to -4 volts, at which time the servomechanism will turn on and drive the concentrator unit slightly past zero again. A suitable differential between the forward and reverse drive limits is necessary to prevent a continuous limit cycle oscillation about zero error position. It is noteworthy that the reverse drive is never switched on during this normal tracking hysteresis cycle. For correction of large errors by movement in the reverse direction, the reverse drive operates in this same manner as the forward drive. Therefore, the drive will fall into step from either direction and track the correct direction without any presetting of the logic or memory of previous events. The hysteresis logic function is provided by a clocked J-K flip-flop. The forward and reverse drive commands are further interlocked to prevent simultaneous drive application.

The purpose of the wake-up and catch-up logic is to preposition the concentrator array to the approximate position of the rising sun in the

morning and also to move the array to fixed positions during the course of the day if the level of insolation becomes insufficient for automatic tracking. The input information for this logic consists of array position data from the azimuth encoder (3 bit) and the elevation position mercury switches. The positional information is logically combined with time information from a 24-hour clock and information from an insolation level comparator that determines whether the system is automatically tracking as it would be if the insolation level were high enough. The purpose of the catch-up logic is to move the array to a programmed position if the system is not automatically tracking at a certain time. The 60° width of the view angle of the sun sensor is such that the array will be able to catch up to the correct tracking position from the programmed position. The programmed positions and times were carefully determined by plotting all possible positions of the sun at various selected times for all seasons and all latitudes within the contiguous United States.

The 24-hour clock is basically an electronic equivalent of a mechanical four-station timer of the type used to control process solenoids. The clock uses a separate divider circuit that divides a standard 3.58 MHz crystal oscillator down to 60 Hz. The clock circuitry divides the 60 Hz down into hours and minutes for timing purposes. A four-digit light-emitting diode readout device and an eight-pole momentary switch are used to set the correct time, set the trip points for the four outputs, and verify the set points. The azimuth encoder is a simple 3-bit encoder utilizing a metal disk attached to the pintle bearing and three pairs of phototransistors and infrared light-emitting diodes shining through a hole pattern corresponding to calculated angular positions. These three bits are decoded and used to clock a type D flip-flop which turns off the drive when the array reaches these positions, if the array was turned on because it was not tracking automatically. The 24-hour clock outputs are used to clock additional type D

flip-flops whose D input is determined by whether the array is automatically tracking or not. If the array is tracking at the transition of the time clock pulse, nothing happens. If the array is not automatically tracking at the time of the clock pulse, the array is turned on until it reaches the preselected position, at which time it turns off due to the position flip-flop. At the selected morning time, all flip-flops are reset and the array is driven back to the wake-up position. Prepositioning will only occur if the array is not automatically tracking at the selected times. Furthermore, any particular prepositioning will occur only once during a 24-hour cycle because the flip-flops are triggered by the transition of the time clock and the position information. This makes the system very immune to noise.

The purpose of the sun sensor is to provide the necessary signals to produce azimuth and elevation position errors with reference to the position of the sun. The selected scheme uses the differential shadowing of two pairs of orthogonal photocells to produce the required signals. Additional refinements include an angular offset of the photocells from the normal to provide wide peripheral vision and the inclusion of a reference cell to provide position error independent of insolation levels.

The parameters considered in the sun sensor design include the following:

1. Characteristics of photocells.
2. Height of sensor assembly.
3. Percent of shadowing for on-axis null.
4. Amount of photocell angular offset from normal.

The current output of the photocell will be directly proportional to the insolation level. The output of each photocell will be terminated in a current-to-voltage operational amplifier that will provide a voltage

proportional to the insolation level. A photocell size of 1 inch by 1 inch was chosen due to its availability, cost, and output levels.

The height of the sensor assembly directly affects the maximum linear range, and therefore, the sensitivity of the position error signal. To evaluate this parameter, a geometrical analysis was made and a height of 15 cm was chosen as a suitable compromise to give a minimum physical height, a minimum sensitivity to height variations and a linear range of about $\pm 3^\circ$. This analysis indicates that there is little advantage to a "tall" sensor (over 30 cm in height) and that a "short" sensor (under 10 cm) becomes very sensitive to height variations.

Shadowing of the photocells is not a requirement but does provide several advantages, among which are reduced power consumption of the electronics and a higher error gradient for a given height. Since the current-to-voltage amplifier draws current from its power supply directly proportional to the current output of the photocells, it is advantageous to reduce this average current by optimized shadowing of the photocells. Sensor tracking accuracy is in the $\pm 0.4^\circ$ range as illustrated in Figure 3.13. The sun sensor assembly incorporates mercury switches that will be used as the elevation limit switches. These are mounted on a removable side panel, which also permits termination of the photocell leads and the external cables. A four-point mechanical mounting allows fine position adjustment of the sensor assembly. The sensor housing will be made with sheet metal. With no offset, the peripheral vision of the sensor will be limited to $\pm 50^\circ$. To increase this to $\pm 90^\circ$, the photocells will be offset from the normal by 30° .

The final mechanical configuration is shown in Figure 3.14. The position of the four error photocells is determined by the housing, thereby eliminating any measuring or assembly jigs. The positioning of the reference

Figure 3.13. TRACKING ERROR GRADIENT
(15-CM HEIGHT, 50-PERCENT SHADOWING)

Figure 3.14. TRACKING SENSOR GEOMETRY

photocell is noncritical. All photocells are held in place by a suitable adhesive. The only critical dimensions are the height (15 cm), the offset angle (30°), and the overhang of the shadow plate (8.7 mm). All other dimensions are noncritical and should allow inexpensive manufacturing.

3.1.8 Subsystem Environmental Tolerance

The subsystem was designed to meet the following environmental design goals:

1. Life: 20 years with 10 percent performance degradation maximum, periodic maintenance allowed.
2. Temperature Extremes: -30°C to $+40^{\circ}\text{C}$ while operational in still air; peak power to decrease no more than 0.5 percent for each 1°C rise in ambient temperature. Peak power was considered to be that produced under standard environmental test conditions of $1\text{kW}/\text{meter}^2$ insolation, 28°C ambient temperature, and 1 meter/second wind velocity.
3. Wind: Operational 14 meters/second maximum with no more than 5-percent reduction in peak power. Survival, nonoperating: 40 meters/second maximum.
4. Hail: Survival with no permanent damage: 1.3 cm hailstones traveling at 22 meters/second.
5. Humidity: Operating and nonoperating: 0 to 100 percent relative humidity.
6. Rain: Nonoperating: Survival through rains of normal extremes found in the contiguous United States.
7. Dust, windblown sand, corrosive atmospheric constituents, bird droppings: Subsystem to be operational after mirror cleaning

with no more peak power reduction than consistent with life goals (5-percent reduction after 20 years). Capable of operation with minor power degradation when light dust and sand remain on mirror.

8. Lightning: Survival of nearby lightning strike.

Wind, ambient temperature, and lightning were extrapolated to stress, deflections, local temperatures, and local currents by computer techniques for each subcomponent and part. Humidity and rain protection techniques are known from similarity to existing equipment. Open-air tests have been conducted at Spectrolab beginning before this project was conceived and continuing. These tests yield useful data on the effects of dust, wind-borne sand, atmospheric contaminants, bird droppings, and solar ultraviolet effects.

All components, subcomponents, parts, and materials were designed or selected to meet or exceed their localized environmental extremes based on computations and tests. Many commercial subcomponents, parts, and materials are used in the subsystem; each was reviewed before selection from its manufacturer's data to assure its ability to meet or exceed its environmental requirements. Table 3.3 contains information on the expected overall annual efficiency and material costs for the photovoltaic array.

Process characteristics were also reviewed to assure that the process parameters used produced a final part or material which meets or exceeds its environmental requirement. For example, the cell string adhesive, after application, is cured at a temperature in excess of its maximum temperature in the subsystem. Joints and electrical connections are designed to prevent moisture or sand entry into sensitive subcomponents or parts; and protective sleeving, gaskets, and encapsulants are employed to protect and seal sensitive areas and avoid moisture traps. In a few areas it was found necessary to stipulate

TABLE 3.3

MATERIAL COSTS FOR ONE 10 kW SUBSYSTEM

<u>Material Description</u>	<u>Amount in Lbs. Unless Otherwise Noted</u>	<u>Projected Cost Per Lb. Unless Otherwise Noted (\$)</u>	<u>Projected Costs (\$)</u>	<u>Revised Costs (\$)</u>
CONCENTRATOR UNITS				
1. Aluminum				
a) Extrusions	2,920	0.85	2,482	2,044
b) Honeycomb	1,600	11.00	17,600	5,520 (1)
c) Structural	320	1.05	336	336
2. Low-Iron Glass	40	1.20	48	48
3. RTV Silicone	88	13.00	1,144	616 (2)
4. Aluminized Film	1700 ft ²	0.20/ft ²	340	340
5. Kovar	7 oz	23.00	10	10
6. Electrical Cable and Wiring Parts	625	1.35	844	844
7. Cells and Inter- connections	53,200 cm ²	0.25/cm ²	13,300	13,300
8. Fasteners	200	0.50	<u>100</u>	<u>100</u>
Subtotal			36,204	23,158
SOLAR TRACKING STRUCTURE				
9. Structural Steel Trusses	18,135	0.38	6,891	4,548 (3)
10. Misc. Steel	2,450	0.50	1,225	1,225
11. Gearboxes	195	4.00	780	780
12. Linear Actuators	240	4.00	960	960
13. Bearings	30	4.00	120	120
14. Wheels	320	2.00	640	640

TABLE 3.3 (Continued)

MATERIAL COSTS FOR ONE 10 kW SUBSYSTEM

<u>Material Description</u>	<u>Amount in Lbs. Unless Otherwise Noted</u>	<u>Projected Cost Per Lb. Unless Otherwise Noted (\$)</u>	<u>Projected Costs (\$)</u>	<u>Revised Costs (\$)</u>
15. Couplings, Bushings	50	4.00	200	200
16. Hardware, Pins	440	0.50	220	200
17. Drive Motors	40	3.00	120	120
18. Paint	500	2.00	1,000	1,000
19. Electronics	65	18.00	2,970	1,170 (4)
20. Cable and Wiring Connections	240	1.35	324	324
Subtotal			15,450	11,307
TOTAL			51,654	34,465

RECENT ADDITIONS TO
CONCENTRATOR UNITS

Cell Mounting Tape	142 ft ²	5.75/ft ²	-	817
Absorber Polyester Reflective Tape	260 ft ²	3.60/ft ²	-	<u>935</u>

NEW SYSTEM TOTAL FOR MATERIAL 36,217

Clear Aperture Area 131.7 m²Cost Per Unit Area 275/m²

- (1) Cost estimate at \$3.00/lb. in system quantities of 1000/yr. from Hexcel Corp.
- (2) Estimate from General Electric at \$71/lb. (Cost review for program on flat-panel technology at Jet Propulsion Laboratory).
- (3) Estimate on reduced structure requirement from Ford Aerospace and Communications Corporation.
- (4) Estimate from Spectrolab on reduced component count by redesign of central circuits.

external aids, such as periodic mirror cleaning, actuator lubrication, and central lightning protection.

3.2 Power Conditioning System

3.2.1 General Information

A power conditioning system was selected by a competitive process. Initially, an attempt was made to select a supplier through a bid procedure. A set of specifications was written containing certain design criteria and requirements. These design criteria were developed as a consequence of several meetings with interested vendors to discuss the project requirements. Topics discussed with the vendors included the following:

1. Suitability of existing products for project requirements.
2. Level of development or modification required to achieve suitability with project requirements.
3. Ability to develop control circuitry for peak array power tracking.
4. Interest in developing a prototype for a future standard product line.
5. Vendor's technical competence and manufacturing facilities.
6. Cost and lead time required to deliver the necessary product.

With the assistance of LADWP's Purchasing Division, a set of specifications requesting proposals to supply the power conditioning system was released. At a later date, a bid opening was held to determine the type of response to the aforementioned advertisement for proposals. Although there were several responding parties, no bid fully met all requirements of the specifications. Consequently, a follow-up advertisement using the same technical

specifications with a different cover number was released. This second advertisement produced results similar to the first advertisement, namely no fully complying responses. A determination was made to negotiate with all those vendors responding to the second advertisement and thereby reach an agreement with one of them to supply the power conditioning system. The selected vendor was Exide Power Conversion Division of ESB, Inc.

The power conditioning system which was specified by LADWP is to meet the following broad requirements:

1. Self-commutated DC-to-AC converter.
2. Specified control mechanisms.
3. Capable of parallel operation with utility service connection.
4. Capable of stand-alone operation, isolated from utility system.
5. Capable of peak power tracking for parallel operation.
6. Modular design using proven technology wherever possible.
7. A single inverter or alternately a group of parallel inverters.
8. Tested and inspected in compliance with LADWP requirements.

Detailed specifications including numerical design parameters were generated, and Exide contracted to meet these requirements. The contract which was arranged is conditional upon LADWP being selected as a participant in Phase 2 and upon DOE ratification of the agreement as it is written or with necessary modifications. It was necessary to execute a conditional contract as described above in order to comply with LADWP procurement practices. This procedure for arranging a conditional contract with subsequent ratification by DOE (if LADWP is selected for Phase 2) was discussed with DOE's Contracting Officer for Phase 1, and his concurrence with the procedure was obtained. In the following two subsections a detailed description is given of the technical characteristics of the power conditioning system, as specified by LADWP and proposed by Exide to meet LADWP requirements.

3.2.2 Specifications

The power conditioning system (hereafter referred to as the conditioner) will consist of a self-commutated DC-to-AC inverter and power system controller and will be designed to deliver AC power output when in a normal mode of operation in parallel with LADWP's Valley Generating Station 480-volt service system and when in an emergency stand-alone mode of operation with an isolated load. The electrical input to the conditioner coming from the photovoltaic concentrator array will consist of variable DC power. The conditioner will be capable of peak power tracking of the photovoltaic array output when in the parallel operating mode. The conditioner will be designed explicitly for photovoltaic application using proven technology and adaptation of existing design wherever possible. The inverter section will be modular in design, utilizing plug-in circuit modules.

All parameter values for the photovoltaic system used in the conditioner specifications were estimates based upon the latest information at the time from Spectrolab. The photovoltaic array's nominal DC output voltage was taken as 371 volts. The DC output voltage was assumed to fluctuate from 293 to 434 volts under normal conditions. The maximum open-circuit voltage produced by the array under normal conditions was taken to be 550 volts. Final parameter values based upon Spectrolab's completed design will be furnished to the selected supplier within 15 calendar days after the date of notification to proceed with the work. The selected conditioner will use a single inverter; however, vendors were also allowed to offer proposals involving two or more inverters in parallel to achieve rated output. The conditioner will be designed, constructed, and tested to meet all of the applicable requirements of the IEEE, ANSI, NEMA, and ASME Standards; and it will be rated as follows:

1. Input Voltage: The conditioner will provide rated output of 200 kW at 0.8 power factor for a DC input voltage range of from 293 to 434 volts. The conditioner will initiate automatic shutdown sequencing for DC input voltages less than 293 volts or more than 550 volts.
2. Output Voltage and Phase: The conditioner will be regulated to provide 3-phase, 4-wire, 480 AC volts (line-to-line) ± 5 percent, 277 AC volts (line-to-neutral) ± 5 percent, and will maintain an output voltage angular waveform displacement of 120 ± 5 degrees between Phases A and B, B and C, and C and A, when in the stand-alone operating mode. Provision for manual adjustment of the output voltage for a range of ± 5 percent nominal voltage will be provided. In the parallel operating mode, the actual line voltage and phase angles will match those of the 480-volt station service system. The conditioner will track the 480-volt station service system over line voltage variations of ± 10 percent, balanced or unbalanced, and phase angle variations of ± 10 degrees. A transformer will be provided at the output of the inverter section to provide isolation.
3. Output Frequency: The conditioner will track the frequency of the 480-volt station service system from 59 to 61 hertz in the parallel operating mode. The conditioner's output frequency will be 60 ± 0.06 hertz in the stand-alone operating mode.
4. Output Power: The conditioner will be capable of supplying up to and including 200 kW at 0.8 power factor to an electric motor load.
5. Power Factor: The conditioner will be designed to deliver 250 kVA at unity to 0.8 lagging power factor. Transient excursions

to zero power factor within the kVA and current rating will not result in damage to the conditioner.

6. Harmonic Voltage Distortion: Total harmonic voltage distortion will be limited to 5 percent with a maximum of 3 percent for any single harmonic, with the conditioner operating at any load from no load to rated load and at any power factor from 0.8 lagging to unity.

7. Current Distortion: Total current distortion will not exceed 10 percent from no load to full load in the parallel operating mode.

8. Efficiency and Losses: The conditioner will have an overall efficiency greater than 90 percent from half load to full load for the specified input and output voltage and load characteristics.

9. Peak Demand and Overload: The conditioner will sustain, without damage, peak loads of 150 percent of rated output for 30 seconds and 125 percent of rated output for 10 minutes.

10. Output Current: The conditioner will be designed to limit output current in any phase within required limits to prevent damage to the unit.

11. Voltage Transient Response: The conditioner will have a voltage drop not to exceed 10 percent with a 50-percent step-load application, returning to full regulation within 0.1 second.

12. Operating Conditions: The conditioner will be designed to operate at full load under the following conditions:

Ambient temperature	0 to 40°C
Relative humidity	0 to 90 percent (noncondensing)
Altitude	0 to 4000 feet

The conditioner will be designed to deliver rated power output in both the parallel and stand-alone operating modes. The operating mode will be determined by means of a selector switch. In the stand-alone operating mode, with rated input power available, the conditioner will be capable of starting one of the fan motors of the selected load application in its 40-horsepower mode.

The conditioner will initiate automatic start-up when the following conditions exist:

1. Photovoltaic array output is sufficient to supply the inverter losses.
2. Conditioner's input terminal voltage is between 345 and 550 DC volts.
3. Conditioner's output open-circuit voltage is within the regulation specified above.
4. Conditioner's output voltage is matched to the 480-volt station service system in magnitude, frequency, and phase if in the parallel operating mode.

The conditioner will be designed to automatically initiate shutdown sequencing for any of the following conditions: input overvoltage, input undervoltage, input overcurrent, output overvoltage, output undervoltage, overload, and overtemperature. The cause of shutdown will be displayed visually, and an audible alarm will be sounded. The conditioner will be protected against reverse power flow from the 480-volt station service system and reversal of input voltage. The conditioner will have input and output circuit interrupters activated by automatic and manual start-up and shutdown procedures.

The conditioner will be equipped with an output control switch. In the "On" position, the switch will allow the conditioner circuit interrupter to close if the system is within operating tolerances. In the "Off" position, the switch will cause the conditioner circuit interrupter to disconnect the conditioner from the load or 480-volt station service system. The conditioner will incorporate automatic closed loop control of power flow from the photovoltaic array to either the isolated load or the 480-volt station service system. The conditioner will control the inverter to supply all load demand within the instantaneous capability of the photovoltaic array and conditioner.

The conditioner will be designed to provide peak power tracking of the photovoltaic array output within the rated output of the conditioner, when in the parallel operating mode. Both automatic and manual operation of the peak power tracker will be provided. In the automatic position, the peak power tracker will continuously adjust the inverter to deliver the maximum power available from the photovoltaic array. The actual maximum power point is the knee of the current-voltage characteristic of the photovoltaic array. This characteristic is dynamic and will change with temperature and incident insolation level. The peak power tracker will control the inverter to keep it operating at the knee of the current-voltage characteristic of the array so that the maximum available power will be delivered continuously by the conditioner.

In the manual position, power to the 480-volt station service system can be increased or decreased by manual adjustment of the peak power tracker. A wattmeter will be provided at the conditioner output so that the peak power point can be identified. The peak power tracker will be switched out of operation in the stand-alone operating mode.

The conditioner will be capable of accepting additional inverters of equal or lower kVA ratings in parallel with its existing inverter to increase the conditioner's overall output kVA capability. The conditioner will be provided with a redundant fan cooling system. A normally closed contact will be provided which opens in the event of a failure of the cooling air flow. Semiconductor devices will be employed in all active circuitry, and power semiconductor circuits will be fused so as to prevent cascaded or sequential semiconductor device failures. Indicators will be provided to denote blown-fuse conditions. All semiconductor devices will be hermetically sealed.

A control and display panel will be located on the equipment cabinet which will contain the entire metering, control switching, and alarm systems required for operation of the equipment. The following metering will be furnished on switchboard-type meters with a minimum accuracy of ± 2 percent:

1. Conditioner input voltage.
2. Conditioner input current.
3. Conditioner input power.
4. Conditioner input energy (watthours).
5. Conditioner output voltage.
6. Conditioner output current.
7. Conditioner output power.
8. Conditioner output energy (watthours).
9. Conditioner output vars.
10. Conditioner output frequency.

The following alarms will be displayed:

1. Conditioner input overvoltage.
2. Conditioner input undervoltage.

3. Conditioner input overcurrent.
4. Conditioner output overvoltage.
5. Conditioner output undervoltage.
6. Conditioner overload.
7. Conditioner overtemperature.
8. Conditioner low cooling air.
9. Conditioner out of phase with utility system.
10. Conditioner blown fuse.

A separate isolated normally closed contact will be furnished which will open for any of the above alarm conditions. Alarm indicators will utilize light-emitting diode displays. The average audible sound level of the conditioner will not exceed 75 dB measured 6 feet from any surface.

The equipment will be furnished in enclosures with front access by means of hinged doors. All equipment therein will be readily accessible for maintenance and installation. Cabinets and doors will be free of twist or warp with doors in the open position. All ventilation intakes will be fitted with reusable dust filters. All cabinet surfaces will be prepared for painting by either pickling or blast cleaning. All welds will be thoroughly cleaned to remove any weld flux, spatter, condensates, slag, or heat oxides. All rust, mill scale, grease spots, or other foreign material will be completely removed. Blast cleaning and pickling will comply with the Steel Structural Painting Council Specifications SSPC-SP6 and SSPC-SP8, both as last revised, as the minimum acceptable degree of cleaning. After cleaning, the metal will be primed with one or more coats of paint complying with Federal Specification TT-P-636, as last revised.

One or more coats of finish paint will be applied over the primer and will comply with Federal Specification TT-E-527, as last revised. The

light gray color will be No. 36314, lusterless, of Federal Standard No. 595 or ANSI Standard 61. The color variation from the standard will not be more than ± 0.5 N.B.S. units. The dry-film thickness of both the primer and finish coats at any point will be a minimum of 3.0 units. In the event that the specified film thickness is not achieved, additional coats will be applied until the required thickness is obtained.

Inspection will be made and tests will be witnessed by LADWP in the supplier's mill, factory, yard, or warehouse. The power conditioning system will be completely assembled, energized, and will carry full-rated load. Under these conditions, all controls, alarms, and control circuits will be activated to test for specified performance. The conditioner will be tested in both the stand-alone and parallel operating modes. The conditioner will be checked for proper tracking over the full operating range. LADWP will then install, energize, and field test the conditioner for full compliance with the above specifications.

3.2.3 Manufacturer's Data

Exide will supply a power conditioner that meets the above specifications by adaptation of an existing 250 kW inverter which is currently used in its uninterruptible power supply product line. This product line is described in literature available from Exide which is not included here due to space limitations. Exide's method for controlling real and reactive power flow between an inverter and another AC source makes use of the fact that the real power flow from the inverter can be controlled by varying the "power angle" or relative phase angle of the inverter output with respect to the other source, which in this application is the utility system. An increase in the power angle increases the real power being provided by the inverter. This means that the

overall peak power tracking problem is one of sensing the actual power being provided by the photovoltaic array and then modulating the power angle to maximize power delivered. The control can be designed either to track array DC power or the actual AC output from the inverter; the difference is small, but intuitively it is the end-use power that is to be maximized and thus the AC power will be tracked.

A microprocessor will slew the power angle in either the increasing or decreasing direction depending upon its previous command. Approximately 1,000 times per second it will sample the present power output and compare it with the previous sample. If the power is larger, it will continue to slew in the same direction. If it is smaller, it will reverse direction. A totally adaptive control will result that seeks the maximum power point. The tracker will very rapidly correct for changes in illumination and ambient temperature.

3.3 Other Facilities

3.3.1 Switchgear and Control System

In the normal operating mode the power conditioning system output will be in parallel with LADWP's 480-volt distribution system at the Valley Generating Station, i.e., the station service, to energize the power center for the Unit 2 cooling tower (PC2B). (Refer to Figure 3.15.) The normal operating mode will be obtained by closing control switches A and B (to be located in the control center for the Valley Generating Station) thereby paralleling the conditioner with the 480-volt service and energizing PC2B. The conditioner output control switch will be closed to synchronize the conditioner to the 480-volt service and deliver power from the photovoltaic array. The seven cooling tower fan motors would be switched on, as needed, by the control room operator.

Figure 3.15. SCHEMATIC OF CONTROL SYSTEM

Synchronism of the conditioner with the utility system will be provided by means of a synchronizing circuit from the conditioner to the utility system. The synchronizing circuit will provide for in-phase switching between power sources. If a sustained fault or overload occurs at the conditioner output, the conditioner will disconnect from the load and initiate automatic shutdown. The conditioner would have to be restarted manually after a fault condition.

In the parallel operating mode, the conditioner will provide peak power tracking of the array to deliver maximum available power. The peak power tracker will be automatically switched out on loss of the utility service. During periods of darkness, the conditioner will initiate automatic shutdown, and power to the load will be supplied by the utility service. When sunlight is again available, the conditioner will initiate automatic start-up and deliver available power.

If an undervoltage appears on the 4.16 kV unit auxiliary bus feeding PC2B, undervoltage relay UVR1 opens contactor "A", isolating PC2B from the 4.16 kV system. With contactor "A" open, power is supplied to PC2B from the conditioner output. Should the power available from the array become insufficient to supply the motor load, and if power has been restored to the 4.16 kV bus, then undervoltage relay UVR2 will activate a time delay relay to close contactor "A", thereby returning the system to normal parallel operation. If power is not available from 4.16 kV bus, the control room operator would shed load, as required, to ensure that the remaining load demand does not exceed the available output of the photovoltaic system.

For purposes of experimentation, the stand-alone mode of operation can be obtained by opening circuit breaker "A". The photovoltaic system is then the only energy source for PC2B. Under these conditions, the impacts

on a photovoltaic system associated with motor starting and switching can be investigated. Opening circuit breaker "A" prevents the automatic reclosure of the contactor "A" due to undervoltage at the conditioner output, as described previously. When plant reliability cannot be disturbed, the circuit breaker "A" should not be opened. By opening the contactor "A", stand-alone operation can be achieved, with automatic return to parallel operation should the voltage at the conditioner drop below an acceptable level.

3.3.2 Electrical Interconnection System

The layout of 20 subsystems in an array is illustrated in Figure 3.16. The illustration also shows the locations and sizes of the conduit and cable used for interconnection. The indicated conduit and cable sizes are representative of those that will be used, and the actual sizes will depend upon available stock at the time of installation. The visitor facility will be positioned as shown to avoid shadowing on the southern side of the array while simultaneously keeping the cable lengths from being excessive. All electrical interconnections will be installed underground, and the number of required trenches will be minimized by collocating cables wherever possible.

3.3.3 Equipment Building and Visitor Facility

The equipment building and visitor facility will be a prefabricated demountable steel building approximately 20 feet by 20 feet in area. The building will house the power conditioning system, electrical switchgear, a metering panel display, and an area for visitor briefing and observation. Cooled air will be supplied to both the equipment and visitor areas. A parking area for 6 to 10 cars will be provided at the building. The building's construction will consist of the following:

Figure 3.16. SYSTEM LAYOUT AND ELECTRICAL INTERCONNECTION SCHEME

1. Floor: Concrete slab, steel trowel finish.
2. Walls: Steel "monopanel" system, insulated.
3. Roof: Steel-ribbed panels with rigid insulation below.
4. Structure: Prefabricated steel rigid frame.
5. Design: Modest, functional, no facilities for manned operation.

The equipment and visitor areas will be separated by the metering panel display. LADWP's architectural design staff has estimated the cost of the building to be in the range of \$25 to \$30 per square foot. A tentative schedule of design and construction milestones is provided in Table 3.4. The following building codes and agencies are expected to be involved: the Los Angeles Municipal Arts Commission; the Los Angeles Planning Commission; the Los Angeles Building Code; and the State Energy Conservation Standards. The preliminary building design, as described above, was selected based on the rationale that the primary purpose of the project is to assess the performance of a system of photovoltaic concentrators; and the cost of related facilities should be kept to a minimum so long as doing so does not interfere with meeting the project objectives. An LADWP architect will oversee the final design, procurement, and installation of the facility to assure that the requirements of pertinent building standards and codes are met.

3.4 Optional System Design

This section discusses a smaller system configuration which was designed as an option during Phase 1. The optional system would involve the same load configuration and would be located at the same site as the baseline system. However, less land would be required for installation of the smaller

TABLE 3.4

EQUIPMENT BUILDING AND VISITOR FACILITY
DESIGN AND CONSTRUCTION SCHEDULE

<u>Activity Description</u>	<u>Time Required in Weeks</u>
Starting Date	0
Conceptual Design and Landscape	2
Client Approval	1
Rendering	1
Art Commission Approval and Authorization for Expenditure Approval	3
Conditional Use Permit, Detailed Design and Drafting	9
Drawing Approval and Building Permit	4
Construction Contract	<u>8</u>
TOTAL	28

system. If it is installed, the optional system will employ Spectrolab 10 kW subsystems identical to those described for the baseline system, but 12 rather than 20 of these subsystems will be used. Hence, the net expected power output under standard environmental test conditions will be approximately 120 kW for the overall optional system.

The remaining features of the optional system design are similar to those in the baseline system design. The power conditioning system will be supplied by Exide Power Conversion Division of ESB, Inc., and will have the same rating as it would for the baseline design. Exide has furnished efficiency curves for this planned conditioner as well as their next smaller size conditioner. Although the peak array output is within the capability of the smaller conditioner, the larger conditioner operates more efficiently at the 120 kW level than the smaller conditioner does. This somewhat unexpected result is attributable to the fact that the fixed component of the total losses is a great percentage of the rating of the smaller inverter. Furthermore, the larger conditioner costs very little more than the smaller conditioner. The larger conditioner would provide excess power conditioning capability beyond the requirement of the optional photovoltaic array size. Thus, additional photovoltaic array capacity could be added to the system at a later date without the need for an added inverter module in the power conditioning system. LADWP is aware that if this were done and if another photovoltaic supplier's hardware were used as this additional future increment of array capacity, the conditioner's peak power tracker would track the combined peak power output of the overall array which is likely to be somewhat less than the arithmetical sum of the outputs from the initial module type and the added module type. The difference in the individual peak power points is attributable to basic design differences between the two module types. It is also noteworthy that LADWP has

already arranged a contract for the larger power conditioner which requires only to be ratified by DOE upon entry into Phase 2, and use of this larger conditioner in the option would eliminate the need to repeat the selection procedure used to identify a supplier and conditioner for the project.

The switchgear and control system will be the same as described in the baseline design. The equipment building and visitor center will be also be the same. The cable type used for interconnecting the individual subsystems will be similar. However, fewer spans and feet of interconnecting cable will be required. The layout of subsystems in an array will be the same for the optional design as the baseline design, but the eight subsystems which are most distant from the load will be eliminated in the optional configuration. This layout and interconnection scheme are illustrated in Figure 3.17. The remaining design features will be identical in both designs. It is expected that DOE will provide the same on-site data acquisition system for either design, but it is expected that fewer measurement transducers will be required in the optional design.

The primary advantage of the optional design is its lower overall cost of installation and operation. Within this lower cost, most of the reduction is expected to be due to lower cost of photovoltaic array purchase and installation. Although the overall photovoltaic system cost is lower in the option, the cost per subsystem will be higher due to the smaller production quantity involved, together with the fact that Spectrolab is at the initial point of commercialization for this product. The smaller system will require less land, but this fact is not expected to result in any reduction of required funding because a site already owned by LADWP will be used in either case. If a smaller power conditioner were used, a very insignificant additional reduction of cost could be achieved; but the advantages of using the baseline design conditioner, as described in the previous section,

Figure 3.17. OPTIONAL 120-KILOWATT SYSTEM CONFIGURATION

outweigh the cost reduction from selecting a smaller conditioner for the system. Furthermore, a cost reduction is expected from the requirement for fewer subsystem interconnections; but this saving is expected to be relatively small.

It is expected that Spectrolab could complete fabrication and delivery of 12 subsystems at an earlier date than 20 subsystems. Hence, the optional system has the advantage of an earlier expected date of completed installation. No reduction in lead time for the remaining facilities, such as the conditioner and the equipment building, is expected; and the equipment building may have the longest lead time in the option, whereas the array is expected to have the longest lead time in the baseline case. Because a smaller system is involved, the cost of operating and maintaining the optional system in Phase 3 will be less than in the baseline case.

A side effect of buying fewer subsystems at a higher unit cost is that less market creation for the product will be a consequence of using the optional design rather than the baseline design. From the viewpoint of the intended goals of the National Photovoltaic Conversion Program, this disadvantage of the option may be the single greatest deterrent to its use versus use of the baseline design. As noted in the baseline design proposal, one of the primary objectives of this project as well as the National Photovoltaic Conversion Program is to develop low-cost photovoltaic equipment through growth of market demand.

From a technical standpoint, the smaller system will have most of the same performance characteristics as the larger system. The most significant difference in operational considerations will be the more frequent inability of the smaller system to start one of the load motors for operation in the stand-alone mode. However, motors will normally be started in the parallel operating mode anyway. It is expected that the rated system output of either the optional or baseline configuration will be able to start one of the load

motors with relative ease. In either case, as the output of the array falls below its maximum daily capability, the usefulness of the system for motor starting diminishes. Some as yet unidentified array output power level will be a threshold below which a motor cannot be started. Obviously, the smaller system will be operating below this threshold more often than the larger system.

The smaller system will allow LADWP to address nearly all of the same technical and nontechnical experimental issues as the larger system. An exception to this statement is that the smaller system constitutes a smaller statistical sample size; and hence, less experience with failure rates of the equipment will be gained. The overall annual energy production of the optional system will be approximately 40 percent lower than that of the baseline system. Consequently, displacement of fossil-fuel requirements for equivalent conventional energy production will be less for the optional configuration than for the baseline configuration. Displacement of energy derived from fossil fuels by alternative technologies, such as photovoltaic conversion, is a major goal of national energy policy.

In conclusion, use of the optional design is a strategy for lowering the overall project cost while keeping the project definition close enough to the original plan so that nearly all of the experimental objectives intended in the baseline case can be accomplished. If funding availability becomes the overriding consideration as to continuance of the project into Phase 2, this option will enable use to be made of the design effort of Phase 1 at a lower funding level than would be possible with the baseline proposal. However, the baseline design is preferable to the optional design for certain reasons, especially the fact that it would cause larger market growth in the photovoltaic supply industry and a larger penetration of photovoltaic energy conversion into our Nation's total energy supply scenario.

CHAPTER 4

DETAILED SYSTEM FABRICATION AND INSTALLATION PLAN

4.1 Overview

In this chapter the plans for fabricating and installing the system are given. Detailed consideration will be given to the fabrication and delivery of the photovoltaic array, and lesser consideration will be given to the other components in the system. Most of the switchgear will be off-the-shelf equipment, and no problem is anticipated in having the hardware available by the necessary schedule date. The switchgear will be obtained by purchase order. The power conditioning system to be obtained from Exide is scheduled for delivery approximately six months after DOE ratification of the subcontract between LADWP and Exide. Site preparation will be performed including test borings and foundation work. Spectrolab has furnished LADWP with recommendations for the site preparation and foundation layout. The site preparation will include installation of the underground power cables for electrical interconnection as discussed in Chapter 3. Design and construction of the equipment building and visitor facility will be coordinated by the architectural design section at LADWP, and completion of the facility is scheduled for the twenty-eighth week after work is initiated. The remainder of this chapter focuses on the more complex issue of fabricating and installing a large-scale photovoltaic array. The manufacturing problem is particularly difficult because the photovoltaic subsystem is a new product line that will require establishment of a well-planned production strategy.

4.2 Photovoltaic Array Procurement Plan

4.2.1 Capabilities of Suppliers

Spectrolab, together with its subcontractors, Ford Aerospace and Communications Corporation (FACC) and Hexcel Corporation, constitute a team which will collectively contribute to photovoltaic array manufacturing from their individually proven areas of strength and experience. For the past seven years Spectrolab has successfully performed numerous terrestrial photovoltaic flat-plate and concentrator programs for various government agencies such as Sandia Laboratories, Jet Propulsion Laboratory, and NASA Lewis Research Center. The Western Development Laboratory (WDL) Division of FACC, on a subcontract basis, will manufacture and install the tracking carousels required for the proposed experiment. WDL currently employs approximately 75 structural, mechanical, and control engineers and designers with a total accumulation of 700 man-years of antenna and solar engineering experience. Hexcel, as a subcontractor, will supply the primary mirrors. The Hexcel plant in Casa Grande, Arizona, is a modern, 200,000 square-foot manufacturing facility which produces over 750,000 square feet of bonded panels annually.

4.2.2 Performance Description

In the performance of the following management, planning, manufacturing, installation, and support services, Spectrolab will provide the array of 20 photovoltaic subsystems installed at the project site. A program office reporting directly to the office of Spectrolab's president will be responsible for completion of all contractual requirements within the required technical, schedule and cost constraints. This program office will function as the management and reporting interface to the Spectrolab product line divisions

performing manufacturing and support services, provide the technical interface to all required subcontract activities, perform the detailed scheduling and coordination between Spectrolab and LADWP, and provide the specified reports on costs and technical activities in the program.

The fabrication and installation plan for the specified 20 photovoltaic subsystems is described below. The planning, internal controls, manufacturing, installation and testing required for the system are discussed. In addition, a procedure for review of both component performance and quality assurance is provided so that Spectrolab data and LADWP verification can support the decisions related to subsequent fabrication steps and to installation activities. These decision points are described later in this chapter; and Spectrolab will include the technical, cost and schedule information for LADWP review prior to these indicated dates.

Spectrolab will furnish LADWP with certain support services and deliverable software. The support services will include product verification; identification of site requirements; and recommending procedures for data collection, system performance monitoring, fault isolation, trouble shooting and operation. The software requirements to be provided include the following:

1. Complete and updated design package.
2. Operation and maintenance handbook.
3. Instrumentation and data collection procedures.

4.2.3 Manufacturing Requirements and Quality Assurance

The procurement plan presented here will be used by the Spectrolab's program office to establish and control four precursors that lead to satisfying the system hardware requirements: the sources for supporting the internal manufacturing needs at Spectrolab; a subcontract plan for controlling the technical,

schedule and cost requirements of such hardware (carousels and primary mirrors); the organization and procedures for quality control to be met by Spectrolab and its subcontractors; and a plan for verification of component performance prior to release of the production cycle.

The Spectrolab effort will consist of manufacturing the absorber modules, including the photovoltaic cells and associated wiring and packaging materials, reflective tape and heat sink assembly. These devices will be integrated with primary mirrors (produced by Hexcel) to complete the basic concentrator units for installation on the subsystem carousel structure. In order to maintain the specified performance and quality levels required, two control procedures have been established on existing photovoltaic concentrator programs and will be applied in Phase 2. These procedures are used to qualify the vendor sources of materials, tooling and services that are defined by engineering drawings and specifications as basic requirements to the manufacturing process.

A vendor qualification is made for each new requirement to establish product lines by the procurement of a first article that is then reviewed by the originating design engineer to assure suitable quality. The vendor is then placed on an approved vendor list. A second procedure is the use of a materials or process specification that defines a set of test requirements to be met for each lot of material that is used in the internal manufacturing processes. An example of this latter type is the insulation tape used in the laydown cycle that must achieve stringent electrical, thermal and strength requirements in the finished module.

Spectrolab will issue two major subcontracts to FACC for fabrication and installation of the tracking carousels and to Hexcel for fabrication of the primary mirrors. Spectrolab will issue a formal proposal solicitation

complete with software and hardware specifications and schedule requirements. Subject to negotiation and approval, a contract will be finalized and issued to each vendor.

Interface between Spectrolab and the vendors' designated program managers will be established through periodically scheduled meetings and by other meetings or telephone contact as required. All contact will be documented in the program file. Change notices, schedule changes, and so forth will be submitted in writing and initiated by either the Spectrolab subcontract manager or his vendor counterpart.

Hardware specifications will be issued, and the following procedure will be required before production:

1. Using a cited specification, a first article test and acceptance plan will be developed and documented.
2. Spectrolab quality assurance personnel will perform first article inspection of the first completed unit.
3. Spectrolab's principal investigator will review the quality assurance report; and upon acceptance of the first article, he will submit a report to LADWP for review and approval.
4. Upon LADWP approval, Spectrolab manufacturing including its subcontractors will be notified to release production.
5. Further inspection will be made by Spectrolab quality assurance personnel on a statistical sampling basis. Nonconforming hardware will be immediately reported to the principal investigator.

The above procedure will be applied to the FACC carousels which will be assembled at the project site and to the primary mirrors at Hexcel's Casa Grande manufacturing plant. This procedure will also be used at Spectrolab in the first article acceptance of the absorber modules and concentrator units.

The critical subsystem considerations are the photovoltaic absorber modules made at Spectrolab, the primary mirrors fabricated at Hexcel and assembled by Spectrolab, the solar tracking structure fabricated by FACC (with assembly at the project site), the concentrator unit assembled by Spectrolab, and the subsystem integration and acceptance testing performed by Spectrolab. The inspection and tests at Spectrolab, Hexcel, and FACC factories will not differ substantially from those for similar product lines. Additional inspection and test would result in increased cost which is considered unnecessary because the products involved are based upon established technologies. The quality assurance program will begin at the time the contract is signed and will remain in effect until acceptance testing is completed on the last subsystem at the project site.

The quality assurance effort will include, but not be limited to, the following:

1. Review of drawings, specifications, assembly procedures, process specifications, test procedures, and packaging and shipping plans.
2. Review of purchase orders to assure necessary quality provisions are included.
3. Source inspection of major subcontractors.
4. Coordination with quality assurance activities at major subcontractors' manufacturing facilities.
5. Calibration check of process and test equipment.
6. Inspection and test of tooling and fixtures.
7. Monitoring of facility conditions.
8. Monitoring of stockroom and storage conditions; adequacy of identification of materials, parts, supplies, and components; and compliance with shelf-life requirements.

9. Incoming inspection of purchased materials, parts, and other supplies.
10. In-process inspection of workmanship; compliance to procedural requirements; and maintenance of process temperatures, pressures, etc., at their required settings.
11. Preshipment testing of all processed and fabricated parts, components, and assemblies.
12. Inspection of packaging and shipping procedures, serialization and identification.
13. Site inspection.
14. Foundation inspection.
15. In-process inspection of solar tracking structure assembly and concentrator mounting at the site.
16. Solar tracking structure acceptance tests.
17. Subsystem acceptance tests.
18. Issuance of rejection notices at the site location. Such notices identify the material, part or assembly involved, the nature of the deficiency, and the responsible organization. Rejected articles are appropriately tagged. The rejection notices require an answering action by the responsible organization regarding rejection disposition and corrective action.

The quality assurance documentation at Spectrolab is based on the MIL Q-9858A program requirement and the MIL I-45208 inspection system requirement. All military and most commercial satellite programs have been based on the MIL Q-9858A document, and an extensive experience and documentation system has been established within Spectrolab. The latter specification has been

used for previous high-quality production endeavors and is considered to be a satisfactory basis for production integrity, but it will be reviewed for specific concurrence with needs of this program. Both FACC and Hexcel are experienced with use of the described documents and will accept the designated requirements.

Each of the critical subsystem components will be subjected to first article verification before the production release. The first primary mirror assemblies built with production tooling at Hexcel will be completed, inspected and tested for conformity to the specification under witness by Spectrolab engineering and quality assurance representatives from the program office. The documentation can be reviewed, or the testing can be verified by LADWP at its option. Within the Spectrolab facility, the same procedure will be followed for the secondary modules and the concentrator units.

The first carousel assembly will be erected and installed at the project site, and the acceptance test procedure will be completed. In addition, the Spectrolab engineering and quality assurance representatives will review for compliance with the design and quality requirements of the specification. Again, LADWP can accept the documentation or verify at its option. When the document is approved by LADWP, production will be released.

4.2.4 Manufacturing and Integration Plan

The manufacturing and integration plan consists of the overall planning structure for producing the hardware, an internal Spectrolab organization for manufacturing the secondary absorbers and the concentrator units, and subcontracts for the balance of the subsystem elements. Upon receipt of LADWP's order, the program office at Spectrolab will prepare and issue work statements to each subcontractor and organizational unit which must participate in the program. Because the design is essentially complete, the efforts

will be primarily oriented toward production control, purchasing, production, quality control, and field installation. However, the engineering staff will provide assistance, reports, manuals, and other documentation as required. The engineering staff will also review design and performance changes. The issuance of the work statement initiates performance of the tasks therein. The work statement defines the scope of work, the technical requirements, the schedule, and the allocated funds. The work statement will be subdivided into work orders (task work statements) or into lots. The work statement references all related documentation, specifications, and interfacing organizations. Based upon its own work order, each participating organization prepares a detailed work plan, assigns personnel as required, and commences work.

Long-lead items have already been identified, and long-lead procurement will begin one week after receipt of the order. Long-lead items are the gearboxes, actuators, and wheels for the solar tracking structure, 0.032-inch aluminum sheet for the primary mirrors, and aluminum extrusions for the photovoltaic absorber modules. Subcontracts with FACC for the solar tracking structures and with Hexcel for the primary mirrors must be negotiated early in the program. Except for photovoltaic cell materials which are in stock for initial production, other parts and materials require eight to twelve weeks of lead time in the needed quantities and must also be ordered early in the production program.

The production control plan will establish due dates and target prices for each part and material used. Purchase requisitions will be written, and delivery and payment will be obtained. When target dates and prices cannot be met, deficiencies will be brought to the attention of Spectrolab's program manager for corrective action and resolution. Spectrolab will place approved

orders, obtain acknowledgements, and follow the progress of the orders. The production control plan also includes in-house work schedules for fabrication and procurement of necessary tooling, fixtures, test equipment, gauges, packaging materials, and other supplies, as well as facility allocation in coordination with materials, parts and operation schedules.

A production plan and quality control plan are formulated from the work statements and production control plan, which indicate work flow by work station and operation, including target times for each operation. Instruction sheets are prepared for each operation or process. Major subcontracts are planned and scheduled similar to other parts procurements, except additional time allowances are made for initial contract negotiations. Throughout the program, Production Control will continue to monitor the timeliness and schedule conformity pertaining to all parts, materials, tools, operations, etc. Production Control will notify the program office of any significant nonconformities and implement the corrective action directed. Quality Control will continuously monitor quality; conformance to standards, specifications and procedures; and in-plant safety through incoming, in-process, and preshipment inspections and tests. Corrective action, when necessary, will be initiated by Quality Control through the program office to assure that specified program objectives continue to be met. Engineering, after assuring that all documentation is correct and released, will play primarily an assistance and reporting role in the program. Engineering will review and approve all changes; will assist and advise as requested on manufacturing, installation and test problems; will review foundation and installation work; and will review field installation and acceptance test data.

The program includes use of the 61,000 square-foot Spectrolab plant at Sylmar, California, for the manufacture of the photovoltaic cells, absorber

modules and concentrator units; the 200,000 square-foot Hexcel bonded panel plant at Casa Grande, Arizona, for the primary mirrors and sidearms; and the FACC plant at Palo Alto, California, for the planning and procurement of the solar tracking structure. The solar tracking structure is assembled almost in its entirety at the project site using standard materials purchased locally, with catalog parts and components shipped directly to the site.

Because each manufacturer is building equipment similar to his prior manufacturing specialty, in-plant tooling, fixture, and test equipment needs are not critical, especially since some tooling has already been fabricated for prototypes already built. Thus in-plant tooling, fixtures, and test equipment needs are primarily a duplication, where necessary, of already built equipment. Test equipment needed at the site is listed in Chapter 5. All parts, components, and assemblies produced off-site are designed and packaged for shipment by common carrier. To the greatest extent possible, the manufacturing program has been designed to minimize storage of large parts. This is not completely achievable, and storage space for program needs is included at the factory and at the site.

4.2.5 Spectrolab Manufacturing

Spectrolab's manufacturing responsibility includes photovoltaic cell processing to yield a total of approximately 63,000 cells for use in 802 absorber modules and subsequent integration into 802 concentrator units. This total of 802 includes 800 called for by the system design and 2 spares. All cells, absorber modules and concentrator units will be manufactured and tested at Spectrolab.

The facility for the manufacture of the photovoltaic cells is immediately adjacent to the module assembly facility. The photovoltaic cell

fabrication facility encompasses 24,000 square feet. The manufacture of the concentrator photovoltaic cells is integrated into the general photovoltaic cell manufacturing facility with time-sharing of personnel and equipment. Critical operations in the fabrication of the photovoltaic cells are performed in "clean rooms" to preclude the possibility of process contamination. The absorber modules will be assembled in the Spectrolab solar array assembly and test area which covers 16,000 square feet. Use of the area and personnel are shared with other assembly operations of similar requirements.

The fabrication of a functional, environmentally secure, photovoltaic module with photovoltaic cells mounted to the surface of the secondary mirror substrate is accomplished by a carefully integrated set of manufacturing processes developed for concentrator systems at Spectrolab. These operations combine the precision of a highly reliable space satellite design and process technology with additional concepts such as improved thermal efficiency and environmental integrity required of terrestrial systems. The concentrator unit assembly consists of the primary mirror, sidearms, photovoltaic absorber module, and sun shield forming an assembly 5 feet high, 8 feet long, and 6 feet wide. In addition to the absorber module, mirror and sidearm assembly, the concentrator unit assembly and installation requires the interconnection cabling, mounting adapter blocks, junction boxes, sun shield, instrumentation boxes, fastener hardware, adhesives, and supplies. The concentrator unit assembly and installation procedure is summarized in Figure 4.1.

4.2.6 Subcontract Hardware

The major subcontract hardware consists of the primary mirror assemblies and the carousel (tracker) assemblies. Both items have been procured under previous photovoltaic concentrator design and fabrication

Figure 4. 1. CONCENTRATOR UNIT ASSEMBLY AND INSTALLATION

subcontracts so that a minimum of contractual and technical interface problems are anticipated. In addition, both subcontractors, FACC and Hexcel, have long-established experience in these technologies for applications such as solar-thermal and satellite tracking systems.

During the initial phases of the program, a contract will be negotiated with Hexcel for primary mirrors and mirror sidearms. The 200,000 square-foot facility specializes in the manufacture of aluminum honeycomb core-bonded panels and has been manufacturing similar mirrors for Hexcel solar-thermal concentrators since 1974. The fabrication will therefore be integrated with similar operations within the facility and will share manufacturing and quality control personnel and equipment. The mirror sheet aluminum, while a stock item, is classed as a long-lead item for purposes of this procurement; and special provisions will be made for early initiation of the procurement process.

During the initial phases of the program, a subcontract will be let to FACC for solar tracking structures. FACC will then order and maintain production, inventory, and quality control upon the components, parts, trusses, and wire for the solar tracking structure. Sun sensors, the electronic assemblies, and the control panel are assembled and tested at the FACC facility in Palo Alto, California, and then shipped to the job site. These electronic assemblies, sun sensors and similar precision electronic hardware are built in modern facilities presently used in manufacturing high-reliability space and communications systems. Associated with these operations are laboratories, test facilities, engineering and support activities such as quality assurance. Other components, parts, trusses and cabling, etc., are shipped directly to the project site with the structural elements likely to be manufactured at local facilities. The solar tracking structures are then assembled, in turn, with each completed before moving to the next.

In view of the recent experience that has been gained through the design, analysis, procurement, fabrication and installation of the subsystem prototype at FACC and in light of the fact that this proposed application experiment involves multiple subsystem quantities instead of a single prototype, FACC is recommending that a cursory re-engineering and evaluation phase be implemented immediately following contract award. This initial effort will identify areas for potential contract savings if implemented. In no way will this study have any impact upon the satisfactory performance of the overall program within the time span allotted. Some of the more significant areas identified for investigation during this period are listed below:

1. Tubular versus angular truss frameworks.
2. Galvanizing versus painting.
3. Programmed tracking versus sun sensor tracking.
4. Stampings versus weldments.

This phase of the program will also include preparation of fabrication specifications, work statements, and procurement specifications.

4.2.7 Subsystem Installation and Support

The installation of the array of subsystems will be accomplished by a sequence of initial component verification of a carousel (tracker) assembly on the approved foundation at the prepared site; installation of the 40 concentrator modules appropriately aligned, interconnected, and terminated to the fixed power junction box; an acceptance test procedure that confirms the performance of the subsystem; and finally the subsequent installation and acceptance test of the remaining 14 subsystems to complete the array. In addition to the above tasks, Spectrolab will furnish the necessary technical liaison, recommended data collection, and operational training information for reasonable LADWP support.

The foundations will be constructed by LADWP, with requirements, inspection, and approval furnished by Spectrolab and FACC. The results of test borings will be used as a basis for finalizing the track and foundation design. Test boring reports at specific subsystem locations will be required by the end of the second month after contract award. Construction of the foundations will be scheduled to take place over a two-month period starting the fourth month after receipt of award but may be affected by local weather conditions.

The installation of the subsystems will conform to the critical component verifications concept previously described. After the acceptance testing and customer approval has been completed, the installation of the additional 19 units will proceed according to a prescribed schedule. The site installation work will be divided into several concurrent but essentially independent elements, each using separate dedicated crews of workmen. These elements will be: 1) loose assembly of the truss structure; 2) alignment and bolting of the truss structure, the azimuth wheels and pintle bearing assembly; 3) installation and alignment of the drive system mechanical components and linkages; and 4) installation and checkout of the control system.

As tracking structures are completed, power wiring, junction boxes, instrumentation wiring, and concentrator units will be installed. Each subsystem will be completed, tested and made operational in a manner such that modular subsystem start-up is achieved. The process will be repeated until all subsystems are operational. The power wiring will be terminated at a power junction box located just outside the sweep diameter of the subsystems. The LADWP will provide the main bus into which each of the subsystems feeds its output power, the 120-volt AC tracking power for each subsystem, and a 10 kW electrical load for subsystem checkout.

The mechanical installation and maintenance will not require any special purpose tools or machines. Standard construction and mechanical tools will suffice. Electrical performance tests are more demanding. Generally for a solar facility, certain specialized meteorological and electronic units are required. A list of required instruments is given in Chapter 5 in the discussion on maintenance procedures. In addition, a few pieces of safety equipment are needed. These are dark sunglasses for workers to wear when working on or near concentrator units and asbestos gloves for handling photovoltaic cell absorber modules during tests.

Spectrolab will retain personnel at the site for approximately one month after the installation is complete (all subsystems accepted) and provide the following assistance to LADWP:

1. Operational diagnostics and recommendations.
2. Computational assistance.
3. Failure analysis.
4. Repair recommendations.
5. Training assistance.

Following the specified period, additional assistance to LADWP in the above areas will be available to the extent contracted for in Phase 3.

4.2.8 Subsystem Acceptance Tests

Acceptance tests will be conducted on each subsystem. These tests will be designed to establish and document performance and operational capabilities of each individual subsystem. These tests will be broken down into two main categories: 1) tracking and control logic and 2) electrical power generation. Instrumentation required in the performance of these tests will

be LADWP-furnished and will be available for utilization in Phase 3. The acceptance tests to be performed are outlined in the following paragraphs.

Tests will be performed on the subsystem to verify proper tracking and control logic operation. These tests include the following:

1. Safety limits.
2. Manual operation.
3. Wake up and catch up.
4. Low-insolation cutout.
5. Fine solar tracking.
6. Overtemperature offset.

Safety limits are comprised of the azimuth encoder and azimuth limit switch, the elevation encoder and the actuator limit switches, and the control electronics. The purpose of the limits is to prevent array structure motion past the position set points. The logic is such that the safety limits override all other modes of operation. Tests will be performed to demonstrate that these safety limits are operational and perform their required function.

The manual mode operation permits the manual positioning of the structure for such purposes as maintenance and cleaning. Operation is by means of switches on the electronic control panel. This capability can be demonstrated by manually slewing the subsystem in azimuth and in elevation. The angular rate of travel for both axes will be measured. Proper subsystem response for each slewing direction will also be verified.

The subsystem is equipped with wake-up and catch-up logic which will preposition the array to fixed points at fixed times if the system is not automatically tracking at these fixed times. In conjunction with the wide angle of the sun sensor, this logic provides complete coverage of the sun's position throughout the day for all seasons and all points within the contiguous

United States in the event that cloud cover or low insolation levels interrupt the automatic tracking. The wake-up logic automatically prepositions the structure to the sun's average morning position and resets all the catch-up logic. Tests will be performed to demonstrate the proper functioning of this logic. The subsystem utilizes a 24-hour electronic clock. At a preselected morning time, all flip flops are reset; and the array is driven back to a wake-up position prior to sunrise. This wake-up performance characteristic will be demonstrated by simulating the early morning time with no insolation. Actual angular position at reset will be measured in both azimuth and elevation.

The catch-up logic is designed to point the concentrator array in fixed directions during the course of the day if the level of insolation is insufficient for automatic tracking. The input information for this logic consists of the array position data from an azimuth encoder (3 bit) and the elevation position switches. The position information is logically combined with time information from the 24-hour clock and tracking information from an insolation-level comparator that determines whether or not the system is automatically tracking. The catch-up logic moves the array to a new position if the system is not tracking at a certain time and thereby minimizes the time required to acquire the correct pointing direction upon resumption of automatic tracking. Tests will be performed to demonstrate the correct operation of this catch-up logic. These tests will be performed by simulating low-insolation levels by covering the photocell sensors. The actual reset positions both in azimuth and elevation shall be measured and recorded. Tracking rates in this reset mode will be measured for both azimuth and elevation.

A low-insolation cutout has been provided which will inhibit automatic tracking whenever the insolation level is below a preset value. This preset value is approximately 200 W/m^2 . The purpose of the cutout is to minimize hunting for the sun during periods of low-insolation level and hence excessive

power consumption by the tracking system. By the use of neutral density filters to attenuate the signal seen by the sun sensor and in conjunction with insolation measurements, the approximate low-insolation cutout levels will be determined.

Fine solar tracking is accomplished by using the proportional error signal from the sun sensor and associated electronics. The reference photocell is used along with two pairs of error photocells to generate a proportional error gradient which is independent of insolation level. This solar position signal is compared to fixed position set points, and the resultant comparison then drives the structure to a new position when error builds up. To demonstrate the system's ability for tracking in this automatic mode, the short-circuit current of the subsystem and the direct normal insolation as measured with a normal-incidence pyrheliometer will be recorded as a function of time. The variation of short-circuit current with time when normalized by the direct normal insolation will provide a measure of the deadband tracking error. The deadband tracking error for both the azimuth axis and the elevation axis will be measured and recorded.

Overtemperature offset logic is used to point the array ahead in elevation (away from the sun) in the event that the centrally located control concentrator unit experiences a cell temperature of approximately 100°C. This repositioning substantially reduces the sunlight reflected onto the cell assemblies. When the overtemperature condition has subsided, the array will resume automatic tracking. The operation of this logic will be demonstrated by applying a high temperature to the controlling temperature sensor. The temperatures at which the overtemperature logic is actuated and subsequently deactuated will be determined. The angular displacement of the concentrator unit in elevation will be measured under this overtemperature condition.

The electrical output power characteristics of a subsystem are a function of the direct normal insolation, ambient air temperature, wind speed and direction, and load voltage. To determine the electrical characteristics of the subsystem, the subsystem will be placed in the fine tracking mode during a period of normal operating insolation. A variable electrical load will be placed across the output terminals of the subsystem which is capable of sweeping from a short-circuit to an open-circuit condition. In order to relate the electrical performance to the performance which would be obtained with different environmental conditions, it is necessary to record the direct normal insolation, wind velocity and ambient air temperature for a period of at least ten minutes prior to making the test. It is also necessary to operate the system at a voltage approximating the maximum power voltage of the subsystem for at least ten minutes prior to establishing the electrical characteristics in order obtain cell-temperature stabilization. By varying the electrical load a voltage-versus-current output curve will be obtained. The maximum power obtained shall then be extrapolated to the amount of power that would have been generated under the conditions of 1 kW/m^2 insolation, 1 m/sec wind speed, and 28°C ambient air temperature. This test will be repeated at least two times, and the average of three tests will be used to compute the extrapolated value.

4.2.9 Program Management and Planning

The program management office will perform the overall technical and cost review of the program, including the assignment of all work packages to the internal Spectrolab product line organizations and to the subcontractors for both major hardware requirements (carousel and primary mirrors). The program office also will provide review of site installation requirements; the

quality assurance procedures for internal and procurement needs of the program; periodic reports and documentation; and with LADWP concurrence, approval of the acceptance testing of major hardware elements as well as the system verification at the site.

The program structure will be based on the organization established for a similar subsystem development contract with Sandia Laboratories. This contract, initiated in July 1978, was for development of the basic hardware system design and installation requirements of the 10 kW subsystem which is the building block of the system described herein. The schedule for achieving the system fabrication and installation is expected to span a time period of approximately 12 to 18 months. Coordination will be monitored within the program office and will be accomplished by holding monthly technical and cost reviews with representatives of Spectrolab product line management, the quality control representative assigned to the program, the subcontract manager responsible for procurement, and the systems engineer within the advanced programs engineering group that developed and tested the basic 10 kW subsystem design concept.

A reporting plan will include the issuance of monthly technical and cost reports on the progress of the program as well as a final technical report two months after completing all hardware installation and acceptance testing. In addition, there will be a minimum of two formal technical progress review presentations at LADWP and a final program review at Spectrolab within the two-month period after acceptance of the final report. In addition, the final program review will include a proposed plan for supporting LADWP's effort in Phase 3.

4.2.10 Data Collection and Monitoring

The subsystem has been designed to facilitate the monitoring of its performance relative to other subsystems making up an overall system. In addition, for purposes of data collection and trouble shooting, provisions for measurement of series-string current and voltage and of individual concentrator unit performance characteristics have been provided. An instrumentation box installed adjacent to the tracking and control circuit box at the rear of each subsystem provides a central location for these measurements. It is recommended that the current of each subsystem be monitored during normal operation of the system. In this manner the current contribution at a particular operating voltage for each subsystem can be compared on a relative basis with the other subsystems. A significant change in current contribution would be indicative of a problem in that particular subsystem.

Provisions for data collection from an individual subsystem are available for establishing the performance level of the individual series circuits of a subsystem, or for that matter, individual concentrator units. This capability facilitates trouble shooting when the current contribution from a subsystem has decreased relative to the output of other subsystems. For example, the current contribution from each parallel string of a subsystem can be determined quickly by measurement of the voltage across its respective monitoring shunt. This test should isolate the string or strings which are not operating properly. The individual voltage contribution from each concentrator unit in a series string could be measured directly from the same instrumentation box. These tests in most cases can result in locating the source of a problem. Thus, with a system maintaining its operational status, trouble-shooting schemes can be utilized to identify concentrator units that are exhibiting abnormal operating characteristics.

The above simple tests allow quick identification of individual concentrator units that may have a problem but may not allow full identification

of the problem. It is possible to disconnect a series string and leave the remainder of a subsystem in operation, or the entire subsystem can be disconnected. Each series string is isolated by switches at both ends of the string. In addition, there are disconnect switches to isolate any subsystem from the inverter and the rest of the concentrator system. These switches provide the capability to disconnect any defective string or subsystem and to isolate portions of the system to make measurements or to provide for safety during maintenance.

As part of the acceptance tests to categorize the performance of each series circuit and to verify the instrumentation monitoring provisions, the current contribution from each series string for operation near the maximum power point will be measured and recorded. Also, individual current-voltage characteristics of each series string will be measured.

4.3 Environmental Assessment

LADWP, as a public agency, must comply with the California Environmental Quality Act (CEQA). Under CEQA each project must be classified as either exempt or requiring environmental documents.

Exempt classifications can be assigned if a project satisfies one or more descriptions in a list of categories provided within the Los Angeles City CEQA Guidelines. The Sun Valley Photovoltaic Power Project qualifies for exemption on the basis of categories 1(2) and 6(2):

- 1(2). Operation, repair, maintenance or minor alteration of existing facilities of both investor- and public-owned utilities, electrical power, natural gas, sewage, water, and telephone, and mechanical systems serving existing facilities, including alterations to accommodate a specific use.

6(2). Basic data collection, field testing, research, experimental management and resource activities of City departments, bureaus, divisions, sections, offices or officers which do not result in serious or major disturbance to an environmental resource.

If LADWP is selected by DOE as a participant in Phase 2 of its photovoltaic concentrator application experiments, a Notice of Exemption will be filed and made available for public inspection upon approval by LADWP management to proceed with the project.

CHAPTER 5

OPERATION AND EVALUATION PLAN FOR PHASE 3

5.1 Introduction

This chapter describes the data to be monitored and tests to be performed in order to address relevant technical and nontechnical experimental issues and thereby accomplish the project objectives. LADWP will have primary responsibility for operation and evaluation of the system during Phase 3; Spectrolab will serve as a consultant. The types of data to be gathered and experimental issues to be addressed were selected so as to produce as much meaningful information as possible to aid the widespread deployment of photovoltaic systems in both central-station and dispersed applications if economic viability is achieved someday in the future. Some relevant technical issues are:

1. Photovoltaic system component performance and failure rates.
2. Overall photovoltaic system performance.
3. Role of electric utility backup for dispersed photovoltaic power plants.
4. Role of storage.
5. Operating and maintenance requirements.
6. Electrostatic interference with radio and other communication activities.
7. Integration with existing electric utility systems.
8. Impact of transient disturbances during operation.

Some relevant institutional issues are:

1. Siting considerations.

2. Regulatory actions by governmental agencies.
3. Constraints due to building and zoning laws.
4. Rights to sunlight laws.
5. Safety requirements.
6. Environmental impacts.
7. Economic considerations.
8. Vandalism problems.
9. Identification of preferred owners, operators and users for small dispersed photovoltaic power plants.
10. Finance of plant construction.
11. Financial incentives for installation of dispersed photovoltaic power plants, such as tax credits.
12. Utility rate structures for customers having small dispersed photovoltaic power plants on their premises.

Monitoring and processing of data in Phase 3 will be done in accordance with the uniform data requirements and data collection techniques set forth by DOE. DOE is to provide, as government-furnished equipment, a meteorological station and on-site data acquisition system as well as various transducers. The meteorological station will measure the following parameters: total horizontal radiation, direct normal radiation, wind speed and direction, barometric pressure, ambient air temperature, relative humidity, and precipitation. Additional measurements of radiation and several other climatological factors may also be made, but the exact details of the meteorological station are still pending specification by DOE. Insolation data taken by the meteorological instruments is expected to meet the Class 1 archiving criteria of the National Climatic Center of the National Oceanic and Atmospheric Administration. Additionally, LADWP presently has operative at the project

site a meteorological station which is one of six stations that LADWP maintains in the Los Angeles area in conjunction with a monitoring program coordinated by WEST Associates. The instrumentation of this existing station consists of a pyrliometer, a pyranometer, a radiometer, an anemometer, a resistance thermometer, and a psychrometer. This instrumentation allows collection of direct solar radiation, total horizontal radiation, long wavelength terrestrial radiation, wind speed and direction, ambient temperature, wet-bulb temperature, and relative humidity. The data is recorded in 15-minute intervals on magnetic cassette tapes and subsequently removed at 30-day intervals and sent for computer processing. The data from LADWP's solar monitoring stations is used internally for planning purposes and is submitted to the Solar Resource Evaluation Project of WEST Associates. Furthermore, this data will be useful in analyzing the performance of the photovoltaic system for the Sun Valley Photovoltaic Power Project. The station will give records of data for at least one year prior to start-up of the photovoltaic system at the project site, and it will continue recording long-term records of meteorological data for many years after the experiment ends.

The on-site data acquisition system (ODAS) will have the built-in capability of accepting 40 or more channels of transducer data as well as the capability of accepting expansion modules to provide up to 1,000 channels for very large installations. The ODAS will be able to record all data required for archival by DOE as well as additional data to meet LADWP's project needs and objectives. It is expected that the ODAS will have the ability to monitor any input channel in real time. In the remainder of this chapter, a detailed description of the data to be monitored and collected is given along with an explanation of the methodologies to be used in applying this data to study the experimental issues and accomplish the project objectives as set forth in Chapter 1.

5.2 Operation and Evaluation of Photovoltaic Array

5.2.1 Rationale

Operation, evaluation, and maintenance for the photovoltaic system are discussed. It is recognized that the purpose of the system is not solely the generation of environmentally clean, quiet, and fuel-saving power, but also the realistic, quantitative evaluation of the viability and effectiveness of the photovoltaic concentrator concept as a power generator in its intended application and environment. The operation and evaluation recommendations of this section are therefore in excess of those required for system use as a power generator and include data gathering, analysis, correlation, and reduction measures directed toward comprehensive evaluation of system performance, reliability, and durability.

5.2.2 Operating Modes

The system is composed of 20 independently operating photovoltaic concentrator subsystems whose electrical output is fed to a common bus and whose tracking power is independently supplied by an unregulated, LADWP-furnished 120-volt AC power supply. System operating modes will be established and implemented by the user. Within the system, however, each concentrator subsystem may be in any of the following modes:

1. Automatic Operating

- A. Fine Tracking: The subsystem is tracking the sun and generating power.
- B. Night Dormancy: The subsystem is not tracking and is not generating power. Clock has returned the subsystem to its morning wake-up position.

- C. Special Condition Dormancy: The subsystem is not tracking the sun, and power generation is negligible. The subsystem will automatically recover when normal conditions return. Special conditions causing this dormancy are low insolation and absorber module temperature limit.
- D. Safety Limit Dormancy: The subsystem is not tracking the sun, and power generation is negligible. Manual reset is necessary to return the system to operation after correction of a safety problem. Safety limit dormancy will occur when structural travel limits are exceeded.
- E. Wake-up and Catch-up Tracking: Following a condition of dormancy, the subsystem is slewing in azimuth and elevation at an accelerated rate in order to reacquire alignment to the sun.

2. Manual Operating

- A. The subsystem is not tracking the sun, and power generation is dependent on the extent of misalignment between the concentrators and the sun. Manual slewing signals may be applied through the central panel for both elevation and azimuth.
- B. Output Power "Off": The subsystem may be tracking, but the output power is disconnected from the main bus by the disconnect switch at the output power junction box. It should be noted that a voltage exists at all output terminals under this "off" condition.
- C. Input Power "Off": The subsystem is not tracking the sun, and input power is disconnected from the control and

tracking drives by the disconnect switch at the input power junction box. Output power will depend on the extent of concentrator misalignment with the sun.

- D. Output and Input Power "Off": Output and input power are disconnected at the disconnect switches at the respective junction boxes. A voltage may exist across output power terminals even under these conditions.

5.2.3 Data Collection and Monitoring

The 10 kW subsystem has been designed to facilitate the monitoring of its performance relative to other subsystems making up an overall system. In addition, for purposes of data collection and trouble shooting, provisions for measurement of series string current and voltage and of individual concentrator unit performance characteristics have been provided. An instrumentation box installed adjacent to the tracking and control circuit box on the tracker structure of each subsystem provides a central location for these measurements.

It is recommended that the current of each subsystem be monitored during normal operation of the system. In this manner the current contribution at the particular subsystem operating voltage can be compared on a relative basis with the other subsystems. A significant change in current contribution would be indicative of a problem in that particular subsystem. Provisions for data collection from an individual subsystem are available for establishing the performance level of the individual series circuits of a subsystem or for that matter individual concentrator units. This capability facilitates trouble shooting when the current contribution from a subsystem has decreased relative to the output of other subsystems. For example, the current contribution from

each parallel string of a subsystem can be determined quickly by measurement of the voltage across its respective monitoring shunt. This test should isolate the string or strings which have a problem. The individual voltage contribution from each concentrator unit in that series string could be measured directly from the same instrumentation box. These tests in most cases can result in locating the source of the problem.

With a system maintaining its operational status, trouble-shooting schemes can be utilized to identify certain concentrator units that are exhibiting abnormal operating characteristics. The above routine tests allow quick determination of individual concentrator units that may have a problem but may not allow full identification of the problem. It is possible to disconnect that series string from the rest of the subsystem leaving part of the subsystem on an operational basis, or the entire subsystem can be disconnected from the system. Each series string is isolated by switches which are at both ends of the string. In addition there are disconnect switches to cut off any collector subsystem from the inverter and the rest of the concentrator system. These switches provide the capability to disconnect any defective string or subsystem and to isolate portions of the system to make measurements or to provide for safety in working on it.

Output performance may be obtained by recording DC output line voltage and current at the output junction box, while simultaneously recording load, wind speed (near the height and location of the concentrator unit), ambient temperature, and insolation level. Instantaneous output power level may then be computed, standardized to its value equivalent at Standard Environmental Test (SET) Conditions (insolation steady at one kW/meter, ambient temperature of 28°C, wind of one meter/second), and compared with its predicted value at SET Conditions. The standardization to SET values is best accomplished by

machine computations. Spectrolab has computer programs which have been modified for this application to accomplish the standardization of measured instantaneous power values, given data on load, insolation, wind speed, and ambient temperature. Alternatively, predicted instantaneous output power may be tabularized for a range of loads, insolation levels, wind speed, and ambient temperature levels by computer means; and the instantaneously measured power level may be compared to the matching predicted tabularized value.

Daily energy delivery may also be measured. Average hourly insolation, wind velocity, and ambient temperature and load should also be monitored and recorded, as well as system or subsystem down time, atmospheric events and phenomena, mirror cleanliness, and dates and times of system operation. Daily energy delivery may be summed on a weekly, monthly, seasonal, or yearly basis and either compared with existing simulation data (adjusted for atmospheric conditions) or with newly generated simulation data predicting energy delivery under the same average load, atmospheric conditions, and operation time.

Input AC line voltage (120 volts) and current to the tracking and control assemblies may similarly be monitored to assure that demand limits are being met and to assure that AC line power is continuously available as required. Module performance should also be recorded: low insolation or high temperature, cutoffs, overtravel cutoffs, nighttime return to morning position, and inability of the system or subsystems to "wake up" or "catch up". When discrepancies are noted between actual and predicted values, obvious conditions such as shadowing, primary mirror contamination, loss of 120-volt AC line power, and loss of or excessive load should first be checked. If no information is found to resolve the discrepancy, the next step would be test and checkout of individual subsystems, then trouble shooting the deviating subsystem. It is desirable to periodically check mode capability. Such checks are best accomplished on individual subsystems.

5.2.4 Environmental Effect Evaluation

Environmental effects may be evaluated by operational status checks, inspection check, and performance tests before and after the occurrence of the condition. Operational and inspection checks will include number and location of subsystems affected and the nature of any problems or damage noted. Performance tests will similarly include recording of the number and location of the subsystems adversely affected. Quantitative evaluation of the applied environment is also valuable. Such quantification will include, but not necessarily be limited to, the following:

1. Temperature: Extremes reached and duration.
2. Wind: Extremes reached and duration.
3. Hail: Hailstone maximum size and estimated frequency (stones per square meter) and concurrent wind velocity.
4. Humidity: Relative humidity and duration of extremes.
5. Rain: Rainfall maximum rate (inches per hour), extent (inches), duration, and resultant ground condition.
6. Dust and Windborne Sand: Extent of ground accumulation and concurrent wind extreme duration.
7. Dust and Sand Accumulation: Estimate of accumulation extent on primary mirror (percent coverage and distinction between light, medium, or heavy).
8. Lightning: Nearness of strike.
9. Vandalism: Nature and extent.
10. Mirror Contaminants: Nature and extent.
11. Atmospheric Contaminants: Nature, extent, duration, and cause.
12. Ground Vibration: Frequency, magnitude, duration, and cause.
13. Ground Disturbance: Magnitude, duration, and cause.

14. Other: Obviously, other adverse environments can be envisioned which may affect the system. Often, occurrences of the environmental conditions above are in combination.

It will be useful to correlate system damage or performance degradation to the occurrence and extent of environments, if only on a qualitative basis. Records of the effect of any protective or corrective measures taken will also be useful.

5.2.5 Data Monitoring Recommendations

Operational problems may be of system or subsystem origin. In the event of problems not immediately traceable to a particular subsystem, system causative factors such as loss of 120-volt AC line power, inverter malfunction, bus connection problems, shadowing, load loss or excess, and reverse power flow should first be examined. The system should be examined for gross visual indications such as primary mirror contamination or damage, foundation shifts, azimuth tracking blockage, failure to track, modal safety cutoffs, and other readily apparent problem symptoms and causes. Should the preceding steps fail to indicate the cause of the problem, individual subsystems should be tested to isolate the malfunctioning subsystem(s), after which the fault in that subsystem may be determined. Regardless of the type of equipment fault, recent or concurrent events of an environmental nature should be reviewed for possible correlation to the equipment fault noted. Table 5.1 summarizes data monitoring recommendations for system operation and evaluation.

5.2.6 Maintenance

This section covers recommended system protective steps, routine maintenance, supplies, spares, and subsystem test and trouble shooting. The recommended system protective steps are:

1. Adequate drainage at site.
2. Lightning protection.
3. Fencing perimeter of site, 8 to 12 feet high, a minimum of 85 feet from closest subsystem.
4. Maintenance of access road.
5. Entry to site restricted to authorized personnel.
6. Training of operation and maintenance personnel in the care and handling of the system.

The recommended system routine maintenance consists of:

1. Primary mirror tape replacement at 5-year intervals.
2. Relubrication of elevation actuators every 5 years.
3. Water washing of primary mirror surfaces, followed by air drying, as required.
4. Clearing of dry leaves and brush from site, as required.
5. Cleaning of foundation in path of azimuth wheels, as required.
6. During periods of extended nonoperation, the system should be periodically subjected to manual "exercising" slews.
7. During nearby spray-painting, roofing, or tarring operations, protection should be afforded to the primary mirror reflective surfaces.

Table 5.2 summarizes routine protective and maintenance steps recommended for various environmental occurrences.

The following equipment and supplies should be available for maintenance and repair activities:

1. Forklift carts.
2. "Cherry picker" hydraulic crane.

3. Lumber to form temporary maintenance deck atop trusses.
4. Crescent wrenches.
5. Wiring tools.
6. Lubricants.
7. Grease guns.
8. DC voltmeters.
9. Brooms (track brushing).

The following spare components and parts are recommended for the 200 kW array:

<u>Quantity</u>	<u>Item</u>
2	Concentrator Unit
1	Drive Wheel Subassembly Set
1	Sun Sensor
2 Sets	Key Components; Central Electronics Power Supply
4	Wheels
2	Elevation Actuator
2	Elevation Gearbox
2 Sets	Key Encoder Components
2	Drive Motors

5.2.7 Subsystem Test and Trouble Shooting

To isolate the problems to a subsystem level, the malfunctioning subsystem must first be detected. If visual inspection does not suffice, electrical performance tests may be conducted. Power output, voltage and current readings are obtained for each subsystem in turn and compared to their original value at time of installation until the deficient subsystem

TABLE 5.1
SUMMARY OF DATA MONITORING RECOMMENDATIONS

Electrical Load
Wind Velocity
Ambient Temperature
Insolation Level
Array Voltage and Current
Individual Subsystem Current and Voltage
Environmental Data and Phenomena
Mirror Cleanliness
Chronology of Data
Low-Insolation Cutoffs
High-Temperature Cutoffs
Overtravel Cutoffs
Deficiencies/Problems: Nature, Cause
and Resolution
Maintenance Actions: Labor, Part, Tool
and Supplies Required
Trouble Shooting Actions: Labor and Tools
Required
Repair Action: Labor, Parts, Tools and
Supplies Required
Energy Delivered

TABLE 5.2

ENVIRONMENTAL SPECIFICATION GUIDE
(with maintenance recommendations)

<u>Environment</u>	<u>Limits</u>		<u>User Protection Recommendations</u>
	<u>Operational</u>	<u>Survival</u>	
Life	20 years	20 years	Periodic cleaning, 5-year mirror-tape replacement routine maintenance.
Temperature	-30°C to	Maximum	-
Extremes	+40°C Maximum	possible	-
Wind	14 m/sec.	40 m/sec.	-
Hail	-	-	-
Humidity	0 to 100 percent	0 to 100 percent	-
Rain	-	Normal extremes of continental U.S.	Drainage provisions for system site
Dust and Wind-borne Sand	Light	-	Water wash
	Medium	-	Water wash
	Heavy	-	Water wash
Bird Droppings	Occasional	-	Water wash Spot wipe
Atmospheric Contaminants			
Soot	-	-	Water wash
Oil	-	-	Spot wipe
Paint	-	-	Mirror pre-protection
Lightning	480 volts	480 volts	Central-system protection
Vandalism	-	-	Fence, patrol, setback, alarm, drainage
Fire	-	No readily flammable exposed materials	Site clearing of brush and leaves

is found. If the problem is not with the solar tracking structure, it will probably be necessary to isolate a faulted concentrator unit. Each concentrator unit's electrical performance may be characterized with current and voltage readings until a deficient concentrator unit is found. The nature of the readings gives an indication of the specific problem.

The tracking and sensor systems are adjusted during manufacture and will only need periodic verification of operation after installation in the field. This verification is done with a sunsight which has a graduated target. The sunsight is first attached to the main framework and aligned with the azimuth axis. The system is turned on, and operation is observed. The drives move the structure to 0.4° in advance of the sun's position, turn off, and again start up when the sun is 0.3° behind the azimuth axis. If positioning is not quite right, adjustments are made to compensate. A similar operation is carried out for the elevation axis.

The optical system is aligned at the time of installation and will not normally require realignment. If realignment is required or if alignment is to be checked, each concentrator unit may be pointed individually and aligned in the following manner.

The "master" concentrator unit is connected to a 4-wire electronic load, Spectrolab D1550, and an X-Y recorder; and the load is set to near the peak power point. The sun tracker is turned on; and the "slave" concentrator unit is attached to an electronic load, set at peak power, and adjusted in elevation for maximum output by small adjustments of the mirror adjustment arm. After adjustment, the mirror is locked in place by tightening the mirror nuts. The total optical field of view for each concentrator unit is 3.0° . As the optical axis is aligned with the sun, the system power goes up, peaks, and falls off when additional motion occurs. The output power versus optical pointing resolution is shown in Figure 5.1.

Figure 5.1. OUTPUT POWER VERSUS OPTICAL POINTING ERROR FOR A CONCENTRATOR UNIT

Figure 5.2. INFLUENCE OF OPTICAL ALIGNMENT ON CONCENTRATOR UNIT PEAK POWER LOADING

Specifically, each concentrator unit is electrically loaded to its peak power point as shown in Figure 5.2. This point on the current-voltage curve is the most sensitive to output variations, and thus serves as the best point to adjust the system. Curve "A" shows a concentrator unit adjusted for best power. Curves "B" and "C" show the effects of nonoptimum pointing. On both "B" and "C" the peak power point is well below that of curve "A".

The subsystem and modular approach to the entire system permits rapid and straightforward trouble shooting. From the records of initial performance tests, system and subsystem outputs under any particular set of operating conditions can be projected. If system output is below expectation, it is first determined if this is caused by degradation of all subsystems or just one. If all subsystems are low, dirty optical components are the most likely problem; and cleaning will be required. However, if only one subsystem's output is low, then there is a specific problem with the subsystem.

The first checkpoint is the tracking system. If all concentrator units are pointing to the sun and no light is spilling out of the aperture of any absorber module, the problem is elsewhere. If one concentrator unit is not properly pointed, it will be the problem and must be readjusted to coincide with all other concentrator units.

The next level of testing involves running current-voltage curves on each series-connected string. After the string in which the problem exists is located, it is then tested one concentrator unit at a time. During these tests, each concentrator unit is loaded to its peak power point; and the alignment is fine tuned to get maximum power out of the particular concentrator units under test. If all units are all right, very nearly like when first installed, then the problem is fine tuning the mechanical adjustments between all concentrator units in the series string. If one unit's output is low,

careful physical observation of optics, wiring, and heat sink is required. Also, the shape of the current-voltage curve can indicate problems such as shading or partial shading of one cell, shorting, shunting, or other problems associated with the cell string. Depending upon the nature of the trouble discovered, the appropriate cleaning, adjustment, or replacement of one concentrator unit will be required. The above operations are outlined in the trouble-shooting flowchart provided in Figure 5.3.

Operating and maintenance personnel will be advised that, even during periods of low insolation or when shadowing or mirror misalignment reduce output power, substantial current and voltage may be generated by the photovoltaic modules; and prudent handling precautions must be observed. Furthermore, they will be advised that, even with diminished output power, the primary mirrors are concentrating sunlight in the area of the photovoltaic absorber modules; and high temperatures will exist on the photovoltaic cells and secondary mirrors.

5.2.8 Instrumentation Requirements

For the data gathering recommended above, certain specialized meteorological and electronic instruments will be required. Specifically, the following must be available:

1. Pyranometer - To measure total insolation.
2. Normal Incidence Pyrheliometer - To measure direct normal insolation.
3. Anemometer - To measure wind speed and direction.
4. Temperature Recorders - For monitoring ambient and system test points.
5. Electronic Load, Spectrolab DI550 - To measure electrical output of one concentrator unit.

Figure 5.3. TROUBLE-SHOOTING FLOWCHART

6. X-Y Recorder - Used in conjunction with D1550.
7. Large Rheostat Bank - To test one series string.
8. Digital Voltmeters - To precisely monitor system current and voltage.

In addition, a few pieces of safety equipment are needed, such as dark sunglasses for workers to wear when working on or near concentrator units and asbestos gloves for handling solar cell absorber modules because they must be handled during operation.

5.3 Overall System Monitoring and Supporting Analytical Assessment

The procedure used for monitoring and collecting data will conform to that specified by DOE in the Contract Initiation Meeting Handout for Phase 1. Because the on-site data acquisition system is to be government-furnished equipment and its characteristics are not available at this time, difficulty was encountered in specifying the transducers that would be used to monitor the data. A preliminary list of the analog signals that will be provided for sampling by the on-site data acquisition system follows:

<u>Quantity</u>	<u>Type</u>
23	330 DC volts with a maximum capability of 450 DC volts
33	0.1 DC volts
10	480 AC volts
10	0.1 AC volts

Additionally, 23 digital signal channels will be required for switch indications. The transducer selection will be finalized upon receipt of the description of the data acquisition system from DOE.

Analytical studies will be done to support the experimental work in the program. Anticipated life-cycle cost information for the hardware which will be prepared by Spectrolab, together with actual failure rates for components experienced in the field, will be used as inputs to these studies. Utility system planning tools will be used to study system configurations in a hypothetical future scenario into which large numbers of photovoltaic systems have been integrated. These tools will include computer codes for utility system reliability analysis and energy production costing. In the interest of brevity, the details of this analytical work are not provided here. However, a discussion of this analytical methodology and its suitability for estimating the economic worth of photovoltaic systems to an electric utility is provided in a recent paper (2).

Overall coordination of activities will be done by the project manager. Spectrolab will serve as an adviser in operating the photovoltaic system and in performance testing of the photovoltaic system. Day-to-day operation of the photovoltaic system will be under the direction of the plant operating engineer. It is felt that under normal operation only a few minutes per day would be required of a plant equipment operator to attend any necessary fan motor switching. Any electrical maintenance requirements that arise will be handled by an electrical mechanic, while all mechanical maintenance requirements will be performed by a maintenance mechanic. Operating experience will disclose whether or not the instrument shop personnel will be involved in maintaining the system. All testing and data collection required during the evaluation portion will be arranged through and coordinated by the plant results engineer.

The time interval between successive cleanings of the primary mirrors will be varied to determine an optimum interval. It is not expected that the

mirrors will require cleaning more frequently than once per month. Spacing between array rows will be 108 feet from subsystem center to subsystem center, which will provide a minimum clearance of 14 feet between subsystems. Hence, maintenance trucks can be driven between rows when necessary. A trailer and sprayer rig will be purchased by LADWP for cleaning the mirrors. The trailer will be towed by a small truck. Cleaning the mirrors will require a two-man working team.

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1. Spectrolab, Inc., System Design Report for a 10 Kilowatt Photovoltaic Concentrator System, Report No. SAND78-7025, May 1978.
2. F. R. Goodman, Jr., "Photovoltaic Electric Power Generation from a Utility Perspective," ASME Transactions, Journal of Engineering for Power, Scheduled for Publication in 1979.

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