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**PHOTOVOLTAIC CONCENTRATOR SYSTEM FOR
ROXBOROUGH PARK**

Final Report for June 1978—February 28, 1979

**By
R. L. Donovan**

MASTER

March 1979

Work Performed Under Contract No. ET-78-C-04-5312

**Martin Marietta Corporation
Denver, Colorado**

U.S. Department of Energy

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Solar Energy

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I. PROJECT SUMMARY

Environmental issues, energy conservation, and the use of non-depletable and renewable energy sources are key factors impacting our quality of life today and in the future. The Roxborough Park Photovoltaic Concentrator project demonstrates that modern technology can address these factors and complement the natural environment while supporting power requirements of the population. The Roxborough project blends innovative energy conservation, esthetically pleasing designs, solar/thermal collection systems, and photovoltaic concentrator systems into an environmentally sensitive park area. High public visibility at Roxborough can significantly enhance the future development and use of solar energy in the United States.

The theme of the Roxborough Park experiment will illustrate an application where the sun is the only source of energy working through multiple solar technologies. The project represents a remote installation of moderate size where the true cost of utility power is high due to transmission line construction in rough terrain.

An aerial view of the park and surrounding area is shown in Figure I-1. The park is approximately 25 miles southwest of the Denver metropolitan area, shown in the upper right corner and 4 miles south of the Martin Marietta facility, shown in the upper left corner. The bright red Fountain formation outcropping throughout the Roxborough site is the oldest sedimentary rock along the front range of the central Rocky Mountains. It overlies the older Precambrian metamorphic Idaho Springs formation running west to the mountains. Where exposed, the Fountain provides spectacular and unusual rock formations. Major Fountain outcroppings occur at Red Rocks Park and amphitheater west of Denver and the Garden of The Gods west of Colorado Springs. A similar outcropping occurs at Roxborough Park.

Roxborough Park is intended to provide its visitors a quiet experience of personal recreation amid the park's natural beauty. In development of the park, the state has as its stated goal the creation of an "urban wilderness". To achieve this goal the state has defined a visitor interpretive program. The interpretive program encompasses the photovoltaic system and includes trail and overlook design, slide and moving picture shows in the theater, and brochures and other written materials for distribution in the Visitors Center.

Figure I-1 Roxborough Park Site - View Looking North

The Visitor's Center is designed to complement its natural surroundings. It is located between two rock outcroppings and is partially buried as shown in Figure I-2. The building is to be a poured-in-place concrete structure with red limestone aggregate complementing the color and form of the adjacent rock outcroppings. A two-level interpretive center is provided. Visitors enter on the upper outdoor level among a display of six ecosystems transplanted there from within the park. Then, they wind their way down stairs built into the rocks to enter the lower indoor level where windows frame majestic views of the park as a backdrop to further interpretive displays.

The Visitor's Center incorporates a number of active and passive solar systems, which are not a part of the photovoltaic system, but directly benefit the project in demonstrating energy independence. One unusual feature is the sod roof that serves the purposes of both energy conservation for the building interior and a display of native grasses on the exterior. The building shape has been designed and oriented specifically to accommodate sun patterns, allowing winter sun to enter and warm interior spaces, yet using overhangs to shield against the hot summer sun. Windows and skylights are strategically placed to obtain maximum natural light. Also, task lighting (i.e., light source located close to the work surface) is extensively used to eliminate unnecessary "general illumination".

During cold winter days, the sun heats surfaces inside the building. At night, insulated panels will be closed over the windows to help retain this heat. Also, concrete surfaces warmed in the daytime will radiate stored heat at night. Materials warm to touch, such as wood and fabric, will be used in the building. The terrain and vegetation surrounding the Visitor's Center serves to naturally block cold westerly winds in the winter. The building interior walls and columns are thick concrete masses. These work in conjunction with the earthen roof to create a "thermal mass" to stabilize building temperature by time-lag and insulation.

During the summer, opening windows make natural cooling and air circulation possible. In Colorado's climate, summer days are warm and nights are cool. At night, the building will be flushed of hot daytime air to precool it for the next day.

Active solar heating and cooling is also used. The active system consists of a flat-plate air collection system and an underground rock storage area. The active system will be used for both hot water and space heating. It is sized to heat a minimum of 21% of the interior space in winter. This is the primary use area of the Visitor's Center and its size corresponds to expected winter usage of the building. During summer, rock storage will be cooled with nighttime air for cool air recirculation during the day.

Figure I-2 Roxborough Park Visitors Center

The facility is highly self-sufficient with independent support systems as shown in Figure I-3. Besides the sod roof, flat-plate collectors, and photovoltaic concentrator system for energy independence, there is a septic field, a well, a fireplace, and a radio telephone. No telephone line to the facility is planned. Backup operation, if necessary, is provided by the Intermountain Rural Electric Administration (IREA).

The Roxborough Park experiment has a daily and seasonal load well matched to the sun because visitor traffic itself follows the sun. In addition, the experiment provides for people management and allows portions of the Visitors Center to be closed-back or shut-down during extended bad weather. Energy can be conserved by lowering winter operating temperatures, wearing warm clothes, and sending staff home on the coldest days.

A nontangible but important aspect of this project is the general level of enthusiasm shown for solar energy systems. A quotation from a local newspaper article on the Roxborough experiment is appropriate.

"History is repeating itself at Roxborough Park as the Martin Marietta Corporation continues what early man started over 7,000 years ago. Roxborough Park offers the same challenge to modern day technicians as it did to primitive man who roamed the 756 acres south of Littleton as they tried to capture the sun's rays.

"Evidence has been uncovered and documented that man used the south slope of what is now the state park to be a target for the sun's energy. The date has been set at between 4000 to 5000 B.C., according to Butch Daniel, Colorado Division of Parks and Outdoor Recreation.

The use of solar energy by the Indians mentioned in the article was primitive but practical. During the day, the sun heated the rocks. At night the Indians slept on them.

A. SYSTEM DESCRIPTION

The complete electrical power system for Roxborough Park incorporates as major elements a solar array field, battery, shunt regulator, and inverter as shown in Figure I-4. These major components are all connected to a common dc bus to form a direct energy transfer system without the need for intermediate power processing equipment. The simplicity and high performance of the direct energy transfer system increases reliability and decreases cost.

Figure I-3 Isolation

Figure I-4 Roxborough Park Electrical Power System

The dc bus operates nominally at 240 Vdc. This voltage was selected over a lower 120 Vdc system to minimize losses in the distribution cable connecting the array field to the Visitors Center. For a given cable design, system power losses decrease with the square of the bus voltage. Thirty-six photovoltaic concentrator arrays designed by Martin Marietta (Fig. I-5) are used for power generation. These arrays use Fresnel lenses to concentrate sunlight approximately 40 times on silicon solar cells. The arrays are passively cooled and track the sun in two-axes. Individual arrays are series connected in groups of three to obtain the correct system operating voltage, and the twelve groups are connected in parallel. One point should be noted with respect to the array design in this application; the array foundations are of the caisson- or pedestal-type. This was found to be particularly important to their use in the environmentally sensitive park where minimum site activity was a requirement.

The battery consists of 110 lead-acid cells of the locomotive type. The decision to use lead-acid batteries was made on the basis of their demonstrated capability in systems of this type. The locomotive battery was selected since it is designed for continuous loads at moderate rates in contrast to other types such as automobile batteries which are designed for high rate low duration operation. The battery is rated at 1500 amperes-hours.

Figure I-5 Martin Marietta Photovoltaic Concentrator Array (PCA)

Two inverters are used to supply ac power to the Visitor Center; one rated at 30 kVa and one rated at 7.5 kVa. The larger inverter powers those loads, that can be switched off at night. The parasitic power drain required by inverter no-load or tare power is thereby saved and battery drain is minimized. The 30 kVa inverter output loads are themselves subdivided into two groups: controlled loads and uncontrolled loads. The uncontrolled loads are critical and must be powered as required. The controlled loads are low priority and may be switched off when the system is energy limited. The controlled loads are managed by a Load Demand Controller (LDC) which performs the load limiting function using a control signal from the System Control Center. Detailed load profiles were developed for system sizing and analysis. The peak load is 24.8 kW (19.5 kW on the 30 kVa inverter and 5.3 kW on the 7.5 kVa inverter).

To minimize both the cost and the thermal output problems of the shunt regulator, the twelve array strings can be automatically switched on or off under control of the System Control Center. The shunt regulator is thus required to handle only a fraction of the maximum solar array power available.

The system is designed to operate independent of utility. During periods of extended bad weather, switch-over to IREA utility power is made as a result of one of several factors. The system can be switched manually or automatically due to low battery state-of-charge, charge, or bus undervoltage. The actual switching occurs in the static transfer switches associated with the inverters.

B. SYSTEM PERFORMANCE

Roxborough Park represents an energy independent application. To portray such a system at reasonable cost, it was sized to supply the Center with satisfactory loads through a nominally cloudy day and through 3 hours past sunrise on a subsequent completely overcast day. The annual energy generated by the solar array with nominal weather conditions has been calculated at 151,124 kWh, with 98.3% of the actual load, 126,721 kWh, being supported. The key energy collection and load analysis data are in Table I-1.

Table I-1 System Performance Summary

Month	Solar		Per-cent of Maximum Load Supported, %	Actual Load, kW-hr
	Input ¹ kW-hr	Collected ² kW-hr		
Jan	113,866	9,736	94.0	9,004
Feb	113,627	10,450	100.0	8,137
Mar	143,976	13,353	100.0	9,016
Apr	147,115	13,415	100.0	11,464
May	152,981	14,133	98.7	12,411
Jun	117,658	15,944	100.0	12,464
Jul	174,901	15,396	100.0	12,740
Aug	160,337	14,227	100.0	12,188
Sep	149,107	13,174	100.0	10,991
Oct	142,432	12,527	100.0	10,586
Nov	115,320	10,011	97.8	8,716
Dec	108,630	8,758	84.9	9,004
<p>Note: 1. Solar array input energy defined as total insolation available to the total array aperture area with nominal cloud conditions and without regard to shading.</p> <p>2. Total solar array electrical energy provided to bus.</p>				

Accurate and comprehensive system analyses are critical in the Roxborough Park application because the experiment theme is energy independence. Hence, sizing the major components for optimum cost and performance is more critical here than for applications where solar energy is used to supplement available energy sources. The primary thrust of our system analysis was to obtain a highly accurate system operating portrayal and performance prediction and verify that experiment objectives were met with an optimized system. Accurate and effective system simulation studies, in turn, require both a good weather data base and accurate simulation models. Both of these were available for the Roxborough Park analyses.

The park is located near Waterton, CO at 39.45° latitude and 105° longitude. It is approximately four miles south of the Martin Marietta facility and is nestled in the same geological formations (between the same foothill formations). Hence, the park receives the same weather and solar insolation as the Martin Marietta facility. Extensive weather data was taken at Martin Marietta on an earlier solar program during 1976, and this data was directly applicable to Roxborough Park.

The second key element is our solar insolation model (SIM). The initial model was prepared at Martin Marietta in extended Fortran IV in October 1977 and patterned after a section of the National Bureau of Standards Load Determination Model (NBSLD) called SUN. The model is based on an initial model compiled by Yellott and MacPhee as a result of an NSF grant to ASHRAE in 1974. This model was expanded to include cloudy-day conditions by Tamami Kusuda for the National Bureau of Standards. The Martin Marietta model, SIM, has been revised specifically for photovoltaic concentrator system simulation studies for the Roxborough Park project and is called SIMPCA.

Selection of an electrical power system configuration connecting solar array, battery, inverters, and loads is critical to overall system cost. Three candidate power system configurations were considered. These are shown in Figure II-1. All include a solar array, battery, and inverter. The systems differ in the manner in which they control the solar array output bus.

Configuration I [Fig. II-1 (a)] features a dc battery charger and peak-power tracker combination. The peak-power tracker integral to the battery charger provides for maximum solar array energy collection.

Figure II-1 Candidate Electrical Power System (EPS) Configurations

Configuration II [Fig. II-1 (b)] differs from configuration I in that the battery charger is not in series with the entire power flow but powers the battery only. As a result, the battery charger in II is physically smaller than in I, and normal daytime loads powered by the solar array do not have the efficiency loss of the dc charger. This inherent efficiency advantage of Configuration II tends to compensate for the energy loss due to operating the array off the peak power point.

Configuration III [Fig. II-1 (c)] requires no dc battery charger but relies on the shunt regulator to limit battery charge voltage. The shunt regulator is designed to handle only a fraction of the maximum excess solar array power available. When more power is available than the shunt regulator can handle, arrays are switched off to reduce the available power level. This arrangement eliminates the cost contribution of the dc charger and the efficiency loss due to charger operation. The increase in total system efficiency gained by deletion of the charger more than offsets non-optimum solar array use due to operation off the peak power point.

Configuration III was selected for Roxborough because the overall system efficiency is the highest of the configurations analyzed. The overall system cost is also lowest for configuration III because intermediate power processing equipment is eliminated and the array on/off switching methodology permitted the shunt regulator to be sized to handle only a fraction of the total available array power. The high system efficiency of configuration III has been shown in independent studies. A Martin Marietta study* showed it to be slightly more efficient than configuration II and significantly more efficient than configuration I. A General Electric Study† indicated that configurations I and III exhibited essentially equivalent performance for a specific application considered (0.389 energy displacement factor for configuration I versus a 0.381 factor for configuration III).

*M. S. Imamura, R. Hulstrom *et al.*: *Definition Study for Photovoltaic Residential Prototype System*. Final Report, ERDA/NASA-19768. Martin Marietta Corporation, Denver, Colorado, September 1976.

†A. Kirpich *et al.*: *Conceptual Design and Systems Analysis of Photovoltaic Systems*. Final Report, Vol. II, ALO-3686-14. General Electric Space Division, Philadelphia, Pennsylvania, March 19, 1977.

A. SYSTEM DESIGN

A detailed block diagram of the Roxborough Park power system is shown in Figure II-2. Thirty-six photovoltaic concentrator arrays are used to collect solar energy. The arrays are series connected in groups of three. The 12 groups are connected in parallel--through insolation diodes--to the dc distribution bus. At the Visitor's Center the dc-bus is connected to the battery, shunt regulator, and two inverters. A large 30-kVA inverter is used to power daytime loads only, and a small 7.5-kVA inverter is used to power continuous and nighttime loads. Low priority loads are controlled by a Load Demand Controller (LDC) which has the capability to shed or restore loads automatically, depending on power availability. Both inverters are connected to the loads through a static transfer switch to provide automatic or manual transfer to IREA utility power when array power or battery energy is diminished.

All system control functions are contained in the System Control Center (SCC). The SCC receives data signals from a weather station located in the array field, from the Analog Shunt Regulator, and from the battery state-of-charge (SOC) meter. From these data, the SCC forms commands for array control, Analog Shunt Regulator voltage selection, Load Demand Controller limit set, 30-kVA inverter on/off control, and utility switchover.

The operational strategy of the power system is as follows (in order of priority):

- 1) Solar derived electrical energy is used directly to supply the loads. If the available energy exceeds the load requirements, it is stored. If the battery storage capability is exceeded, excess current is diverted through a shunt regulator to maintain system energy balance.
- 2) If available energy from the arrays is not sufficient or not available (as during night hours and periods of cloudiness) to sustain the load, the loads are supplied by the battery.
- 3) The Load Demand Controller limits loads according to battery state-of-charge. The load setting is minimum at 50 percent SOC and increases linearly to a maximum at 100 percent SOC.
- 4) The system is automatically switched to utility power if battery SOC falls below 25 percent. The system is automatically switched back to photovoltaic power when the battery SOC rises above 50 percent.

Figure II-2 System Block Diagram

System Sizing - Since all power processing components are connected by the dc distribution bus, a description of the bus operating modes can determine the characteristic of the major system elements. Bus operation is shown in Figure II-3. The bus operating range of 206-V to 270-V is determined by battery characteristics, the range of 206-V to 230-V corresponding to battery discharge, and 230-V to 270-V corresponding to battery charge. The 270-V upper limit corresponds to shunt regulator turn-on voltage. A second shunt regulator turn-on voltage, at a reduced level of 258-V, is used as a "float-charge" regulation limit after the battery has been fully charged. Provision for two regulation limits has been incorporated into the system as a means of reducing battery stress and thermal dissipation due to overcharge. The lower limit of 206-V corresponds to a depleted battery. If this limit is reached, the system is automatically switched to utility power.

Figure II-3 Nominal Bus Operating Modes

The bus operating levels previously discussed were selected to be compatible with standard commercially available inverters. Inverters are readily available in two voltage ranges: 120-V and 240-V. The 240-V system was selected for the Roxborough Project to obtain economies in distribution cabling from the array field to the Visitor's Center. For a given distribution cable power loss, cable cost decreases with the square of the bus voltage. Hence, a 240-V system incurs only 25% of the cabling cost of a 120-V system.

Once the bus operational limits were specified, the number of battery cells required was readily determined. The battery contains 110 cells. The ampere-hour rating of the cells was then selected to be sufficient to meet the system design criteria of supporting the load through one nominally cloudy day and through three hours of a subsequent overcast day for any day in the year.

The solar arrays were sized to be compatible with bus operating voltage and the system design criteria mentioned above. The array field design has a total of 36 arrays configured in 12 parallel groups of three series-wired arrays each. To optimize operation over the prescribed bus operating limits, the array design was modified somewhat from the basic design developed for the Sandia 10-kW program. The Sandia arrays contain 272 solar cells each. The Roxborough arrays will contain only 224 cells each. This change has been obtained by reducing the number of 8-cell photovoltaic modules from 34 to 28 and by shortening the center support tube accordingly. Each array is nominally rated at 1871 W each (9.0% efficiency) under standard test conditions of 1.0 kW/m² insolation, 28°C ambient temperature, and 1.0 m/sec wind speed. The 36 array field is nominally rated at 67.4 kW.

An additional array change was to include a digital shunt regulator (DSR) into the array electronics package. The DSR is basically an on/off switch that shorts an array upon command from the System Control Center. This control methodology achieves significant economies in the Analog Shunt Regulator (ASR) that regulates bus voltage. The ASR is sized to accommodate only a fraction of total available array power. Not only is the size and cost of the ASR minimized as a result of using the DSR concept, but thermal problems associated with the ASR heat output in the Visitor's Center are also minimized.

B. SYSTEM CONTROL

The overall system control methodology was a major area of development emphasis. The control system is designed to be highly autonomous so it can be left unattended, yet have a simple manual interface for relatively unskilled personnel to perform routine maintenance and checkout. All system control is contained in the SCC. The essential control functions provided by the SCC are:

- 1) Array motor and digital shunt regulator control;
- 2) Shunt regulator voltage limit select (high charge or float charge);
- 3) Load Demand Controller limit set;
- 4) Automatic transfer to utility;
- 5) Manual interface providing operator control of functions 1) through 4) above.

Each of these control functions is described in the following paragraphs.

1. Array Control

The array field control methodology was developed with the objective of minimizing field cabling requirements. To achieve this, all arrays are "daisy-chained" to a common control bus rather than provided with separate signal lines. Serial rather than parallel data transmission is used to minimize the number of signal lines required. Low frequency data transmission rates are used to minimize cable requirements, and the 60-Hz array power line is used for a timing clock. The signal lines required for array operation are thus reduced to two: An ENABLE line (commanding the arrays to accept a data word) and the DATA line (transfers data serially from the SCC to array holding registers). The data word is updated in the SCC and transferred to the arrays once per second. The data word is subdivided into the following blocks or "bytes":

- a. *Array Command Address (ACA)* - The address of the array to be operated in accordance with the Array Command Byte (ACMD).
- b. *Array Command (ACMD)* - The command signals controlling array operation are: array motion commands (up, down, east or west); a command signifying whether all arrays are to respond or only the single array corresponding to the array command address (ACA);

a separate STOW command that, when present, causes all arrays to immediately stow in the "lenses" down position; and a Digital Shunt Regulator command controlling whether the array is on-line providing power to the bus, or is shorted out.

c. *Synthetic Track (SYNTR)* - The synthetic track word provides timing information for array synthetic tracking and day/night transition operation.

d. *Array Shunt Regulator Address (SHA)* - The array shunt regulator address determines which arrays are on and which are off. All arrays with addresses less than the SRA are switched off (i.e., shorted out). The SRA, in general, is different than the ACA (i.e., array motor control is independent of array shunt regulator control).

Cost-effective feature of the overall array control methodology is that only a quarter of the array motors can be energized simultaneously. A command for all arrays to move is implemented on successive command cycles at one second increments, and the total motor transient load is thereby lowered.

2. Shunt Regulator Voltage Limit Select

The shunt regulator clamp voltage corresponding to battery high-charge or float-charge operation is controlled by a signal from the SCC. The high-charge limit is selected whenever battery state-of-charge is less than 90%. The float-charge mode is selected when battery state-of-charge is greater than 90%. The dual limit function is incorporated to minimize battery stress and heat dissipation due to overcharge.

3. Load Demand Controller Limit Set

The SCC provides an analog signal to the LDC that determines the load demand limit. The signal is based on battery state-of-charge and is minimum at 50% SOC and maximum at 90% SOC.

4. Automatic Transfer to Utility

The SCC automatically transfers the system to utility power when the battery SOC falls below 25% or when a fault (such as a low battery cell voltage) is detected.

5. Manual Interface

The SCC has a control panel for manual interface by an operator. All control functions can be performed at the SCC console (including array and array shunt regulator address select). System voltages, currents, and status indications are displayed.

C. SYSTEM ANALYSIS DESCRIPTION

Two basic model formulations exist for an energy demand system. The first is by power flow representation. This approach requires exceeding, or at least satisfying, an energy balance condition. That is, the total energy available from the solar array must equal the energy required to recharge the battery and support the load, including power conditioning losses. One advantage of this approach is that the math model is easily defined, and all energy dissipation elements as well as power reduction parameters can be expressed as lumped parameters, either variable or constant. A disadvantage is that the method is approximate and does not provide an in-depth description of detailed system operation.

The second formulation, and the one chosen for the Roxborough Park analysis, is to prepare equivalent circuits containing voltage and current sources and discrete devices that represent actual component behavior. The resulting model is a set of independent equations. If a system consists of linear elements, a solution is easily obtained by matrix methods. If it has nonlinear devices, as the Roxborough Park system, a solution must be obtained using numerical iteration techniques. The equivalent circuit formulation has two key advantages that warranted its selection for the Roxborough Park Analysis: (1) It is highly accurate, and (2) it has a high degree of flexibility for parametric analysis. Once the basic model has been established, the effect of component size and interconnection arrangements can be quickly ascertained. This approach has been extremely effective in the Roxborough Park analysis where the effects of alternative array field layouts and system configurations were of critical interest.

The key elements of the computer system simulation program are shown in Figure II-4. The solar insolation model (SIMPCA) provides direct normal insolation data for the solar array model, and solar angle data for the array shading model (SHADE).

The SHADE model determines the number of unshaded array strings (accounting for the effects of both terrain and adjacent arrays) for use by the solar array model (ARYMOD). ARYMOD operates on this data and supplies total instantaneous array field current, I_{SA} , under control of the solar electrical power system model driver (SEPS). SEPS also receives battery current, I_B , and inverter currents, I_{I1} and I_{I2} , from the battery model (BATMOD) and inverter model (INVMOD), and calculates system output parameters. Both the battery model and the inverter model use configuration description input data in addition to stored model constants. The inverter

II-II

Figure II-4 System Computer Simulation Program Major Elements

model also receives instantaneous load data from the load model (LOAD). LOAD distributes individual loads over a daily profile in accordance with prescribed duty cycles and daily operating times.

1. Solar Electrical Power System Model Driver

The computer simulation driver, SEPS, is responsible for control flow of the computer models discussed above. SEPS makes "command" decisions to call each model when needed. The SEPS basic flow diagram is shown in Figure II-5. SEPS initializes all inputs to default values so that only changes to the input database need be read on any given run. This eliminates redundant computer set-up time. All inputs are defined in individual modular sections describing each model. Inputs to SEPS, described in Table II-1, are contained in namelist format and read once per run. SEPS calls first the solar model (SIMPCA) to determine sunrise and sunset. This is done once per day at midnight to choose the applicable solution algorithm. The system solution algorithm (when insolation is not present) is much simpler and efficient than the algorithm with insolation. Once the solution is obtained, the results of the system solution at a specific time are written onto the output file. The time of day is then incremented and the program is iterated as indicated in Figure II-5. After the solution for a complete day is finished, the program is again iterated until a solution is obtained for the number of days specified.

Table II-1 *Driver Inputs*

Variable	Example Value	Description
IDATE	781221	First Day of Run (yr, mo, day)
ITIME	0010	Initial Time of Run (hr x 100)
INCTIME	0025	Increment of Time (hr x 100)
LDATE	781222	The Last Day of Run (yr, mo day)
INDATE	0001	Increment of Day

2. Solar Insolation Model

The analytical methodology of the SIMPCA model was selected rather than empirically recorded weather and insolation data for our system analysis effort for several reasons:

- 1) The SIMPCA model is inexpensive to run, yet it has tremendous versatility for system sizing and performance assessment purposes.
- 2) Long term continuously recorded weather data is not available for the Roxborough Park site, and available weather data tapes do not represent Roxborough Park.

Figure II-5 Basic Program Flow Diagram

- 3) Weather data based on a statistical average over several years has limited value in parametric system performance analyses.

An insolation database was established at the Martin Marietta facility during 1976, and this data was used in the Roxborough Park analysis to generate an accurate solar insolation model. Daily data for direct normal insolation was taken once per month for seven months. Data was missed for April, July, August, October, and November and, for these months, interpolation was used to provide model parameters. Cloud and temperature information for Denver, Colorado, was taken from the *National Climatic Atlas*.

SIMPCA requires three types of input data: location, time, and weather. These data, defined in Table II-2, are read once per day by SEPS. The fundamental equation for the solar insolation model is:

$$[II-1] \quad \Phi_T = C_n \Phi_o(d) \exp(-\tau/\cos\theta z)$$

where

Φ_T - Normal incident clear-day irradiance

$\Phi(d)$ - Extra terrestrial solar irradiance on day d.

τ - Optical depth

θz - Solar zenith angle

C_n - Clearness number

Using an extra terrestrial solar constant of 1353 W/m^2 allows Eq [II-1] to be simplified to

$$[II-2] \quad \Phi_T = C_n 1353 (1-K_d) \exp(-\tau/\cos\theta z)$$

In the model, K_d and τ are contained in lookup table with separate values for each month, and interpolation is used to obtain values for intermediate days. Clearness number is used as a curve-fitting constant, and, for the Roxborough Park analyses, was used to fit the model to available weather data. The actual parameter values used in the Roxborough Park analysis are shown for the 21st of each month in Figure II-6.

Table II-2 SIM Input Data

Location

LOCATN - Location Description (Hollerith)
XLAT - Latitude, Degrees (+ North, - South)
XLON - Longitude, Degrees (+ West, - East)

Time

TZN - Time Zone Number (MST = 7)
MON - Month Number (January = 1)
IYEAR = Year
DST - Daylight Saving Time Indicator
LEAPYR = Leap Year Indicator

Weather

NUMCL - Cloud Cover (%)
ISTART - Beginning of Cloud Cover Period (Time)
IEND - End of Cloud Cover Period (Time)
TAMB - Mean Daily Temperature (°C)

Figure II-6 SIMPCA Parameters

Solar position angles are derived in the program from the relations

$$\cos \theta_z = \sin \theta_e = \cos L \cos \delta \cos h + \sin L \sin \delta$$

and

$$\sin \theta_a = \frac{\cos \delta \sin h}{\cos \theta_e}$$

where θ_a is the solar azimuth angle, true south being zero, and positive angles representing afternoon. The hour angle, h , and the solar declination angle, δ , are dependent on time-of-year as shown in Figure II-6 and must also be modeled. The hour angle is defined by

$$h = 15 (t-12-ET)$$

where ET is the equation of time given by

$$ET = -(0.12357 \sin b - 0.004289 \cos b + 0.153809 \sin 2b + 0.060783 \cos 2b)$$

and

$$b = \frac{(d-1) 360^\circ}{365.24}$$

describes the angular fraction of a year represented by a particular day. The solar declination angle is defined by

$$\sin \delta = \sin (23.44383^\circ) \sin \sigma$$

where

$$\sigma = a + 0.4087 \sin a + 1.8724 \cos a - 0.0182 \sin 2a + 0.0083 \cos 2a$$

and

$$a = 279.9348^\circ + \frac{(d-1) 360^\circ}{365.242}$$

represents the angular fraction of the year at a particular day for the declination angle calculation.

In addition to accurate insolation calculation, SIMPCA can also be programmed to handle complex cloud patterns. Since only direct normal insolation is of interest to the Roxborough Park studies, the insolation is considered either full-on or full-off

depending on whether clouds are present or not. Cloud cover is programmed each day by specifying a total cloud amount (35%) and a cloud cover period (6 am to 11 am).

The total cloud amount is adjusted according to the cloud cover period. Thus, specifying 35% cloud cover and a 6-hour cloud cover period on the equinox would result in 70% cloud cover during the 6-hour period. Cloud and temperature data are also shown in Figure II-6.

Cloud data is automatically adjusted for actual sunrise and sunset by entering cloud cover time before sunrise and after sunset. SIMPCA also calculates cell temperature based on ambient temperature, T_A , and the amount of insolation. A cell-temperature rise above ambient is proportional to insolation, as described by a "thermal resistance" factor in the program. The control flow within SIMPCA, shown in Figure II-7, shows that day-dependent data is calculated only once at the beginning of the day to increase program efficiency.

SIMPCA model performance is shown in Figure II-8 compared to the database at the Martin Marietta facility for September 21, 1976. As mentioned earlier, the clearness numbers used in the model were selected to fit the output to the measured data.

3. Electrical Power System Model

The Roxborough Park electrical power system analysis model is shown in Figure II-9. The dc bus forms a common node connecting the solar array, battery, inverters, and shunt regulator. Two inverters, corresponding to the actual large and small inverters used to power day and night loads in the actual system, were modeled separately to enhance model accuracy. The fundamental equation describing system operation at a given instant is

$$[II-3] \quad i_{SA}(V_B) = i_{SR}(V_B) + i_B(V_B) + i_{IA}(V_B) + i_{IB}(V_B)$$

where the parameters are defined in Figure II-9. When solved, Eq. II-3 describes all component currents and operating bus voltage V_B at a given time for specified load, insolation, weather, and model parameters. For system computer simulation studies, this model was solved iteratively at discrete time intervals to generate daily and multidaily system operating profiles.

Figure II-7 SIMPCA Flow Diagram

Figure II-8 SIMPCA Performance

Figure II-9 Roxborough Park Electrical System Model

Despite the apparent simplicity of Eq. II-3, the second tier equation describing the component currents as a function of individual component parameters are complex. This is particularly true for the solar array current, i_{SA} . The solution methodology is repeated at each discrete time interval with new load, insolation, and model parameters to generate the system operating profile.

The highly iterative nature of the solution methodology implies a large amount of computer time, but this was found not to be the case. Efficient, rapidly converging algorithms were used. Programming efficiency is enhanced by calling SIMPCA, SHADE, and ARYMOD only when there is insolation.

a. *Shunt Regulator Model* - The system simulation program begins with a test for shunt regulator state. All component currents are derived with the bus voltage set equal to the shunt regulator clamp voltage (either the full charge or trickle charge level as determined by battery state-of-charge). As shown in Figure II-10, if current balance using Eq. II-3 indicates positive shunt regulator current, the system operating condition is solved (all component voltages and currents have been established and are valid) and the program proceeds to the next time increment. If the shunt regulator current is negative, a nonvalid condition is indicated, the shunt regulator current is set to zero, and a solution is found to balance the solar array, battery, and inverter currents.

The model assumes a full shunt regulator with no array on/off switching in contrast to the actual system design using a partial shunt regulator in combination with array on/off switching to regulate the bus. This model approach was selected for several reasons. First, system performance prediction is not impaired since bus voltage and battery and inverter currents are identical with either modeling approach. Second, since all arrays are considered active, the model implementation chosen

Figure II-10 Solution Validity Test

allows calculation of total array energy collection *potential*, and this is important for system performance evaluation.

b. Inverter Model - Inverters used in this experiment are high efficiency switching types. This class of inverter is characterized by an efficiency characteristic that rises from zero at no load (due to tare losses), to a maximum value at moderate loads, and then falls off slightly at high loads due to the effects of series resistance losses. This efficiency characteristic can be modeled to high accuracy with three parameters as shown in Figure II-11. A resistor, R_T , in parallel with the input represents power transfer in the high efficiency switching circuitry, and an output resistance, R_O , represents series resistance losses which become significant at high loads. The end-to-end inverter efficiency defined by

$$[II-4] \quad \eta = \frac{P_L}{P_i} = \frac{\text{Load Power}}{\text{Input Power}}$$

can be derived from these three model parameters.

The total input power at a given load P_L , and line voltage, V_i , is given by

$$[II-5] \quad P_i = \frac{P_L + P_L^2/P_S}{\eta_o} + P_T$$

where P_S , a power parameter representing loss in the series output resistance, is given by

$$[II-6] \quad P_S = V_L^2/R_O$$

and P_T , a power parameter representing tare loss is given by

$$[II-7] \quad P_T = V_i^2/R_T$$

Figure II-11 Equivalent Circuit.

The inverter efficiency is then obtained by substituting Eq. II-5 into II-4 to obtain

$$[II-8] \quad \eta = \frac{\eta_o}{1 + \eta_o \frac{P_T}{P_L} + \frac{P_L}{P_S}}$$

For general applicability, Eq. II-8 can be normalized to maximum power output rating, P_M , by defining

$$[II-9a] \quad P_L = P_L / P_M$$

$$[II-9b] \quad P_T = P_T / P_M$$

$$[II-9c] \quad P_X = P_S / P_M$$

then

$$[II-10] \quad \eta = \frac{\eta_o}{1 + \eta_o \frac{P_T}{P_L} + \frac{P_L}{P_S}}$$

The general efficiency characteristic of the inverter model represented by Eq. II-8 is shown in Figure II-12(a) for two values of P_S . The characteristic can be tailored to different inverters by calculating the three model parameters R_o , R_T , and η_o from inverter specifications. Once the model parameters are selected, the inverter input current as a function of bus voltage and output load is obtained from:

$$[II-11] \quad i_I = \frac{V_i}{R_T} + \frac{P_L + P_L^2 / P_S}{\eta_o V_i}$$

Equation II-11 is the basic equation used to model the two inverters in the computer system simulation program. The accuracy of the model is shown in Figure II-12(b) where it is compared to specifications provided by the inverter manufacturer.

The 30-kVA inverter is turned off at night so that tare losses are saved. The flowchart, Figure II-13, shows that calculations are not made for the 30-kVA inverter when it is night time, thus simulating the actual case.

Figure II-12(a) General Efficiency Characteristic of the Inverter Model

Figure II-12(b) Model Perturbations

c. *Battery Model* - The lead acid battery represented the most difficult modeling task of all system components. Only two model elements are required, a voltage source and a series resistor as shown in Figure II-14. However, these two parameters vary with battery operating conditions and state of charge (SOC) in a complex manner. Consequently, three distinct models were used in the analysis: one for discharge, a second for charge where battery SOC was less than 90%, and a third for charge (or overcharge) where battery SOC was greater than 90%. Each model uses the configuration shown in Figure II-14 with both voltage source and resistor parameters functions of SOC. The functional relationship of the battery parameters on SOC is different for each of the three models.

For system simulation efficiency and convenience, the three models were developed for a single battery cell, normalized to capacity, and scaled in series/parallel arrangements with varying capacity ratings to investigate alternative battery sizes on system performance. The specific battery equations are

$$[II-12] \quad E_B = N (E_0 + K_E \cdot SOC)$$

Figure II-13. INVMOD Flow Diagram

Figure II-14 Battery Cell Model

$$[II-13] R_B = N (R_O + K_R \cdot SOC)/C$$

where

N = number of series cells

SOC = battery state of charge

E_O = cell model voltage source

R_O = cell model resistance normalized to capacity rating

C = cell capacity or ampre-hour rating

K_E = State of charge coefficient for voltage

K_R = State of charge coefficient for resistance

Both N and C are system design parameters and are constant throughout any given system simulation. Parameter SOC varies throughout a system simulation as the battery is charged or discharged. The state-of-charge is calculated at each discrete time interval in the computer simulation according to the charge input to the battery and the ampere-hour efficiency characteristic shown in Figure II-15. Parameters E_O , R_O , K_E , and K_R have three values, each

Figure II-15 Battery Ampere - Hour Efficiency vs State of Charge

determined by the battery model applicable at a given time in the program. These parameters are listed in Table II-3.

Table II-3 Battery Cell Model Parameters

Model	Conditions	Parameters			
		E_0	R_0	K_E	K_R
I	Discharge	1.941	0.555 Ω /A-hr	0.186	-0.222
II	Charge (0.0 < soc < 0.9)	2.08	0.001	0.027	0.864
III	Overcharge (0.9 < soc < 1.0)	-1.2602	-4.019	3.738	5.33

BATMODs flow diagram, Figure II-16, shows the methodology for choosing the correct model; discharge, high charge, or float charge. The battery cell voltage is calculated in the high charge model if SOC is less than 0.9 or in the float charge model if SOC is greater than 0.9. The battery cell voltage is then compared to the normalized bus voltage. As the flowchart shows, if the normalized bus voltage is greater than the battery cell voltage,

Figure II-16 BATMOD Flow Diagram

the correct model is known and the respective resistance is calculated. If in either above case the bus voltage is less than battery cell voltage, a similar process is done in the discharge model. After the battery cell voltage and resistance are calculated in the correct model, the current and its derivative are calculated.

The derivative is calculated for use in the major Newton iteration as discussed later in the subsection: *System Solution*. Model performance is shown in Figure II-17 where the three model cell terminal voltage-current characteristics are compared to battery cell data for various SOC's of interest.

Figure II-17 Lead Acid Cell Model Limit Conditions

d. *Solar Array Model* - The solar array model was constructed from a basic solar cell model scaled in series/parallel arrangements to simulate total array configurations. Alternative array configurations were conveniently investigated by changing series and parallel parameters without altering the basic solar cell model. A conventional five parameter, lumped-element cell model was used in the analysis. This model is shown in Figure II-18. A current generator, I_L , represents the photoelectric effect. The value of I_L is directly proportional to insolation. The diode junction is characterized by two parameters, I_0 and A , representing reverse saturation current and a curve-fitting constant respectively. A parallel resistor, R_p , representing resistive shunt losses and a series resistor, R_s , complete the model. The

Figure II-18 Solar Cell Model

fundamental equation for this model is

$$[II-14] \quad i = I_L - \frac{V + R_S i}{R_P} - I_0 \left[\exp \left(\frac{v + R_S i}{0.026 \text{ A}} \right) - 1 \right]$$

Equation II-14 is transcendental in nature (containing the variable i in the exponent) and cannot be solved in closed form but must be solved by iterative techniques. To simplify computation, Eq. II-12 was reformulated as

$$[II-15] \quad i(i, v) = a_1 - a_2 v - a_3 e^{a_4 v} e^{a_5 i}$$

where

$$a_1 = (I_L + I_0) / (1 + R_S/R_P)$$

$$a_2 = 1/(R_S + R_P)$$

$$a_3 = I_0 / (1 + R_S/R_P)$$

$$a_4 = 1/0.026 \text{ A}$$

$$a_5 = R_S/0.026 \text{ A}$$

Equation II-15 is in a more convenient form to solve than Eq. II-14, but it can be simplified further before obtaining an iterative solution. In the system simulation program, a bus voltage is established and component currents are derived for that voltage. If current balance, as specified by the fundamental equation (Eq. II-1), is not achieved, the voltage estimate is improved iteratively until current balance is achieved. At any system iteration step, bus voltage (and, hence, solar cell terminal voltage) is constant, and Eq. II-15 can be simplified to

$$[II-16] \quad i(i) = b_1 - b_2 e^{a_5 i}$$

where

$$b_1 = a_1 - a_2 V$$

$$b_2 = a_3 e^{a_4 V}$$

Equation II-14 is now simply--and efficiently--solved by iteration using the Newton-Raphson method. This method is used twice in the computer simulation program. The first use is here and is termed the "minor." The second use, termed the "major," is in the total system solution, and is discussed in detail in that section.

The five basic solar cell model parameters were obtained from test data from cells proposed for this experiment. Parameters A , I_0 , and R_p were calculated from dark I-V test data, and I_L was obtained from short circuit current measurements with the cells illuminated. R_s was then derived as a curve fitting constant that best simulated cell I-V characteristics under illumination. The cell model parameters used in the system simulation studies are listed in Table II-4. Model performance is shown in Figure II-19, where cell terminal voltage-current characteristics are compared to actual cell data. Provision for cell temperature variation is also provided in the model. Ambient temperature (T_A) input data is modified by insolation (ϕ) to establish actual cell temperature (T_C) according to $T_C = T_A + 37 \phi$

Table II-4 Solar Cell Model Parameters

Parameter	Value
I_L	28.9 A/Sun
I_0	0.56 μ A
A	1.4
R_p	200 Ω
R_s	0.0072 Ω

Figure II-19 Solar Cell Model Performance

The saturation current parameter, I_0 , is then derived from actual cell temperature (I_0 doubles every 10°C). The complete cell model accurately represents daily and seasonal temperature variations. In general, the solar array is more efficient in the winter than in summer due to lower winter temperatures.

The flow diagram, Figure II-20, shows that the program first checks the solar array for a back-biased condition. This condition indicates no solar array current is generated so i_{SA} is set equal to zero. If a forward-biased condition exists, as is usually the case when insolation is present, the array current is calculated. To calculate total array field current in the system simulation program, the array isolation diode voltage is first subtracted from the bus voltage, and the difference is divided by the number of series wired solar cells to obtain individual cell terminal voltage. Cell output current is then found by iteration as previously described. Total array field current is then obtained by multiplying cell current by the number of parallel array strings.

e. *Array Shading Model* - The array shading model, SHADE, was originally developed to improve array positioning with respect to interarray shading versus packing factor. The model was developed in three-dimensions to describe irregularly sloped fields, and it was kept highly versatile and easily adaptable to high-speed computers. For Roxborough, SHADE was expanded to include array electrical interconnection to indicate where a shaded array disables

Figure II-20 ARYMOD Flow Diagram

an entire series-string of arrays. This modification allowed insight into the optimum series-parallel connection of an array field. The inputs to the model are defined in Table II-5.

Table II-5 Shade Inputs

N	- Number of Arrays
W	- Width of Array
H	- Height of Array
X,Y,Z	- Array Coordinates
θAZ,θEL	- Sun angle pair, Azimuth and Elevation from SIMPCA
E1,E2,...EN	- Electrical configuration

SHADE operates on array pairs. For every array pair (e.g., arrays A1 and A2 in Figure II-21) there exists three shading possibilities:

- 1) there is no shading between A1 and A2
- 2) A1 shades A2
- 3) A2 shades A1

Once calculations are made for checking array A1 shading A2, information exists for checking A2 shading A1, and calculations for the ordered pair, {A1,A2}, need not be repeated for the inverse {A2,A1}. For this reason, in a field with total number of arrays, N, the number of array pairs, P, is described by:

$$[II-17] \quad P = \sum_{n=1}^{n=N} (N-n)$$

SHADE initially defines relative positioning for each array in the pair. The model always uses the lowest numbered array of the pair as the possible shader, (e.g., A1 of the {A1,A2}) pair. SHADE performs an axis translation, Figure II-22, locating the origin at the center of the shader. Translation formulas for the array pair A1,A2 are:

$$X_{1,1} = 0 \quad , \quad X_{2,1} = X_{2,0} - X_{1,0}$$

$$Y_{1,1} = 0 \quad , \quad Y_{2,1} = Y_{2,0} - Y_{1,0}$$

$$Z_{1,1} = 0 \quad , \quad Z_{2,1} = Z_{2,0} - Z_{1,0}$$

Figure II-21 Array Shading Model Methodology

Figure II-22 Translation of Coordinate System

where

the first subscript denotes array number and the second subscript denotes the number of times the coordinate has been transformed.

Following the translation, the coordinate system is rotated so that the y-axis is parallel to the sun ray vector simulating two-axis tracking. This transformation consists of two independent rotations. The X-Y plane is rotated around the Z-axis so that the Y-axis parallels the sun's azimuth angle. This rotation shown pictorially in Figure II-23 for the example pair {A1,A2,} is calculated as follows:

$$X_{1,2} = 0 \quad , \quad X_{2,2} = X_{2,1} \cos \Theta_{AZ} + Y_{2,1} \sin \Theta_{AZ}$$

$$Y_{1,2} = 0 \quad , \quad Y_{2,2} = X_{2,1} \sin \Theta_{AZ} + Y_{2,1} \cos \Theta_{AZ}$$

$$Z_{1,2} = 0 \quad , \quad Z_{2,2} = Z_{2,1}$$

where Θ_{AZ} is sun azimuth from due south (-east, +west). The Y-Z plane is then rotated around the X-axis so that the Y-axis points toward the sun.

The transformation equations are:

$$X_{1,3} = 0 \quad , \quad X_{2,3} = X_{2,2}$$

$$Y_{1,3} = 0 \quad , \quad Y_{2,3} = Y_{2,2} \cos \Theta_{EL} + Z_{2,2} \sin \Theta_{EL}$$

$$Z_{1,3} = 0 \quad , \quad Z_{2,3} = -Y_{2,2} \sin \Theta_{EL} + Z_{2,2} \cos \Theta_{EL}$$

where Θ_{EL} is sun elevation from horizontal.

The final coordinates of the array pair, with respect to the original coordinates, are described by the following expanded equations:

$$X_{1,3} = 0$$

$$Y_{1,3} = 0$$

$$Z_{1,3} = 0$$

Figure II-23 Rotation of Coordinate System

$$X_{2,3} = (X_{2,0} - X_{1,0}) \cos \theta_{AZ} + (Y_{2,0} - Y_{1,0}) \sin \theta_{AZ}$$

$$Y_{2,3} = ((X_{1,0} - X_{2,0}) \sin \theta_{AZ} + (Y_{2,0} - Y_{1,0}) \cos \theta_{AZ}) \cos \theta_{EL} \\ + (Z_{2,0} - Z_{1,0}) \sin \theta_{EL}$$

$$Z_{2,3} = ((X_{2,0} - X_{1,0}) \sin \theta_{AZ} + (Y_{1,0} - Y_{2,0}) \cos \theta_{AZ}) \sin \theta_{EL} \\ + (Z_{2,0} - Z_{1,0}) \cos \theta_{EL}$$

The final coordinate system is shown pictorially in Figure II-21. The results of this transformation yield sufficient information to ascertain, by simple inequality testing, which of the three shading conditions exist. The algorithm, Figure II-21, maximizes program efficiency by calculating only those coordinates that must be tested. As the figure shows, calculations for a given pair cease when the possibility of shading is found not to exist.

The algorithm first calculates the X2 coordinate, which is dependent only on azimuth, then checks for possible shading due to azimuth. When the absolute value of the X-coordinate, $|X_2|$, is greater than the width, W, of the array face, there can be no shading, and calculations cease.

If there is a possibility of shading, the Z2-coordinate, a function of both azimuth and elevation, is calculated. Similar to the " $|X_2|$ " test, if $|Z_2|$ is greater than the height, H, there can be no shading. When both the $|X|$ and $|Z|$ tests show shading, then shading exists. The final task is to determine which array is shaded by calculating the Y2-coordinate and comparing it to zero. In effect, this test determines which array of the pair is farthest from the sun. That array, of course, is shaded.

Program SHADE is called once for every sun angle pair. As mentioned previously, the SHADE program accomplishes shading calculations for every array pair in the field. In addition, shade calculates terrain shading and accounts for series-parallel connections. The program flow chart is presented as Figure II-24. The flow chart shows that coordinate translation and rotation, as previously described, are performed by the program driver, SEPS. This technique increases efficiency because translation needs only be performed once per run. Therefore, the first task of SHADE is determining terrain shading. Terrain shading, in effect, determines actual sunrise and sunset for the field. The critical elevation angles for am and pm are measured and used as input. The applicable angle is compared to the elevation of the sun. If the sun's elevation is less than the critical elevation angle, all arrays are shaded and no further calculations are

Figure II-24 SHADE Program Flow Chart

made. If the sun elevation is greater than the terrain critical elevation angle, the program starts with array pair $\{A1, A2\}$ and calculates interarray shading as described previously. After the pair is checked, the second array ($A2$ in this case) is incremented so the next pair is $\{A1, A3\}$. This is repeated until $A1$ is checked with all remaining arrays. After this process is complete, the flow chart shows the first array ($A1$) is incremented so the next pair is $\{A2, A3\}$. Array $A2$ is then checked with all remaining arrays, etc. This cycle continues until all array pairs have been checked for shading. If an array is found shaded, appropriate program flags are set to indicate shading of that particular array.

Accounting for specific interarray shading is important in the next process of the SHADE program: determination of shading effects on field output. The output of an electrically connected series-string of arrays is set to zero whenever any one array becomes partially shaded. The program reads the order in which arrays are series connected, then steps through the arrays in that order. The number of unshaded arrays encountered is summed and compared to the number of arrays in a string. If the two numbers are equal, the string is considered active. After all series-strings are checked, the number of active strings and control are returned to SEPS.

f. Load Model - The load model calculates the individual inverter loads for a specific time of day and year. Individual visitor center loads are defined as inputs and are summed in the program according to time of year. The major sections, summer and winter, are each divided into subsections (day and night). Applicable duty cycles are defined for each load. The result is the instantaneous load for the time specified.

The Visitor's Center has two basic load regimes: a spring/summer/fall profile for the months of April through October. The daytime loads are present from sunrise to sunset for this profile. The second load regime is the winter profile that applies for November through March. The daytime loads are confined to 8:00 am through 5:00 pm for this profile. The average loads for these regimes are shown in Tables II-6 and II-7 and Figures II-25 and II-26.

g. System Solutions - The control flow of SEPS, although discussed previously, is covered here in more detail to show actual solution algorithms and subprogram interaction. The detailed flowchart is presented as Figure II-27. The flow chart is started with the time increment to expand the high-level control flowchart of Figure II-5. As shown in both figures, SEPS determines the possibility of insolation. If there is no possibility of insolation, there is no solar array current and no shunt regulator

Figure II-25 Summer Load Profiles

Figure II-26 Winter Load Profiles

Table II-6(a) Daytime Load Characteristics for Spring/Summer/Fall

Classification	Type of Load	Average Power, kW	Voltage, V	Average Current, Amp	Inrush Current 50 msec Amp	Duration of Load, hr
Uncontrolled	Well Pump	1.84	240	7.6	18	Sunrise-Sunset
	*PCA Motors (Tracking)	0.2	120	1.6	--	Sunrise-Sunset
	(Starting)	4.8	120	52.5(pk)	--	125 msec
	(Stowing or Slewing)	4.8	120	39.6	--	15 minutes am
					--	30 minutes pm
	UV Filter	0.3	120	2.5	--	Sunrise-Sunset
	Lights (A)	1.6	120	13.3	--	Sunrise-Sunset
	Battery & Instrument Room	1.0	120	8.3	--	Sunrise-Sunset
	Receptacles (A)	0.5	120	4.15	--	Sunrise-Sunset
	Vent Fan	1.7	240	7.1	35.5	Sunrise-Sunset
	Water Pump	2.8	240	11.7	121	2 hr after Sunrise to Sunset
High Priority	Water Heater	2.0	240	8.3	--	2 hr after Sunrise to Sunset
	Receptacles (B)	1.0	120	8.3	--	Sunrise to Sunset
	Lights (B)	3.9	120	32.5	--	Sunrise to Sunset
Low Priority	Ventilation Fans (2)	3.4	240	14.2	71	Sunrise to Sunset
	Air Conditioning	3.0	240	12.5	62.5	10:00 am-4:00 pm
	Lights (C)	3.5	120	29	--	Sunrise-Sunset
	Golf Cart Battery Charging	0.2	120	1.7	--	2 hr after Sunrise-Sunset
*Based on 36 PCAs						

Table II-6(b) (concl) Nighttime Loads for Spring/Summer/Fall

Classification	Type of Load	Average Power, kW	Voltage, V	Average Current Amp	Inrush Current 50 msec Amp	Duration of Load, hr
Uncontrolled	Well Pump	1.84	240	7.6	18	Sunset-Sunrise
	UV Filter	0.3	120	2.5	--	Sunset-Sunrise
	Ventilation Fan	1.7	240	7.1	35	4.5 hr after Sunset
		0.83	240	3.5	35	Remainder of Night to Sunrise
	Receptacles (A)	0.3	120	2.5	--	4.5 hr after Sunset
	Exterior Lights	1.3	120	11.0	--	4.5 hr after Sunset
	Lights (A)	0.9	120	7.5	--	1.0 hr after Sunset
	Water Pump	5.8	240	24.2	121	1.0 hr after Sunset
	Inst. Rm Receptacles	0.6	120	5.0	--	Sunset-Sunrise

Table II-7(a) Daytime Loads for Winter

Classification	Type of Load	Average Power, kW	Voltage, V	Average Current Amp	Inrush Current 50 msec Amp	Duration of Load, hr
Uncontrolled	Well Pump	1.84	240	7.6	18	8:00 am-5:00 pm
	*PCA Motors (Tracking)	0.2	120	1.6	--	Sunrise-Sunset
	(Starting)		120	52.5(pk)	--	125 msec
	(Stowing/Slewing)	4.8	120	39.6	--	15 minutes am
						30 minutes pm
	UV Filter	0.3	120	2.5	--	8:00 am-5:00 pm
	Lights (A)	1.6	120	13.3	--	8:00 am-5:00 pm
	Battery & Inst Bldg	1.0	120	8.3	--	8:00 am-5:00 pm
	Receptacles (A)	0.5	120	4.15	--	8:00 am-5:00 pm
	Heating Fan	1.7	240	7.1	35.5	8:00 am-5:00 pm
	Water Pump	2.8	240	11.7	121	8:00 am-5:00 pm
High Priority	Water Heater	2.0	240	8.3	--	8:00 am-5:00 pm
	Receptacles (B)	1.0	120	8.3	--	8:00 am-5:00 pm
	Heating Fans (2)	3.4	240	14.2	71	8:00 am-5:00 pm
	Lights (B)	3.9	120	32.5	--	8:00 am-5:00 pm
Low Priority	Lights (C)	3.5	120	29	--	8:00 am-5:00 pm
*Based on 36 PCAs.						

Table II-7(b) (concl) Nighttime Loads for Winter

Classification	Type of Load	Average Power, kW	Voltage, V	Average Current, Amp	Inrush Current 50 msec, Amp	Duration of Load, hr
Uncontrolled	Well Pump	1.84	240	7.6	18	5:00 pm-8:00 am
	UV Filter	0.3	120	2.5	--	5:00 pm-8:00 am
	Heating Fan	1.7	240	7.1	35	5:00 pm-8:00 am
	External Lights	1.3	120	11.0	--	5:00 pm-6:00 pm
						If necessary
	Inst Rm Receptacle	0.6	120	5.0	--	5:00 pm-6:00 pm

Figure II-27 Solution Flow Chart of SEPS

current. In this case, it is also known that the battery is discharging so the battery discharge model is used. Furthermore, Eq. 3 reduces to

$$i_{IA}(V_B) + i_{IB}(V_B) + i_B(V_B) = 0.$$

Solving this equation for V_B yields a quadratic. V_B can then be calculated for use in finding individual battery and inverter currents using the equations of those models.

If there are no loads on the 30-kVA inverter, as is the case at night, the 30-kVA inverter is turned off to eliminate its parasitic power drain. The solution is then written on the output file, time is incremented, and the process is repeated.

If SEPS determines that there is possible insolation, SIMPCA is called to calculate insolation and sun angles. SHADE is then called to determine the number of active array series-string. If there are no active strings, the solution is again obtained directly as in the above case. If SHADE produces at least one active series-string, the more complex solution involving all currents must be sought. The initial selection (for iteration) of bus voltage, V_B , is set to shunt regulator, clamp voltage, VSR1 or VSR2, corresponding to high and low respectively. The battery, array, and inverter models are then called. After these currents are defined, shunt regulator current, i_{SR} , is calculated algebraically from

Eq. 3. If i_{SR} is positive, the solution is valid as explained in the shunt regulator model. If i_{SR} is negative, V_B is set to battery charge model voltage, high or float charge, dependent on battery SOC. The battery, array, and inverter models are again called. If the battery current i_B is positive (charge, indicating a good initial selection of V_B) the major Newton-Raphson method of iteration is entered to find the solution within the specified tolerance (0.001 ampere).

If i_B is negative (indicating discharge), V_B is set to the discharge model voltage and the models are called. If i_B remains negative, the major Newton-Raphson methods is entered directly. If i_B is positive, i_B is set to zero before proceeding to the iteration.

The major Newton-Raphson method of iteration first calculates i_{SR} and its derivative i'_{SR} from the models and Eq. 3. If the solution is within tolerance, the results are written on the

output file. If the solution is not within tolerance, a new V_B is chosen as V_{B1} :

$$V_{B1} = V_B - i_{SR}/i'_{SR}$$

The models are called with this new V_B and the process is repeated until a solution within tolerance is obtained.

The Newton-Raphson method of iteration is extremely fast and efficient. A typical solution requires 3 to 4 iterations for this voltage. It is important in the model that the initial "guess" (in this case V_B) be within the radius of convergence of the solution. This problem was eliminated by developing the above methods of choosing the initial V_B .

D. SYSTEM PERFORMANCE PREDICTION

The energy independence theme of the Roxborough Park experiment required detailed and comprehensive system analysis to verify that the experimental objectives were met. The system modeling methodology previously described was developed specifically to serve that purpose. A baseline insolation, weather, and load profile data base was established early in the program and formalized by including it in the System Design Criteria document. The actual load profile is discussed in Section III.

Our system analysis program was structured for flexibility in performing parametric analyses with respect to component configuration (e.g., number and arrangement of solar cells or battery cells); array location, interconnection, and shading effects; varying load profiles; and varying weather conditions.

System performance prediction results are shown in Table II-8 for a single sunny day on the 21st of each month. The battery SOC was begun at 70% for each day. An increase in SOC after 24 hours indicates positive energy balance. The clear-day results in show net gain in SOC for all months, with December having the least increase in SOC from 70% to 74.8%. June 21 shows the highest energy collected (429 kW/hr).

Table II-8 Sunny Days Results

Month	Solar		Load kW-hr	Battery Soc ³ (%)
	Input ¹ kW-hr	Collected ² kW-hr		
Jan	5611	495	288	79.0
Feb	6316	587	289	84.6
Mar	7304	680	289	88.8
Apr	7874	730	387	77.6
May	8151	758	410	77.6
Jun	8593	759	418	77.9
Jul	8256	713	411	77.9
Aug	7544	657	389	77.9
Sep	6900	606	362	76.9
Oct	6323	557	336	75.9
Nov	5581	482	288	76.0
Dec	5312	429	288	74.8

Note: 1. Solar array input energy defined as total insolation available to the total array aperture area.
2. Total solar array electrical energy provided to bus.
3. Battery state-of-charge after 24 hours.

The initial runs summarized in Table II-8 for sunny days were continued through a cloudy day, and the cloudy day results are summarized in Table II-9.

Table II-9 Nominal Cloud Results

Month (22nd)	Cloud Cover (%)	Solar		Load ³ kW-hr	Battery Soc ⁴ (%)
		Input ¹ kW-hr	Collected ² kW-hr		
Jan	33	3783	333	288	72.8
Feb	33	4263	398	289	82.2
Mar	35	4787	444	289	85.5
Apr	37	4982	466	388	70.8
May	39	4982	466	410	68.0
Jun	31	5926	530	418	73.5
Jul	32	5596	493	410	72.6
Aug	32	5102	449	389	69.9
Sep	29	4945	430	362	71.1
Oct	29	4450	389	336	68.2
Nov	33	3678	316	288	66.8
Dec	35	3454	274	288	57.3
<p><u>Note:</u> 1. Solar array input energy defined as total insolation available to the total array aperture area.</p> <p>2. Total solar array electrical energy provided to bus.</p> <p>3. Actual load.</p> <p>4. Battery state-of-charge at midnight.</p>					

Our fundamental system design criterion was defined as supporting the load for three hours after sunrise on a completely overcast day that followed a nominally cloudy day (preceded by a clear day). The runs summarized in Tables II-8 and -9 were continued into a third day with 100% cloud cover. Table II-10 summarized the time of day on the third overcast day that battery SOC fell to 25% corresponding to system switchover to utility. The minimum sustaining time was in May when high summer loads are in effect and previous day-nominal cloud cover (39%) is the year's heaviest. Computer generated plots for all months. Figure II-28 through II-33 show the instantaneous insolation, weather, load, and battery SOC profiles for those three days in each month. Data in the above figures does not include the load demand controller function.

Figure II-28 System Operation for January and February with Zero, Nominal, and Total Cover

Figure II-29 System Operation for March and April with Zero, Nominal, and Total Cover

Figure II-30 System Operation for May and June with Zero, Nominal, and Total Cover

Figure II-31 System Operation for July and August with Zero, Nominal, and Total Cover

Figure II-32 System Operation for September and October with Zero, Nominal, and Total Cover

NOVEMBER

DECEMBER

Figure II-33. System Operation for November and December with Zero, Nominal, and Total Cover

Table II-10
System Independence with
No Insolation

Month (23rd)	Hours of Independence (from Midnight)
Jan	12.7
Feb	13.8
Mar	14.2
Apr	10.7
May	10.0
Jun	10.6
Jul	10.7
Aug	10.7
Sep	11.2
Oct	11.2
Nov	11.8
Dec	10.6

So total load supported under continuous nominally cloudy conditions could be accurately assessed, a type of load control device was modeled by removing loads on the 30-kVA inverter when the battery SOC falls to 25%. These load, while still calculated, are not re-applied to the system until the battery recharges to 50% SOC. This simulates the hysteresis of the actual load controller and allows computer analysis to continue with meaningful results even if the system fails to completely support the load.

The program, with the load controller instituted, was executed in ninety six 15-minute intervals/day for each month with all nominally cloudy days. The first day of each month was started with the battery initialized at 70% SOC. The results, shown in Table II-11, are divided into three major classifications: solar, inverter input, and load. The solar classification, consists of array input and collected energy. Solar input energy is defined as energy available (after clouds) to the total array field aperture area, 8064 square feet. This energy is calculated without regard for shading, either between arrays or by terrain. As expected, this energy is highest (177,658 kW-hr) in June when the daylight hours are longest. June also has the highest collected energy, 15,944 kW-hr. Collected energy is defined as the energy delivered to the bus including all shading effects.

The second major data classification in Table II-8 is inverter input energy. This energy is subdivided between the 7.5-kVA interter and the 30-kVA inverter. Results show the annual 7.5-kVA inverter input is 42,955 kW-hr and the annual input to the 30-kVA inverter is 95,078 kW-hr.

Table II-11 Monthly Energy Balance

Month	Solar		Inverter Input		Load Supported		Actual	Percent of Maximum Load Supported
	Input kW-hr	Collected kW-hr	7.5 kVA kW-hr	30 kVA kW-hr	7.5 kVA kW-hr	30 kVA kW-hr	kW-hr	
Jan	113,866	9,736	3,704	5,574	3,417	5,044	9,004	94.0
Feb	113,627	10,450	3,366	5,628	3,087	5,050	8,137	100.0
Mar	143,976	13,353	3,739	6,319	3,418	5,598	9,016	100.0
Apr	147,115	13,415	3,468	9,247	3,186	8,278	11,464	100.0
May	152,981	14,133	3,623	10,042	3,335	9,026	12,411	98.7
Jun	177,658	15,944	3,552	10,320	3,250	9,214	12,464	100.0
Jul	174,901	15,396	3,653	10,492	3,348	9,392	12,740	100.0
Aug	160,337	14,227	3,609	9,911	3,313	8,875	12,188	100.0
Sep	149,107	13,174	3,445	8,779	3,158	7,833	10,991	100.0
Oct	142,432	12,527	3,503	8,274	3,214	7,372	10,586	100.0
Nov	115,320	10,011	3,592	5,809	3,307	5,215	8,716	97.8
Dec	108,630	8,758	3,701	4,683	3,418	4,228	9,004	84.9
Annual Total	1,699,950	151,124	42,955	95,078	39,451	85,125	126,721	98.3
Total Load Supported					124,576			

The third major data classification is the load, both actual and supported. The supported load is divided into outputs of the 7.5- and 30-kVA inverters. Results show that the total annual output of both inverters, which is annual load supported, is 124,576 kW-hr. The supported load data is compared with the actual load to determine the percent load supported. The results show that the Roxborough loads can be completely supported for all months except January (94.0%), May (98.7%), November (97.8%), and December (84.9%). Annual totals show that 98.3% of the actual load is supported by the system under nominal weather conditions. Results also show the yearly load trends parallel the solar energy collection trends and visitor patterns at Roxborough Park. These are important factors in the experiment.

It should be cautioned that a review of the data presented in Table II-10 must account for the differing number of days in each month.

III. COMPONENT DEVELOPMENT AND SPECIFICATION

The design emphasis of the Roxborough experiment was to define a system meeting the objectives of a photovoltaic concentrator experiment at minimum technical risk. As a result of this philosophy, major system components other than the photovoltaic concentrator arrays themselves were selected on the basis of proven history to the maximum extent possible. The battery, inverters, load demand controller, and state-of-charge monitor are examples of readily available "off-the-shelf" hardware employed in power system applications similar to Roxborough.

The photovoltaic concentrator arrays developed by Martin Marietta under previous contract to Sandia have the least hardware maturity. They are, however, essential to the experiment concept, and the key subassemblies have advanced past the prototype stage to a second generation.

Prototype photovoltaic concentrator modules were delivered to Sandia during late 1977 and early 1978. The basic array producibility has been demonstrated, and the techniques for fabrication, assembly, checkout, and operation have been developed.

Only two system components are of completely new design: The Analog Shunt Regulator and the System Control Center. Both of these components reflect common practice rather than advanced technology, and are considered to be low technical risk. Both were extensively analyzed and "breadboard" to verify operation.

The major system component application history is summarized in Table III-1.

A. PHOTOVOLTAIC ARRAY

1. Photovoltaic Concentrator Array (PCA)

An illustration of the Photovoltaic Concentrator Array (PCA) is shown in Figure I-5. As mentioned in Section I, the PCA uses Fresnel lenses to concentrate sunlight approximately 40 times on silicon solar cells. Each lens is 1x4 ft and contains four one-foot-square point focusing patterns. The lens is supported by a plastic housing, which also serves as environmental enclosure protecting the cells and the ground surface of the lens. Eight solar cells consisting of four cells per housing are mounted on an aluminum heat exchanger, which provides functions

of both passive thermal dissipator and structural support member. The two housing groups on the heat exchanger constitute a module easily installed on or detached from the array horizontal support tube. Each four-cell housing group has an associated bypass diode.

Table III-1 Major Component Summary

<u>Item</u>	<u>Mfg</u>	<u>Delivery</u>	<u>Experience</u>
Photovoltaic Concentrator Array	MMC	--	<ul style="list-style-type: none"> - Designed Under Sandia Contract - Prototype Modules Delivered to Sandia under Test Since Nov. 1977. - Four Full-Size Arrays Being Fabricated under Sandia Contract. Delivery Scheduled for Feb. 1979.
Inverter	NOVA	180 Days ARO	<ul style="list-style-type: none"> - Mead Nebraska Irrigation Project - MIT Lincoln Labs - JPL - Johns Hopkins Univ. - Applied Physics Lab - Canadian Dept. of Transportation - Air Droppable Nav Aids
Lead Calcium Battery	C&D	20-25 Wks ARO	<ul style="list-style-type: none"> - Mead Irrigation Project (375 A-h, C&D) - Papago Indian Village at Schuchuli (2380 A-h) - Forest Service Lookout Towers (3015 A-h)
Load Demand	Dencor	1 Wk ARO	<ul style="list-style-type: none"> - Commercial Product
State-of-Charge Monitor	Curtis Instruments, Inc.	3 Wks ARO	<ul style="list-style-type: none"> - Commercial Product

The complete array designed for Sandia is 42 ft long, 9 ft high, and is a complete functional entity including elevation and azimuth drive mechanisms, control electronics, and sunsensor. The array mounts to a 5-ft-high pedestal using six 5/8-in.-diameter nuts. For Roxborough, the array was shortened from 34 modules to 28 to optimize power transfer to the dc bus as described in Section II. This change was incorporated without impact on the remainder of the structural design. The tube was shortened to accommodate three less modules on each end.

The entire assembly is environmentally sealed. In the case of four-cell Photovoltaic Concentrator Modules (PCM), the lenses are bonded to the housing and the housings are gasket sealed to the heat exchangers. Electrical conductors are also sealed in and out of the housing. The drive and bearing arrangement for the elevation drive assembly is also enclosed in a molded plastic housing, which incorporates shaft seals for sealing the main

structural tube. The azimuth drive constitutes an integral gearbox which is sealed against the environment.

The PCA design shown in Figure I-5 has a number of advantageous features as listed below:

Minimum Foundation Requirements - The PCA foundations are simple straight-shaft caissons constructed by drilling holes with an auger rig and pouring concrete. This foundation design is attractive because of its simplicity, and is particularly attractive for Roxborough Park because minimum site disturbance was a requirement.

Inherent Safety - Because concentrated sunlight is contained within an enclosure, the possibility of accidental burns or eye damage is eliminated. The possibility of fire due to combustible debris blowing into the concentrated beam and igniting is also precluded. This again was an important feature for the Roxborough Park application in a semiarid environment with significant fire potential.

Ease of Maintenance and Cleaning - The flat lens surface provides an optimum geometry for automated cleaning. The cleaning operation can be conducted by commanding all arrays in the field to an upright position and driving a truck containing cleaning equipment down the array rows. This again was an important consideration for Roxborough where minimum site maintenance is desired.

The required cleaning period for the lens system (or for any photovoltaic concentratory system) is dependent on many variables including local weather conditions. We project the Fresnel lens system to be inherently less sensitive to dirt accumulation than second-surface mirror systems because the sunlight only "sees" the dirt particles once as it is transmitted through the lens. In second surface mirror systems, the sunlight sees the dirt particles twice: first on entry and again on exit after reflection. In multiple reflection mirror systems, the efficiency loss due to dirt is compounded on each reflection.

Low Collector to Aperture Area Ratio - For the flat lens used in Martin Marietta design, this ratio is unity - the minimum achievable. The lens surface area is thus the minimum possible for a given collector aperture.

High Optical Efficiency - Generally speaking, a transmission efficiency of 85% is a practical design parameter after accounting for the effects of theoretical reflection, absorption loss, and manufacturing defects. Actual lens efficiency demonstrated on the 10 kW fabrication project is 80%.

Good Target Uniformity - Uniform light intensity distribution over the solar cell target is easily obtained in Fresnel lens systems by appropriate design of the lens facet or "groove" angles. Obtaining uniform intensity distribution can be a difficult problem in mirror systems and an impossible problem to overcome in nontracking CPC systems where the intensity distribution is dependent on the sun angle.

Inherent Cell Protection - The environmental enclosure protects the cell from the elements and permits the cell to be used without a cover slide, thus achieving a significant reduction in cell assembly cost.

In addition to maintenance ease, protection of the solar cell by the environmental enclosure eliminates any need for solar cell cleaning.

Vandal Resistant - The rugged construction of the PCA can tolerate thrown rocks. It should be noted that the lens material, cast acrylic, is extensively used in aircraft transparencies and bus windows.

Low Cost Potential - Fresnel lens construction (acrylic plastic with a grooved surface) is reminiscent of high fidelity records. Fresnel lenses are presently used as the focusing component in such applications as overhead projectors and traffic lights.

Environmental housing used in the PCA are plastic and can be injection molded in high quantities at very low cost. Aluminum heat sink extrusions on which the solar cells are mounted are a significant cost element. Their impact on PCA cost has been compensated to some extent by designing them to serve functions of both heat sink and structural member.

Support for the concentrator modules is provided by a simple tube design. This tube requires minimum modification from the as-drawn stock material.

The wind induced torques and base bending moment, which constitute the major loads that the drive mechanisms must accommodate, have been minimized by arranging for the two-pivoted axes, azimuth and elevation, to intersect at the centroid of the array. This design concept provides for minimum cost drive mechanisms.

2. Solar Cell Assembly

Solar cells are the key element in any concentrating system. In general, and particularly for the higher concentrating systems, solar cell cost tends to be a secondary (although not insignificant) consideration in total system cost. Cell performance,

however, is crucial to cost. Any cell efficiency improvement provides a direct reduction in field size and total system cost. For this reason, cost effective design techniques for reducing cell temperature and for minimizing cell interconnection losses were important in the PCA design.

The PCA design uses a concentrating silicon solar cell specially designed for Martin Marietta by OCLI. Cell development has progressed to a second generation design as illustrated in Figure III-1. The old cell design used on the early prototypes delivered to Sandia has a lower base resistivity, thinner bus bar, and a different grid pattern than the new cell for the 10 kW fabrication project. The new cell achieves more than 10% performance improvement over the old cell due to an increased fill factor. Construction details for the cells are listed in Table III-2.

Figure III-1 Solar Cell Evolution

Table III-2 Solar Cell Parameters

Item	Old Cell	New Cell
<u>Dimensions</u>		
Cell Diameter	2.25 in.	<div style="text-align: center;"> Same </div>
Cell Thickness	14 mils	
Active Area	3.3 sq in.	
<u>Material</u>	Single Crystal Czochralski Grown Silicon	
<u>Orientation</u>	(100)	
Doping	P-Type, $10^{17}/\text{cm}^3$ Boron	
Bulk Resistivity	1.0 - 5.0 ohm-cm	
<u>N-Diffusion</u>		
Junction Depth	0.4 micron	
Sheet Resistivity	20 ohms Per Square	
<u>Black Contact</u>	P ⁺ Layer Formed by Alloying Aluminum Followed by Evaporated Ti-Pd-Ag Contact	<div style="text-align: center;"> Same </div>
<u>Front Contact</u>	Vacuum Evaporated Ti-Pd-Ag	
Thickness	4-8 microns (Increased by Electroplating)	
Grid Line Width	50 microns	
<u>Antireflective Coating</u>	Proprietary Multilayer	

The solar cell and contacts are solder bonded to an alumina substrate as shown in Figure III-2. The alumina substrate serves the threefold functions of a mounting base for the solar cell, mount for the front and back electrical terminals, and electrical insulator between cells and heatsink. The N-contact has also evolved to a second generation. The contact for the older prototypes has eight current-collection fingers while the new contact has fifteen (Fig. III-3).

3. Heat Exchanger Assembly

The completed solar cell assemblies are screw mounted to the aluminum heat exchanger as shown in Figure III-4a. Electrical terminals and bypass diode assemblies are also mounted on the heat exchanger (one bypass diode for each group of four cells). The heat exchanger has also evolved to a second generation as shown in Figure III-4b. The new heat exchanger has a tapered base plate and a new fin arrangement optimized for heat transfer. The weight of the new heat exchanger has been reduced approximately 30% while maintaining the same thermal transfer properties as the old. The new heat exchanger is fabricated from a custom extrusion die and requires minimum machining from the as-drawn stock configuration.

a) Cell-Substrate Assembly Components

b) Final Assembly

Figure III-2 Cell Substrate Assembly

Figure III-3 Cell Contact Evolution

a) Cell-Substrate Assemblies Mounted on Heat Exchanger (One Half Section)

b) Heat Exchanger Evolution

Figure III-4 Heat Exchanger Assembly

4. Module Assembly

The four-point Fresnel lens is bonded to a plastic housing. The housing also contains four aluminum foil "liners" that protect it from concentrated sunlight during off-axis pointing. All three components have evolved to second generation. The new lenses are cast as a single unit rather than individual one-foot-square sections bonded together. The housings have been redesigned for ease of assembly. They are vacuum formed and have additional stiffening "ribs" for exact positioning of the liners. The liners have been redesigned to provide increased protection due to off-axis pointing. Under certain pointing error conditions, the old units permitted concentrated sunlight to reach certain portions of the housing and burn it.

The Fresnel lens used in the PCA is made of cast acrylic and was designed for Martin Marietta by Swedlow, Inc. The lens facet angles were optimized with the aid of computer programs to provide uniform solar cell illumination. A key objective of the

design was to minimize the centerline intensity "spike" characteristic of lenses.

Once the lens, housing, and liners are assembled, they are mounted on the heat exchanger assembly shown in Figure III-4a. A photograph of one of the old prototype 4-cell modules is shown in Figure III-5.

Figure III-5 Photovoltaic Concentrator Module Prototype

5. Structure and Drive Mechanism

As shown in Figure I-5, the support structure for the PCMs is simple. It comprises a 12-in. diameter thin-walled steel tube with spaced mounting brackets for module and electronics box attachment. The center section is of thick wall tube cradled on needle-bearing cam rollers as shown in Figure III-6.

The inherent deflection of the tube and its resulting effect on pointing accuracy is compensated by positional control of the mounting brackets during fabrication. This is a cost-effective measure to permit use of a lightweight tube.

As shown in Figure III-6, the drive mechanism for elevation control is composed of a chain and sprocket drive, driven from a self locking (nonbackdriving) worm reducer. The chain is tensioned by pivoting and spring loading the reducer so no slack is developed at wind velocities up to 30 mph. The chain is sized to limit elastic deflection so as not to influence tracking stability. The elevation drive is shown in Figure III-7a.

Figure III-6 Drive Mechanism Design

The azimuth drive (Fig. III-7b) also serves as the azimuth pivot. Its output shaft and bearings are sized to limit both bending and torsional deflections to acceptable levels. It is designed to withstand a 90 mph wind at 10 degree angle of attack relative to a horizontally stowed array.

The azimuth drive incorporates helical final stage and a primary worm stage (the latter is incorporated to avoid back driving). The drive motors incorporate gearheads and may be either ac or dc as best suits the installation.

6. Tracking and Control

The PCA uses active feedback sun sensing to track the sun in two axes. A sun sensor is mounted in the electronics control box near the center of the array with sense axis oriented normal to the array aperture plane. The sun sensor contains solar cells separated by a shadow column. The cell outputs establish an error signal when the sun is off-axis that causes the control electronics to drive the array to face the sun.

Both fine and coarse sun sensing is used. The coarse sensors have a wide ($\pm 90^\circ$) field-of-view and are used to acquire the sun at sunrise or after transient conditions have caused the fine sensors to lose the sun. The fine sensors assume tracking control once the coarse sensors bring the array near normal pointing. A novel tracking circuit has been developed that provides angular

a) *Elevation Drive*

b) *Azimuth Drive*

Figure III-7 Drive Mechanism

error indications insensitive to solar intensity variations. This technique is the subject of a new technology disclosure by Martin Marietta.

The control electronics for the Roxborough arrays are similar to the Sandia fabrication project electronics. The primary difference is that a "digital interface" was designed for Roxborough arrays to be compatible with the Roxborough system control methodology. Control of the array field is achieved by two control lines which are "daisy-chained" between the arrays to minimize cabling. The circuit modifications required for this were breadboarded and tested. Lightning protection provisions were also incorporated into the Roxborough design and are not in the Sandia 10 kW design.

7. Performance

Each of the Roxborough PCAs contains 224 solar cells connected in series. The array is nominally rated at 9.0% minimum peak power efficiency when operated in a standard test environment of 1.0 kW/m² insolation, 1 m/sec wind speed, and 28°C ambient temperature. Based on data for the new cells received from OCLI for the 10 kW fabrication project, we feel the 9.0% rating is significantly lower than what will be achieved on this project. We expect the nominal module efficiency to be in the 10% range.

New and old cell I-V curves are compared in Figure III-8. The array performance characteristics are summarized in Table III-3. An array material cost estimate was prepared for the Roxborough Park array configuration (224 cells, 28 modules). Data are summarized in Table III-4.

The annual energy collected by the array has been determined from our system analysis studies for Roxborough Park. These data are described in Section II-C. These data include the effects of shading due to terrain and adjacent arrays, cloud cover, ambient temperature variations, and mismatch between bus and array peak-power point. On this basis, the array field collected 151,124 kWh for a maximum input solar energy of 1,699,950 kWh as shown in Table III-5a. This corresponds to an 8.9% annual efficiency.

(A)

LEGEND		
Item	Old	New
Cell Temperature	33.6°C	32°C
Power Input	68 W	75.6 W
V_{OC}	0.637 V	0.662 V
I_{SC}	22.6 A	24.9 A
V_{MP}	0.426 V	0.545 V
I_{MP}	19.6 A	22.8 A
Power Output	8.37 W	12.43 W
Efficiency	12.3%	16.4%
Fill Factor	0.58	0.75

(B)

Figure III-8 Solar Cell Improvement

Table III-3 Roxborough PCA Performance Characteristics (224-Cell Unit)

Item	Value
<u>Conditions</u>	
Solar Insolation	1.0 kW/m ² (92.8 W/ft ²)
Temperature	28°C (82°F)
Wind Speed	1.0 m/s (2.24 mph)
<u>Array Characteristics</u>	
Effective Aperture	20.8 m ² (224 ft ²)
Incident Flux (at 1.0 kW/m ²)	20,800 W
Power Output (at 9.0% Efficiency)	1875 W
Output Voltage (at V_{mp} - 0.42V/Cell)	94 V
Output Current (I_{mp})	19.9 A
Wind - Tracking	14 m/s (31 mph)
- Stowed	40 m/s (90 mph)

Table III-4 Array Material Cost

Material/Item	Material Cost Parameter \$/lb	Individual Part Weight	Roxborough Array		(224 Cell)	Sandia Array (272 Cell)		Subtotal
			Qty/ Array	Cost/ Array	Subtotal	Qty/ Array	Cost/ Array	
<u>Aluminum</u>								
Extruded - Heat Exchanger	\$0.85	43.00 lb	28	\$1,023.40		34	\$1,242.70	
Structural - Diode HS. Assy	1.05	0.11	56	6.47		68	7.85	
- Sun Sensor Assy	1.05	0.46	1	.48		1	.48	
Foil - Housing Liners	1.50* Est.	0.33	224	110.88	\$1,141.23	272	134.64	\$1,385.67
<u>Steel</u>								
Structural - Support Tube Assy	0.38	850	1	323.00		1	323.00	
- Cradle	0.38	60	1	27.80		1	22.80	
- Azimuth Ret. Plate	0.38	3	1	1.14		1	1.14	
Gear Boxes - Azimuth	4.00	110	1	440.00		1	440.00	
- Elevation	4.00	40	1	160.00		1	160.00	
Chain & Sprocket	4.00	20	1	80.00		1	80.00	
Sheet - Module Bracket	0.25	3.5	28	24.50		34	29.75	
- Electronics Box Bracket	0.25	5	2	2.50		2	2.50	
- Bracket	0.25	0.5	1	.12		1	.12	
Misc. Steel Parts	0.50	--	468 lb	234.00	1,293.06	568 lb	284.00	1,343.31
<u>Motors</u>								
Azimuth	3.00	13	1	39.00		1	39.00	
Elevation	3.00	13	1	39.00	78.00	1	39.00	78.00
<u>Alumina</u>								
Mounting Substrate	15.00	0.0678	224	227.81	227.81	272	276.62	276.62
<u>Copper</u>								
Cell Contacts	1.70	0.00875	224	3.33		272	4.05	
No. 6 AWG Conductor	1.70	81.1b/1000 ft	514 ft	70.78	74.11	606 ft	83.45	87.50
<u>Plastic</u>								
ABS - Cover Assy	0.75	10	1	7.50		1	7.50	
Acrylic - Fresnel Lens	0.90	4.54	56	228.82		68	277.85	
- Housing	0.90	4.2	56	211.68		68	257.04	
- Terminal Cover	0.90	0.25	56	12.60	460.60	68	15.30	557.69
<u>Cells & Interconnections</u>	0.25/cm ²	23.2/cm ²	224	1,299.20	1,299.20	272	1,577.60	1,577.60
<u>Total</u>					\$4,574.01			\$5,306.39
Array Aperture					20.78/m ²			25.23/m ²
Array \$/m ²					\$ 220.16/m ²			\$ 210.34/m ²

Table III-5 Battery Characteristics

- Railroad Type Battery Designed for Car Lighting and Air Conditioning Applications Characterized by Moderate Discharge Rates (8 Hr)
 - Flooded Lead-Acid Battery - Hybrid:
 - Negative Grid - Calcium Lead Alloy
 - Positive Grid - Antimony Lead Alloy
 - 41 Plates Per 2 V Cell (Extra Negative Plate)
- Calcium Alloyed Negative Grid:
 - Enhances Float Life
 - Reduces Electrolyte Loss
 - Adds Mechanical Strength
 - Has Low Maintenance Requirements
- Antimonial Positive Grid With High Metallic Lead Content (50%):
 - Enhances Deep Cycle Life
 - Greater Current Capacity (Less Internal Resistance)
- Glass Fiber Separators (Slyver-Clad):
 - Prevents Shedding
 - Provides High Electrolyte Exposure
 - Minimum Sediment Space Required (Will Provide 5/8 in.)

B. BATTERY

The storage battery will be assembled from 55 series-connected 2-cell 2CB-41 (C&D batteries part number) battery packs. The batteries are flooded lead-acid types, designed specifically for railroad car lighting and air conditioning applications. This application is similar to Roxborough in that relatively low-level continuous loads are supported. The battery is rated at 1500 ampere-hours and provides 330 kWh of energy storage.

The C&D battery chosen was selected after a thorough survey of available batteries and technical discussion with several battery vendors. It has excellent standby and cyclic capability for Roxborough. It is designed for low maintenance and long life; has a high charging efficiency compatible with the Roxborough charging methodology; and it can supply large transient currents with minimal voltage drop. The battery characteristics are summarized in Table III-5 and the results of our battery survey in Table III-6.

The battery has calcium alloyed negative grids which enhance float life, reduce electrolyte loss, provide mechanical strength and minimize maintenance requirements. The antimonial positive grid, which is 50% grid metal, extends deep-cycle life and increases the current handling capability.

Table III-6 Lead Acid Battery Survey

Battery Application	Grids		Designed For
	Alloy*	Thickness	
UPS	Calcium	200 mil	Stand-by Application Short Discharge (~ 1 hr) High Current Electrolyte Limited DOD
Auto	Calcium	60-80 mil Many Plates	Stand-by Application Very Short Discharge (Seconds) Very High Currents
Industrial	Antimony	250-280 mil	Cyclic Application Longer Discharge (~ 8 hr) High DOD Capability Long Cycle Life
Railroad	Calcium Antimony	256 mil	Stand-by Cyclic Application RR Light & A/C Moderate Currents (~ 8 hr) Low Maintenance
*Calcium - Extends Float Life Antimony - Extends Cycle Life			

The grid separators are patented, slyver-clad glass fiber separators that prevent grid shedding, increase exposure to the electrolyte, and minimize sediment space. Battery construction features are identified in Figure III-9 and detailed performance specifications in Table III-7. The battery life is 1900 cycles at 75% depth-of-discharge. End-of-life corresponds to capacity degradation to 80% of rating. The low electrolyte specific gravity also enhances life by reducing the rate of corrosion and plate expansion.

C. POWER CONDITIONING EQUIPMENT AND SWITCHGEAR

The major power conditioning component associated with the ac power system are two inverters and the load demand controller. These components along with the key switchgear and load distribution circuits are shown in Figure III-10.

Two inverters are used in the power system: a small 7.5 kVA inverter to power continuous and nighttime loads, and a large 30 kVA inverter to power daytime loads. At night, the 30 kVA inverter is switched off to minimize battery drain. Both inverters are standard single-phase, 60 Hz, 120/240 VAC static units. The 7.5 kVA unit (Nova P/N 7.5K60-240) is a standard Taurus series inverter from Nova Electric Manufacturing Co. The 30 kVA unit is assembled from three 10 kVA inverter (10K60-240). These inverters are similar to those used in other flat-plate photovoltaic systems. Photovoltaic applications using this line of Nova inverter include projects managed by MIT Lincoln Labs, JPL, Applied Physics Laboratory at John Hopkins, and others. The inverters for these applications are used either as stand-alone single units or paralleled for increased load rating.

The 30 kVA inverter loads are divided into two groups as shown in Figure III-10: controlled loads and uncontrolled loads. The uncontrolled loads are those considered incapable of being cut back for energy conservation. The controlled loads are loads of lower priority which can be cut back when energy is limited. Control is provided by a load demand controller (LDC). The LDC contains a current sensing circuit around the power mains to measure load power consumption. Control circuitry within the LDC evaluates both instantaneous and "long-term-average" power consumption and makes a decision every 15 seconds to shed or restore a controlled load. The decision is based on the measured level versus the level corresponding to the demand limit signal from the SCC. Loads are shed in a fixed priority; highest priority loads being shed last and restored first. The loads are controlled through eight normally closed double-throw, single-throw

a) Two Cell Battery Pack (2CB-41)

Grids & Separator

VENT, made of unbreakable polypropylene

CELL COVER, molded of special Hi-Impac compound which virtually eliminates breaks and leaks.

MOSS SHIELD, made of high impact rubber, prevents separator breakage

PERFORATED PLASTIC RETAINER made of long-life Koroseal forms an envelope around the positive plate. Non-perforated portions insulate the plate edges.

JARS (for 16-cell batteries) are made of high-density, crosslinked polyethylene. Won't soften at 400°F, will take 280 inch-pound of impact at -20°F without breaking. Cells in 4-cell batteries are contained in extra-strong, hard rubber monobloc container.

LEAD BUSHING in cover eliminates post corrosion and leakage.

POSITIVE PLATES are a full 0.256 inches thick. ("Lifetime" CSCK45 plates are 0.290 inches thick.) All have maximum active area.

SLYVER, made of glass fibers 0.00025" to 0.0003" in diameter, keeps active material in place while permitting exposure of active material to electrolyte and the escape of gas formed during charging.

EXPANSION MATS—Keep SLYVER firmly against active material while providing for normal expansion of the positive plate.

THREE-RIB BRIDGE prevents short circuits on bottom of plates. Negative plate rests on foot ... positive plate is supported by two ribs.

Other Features

Unbreakable polypropylene vent.

High sustained voltage during cranking is assured by heavy copper inserts in terminal posts and connectors.

Post corrosion and leakage eliminated by lead bushing in cover

Cell cover molded of special Hi-Impac compound which virtually eliminates possibility of breaks and leaks.

Extra-strong monobloc container is hard rubber, has heavy reinforced corners and sidewalls.

Sturdy, three-rib bridge prevents short circuits on bottom of plates while providing adequate sediment space.

Rugged bottom skids increase stability, reduce stress throughout case make it easy to remove battery from compartment.

b) Battery Construction Details

Figure III-9 Battery

Figure III-10 Power Conditioning and Load Distribution Equipment

Table III-7 Battery Specifications

Type - Lead Calcium
Number Cells - 110 (55 2-Cell Packs)
<u>Cell Specifications</u>
Manufacturer - C&D Batteries
Part Number - 2CB-41
Ampere Hour Capacity - 1500 Ah at 8-Hour Rate
Nominal Voltage - 2 V/Cell
Weight - 309 Pounds/Cell
Dimensions - 34.69 x 10.50 x 19.75
Electrolyte Specific Gravity (25°C) - 1.250
Number of Positive Plates - 20
Number of Negative Plates - 21
Plate Thickness - 0.266 Inch
Alloying Agents - Calcium (Negative Grid)
- Antimony (Positive Grid)
Cycle Life - 1900 Cycles at 75% DOD (to 80% Capacity Rating)

relays rated at 30A, 240 VAC. The LDC has manual override capability that can be used to bypass automatic control by the SCC.

Details of the individual load characteristics are shown in Figures III-11 and III-12.

1. Inverters

The 7.5 kVA inverter is a Nova model 7.5K60-240. The 30 kVA inverter is composed of three Nova model 10K60-240 inverters with inputs and outputs paralleled. Both inverters are similar in design, features and specifications. Detailed inverter specifications. Detailed inverter specifications are listed in Table III-8.

Operating Description - The inverter circuit consists of a phase control, a voltage regulator, a current regulator, a current limiter and a power inverter. The phase control keeps the 7.5 kVA inverter operating in phase with the utility line as long as utility voltage is present. In the absence of utility voltage, the inverter will operate on its own oscillator at 60, +0, -1%. When line voltage returns the inverter frequency will increase approximately 1% until the inverter locks in phase with the line. This slow return to phase prevents any sharp voltage or phase change due to ac line voltage problems. The phase control circuit becomes operational before the inverter provides power so that no problem is encountered in switching to the inverter source. The 30 kVA inverter is phase locked to the 7.5 kVA inverter as long as the 7.5 kVA inverter output is present.

Figure III-11 Spring/Summer/Fall Day-Night Load Profile

Figure III-12 Winter Day-Night Load Profile

Table III-8 Detailed Inverter Specifications
(7.5 kVA and 50 kVA Units)

Manufacturer - Nova Electric Manufacturing Co.	
Model - 7.5k60-240(7.5kVA) and 10k60-240(10kVA, 3 Each)	
<u>Features</u>	
a)	Reverse Input Polarity Protection
b)	Input Circuit Breaker
c)	Output Current Limiting
d)	Input Under-Voltage Protection
e)	Input Over-Voltage Protection
f)	Thermal Protection
g)	Panel Mounted Current and Voltage Meters
h)	"Power-On" Pilot Light
i)	Phase Lock
<u>Specifications</u>	
a)	Efficiency - 90% Minimum Over the Load Range of 40 - 100% of Rated
b)	Power Rating - Continuous Rating for a Power Factor (P.F.) Range of 0.7 Lag to 0.7 Lead
c)	Input Voltage Range - 200 to 280 VDC
d)	Output Voltage - 120/240 VAC, 60 Hz
e)	Voltage Regulation - $\pm 1\%$ No Load to Full Load
f)	Frequency Regulation - $\pm 1\%$ No Load to Full Load
g)	Overload Rating -
	125% of Rated - Continuous
	150% of Rated - 15 Minutes
h)	Input Under-Voltage Threshold - 190 ± 5 VDC
i)	Input Over-Voltage Threshold - 290 ± 5 VDC
j)	Recovery Time - 50 msec for 100% Load Change
k)	Total Harmonic Dist. - 5% Max
l)	Operating Temp Range - 0°C to 50°C

In the absence of an output from the 7.5 kVA inverter the 30 kVA inverter will run on it's own oscillator at 60 Hz, ± 0 , $\pm 1\%$. When the 7.5 kVA output returns, the 30 kVA inverter frequency will slowly increase until it locks in phase with the 7.5 kVA output.

A conduction control circuit provides gate signals to the SCRs in the power inverter and provides the means of obtaining pulse-width modulation from that circuit. This circuit produces four square wave signals at the operating frequency. The signals are produced in two pairs, each pair composed of two signals 180 degrees out of phase. The phase relationship between the signal pairs is varied by the voltage and current regulations and the current limit circuit. This circuit is arranged so that the voltage control circuit normally controls the phase relationship and therefore the output voltage. If the load calls for a current higher than rated, the current control circuit overrides the voltage circuit and controls the phase relationship of the gate signals. The current regulating circuit is relatively slow in response as it is intended as a thermal protection. The current limit circuit has a fast response and overrides both the voltage and current regulators to protect the inverter from heavy overloads, including short circuits.

The voltage regulator circuit rectifies and filters the ac inverter output and compares a portion of this voltage to a reference zener. Any difference between the sample voltage and the zener is amplified by an integrated circuit and fed to the conduction control circuit causing the inverter to correct the difference.

The filter section of the sample voltage normally provides a time constant to the voltage regulating amplifier. This timing is of 2 to 2-1/2 cycles. Time constants of this order of magnitude are required to obtain stable operation under high regulation conditions. The time constants in the proposed regulating system are bypassed with diodes so that voltage deviations greater than 5% are fed to the amplifier with practically no delay. This system provides a dual-time constant response circuit. One that responds fast for large deviations in output voltage and slow with extremely stable response for normal operation. This combination keeps the output voltage well within transient and normal operating specifications.

The current regulation circuit operates in a similar way. It samples the dc input current to the inverter and when this average current becomes too high it provides a signal to the conduction control circuit to retard the conduction period.

The current limit uses the same dc current sample without filtering. The fast action of this circuit allows the inverter to continue to operate into a complete short circuit.

All three of these control circuits provide signals to the conduction control. A simple diode circuit allows any one of these circuits to limit the conducting period of the SCRs and therefore provide regulated ac output with a maximum of reliability. Fuses or circuit breakers will not open even under short circuit conditions.

Each inverter incorporates an automatic transfer switch to provide for automatic transfer of loads from the inverters to the utility when a control signal from the SCC is received, indicating battery state-of-charge is below 25%. Loads will remain on the utility line until another signal is received indicating that the battery state-of-charge is 50% or greater. When that signal is received the loads are returned to the inverter. The automatic transfer switch also transfers loads to the utility grid when the inverter input voltage or output voltage drops below prescribed limits. The automatic transfer switches are electromechanical relay contactors driven by solid-state control circuits. The inverter is shown in Figure III-13.

Figure III-13 Invertor, Nova Taurus Series

2. Inverter Transient Capability

The 7.5 kVA inverter is current limited to 150% of full load current. The inverter is sized to insure that the well pump motor will be able to start even with other loads at maximum. The vent fan runs continuously and therefore need not start simultaneously with the well pump. The appropriate maximum currents are shown below.

Load	Steady State Pwr.	Equiv. Current @ 240V	Equiv. Inrush Current @ 240V
UV Filter	0.3 kW	1.25A	
B&I Bldg.	1.0	4.15	
Vent Fan	1.7	7.10	
Well Pump	1.84		18.0

Summing steady state currents for UV filter, battery and instrumentation room, and vent fan with the start currents for the well pump yields 30.5 amps while the inverter transient current capability is 46.88 amperes. A comfortable margin therefore exists. In addition, excessive inrush current at inverter turn-on is precluded by the inverter four second turn-on ramp. To further guarantee no turn-on inrush problem, the well pump will be turned

on manually after the inverter and ventilation fans are on.

To prevent transient 30 kVA inverter overload at inverter turn-on each morning, special turn-on sequencing is incorporated. The Load Demand Controllers ability to add or remove loads based on a control signal will be used to remove controlled loads during inverter start up. The LDC control will be set to zero which allows a maximum of only 3 kVA controlled loads. These are the only loads at inverter turn-on. A few minutes after inverter start up the arrays will be brought up. Therefore the following loads apply during inverter turn-on:

Lights (A)	6.7	amps	
REceptacles (A)	2.1		(One-Half Maximum Loading)
Water Pump	135.0		(Peak Inrush Maximum)
Water Heater	8.3		
Receptacles (B)	2.1		(One-Half Maximum Loading)
	<u>156.2</u>	amps	

The inverter capability is 187.5 amperes. Therefore adequate start-up margin exists. The margin is further enhanced by the 4-second ramp start-up characteristics of the inverter that will greatly reduce the maximum peak inrush.

The water pump is a hydro constant type which runs continuously throughout the day and therefore only its maximum run current need be considered in analyzing the peak currents that can occur during normal daytime cycling of the PCA motors and air conditioner motors. The worst case condition includes simultaneous start-up of one-fourth of the PCA field along with air conditioner strat-up. This could occur with all other steady state loads on. The table below demonstrates sufficient margin for this worst case motor start-up condition:

PCA	26.8	amp	(3/4 of Field On, 1/4 of Field Turning On)
Lights (A)	6.65		
Receptacles (A)	1.04		(One-Half Maximum Loading)
Water Pump	22.00		(Full Load Run Current)
Water Heater	8.3		
Receptacles (B)	2.1		(One-Half Maximum Loading)
Lights (B)	16.25		
Vent Fans (2)	14.2		
Air Cond.	62.5		(Peak Inrush Maximum)
Lights (C)	14.5		
Golf Cart	0.85		
Battery Chg.			
	<u>175.19</u>	amps	

The inverter capability of 187.5 amperes is greater than the worst case combination of steady state and transient loads shown above.

The water pump current shown above is taken for maximum load. The minimum run current will be approximately 8.0 amps. On a 24 hour basis, the water pump only runs the equivalent of 2 hours at 22 amperes, therefore the average current will be much closer to the 8 ampere minimum than to the 22 ampere maximum.

3. Load Demand Controller

The load demand controller is a production stock unit manufactured by DenCor, Inc. It is designed specifically for applications where utility bills can be reduced by avoiding peak "demand" charges. In a typical household, application the LDC sheds low-priority loads such as basement heaters or accessory appliances when high-priority, high-demand loads are present. The demand set point is controlled by the homeowner with a potentiometer adjustment.

For the Roxborough application, a standard unit will be modified to replace the demand limit potentiometer adjustment with an analog input voltage signal. This voltage signal is generated in the SCC and is based on available photovoltaic energy, battery state-of-charge, and shunt regulator dissipation. Details of the control methodology are described in Section III-F.

Detailed specifications for the LDC are listed in Table III-9. The unit is shown in Figure III-14.

*Table III-9 Load Demand Controller
Specifications*

Manufacturer: Dencor, Inc.
Model - 720-1ASD, Power Master Demand Controller
<u>Outputs</u>
Qty - 8 DPS7 Relays
Rating - 30A, 240 VAC
Load Capacity - 7,200 W Per Output
<u>Input</u> - 120/240 VAC, $\pm 10\%$, 60 Hz
<u>Power Consumption</u> - 40 W
<u>Demand Control</u>
Load Control Range - 3 to 30 kW
Sensitivity - 200 W
Input Voltage Control Range - 0.5 to 6.0 V
<u>Mechanical</u>
Mounting - Indoor, Wall Mount
Dimensions - 21 in. x 14.25 in. x 4 in.
Current Transformers - Will Fit 4/0 Cable, 200 A Service

Figure III-14 Load Demand Controller

D. STATE-OF-CHARGE MONITOR

Both the Load Demand Controller and the Analog Shunt Regulator are controlled by battery state-of-charge (SOC) through the System Control Center. The battery SOC is measured by an SOC monitor manufactured by Curtis Instrument, Inc. (P/N 966-SFR). Detailed specifications for this instrument are listed in Table III-10. The unit is a single standard instrument factory installed in a standard 19 in. rack panel 8.72 in. high.

The SOC monitor is basically an analog bipolar dc integrator which integrates low level (0 to ± 100 millivolts) signals with respect to time. The charge and discharge integrals are independently programmable for any integral between 5 millivolt-hours and 40,000 millivolt-hours, full scale. The net integral is displayed on a 4 1/2 in. panel meter and is simultaneously presented as a 0.33 to 5.00 VDC analog output signal. Three isolated single pole, single throw control relays are provided for auxiliary control and alarm functions and are used by the SCC. Three LED indicators continuously display each control relay's status. All outputs are maintained in a nonvolatile memory

Table III-10 State-of-Charge Monitor Specifications

Manufacturer: Curtis Instruments, Inc.

Part Number: 966-SFR with 1127 Option (Isolated Power Supply)

Electrical

Power - Voltage: 100 to 130 VAC, 48 to 62 Hz

Current: 20 mA rms

Input Signal - Amplitude: 0 to 100 mV, Overrange to 120 mV

Unidirectional Frequency Response: dc to 100 kHz = 1% Error

Bidirectional Frequency Response: 50 mV/6 Second = 3% Error

Input Impedance - 2000 Ω dc, 1000 Ω ac

Output Signal - Linear Voltage Ramp Analagous to Net Integral

- 0% Capacity = 0.33 Vdc

- 100% Capacity = 5.00 Vdc

- Linearity = + 1% Full Scale

- Accuracy = + 2% Full Scale

- Drive Capability = 1.0 mA Maximum

Output Display - 4½ Inch Panel Meter

- Graduations = 0% to 100% Capacity, 50 Division Scale

- Linearity: + 2% Full Scale

- Accuracy: + 3% Full Scale

Control Delays - Three SPS7 Adjustable Reed Relays

- Contract Rating: 200V, 0.5A, 10W Each

- Control A Closes Above Its Preset Level

- Control B and C Close Below Their Preset Levels

- Independent Adjustments

- Adjustment Range: 5% to 95% Capacity

- Anti Chatter Hysteresis: 2% Full Scale

LED Status Indications - Three LEDs, One for Each Relay

- LED "On" Signifies Closed Contact

Memory - Non-Volatile, All Outputs Resume Previous State after Power Restoration

Integral Range - 5 mV Hours Full Scale to 40,000 mV-Hour Full Scale

- Charge and Discharge Integrals Independently Adjustable

Asymmetry - Inherently Programmable

Suppression - Integration Can Be Suppressed Below 1 mV

during periods of power outage. A switch selected integration suppressor can be used to prevent long term drift during quiescent intervals.

Charge and discharge integrals are independently established by selecting appropriate charge and discharge constants with jumpers and adjusting the appropriate charge and discharge multipliers with potentiometers. The fullscale charge and discharge integrals (in millivolt-hours) are equal to the product of the selected constants and the adjusted multipliers. Asymmetry adjustment is inherent in the integral calibration procedure and can be used to set desired coulometric overcharge limits.

A toggle switch is provided to control integration on set levels for both charge and discharge input signals. In the OFF position there is no suppression, while in the ON position, signals below 1.0 mV are ignored. This feature can be used to minimize drift during extended quiescent periods. The integrators can be quickly positioned at any percent capacity by actuating a charge/discharge switch. The three control relays can be adjusted to any threshold level between 5% and 95% capacity with their individual potentiometers. The mechanical layout and dimensions of the SOC monitor are shown in Figure III-15.

E. ANALOG SHUNT REGULATOR

The analog shunt regulator (ASR) was one of the key development items for the Roxborough Park system. It performs three functions:

- 1) Limit maximum dc bus voltage to prevent inverter over voltage.
- 2) Provide battery charge control.
- 3) Provide status signals for the SCC which are used in switching arrays on or off-line.

A functional schematic of the ASR is shown in Figure III-16. Temperature compensated voltage regulation is provided by a temperature sensor located in the battery room. The temperature sensor is compensated reference voltage for ASR regulation control. Temperature compensation is not commonly used for lead acid battery charge control, but it is incorporated in the Roxborough design to minimize battery overcharge. In this way, battery gassing and heating are minimized, battery stress is reduced.

Figure III-15 State-of-Charge Monitor

Figure III-16 Analog Shunt Regulator Functional Schematic

Two-limit charge control is provided by the V_{HC}/V_{FC} signal that controls bus voltage at either a high value corresponding to a high charge rate, or a low value corresponding to float charge. ASR regulation characteristics are shown in Figure III-17. The upper end of the regulation range is clamped at 277V and a temperature compensated slope of $-0.55 \text{ V}/^{\circ}\text{C}$ relates to temperatures above 10°C .

The ASR provides three digital output signals, (ASRH, ASRL, and OLH) that are used by the SCC to either off-load arrays or bring additional arrays on line. The significance of these signals is interpreted as follows:

ASRH - The ASR shunt current is close to maximum and an array string should be switched off-line to lower ASR current.

ASRL - The ASR shunt current is close to minimum and an array string should be brought on-line to increase ASR current.

OLH (Out-of-Limit-High) - The ASR has saturated (i.e., overloaded) and array strings should be rapidly off-loaded.

Figure III-17 Nominal ASR Regulation Characteristics

Power for the ASR cooling fans is provided by 120 VAC, 60 Hz power. The ASR contains eight parallel fail-safe protection, a thermal switch is mounted on each power stage to disconnect it if the heat sink temperature rises above limit. Shutdown of a single power stage in this manner will not disable the complete ASR, but will only reduce its power handling capability by one-eighth.

A second thermal switch is used to sense low heat-sink temperatures and disconnect the fans when the ASR is off or operating at very low load. The standby ASR power requirements are thereby reduced to a minimum.

Detailed shunt regulator specifications are listed in Table III-11. During phase I, the control circuitry was designed and verified by breadboard test. One of the eight power stages was also designed, fabricated, and verified by test. The power stage is shown in Figure III-18. In the complete assembly, the eight power stages are installed in four drawers in a standard rack for easy access.

Table III-11 Analog Shunt Regulator
Specifications

Regulation at 25°C

High Charge Mode - 269.5 V + 0.5%

Float Charge Mode - 258.5 V + 0.5%

Temperature Coefficient - $-0.55 \text{ V/}^{\circ}\text{C} \pm 2\%$

Maximum Clamp Voltage - 277 V $\pm 1\%$

Shunt Current Range

ASR on - 27 A Minimum

ASR off - 10 mA Maximum

V_{Hc}/V_{Fc} Control Signal Input

"High" (Indicates High Charge) - 5 to 15 V

"Low" (Indicates Float Charge) - 5 Microamperes Maximum

Load Impedance - 5 Kilohm Minimum

Output Signals

ASRH - High Level Indicates ASR Shunt Current Greater Than 25 A

ASRL - High Level Indicates ASR Shunt Current Less Than 1 A

OLH - Low Indicates dc Bus Voltage 2% Greater Than Regulation Voltage

Signal Levels - High: 8 to 15 V

Low: 15 Microamperes Maximum

Power

Input - 120 VAC + 10%, 60 Hz

Fan Current - 4.0 A

Fan Power - 500 W

Circuit Current - 0.8 A

Circuit Power - 10 W

Mechanical

Dimensions - 63 3/8 in. x 21 1/16 in. x 22 in. (Standard 19 in. Relay Rack)

Fan Mounting - Front

Figure III-18 Analog Shunt Regulator Power Stage

F. SYSTEM CONTROL CENTER (SCC)

The system control center (SCC) provides all system control functions in one centralized location. Development of the SCC was a major development task. It interacts with all major system components, monitoring their status and issuing appropriate control signals. The major objectives of the SCC development were to achieve highly automated system control for unattended operation, yet provide a simple manual interface capable of operation by relatively unskilled personnel for maintenance, repair, or demonstration.

The integration of the SCC into the power system is shown in Figure III-19. The SCC performs the following functions; Array control, battery charge control, inverter control, and load demand controller control. These are discussed separately below.

Figure III-19 SCC Interface

1. Array Control

The SCC controls array synthetic tracking. It also receives wind/precipitation signals from a field weather station and issues array stow commands based on these signals.

Array electrical mode is determined by status signals from the ASR which indicates that the ASR is near saturation or cut-off limits. The SCC commands arrays to switch on or off, as appropriate, when these commands are received.

Several features of the array control methodology bear special mention. Only two field control lines are required; an Enable line and a Data line. These two lines are daisy-chained between all arrays in the field and work in conjunction with the 170 VAC power line which also serves as a "clock" for digital transmission. System timing is shown in Figure III-20. A given command word is 30 bits long and consists of three 8-bit bytes and one 6-bit byte. The first byte shown in Figure III-20, SRA, is the array shunt regulator address. All arrays with addresses below or equal to SRA are switched off. The second byte, ACA, is the array command address. This is the address of the particular array that is to respond to the array command, ACMD.

Figure III-20 PCA Command Word Timing

The array command contains all the required commands for array motion control. The 8-bits constituting ACMD are individually identified in Table III-12. The last byte in the command word, SYNTR is used for synthetic tracking. It contains timing information corresponding to certain diurnal angular positions to which the arrays should have travelled when the command is received. These signals are identified in Figure III-21. For purposes of illustration consider the θ_3 bit. When it goes high at 11:00 am, all arrays should have rotated in azimuth to at least 60° . If they have not travelled this far (e.g., due to cloud cover that inactivated the automatic tracking function) they will do so when the θ_3 command bit is received. Each array "knows" its own azimuth position by means of a potentiometer attached to the azimuth drive.

The complete array command word shown in Figure III-20 contains 30 bits clocked at a 60 Hz rate. The command thus takes 0.5 second to transmit, and it is updated and retransmitted once every second. The data is automatically transferred out of the SCC registers and into all array input registers starting when the enable line goes high and ending when the enable line goes low. When the enable line is low, the data is "latched" in the array holding registers and does not respond to changes in the data line signal. During the 0.5 second interval, the enable line is low, the SCC updates the data word according to its prescribed control methodology, and applicable system status signals.

Table III-12 PCA Command List (ACMD)

Command Bit	Nomenclature	Description
C ₇	Stow	When Low, Array Stows
C ₆	All/Single	Indicates Whether All Arrays to Respond or Single Array Corresponding to Array Command Address (ACA)
C ₅	Up	Elevation and Azimuth Motor Commands 00 - Auto Track 01 } Respond As Indicated 10 } 11 - Stop
C ₄	Down	
C ₃	E	
C ₂	W	
C ₁	SR On	
C ₀	Not Used

Figure III-21 SYNTR Format and PCA Response

2. Battery Charge Control

The SCC controls battery high-charge and float-charge limits by a charge control command to the analog shunt regulator which controls the ASR clamp voltage. The charge control command is based on battery charge current. When battery current falls below SA the ASR is switched to the float-charge limit. When battery charge current is above SA high charge is selected.

3. Inverter Control

The SCC controls utility transfer for both inverters and provide on/off control for the 30 kVA inverter. Transfer to IREA is made when battery SOC falls below 25%. Transfer back to photovoltaic system power occurs when battery SOC recovers to 50%.

The 30 kVA inverter is shutdown at night under control of the SCC timer circuits.

4. Load Demand Controller Limit Set

The SCC provides a demand limit signal to the LDC corresponding to available system energy. There are two basic modes of operation; one when the ASR is on indicating "excess" available solar energy, and a second when the ASR is off indicating an energy limited condition (i.e., all available solar energy can be used to charge the battery - a high priority consideration). When the ASR is off, the SCC provides and LDC demand limit signal proportional to battery state-of-charge, the demand limit signal varying from 0 at 50% SOC to maximum at 90% SOC. This control strategy is based on gradually shifting priority from the batteries to the loads as the battery charges. The second mode of operation occurs when the ASR is on. Under these conditions it is necessary to establish a demand limit corresponding to available power. This is accomplished by synthesizing a demand limit signal described by

$$I_{LDC} = I_{DSR} + I_{SA} - I_B - I_{LU}$$

Where I_{LDC} represents the demand limit setting, I_{SA} the solar array field current, I_{DSR} the available solar array current represented by arrays which may be switched off, I_B the battery current, and I_{LU} the current drawn by the uncontrolled loads.

5. SCC Development Status

The SCC was breadboarded during Phase I and subjected to extensive test and evaluation. The SCC breadboard is shown in Figure

III-22. As can be seen from the photograph, the SCC console design is exceptionally simple in view of the amount of functions it provides, and it can be readily mastered by unskilled personnel.

Figure III-22 SCC Console Breadboard

IV. ARRAY INSTALLATION PLAN

The array field is the dominant feature of the Roxborough Park photovoltaic system with respect to environmental factors. Deployment of 36 individual arrays on the land surface is a basic design requirement of the concept. This requirement creates the only significant environmental intrusion associated with the system: that of land preemption. The sensitive nature of the system in the Roxborough Park application derives not from environmental considerations alone, but also from the natural theme of the park as an urban wilderness. A baseline requirement for the system design stipulated that site disturbance be minimal, and that all design procedures and site activity be thoroughly reviewed to comply with this requirement throughout phase I.

During phase I, a number of system configurations were considered and reviewed. The intent of the overall design concept is not to hide or camouflage the photovoltaic system, but to introduce it quietly into the visitor experience.

A. SITE ACTIVITY

The selected array field site (see Fig. IV-1) was the best choice to accommodate sun patterns, construction access, and visitor sight line relationships. The selected site is relatively close (approximately 800 ft) to the visitor's center, and it has a relatively elevated position with respect to adjacent terrain. Hence, morning and afternoon shading by the foothills are much less than for alternative locations. An old "field" road, intended to be used for access during construction, also runs close to the site. The site is hidden from view from most areas of the park so the arrays do not become a burden as an ever-present visual element. Interested observers can, however, walk up mildly sloping paths to view the arrays at two proposed overlooks.

The rock outcrops in the vicinity of the array site are composed of the Fountain formation to the west and the Lyons sandstone and Lykkens formation on the east. These bedrock formations have a fairly steep dip to the east. In the area of the array, the bedrock has been measured dipping 50 degrees to the east. The contact between the underlying Lyons formation and the overlying Lykkens formation occurs on the east side of the site. On the surface, a buried valley separates the resistant Lyons sandstone from the resistant Fountain outcrops on the west. The depth of

this valley is not known, but test holes drilled during phase I penetrated 30 ft without encountering bedrock on the west side.

Subsoil conditions at the array site were investigated by drilling five test holes at the locations shown on Figure IV-2. Drilling results indicated erratic conditions as depicted on the graphic logs of the exploratory holes (Fig. IV-3). The subsoils are erratic over the array site both in type of bedrock and depth of the overburden soils. On the east side of the site, bedrock was within 3 ft of the ground surface and consisted of hard to very hard, moderately to well cemented claystone, siltstone, and sandstone. The sandstone represents the Lyons formation, whereas the siltstone and sandstone are members of the lower Lykkens formation.

Figure IV-2 Location of Exploratory Holes

Figure IV-3 Logs of Exploratory Holes

On the west side of the site, the clay overburden soil extends to depths of over 30 ft. The shallow overburden clay soils are similar to the deeper ones found on the west. These soils show low swell potential and moderately high consolidation characteristics under loading and wetting. They are of medium plasticity and contain a relatively high percentage of fines. They have moderate to low densities and have probably been fairly rapidly deposited and compacted only by desiccation. Unconfined compressive strengths are fairly high in the natural moisture condition. If the moisture contents increase, these soils can be expected to weaken. Figure IV-2 shows an estimate of where overburden soils may be more than 10 ft deep.

1. Site Care, Access, and Drainage

Construction activity is planned to be limited to the array site and access route, and will follow an existing "field" road. Only minimal grading and clearing will be necessary. One 100-ft long section for vehicle turn-around (Fig. IV-4) may be graded down for construction access due to the slope steepness.

Figure IV-4 Array Installation Access

A small part of the site area will need to be cleared of native scrub oak. This area will be taped during construction and removal of the scrub oak will be limited to these areas. After construction, the cleared area and all areas disturbed by trenching or other construction activity will be graded and seeded.

The maximum elevation difference across the site is 80 ft. The slope averages 9% down to the northwest. Drainage is mostly by sheet flow with the defined drainages located off-site. During construction, it will be necessary to avoid excessive wetting or drying of the foundation excavations. Backfill around the foundations need to be moistened and compacted to at least 85% standard Proctor density, and the ground surface immediately surrounding the foundations must be sloped to drain in all directions away from the foundations.

2. Foundation

The individual array pier foundations need to be tailored to each installation location with respect to depth below ground and height as determined by site slope (nominally 9.0%). The arrays need to be mounted high enough to clear the ground during their diurnal tracking of the sun.

Several parameters are needed to calculate lateral support in a pier or spread footing foundation. For Roxborough, these values were taken from typical values of the soils and bedrock encountered rather than from direct measurements. Table IV-1 lists the typical design values used for Roxborough.

Table IV-1 Array Site Soil Parameters

Parameter	Clay Soil	Bedrock
Modulus of Horizontal Subgrade Reaction K_s ^{1/}	75 tcf	300 tcf
Passive Earth Pressure Coefficient K_p	2.5	5.0
Active Earth Pressure Coefficient K_a	0.45	0.20
Angle of Internal Friction ϕ ^{2/}	15°	35°
Angle of Friction Soil to Concrete α	20°	30°
Consistency	Cohesive	Cohesive
Unit Weight (Dry)	100 pcf	125 pcf
Note ^{1/} Terzaghi values for one foot square plate.		
^{2/} Unconsolidated, undrained shear strength.		

The array foundations are small enough in diameter and length to use a track-mounted drill rig with an open helix auger, which has a knife cutting edge. A truck follows the drill rig to remove the excavated material from the site. Premanufactured reinforcing cages attached to anchor bolt assemblies are then brought in and a concrete mixer mixes and pours the concrete. To prevent concrete separation while it is being poured, the mixer will have an elephant trunk type of funnel. Other than the field distribution terminal (Fig. IV-5), a wind/percipientation detector station (Fig. IV-6), and the DOE-furnished meteorological station, in other photovoltaic system installations are required in the field.

Exploratory test holes drilled during phase I indicate overburden depths ranging from 3 ft on the east side of the site to 30 ft on the west side. Since the vertical load on the array foundation is relatively light, the most critical requirement is for lateral support. The bedrock, provides excellent lateral support for the straight shaft caisson foundations and the overburden soils provide moderate to good support.

Drill -002
for 3/4 I.D. Pipe

Spot Weld
(PLCS) Typ

Figure IV-5 Field Distribution Terminal

Figure IV-6 Wind/Precipitation Detector Station

3. Trenching

All field cable distribution is planned to be underground. The trenching requirements are identified in Figure IV-7. In addition to power and signal cabling, the field has a counterpoise system for lightning protection. The counterpoise consists of a ground grid throughout the complete field. A number 2/0 bare copper cable is used in the counterpoise around the field periphery, and a number 2 bare copper cable is used in the internal grid. All trenches are 6 in. wide and from 24 to 30 in. deep depending on cable current carrying requirements. The cables are buried in sand and the trench backfilled with the excavated material.

4. Array Installation

The 36 arrays, which are completely assembled off-site, will be brought to the site location by a tractor-trailer. Four arrays can be transported at a time (see Fig. IV-8). At the site, the fully assembled arrays will be removed from the support cradle by a 15-ton, rough-terrain crane and installed on the foundations. To complete installation, the individual arrays are fastened to the pedestal foundation with six nuts and electrical connections made, consisting of a three-wire twisted signal line, 170 Vac motor power, dc output power, one ground strap, and instrumentation wires for ODAS. Nine trips with the tractor-trailer are required to transport all arrays.

Figure IV-7 Field Trenching

Figure IV-8 Loading Provisions for Tractor-Trailer

5. Restoration

After foundation excavation, trenching, cabling, and array installation is complete, the disturbed areas will be seeded with native grass. The residual spoil from the foundation holes not used for back filling will be disposed of outside the park. Except for construction access and interface paths, landscaping will be limited to natural restoration of the site.

6. Maintenance

The primary maintenance effort will be cleaning the Fresnel lenses. The cleaning will be done with a spray tank mounted on a jeep.

B. ENVIRONMENTAL IMPACT

The impact of the photovoltaic arrays on the topography, flora, fauna, site materials, and site microclimate were evaluated and are described in detail below.

1. Topographic Modifications

Construction modifications affecting the pre-existing topography of the array field include access road improvement, grading at the vehicle turn-around area, array foundation excavation, trenching for cabling, visitor path and overlook landscaping, clearing of a moderate amount of scrub oak, and installation of a perimeter fence. These modifications will contribute to changes on the ground surface. To minimize their effect, the total disrupted area has been held to a minimum. The caisson-type array foundations require minimum site disturbance and the slope of the site provides natural drainage without additional grading. The decision to use a spray tank mounted on a jeep for lens cleaning in lieu of larger vehicles eliminates the need for extensive road paving.

Experience in rough terrain installation of structures similar to the photovoltaic concentrator arrays has been obtained on previous heliostat programs at the Martin Marietta facility in terrain identical to the Roxborough Park site. Five heliostats were installed in 1976 (Figs. IV-9 and IV-10) and there is presently little evidence of site disturbance. Implementation of the additional construction controls at Roxborough (e.g., removal of excess excavated material and seeding) are expected to return the park site to an almost completely natural condition within one year.

2. Array Shading

The microclimate of the array site will be slightly modified due to shading of the ground surface by the arrays. This could result in minor changes to local flora and fauna. Species not normally indigenous to the area may be attracted to the cooler shaded area, and species favoring direct insolation may be discouraged. However, the affected area is small (the array packing factor is only 0.093), and the array shadow patterns are not fixed, but move continuously as the arrays track the sun.

The total thermal energy intercepted by the arrays (748-kW peak at 1.0-kW/m² insolation) is partially converted to electricity (approximately 67-kW). Approximately 90% of the heat flux intercepted by the arrays is returned to the local atmosphere through the finned array heat exchangers.

Figure IV-9 Rough Terrain Heliostat Installation

Figure IV-10 Completed Heliostat Installation

3. Lens Washing

Periodic lens washing will contribute to total water input to the ground surface. It is anticipated that washing will be necessary every four to six weeks. The water quality of the area will be preserved by using demineralized water without chemical cleaning agents. If cleaned monthly, the total water used for lens cleaning will be approximately 6171 liters (1620 gal) per month. This corresponds to an average of 0.054 cm (0.021 in.) of rainwater over the site area. The additional water contribution due to lens cleaning is considered negligible with respect to modifying the site biology.

Of more significance to the environment is the washer vehicle itself. It will be either a jeep or a 4-wheel drive pickup truck equipped with low ground pressure tires to minimize damage to vegetation. The vehicle will be operating on the site on the site for approximately 4 hr per month not counting trips for water refill. Lens cleaning times will be restricted to early morning and late afternoon hours and only when the site is dry.

4. Array Desteering Operation

Environmental effects during array stowing or unstowing operations are negligible. The array design is such that the concentrated light is completely contained behind lenses and within the array module. No spurious reflections are produced to cause either personnel or fire hazards or objectionable distractions.

5. Accident Potential

The nature of the array design is inherently safe with respect to a number of systems. The concentrated light is completely enclosed behind the lenses in the array modules and is not a hazard to personnel, flying fauna, or ground fauna. The possibility of igniting debris blowing through the concentrated light beam is also precluded.

The cooling system for the solar cells is entirely passive and, therefore, free from potential accidents involving failure of hot water piping. The maximum surface temperatures on the exposed array heat exchanger will be less than 85°C. This will not be a hazard to any personnel or fauna that might touch the heat exchanger surface.

Electrical shock is the major area of accident potential. The arrays are powered from 120 Vac, 60 Hz power and provide up to 300 Vdc solar derived output power. All electrical terminals are contained in fastened enclosures to prevent accidental contact by personnel or fauna. Additional precautions to prevent personal shock include restricted access to authorized personnel or groups guided by authorized personnel; permanently located warning signs; a perimeter fence separating park visitors from the array field; and specific procedures for maintenance personnel.

V. PHASE III PLAN

During Phase I, a plan was developed to define the hard (transducer) and soft (manually collected) data requirements for the Roxborough Park power system and the methods for acquisition of these data. The data requirements for the hard data, method of acquisition (transducer type) selected, and the hardware requirements for data acquisition system, were defined.

A. TECHNICAL PLAN

Data requirements for the On-site Data Acquisition System (ODAS) were selected to satisfy DOE Uniform Data Collection Requirements and to supplement those requirements with necessary system peculiar measurements.

Hard Data Requirements - Table V-1 defines DOE data requirements and the measurements which satisfy the requirements at the Roxborough installation. All of the applicable data are obtained by the ODAS using direct measurements or transducers integrated in the power system. The photovoltaic arrays for this power system are passively cooled and therefore no measurements are required for thermal systems. The location of equipment in the facility makes it practical to use the same ac voltage and current measurements for both the power conditioning data group and the electrical load characterization data group requirements. Provision has been made for a DOE supplied meteorological station. Additional transducer data required to better define the Roxborough Park power system performance and design are listed in Table V-2. These data will define the ASR, the approximate battery state-of-charge, the control level of the Load Demand Controller (LDC), the battery room temperature, and the PCA digital command word.

Table V-1 Transducer Data. DOE Uniform Data
Collection Requirements

I. Array Field or Subfield	
<u>Data Item</u>	<u>Measured Parameter</u>
1. Array Subfield Voltage	PCA Voltage
2. Array Subfield Current	PCAN Current
3. Array Field Voltage	PCA Field Voltage
4. Array Field Current	PCA Field Current
5. Array Field Energy	PCA Field WH
II. Power Conditioning	
<u>Data Item</u>	<u>Measured Parameter</u>
1. Inverter Input Voltage	DC Bus Voltage
2. Inverter Input Current	Inverter Current (ea)
3. Inverter Output Voltage	Inverter Voltage (2 ea)
4. Inverter Output Current	Inverter Current (2 ea)
5. Inverter Output Power	Inverter Power Out (ea)
III. Meteorological Data	
<u>Data Item</u>	<u>Measured Parameter</u>
1. Direct Normal Radiation	DOE Provided System
2. Total Horizontal Radiation	
3. Reference Solar Cell (Short Ci Circuit Current)	
4. Wind Speed/Direction	
5. Barometric Pressure	
6. Ambient Air Temperature	
7. Humidity or Dew Point	
8. Precipitation	
IV. Array Thermal Properties	
<u>Data Item</u>	<u>Measured Parameter</u>
1. Passively Cooled Systems	
1. Cell Operating Tempera- ture	PCA Temperature
2. Actively Cooled Systems	N/A
V. Battery Storage	
<u>Data Item</u>	<u>Measured Parameter</u>
1. Battery Voltage	Battery Voltage
2. Charge/Discharge Current	Battery Current
3. Battery Temperature	Battery Temperature
VI. Thermal System	
N/A	
VII. Electrical Load Characterization	
<u>Data Item</u>	<u>Measured Parameter</u>
1. Power Source	Inverter/Bus Indication
2. Load Voltage	Inverter Voltage
3. Load Current	Inverter Current Out
4. Load Power	Inverter Power Out
5. Load Energy	Inverter WH Out
VIII. Miscellaneous	
<u>Data Item</u>	<u>Measured Parameter</u>
1. Tracking or Desteer Mode	Command Word from SCC
2. PV Master System Switch (On or Off)	N/A
3. Date and Solar Time	ODAS

Table VII-2 Transducer
Data-Non DOE
Requirements

Measured Parameter
1. ASR Current
2. SOC Output
3. LDC Command
4. Battery Room Temp
5. PCA Command

Data Acquisition - The parameters required to be measured and the characteristics of the measurement are defined in Table V-3. To satisfy the uniform data requirements and the system peculiar requirements, 130 measurements have been identified. Ninety-one of these (including three meteorology) are monitored only during daylight hours. All others are monitored day and night.

The sampling and recording rates meet the uniform data requirements. The dc bus parameters are generally sampled twice per minute and recorded each ten minutes. The ac bus parameters are sampled once per minute and twice per hour. Other measurements are sampled at rates of once per second for the PCA Command Word (digital) to once per hour. These measurements are recorded when a change occurs for the command word or at times compatible with other data blocks.

Data Volume - The number of measurements to be recorded each hour varies from approximately 120 at night to 650 during the day. The resulting volume of data to record each day varies from 8200 measurements in December to 10,700 in June.

Data Retrieval - Roxborough Park is located at a remote area southwest of Denver. This facility will have ac power available, but will not have telephone service. Communication will be limited to business radio service. Therefore, the raw data must be collected from the site by changing the tape or disk and sending it off-site for processing.

Transducers - Transducers are provided in the power system for current, temperature, power, and energy measurements and are generally separated from those required for system control. Voltages are recorded directly by sensing leads tied to the desired measurement point. Table V-4 shows the measurements and associated transducers. Where direct measurements of voltages are made, current-limiting devices (fuses or resistors) are installed to protect the power system from an instrumentation system fault.

Table V-3 Measurement Quantities, Sample Rates & Ranges

Measurement	Quantity	Sample Rate	Record Rate	Range
<u>DC Bus</u>				
PCA Volts	36	2/min (D)	6/hr (D)	0-100 Vdc
PCAN Current	12	2/min (D)	6/hr (D)	0-10 Vdc
PCA Field Voltage	1	2/min (D)	6/hr (D)	0-300 Vdc
PCA Field Current	1	2/min (D)	6/hr (D)	0-10 Vdc
PCA Field Watts	1	2/min (D)	6/hr (D)	0-10 Vdc
PCA Field Watt-Hours	1	2/hr	Daily	0-10 Vdc
Battery Voltage	1	2/min	6/hr	0-300 Vdc
Battery Current	1	2/min	6/hr	0-300 MVdc
Bus Voltage	1	2/min	6/hr	0-300 Vdc
ASR Current	1	2/min (D)	6/hr (D)	0-200 MVdc
30 KVA Inverter Current	1	2/min	6/hr	0-200 MVdc
7.5 KVA Inverter Current	1	2/min	6/hr	0-200 MVdc
<u>AC Bus</u>				
30 KVA Inverter Voltage	2	1/min	2/hr	0-125 Vac
30 KVA Inverter Current	2	1/min	2/hr	0-10 Vdc
30 KVA Inverter Watts	1	1/min	2/hr	0-10 Vdc
30 KVA Inverter Watt-Hours	1	1/hr	Daily	0-10 Vdc
7.5 KVA Inverter Voltage	2	1/min	2/hr	0-125 Vac
7.5 KVA Inverter Current	2	1/min	2/hr	0-10 Vdc
7.5 KVA Inverter Watts	1	1/min	2/hr	0-10 Vdc
7.5 KVA Inverter Watt-Hours	1	1/hr	Daily	0-10 Vdc
<u>Temperatures</u>				
PCA	36	1/min (D)	2/hr (D)	0-10V
Battery	8	12/hr	1/hr	0-10V
Battery Room	1	12/hr	1/hr	0-10V
<u>Meteorology</u>				
Direct Normal Radiation	1	2/min (D)	6/hr (D)	TBD
Total Horizontal Radiation	1	2/min (D)	6/hr (D)	TBD
Reference Solar Cell	1	2/min (D)	6/hr (D)	TBD
Wind Speed	1	1/min	2/hr	TBD
Wind Direction	1	1/min	2/hr	TBD
Barometric Pressure	1	1/min	2/hr	TBD
Ambient Air Temperature	1	1/min	2/hr	TBD
Humidity	1	12/hr	1/hr	TBD
Precipitation	1	1/hr	1/hr	TBD
<u>Miscellaneous</u>				
SOC Output	1	6/hr	6/hr	0-5 Vdc
LDC Command	1	1/min	2/hr	0-5 Vdc
Utility/System Indication	2	2/min	6/hr & Chgs	0-10 Vdc
PCA Command Word	1	1/sec	Each Change	Digital
Date/Time	1	AR	Each Record	Digital

Table V-4 Transducer Requirements

Measurement	Transducer	Manufacturer
<u>dc Bus</u>		
PCA Volts	Direct	--
PCAN Current	CT50LT	Ohio Semitronics, Inc.
PCA Field Voltage	Direct	--
PCA Field Current	Shunt (SCC Rack)	
PCA Field Watts	WH7-38	Ohio Semitronics, Inc.
PCA Field Watt-Hours	(W&WH Outputs)	
Battery Voltage	Direct	--
Battery Current	Shunt (SCC Rack)	
ASR Current	8401-50	Janco
30 kVA Inverter	8401-50	Janco
7.5 kVA Inverter Current	8401-50	Janco
<u>ac Bus</u>		
30 kVA Inverter Voltage	Direct	--
30 kVA Inverter Current	CT200LT	Ohio Semitronics, Inc.
30 kVA Inverter Watts	WH3-70	Ohio Semitronics, Inc.
30 kVA Inverter Watt-Hours	(W&WH Outputs)	
7.5 kVA Inverter Voltage	Direct	--
7.5 kVA Inverter Current	CT50LT	Ohio Semitronics, Inc.
7.5 kVA Inverter Watts	WH3-23	Ohio Semitronics, Inc.
7.5 kVA Inverter Watt-Hours	(W&WH Outputs)	
<u>Temperatures</u>		
PCA	AD590J	Analog Devices, Inc.
Battery	AD590J	Analog Devices, Inc.
Battery Room	AD590J	Analog Devices, Inc.
<u>Meteorology</u>		
System	--	GFE
<u>Miscellaneous</u>		
SOC Output	Direct	--
LDC Command	Direct	--
Utility/System Indication	Direct	--
PCA Command Word	Serial/Parallel Converter (SCC Rack)	Martin Marietta
Date/Time	ODAS	GFE

ODAS System - During Phase I, the capabilities of two candidate systems were evaluated and the Hewlett-Packard 3052 data acquisition system was selected as the baseline system for the Roxborough design. This system, with appropriate options, is capable of fulfilling the data acquisition requirements for Roxborough Park and will meet the DOE defined requirements for data sampling and storage power failure protection, and on-site printer and display. Figure V-1 is a block diagram of the ODAS system defining the elements of the HP3052 required and the sources of each measurement.

HP3455A DVM - Two DVMs are standard in the HP3052A system. However, only the HP3455A DVM is required. This unit has the capability to: (1) measure ac voltages above 125 V, (2) measure dc voltages above 300 V, and (3) withstand and accurately measure voltages.

The DVM will measure all system voltages, both ac and dc, without signal conditioning, and it provides adequate isolation to eliminate ground loop problems.

HP3498A Scanner - A total of 128 channels must be switched by the scanner to the input to the DVM. In addition, three contact closures are required to reset each of the watt-hour meter counters. Several channel assembly options are available for use in the Scanner. Three of these option types are required for this system. A 20-channel, low-thermal relay assembly (option 004) will be used for measurements with a peak voltage of less than 43 V. A 10-channel, low-thermal relay assembly (option 001) is required for voltages greater than 42 V but not exceeding 230 V peak. For measurements exceeding 230 V, a 10-channel relay actuator assembly Scanner (option 002) will be used to control auxiliary relays located in the ODAS assembly part of the System Control Center rack. These relays provide the actual switching of the high voltages to the DVM. The output of these auxiliary relays will be paralleled to common signal wires that provide the connection to the DVM. A slaved relay at the DVM will be added to transfer the DVM input from the scanner to the auxiliary relays. The relay actuator assembly is also used to permit computer controlled reset of the watt/hour meter counters. Watt/hour meters operate by incrementing a counter of 10 W increments. The 120 bit counter used is capable of storing an energy word indicating 40.9W maximum. When this word is read by ODAS, the counter is reset.

Of the 128 measurements, 86 are less than 42 V, 28 are less than 230 V, and 15 require auxiliary switching. The system requirements can be met with three scanner frames capable of holding four assemblies each: five, 20-channel, low-thermal assemblies;

Figure V-1 Block Diagram - On-Site Data Acquisition System

three 10-channel, low-thermal assemblies; and two 10-channel relay actuator assemblies. Measurement allocation is shown in Table V-5.

HP9845 Computer - The computer provides control of the ODAS system, data compression, data averaging and units conversion for local display. The HP9845 has more capability than required to meet the minimum system needs, but was the best suited of the alternative systems evaluated when the DOE requirements for printing and display are incorporated. The computer has the capability to control the DVM and Scanners; collect, average, store, and record the data; provide automatic restart in the event of a power failure as required by the DOE; perform necessary calculations to convert measurements to engineering units; and perform the necessary operations to print or display data of interest. The calculator, DVM, and scanner can complete the acquisition of one sample of each channel in approximately 10 to 15 seconds. Since all data are not sampled each cycle, there is adequate capability to perform the data analysis, recording, and display functions.

Other Hardware - To provide an interface with the 30-bit PCA Command Word from the System Control Center, two 98032A 16-bit parallel I/Os are required. These permit inputting the command each second using an interrupt to indicate when data are available during PCA field operation.

A clock is required to provide time-of-day from which solar time may be calculated. Outputs from the clock must also be provided to start data acquisition and data recording. In the event of a power failure, the clock must continue to run. This is accomplished by a battery in the clock module (a standard HP option).

Two cassette tape drives are required. The first drive is used for data storage. The second drive stores the operating system programs.

Printer and Display - A printer and display provide the capability to view the system status or selected measurements and to obtain printed copy.

Data-Recording - As stated above, data will be recorded on one of two cassette tapes. The tape has a capacity of 217 k-bytes of data. This is enough to permit storing data for approximately 5 days during the summer (approximately 10,700-4-byte elements per day). The data allocation format includes an allowance for a tape header (label), record labels and record time tags. With the data recording specified, the tape will be scheduled for a

Scanner Frame/Assy	1A	1B	1C	1D	2A	2B	2C	2D	3A	3B
Scanner Relay Option Number	002	002	001	001	004	004	004	004	004	001
1	PCA3V	PCA32V	PCA1V	PCA17V	PCANAI	PCA1T	PCA21T	30KVAIAC1	BAT1T	PCA31V
2	PCA4V	PCA35V	PCA2V	PCA18V	PCANBI	PCA2T	PCA22T	30KVAIAC2	BAT2T	PCA33V
3	OCA10V	PCANV	PCA5V	PCA19V	PCANCI	PCA3T	PCA23T	30KVAWAC	BAT3T	PCA34V
4	PCA11V	BATV	PCA6V	PCA20V	PCANDI	PCA4T	PCA24T	30KVAWHAC	BAT4T	PCA36V
5	PCA14V	BUSV	PCA7V	PCA21V	PCANEI	PCA5T	PCA25T	7.5KVAIAC1	BAT5T	30KVAVAC1
6	PCA15V	30KVAWHAC-R	PCA8V	PCA24V	PCANFI	PCA6T	PCA26T	7.5KVAIAC2	BAT6T	30KVAVAC2
7	PCA22V	7.5KVAWHAC-R	PCA9V	PCA27V	PCANGI	PCA7T	PCA27T	7.5KVAWAC	BAT7T	7.5KVAVAC1
8	PCA23V	PCAWH-R	PCA12V	PCA28V	PCANHI	PCA8T	PCA28T	7.5KVAWHAC	BAT8T	7.5KVAVAC2
9	PCA25V		PCA13V	PCA29V	PCANJI	PCA9T	PCA29T	30KVABUS	BATRT	
10	PCA26V		PCA16V	PCA30V	PCANKI	PCA10T	PCA30T	7.5KVABUS		
11	--	--	--	--	PCANLI	PCA11T	PCA31T	SOC	DNRAD	--
12	--	--	--	--	PCANMI	PCA12T	PCA32T	LDC	THRAD	--
13	--	--	--	--	PCAI	PCA13T	PCA33T		REFSC	--
14	--	--	--	--	ASRI	PCA14T	PCA34T		WSP	--
15	--	--	--	--	30KVAI	PCA15T	PCA35T		WDR	--
16	--	--	--	--	7.5KVAI	PCA16T	PCA36T		BARO	--
17	--	--	--	--	BATI	PCA17T	PCAW		AIRT	--
18	--	--	--	--		PCA18T	PCAWH		HMDY	--
19	--	--	--	--		PCA19T			PRCP	--
20	--	--	--	--		PCA20T				--

Table V-5 Scanner Channel Assignments

change twice each week. This will provide a margin that will prevent loss of data if access to the facility is limited by weather conditions.

Software - The basic software for the ODAS is assumed to be provided by DOE with the capability to provide local programming of the data sampling rates, the data recording intervals, and the transducer calibration factors. The Roxborough Park ODAS will also require program changes to provide reset commands and respond to digital inputs upon interrupt.

To provide capability to assess the system performance. An off-site computer program is required which will be used to determine array performance, cost of energy produced, and duration of system downtime.

Soft Data Requirements - During Phase II data will be acquired to provide cost, schedule, maintenance and reliability assessments. These data will continue to be collected during Phase III. Table V-6 shows the data requirements and anticipated reporting/recording frequency. Except for items 5, 6, 14, and 15, the report will generally be completed during Phase II or early Phase III unless significant changes occur. To determine the recurring costs, records will be maintained to define the occurrence, the time and materials required to complete, and when unscheduled, the cause. These data will be entered in ledgers and logs in a format that will provide direct input to a uniform cost account structure.

B. TECHNICAL AND ECONOMIC EVALUATIONS

During Phase III, detailed technical and economic evaluations will be conducted. The ODAS tape data will be forwarded to the DOE.

A key area of interest for this system is maintenance; particularly with respect to lens cleaning. Detailed investigations on cleaning frequency and cleaning techniques and the resulting performance improvements are planned. Alternative maintenance strategies shall also be investigated, for example, periodic full-field cleaning versus more frequent partial field cleaning. Natural cleaning by rain will also be investigated.

Two basic economic evaluation studies are planned: the first in accordance with the PRDA-35 costing methodology which assumes utility ownership, and the second oriented specifically

Table V-6 Soft Data Requirements

Data Item	Recording/Reporting Frequency
1. Site Description	Phase II Report - Updated If Significant Modifications Are Made
2. Purchased Equipment Costs	Phase II Report - Updated If New Equipment Is Required
3. Capital and Construction Costs	Same As 1.
4. Construction Schedule	Same As 1.
5. Scheduled Cleaning, Maintenance, Calibration and Repair	Started during Phase II But Regular Reports during Phase III
6. Unscheduled Cleaning, Maintenance, and Repair	Each Occurrence
7. System Downtime	Same As 6.
8. Equipment Failures	Same As 6.
9. Pre-Operational Testing and Checkout	One-Time When Preoperational Testing is Complete
10. Environmental Considerations	Phase II Report - Updated If Additional Items Are Encountered during Phase III
11. Utility Interface	Same As 1.
12. Safety Considerations	Phase II Report - Updated to Reflect Any New Requirements or Significant Accidents
13. System Schematic	Same As 1.
14. Inverter Output Harmonic Content	Each 6 Months
15. Battery State-of-Charge (Electrolyte Specific Gravity)	Weekly
16. System Description Parameters	Same As 1.

to the Roxborough application using interest, tax, incentive, and utility rate parameters specifically applicable to Roxborough.

A key feature of our experiment is the ability to cut back visitors center usage during extended inclement weather. Our studies will quantify the extent to which such procedural factors can improve solar system effectiveness.

C. NONTECHNICAL ISSUES

All of the nontechnical issues applicable to Roxborough Park (i.e., safety, insurance, taxes, codes, environmental impact, and vandalism) have been addressed during Phase I, and additional information will be acquired during Phase II. In Phase III, the primary issue to be addressed is public reaction to the system. The state will incorporate the photovoltaic system into its overall visitor interpretive program, and Martin Marietta will provide descriptive material and illustration for use in brochures and pamphlets. An aggressive program of public education geared to different age groups and levels of understanding is planned.