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RTI PHOTOVOLTAIC CONCENTRATOR APPLICATIONS
EXPERIMENT. PHASE I—SYSTEM DESIGN

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

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Research Triangle Institute
Research Triangle Park, North Carolina

U.S. Department of Energy

Solar Energy

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RTI PHOTOVOLTAIC CONCENTRATOR APPLICATIONS EXPERIMENT PHASE I — SYSTEM DESIGN

FINAL REPORT

For the Period
1 June 1978 - 28 February 1979

ROBERT M. BURGER
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ABSTRACT

An experiment has been designed in which a 100 kW photovoltaic concentrator system serving the electrical load provided by an energy-efficient office-laboratory building will be built and operated in the Research Triangle Park of North Carolina. Since the purpose of the experiment is to provide the essential data for design and installation of future operational systems, the system is designed for operational flexibility. In its main operational mode, a defined primary load is diverted from the utility during all peak-demand periods. This requires the use of 1000 kWh of lead-acid batteries for energy storage. Other operational modes provide for obtaining data on peak demand reduction, on alternative battery use strategies, and on system performance with an isolated load. Operation of the system in parallel with utility-supplied power requires that the photovoltaic array outputs be inverted and that the power be controlled to achieve the operational objectives. Ten 2-axis tracking arrays consisting of 70X parabolic concentrators are used. The system will provide approximately 103 megawatt-hours of power annually to the load and the design is compatible with future retrofits including more efficient solar cells, higher concentration ratios, thermal energy collection, and other technological developments, ensuring its usefulness in research and development beyond the PRDA-35 experiment.

PHOTOVOLTAIC CONCENTRATOR APPLICATIONS EXPERIMENTS
PHASE I - SYSTEM DESIGN

FINAL REPORT

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1.0 SUMMARY

1.1 INTRODUCTION

The first phase of the Research Triangle Institute (RTI) Photovoltaic Concentrator Applications Experiment (PCAE) has resulted in the design of a 100 kW(peak) system and a plan for its application using an RTI building as the system load. The resulting experiment will provide data and operating experience applicable to a variety of future photovoltaic system applications. The results presented here were obtained by a design team led by RTI and including Motorola, the J. E. Sirrine Co., ESB Inc., and Duke Power Co. This organization is shown in Figure 1-1. The photovoltaic concentrator array was independently designed by Motorola and is identical to that being used in the Arizona Public Service Co. experiment. That design was selected by RTI for this experiment for reasons that are discussed later. Motorola provided the required data, studied array-related design issues, and participated in the conceptual design of the RTI PCAE. Sirrine provided design engineering support, ESB provided technical support for selection and specification of the power conditioning and battery storage subsystems, and Duke Power assisted in the definition of a compatible utility interface. The general objectives given in Table 1-1 guided the design effort.

Table 1-1. GENERAL OBJECTIVES OF RTI EXPERIMENT DESIGN

-
- To design and implement a photovoltaic concentrator system experiment in a realistic operational configuration so as to acquire technical data on the performance of such systems and non-technical data on the viability of such systems, and to do so with a cost-effective experiment.
 - To design, fabricate, install, and operate a solar photovoltaic concentrator system that is reliable and representative of state-of-the-art technology, that serves a significant portion of the energy needs of a representative building, and that has a potential for long-term use as an energy devices/components/systems research vehicle.
 - To implement a solar photovoltaic system powering an energy-conservative RTI building so as to provide visible evidence of commitment to energy research.
-

Figure 1-1. Organization of RTI PCAE Design Effort

These objectives lead to the design of an experiment that, in turn, requires the design of a photovoltaic concentrator system (PVCS) which collects solar energy and converts it to useful electrical energy. The experiment requires, in addition to the collection and conversion system, consideration of (1) the system loads and the overall strategy for reliably serving these loads, (2) the means for acquiring the data that is required for analysis of the system performance and the derivation of results and conclusions, and (3) the implementation of the experiment in a working environment where practicality and acceptability can be demonstrated.

The general objectives of Table 1-1 were translated into the more specific system design objectives listed in Table 1-2 and discussed in the following sections.

Table 1-2. SYSTEM DESIGN OBJECTIVES

-
- Provide competitive state-of-the-art design
 - Obtain high efficiency in use of solar energy
 - Reduce peak demand on utility
 - Provide an operationally compatible interface with utility
 - Provide a system capacity consistent with future applications
 - Enable meaningful analysis with respect to a well defined load
 - Maximize acquisition of useful data
 - Provide usefulness for system beyond the term of the experiment
-

The design of the experiment is influenced by the institutional environment in which it will be implemented. The PVCS is to be located on the RTI campus and will use a building housing engineering research activities for its load. The array structures and the building are illustrated in Figure 1-2. The continued close proximity of the design and operating engineers to the system permits more latitude in design than would otherwise be the case. Changes in system hardware or software can be

Figure 1-2. RTI Photovoltaic Concentrator Applications Experiment Site

readily implemented. In addition, the provision of a useful life for the PVCS beyond the term of the experiment is aided by its location. When new cell, concentrator, or system technologies become available, the PVCS will serve as a research vehicle for testing and evaluation.

The approach used in this design effort consisted of the following steps:

- Identify Experiment Options, Attributes, and Trade-Offs
- Specify System Load Characteristics
- Select General System Approach
- Simulate System Performance
- Evaluate Costs
- Select Specific Experiment and System Design
- Specify System Components
- Iterate These Steps to Obtain Acceptable Design

A number of decisions had been made before the design effort began. The photovoltaic concentrator was to be the Motorola Meinel Cassegrain design that provides about 40 W(peak) from a circular 3-inch solar cell. The cell is divided into quarters which are connected in series electrically. This choice was based on the 70X concentration ratio and technology growth capability inherent in that concentrator design. Practical modifications will allow concentration ratios of as much as 400X and a capability for collecting thermal energy from the cell mount. A decision had also been made to use some of the electrical loads of a new RTI engineering building as the system load. In order to enhance the building's compatibility with the experiment, the building has been designed with emphasis on energy efficiency. An additional decision had been made to design the experiment to respond to potential future availability of a time-of-day rate structure for utility power. This will provide both a useful data base and favorable conditions for photovoltaic power since peak insolation usually occurs in periods of peak demand for electric power.

1.2 ANALYSIS

The analysis of PVCS performance is based on site-specific solar energy availability as determined by the site topography, geography, and meteorology; on the characteristics of the loads that will be served by the system; on the cost of electrical energy supplied by the utility; and on the PVCS configuration and subsystem performance. A computer simulation employing TRNSYS codes supplemented by models of the solar cell arrays, inverter, battery, loads, and rate structures was used. The analysis was an evolutionary process, and many PVCS operating modes and subsystem parameters were investigated in addition to those of the final system design. In the following paragraphs, environmental factors, system loads, system configuration, and analytical results are discussed.

1.2.1 ENVIRONMENTAL FACTORS IN SYSTEM PERFORMANCE

PVCS performance is affected by geographical location, site topography, and local meteorological conditions. The site for the solar array is in the Research Triangle Park of North Carolina at coordinates $78^{\circ}50'W$ and $35^{\circ}54'N$ and with an elevation of 434 feet. The latitude determines the solar elevation and azimuth angles for any given hour of any given day through the zenith equation which is included in the TRNSYS model. The vertical lines in Figure 1-3 define the time period in which the illustrated array would receive solar energy for a 20° acquisition angle, i.e., the angle at which the sun clears obstructions on the local horizon. The two curves are for the shortest and longest days of the year.

Local topography affects the PVCS performance by determining the actual acquisition angle and thus the time period in each day that the array receives solar energy. The RTI array site is relatively flat so that buildings and trees are the primary determinants of minimum acquisition angle. As diagrammed in the figure, an 80-foot tree at a 220-foot distance from an array gives an acquisition angle of 20° , the minimum acquisition

Figure 1-3. Calculation of Shadow Angle and Effect on Insolation

angle chosen for the final system. Considerations leading to this selection were:

- the spacing between subarrays within the Motorola array,
- dedication of unobstructed land area to the solar array field, and
- variation of array output with minimum acquisition angle.

The meteorology of the Research Triangle site is summarized briefly in Table 1-3. Typical meteorological year data from the most comparable SOLMET site, Nashville, Tennessee, were selected for use in the analysis. General meteorological data and a 1-year insolation record for the Research Triangle indicates that the performance prediction resulting from use of the Nashville data is probably a conservative estimate of the PVCS energy output.

Table 1-3. METEOROLOGICAL DATA ON RESEARCH TRIANGLE AND NASHVILLE

Parameter	Research Triangle	Nashville
Normal high temperature (°F)		
January	51	48
July	88	90
Normal low temperature (°F)		
January	30	29
July	67	69
Mean wind speed (mph)	8	8
Degree days, heating	3514	3599
cooling	1394	1643
Annual direct insolation (kWh/m ²)	1468*	1288**
Number of hours in which ratio of actual to maximum possible direct-normal insolation exceeds		
0.75	811*	444**
0.50	1542*	1302**
0.25	2088*	1922**

*From EPA-RTI data, 1976 only.

**From Nashville TMY data.

1.2.2 SYSTEM LOAD CHARACTERISTICS

System loads will be provided by a 39,000 sq. ft. RTI engineering building. These loads have been separated into lighting system loads and service loads for the two wings of the building and an HVAC load for the entire building. The size and time dependence of these loads are based on experience with similar RTI facilities, knowledge of specific equipment and operations planned for the building, and information provided by the design engineer for the building. The estimated demand for each of the load categories is given in Figure 1-4. The east-wing lighting system load has been chosen as the primary load for the PVCS system, and the remaining

*Loads for nonworking days are shown in parentheses if different from those of working days.

Figure 1-4. Demand Levels (kW) for System Loads

lighting load and the service load are the alternative loads to be served when energy is available. A design objective is to furnish all of the energy requirements of the primary load during periods of peak demand on the utility (either directly from the solar array or from the batteries). It is expected that actual loads will vary somewhat from these estimates; however, the estimates are considered to be reasonable for design purposes. Actual loads will probably be lower on the average.

1.2.3 SYSTEM CONFIGURATION

The final system configuration resulting from the design effort is shown in Figure 1-5. Models for the array, battery charger, inverter, and storage battery were included in the simulation. The array model simulates operation at a given insolation, temperature, and windspeed, either at the output voltage that gives maximum power output or at an output voltage determined by the battery voltage. A solar cell temperature model was developed from data provided by Motorola. Motorola also supplied a cell efficiency model. The efficiency of the inverter and that of the battery charger were modeled as rational functions of their output power level. The storage battery model assumed a constant throughput efficiency of 77 percent. Design issues that were considered during evolution of the system configuration are listed in Table 1-4.

Engineering analyses were used to resolve several design issues. Consideration was given to use of a direct current (DC) distribution system in order to avoid DC/AC inversion. This approach involved the use of lighting fixtures and motors that would operate on DC. Efficiencies and costs of comparable DC and AC systems were obtained and found to be approximately equal for the two approaches. Since the postulated advantages of DC distribution did not materialize, the decision was made to use an AC distribution system with conventional fixtures and components for the loads. Advantages of this approach are that the system can be more easily maintained and that the required components are readily available.

Consideration was also given to use of an active solar cell cooling system and utilization of the collected thermal energy. It was found that there is limited usefulness for the 55°C cooling fluid, so that the considerable costs involved were not warranted. In the same analysis, consideration was given to the design of a system that would provide most of the energy requirements of the entire building. However, such a design would require a system capacity substantially larger than that of the final design without a commensurate increment in the experimental value of the system.

1.2.4 ANALYTICAL RESULTS

Only those results of significance to the final design are described. As the design evolved, a wide spectrum of analyses were performed to determine the influence of the array and battery capacities, array acquisition angles, the type and size load, and the necessity of having a power

**FIGURE 1-5. PROPOSED RTI SYSTEM CONFIGURATION
PVCS APPLICATIONS EXPERIMENT.**

Table 1-4. SYSTEM DESIGN ISSUES

-
- Array:
 - Size and configuration of tracking module
 - Flexibility of configuration for technology growth
 - Cell temperature control
 - Possibility of useful thermal energy collection
 - Array acquisition angle and array shadowing
 - Material and component costs
 - Solar cell and array analytical models
 - Deployment procedures
 - Cell wiring configuration
 - Optical losses and concentrator design
 - Cell efficiency
 - Power Conditioning:
 - Implementation of maximum-power tracking
 - Array-battery-inverter interface
 - Inverter-utility interface
 - Inverter control approaches
 - Efficiency
 - Performance model
 - Energy Storage:
 - Size of battery
 - Equalization requirements
 - Battery performance models
 - Efficiency
 - Loads:
 - Sizes and diurnal patterns of loads
 - DC versus AC distribution systems
 - Load strategy
 - Utility interface
 - Load models
 - Load selection
 - Data Acquisition:
 - System interface to DOE onsite data acquisition system
 - Requirements for system data acquisition and control system
 - Identification of data needs and transducers
 - System:
 - Overall control strategy
 - Performance prediction
 - Costs
-

controller from the system design. Results of the analysis have indicated that:

- A nominal array capacity of 100 kW(peak) is compatible with a primary load of 34 kW (the east-wing lighting system).
- The power losses in the DC power controller were greater than the power gained by its maximum-power tracking function. Consequently, it was removed from the system, and the maximum-power tracking function was assigned to the inverter.
- In order to obtain high system efficiency, only that energy required to divert the primary load from the utility during peak-demand periods should be maintained in the battery by the battery charger.
- Utility power losses are substantial when the charger-to-inverter-to-load connection path is used. For this and other reasons, the direct, parallel connection of inverter output with the utility was selected in the final design.
- The size of the battery was determined from weekly, rather than annual, energy flow patterns.
- When the array output is less than the total load but greater than the primary load, the battery should be disconnected from the system, and the inverter should track the maximum-power voltage of the array.

The system operating strategy that results from the analysis is described in Table 1-5. This strategy is designed for a time-of-day utility rate structure. Additional operating strategies that were evolved for the experiment are described later. The analyses resulted in considerable data on the relationships among array size, battery size, load size and schedule, and system performance.

1.3 SYSTEM DESIGN

In the resultant system design, the photovoltaic concentrator is located in the middle of the RTI campus as shown in Figure 1-2. The centrally located building in the figure, which is partially recessed into the hill, is the new engineering building that will provide the system loads and house the battery, inverter, data acquisition and control system, and visitors' center. The arrays, as shown, occupy about 3.5 acres of land central to the campus.

Table 1-5. MODE 1 OPERATING STRATEGY

During peak periods:

- if array output is sufficient to supply primary load
and if total load exceeds the PVCS output, then battery is disconnected, and the inverter is operated with maximum-power tracking.
- and if total load is less than PVCS output, then battery is connected for charging, and the inverter is operated with output-power control.
- if array output is not sufficient to supply primary load, then battery is connected, and the inverter is operated with output-power control.

During off-peak periods with the array output greater than zero:

- if array output is less than 10 percent of its peak rating, then the battery is connected for PV charging, and the inverter is disconnected from the load.
- if array output exceeds 10 percent of its peak rating
and if the total load exceeds the PVCS output, then the battery is disconnected, and the inverter is operated with maximum-power tracking.
- and if the total load is less than the PVCS output, then the battery is connected for PV charging, and the inverter is operated with output-power control.
- and if array output exceeds battery charging and load requirements, then array output is decreased by stowing arrays.

During off-peak periods and with no array output:

both battery and inverter are disconnected from the load.

The Motorola designed photovoltaic concentrator array is shown in Figure 1-6, and the general characteristics are given in Table 1-6. Analyses of the cell characteristics, tracking system, array structure, concentrator optics, heat dissipation, weight, and costs of this design have been performed in order to assure that it provides a competitive and reliable response to the system requirements.

Figure 1-6. Tracking Photovoltaic Concentrator Array

Table 1-6. GENERAL ARRAY SPECIFICATIONS

• Concentrator Modules per Array	240
• Panels per Array	20
• Concentrator Modules per Panel	12
• Maximum Peak Power Output (for ambient temp. = 28°C, direct-normal insolation = 1000 W/M ²)	9,576 watts
• Number of Arrays in Field	10
• Turning Diameter of Array	82 feet
• Diameter of Support Rail	58 feet
• Maximum Height of Array	10 feet
• Total Weight of Array	15,250 pounds
• Maximum Operational Windspeed	30 mph
• Tracking System	active sun sensor with open-loop backup

An individual concentrator is shown in Figure 1-7. The basic collector design is a 30-inch diameter Cassegrain reflector that produces a solar intensity of 70 suns on a 3-inch diameter solar cell. The peak output of each cell is 39.9 W so that the 240 of these modules that are assembled in an array produce 9576 W (peak). The cell temperature is limited to a maximum of 55°C by an innovative reflux cooler. Sun pointing for each of the arrays is maintained with a hybrid, open-loop/closed-loop tracking system that activates separate azimuth and elevation motors. RTI's system requires ten arrays to produce 96 kW.

This concentrator module was chosen from the many available designs of modules and arrays because studies have shown that high efficiency and high concentration ratio solar cells are required to meet the cost goals of the DOE national photovoltaic plan and because of the opportunities for technology growth with respect to higher concentration ratios, higher temperature operation of the cells, and thermal energy collection.

The system inverter is based upon a standard commercial line of inverters used in uninterruptable power supplies manufactured by Exide. The inverter includes control features that allow its output to be connected in parallel with the utility power line and to track the maximum-power voltage of the array. The efficiency of the inverter is in

Figure 1-7. Cross Section of Concentrator Module

excess of 90 percent for outputs in excess of 30 percent of its rated capacity, and its operating parameters meet or exceed those required for the application. The inverter output is controlled by the Data Acquisition and Control System (DACS) to establish the desired ratio of PVCS and utility power for the solar power availability, load conditions, and time-of-day.

The battery storage system is designed with a nominal capacity of 1000 kWh. Battery life is increased if depth of discharge is limited to 75 percent of this rating; therefore, the effective capacity is 750 kWh. Lead-antimony batteries with nominal ratings of 2.0 VDC and 4.2 kWh per cell are used. These cells are adapted from the Exide standard line of industrial batteries. A series string of 240 cells will provide a nominal output of 480 VDC and a current of up to 225 amperes for a delivery rate of 108 kW which is slightly in excess of the peak array output. This margin provides for maintaining battery output power close to the array output

rating over the range of battery charge states. This battery capacity is compatible with the basic stored energy requirements as defined by the system operating mode (400 kWh) and provides reserve capacity for storing array output when it exceeds available loads, as is the case on days when the building is not in use.

The DACS performs two essential functions. First, it acquires data on the performance of the system and makes it available for analysis. In addition, it controls the collection, inversion, conditioning, and distribution of power. In its data acquisition function, it obtains data from the standard meteorology sensors, on the performance of each subsystem, and on power flow to the loads. It processes the data for recording, monitoring, or display. A local, serial data link to an RTI PDP-11/60 computer is provided for data analysis and reduction. In its control function, the DACS uses the acquired data to establish system operational modes in conformance with the programmed strategy. For example, it causes the inverter to pull power from the battery during peak-demand periods when photovoltaic power is insufficient to supply the designated load, provides for battery charging during off-peak hours as required by the battery charge state, and stows the arrays when the sustained wind velocity exceeds 30 mph. The DACS provides a capability for controlling system operation in the primary (normal) mode and also is capable of modifying this strategy to provide alternate modes of operation. System performance in response to different utility rate structures or different load combinations will be determined during the course of the experiment.

The overall efficiency of the PVCS is indicated by simulation to be between 7 and 7.5 percent. This is for an array efficiency of 8.6 percent in collecting and converting solar energy to electrical energy and an efficiency of approximately 85 percent in taking the electrical output of the array, conditioning it, and delivering it to the loads. These estimates are conservative and should be exceeded by the actual system.

Annual power flows predicted for the system are shown in Figure 1-8. The primary load receives 77 percent of its energy requirements from the inverter which, in turn, receives 76 percent of its input from the photovoltaic array, either directly or through the battery. In addition,

Figure 1-8. Annual Power Flow in RTI PVCS System

about 12 percent of the substantial alternative service loads of the facility are supplied by the inverter.

The monthly pattern of energy flow in the system as indicated by the simulation is shown in Figure 1-9. The array output is directly dependent on insolation variations and is an important indicator of system performance. The curve for battery charger power is another indicator of system performance in that it shows the utility power required for the primary load during peak periods but stored in the battery during off-peak periods. No more than 1.25 MWh of the array output flows to the battery in any month.

Figure 1-9. Energy Flow in Photovoltaic System

The estimated costs of implementing the RTI photovoltaic concentrator experiment are as follows:

Array hardware	\$11/watt
Array installation/site	4/watt
Battery	2/watt
Power conditioning	2/watt
Power switchgear and distribution	3/watt
Data acquisition and control system	3/watt
Facility for system control/visitors' center	1/watt
Program management and control	<u>2/watt</u>
 Total Experiment Implementation Costs	 \$28/watt

These estimates include all reasonable inflationary factors for material and labor costs.

1.4 OPERATION AND EVALUATION

The third phase of the Photovoltaic Concentrator Applications Experiment includes the system operation, data collection, and evaluation activities designed to acquire data on the operational performance of the system and on the success of the system in meeting its design objectives. These data will be applied in subsequent technical and policy decisions relative to future experimental or operational photovoltaic concentrator systems. For the RTI system, the objectives of the Phase III effort are specifically to characterize the:

- solar energy available to the system
- natural environmental factors that impact system performance
- performance of the photovoltaic concentrator array
- performance of the control system
- efficiency and reliability of the overall system

- system effectiveness in meeting the load for which it is designed
- value of the photovoltaic power supplied to the load
- economics of the system
- impact of the battery system on performance
- relative merits of different control strategies
- efficacy of load sharing with utility
- maintenance requirements for the system
- operational impacts of system

The Phase III plan is directed to acquisition of these data. The system operational modes are listed in Table 1-7, and the resultant analyses that will be performed for evaluation are listed in Tables 1-8 and 1-9.

Table 1-7. OPERATING MODES FOR EXPERIMENT

Mode 1. Time-of-day

Objective - To determine system performance when it is operated so as to completely remove the lighting load from the utility during peak demand periods.

Mode 2. Demand reduction

Objective - To determine system performance when it is operated so as to reduce the peak demand for the entire facility load.

Mode 3. Parallel battery

Objective - To determine system performance when the battery is connected in parallel with the array.

Mode 4. Isolated load

Objective - To determine system performance in satisfying a dedicated load.

Table 1-8. GENERAL ANALYSES - ALL MODES OF OPERATION

Analysis	Dependent Parameters	Independent Parameters
Cell, subarray, and array performance	Voltage Current Power Efficiency	Time Ambient temperature Wind speed and direction Atmosphere obscurants Insolation Tracking accuracy System dysfunctions
Tracking system performance	Deviation of tracking angles	Elevation/azimuth angles Time
Inverter performance	Efficiency	Input power Time
Battery performance	Efficiency (losses) Use level	Input power Output power Cell temperature Time
System performance	Proportion of loads supplied by solar energy directly and through battery System efficiency and reliability	Utility energy demand Inverter energy, in/out Battery energy, in/out Array energy Lighting system energy Alternate load energy Time System dysfunctions and degradation

Table 1-9. SPECIALIZED ANALYSES - MODE DEPENDENT

Analyses	Dependent Parameters	Independent Parameters
System figure-of-merit	Utilization factor	The independent parameters listed below are required for most of the analyses in this table.
System energy output	Value of energy derived by solar conversion	Time Insolation Array output power Battery input
System economics	Ratio of present and projected system costs to present and projected value of produced energy	Battery output Inverter output Lighting load Alternative loads Utility demand System costs
Storage economics	Calculated incremental benefit of battery	Rate structures Discount rates Projected rate
System design	Sensitivity of performance parameters to design parameters	structures Projected system costs

1.5 CONCLUSIONS

The RTI Photovoltaic Applications Experiment design provides an opportunity to acquire data and experience that will be of considerable value to the DOE National Photovoltaic Energy Plan. The flexibility designed into the system, which allows operation in response to different conditions and with different loads, assures broad applicability of the information to the design and implementation of future systems. This same flexibility will allow the system to serve as a test bed for advanced solar cells or other new system technologies as they become available. With these attributes, and with the integration of the experiment into an existing operating research facility, implementation of the experiment will provide a significant step toward the ultimate practicality of photovoltaic concentrator systems.

2.0 INTRODUCTION

The design of the RTI Photovoltaic Concentrator Applications Experiment is directed to meeting present and long term data needs relative to the design, location, operation, and evaluation of photovoltaic concentrator systems. There is no presumption of current economic viability for such systems nor is there intent to imply that the system design is to be demonstrated as a currently applicable technology. In this context the design effort focused on the experiment and the maximization of the useful data to be acquired. Consequently, this approach required more than just the design of a compatible hardware configuration for a photovoltaic concentrator system (PVCS); the system was designed for specific load requirements and for versatility of load interfacing so as to provide data for future application scenarios. To reach this design objective, the interface with the electric utility was a key issue in the design.

The starting point for the design is presented in Figure 2-1.

Figure 2-1. Basic System Concept

In this design concept, the PVCS is simply an alternative source of energy for the load. The utility is an infinite source of energy and is characterized by several possible rate structures that determine the cost of the energy. These rate structures include factors such as quantity, demand level, and time-of-day. The load is characterized by demand levels and temporal patterns determined by its nature. Certain aspects of the load characteristic may be modified in response to the system design, e.g., using thermal storage to displace heating and cooling loads to different periods of the day. In the present case, the load is to be a new building providing the opportunity to configure the building systems in conformance with the overall experiment objectives. The PVCS power output is characterized largely by the temporal pattern and magnitude of insolation. Other important PVCS features, such as energy conversion, storage, conditioning, and control systems, are products of the system design. The experiment design effort required that those factors which could be controlled or modified be identified and that an experiment and PVCS design be evolved using system simulations to predict overall performance. The approach in the general design effort was thus to:

- Identify Experiment Options, Attributes, and Trade-offs
- Specify System Load Characteristics
- Select General System Approach
- Simulate System Performance
- Evaluate Costs
- Select Specific Experiment and System Design
- Specify System Components
- Iterate These Steps to Obtain Optimum Design

In approaching the design of both the experiment and the PVCS a number of decisions had already been made. The photovoltaic concentrator was to be the Motorola Meinel Cassegrain design that provides about 40 W(peak) from a quadrifid 3-inch solar cell. This choice was based on the 70X concentration ratio obtainable and on the technology growth capability inherent in that concentrator design. By modification of the concentrator, concentration ratios of as much as 400X and a capability for collecting thermal energy from the cell

mount appear to be feasible. A decision had also been made to use some of the electrical loads of a new RTI engineering building as the system load. In order to enhance the building's compatability with the experiment, the building has been designed with emphasis on energy efficiency. An additional decision had been made to design the experiment to respond to potential future availability of time-of-day rate structure for utility power. This would provide a useful data base and provide a favorable condition for photovoltaic power since peak insolation usually occurs in periods of peak demand for electric power.

In the following subsections of this introduction the RTI environment, as it relates to the experiment; the system design objectives; and the procedures used in the design effort are discussed.

2.1 RESEARCH TRIANGLE INSTITUTE ENVIRONMENT AND SITE

In developing a proposal for design of the PVCS, the Research Triangle Institute (RTI) made an early decision to integrate the PVCS Experiment with a planned facility expansion on its campus. This decision removed complications that would have resulted with placement of the experiment on a site controlled by another organization. In addition, the RTI site ensures a continuing close association of the system designers with the construction and operational phases of the experiment. In the following paragraphs the Institute, its campus, the array site and the facility load are described in order to give a full picture of the RTI environment.

RTI is a not-for-profit research organization located on a 157-acre campus in the Research Triangle Park which is located centrally in the triangle formed by Raleigh, Durham, and Chapel Hill in North Carolina. RTI was incorporated in 1958 by the University of North Carolina in Chapel Hill, Duke University in Durham, and North Carolina State University in Raleigh. The Institute performs research under contract with federal, state and local governments, foundations, and industry. Its research agenda has a very broad multi-disciplinary nature ranging from the social and physical sciences to a variety of application areas including policy, operations, economics, systems, devices, and materials. Most germane to the PVCS experiment are energy research activities ranging from materials to systems with strong programs in solar energy. Photovoltaic system

applications, insolation variances, materials degradation, wind energy siting studies, and OTEC environment analyses are included in the solar energy research activities of the Institute, but the largest effort is directed toward development of more efficient solar cells.

The Institute campus as it now exists is shown in Figure 2-2. In addition to the eleven buildings shown, two off-campus buildings are also used to house the one-thousand person staff. Two facility construction projects at the sites indicated by asterisks are now underway.

The next planned addition to the Institute facilities is an engineering research building. In planning the PVCS Experiment a decision was made to design and construct that building on the same schedule as the PVCS and to use the building, or part of it, as the load for the system. It was recognized that this could create problems in maintaining an accelerated schedule for building design and construction but that the advantages obtained for the experiment would be of considerable value.

Therefore, in parallel with the design effort on the PVCS Experiment, RTI has selected a site on the campus for the building and array and is designing a building that will be compatible with the experiment. Several sites were considered. The building site requires an adjacent land area for the solar array. This proximity was required in order to provide a cohesive experiment and to allow consideration of the thermal energy collection and utilization option with the photovoltaic arrays, if not in the beginning, during a later retrofit. After consideration of two alternate sites the location indicated by an "X" in Figure 2-2 was selected. The reasons for selecting this site were 1) the central location made the solar arrays a central feature, rather than a peripheral part, of the Institute campus, 2) the central location is consistent with the high degree of cohesiveness required in the Institute multi-disciplinary research agenda, and 3) good access to roads, parking, and utilities was available without excessive added expense. A more detailed site plan for the PVCS Experiment is shown in Figure 2-3. Here one may note that the ten concentrating arrays fit into a central 3.5 acre area. Analysis of the elevations of the adjacent buildings indicates that any shadowing effects on the arrays will be minimal. This plan provides an attractive setting for the PVCS Experiment.

* CURRENT CONSTRUCTION

X LOCATION OF NEW ENGINEERING BUILDING

Figure 2-2. Research Triangle Institute Campus

Figure 2-3. Detailed Site Plan for PVCS Experiment and New Engineering Building

The new engineering building is to be located adjacent to the array site as shown in Figure 2-3. An artist's rendition of the building and the arrays is shown in Figure 2-4. Here it must be noted that a portion of the approximately 39,000 sq. ft. building is recessed into the slope of the hill and is not visible in the picture. The portion of the building that is closest to the arrays (the east wing) is predominantly laboratory facilities while the other two wings of the triangular building are primarily office-type facilities.

The building is being designed for energy efficiency. Heat flow into and out of the building is minimized by recessing the building into the slope, placing approximately twelve inches of earth on its roof, and berming certain of the outer walls. Energy consumption for lighting is minimized by use of efficient fixtures, keeping illumination levels low, and making efficient use of natural lighting. The building will be provided with a thermal storage tank so that the energy employed for temperature control will be used only during off-peak periods consistent with the objectives of the PVCS Experiment. Photovoltaic system application studies have shown that there are a large class of applications that are similar in their energy use patterns to the planned building, i.e., they are basically 8 AM-to-5 PM operations with most of the energy use associated with lighting and air conditioning. While the electrical loads associated with the laboratory operations are departures from the normal, they are not very different from other equipment loads often associated with operations in such buildings.

The new engineering building serves two functions in the PVCS Experiment. First, it provides the loads that the system serves. The specific load estimates are discussed in Section 3.0 in association with the performance analysis. Secondly, the building provides facilities to house PVCS system components and to provide access to these components for persons who wish to observe and evaluate the performance of the PVCS Experiment. The plan for accommodating this latter function is described below.

Figure 2-5 shows the plan for the PVCS components and visitor accommodations in the RTI engineering building. The two battery rooms accommodate the 1000 kWh electrical energy storage. The PVCS Data Acquisition and Control System (DACS) is in a separate room from the DOE-supplied Onsite Data Acquisition System (ODAS) in order to emphasize the independence of their functions.

Figure 2-4. Expected Appearance of RTI Campus with PVCS Installed

↑
SOLAR ARRAYS

Figure 2-5. Location of PVCS Components in Engineering Building

The system inverter is also shown in a separate room. In the final layout it may be possible to make this arrangement more compact.

The engineering building will house Institute staff involved in systems research and in development of advanced solar cells. The PVCS is intended to be a continuing integral part of the activities of the facility occupants. Advanced solar cell designs, improved energy storage technologies, thermal energy collection and utilization systems, and other innovations are envisioned as future retrofits to the system so that beyond the PVCS Experiment, it will continue to play a useful role and to contribute data for photovoltaic applications consistent with the National Photovoltaic Program Plan.

In summary, the PVCS Experiment is designed to be an integral part of the facilities and program of Research Triangle Institute. The designers and operators of the system will be users of the energy obtained. The PVCS will serve an energy-efficient building and will be representative of a broad class of potential future applications. It is intended that the PVCS be employed as the basis of continuing experimental programs beyond that for which it is specifically designed.

2.2 SYSTEM/EXPERIMENT DESIGN OBJECTIVES

Early in the design effort it was recognized that there exist three levels of objectives for the PVCS experiment and that it is necessary to satisfy all of these objectives to have a successful experiment. These objectives are given in Table 2-1. From these broad objectives a more specific set of nine system design objectives were derived. These are given and briefly discussed in the following paragraphs.

1. Competitive Design - The system should be a competitive state-of-the-art design. So that the role of photovoltaic concentrator arrays among the various alternative photovoltaic technologies can be rationally determined, it is essential that the system design represent the "best" technology now available. "Best" means that the cost of the output energy calculated on the basis of life-cycle costs is minimized within the constraints of potential user acceptability, i.e., the system should be acceptable with respect to appearance, operational convenience, and dependability.

Table 2-1. OBJECTIVES OF RTI-PVCS EXPERIMENT

DOE	To design and implement a photovoltaic concentrator system experiment in a realistic operational configuration so as to acquire technical data on the performance of such systems and non-technical data on the viability of such systems, and to do so with a cost-effective experiment.
RTI	To implement a solar photovoltaic system powering an energy-conservative RTI building so as to provide visible evidence of commitment to energy research.
Project Team	To design, fabricate, install, and operate a solar photovoltaic concentrator system that is reliable and representative of state-of-the-art technology, that serves a significant portion of the energy needs of a representative building, and that has a potential for long-term use as an energy devices/components/systems research vehicle.

2. High Efficiency - The system should provide the highest efficiency possible. This is a corollary of (1) but is sufficiently important to be separately stated. The nature of the PVCS is such that there is a high premium on system efficiency since system acquisition costs are by far the largest factor in the cost of the delivered energy. System efficiency is a product of the individual efficiencies of the optical concentrator, solar cell, cell cooler, batteries, inverter, and system power distribution facilities. It also includes the effects of array shadowing and the performance of the sun tracking system. Because of the multiplicative relationship of the efficiencies, the component with the lowest efficiency, i.e., the solar cell, is most important. This objective means not only that the most efficient concentrator and solar cell should be used but that the system operational strategy should be designed carefully with respect to usage of stored energy from the battery since significant losses occur in charging and discharging batteries.

3. Demand Reduction - The system should be used primarily to reduce peak demand on the utility. The cost of utility peaking power is several times the cost of base load power. This cost differential is reflected to some extent in conventional rate structures and more strongly in time-of-day rate structures. Recognizing that photovoltaic power costs are high, it is of considerable advantage to displace the more expensive peak load from the utility than the less expensive base load. This objective is generally, although not completely, consistent with the availability patterns for photovoltaic power. The enhancement of the system's ability to displace the peak loads by use of energy storage largely justifies the use of batteries.
4. Utility Compatibility - The system should be compatible with the electric utility. The PVCS cannot operate independent of the utility and supply the intended load. Therefore, if such systems are to find wide acceptance, they must be both technically and operationally compatible with electric utilities. Operationally, the peak-shaving objective as described above has been enthusiastically accepted by the utility because it is supportive of their load management strategy. All of the technical problems can be eliminated by use of a reverse power relay so that PV power is blocked from the utility grid. Beyond this however, the objective must be to maintain close liaison with the local utility in order to avoid barriers to acceptance of the experimental PVCS or of the class of operational photovoltaic system represented by the experiment.
5. Significant Capacity - The system should be of a meaningful capacity with respect to both the load and future applications. In order to obtain acceptability of the data produced by the experiment, energy output of the system must be sufficient to represent conditions expected in future applications and must also provide a significant portion of the energy requirements of the primary load. Future applications include a wide spectrum of loads but those of interest in this experiment fall in the range of about 50 kW to about 500 kW, i.e.,

buildings from about 1000 to several hundred thousand square feet of floor area. The peak load estimate for the RTI building is 130 kW but the lighting load for one wing is 34 kW. This latter load is that which is ultimately defined as the primary load. The load composition and pattern is described in detail in Section 2.0.

6. Load Match Analysis - The system should be designed so that its performance with a well defined load can be determined. An important question in the experiment relates to the extent to which the photovoltaic system can meet the energy needs of a given load. In the design of the PVCS, other objectives dictate features that ensure full use of the system output by provision of additional alternative loads. In doing this, it would be easy to follow a typical design trend in which the PVCS output is used to supply an essentially infinite load, no matching of the photovoltaic energy to load requirements is utilized, and the PVCS performance is compared to base load utility costs. At a minimum, the experiment should establish a data base that permits analysis of the system performance with respect to the primary load as if it were the only load and should provide the capability for confirming this analysis in one of its alternative operating modes.
7. Output Utilization - The system design should assure maximum utilization of the PVCS output. Because the PVCS system will serve a 40-hour-per-week operation, and in view of the current high cost of photovoltaic power, it is imperative that attention be given in the design to utilization of the PVCS output available on nonworking days. On weekends and holidays when the load is small, considerable energy can be collected. A balance must be obtained in load design, energy storage, and system operational strategy that results in almost total utilization of the PVCS output. To accomplish this, alternative loads, battery storage, and thermal storage must be considered.
8. Data Acquisition - The experiment must be designed to produce as much useful data as possible, commensurate with other design objectives and

costs. Acquisition of data on a PVCS system that describes the performance of the collectors, cells, tracking system, and inverter is necessary and valuable. It allows evaluation of such arrays in the geographical area in which they are located and allows specific conclusions to be obtained on their performance and general conclusions on their applicability. However, in designing the system with an adaptable data acquisition and control system and with the ability to alter both the PVCS system and the load configurations, additional valuable data can be obtained on specific application modes that are of equal value. Data can be obtained that allow assessment of the system value with different utility rate structures, different load characteristics, and different relationships between energy storage and load profiles. These data are applicable to planning subsequent development of photovoltaic systems.

9. Lasting Value - The system should have a potential life beyond the term of the experiment. The PVCS system will require a significant investment and can provide a greater usefulness than that represented by the operation and data acquisition phase of the experiment. For example, it may be employed to obtain more extensive data; to provide a research vehicle for technology advances in solar cells, concentrators, and tracking systems; or to study system design and application alternatives. The system should be designed to provide for these alternatives. This entails hardware design capable for retrofit, system reliability to maintain operational viability, and an expandable control system.

2.3 DESIGN PROCEDURES AND APPROACH

The design effort oriented to achieving the defined objectives required the participation of the RTI experiment/system design team and four subcontractors. The roles of each of these is described in the following paragraphs.

The RTI design team was responsible for the experiment and system design for the analytical activities that supported this design. This effort included:

- Definition of experiment objectives
- Identification and characterization of loads
- Conceptual design of system
- Specification of performance and operational requirements
- Simulation and analysis of system performance
- Economic analysis
- Final system design

J. E. Sirrine, the subcontractor for architectural and engineering support, was responsible for translating the system design into hardware specifications and for designing the system installation. This included identification of transducer needs, design of the power distribution system, preparation of complete system specifications, and cost estimates for site preparation and installation.

ESB, Inc., through its Exide Power Systems Division, prepared the specifications for, provided the simulation model for, and assisted in defining the system interface characteristics for the power conditioning equipment and battery charger. Critical issues involved were the voltage window for the inverter, the maximum power tracking capability of the inverter, and the ability to have the inverter output connected in parallel with the utility power line. The Wisco Division of ESB provided design data on batteries and designed the storage battery system.

Motorola's design effort on the photovoltaic arrays was undertaken with other funding. As a subcontractor to RTI, Motorola provided complete design and specification information on the arrays, studied design modifications considered for the RTI application, and participated in reviews of the RTI design.

Duke Power Company provided guidance to the system design effort with respect to the utility interface and participated in design reviews of the experiment and PVCS.

Technical issues that arose with respect to the system design are listed in Table 2-2 and are resolved in the following sections of this report.

Table 2-2. System Design Issues

-
- Array:
 - Size and configuration of tracking module
 - Flexibility of configuration for technology growth
 - Cell temperature control
 - Possibility of useful thermal energy collection
 - Array acquisition angle and array shadowing
 - Material and component costs
 - Solar cell and array analytical models
 - Deployment procedures
 - Cell wiring configuration
 - Optical losses and concentrator design
 - Cell efficiency
 - Power Conditioning:
 - Implementation of maximum-power tracking
 - Array-battery-inverter interfaces
 - Inverter-utility interface
 - Inverter control approaches
 - Efficiency
 - Performance model
 - Energy Storage:
 - Size of battery
 - Equalization requirements
 - Battery performance models
 - Efficiency
 - Loads:
 - Sizes and diurnal patterns of loads
 - DC versus AC distribution systems
 - Load strategy
 - Utility interface
 - Load models
 - Load selection
 - Data Acquisition:
 - System interface to DOE onsite data acquisition system
 - Requirements for system data acquisition and control system
 - Identification of data needs and transducers
 - System:
 - Overall control strategy
 - Performance prediction
-

2.4 REPORT ORGANIZATION

In Section 3.0, following this introduction, the system configuration is discussed and the results of system performance analyses are presented. The system components are described in Section 4.0, as specified from the studies and analyses. In Section 5.0 the final system design is described as proposed for installation and in Section 6.0, the data acquisition and operating plan for the evaluation phase of the experiment is described.

3.0 SYSTEM ANALYSIS

3.1 SYSTEM CONFIGURATION

The overall function of the photovoltaic concentrator system designed by RTI is to convert solar energy to electrical energy and to make it available when required so as to significantly reduce the consumption of utility power by a new RTI office-laboratory building. The building incorporates significant energy conservation and storage features which provide a contemporary energy conservation environment for the applications experiment. An early concept of the system configuration is depicted in Figure 3-1. The concept underwent various refinements during this analysis, and the final configuration (Figure 1-5) is somewhat different; however, the design evolution is best described by first considering this configuration.

Figure 3-1. Initial System Concept—RTI Photovoltaic Concentrator System (PVCS) Applications Experiment

Several analysis considerations are suggested by the system function and the configuration shown. First, since the building is being designed concurrently with the PV system, a number of load options have been examined to assess their impact on the PV design system. These are described in Section 3.2. For example, the possibility of a significant direct current (DC) load and its impact on the PV system complexity and cost was considered. The thermal energy collection potential of the system was also considered because of its potential effect on system value. In the design, such options were evaluated and either adopted or rejected as indicated by the evaluation.

Second, an important objective of the design is to reduce demand on the electric utility during peak demand periods. The RTI building is typical of those whose existing electric rates include a demand charge under conventional rate forms, and which would also pay both a demand charge and a higher energy charge during peak demand periods under proposed time-of-day (TOD) rate forms. Reduction of the peak period demand reduces electricity costs with either rate structure. Further, since both TOD and demand charges reflect high utility costs for generation of peaking power that might be avoided if solar conversion becomes widespread, this design objective is advantageous to both the utility and the customer.

A third objective of the RTI system design is to provide electric storage capacity to more reliably provide demand reduction with the natural high variability of solar energy through the year.

A fourth objective of the design is to provide a data acquisition and control system that will measure power flows between various components of the system and control these power flows to enhance PV array performance and reduce electric power bills. This control manipulates the interaction of the arrays, the battery storage and the utility power with specific control strategies for corresponding operating modes designed to enhance overall system performance.

A final objective of the design is to achieve the preceding objectives with a system that is compatible with the overall PRDA-35 experiment. This objective is pertinent to RTI's design process and

has affected the RTI building design so as to provide distinct system operating options.

3.2 SYSTEM LOAD DEFINITION

System loads will be provided by the new RTI engineering building. These loads have been separated into lighting system loads and service loads for the two wings of the building and an HVAC load for the entire building. Estimates of the size and time dependence of these loads are based on experience with similar RTI facilities, knowledge of specific equipment and operations planned for the building and on information provided by the design engineer for the building. The building and each of the load categories are described in the following subsections.

3.2.1 BUILDING DESCRIPTION

The engineering building will comprise approximately 40,000 square feet of office and laboratory facilities. It consists of an east wing with predominantly laboratory facilities with some associated office space, and a west wing that will be predominantly offices. The east wing of the building will contain laboratory facilities oriented to systems research and solar cell development. A rendition of the building design is shown in Figure 2-1. The building is designed to fit into the natural contours with an earthen berm to minimize heat transfer. The west wing of the building is only partially exposed in the figure. Between the wings is a court. The walls surrounding the court are mostly insulated glass which is supplemented by skylights to provide natural light within the building. The building incorporates additional energy conservative features such as heat recovery laboratory hoods. The building electrical system interfaces the RTI power distribution system at a 12kV/480V transformer. A reverse power relay prevents power from feeding from the building into the high voltage line.

Nominal building operating hours are from 8:15 A.M. to 5:00 P.M. Monday through Friday. Experience has shown that significant occupancy takes place from 8:00 A.M. to 6:00 P.M. so these hours are used as the

operating period in the analyses. Sporadic occupancy occurs on weekends and there are nine holidays when occupancy is very low. Neither of these are factored into the analyses.

3.2.2 LIGHTING SYSTEM

In consultation with the building architect and design engineer and with careful consideration of the operations in the building, an artificial lighting level of 1.7 watts per square foot was established. Each of the two building wings will thus provide a maximum 34 kW load which, for the calculations, was assumed to be as shown in Table 3-1. This load profile was used in the final design analyses while somewhat higher demands were used in early calculations.

TABLE 3-1. LIGHTING LOAD (kW)

	Weekday	Weekend	
	8 A.M. - 6 P.M.	8 A.M. - 6 P.M.	24 hours
Load - East Wing	34	1.7	1.7
Load - West Wing	34	1.7	1.7
Load - Total	68	3.4	3.4

The only design option that impacted the lighting system load was consideration of a DC lighting system. Energy efficient fluorescent lighting fixtures that will operate from DC sources are available. The motivation for their use is the fact that a photovoltaic array produced DC power, and it could be more efficient to use DC than to convert to AC power and use conventional lighting ballasts. The characteristics and availability of DC powered lighting fixtures were investigated and representative systems were designed. Since the energy efficient lights operate from AC as well as DC power and their performance is virtually the same with either, the trade-off analysis did not differentiate in that respect. The major interest in DC loads was in elimination or reduction in power conditioning equipment. The DC-AC analysis considered the compressor motors associated with the building HVAC system along with the lighting system. These designs are shown in Figure 3-2. The specific

(a) AC DISTRIBUTION SYSTEM

(b) DC DISTRIBUTION SYSTEM

Figure 3-2. System Designs Used in AC/DC Comparison

parameters of the system differ from those in the final RTI design because this analysis was performed early in the project. However, the conclusions reached are independent of the capacity of the system.

As seen in the figure, the DC system requires a DC regulator in order to match the voltage of the battery in its various charge states to the requirements of the lighting system. The limited availability of DC components necessitates a number of significant differences in the AC and DC systems. With these two designs, the system efficiency and costs associated with each was determined. It was found that the efficiency in transferring power from the arrays to the loads did not differ significantly. Analysis of the overall costs indicated that the DC system costs about 14 percent more than the AC system. The array cost is not included in this comparison. Summaries of the efficiency and cost calculations are given in Table 3-2 and 3-3, respectively.

TABLE 3-2. COMPONENT AND SYSTEM EFFICIENCY FOR AC AND DC DISTRIBUTION SYSTEMS

Component	Distribution System	
	AC	DC
Array Feeder	0.981	0.982
DC/DC Controller	0.960	0.960
Inverter	0.940	
DC Regulator		0.960
Float Charger	0.940	0.940
Distribution Feeder	0.996	0.996
Branch Circuit Wiring	0.966	0.946
Ice Maker Motors	0.860	0.820
Array to Lighting Load	0.852	0.853

The conclusion that was reached in this analysis was that the anticipated advantages of the DC system did not materialize. Moreover, the necessity for providing considerable power to the DC loads through the

TABLE 3-3. COMPONENT AND SYSTEM COSTS FOR AC AND DC DISTRIBUTION SYSTEMS

Component	Distribution System	
	AC	DC
Array Feeder	\$ 5,350	\$ 16,050
DC/DC Controller	30,000	30,000
Battery	145,000	145,000
Float Charger }		20,000
Inverter }	60,000	
DC Regulator		30,000
Distribution Feeder	500	1,605
Transfer Switch		12,000
Lighting Panel	1,290	2,580
Branch Wiring	7,500	8,878
Lighting Fixtures/Ballasts	61,465	61,465
DC Motor Controllers		8,000
DC Motors		30,000
AC Motor Starters	3,200	
AC Motors	4,950	
Total (less array)	\$319,255	\$365,578

battery charger further reduces the DC system efficiency and that effect is not included in this analysis. The cost of maintenance of the DC system was expected to be considerably greater than for a conventional AC system, and mixed AC/DC loads in the building would reduce the flexibility in operation of the system during Phase III of the experiment. For these reasons, the decision was made to design a system that would service only AC loads.

3.2.3 SERVICE LOADS

The service loads for the building are defined as all electrical loads other than the lighting system and HVAC system. This includes such diverse applications as:

1. office equipment - typewriters, copiers, word processors, vending machines, coffee makers, drafting tables, and computer terminals.
2. laboratory equipment - computers, displays, test equipment, ovens, furnaces, analytical equipment, vacuum pumps, heaters, hot plates, and illuminators.

Institute plans for the building include a semiconductor processing facility that uses high-temperature diffusion and epitaxy furnaces and computers that remain on constantly. An inventory of this continually operating load has established a base of 30 kW. Estimates of additional service loads (approximately 30 kW) that are required only during operational hours are based on Institute experience and ASHRAE design standards. The total service load profile for the east wing of the building is shown in Table 3-4.

TABLE 3-4. SERVICE LOAD PROFILE (kW)

	Hours			
	Weekday			Weekend
	8 A.M. - 6 P.M.	6 P.M. - 8 A.M.		24 hours
Service Load (east wing)	60	30		30

3.2.4 HEATING, VENTILATING, AND AIR CONDITIONING (HVAC) LOAD

Early concepts of the PVCS system included the building HVAC load playing a significant role, particularly in utilizing excess weekend array output. Simulation analyses showed that there is a nearly year-round air conditioning component of the HVAC load. Changes in the building design to reduce the load magnitude somewhat and the preliminary design of an ice storage system for the building have shown, however, that an air conditioning (ice maker) compressor of 25 kW that operates in off-peak hours will be adequate. This is well below the 100 kW peak array output and is thus attractive as a load. Subsequent analyses have not explicitly considered HVAC as an array load since other loads with better diurnal profiles have been shown to result in good PVCS performance. The HVAC

system is still recognized as providing an alternative load, and its thermal storage will be of value in obtaining full use of the array output.

3.2.5 PVCS LOAD

AC power is required by the PVCS system to operate the two-axis tracking system of the arrays and to power the electronic control systems. The major load, that of the tracking system, is only active when the PVCS is providing an output and amounts to 2.0 kW when tracking and 0.5 kW when not tracking (the main control system operates continuously).

3.2.6 LOAD SUMMARY

The overall system load is the total of those described in the previous subsections. Loads during various time periods relating to working hours and utility peak load periods are summarized in Table 3-5. The utility peak periods are based on those hours in which the load on the utility exceeds 90 percent of the peak load. These hours are:

June - September	11 A.M. - 10 P.M.
October - May	6 A.M. - 1 P.M. and 5 P.M. - 10 P.M.

(Apply Monday through Friday only)

3.3 OPERATING ENVIRONMENT

The RTI photovoltaic concentrator system is to be located on the RTI campus in Research Triangle Park, North Carolina, at the location shown in Figure 3-3. The coordinates are 78°50'W and 35°54'N and the elevation is 434 feet.

The photovoltaic arrays are located with respect to the building as shown in Figure 2-4. A site plan is shown in Figure 2-3. The visitors' center, control systems, and battery for the PVCS will be located in the engineering building near the entrance closest to the arrays.

TABLE 3-5. LOAD SUMMARY (kW)

Load****	Local Time							
	10P-6A	6A-8A	8A-11A	11A-1P	1P-5P	5P-6P	6P-9P	9P-10P
Lights								
East Wing**	1.7	1.7	34 (1.7)	34 (1.7)	34 (1.7)	34 (1.7)	1.7	1.7
West Wing	1.7	1.7	34 (1.7)	34 (1.7)	34 (1.7)	34 (1.7)	1.7	1.7
Total	3.4	3.4	68 (3.4)	68 (3.4)	68 (3.4)	68 (3.4)	3.4	3.4
Service	30	30	60 (30)	60 (30)	60 (30)	60 (30)	30	30
HVAC - June -	23.5	23.5	23.5	0 (23.5)	0 (23.5)	0 (23.5)	0 (23.5)	0 (23.5)
Sept -								
Oct -	23.5	0	0	0	23.5	0	0	23.5
May -		(23.5)	(23.5)	(23.5)		(23.5)	(23.5)	
System	0.5	2.0*	2.0*	2.0*	2.0*	2.0*	0.5	0.5
Total***	33.9	35.4	130 (35.4)	130 (35.4)	130 (35.4)	130 (35.4)	33.9	33.9

* Dependent on day of year and insolation conditions.

** Primary load for PVCS system.

*** HVAC not included in totals. Assumed continuous operation in non-peak periods.

**** Loads of nonworking days are given in parentheses if different from those of working days.

Figure 3-3. Location of Research Triangle Park in North Carolina

The Research Triangle Park (RTP) provides an ideal "showcase" for the RTI Photovoltaic Concentrator Experiment. Because RTP is the most successful of modern research parks with the highest per capita population of Ph.D.'s of any Standard Metropolitan Statistical Area in the U.S., and because of the strengths of the educational complex in the area, RTP has a large number of visitors from both the U.S. and other countries. The design of the system and site have been carried out to enhance the public image of the experiment.

3.3.1 METEOROLOGICAL CONDITIONS

At RTI's latitude of 35.9° N, the sun's zenith elevation angle varies between 30.65° and 77.55° , with a mean of 54.1° . The solar elevation angle is greater than 20° for about 5 hours near the winter solstice and for about 11 hours near the summer solstice. The sun's dawn and dusk azimuths vary 30° from east and west, respectively.

The solar distance is about 152 million km in July and 147.2 million km in January. Consequently, the solar constant is approximately 7% higher

in January than in July. However, the sun is at lower elevation in winter, and optical air mass is increased. The sun (diameter 1.39 million km) subtends an angle of about 0.53° .

Long-term insolation data is not available for the Research Triangle Park. The selection of a SOLMET site as representative of RTP was necessary. Nashville was chosen because it is nearly the same latitude and has similar general climate characteristics. Table 3-6 compares a relevant meteorological parameters.

TABLE 3-6. METEOROLOGICAL COMPARISON

	Nashville	RTP
Heating Degree Days	3599	3514
Cooling Degree Days	1643	1394
August Average Maximum Temperature	89°F	87°F
January Average Minimum Temperature	29°F	30°F
Total Annual Direct Insolation	1288 kWh/m ² **	1468 kWh/m ² *
Number of hours in which ratio of actual to maximum possible direct-normal insolation exceeds		
75%	444**	811*
50%	1302**	1542*
25%	1922**	2088*

* From EPA-RTI data, 1976 only.

** Nashville TMY data.

This comparison shows somewhat similar distribution of insolation (Figure 3-4 and Table 3-6). The general insolation level at RTP for 1976 is higher than for the Nashville TMY data. Analysis of the Nashville data shows that during the hours of insolation, the mean temperature is 64.4°F and the mean wind speed is 4.2 meters per second. Mean wind speed for RTP is 3.6 meters per second.

Temporal variations of the Nashville TMY data were investigated in preparation for use in the system simulation. Figures 3-5 and 3-6 show the insolation by week and by month, respectively. Figures 3-7 and 3-8 show the insolation by day for June and December, respectively. For these figures, the acquisition angle was 0° (no cutoff).

Figure 3-4. Comparison of Nashville TMY and RTP Insolation Data

The conclusions drawn were that

- insolation is extremely variable in all seasons, and
- insolation is about twice as high in June as in December (note that this correlates well with the length of the solar day).

Because the tracking array structures had to be designed to withstand wind velocities that will typically exist while in the tracking mode, the association of insolation and windspeed was also examined (Figure 3-9). Almost all insolation was associated with windspeeds between 1 and 10 m/se (both for Nashville and Washington). The peak windspeed at times of insolation was about 15 m/sec.

3.3.2 UTILITY ENVIRONMENT

Duke Power Company, a participant in the design effort, is the utility serving the Research Triangle Park. Duke Power has cooperated fully in the design of the experiment and views it as an important data source for their efforts in reducing demand peaks.

Figure 3-5. Nashville TMY Insolation Profile By Week

Figure 3-6. Nashville TMY Insolation Profile (By Month)

Figure 3-7. Nashville TMY Insolation Profile (June)

Figure 3-8. Nashville TMY Insolation Profile (December)

Figure 3-9. Association of Insolation and Windspeed — Nashville and Washington, TMY

Two utility rate structures are of direct interest to the experiment and have been applied in the economic analyses for the system. These are given in Tables 3-7 and 3-8.

TABLE 3-7. GENERAL SERVICE RATE STRUCTURE

<u>For the First 125 kWh per kW Billing Demand per Month:</u>		
\$1.51	for the first	10kW or less
7.50	cents per kWh for the next	40 kW
4.91	" " " " " "	1,220 kW
4.03	" " " " " "	1,730 kW
3.51	" " " " " "	27,000 kW
3.35	" " " " " "	30,000 kW
3.17	" " " " " "	30,000 kW
2.54	" " " " " "	910,000 kW
2.52	cents per kWh all over	1,000,000 kW
<u>For the Next 275 kWh per kW Billing Demand per Month:</u>		
3.32	cents per kWh for the first	3,000 kW
2.51	cents per kWh for the next	3,000 kW
1.89	" " " " " "	20,000 kW
1.77	" " " " " "	75,000 kW
1.59	" " " " " "	89,000 kW
1.43	cents per kWh for all over	190,000 kW
<u>All Over 400 kWh per kW Billing Demand per Month:</u>		
1.43	cents per kWh for the first	1,000,000 kWh
1.37	cents per kWh for all over	1,000,000 kWh

Note: Approved fuel charges over and under rates shown above apply.

3.4 HARDWARE OPERATING CHARACTERISTICS

The design of a successful PVCS system takes into account not only the external influences of loads and meteorological variables, but also the inherent characteristics of the major system components. These are generally well known and do not require extensive review but a statement of some critical characteristics provides a framework for the analysis in Section 3.6. It also aids in describing some choices of basic steady state operating parameters.

TABLE 3-8. PROPOSED MANDATORY TIME OF DAY RATES

	Residential	General Service		Industrial	
		Less Than 15 kW	More Than 15 kW	Less Than 15 kW	More Than 15 kW
Customer Charge					
\$ per Month	\$10.75	\$11.00	\$16.60	\$12.70	\$16.65
On Peak Hours Energy Charge					
Cents/kWh	1.70¢	1.70¢	1.70¢	1.70¢	1.70¢
Off Peak Hours Energy Charge					
Cents/kWh	1.20¢	1.20¢	1.20¢	1.20¢	1.20¢
Demand Charge June-September					
\$ per kWh	\$ 2.84	\$ 5.95	\$ 5.95	\$ 3.87	\$ 3.87
Demand Charge October-May					
\$ per kWh	\$ 1.42	\$ 2.98	\$ 2.98	\$ 1.93	\$ 1.93
Economy Demand Charge					
\$ per kWh	----	----	\$ 0.50	----	\$ 0.50

Peak hours: Apply Mondays through Fridays only.

June - September (summer) 11:00 A.M. - 10:00 P.M.

October - May (base) 6:00 A.M. - 1:00 P.M.

5:00 P.M. - 9:00 P.M.

3.4.1 PHOTOVOLTAIC ARRAY

The arrays considered here are two-axis tracking devices receiving essentially direct normal radiation only. The concentrator solar cells are nearly constant voltage devices whose current output is a strong function of insolation level. Output efficiency is decreased as cell temperature increases so that ambient temperature and wind speed both influence efficiency. Therefore, the array field has a maximum power point which is function of insolation, temperature, and wind speed. It is desirable to operate as near to this maximum power point as possible. Table 3-9 illustrates the range of voltages at the maximum power point over a year using a simulation of the Motorola array.

The Motorola array chosen for this application with its quarter-cells-in-series approach is designed to allow design output voltages of either 120, 240, or 480 volts nominal. Early analysis of power distribution efficiency and associated costs for the overall system showed a 120 volt system to be prohibitively costly, with 240 or 480 volts being preferable. Costs favor the 480 volt system and it was chosen. Array field power levels were then selected on the basis of performance simulations.

TABLE 3-9. MAXIMUM-POWER POINT VOLTAGE RANGE, MOTOROLA ARRAY*

Voltage Range	Number of Hours of Occurrence	Voltage Range	Number of Hours of Occurrence
450-460	0	530-540	389
460-470	13	540-550	312
470-480	18	550-560	184
480-490	143	560-570	140
490-500	325	570-580	102
500-510	348	580-590	89
510-520	425	590-600	6
520-530	431	600-610	1
* 240 cells per string			

3.4.2 STORAGE BATTERY

Electric batteries are, like the array, nearly constant voltage devices, with low internal impedances. In normal operation, a fully charged battery is maintained by a charger at a "float voltage" of about 2.2 VPC (volts per cell) for lead acid batteries. During discharge, the battery voltage drops to about 2.0 VPC within a few minutes, and will then decrease somewhat linearly (at constant discharge rate) to about 1.85 VPC when about 80 percent of the capacity has been used. Thus, depending on whether the battery is "floated" on the array output (i.e., continuously connected) or connected only during discharge, will determine the number of cells in the series string. Battery charge capacity is determined by the number of parallel plates in the cells. If the battery is floated on the array, then the design array maximum power point voltage corresponds to the battery float voltage of 2.2 VPC. If the battery is connected only during discharge, then the nominal 2.0 VPC determines the number of cells. The system performance determines the strategy of battery use and it will be seen that the initial choice of floating the battery evolved to the alternate approach as the analyses proceeded.

The other major consideration in storage battery use is the efficiency. This depends on many factors including battery temperature, charge and discharge rates, depth of discharge and battery design. A nominal round-trip efficiency is about 80 percent, so that for energy storage that is significant with respect to the array output, battery

efficiency strongly affects the system performance.

Since the design battery voltage is achieved by connecting a number of cells in a series, a 480 volt nominal battery bank is quite feasible, and is the choice assumed in subsequent analyses.

3.4.3 POWER CONDITIONING EQUIPMENT

The power conditioning devices contemplated in the conceptual design (maximum power tracker, inverter, and battery charger) are all solid state devices exhibiting excellent waveforms, transient performance, regulation, and overload performance. The major system considerations are input voltage range and partial-load efficiency. Table 3-9 shows that maximum array power will almost always be obtained at voltages between 480 and 580 volts, and this range is accommodated by the power conversion devices. The battery voltage swing is also accepted by the devices since they operate in the battery floating configuration when serving as uninterruptable power sources.

The nominal design input voltage of the power conditioning devices depends on breakdown voltage ratings of their semiconductor devices and a 480 V input design is available and assumed in the analysis.

The power conditioning devices have an efficiency of 90 percent or better at loads above 30 percent of their rated load, and begin to fall significantly when operated below that load. This makes it important to maintain the inverter load above 30 percent, although it is recognized that if the array output is low and there is no storage available, putting it through the inverter at low efficiency is better, within limits, than stowing the array. Accurate efficiency models based on commercial experience are used in the subsequent analysis.

3.5 OPERATING MODES AND CONTROL FUNCTIONS

Control functions used in the RTI photovoltaic concentrator system (PVCS) are not conceptually complex. Basic control provides for a number of conditioned responses to the system transducer outputs and

establishment of any one of four operating modes for the system. These operating modes determine the interaction of the PVCS subsystems and constrain the system operation so as to meet defined operational objectives. The control functions that establish the operating modes investigated are discussed first.

The power delivered by the PVCS to the loads is manipulated by the inverter. In the inverter design adopted during this design process, there are three control methods that are established by its self-contained microprocessor in response to commands from the Data Acquisition and Control System (DACS). These three inverter control methods are (1) maximum-power tracking, (2) constant-voltage, and (3) output-power control. In maximum-power tracking, the inverter output is controlled so as to maximize inverter input power obtained from the array. In this mode, the battery is disconnected from the inverter input and power is delivered by the PVCS to the loads in proportion to the available direct normal insolation. In the constant-voltage control method, the output voltage is controlled to the specified 208 VAC level and the output power is determined completely by the load. This control method would be used for supplying loads isolated from the utility. In the last inverter control method, the output power level is determined in response to inputs from the DACS. This control method for the inverter would be used when the solar insolation is low and the battery is connected into the system.

Four operating modes for the PVCS are established by operational objectives as described in Section 6.0. These four operating modes are time-of-day, demand reduction, parallel battery, and isolated load. Each mode responds to a different type of potential application. The first two operating modes involve operating in parallel with a utility but with different rate structures. The third mode is to test the efficacy of keeping the battery connected to the array continuously, and the last addresses performance capability with a load not connected to the utility.

Examining, as an example, the first mode and the inverter control methods that apply, one may define a set of control functions. (Similar control functions exist for the other three operating modes; however, only those of the first mode are discussed here.)

As seen in Table 3-10, the control system follows a multi-level decision path in establishment of mode 1 operating conditions. In providing conditional responses to system transducer outputs, the decision paths are typically single level. For example, if wind speeds exceed 30 mph, the arrays will be stowed, and if the batteries are being charged, the exhaust of the battery room will be increased.

3.6 SYSTEM PERFORMANCE AND COST TRADEOFF ANALYSIS

In the description of the simulation, it is important to note that in the iterative development process, system operating modes and parameters which are not part of the final system design have been simulated. For a succinct description of the final operating mode, see Section 3.6.2.8.

3.6.1 SIMULATION STRUCTURES

3.6.1.1 General Approach

Two TRNSYS-based simulations were developed for the analysis. The first was a simulation of the building's HVAC demand resulting from meteorological conditions given by the Nashville TMY. This simulation was run in the early stages of analysis, before the building's architectural design was completed; therefore, it cannot be regarded as being totally accurate. It did, however, provide a load profile estimate and some useful insight into demand patterns.

The second simulation was used to analyze the PV system, and it evolved into a form which is thought to fairly accurately represent the operating strategy, the efficiency, and the power output of the designed system.

The computer simulation of the PVCS and of its loads has been assembled from several sources. The executive and I/O portions of the TRNSYS simulation were combined with a PV array model (structured like that used in the SOLCEL simulation), a new power conditioning model, and an economic model. The simulation is run with Typical Meteorological Year data for Nashville, Tennessee. The PV array model simulates operation (whenever the acquisition angle is exceeded) at a given insolation,

TABLE 3-10. MODE 1 OPERATING STRATEGY

During peak periods:

- if array output is sufficient to supply primary load
and if total load exceeds the PVCS output, then battery is disconnected, and the inverter is operated with maximum-power tracking.
- and if total load is less than PVCS output, then battery is connected for charging, and the inverter is operated with output-power control.
- if array output is not sufficient to supply primary load, then battery is connected, and the inverter is operated with output-power control.

During off-peak periods with the array output greater than zero:

- if array output is less than 10 percent of its peak rating, then the battery is connected for PV charging, and the inverter is disconnected from the load.
- if array output exceeds 10 percent of its peak rating
and if the total load exceeds the PVCS output, then the battery is disconnected, and the inverter is operated with maximum-power tracking.
- and if the total load is less than the PVCS output, then the battery is connected for PV charging, and the inverter is operated with output-power control.
- and if array output exceed battery charging and load requirements, then array output is decreased by stowing arrays.

During off-peak periods and with no array output:

both battery and inverter are disconnected from the load.

temperature and windspeed, either at the maximum power operating point or at an alternate array output voltage (e.g., the battery voltage, if the battery and PV array are directly connected). An electric power distribution loss of one percent was used for all configurations based on the engineering design.

The modeled components of the system are:

- array
- lighting load
- battery charger
- service load

- battery
- battery load
- inverter (with and without maximum-power tracking)
- direct utility backup
- DC power controller with maximum-power tracking

When battery charge state, array output, and loads allow, the battery is charged from PV and, when required, the battery is charged from the utility during off-peak hours to meet the defined "battery load" for the peak period of the next day. When the battery charge state exceeds the next day's battery load requirements, the battery will be used to supply any part of the primary load (i.e., lights plus service). The PV array output is used to charge a partially-charged battery in two distinct cases:

- PV power exceeds the primary load requirements
- PV power is available during off-peak hours but is inadequate for efficient inverter operation

The loads have high and low levels, representative of working hours and non-working hours (i.e., nights and weekends). The battery-dedicated load, which also has two levels, is chosen to be equal either to the lighting load or to the lighting load plus a fraction of the service load.

Although the primary load is always supplied through the inverter during peak hours, a very low efficiency results when the load is very small (say, less than 10 percent of the inverter rating). In non-peak hours, this low efficiency operation is avoided when the PV energy can be used to charge the battery instead.

When the battery is fully charged, all PV power flows through the inverter. Certain parameter combinations (e.g., large array and small battery) result in excess AC power. This excess would be utilized (e.g., for the HVAC load), but no credit for this excess is given in the economic model. The battery voltage model is a piecewise-linear function of the charge state as defined by Table 3-11.

Table 3-11. BATTERY VOLTAGE/CHARGE STATE MODEL

State of Charge	Voltage/Cell	PV Array Operating Voltage When Connected to Battery*
1.00	2.20	528.0
.95	2.05	492.0
.2	1.83	439.2

*There are 240 battery cells in a series string and 960 Motorola quarter cells in a series string.

The simulation also includes models of conventional declining block rate forms (Hopkinson Demand and Wright Demand) as well as a time-of-day rate form. The value of electric energy produced by the array, as well as the cost of electricity purchased from the utility is computed from these models. A life cycle cost model incorporates the essential features of the system including purchased energy, capital investment, depreciation and other factors according to accepted practices. These models allow comparison of PV-produced energy with purchased energy on a present worth basis over the system life.

3.6.1.2 PV Simulation Structure

The TRNSYS-based simulation structure is indicated in Figure 3-10.

Originally, the PV array power subroutine comprised several subroutines from the SOLCEL simulation, adapted to the TRNSYS format. Eventually, most of these subroutines were replaced in order to simulate the specific RTI system more realistically.

For example, a new cell-temperature model was developed by using equation forms based on theory and fitting these models to data provided by Motorola for their cell (the SOLCEL cell temperature subroutine is not directly applicable to the Meinel module). Selected temperature rises predicted by this model are shown in Table 3-12. Since insolation is usually accompanied by some wind (see Figure 3-9), forced stowing because of high cell temperature would seem to be an extraordinary situation.

Figure 3-10. Structure of TRNSYS — Based PV Simulation

TABLE 3-12. CELL TEMPERATURE RISE ABOVE AMBIENT AS PREDICTED BY RTI MODEL

Wind Speed m/sec	Insolation Watts/m ²	Temperature Rise Degrees C
0	0	0.0
0	250	12.6
0	500	22.3
0	750	31.3
0	1000	39.8
<hr/>		
3	0	0.0
3	250	5.3
3	500	10.6
3	750	15.8
3	1000	21.1
<hr/>		
15	0	0.0
15	250	3.3
15	500	6.6
15	750	9.9
15	1000	13.3

The cells' I-V characteristics at specified cell temperatures and insolutions were simulated using a FORTRAN subroutine provided by Motorola. Selected characteristic curves are shown in Figure 3-11. Note that these curves represent the effect of concentrated insolation on four quarter-cells in series. The maximum power points are indicated. Recent data on Motorola cells show that this model is somewhat conservative in its maximum power estimates. Figures 3-12 and 3-13 show the effect of cell temperatures on quarter-cell power and voltage, respectively, at the maximum power point. Note especially the small change in maximum power point voltage with a ten-to-one change in concentrated insolation.

To avoid excessive computation time, the PV power subroutine adopts the SOLCEL approach of generating, in the initialization phase, a maximum power table as a function of insolation and cell temperature and then interpolating within this table for the remainder of the simulation. In the RTI simulation, a maximum power point voltage table is also generated in order to investigate the variability of operating voltage. The SOLCEL subroutine PVMAT was found to interpolate across the wrong interval; this error was corrected in RTI's simulation.

Figure 3-11. Motorola Full Cell I-V Curves From Fortran Model

Figure 3-12. Motorola Quarter — Cell Power vs. Cell Temperature

Figure 3-13. Motorola Quarter — Cell Voltages at Maximum-Power Point vs. Cell Temperature

With the battery connected to the DC bus, it is necessary to simulate array operation away from the maximum-power point. The simulation was changed to predict the powers available in two cases: at the maximum-power point and, also, at a specified input voltage. This input, for the purposes of the present simulation, was simply the battery voltage at the end of the previous timestep. The choice between the two modes of operation is made in the power conditioning subroutine. On the runs which were made, it was always possible to operate the array at the battery voltage when series strings comprised 240 battery cells and 960 Motorola quarter-cells, respectively.

The power conditioning subroutine is completely new. It models a PV power conditioning/battery storage system subject to peak load pricing. The components of the system are:

- photovoltaic collection system,
- optional maximum-power-tracking DC-DC converter,
- battery,
- utility-operated charger (used only in off-peak periods,
- inverter to supply AC loads,
- AC lighting and service load (the primary load),
- a portion of this load to which the battery is dedicated (If this portion cannot be supplied with PV energy during peak periods, the deficit is met from the battery rather than the utility. Ordinarily, this "battery load" is the lighting load plus some fraction of the service load.), and
- other AC loads to be supplied when excess PV energy is available (e.g., HVAC).

The inverter, battery charger and maximum-power tracker efficiency models, obtained from EXIDE, each have the form of a rational function of output power as a fraction of rated power.

A simple energy storage model is used for the battery, with input and output efficiencies preset at 88% each. This yields a throughput efficiency of approximately 77.4%. Charge and discharge are limited to the 4-hour rate, and the state of charge (fraction of total rated energy capacity) is held between 0.2 and 1.0. Battery voltage is modeled as a piece-wise linear function of state-of-charge (SOC):

$$\text{CELL VOLTAGE} = 2.05 + 3.0 * (\text{SOC} - .95), \text{ when } \text{SOC} \geq .95$$

$$\text{CELL VOLTAGE} = 2.05 + .293 * (\text{SOC} - .95), \text{ when } \text{SOC} < .95$$

A variation of the SOLCEL subroutine BATRY was used initially, but it was replaced by this simple model when BATRY was found to show a throughput energy efficiency of about 93%, which is much too high for the batteries being simulated.

The power conditioning subroutine first characterizes the system's operating conditions very thoroughly by logical variables and then uses these logical variables to determine power flows between system components, simulating control by digital gates. After the flow to or from the battery has been calculated by applying the battery model, the remaining power flows may be determined very directly using the operational strategy, which has been defined in 3.6.1.1 and elsewhere in this report.

3.6.1.3 Structure of Load Simulation

The basic structure of the load simulation is shown in Figure 3-14. Arrows indicate the flow of information at each timestep. The components of the simulation are detailed below and results, by week, for a simple block building, are indicated in Figure 3-15.

The building simulated was a (two-story) 45 x 45 x 6 meter structure with a slab floor and a flat roof. The wall parameters were those of an ASHRAE #58 wall and the roof was an ASHRAE #13 roof (see ASHRAE Fundamentals, 1977, Chapter 25).

FORCING FUNCTIONS (WEEKLY CYCLE)

Figure 3-14. Structure of TRNSYS Load Simulation

Figure 3-15. Nashville TMY Weekly Log Profiles

The meteorological data file contained Nashville, TMY, data for the following:

- ambient dry-bulb temperature
- total insolation on a horizontal surface
- windspeed
- energy required to condition a cubic meter of ventilation air under these conditions

The latter was obtained by preprocessing the dry-bulb and dew point temperature data, using the methods outlined in the ASHRAE Fundamentals, 1977, including the Goff formula for saturation pressure (Equation 4 of ASHRAE, Chapter 5). An atmospheric pressure of one atmosphere was assumed for this preprocessing. Enthalpy control is simulated in the cooling season, but not in the heating season; however, the interior conditions are always assumed to be 22°C at 50% relative humidity. This leads to a slight error at high humidity in the heating season. Selected conditioning energy estimates appear in Table 3-13. In the block diagram, Figure 3-14, the quantity of ventilation is specified by a forcing function (TRNSYS Type 14), and the ventilation processor simply converts to its conditioning-energy equivalent (by multiplication).

TABLE 3-13. ENERGY REQUIRED TO CONDITION VENTILATION AIR,
CALCULATED BY ASHRAE METHODS

Dry-Bulb Temperature Degrees C	Dew Point Temperature Degrees C	Conditioning Energy Required (KJ/m ³)
10	1	-28.6
20	11	- 3.5
20	15	3.8
30	15	15.4
30	19	24.1
30	21	29.2

The solar radiation processor (TRNSYS Type 16) determines the insolation on exterior wall surfaces from the value on a horizontal surface.

Heat gain or loss through walls and roof are simulated by TRNSYS Type 17 subroutines. Exterior ambient temperature, windspeed, total insolation, and interior temperature are inputs to these subroutines. The latter temperature is fed back from the building load subroutine (TRNSYS Type 19). This model also incorporates a model for heat loss through a concrete slab floor. The effect of walls, roof, and slab are combined with that of ventilation and internal heat generation associated with lights, service, and the sensible and latent components of occupancy in the building load model to compute a single heating or cooling load figure. Forcing function parameters used in the load simulation runs are tabulated in Table 3-14.

TABLE 3-14. LOAD SIMULATION FORCING FUNCTION PARAMETERS

Forcing Function	High Level (for days)	Low Level (for nights and weekends)
Ventilation (Including Hoods)	9,760 m ³ /hr	3,644 m ³ /hr
Occupancy (Sensible and Latent)	80,000 KJ/hr	0 KJ/hr
Lighting	313,900 KJ/hr	0 KJ/hr
Service	324,200 KJ/hr	0 KJ/hr

3.6.2 ANALYSES AND RESULTS

3.6.2.1 General Approach

The RTI design is based on simulations as defined above incorporating the loads, environmental data, and operating modes as described. Because the RTI engineering building was being configured at the same time as the PV system, the system loads to be included in the Phase III experimental program were chosen along with the appropriate PV system design. The analyses described here lead to the choices of system parameters for each of those loads in arriving at the final design.

Given the number of load and system options combinations possible, only a limited number of these could be evaluated. Thus, a somewhat evolutionary, rather than exhaustive, approach was followed to select a suitable system design.

Predictably, there has also been an evolution of the RTI engineering building design as the project progressed. These changes are reflected as changes in some of the basic load parameters. Care has been taken, however, to maintain constant load definitions in evaluating a particular design choice.

3.6.2.2 Shading Analysis

Figure 3-16 shows the effect of acquisition angle upon annual insolation for Nashville TMY data. For very small elevation angles, insolation tends to be reduced by the effects of a large optical air mass or local ground fog, so the effect of a 5° acquisition angle is minimal. As the acquisition angle is incremented, the loss increment is increased. The gain in usable insolation resulting from a decrease in acquisition angle must be balanced against the difficulties of shadow avoidance and other factors. The basic shading constraints are shown in Figure 3-17. The shadow of a W X H tracking array is a rectangle of width W and length S given by the upper curve of Figure 3-17. Other arrays must be outside this shadow region. It is difficult to determine the extent of intrafield shadowing of a complex array field for an entire year's combinations of solar azimuth and elevation, so a computer program was created for this purpose. This program simulates the intranetwork shadowing of general fields of rectangular arrays undergoing two-axis tracking of the sun (with one axis vertical). The arrays must have their centers on a single plane, but the plane may have a N-S slope.

The shading analysis shows that:

- it is impossible to avoid E-W shading for all solar elevation angles,
- it is possible to avoid intranetwork shading at all times using a single N-S row of arrays, but extranetwork shading is still a problem. The stressing case is then near solar noon at mid-winter zenith (the exact time is dependent upon array dimensions),

Figure 3-16. Insolation Loss Due to Acquisition Geometry Alone

Figure 3-17. Shadow Length vs. Solar Elevation Angle

- a North-to-South land slope reduces North-South spacing requirements except near the summer solstice, when the sun has northern azimuths at fairly large elevations.

Some system configurations permit the utilization of some unshaded arrays of an array field while other arrays are shaded. For example, the array front rows, with respect to current sun position, will not be shaded by other arrays. Partially shaded series strings of cells were assumed to be useless because of high series resistance.

Several reasons for not choosing a very small acquisition angle can be enumerated:

- Smaller acquisition angles are associated with larger optical air masses, hence, more absorption.
- The sun's angular subtense is increased by scattering at low angles so that tracking restrictions become more stringent.
- The tracking system is complicated by refraction for low angle tracking.
- The system is more sensitive to local weather conditions (e.g., ground fog).
- East-West shadowing cannot be totally avoided by any spacing.
- Low elevation time periods are often low demand periods.
- Power consumption for tracking is reduced.
- Large spacing requirements restrict original installation and expansion flexibility.
- Large spacing implies higher losses in the interconnecting wiring and in the main feeder.
- Low level PV energy is used less efficiently by system components.

3.6.2.3 Initial Design

In order to define a reasonable point of departure for the system definition and performance analysis, two design rules were established. First, the array would be designed to provide the energy for the total

building lighting load. Second, the system would incorporate electric storage so that the lighting load would not be imposed on the utility during defined utility peak load periods should low insolation provide insufficient PV energy. It is in this sense that the lighting load is referred to as the "primary" load. In subsequent parts of the analysis, the primary load includes the lighting and service loads determining the battery power flows. The analysis would also examine the degree to which the total system output would be utilized.

An initial design goal of 1.7 watts per square foot of floor area for lighting and 44,000 square feet of area, required a lighting load of 74.8 kW. The defined lighting diurnal profile of full capacity for 10 hours and 5 percent for 14 hours requires 800 kWh per working day. The Motorola array design peak output is 9576 W and system losses were estimated in Section 3.2.1.2 at 15 percent. On the winter solstice day, an array acquisition angle of 15 provides 6.4 hours of array operation. Taking into account the form of the measured diurnal direct normal insolation, the ratio of average array output to peak output is about 0.9. Therefore, the required number of arrays for this load is

$$\text{No. arrays} = \frac{800 \text{ kWh/day}}{(9576\text{W})(0.85)(0.9)(6.4\text{hr/day})} = 17.1$$

This 18 array field was a convenient size since it would have a rated capacity of 172 kW and 180 kW is a standard ESB inverter capacity.

The initial battery capacity was determined as the lighting energy required from 3 P.M. to 9 A.M. (these being the hours when solar power is unavailable) plus energy for the maximum seven hour peak demand period following. This totals 875 kWh of usable battery capacity, or approximately 1100 kWh total capacity.

3.6.2.4 Simulation Analysis

In order to present concisely the rationale for the selected design, the various analyses carried out are organized in Figure 3-18 according to the basic definitions, power conditioning options, battery use strategy, component size parameters. The letters in parentheses after the size

Figure 3-18. Load/System Analysis Cases Considered

parameters are used subsequently to identify the various cases considered. All of the performance indicators were computed for each case considered, and the more important results are given here in support of the design choices made. Basically, two system designs have been considered. The first, System I, is a 180 kWp system for the full building lighting load as described in the preceding section. The second, System II, is a nominal 100 kWp system defined to serve the east wing lighting and service loads.

3.6.2.5 System I Analysis

The overall system performance has been computed for parameter cases 1Aa, 2Ba, 3Ca, 3Ea, and 4Fa of Figure 3-18, and the performance is illustrated in Figure 3-19(a-d). The 10 and 26 array configurations are nominally 100 kWp and 250 kWp and include compatibly rated subsystem components. The percent of the lighting load (74.8 kW) supplied from the array varies from 35 percent to 62 percent as the array field size increases from 10 to 26 arrays with the nominal 18 array size providing 55 percent (Figure 3-19(a)). Note also that one-third of the power passing through the battery, at times dictated by the operating strategy, comes from the array and two-thirds from the utility in the 18 array case. The proportion of battery energy from the PV array is larger for a larger array.

One of the objectives of the analysis was to determine the amount of energy available to other loads, designated in Figure 3-19(b) as "excess", and to select other loads to absorb the energy. Figure 3-19(b) shows about 2 percent excess for 10 arrays, increasing to 30 percent for 26 arrays. Losses of array power in the system run about 20 percent for all array sizes. Figure 3-19(d) shows that for the battery size range investigated, the storage capacity has almost no influence on the distribution of power in the system. Other computations show that a nearly constant 28 percent of the utility power is lost in the system. Total losses from array and utility are about 41 percent of the array output, suggesting a design with much too high energy losses.

Figure 3-19. System I Performance, Annual

One further case (1Aa) was examined for System I in which the utility power was forced to flow through the charger/inverter rather than in parallel with the inverter. The result was an increase in the loss of utility power to 34 percent and an increase in total utility power of about 20%. The proportion of utility and array energy provided to the loads is shown in Figure 3-19(c). Note that a significant amount of utility power is required even for the largest array due to extended cloudy periods and other low insolation days.

The conclusions to be drawn from the System I analyses are:

- The 18 array configuration provides the best balance of percentage lighting load supplied versus array size.
- System losses of array power are too high (20%)
- Increasing array size above 180 kWp provides marginal increase in power supplied to the lighting load but considerable increase in power available for other loads.
- The useful energy from the battery originates about one-third from the array and two-thirds from the utility.
- Paralleling of the inverter with the utility is significantly more efficient.

3.6.2.6 System II Analysis

System II essentially consists of the array serving both the lighting and service loads in the east wing of the building. The inverter is operated in parallel with the utility. Two options with regard to the maximum power tracking function were investigated (Figure 3-18): (1) the MPT was modeled as a separate device which allowed the battery to float on the DC bus and (2) the MPT was combined into the inverter which requires that the battery be connected to the DC bus only during discharge and

photovoltaic charge. In the latter case, the array operating point is determined by the battery voltage (i.e., no maximum-power tracking). Two options with regard to the battery use strategy were also examined. First, the battery charge state was controlled to provide lighting and service loads during the peak utility load periods. Second, the battery provided lighting energy only. The options essentially define levels of demand management that can be easily defined and monitored.

3.6.2.6.1 System II, Option 1-- Option 1 was analyzed with the simulation program for array fields of 60, 100 and 180 kWp nominal capacities and battery capacities of 1000, 1250 and 1500 KWh (cases 6Hc, 6Ic, 6Jc, 7Hc, 7Ic, 7Jc, 8Hc, 8Ic, and 8Jc). The array solar acquisition angle simulated was 20°. The 3-tiered wiring arrangement (6°/12°/18° acquisition angles) was abandoned when the engineering building was located by the architect at the center of the RTI campus instead of near the periphery. At this central location, it is obvious that low acquisition angles of 6 -12 are not feasible due to obstructions.

The performance predicted for this configuration is illustrated in Figure 3-20(a-d). The percentage of the designated loads supplied by the array varies from about 10 to 30 percent, reflecting the smaller array/load size ratio as compared to System I. The PV energy routed to the battery is very small (about 6.5 percent of load, maximum), indicating that most of the battery energy is supplied from the utility. Figure 3-20(b) shows that the system is more efficient since array losses are in the range 16-20 percent, but still too high. Almost no energy beyond that needed to supply the loads is available. Battery capacity in the range examined has nearly no effect on the energy flow to the design loads as seen from Figure 3-20(d). The relatively smaller array field of System II supplies only about 20-50 percent as much power as the utility over the range of array sizes examined.

Array solar acquisition angle was examined for this option to determine whether a significant difference in performance between 15° and 20° existed. The acquisition angle is determined by the subarray spacing which was set by Motorola for the Arizona Public Service array at 27 feet (20°). The angle could be changed at the cost of producing two array

Figure 3-20. System II Option I Performance, Annual

designs with some additional fabrication cost. Simulation results (case 71c, 71d) show annual array outputs of 111,000 kWh for 15° and 106,000 kWh for 20°, a reduction of 4.5 percent. Variations in the various power flows and efficiencies differ by generally less than 1 percent. In addition, additional clear space around the arrays would be required for 15°. It was decided that the additional energy available did not warrant the manufacture of a modified array design and a 20° acquisition angle was adopted.

Conclusions to be drawn from the System II, Option I analyses are

- The smaller array size relative to load has slightly lower losses.
- The battery is charged almost entirely with utility power.
- About 20 percent of the design load is satisfied by PV energy.
- Over the range considered, battery capacity has no effect on energy distribution.
- A 20° solar acquisition angle provides adequate performance.

3.6.2.6.2 System II, Option 2-- A single parameter case (5Gb) was simulated to determine the effect of a significantly smaller load for System II (i.e., lighting only). The result, as compared to lighting and service loads, was a much higher percentage of the load from the array (71 percent vs. 20 percent) and an increase in the fraction of battery energy from the array (66 percent vs. 3.6 percent). Array loss went up substantially from 16.8 percent to 27.9 percent and utility power loss went up from 19.5 percent to 26.5 percent. It was concluded that, as in System I, the array capacity needs to be closer to the load size to reduce losses and Option 2 is not a good design.

3.6.2.6.3 System II, Option 3-- It was obvious from the previous analyses that the battery was, in the systems with lower losses, being used principally with night-charged utility energy to maintain the load reductions in cloudy periods. This suggested that the battery could be

disconnected from the DC bus except when discharging, and this then permits the maximum power tracking function to be included in the inverter hardware. The reduced hardware complexity reduces power conditioning costs. The only question is then whether performance is degraded because the array operates off the maximum power point when the battery is connected. (See Figure 3-21.) In this option, the load served by the battery (i.e., the level of assured demand reduction) was the lighting load, but the service load was also supplied as secondary load. Array power was first allocated to the lighting load and second to the service load, with battery capacity being maintained for the lights only.

Performance of Option 3 was much improved over other options. When compared with Option 2 (cases 7Ic and 9Ne), the array energy output did drop 3 percent for Option 3 but array loss also dropped from 16.8 percent to 5.8 percent. Available PV power above the two designated loads is virtually zero for Option 3.

Past analyses had indicated little impact of battery capacity on system performance, but all of the capacities investigated have been substantially larger than the minimum required to store the seven hours' energy needed to assure demand reduction equivalent to the lighting load (34.7 kW) for seven hours. For Option 3, battery capacities from 250 to 1250 kWh were simulated. Pertinent performance characteristics are summarized in Table 3-15.

At 250 kWh capacity, these results show that some PV energy is generated which cannot be used in the design loads and is declared "excess" (3.5 percent) and is available for other loads, such as HVAC. Since the small battery is connected less, the array can operate at its maximum power point more often, and the total output is very slightly higher. For battery capacities over 250 kWh, the data show little effect of battery capacity. Losses are uniformly low for the combinations of load, array size and battery capacities considered in Option 3.

MAXIMUM POWER POINT VOLTAGE

BATTERY VOLTAGE

SIMULATED ARRAY OPERATING VOLTAGE

Figure 3-21. Voltage Histograms For Nominal System

TABLE 3-15. EFFECT OF BATTERY CAPACITY

	Battery Capacity, kWh			
	250	750	1000	1250
Array output, kWh	104,000	103,000	103,000	103,000
Utility energy, kWh	373,000	371,000	371,000	395,000
Array to lights, %	47.5	49.7	49.7	49.6
Array to service, %	38.5	38.8	38.9	38.9
Array to excess, %	3.5	0.15	0.06	0.08
Array loss, %	10.5	11.4	11.4	11.4
Utility to lights, %	13.4	12.9	13.0	13.0
Utility to service, %	80.7	81.2	81.2	81.2
Utility loss, %	5.9	5.9	5.9	5.9
Battery energy from PV, %	14.9	19.3	19.2	19.0
Battery energy from utility, %	85.1	80.7	80.8	81.0

(Note: Refer to Figure 3-18 for configurations of system and loads.)

Several conclusions are drawn from the analysis of Option 3.

- Option 3 represents the best configuration simulated of load, array size and battery capacity.
- The system is simpler and less costly due to combining the inverter and maximum power tracking functions.
- The PV system supplies about 22 percent of the total energy to the design loads, with the remainder from the utility.
- The battery uses about 80 percent utility energy and 20 percent array energy.

3.6.2.6.4 System II, Option 4-- In order to be able to experiment in Phase III with the effects of various degrees of load reduction during peak hours, a battery capacity greater than the minimum required for the lighting load might be desirable. Option 4 was defined to simulate the effect of a larger defined primary load on the battery. The lighting and service loads were the same as in Option 3 (i.e, 34.4 kW/1.7 kW lights and 60 kW/30 kW service in working/ non-working hours). The demand served by

the battery was arbitrarily taken as 75 kW/3.75 kW. Results of this simulation are given in Table 3-16 in comparison with Option 3 for a 1000 kWh battery. Option 4 forces more than twice as much utility power into the battery with significantly higher loss. Option 4 does, however, indicate the range of performance which might be expected at higher levels of utility demand reduction.

TABLE 3-16. OPTION 4 VERSUS OPTION 3 PERFORMANCE

	<u>Option 4</u>	<u>Option 3</u>
Array output, kWh	102,000	103,000
Utility energy, kWh	395,000	371,000
Battery energy from PV, %	7.7	19.2
Battery energy from utility, %	92.3	80.8
PV energy to battery, kWh	9,850	9,800
Utility energy to battery, kWh	119,000	41,400
Array loss, %	10.5	11.4
Utility loss, %	11.7	5.9
Inverter efficiency	90.3	88.0

3.6.2./ Component Efficiencies

The analysis has modeled the major component efficiencies (array, power conversion, batteries and power distribution). Array efficiency depends upon the separate efficiencies of the optics, the solar cells, and the interconnecting wiring. Optical efficiency was modeled as a constant 64 percent and interconnecting wiring losses, expected to be 1 percent or less, were neglected. The solar cell V-I characteristic and efficiency are functions of cell temperature and insolation. As modeled, cell temperature is influenced by ambient temperature and wind velocity. The array performance over the TMY year for Nashville was computed as 8.65 percent.

Efficiencies of the power conditioning elements (maximum power tracker, inverter and battery charger) generally depend on the

instantaneous throughput as a fraction of design output power. An annual overall efficiency was calculated by integrating power in and out of these devices during the simulated year and computing efficiency as the quotient. The simulations reveal a very narrow range of power conditioning efficiencies as shown in Table 3-17. These ranges represent efficiencies found with parameter variations defined in Figure 3-18 and the System and Option columns represent system configuration and load variations. The nature of the load definitions has a greater effect on inverter efficiency, for example, than do the variations in parameters within a System/Option. Basically, system/load choices which maximize power throughput result in higher efficiencies. All of the power conditioning efficiencies are greater than 85 percent and in general, range between 88 and 93 percent.

TABLE 3-17. POWER CONDITIONING COMPONENT EFFICIENCIES

	System I		System II		
		Option 1	Option 2	Option 3	Option 4
Maximum Power					
Tracker	92.0-93.9	93.3-93.1	93.0	N/A	N/A
Inverter	89.9-89.2*	90.1-92.1	85.0	88.0-88.3	90.4
Charger	No data	91.9-93.5	87.5	83.6-86.5	92.4

*86.2 if not paralleled with utility.

N/A = Not applicable

Battery efficiency was not modeled on a dynamic basis in the simulations. Early use of the SOLCEL battery model produced efficiencies judged unrealistically high and a simpler model with a constant 77 percent round-trip efficiency was used. This is probably on the conservative side.

A constant 1 percent loss in the power distribution wiring was assumed for the simulations and the design of the RTI system distribution system implements this assumption.

3.6.2.8 Cost/Benefit Analysis

A limited cost/benefit analysis for System II, Options 1, 2 and 3 (Figure 3-18) was carried out based on a conventional life cycle cost (LCC) methodology (Ref: Ruegg, "Solar Heating and Cooling of Buildings, Methods of Economic Analysis"). Results were compared on a present worth basis. Using the system simulation outputs, PV energy supplied to the load(s) and total load(s) were input to an electricity rate model to compute the value of PV energy to the load, (2) the cost of additional utility energy required to meet the load, and (3) the total cost to meet the load with utility energy in the absence of a PV system. Each of these costs were computed for both a conventional Wright Demand declining block (DB) rate and a proposed time-of-day (TOD) rate from the local utility (Tables 3-7, 3-8). The LCC values include the cost of land (\$20,000), other area related costs (\$1/Wp), battery cost (\$120/kWh), array cost as a parameter (\$0.50 - \$5.00/Wp), cost of building space occupied (\$50,000), and maintenance cost of 1 percent of capital cost. The total investment is assumed mortgaged at 10 percent and a discount rate of 10 percent was assumed. System life was 30 years and battery life 10 years.

Under the TOD rate, the present worth of the electricity to satisfy the full load was \$186K, and under the DB rate, it was \$217K. Table 3-18 gives the ratios of the present worth of the PV system to these utility energy values for a few selected cases. A system with a ratio greater than one is not cost effective.

Several observations on cost effectiveness can be made from Table 3-18 and these can be generalized somewhat since other calculations, not shown, follow similar trends.

1. None of the system options investigated are cost effective under the assumptions used (lines 1-9).
2. Option 3, with the maximum power tracking function included in the inverter, is most cost effective (Lines 2,4,9).
3. The declining block (DB) rate is more favorable to the PVCS than the time-of-day (TOD) rate (Lines 1-9).

4. Smaller batteries are more cost effective than large ones (Lines 2-9).
5. Smaller PVCS systems are more cost effective than larger ones (Lines 1-3).

TABLE 3-18. COST/BENEFIT COMPARISON

Line	Option	Array	Battery	Array	Ratio	
		Capacity (kW)	Capacity (kWh)	Cost (\$/Wp)	DB Rate	TOD Rate
1	1	60	1250	.50	3.19	3.42
2	1	100	1250	.50	4.09	4.21
3	1	180	2250	.50	5.99	6.44
4	2	100	1250	.50	4.02	4.39
5	2	100	1250	2.00	4.26	5.23
6	2	100	250	5.00	6.20	6.42
7	3	100	1250	.50	2.66	2.87
8	3	100	750	.50	3.25	3.46
9	3	100	1250	.50	3.84	4.15

It should be noted that these data and observations should be used only in a relative sense since none of the cases is cost effective and other assumptions can lead to different results.

3.6.2.9 System Selected

Based upon all of the foregoing analysis, RTI feels that a beneficial Phase III experiment can be carried out on a system having an array nominal peak capacity of 100 kW and incorporating a battery capacity of 1000 kWh (Figure 1-5). The inverter will provide the peak power tracking function and no separate power tracker will be employed. The battery will be connected to the array/inverter bus only for discharge and photovoltaic charge. The PVCS system will drive both the lights and service loads of

the east wing of the new engineering building, with the battery being charged to supply primarily the lighting load, but obtaining data on the larger battery loads will be part of the data acquisition plan.

A more detailed description of the final system design is provided in Section 5.0.

4.0 COMPONENT DEVELOPMENT AND SPECIFICATION

4.1 SOLAR ARRAY

4.1.1 INTRODUCTION

An artist's concept of the Motorola Concentrator Solar Array designed for RTI is shown in Figure 4-1. It is a two-axis tracking array supporting 240 concentrator modules with a total peak output of 9576 watts. The base of the array is a frame mounted on wheels which roll on a circular track, for azimuthal orientation. On the base are mounted three subarray frames (two end frames and one center frame) which rotate to provide elevation tracking. Concentrator modules are mounted on individual panels, 12 to a panel. Twenty of these panels are then mounted on three large subarray frames (six on each end frame and eight on the center frame). Table 4-1 lists the general specifications for the array system.

TABLE 4-1. GENERAL ARRAY SPECIFICATIONS

• Concentrator Modules per Array	240
• Panels per Array	20
• Concentrator Modules per Panel	12
• Maximum Peak Power Output (for ambient temp. = 28°C, NIP = 1000 W/M ²)	9,576 watts
• Number of Arrays in Field	10
• Turning Diameter of Array	82 feet
• Diameter of Support Rail	58 feet
• Maximum Height of Array	10 feet
• Total Weight of Array	15,250 pounds
• Designed to track in maximum wind of 30 mph	
• In winds above 30 mph, array must be in stow position	
• Tracking system: active sun sensor with open-loop backup	

4.1.2 MOTOROLA CONCENTRATOR MODULE

The Motorola Concentrator is a Cassegrain-type optical concentrator that illuminates a circular target area and achieves good off-axis performance. The module includes a bypass diode to protect the solar cells under shaded conditions. Figure 4-2 is a photograph of a prototype module currently being tested.

Figure 4-1. Tracking Photovoltaic Concentrator Array

Figure 4-2. Prototype Module

Twenty modules using several different reflector materials have been fabricated and are currently being evaluated. Table 4-2 lists the general characteristics of the module.

TABLE 4-2. GENERAL CHARACTERISTICS OF MOTOROLA CONCENTRATOR MODULE

-
- Diameter of Module - 30 inches
 - Maximum Power Output - 39.9 watts
 - Voltage at Maximum Power - 1.94 volts
 - Current at Maximum Power - 20.6 amperes
 - Utilizes 3-in. diameter silicon cell
 - Cassegrain Optical System
 - Passively Cooled
-

4.1.2.1 Optical Design

The Meinel Optical Module consists of two principal reflecting surfaces and a cover. The two-mirror design produces a uniform flux density because, optically, there are six degrees of freedom available. A tertiary reflecting surface, the cusp, is included in the design to extend the off-axis performance of the module as a concentrating collector.

The most significant design factors are the optical efficiency of the reflective elements and the desired flux density pattern on the solar cell. A computer synthesis program was developed at Motorola which includes the efficiency and desired concentration as variables and iterates the module parameters in order to optimize its performance. The concentration ratio of the module is defined as the number of solar constants incident on the cell averaged over its area. The designed flux density pattern is doughnut shaped with a minimum in its center. This pattern provides the greatest uniformity and maximizes the output of the solar cells. A sketch of the flux density distribution is given in Figure 4-3.

The cusp improves off-axis performance by reorienting misplaced ray bundles to the target area. Two basic designs, simple circular-segment cusp and a dual Compound Parabolic Collector (CPC) cusp, were designed and analyzed. These are shown in Figure 4-4. The simple cusp was found to provide limited off-axis performance improvement. The dual CPC cusp significantly improves the collection efficiency of the module.

4.1.2.2 Concentrator Solar Cells

4.1.2.2.1 Performance Requirements - The Motorola module will utilize a cell having the following characteristics:

- (a) Material - silicon
- (b) Physical configuration - 3-in. diameter cell cut into four 90° quarters
- (c) Concentration ratio - designed to operate with an illumination equal to 70 suns (7 W/cm^2) over its active surface

Figure 4-3. Target Area Flux Density Profile

Figure 4-4a. Simple Cusp Design

Figure 4-4b. Dual CPC Cusp Design

- (d) Metallization pattern - shall be optimized for a uniform illumination of 70 suns.
- (e) Metallization materials - materials shall be used which are environmentally inert such that a 20-year cell MTBF can be projected (as a design goal)
- (f) Electrical attachments - shall be compatible with the Motorola cell mount conductor ring assembly
- (g) Conversion efficiency - 14 percent minimum at 70X concentration and 28°C ambient
- (h) Cell operating temperature - 55°C
- (i) Anti-reflective coating - shall isolate the silicon junctions from the atmosphere such that (as a design goal) cell efficiency will not degrade below 13.5 percent after 20 years

4.1.2.2.2 Development Status - In the solar cell analysis and development program, Optical Coating Laboratories and the Motorola Semiconductor Group, each produced a 70X solar cell compatible with the above requirements.

OCLI solar cells of an existing 40X concentration design were used to initiate the cell evaluation program. These cells were used to establish compability with the cell mount and to develop the evaluation techniques.

Sixty 70X solar cells were delivered by OCLI for evaluation. Twenty-five 70X solar cells were delivered by the Motorola Semiconductor Group. 70X solar cells from each supplier were evaluated. Cells produced by OCLI and Motorola Semiconductor Group are shown in Figures 4-5 and 4-6, respectively.

The test bed for the solar cell evaluation program was a searchlight mount modified to add a sun sensor and closed-loop tracking capability. Adapters were provided for mounting a one meter Fresnel lens, optical filters to obtain a uniform flux distribution, and lens apertures to obtain different concentrations on the cell. The mount was also adapted to accept the Motorola concentrator module. Several engineering model concentrators were fabricated and one of these was utilized in the solar cell evaluation program.

The test station was instrumented to provide solar cell electrical characteristics and temperature, normal incident radiation, total hemispherical radiation, and the radiation incident on the cell. Cell temperature was controlled by varying flow through the water-cooled cell mount.

4-7

Figure 4-5. OCLI 70X Solar Cell

Figure 4-6. Motorola Semiconductor Group 70X Solar Cell

Figure 4-7 is a family of EI curves for a typical OCLI quarter cell at various concentrations. Figure 4-8 is a plot of average efficiency versus cell temperature at 50X concentration for several 70X OCLI quarter cells. This cell shows an efficiency of about 13 percent at the design operating temperature of 55°C.

In addition to the OCLI cells, Motorola Semiconductor has developed several 70X cell configurations including a quartered 3-in. diameter cell. Motorola cells have demonstrated efficiencies in excess of 18 percent at 50 suns (AM 1, 27°C).

Figure 4-7. Typical OCLI Quarter Cell EI Characteristics

Figure 4-8. OCLI Cell Efficiency Versus Temperature

Figure 4-9 Shows the I-V characteristics at 40°C, and Figure 4-10 shows the efficiency, fill factor, and open circuit voltage as a function of concentration ratio for four Motorola 70X quarter cells connected in series. These data indicate that Motorola solar cells will have an efficiency of 15.5 percent at 70X concentration and 40°C cell temperature.

4.1.3 SOLAR CELL MOUNT

4.1.3.1 Introduction

The solar cell mount is an important element of photovoltaic concentrator systems. The five mount design objectives that Motorola established for the cell mount design are:

Figure 4-9. Motorola SG 70X Solar Cell Characteristics

Figure 4-10. 1 x 2 Inch Rectangular Motorola N₊P Cell at 27° C

1. Less than a 5°C temperature rise from heat sink to cell.
2. Electrical isolation between the cell and heat sink of 1500 Vdc and between individual quadrants of 2 Vdc with current leakage less than 0.25 mA.
3. Acceptably low thermal stresses over the design to ensure cell integrity and a lifetime of 20 years or longer.
4. A means for series electrical connection of the cell quadrants that allows access to the leads of each mount.
5. A design that is economical to fabricate and assemble using high production methods and production assembly personnel.

4.1.3.2 Description

Several alternate cell mount designs were investigated:

1. A thin mica layer sandwiched between the cell and heat sink by thin silicone adhesive layers.
2. Same, but with adhesives with higher thermal conductivity.
3. Alumina and beryllia insulating discs.

The first design used a thin alumina disc metallized and plated on both sides. This disc was soldered to the cell and mount plate. Contact to the bottom of the cell was facilitated by using the plating as the current carrier and forming the disc larger than the cell.

Motorola's final cell mount design incorporates all the advantages of the alumina disc approach but is simpler and more cost effective. The beryllia disc was rejected due to toxicity and cost. In place of an alumina disc soldered down to the mount plate, a plasma-spray coating of alumina is directly applied on the mount plate. Certain alumina powders in sprayed form offer comparable physical and thermal properties to the fired ceramic.

A cross-sectional view of the mount is shown in Figure 4-11. The cell mount plate is the primary component of the design onto which the cell is mounted. The plate is die cast 300 series aluminum with the necessary holes for mounting and lead attachment. The cell side of the

Figure 4-11. Cross Section of Cell Mount

upper plate is plasma-sprayed with a 3.6-mm layer of 99.6 percent pure alumina. A second plasma-sprayed coating of 0.03-mm copper in a 10-cm diameter quartered pattern is placed on top of the alumina. Electrical contact to the back of the cell is achieved when the cell quadrants are soldered to the electrically conductive copper. The quartered copper pattern isolates the cells so that one substrate can be used rather than four separate ones. The required series connection between the cell quadrants is formed by the interconnect ring and top finger ring. The interconnect ring consists of five, 0.4-cm square bars, three of which connect adjacent quadrants and two of which act as leads from the mount. The three connecting bars are stepped such that they overlap the lead bars and each other to form a single height two-layer piece. All bars are roll formed to create a 10 cm diameter ring shaped interconnect. Insolation of the bars from one another is accomplished by the use of a supported film adhesive between the ring layers.

The supported film adhesive acts to hold the bars as a unit and, additionally, to isolate them from one another. The assembled interconnect ring circumscribed the cell. Electrical contact to the cell back surface occurs upon soldering the interconnect to the plasma-sprayed copper. The final electrical connection to the cell is formed by four upper contact finger ring segments, one for each cell quadrant. The segments are fabricated from .02-cm thick copper to form an outer ring .4-cm wide with an outside diameter of 10-cm and eight fingers for

attaching to the cell. The fingers are soldered to each quadrant and the outer ring is soldered to the copper bars of the interconnect.

Before the cell or interconnect is soldered down, the cell mount is coated with Epon 828. Epon 828 is a non-viscous, epoxy-based resin that seals the plasma-sprayed alumina and copper in order to prevent moisture absorption. The copper surface is prepared for soldering by either mechanical or chemical means.

A computer program based on linear composite theory was used to calculate stresses in the cell mount design due to differing thermal expansion coefficients of the individual layers. While unusually high stress could cause cracking in the cell, the area of particular concern was fatiguing of the solder joints that might occur due to thermal cycling. Results showed the maximum strain in the solder to be 379 MPa. Using the methods of Sandia Report AD SC-RR-70326 (A Methodology for Analysis of Fatigue in Solder Joints), the predicted life of the solder was 20.3 years.

4.1.3.3 Testing

Twelve prototype cell mounts were fabricated and assembled. In addition to testing the cell mounts under actual solar energy conditions, a number of laboratory tests were performed to verify the design.

Thermal resistance measurements were made on several mounts to determine the temperature drop. The temperature drop was measured to be about 5°C, close to the predicted values of 3.8°C.

Dielectric strength tests were performed on seventeen prototypes after plasma spraying and sealing. Over 95% of the quadrants showed dielectric strength of 1500 Vdc. Current leakage under a 500 Vdc potential difference was typically fifty microamps, virtually zero.

Thermal shock tests were performed on five mounts. In these tests the mounts were shocked from -40°C to 70°C. Shock tests were also run between 115°C to 28°C. No failures occurred in the shock tests.

Temperature and humidity cycling tests were performed on several cell mounts that had been sealed with a silicone compound, the sealing compound

first chosen. Tests showed that the dielectric strength of the alumina had been reduced by moisture absorption. New mounts have been fabricated using the Epon 828 epoxy and humidity tests will be performed to verify its moisture sealing characteristics.

4.1.4 HEAT DISSIPATOR

4.1.4.1 Introduction

Since solar photovoltaic cells by nature are not capable of transforming all the energy which strike them into electrical power, the remaining energy is converted into heat. This heat must be removed from the cell area or the cell will be destroyed. Also, the cell efficiency decreases with an increase in temperature, therefore, the need arises for an efficient heat transfer system.

Two basic cooling systems were considered; active and passive. A passive system was chosen since the thermal energy available could not be used effectively in the RTI building. Two types of passive systems were considered; (1) a finned aluminum extrusion and (2) a reflux cooler system using a bond panel.

4.1.4.2 Design

The first heat dissipation system tested was a finned aluminum heat sink. This type of heat sink is commercially available and provides a reasonable thermal resistance from the cell mount to the ambient air. The excessive weight and cost of the finned extrusion and the relatively high temperature drops necessitated an alternate design.

A new heat dissipator was developed using a reflux cooler type design. The operation of the reflux cooler is based on that "heat pipe" concept in which a saturated liquid-vapor fluid is contained in a closed system. With the application of heat the fluid sets up a vaporization-condensation cycle within the system resulting in a nearly isothermal surface for heat transfer.

The reflux cooler is made of 1100-0 series aluminum measuring 32 inches high by 25 inches wide with 0.200 inch nominal fluid passage

depths. A photograph of the panel is shown in Figure 4-12. The panel is produced by silk screening a "stop-weld" chemical between two sheets of .030 inch thick aluminum which are then run through a rolling process which acts to fuse the two sheets together except in the "stop weld" areas. Compressed air is then introduced expanding the "stop-weld" areas forming fluid passages. In fused areas the aluminum has a thickness of 0.060 inch.

Figure 4-12. Reflux Cooler Panel

The reflux cooler panel interfaces with the photovoltaic cell using two aluminum plates machined to match the area in the center of the panel. The panel is sandwiched between the plates providing thermal contact necessary for heat transfer to the panel. The panel is then evacuated and filled with a fluid to a level above the interface area and sealed. The prototype panels have used two pounds of Freon TF as a working fluid. The complete panel uses 5 pounds of aluminum so the total heat dissipator weight is 7 pounds.

Ten prototype panels have been fabricated and several have been tested. Tests have been performed in several panel orientations, in still air, and in a 1.5 m/sec air stream. Test data have indicated that the temperature drop from the cell mount through the panel is independent of orientation. The temperature drop from solar cell to air is 44°C in still air and 34°C in a 1.5 m/sec air stream. Testing is continuing on several design modifications that show promise in reducing the temperature drop.

4.1.4.3 Conclusion

The reflux cooler panel has been tested successfully both under laboratory conditions and on actual solar modules. It provides a lower thermal resistance with a significant reduction in weight and at a lower cost than a comparable finned aluminum extrusion. The prototype panels were fabricated by Olin Brass, Solar Bond Products Division of East Alton, Illinois. They have a large production capability for this type of panel with a delivery time of 8 to 10 weeks.

4.1.5 TRACKING ARRAY

4.1.5.1 Introduction

The array utilizes a two-axis tracking structure as shown in Figure 4-1. The three module-supporting subarray frames rotate in the elevation axis and are mounted on a track-mounted base which rotates in the azimuth axis. Electric motors driving through gear reducers to move the array at the required tracking rates.

The "low profile" concept using three low-height array frames was selected over several alternate configurations because it offered several unique advantages:

- The low height and frame shadowing reduce wind load on the array.
- The low height makes it convenient and safe to erect the array and to install and maintain the solar modules.
- The three frames spread the load more evenly over the base and minimize overturning forces on the array.
- A cost study indicated that the low profile configuration provided the lowest array cost per peak watt.

A cost tradeoff to determine the optimum array size showed that a track diameter of about 60 feet minimized the array cost per peak watt. A large space frame structure was designed to support the modules under the selected wind loads using a minimum of structural materials. A three-dimensional structural dynamic analysis using finite element analysis was used to select the structural member sizes and to ensure that the natural frequency of the system was above 1 Hz.

An active sun sensor interfaces with the azimuth and elevation drive motors to position the array accurately into the sun. An open-loop, microprocessor-controlled tracking system takes over the tracking function when available sunlight into the sun sensor falls below a predetermined level.

4.1.5.2 Wind Load Analysis

Wind load forces on the array structure were a major factor in the structure design. The design wind velocities chosen were 30 mph for any tracking position and 90 mph in the stow position. A computer program was written by Motorola which calculated static wind loads for various array angles based on drag coefficients and center of pressure shifts. Torques on array structural members and vibration due to vortex shedding were investigated. The worst case wind load forces during a 30 mph wind on the chosen array configuration are summarized in Table 4-3.

Table 4-3. Maximum Loads in 30 mph Wind

		Torque (ft-lb)	Force (lb)	Pressure (lb/ft ²)	Corresponding Elevation Angle (degrees)	Corresponding Azimuth Angle (degrees)
Moments about Elevation Axis	82 ft. frame	1,930			80	45
	62 ft. frame	1,460			80	45
	Total	4,855			80	45
Moments about Azimuth Axis	82 ft. frame	31,110			0	50
	62 ft. frame	17,790			0	50
	Total	66,680			0	50
Pressure and Force	82 ft. frame		2,270	3.08	0	45
	62 ft. frame		1,720	3.08	0	45
	Total		5,710	3.08	0	45
Lift on Structure			3,860		60	45
Drag on Structure			5,720		0	45

4.1.5.3 Structural Design

The array structure was designed as a large space frame to minimize the material required while maintaining deflections within specified limits.

The base for the array is supported on a circular rail at four points and is supported at these points on standard monorail crane-type wheels. Rotation of the base on the track provides azimuth tracking.

The subarray frames rotate to provide elevation tracking. The center subarray frame is 78 feet long, and the two outer subarray frames are 57 feet long. The subarray frames mount on pillow block bearings onto supports provided on the array base. The subarray frames have been designed as 25-inch square box beams formed with structural angles at the four corners mounted to formed sheet metal webs on 30.5-inch centers. Diagonal struts are used between the webs near the elevation bearings to limit torsional deflection.

The solar modules are supported on panel frames which are mounted on the subarray frames. The panel frames are 10-foot square frames, each supporting 12 solar modules; eight frames are mounted on the center subarray and 6 frames are mounted to each outboard subarray.

Solar modules will be assembled and aligned on the panel frames in the factory where the solar modules are manufactured. The completely

assembled panel frames will then be shipped to the field for installation onto the array structure. This has been done to have as much assembly as possible done in a manufacturing facility because of the advantages of lower labor costs and more efficient manufacturing techniques. Leveling of the panel frames on the subarray frames will be done in the field.

A proposed source for all of the structural fabrication effort is AZCRA, a division of Equipment Fabricators, Inc., 5301 W. Madison in Phoenix. The lead time for the first array is anticipated to be about 3 months ARO with all 10 arrays completed according to RTI's installation schedule. RTI is investigating with Motorola the cost tradeoffs between shipping the array frame members from Arizona and setting up two frame manufacturers, one in Arizona and one in North Carolina.

4.1.5.4 Stress Analysis

A large space frame structure was designed to support the modules under the specified wind load conditions using a minimum of structural materials. A stress analysis utilizing a standard finite-element computer program was performed on the array structure. Table 4-4 shows that with the array in the stow position, during a 90-mph wind, the worst case stress in the structure is 32,000 psi. This is a limit for the stress in structural steel members; therefore, the proposed structure meets the requirement for survival in a 90-mph wind. Leveling panel frames at final assembly will reduce errors due to static deflections.

4.1.5.5 Tracking Drive Design

4.1.5.5.1 Introduction - Electric motors driving through large-reduction gear reducers are used to position the array in both the azimuth axis and elevation axis to provide sun tracking.

Both air and hydraulic motors were considered for the system and offer feasible tracking drive methods. However, the first cost of a hydraulic system is higher than for electric drives and thus electric motors

TABLE 4-4. MAXIMUM DEFLECTIONS UNDER VARIOUS CONDITIONS FOR
THE ARRAY STRUCTURE

Condition	Maximum Deflection of Subarray Frame
Deflection due to solar module load only - No wind	0.93°
Deflection due to 10-mph wind	0.11°
Deflection due to 30-mph wind	1.00°
Worst case stress in frame under 90-mph wind in stow position	32,000 psi
Lowest resonant frequency	5 Hz

were selected. Worst case wind loads imposed the largest percentage of load on the drive system components. Array weight and friction were a small portion of the design load. The loads on the system in the worst case array attitude into the wind were calculated in a 30-mph wind and the drive train components were sized appropriately.

All of the tracking drive mechanical and electrical components are standard design parts and are all available in from 8 to 12 weeks.

4.1.5.5.2 Azimuth Axis Drive Train - Figure 4-13 shows the mechanical components used for the azimuth drive train. The array base structure is supported on a track at four points. At each point a standard monorail crane trolley assembly is used. Two of the trolleys are used to drive the system; those drive wheels are supplied with a spur gear as shown in Figure 4-13. The drive wheel spur gear is driven by a pinion on the output shaft of a double worm reducer. The input to the reducer is driven by a continuously rotating 1725-RPM motor engaging the reducer through an electric clutch. The drive train is self-locking and no brake is required because the double worm reducer cannot be back driven.

Each azimuth drive motor must deliver 0.1 H.P. under worst case wind loading of 30 mph and maximum azimuth velocity of 1.5°/min. Two 1/8 H.P. single-phase standard AC motors are used. To minimize power consumption,

Figure 4-13. Azimuth Drive System

each motor is continuously energized and is coupled to its load only via a clutch to maintain the tracking error within design limits. This mode of operation requires that each motor operate under load for only a fraction of the solar day. In addition to minimizing the power required to drive the array, this method of operation also eliminates the power consumption and EMI associated with the very high starting current surges demanded by AC motors.

As shown in the schematic of the azimuth control circuitry, the clutch is energized and couples the motor to the load in response to

signals from the Hybrid Sun Tracker (Figure 4-14). Relay K1 provides motor reversing capability to return the array to the sunrise azimuth position at the end of the solar day. Switches Sw-1 and Sw-2 provide bidirectional manual control of array azimuth position. For safety, these switches are spring loaded to return to the positions indicated in Figure 4-14 upon release.

4.1.5.5.3 Elevation Axis Drive Train - Figure 4-15 shows the elevation drive design. Two 5-ton capacity, 48-inch travel jack screws are used to move the subarray panels in elevation. The screws move the center subarray; the two outer subarrays are linked to the center subarray with tie rods.

The jack screw input shafts are linked by drive shafts to a 15:1 gear reducer which is driven by a 72-rpm hysteresis motor for tracking and a 3450-rpm motor for stow. The drive system is self-locking and no brake is required. The machine screw-type jack screws cannot be back driven.

The elevation drive has two separate drive rate requirements. It must be capable of tracking the sun at its maximum velocity of approximately $0.3^{\circ}/\text{sec.}$ in winds up to 30 mph. When weather conditions indicate that winds will exceed 30 mph the elevation drive must also be capable of slewing the array to a horizontal stow position at a rate of $15^{\circ}/\text{min.}$ to prevent wind damage. In order to stow the array at a rate of $15^{\circ}/\text{min.}$ in a 30 mph wind the motor must deliver 1 H.P. Under the same conditions of wind loading only 0.02 H.P. is required to track the sun at its maximum rate in elevation.

Because the high power slew capability is required only a few times per year it is impractical from a power consumption standpoint to use the same motor for both tracking and slewing. The elevation drive system therefore uses a 1 H.P., 3-phase, 3450 RPM standard AC motor for stowing and a 1-phase, 72 rpm synchronous motor for tracking. Both motors are directly coupled to the speed reducer shaft.

During tracking, the slew motor is de-energized and is driven at 72 rpm by the tracking motor. During stow, the tracking motor is de-energized and is driven at 3450 rpm by the slewing motor for the short time (6 minutes maximum) required to stow the array.

Figure 4-14. Azimuth Drive and Control Schematic

Figure 4-15. Elevation Drive

Operation of the elevation drive is unidirectional with the direction of rotation reversed after the sun passes through its zenith position. A schematic of the elevation tracking control circuitry is shown in the lower half of Figure 4-16. The tracking drive motor is the permanent magnet, split-house, AC synchronous type. This motor has the advantage of constant power consumption and freedom from high starting inrush currents. As shown in Figure 4-16 bidirectional operation of the tracking motor is obtained via solid-state relays S1 and S2. Both switches are normally open disconnecting the motor from the single phase AC power source. Depending on whether the sun is ascending or descending one or the other switch is closed only long enough to maintain the tracking error within design limits. This method has been selected to minimize the AC power required for tracking. Efficiency is high in that the average power consumption is directly proportional to the angular velocity of the sun.

A schematic of the elevation slew control circuitry is shown in the upper portion of Figure 4-16. As discussed previously, the slew motor is normally de-energized and is activated only for stow, unstow and manual control operations.

Figure 4-16. Elevation Drive Schematic

Power to the slew motor is controlled via relay K1. Energizing K1 applies power to the slew motor and simultaneously removes single phase power from the track motor. Relay K1 is energized either by a stow/unstow signal from the Hybrid Tracking System or by operator control via the manual slew enable switch SW-1.

The operator may override automatic control of the array in elevation by means of Manual Slew Enable Switch SW1. When held in the ON position, SW1 energizes relay K1 via contact SW1-B. This interrupts AC power to the track motor via contact K1-B and transfers control of slew motor power to Slew Direction Switch SW2. The operator may then select the direction of rotation in elevation using SW2 while holding SW1 in the ON position. Both switches are the spring return type and will return to the positions shown in Figure 4-16 when released.

Upon receipt of a stow command, relay K1 in Figure 4-16 energizes and disconnects the track motor from the AC source via contact K1-B. Power is then applied to the slew motor through the contacts of SW1, SW2 and relay K2 which are in the positions shown in Figure 4-16. The slew motor then drives the array to the stow (horizontal) position at a rate of 15°/min.

4.1.5.6 Hybrid Sun Tracker - The Hybrid Sun Tracker performs the task of steering a tracking array so that it continuously faces the sun as the sun traverses the sky. It is "hybrid" because it can track the sun in two modes: open-loop and closed-loop.

Open-loop tracking is accomplished by calculating the azimuth and elevation of the sun at the moment, sampling the position of the tracking array at that moment and providing motor drive signals to the tracking array that will eliminate the difference between the two. Closed-loop tracking uses a sun sensor which includes four solar cells (two for azimuth and two for elevation) arranged in a rectangular grouping with a sun shade above them. Motor drive signals are provided to the tracking array that will cause the outputs from opposite solar cells to be equal. Closed-loop tracking accuracy can be accomplished within ± 0.1 degree. Total power required for the Sun Tracker, including the Sun Sensor and all circuitry up to the motor drive circuitry, is 20 watts.

4.1.5.6.1 Sun Sensor - The performance specifications of the sun sensor are:

Acquisition Angle	= $+8^\circ$
Active Sensing Region	= $+3^\circ$
Accuracy	= $\pm 0.2^\circ$
Voltage Range	= 0-5 Vdc
Typical Output Voltage	= 2 Vdc

This active closed-loop sensor utilizes four 0.5-inch square solar cells, one in each of four quadrants. Two opposite cells are used for detecting in each axis. An opaque surface above the cells casts a shadow bisecting all four cells when normal to the sun. When the sensor plane is not perpendicular to the sun, the cells produce unequal currents. These currents are fed to the analog/digital converter of the tracking controller through a current to voltage converter. The closed-loop accuracy of the sensor is set at $\pm 0.2^\circ$ which is greater than the mechanical backlash to avoid hunting

In operation, the microprocessor will sense sun sensor voltages until it accumulates specific error angle ($\pm 0.2^\circ$), activate the motor drive system and overshoot the sun by this time error angle ($\pm 0.2^\circ$). This hysteresis effect will reduce oscillations and decrease the duty cycle of the drive system while maintaining tracking within the design error angle.

The sun sensor has been tested, both electrocally and optically, under actual operating conditions. Tests performed confirm that the sun sensor is tracking the sun within its design parameters.

The Sun Sensor package will be weather tight and will feature a key pad for entry of information into the unit (mode, time setting, display select, etc.) and a Liquid Crystal Display for monitoring operating parameters.

4.1.5.6.2 Microprocessor - Figure 4-17 shows a simplified flow diagram of the program in the Sun Tracker. In order to initialize the Sun Tracker, the front panel "Run/Set" switch is placed in the "Set" position, and the month of the year, the day of the month, and the time of the day are set.

In the operate mode, the microprocessor continuously calculates the sun location and measures the array position by means of precision potentiometers. If the calculated sun elevation is negative, i.e., the sun has "gone down," the tracking array is directed to go to the sunrise position. Tracking resumes when the calculated sun elevation becomes positive. The microprocessor enables closed-loop control if the difference between calculated and actual position is less than the present capture angle of the sun sensor in both azimuth and elevation. Until this difference is reached, the tracking array is steered by the open-loop routine. If a

The microprocessor enables closed-loop control if the difference between calculated and actual position is less than the present capture angle of the sun sensor in both azimuth and elevation. Until this difference is reached, the tracking array is steered by the open-loop routine. If a

Figure 4-17. Suntracker Microprocessor Program Flow Diagram

cloud obscures the sun (as determined by a drop in the magnitude of the sum of the solar cell outputs in the sun sensor), open-loop tracking will override the sun sensor.

Figure 4-18 shows the block diagram of the Sun Tracker. An MC6802 microprocessor is the heart of the unit. This device includes a small RAM (Random Access Memory) for scratch pad calculations and variable data. The program will be stored in EPROMS (Eraseable Programmable Read Only Memory). The Sun Tracker includes a time-of-day clock, an analog-to-digital converter for sampling solar cells and position potentiometers, an arithmetic processor for making computations, and front panel controls to allow human interaction and monitoring. An LCD (Liquid Crystal Display) will allow the operator to monitor month, day, time-of-day, calculated azimuth and elevation, and measured azimuth and elevation.

Figure 4-18. Hybrid Suntracker Detailed Block Diagram

4.1.6 ERROR BUDGET ANALYSIS

The concentrator module must be positioned within $\pm 1^\circ$ of the true sun position to ensure full power output. Table 4-5 shows the results of the error budget analysis for the tracking structure system. In a 30-mph wind the array deflection is 1.00° and thus the total off-axis variation could be 1.46° . However, operation in a 30-mph wind is extremely unlikely, and it is not cost effective to increase the strength of the array in order to keep the total off-axis error within $\pm 1^\circ$ in a 30-mph wind.

Table 4-5. SYSTEM ERROR BUDGET

Tracking structure	
Hybrid tracking system	$\pm .10^\circ$
Drive System Backlash	$\pm .20$
Drive System Positioning	$\pm .05$
Subarray Misalignment	$\pm .24$
Panel Frame Misalignment	$\pm .19$
Module Mounting Accuracy (Into panel frames)	
	$\pm .25$
Total	± 1.03
Root Mean Square	
Deflection under 10-mph wind load	$\pm .46$
Total Deflection Variation	$\pm .11$
	$\pm .57$

4.1.7 WEIGHT ANALYSIS AND MATERIAL COST

Minimizing the weight and cost of the array system has been a major goal of the array design activity. Table 4-6 and 4-7 summarize the weight and material cost of the present array design. The material cost numbers are those provided by the Department of Energy in Appendix B of the Proposal Instructions for PRDA EG 77 D04 0035. Several materials, zinc, silicone rubber and freon, were not listed in Appendix B, and current market prices for those raw materials have been used in Table 4-6.

Table 4-6 shows the total raw-material cost for the modules on one array. Table 4-7 shows the total raw-material cost for one array tracking structure. The sum of these two costs, \$13,380.40 represents the total raw-material cost for one complete solar array system. The total aperture area for one array is 112.22 m². Therefore, the cost per unit area for the complete array is \$119.22 per square meter.

Table 4-6. Weight and Material Cost of Concentrator Module

Part Name	Weight, Lbs.	Material	Cost Basis	Cost
Primary reflector	5.00	ABS	\$.75/lb	3.750
Cover	2.10	Acrylic	.90/lb	1.890
Secondary support	.23	Steel	.50/lb	.115
Heat dissipator	5.00	Aluminum	1.10/lb	5.500
Heat transfer fluid	2.00	Freon	.675/lb	1.350
Secondary reflector	.19	Aluminum	1.10/lb	.209
Cusp	.13	Aluminum	1.10/lb	.143
Support ring	1.56	Zinc	.39/lb	.608
Cells and inter-connections	.05	45.6 cm ²	.25/cm ²	11.400
Connector	.13	Copper	1.70/lb	.221
Cell insulator	.02	Alumina	15.00/lb	.300
Misc. hardware	.15	Steel	.50/lb	.075
Seals	.06	Silicone Rubber	1.64/lb	.098
Conductor ring	.26	Copper	1.70/lb	.442
Cell mount plate	2.70	Aluminum	.85/lb	2.295
Total	29.58			\$28.396

240 Modules per Array

Module Cost per Array = 240 X \$28.396 = \$6815.04

Table 4-7. Weight and Material Cost of Tracking Structure

Part Name	Weight, Lbs.	Material	Cost Basis	Cost
Mounting Rail	1822	Steel	\$.38/lb	\$ 692.36
Base, Tracking 27-P00554R	4800	Steel	.38/lb	1824.00
Center Subarray 07-P00553R002	1700	Steel	.38/lb	646.00
Outboard Subarray 07-P00553R001 (2)	2500	Steel	.38/lb	950.00
Panel Frame 07-P00551R (20)	1700	Steel	.38/lb	646.00
Module Wiring	150	Copper	1.70/lb	255.00
Base Wheel Assembly (4)	360	Steel	.50/lb	180.00
Elevation Jack Screw (2)	120	Gear Box	4.00/lb	480.00
Elevation Drive Parts	300	Steel	.50/lb	150.00
Azimuth Gear Reducer (2)	112	Gear Box	4.00/lb	448.00
Azimuth Drive Parts	50	Steel	.50/lb	25.00
Azimuth Drive Motor (2)	26	Motor	3.00/lb	78.00
Elevation Stow Motor	30	Motor	3.00/lb	90.00
Elevation Track Motor	12	Motor	3.00/lb	36.00
Elevation Gear Reducer	10	Gear Box	4.00/lb	40.00
Misc. Hardware	50	Steel	.50/lb	25.00
Total	13742			\$6565.36

4.1.8 CALCULATED ANNUAL EFFICIENCY

The annual efficiency for RTI's array has been determined by simulation using a cell model (OCLI cell performance), an optical efficiency of 0.642, and a cell temperature model fitted to Motorola test data. Nashville TMY insolation, ambient temperature, and wind speed data were input to the model and annual power output computed. An efficiency of 8.65% was determined as the quotient of the annual energy output of the arrays divided by the annual incident solar insolation on the array aperture.

4.2 POWER CONDITIONING

4.2.1 INTRODUCTION

The power conditioning equipment performs three basic functions:

1. inversion of the array direct current to alternating current,
2. control of power flow through the inverter in such a manner that the array operates at its maximum-power point, and
3. conversion of alternating current to direct current for charging the battery at the proper voltage.

The hardware chosen to perform these three functions is based upon a commercial line of uninterruptable power supplies (UPS) manufactured by Exide. The usual form taken by the commercial equipment is that of an in-line AC/DC solid-state rectifier connected to the utility and DC/AC inverter connected to the load. In the uninterruptable power supply configuration, a storage battery is connected at the DC bus interface between the two devices to provide power through the inverter during utility power outage. In normal operation the rectifier serves to keep the battery charged. All utility power flows through the inverter. In case of failure of either device, a solid-state switch closes to bypass both, feeding utility power to the load. The full complement of power conditioning hardware is housed in a single cabinet.

The power conditioning equipment is designed with modular subsystems which are easily adapted to the modifications required by the RTI photovoltaic systems. These modifications are (1) to add the maximum-power tracking function to the inverter, (2) to provide the capability to share power with the utility at the inverter output on a continuous basis (the inverter is currently designed to operate in synchronism with the utility), and (3) to operate the rectifier only as a charger for the battery. The power sharing capability is a minor extension of current capability since the UPS system are, at present, operated in parallel with each other.

4.2.2 EQUIPMENT FEATURES

The features of the conventional power conditioning equipment that are applicable to RTI's photovoltaic system are described here, to be followed by those which depart from conventional. Appendix A, "Reliability and Maintainability Features of Exide Power Conversion Equipment", includes an Exide BackUp (TM) Power System data sheet (labelled Section 74.10) and one-line diagram (AEA 100 004) for their conventional 100 KW inverter/charger system supplements the following discussion.

4.2.2.1 Static Inverter

The inverter is of the 12-step, 3-phase, sinewave-output type. The 12-step design inherently produces an easily-filtered, well-balanced, sinewave output which is completely compatible with the fluorescent lighting and service loads of this application. Operation is normally in exact synchronism with the AC utility; during period of utility outage, the inverter continues to operate from solar and/or battery power with 0.1% frequency stability and no degradation in voltage regulation or load handling capability.

The Exide stepped-wave inverter produces a precisely dimensioned step waveform with no harmonics lower than the 11th. The inverter is built as an array of identical inverter legs, each containing two main power SCR's. Other operating components are two three-phase output transformers, the output breaker, a small output filter assembly to remove the remaining

harmonics, a transient suppressor, a DC input capacitor assembly, and an all digital control.

4.2.2.2 Rectifier/Charger

The RTI system contains a phase-controlled rectifier supply which supplies charging current (current-limit controlled) to the battery, which is wired to the DC link bus through a contactor. The charger uses a pulse connection; hence, the input current draw is inherently free of all even harmonics and of the lower odd harmonics as well. The remaining harmonics are reduced by the inherent leakage inductance in the main transformer plus capacitive filtering. This full 12-pulse configuration minimizes harmonic influence on the AC utility feed. Construction is modular for speed and ease of maintenance. Input and battery circuit breakers with shunt-trip controls are internally-mounted. Both current-limiting and voltage regulation points are externally programmable. Internal construction is, again, modular, corresponding to the inverter section design.

4.2.2.3 Controls and Auxiliaries

All of the components of the static power conversion subsystems are designed to respond to commands from and to report measured system parameters and status conditions to the common-bussed central data link. The input/output devices for local operation and monitoring of the system are grouped for maximum convenience and are concentrated on the module control panel, located behind a sliding Lexan window. Indicators are used to monitor input and output AC and DC, show whether module status is normal, or that an alarm condition exists, or that a failure has occurred. The interior panels serve to identify the precise nature of alarms or the causes of shutdowns which are summarized on a remote panel, and to provide other indications which are useful in maintenance. Details of these controls and auxiliary functions are included in the detailed procurement specification in the drawing package.

4.2.2.4 Inverter/Utility Parallel Operation

Exide inverters are designed to operate in synchronism with the utility in their normal operating mode of uninterruptable power supply so that transfer to the normal bypass can be made in case of inverter failure. The inverters are also designed for normal operation in parallel with each other to share a large load among two or more inverters. The extension of this technology for continuous operation in parallel with the utility is straightforward. Real power flow from the inverter is controlled by varying the phase angle of the inverter output with respect to the utility source. Reactive power flow from the inverter is controlled by inverter voltage control. This parallel operation capability also enables the maximum-power tracking function to be accomplished.

A transfer method is provided for paralleling with and isolation from the utility AC source. All necessary measurements are made within the inverter to verify the proper voltage and phasing for paralleling. Controls are such that an unsynchronized transfer is impossible. A signal, either local or remote, to tie to the utility is obeyed only when the systems are synchronized. Automatic isolation from the utility occurs upon activation of any of the following protective devices: regenerative power, inverter under or over frequency, line-to-line fault, line-to-neutral fault, or inverter shutdown.

4.2.2.5 Maximum-Power Tracking

Maximum-power tracking is accomplished as depicted in Figure 4-19. The array voltage, sensed at the inverter input terminals, and the array current, sensed by means of a shunt and operational amplifier, are provided as signals to a Z80 eight-bit microprocessor. These quantities are processed by an analog-to-digital conversion and then multiplied to obtain array power. The microprocessor will slew the power angle in either the increasing or decreasing direction depending upon its previous command. Approximately 1,000 times per second it will sample the present array power and compare it with the previous magnitude. If the power is

larger, it will continue to slew in the same direction. If it is smaller, it will reverse direction. This will result in a totally adaptive control which will seek the maximum-power point on the array V-I curve. It will very rapidly correct for changes in illumination and, of course, for ambient temperature variations. A voltage override will be included to unload the array whenever the DC voltage at the inverter falls below minimum input for the inverter.

An automatic/manual control will be provided to enable the operator to manually adjust power angle to verify that the system is transmitting maximum power to the utility. In periods of low illumination, the built-in rectifier can be used to simulate the array and both the automatic and manual power tracking can be checked out under power conditions.

The logic components of this control, including the analog to digital conversion, will be located on a single six-by-eight inch printed circuit card to be located in the standard Exide card cage. There is nothing unique about either the sensing (inputs) or control signals (outputs). So the novel circuitry is isolated to this single control card. The card's functions will include an output for display of array power.

Figure 4-19. Maximum Power Tracking Scheme

4.2.3 INVERTER CONTROL MODES

The inverter may be operated in either of two control modes (local or remote). In the local mode, it is controlled by the local microprocessor-based controller. In the remote mode, control setpoints are supplied to the local controller by the central minicomputer of the data acquisition and control system (DACS).

4.2.3.1 Local Control of the Inverter

The inverter is capable of operating under two control methods in the local mode. The first method is used when operation is parallel with the utility. Under this control method, the inverter input voltage (array output voltage) is sensed, and the output power is varied as required to maintain the array voltage at the maximum-power point. The second control method is used when isolated from the utility. Under this method the voltage input is established by the battery state of charge, and the output voltage of the inverter is regulated to provide proper voltage for the AC loads. Under both control methods a maximum current setting provides protection for the inverter.

4.2.3.2 Remote Control of the Inverter

The inverter is also capable of operating under two control methods in the remote control mode. When paralleled with the utility, the minicomputer receives signals from the inverter and provides maximum power tracking of the array by controlling the power flow through the inverter. Synchronization with the utility is accomplished automatically by the inverter internal control system. Provision is made for the central minicomputer to connect or isolate the system and the utility bus on command from the minicomputer. The minicomputer also controls (via 4 to 20 ma analog signals) the real and reactive power delivered by the inverter. A watchdog timer system checks the time intervals between the computer reset pulses to insure presence of the central control. If the system

determines that the central control is absent, the inverter automatically switches to the local control mode..

4.3 ELECTRIC STORAGE BATTERY

4.3.1 BATTERY DESIGN FEATURES

The batteries selected for RTI's PVCS system have been chosen through consultation with Exide and will be purchased from that company. The battery proposed to satisfy this application, the GLB-29, will be adapted from the ESB standard line of industrial batteries. The advanced features of this battery are the specially wrapped positive plates to increase discharge life and to increase performance by preventing positive material shedding and ensuring that almost all active material remains available for electro-chemical activity.

The battery will be a specially engineered lead-antimony cycling type battery that incorporates the use of 1.250 specific gravity sulfuric acid for high discharge capacity. The batteries are sized to discharge to 80% depth of capacity to maximize life and to minimize cost. Under these design criteria the batteries are estimated to have a life of 6.0 years at an average ambient temperature of 77°F. This life is contingent on proper charging regimes that insure equalizing charge of 2.65 volts per cell on a weekly basis.

Batteries will be mounted on standard battery racks designed by Exide to provide adequate structural strength and safety even against shock due to seismic tremors. The Research Triangle Park is in an area of very low seismic risk and Exide recommends their "shock-protecting" battery racks. The various construction features of the batteries are summarized in Table 4-8.

4.3.2 PERFORMANCE SPECIFICATION AND DELIVERY

Table 4-9 lists pertinent performance data for the battery chosen for the RTI application. All batteries will be on-site at the beginning of the eighth project month.

Table 4-8. GLB-29 BATTERY FEATURES

Plate Dimensions	Plate Suspension Type
Positive: 17"h x 13"w x 0.31"	Positive: Bridge Hung
Negative: 17"h x 13"w x 0.21"	Negative: Bottom Supported
Container: Polycarbonate	Bolt Connectors: Stainless Steel
Cover: Polycarbonate	Intercell Connectors: Lead Plated Copper
Separators: Microporous Rubber	
Retainers: Vetrex Glass Fiber	
Post Type: Triple	

Table 4-9. BATTERY PERFORMANCE CHARACTERISTICS

System - Lead/Acid	Depth of Discharge - 75%
Voltages - Nominal = 2.0 VPC	Capacity (kWh) - 1,000
Low = 1.85 VPC	Weight (lbs) - 129,600
High = 2.65 VPC	Floor Space (ft ²) - 1,000
No. Cells - 240	Ventilation (cfm) - 3,000
Acid Specific Gravity - 1.250	Est. Life (yrs.) - 6.0

4.4 LOAD DISTRIBUTION CENTER

4.4.1 GENERAL REQUIREMENTS

The PVCS design requires a distribution center capable of supplying 208/120 volt, 3-phase, 4-wire power to building loads. The ratings, tests and guarantees for the center will be in accordance with the rulings and standards of the Institute of Electrical and Electronic Engineers. Apparatus, supplies and devices will be subject to the approval of the National Board of Fire Underwriters and made in accordance with NEMA and ANSI standards with U.L. labels. The center will be NEMA Class 1, Type-B in enclosures similar to NEMA Type-1, except gasketed.

All power bus bars as well as all other current carrying parts will be copper. The main horizontal bus bars will be rated not less than 600

Amps and will run continuously the entire length of the control center, except when necessary to cut and provide splice plates (as between shipping sections). The main bus will be housed in an isolated compartment at the top of the control center with vertical bus bars, having a current carrying capacity of at least 300 Amps, extending the full height of each section. The vertical bus will be insulated by U.L. listed flame-retardant material. All bus bars will be braced for 22,000 symmetrical amps rms short-circuit current and will be supported by steel framework with insulators of molded glass polyester.

The load distribution center will have a continuous, horizontal, copper, ground bus installed which extends through each section of the control center with solderless connectors at each end for a bare #4/0 AWG copper wire. A fully rated continuous horizontal copper neutral bar will be completely insulated from the equipment frame.

Compression type lugs, for both utility and inverter incoming lines, will be sized for a maximum of 2 to 420 copper stranded cables per phase and will be arranged for feed from below. Space will be provided in each incoming line section so that minimum bending radii of feeder cables will be met when connecting to the main bus terminals.

4.4.2 VERTICAL SECTIONS

The load distribution center will have one or more rigid, free-standing vertical sections bolted together to form a unit assembly. Each vertical section will be nominally 13-inches deep, 20-inches wide, and 90-inches high and designed to isolate the electrical equipment in adjacent sections. Each will have a 6-inch high (minimum) horizontal wireway component with steel covers removable from the front at both top and bottom. Vertical sections will be designed for front mounting of contactors, front connection, and front wiring without removing any units.

Openings, covered by removable gasketed plates, will be provided in ends of vertical sections to allow for future addition of sections at either end. Removable plates will also be used to cover the top and any unused space on the front and back of the control centers.

4.4.3 UNIT COMPARTMENTS

Each control unit will mount within a vertical section in such a manner that each unit will be completely enclosed and isolated from all other units and can be wired from the vertical wiring trough. Circuit breaker units (through 200 Amps) and contactor units (consisting of thermo-magnetic circuit breaker and contactor through NEMA Size 4 will be "plug-in" type construction, equipped with self-aligning stabs of a type that will increase contact pressure on short circuits. Circuit breakers and contactors will be capable of independently and satisfactorily clearing a fault on the load side of the starter with 22,000 symmetrical amperes available at the line side terminals.

Each unit compartment will have an individual front door. Contactors and feeder unit doors will be interlocked mechanically with the unit circuit breaker to prevent unintentional opening of the door with power on and unintentional application of power while the door is open. Means will be provided for releasing the interlock for intentional application of power, if desired, while the door is open. Padlocking arrangements will enable locking the disconnect device in the off position. Contactor circuit breakers will be operable from outside the enclosure and will show position of disconnect device whether compartment door is opened or closed.

4.4.4 CONTACTORS

Contactors will be magnetic type, suitable for "Across the Line" full voltage, and vertical-lift or horizontal-action type. Controller units NEMA Size 1 through 5 will be of the circuit breaker-contactor combination type, 18,000 amperes interrupting capacity at 208 volts, NEMA standard 3-pole magnetic contactor with 120 volt closing coils. Each contactor unit will include a 24VAC interposing relay, Potter and Brumfield catalog No. KRPl1AG24 or equal, a 120VAC/24VAC control transformer, 100VA, with primary fuse, secondary fuse, and grounded X2 lead. Contactors will have suitable fuseholders and a minimum of two extra convertible auxiliary contacts.

The load control center will have NEMA Class 1, Type-B wiring. Only stranded cooper wire will be permitted for control and power wiring. Load connections will be made directly on the load side of the contactor.

Current transformers, will be window type and of 0.3 accuracy class with B-0.1 burden. Watt transducers will connect to the current transformers and provide 4-20ma analog signals for data collection. The transducers will operate on a 3-phase, 4-wire system with three elements.

4.5 POWER DISTRIBUTION SYSTEM

4.5.1 DESIGN FEATURES

The objectives in designing the power distribution system were to provide an efficient, safe, reliable, system using standard available commercial and industrial equipment. An electrical one-line diagram of the RTI PVCS system is included in Figure 4-20.

4.5.1.1 Distribution Wiring

Since studies indicate that the amount of power produced at collection angles less than 20 degrees will be small, the decision was made to produce power only when the collection angle exceeded 20 degrees.

This decision made it possible to wire each array to produce 465 volts. This is accomplished by wiring all of the modules on the array in series which results in a savings of 200 feet of wire per array and 400 feet of interconnecting wire, between two arrays based on the design used. By wiring the front and rear subarray such that left to right is negative to positive and the center subarray such that right to left is negative to positive, a savings of 100 feet of wire and conduit is achieved per array.

The net result in the array field is a savings of approximately 5500 feet of wire, 1000 feet of conduit and the reduction in size of 2400 feet of conduit.

Figure 4-20. RTI PVCS One-Line

Based on the above design considerations, the wire for the system was sized to limit wiring power losses to approximately 1% of the array field maximum power output.

4.5.1.2 Distribution Safety Features

One major safety requirement when paralleling two sources of power is to prevent the accidental paralleling of the sources out of phase. In order to prevent this and to allow flexibility of operation, an interlocking scheme was designed for the utility breaker and the main breaker for the building's east wing. Both of these breakers will be electrically operated. Interlocking for each of the breakers is provided with the DACS computer, each other, and the inverter to prevent an unsynchronized tie. Synchronizing can be accomplished across the main breaker and the inverter breaker.

Another safety requirement is that all fuses be isolated for changing without exposing the maintenance personnel to energized circuits. Since the DC power is available from several sources, disconnect switches were installed on both sides of the fuses to allow the fuse to be completely isolated from the sources. In addition to these special precautions, the National Electrical Code was followed to provide system safety and protection. A safety requirement of the utility company was that no power be fed back into the utility system for protection of their maintenance crews. A reverse-power relay will be provided for this purpose. The relay will be set to trip the utility breaker on the transformer circuit current.

4.5.1.3 Load Shedding

A load shedding scheme has been designed into the distribution system to allow continuous operation upon loss of utility power. Upon opening of the utility breaker, the east-wing main breaker will be tripped with a local interlock. This will prevent power feed into the west wing of the building and also prevent the closing of the utility breaker on an unsynchronized source. In addition, contactors have to be furnished for non-critical loads in the east wing to allow the shedding of these loads by

the DACS computer. The computer will also be able to control the utility breaker, the main breaker for the east wing and the inverter breaker.

4.5.1.4 Lightning Protection

Since the array structures will be installed in an open field, and since the location experiences between 40 and 50 thunderstorms per year, lightning protection will be provided for the array. The lightning protection consists of a grounding system providing less than 1 ohm to ground and a series of rods and cables to provide shielding against lightning without casting shadows on the modules. A drawing, illustrating the protection arrangement, and a discussion of the grounding design calculations are provided in Appendix B.

4.5.2 DC SWITCHGEAR

The following paragraphs describe the switchgear required for operation and control of the DC power equipment.

4.5.2.1 General Requirements

Ratings, tests and guarantees will be in accordance with the rulings and standards of the Institute of Electrical and Electronic Engineers, and apparatus, supplies and devices will be subject to the approval of the National Board of Fire Underwriters and made in accordance with NEMA and ANSI standards with U.L. labels.

The switchgear will be suitable for use on a 600 volt DC system. The enclosure will be NEMA Type 1 for indoor operation, and all power bus bars as well as all other current carrying parts will be of copper. An equipment-ground copper bus will be provided with a solder-less connector for a #4/0 base copper ground wire.

Compression type lugs will be provided for incoming lines. Lugs will be sized for a maximum of 2 to 500 MCM 37 strand cables per phase and will be arranged for feed from above or below as specified. When connecting to the main bus terminals, space will be provided in the incoming line section, so that bending radii of feeder cables can meet the specified minimum.

4.5.2.2 Disconnect Switch and Fuses

The disconnect will be two-pole, single-throw capable of carrying 600 amperes at 600 VDC continuously. The disconnect will be a non-load-breaking disconnect and will be interlocked with the contactors to prevent opening under load. The interlock may be either a mechanized interlock which will allow the opening of the disconnect only when the contacts are open or a key interlocking scheme which will insure the contactors are open before opening of disconnect.

The fuses (Buss FRS-R-600A or equal) will be 600 amperes - 600 volts DC dual element, 200,000 amperes fault current. The fuse holder will be provided in the enclosure suitable for the fuse above. Two fuses will be provided, one in each pole.

4.5.2.3 Contactors

The DC contactors will be mill-type contactors suitable for operation in a 600 Volt DC system. The contactors will have an 8-hour continuous current rating of 600 amperes, and a blowout rating of 600 amperes D.C. Coil voltage will be 230 Volts DC, and the main contacts will be normally-open. The contactor will be NEMA size 6.

Each set of contactors will be equipped with two normally-open and two normally-closed auxiliary contacts (rated 600VDC or AC) for interlocks. Contactors will be General Electric Form 1C2801-AF201A3H or equal.

4.5.2.4 Accessories

An interposing relay will be provided for each set of contactors to allow remote operation of the contactors by computer signal. The relay will operate from an external 24VAC signal. The contacts will be rated as required for the DC contactor coil operation, and the maximum inrush current required for the interposing relay coil will be 2 amperes.

DC current shunts to measure the current flow through each set of contacts will be mounted within the enclosure and will be rated 600

amperes, 50 millivolts. Transducers will be provided for receiving the shunt output and converting to an analog signal 4-20ma for the data collecting system. Also, a transducer will be provided for reading the output voltage of the battery system. Local ammeters will be provided to show voltage of the battery incoming line and current through each of the sets of contactors. Electrical interlocks will be provided to prevent the simultaneous closing of the charger contactor and the inverter contactor.

4.6 CONTROL AND DATA ACQUISITION

The control and data acquisition functions of the RTI PRDA-35 are to be handled by two separate systems:

- o The information required for control computations as well as the control outputs will be handled by the Data Acquisition and Control System (DACS), and
- o The information to be collected under the PRDA-35 uniform data requirements will be acquired by the On-site Data Acquisition System (ODAS).

The two systems are independent in that each will operate alone, regardless of the status of the other. However, as described herein, the two systems are connected by a serial communication line so that from the information previously recorded in the ODAS, the DACS can retrieve data not required for control computations but needed for non-critical analyses. The measurement and control signals and design features of the two systems are described in detail in the following subsections.

4.6.1 MEASUREMENT AND CONTROL SIGNALS

The signals which are analog inputs for the DACS, for the ODAS, or for both, are listed in Table 4-10. Typical transducer types are as follows:

Table 4-10. ANALOG INPUTS FOR DACS AND ODAS

Measured Variable	Number of Points	Sampled By		Sample Period
		ODAS	DACS	
<u>FROM METEOROLOGICAL STATION:</u>				
Direct Normal Radiation	1	x	x	1 sec
Total Horizontal Radiation	1	x		1 sec
Reference Solar Cell	1	x	x	1 sec
Wind Speed	1	x	x	10 sec
Wind Direction	1	x	x	10 sec
Barometric Pressure	1	x		10 sec
Dry-bulb Temperature	1	x	x	10 sec
Humidity or Dewpoint	1	x		10 sec
Precipitation	1	x		10 sec
<u>FROM ARRAY FIELD:</u>				
Array Field Voltage	1	x	x	1 sec
Array Field Current	1	x	x	1 sec
Array Subfield Current	10	x	x	1 sec
Array Drive AC Power	1	x	x	1 sec
<u>FROM FULLY INSTRUMENTED ARRAY:</u>				
Selected Cell Temperature	4	x		10 sec
Cell Mount Temperature	2	x		10 sec
Module Cover Temperature	1	x		10 sec
Primary Surface Temperature	1	x		10 sec
Heat Sink Temperature	2	x		10 sec
Module Internal Air Temperature	1	x		10 sec
Strain Gauge (structural)	6	x		10 sec
Array Elevation Angle	1	x		10 sec
Array Azimuth Angle	1	x		10 sec
<u>FROM POWER DISTRIBUTION SYSTEM:</u>				
Utility Voltage	1	x	x	1 sec
Utility Real Power	1	x	x	1 sec
Utility Reactive Power	1	x	x	1 sec
West Wing Total Real Power	1	x		1 sec
West Wing Total Reactive Power	1	x		1 sec
East Wing Total Real Power	1	x	x	1 sec
East Wing Total Reactive Power	1	x	x	1 sec
East Wing Load Voltage (1 phase)	1	x	x	1 sec
East Wing Load Current (3 phase)	3	x	x	1 sec
HVAC Power	1	x	x	1 sec
East Wing Critical Service Power	1	x	x	1 sec
East Wing General Service Power	1	x	x	1 sec
East Wing Critical Lightning Power	1	x	x	1 sec
East Wing General Lightning Power	1	x	x	1 sec
<u>FROM BATTERY AND CHARGER:</u>				
Battery Temperature	16	x	x	10 sec
Battery Voltage	1	x	x	10 sec
Charger Input Power (3-phase)	1	x	x	1 sec
Battery Current (charge/discharge)	1	x	x	1 sec
<u>FROM INVERTER:</u>				
Output Voltage (phase-neutral)	1	x	x	1 sec
Current Output (3 phase)	3	x	x	1 sec
Real Power Output (3-phase)	1	x	x	1 sec
Reactive Power Output (3-phase)	1	x	x	1 sec

<u>Variable Type</u>	<u>Model Number</u>	<u>Manufacturer</u>
DC Voltage	6271A7	Scientific Columbus
DC Current	6271A7	Scientific Columbus
AC Voltage	VT110PA7	Scientific Columbus
AC Current	CT510PA7	Scientific Columbus
Real Power	XL342K5A7	Scientific Columbus
Reactive Power	XLV342K5A7	Scientific Columbus
Temperature	319-WM-U	Acromag, Inc.
Strain Gauge	319-WM-U	Acromag, Inc.
Tracking Angles	819-WM-U	Acromag, Inc.

The indicated sampling periods are initial estimates; the sampling period of each input will be individually adjustable in both the ODAS and the DACS. There are 82 analog inputs for the ODAS and 57 for the DACS. In order to enable sharing of sensors by the two systems and to gain improved noise immunity, the sensor outputs will be transduced to the standard 4-20 ma signal level. The digital inputs for the two systems are listed in Table 4-11.

Table 4-11. DIGITAL INPUTS FOR DACS AND ODAS

Measured Variable	Number of Points	Sensed By	
		ODAS	DACS
Photovoltaic System Master Switch	1	x	x
Visitors' Center Display Functions	16		x
Array Stow Position Verify	10	x	x
Utility-tie Circuit Breaker Status	1	x	x
Utility Demand	2		x
East Wing Main Circuit Breaker Status	1	x	x
HVAC Load Status	1		x
East Wing General Service Load Status	1		x
East Wing General Lightning Load Status	1		x
Charger Output Connect Status	1	x	x
Battery-Inverter Connect Status	1	x	x
Charger Control Mode (remote/local)	1		x
Charger Status (power on/off)	1		x
Charger Local Alarms	4		x
Inverter Control Mode (remote/local)	1		x
Inverter Status (power on/off)	1		x
Type Operation (utility parallel/isolated)	1	x	x
In Sync with Utility	1		x
Inverter Local Alarms	4		x

There are 50 inputs for the DACS and 16 for the ODAS. All of these inputs will be generated with contact closures.

The analog outputs of the DACS are listed in Table 4-12. The ODAS does not perform control functions; consequently, there are no analog outputs associated with it. There are four analog outputs handled by the DACS.

Table 4-12. ANALOG OUTPUTS FROM DACS

Output Variable	Number of Points
Battery Charger Output Voltage Setpoint	1
Battery Charger Current Limit Setpoint	1
Inverter Setpoint A (array voltage or power output)	1
Inverter Setpoint B (reactive power output)	1

The 28 digital outputs of the DACS are listed in Table 4-13. There are no digital outputs from the ODAS. The digital outputs of the DACS will be handled with latching contact closures.

Table 4-13. DIGITAL OUTPUTS FROM DACS

Output Variable	Number of Points
Array Stow Command	10
Utility-tie Circuit Breaker Trip	1
Utility-tie Circuit Breaker Close	1
East Wing Main Circuit Breaker Trip	1
East Wing Main Circuit Breaker Close	1
HVAC Load Shed Switch	1
East Wing General Service Load Shed Switch	1
East Wing General Lighting Load Shed Switch	1
Charger Output Connect Command	1
Battery-Inverter Connect Command	1
Switch Charger to Local Control Mode	1
Power Down Charger	1
Charger Watch-dog Timer Reset	1
Equalization Charge Command	1
Switch Inverter to Local Control Mode	1
Power Down Inverter	1
Inverter Watch-dog Timer Reset	1
Enable Utility-Parallel Inverter Operation	1
Inverter Setpoint Type (array voltage or power output)	1

4.6.2 DATA ACQUISITION AND CONTROL SYSTEM (DACS)

4.6.2.1 DACS Design Features

The RTI designed PRDA-35 Data Acquisition and Control System (DACS) provides the following functions for the Photovoltaic Concentrator System (PVCS):

- Acquire all sensor-based data necessary for implementation of system control functions.
- Acquire other sensor-based data indirectly via a serial communications link to the ODAS. Data not required for control but needed for analysis are obtained in this way.
- Transfer meteorological and PVCS data which are required for extensive future analyses to an existing PDP-11/60 in the RTI Systems Research Facility. (In addition to the bulk storage capability, this facility also provides use of a floating-point processor and digital plotters.)
- Provide supervisory or direct control of the operation of the inverter, battery charger, the arrays, and the power distribution system of the building. The specific analog and digital outputs are described in Section 4.6.1.
- Manage the operation of an interactive display in the visitors' center to provide information (in response to visitors' selections of functions) such as the following:

Explanation of project purpose

- General description of how the system works
 - System block diagram with energy flows
 - Historical summary of energy use
 - Projected seasonal and annual performance
 - Current, historical, and normal meteorological information
 - Expanded diagrams of arrays, inverter, battery, charger, meteorological station, and building loads
 - General information about solar energy
- Provide alarm-limit and reasonableness checks on all measured data, and log hard-copy messages to describe abnormal conditions, operation mode changes, etc. In addition, provide daily hard-copy summary reports and demand-initiated status reports.

- Provide analysis and alpha-numeric CRT display of technical information such as transducer signal levels during calibration checks, etc. Provide for keyboard entries by System Operator or System Engineer for manual activation of control functions and modification of scan and control parameters or of component model parameters.
- Provide independent capability to implement DACS software modifications and additions entered via terminal keyboards.

The following sections described the software and the hardware configurations required to implement these functions.

4.6.2.2 Software Specifications

The DACS software will be implemented as a set of interacting program modules or "tasks". The modularity of software improves the efficiencies of software development, of software testing, and of the operating dynamics of main memory. The software modules are categorized and listed below:

- Measurement and Control Related Tasks
 - Analog Input Scan
 - Analog Input Scaling and Limit Checking
 - Analog Input Response (computation and control action)
 - Digital Input Response
 - Sequence Control Action
- Visitors' Center Display Tasks
 - Display Generation (for each function)
 - Display Update (for status displays)
- Information Storage, Transmission, and Retrieval Tasks
 - Storage of DACS Information for Modeling and Analysis
 - Information Retrieval from the ODAS
 - Information Transmission to the RTI Systems Research Facility (SRF)
 - Information Retrieval from the RTI SRF
- Unsolicited Hard-Copy Generation Tasks
 - Photovoltaic System Production Summary (daily)
 - Real-time Alarm Messages
 - Alarm Summary (daily)

- Demand Initiated CRT or Terminal Printer Output Tasks
 - Production Status
 - System Status (of measurements and outputs)
 - Subsystem Status (more detail)
 - Unscaled Measurements (for hardware checkout)
- Miscellaneous Tasks
 - System Initialization
 - Parameter Modification (e.g., scan rates, scale factors, etc.)
 - Power Recovery

All of the programming for the DACS will be in FORTRAN. The analog and digital I/O functions will be handled by the ISA-standard FORTRAN-callable subroutines for those functions.

4.6.2.3 Hardware Specifications

The hardware configuration of the DACS is illustrated in Figure 4-21. All of the components illustrated are manufactured by Digital Equipment Corporation (DEC) except the color-graphics CRT for the visitors' display, which is a Ramtek product. The DACS component descriptions and part numbers are listed below in Table 4-14.

4.6.2.4 DACS Hardware Selection Considerations

Equipment manufactured by Digital Equipment Corporation (DEC) has been selected for the DACS because DEC is a leading minicomputer manufacturer and has strong support organizations (sales, field service, and software support) at both the corporate level and in the Research Triangle area. RTI currently owns several DEC minicomputers and a number of RTI's staff are experienced users of DEC hardware, software utilities, and real-time executive systems in industrial and laboratory applications. In addition, RTI is currently using a DEC PDP 11-34 with the Industrial Control Subsystem (ICS) for real-time data acquisition. The ICS includes rugged, well-designed analog and digital input/output modules which can be purchased "off the shelf" and can be operated with the ISA-standard, FORTRAN-callable subroutines for real-time I/O. The ICS is expandable to meet all needs foreseen in this application.

Figure 4-21. Proposed DACS Configuration

Table 4-14. DACS COMPONENTS LIST

Quantity	Model Number	Description
1	SM-30LLB-BA	Packaged System Including: <ul style="list-style-type: none"> - PDP 11/34 CPU - Dual Removable 5 MB Disk Drives and Control (RL11/RL01) - 64K Words Parity MOS Memory - VT100 Alphanumeric CRT - RSX-11M Real-time Operating System - Real-time Clock
1	H775-CA	Battery Backup for MOS Memory
1	DZ11-A	EIA 8-line Serial Multiplexer
1	LA36-CE	30 CPS Printing Terminal
1	LAXX-KG	EIA Adapter for LA36
2	BC03M-25	25' Null Modem Cable to Connect DZ11-A Ports to LA36 and to Visitors' Display CRT
2	BC03M-AO	100' Null Modem Cable to Connect DZ11-A Port to existing RTI SRF PDP-11/60 and to the ODAS
1	QP230-AQ	FORTTRAN IV
1	NCS11-AA	Industrial Control Subsystem
1	NAD-IA	8-Channel, Wide-range A/D Converter
4	NDC-IB	16-bit Digital Input Module
2	NRL-OA	16-bit Latching Relay Output
4	NMX-IA	16-Channel A/D Multiplexer
1	NDA-OA	4-Channel D/A Converter
1	6000	Ramtek Micrographic Terminal (Visitors' Center Display)

The RSX-11M real-time operating system offers several advantages over its predecessors, DOS and RT-11. Its primary advantage is in its memory management capability which allows modular software development for real-time applications. High-frequency and time-dependent functions such as analog scan can be fixed in memory and operated at high priority, thereby ensuring that lower-priority functions will not interfere with their execution. Lower-priority functions are dynamically loaded from disk to main memory, as needed, in a manner that significantly increases the number of such "tasks" which may be runnable on a single system.

In addition to the memory management differences, RSX-11M provides automatic restart after power-failure detection, but DOS and RT-11 do not have this provision.

The 11/34 CPU was selected over the next smaller PDP-11 CPU, the 11/04, because the 11/04 allows only 28K words of usable main memory which is considered to be insufficient for proper support of RSX-11M. The 11/34 allows expansion of 124K words of usable main memory. The cost difference between the 11/04 and the 11/34 is small compared to the difference in potential capability.

The configuration listed above includes 64K words of main memory and dual 5 MB disk drives. The 64K word main memory size is considered to be necessary and sufficient to enable the memory dynamics required to implement the DACS functions listed above. One of the two disk cartridges holds the DEC system software as well as user applications source, object, and data files. The other drive provides the primary software backup device and additional space for user files. It is expected that this disk space will be necessary and sufficient for these purposes and to provide sizable buffers to hold the data collected for modeling studies and other analyses. (Periodically, this data will be transmitted to the Systems Research Facility for off-line storage).

The color graphics CRT will allow generation of visitor displays that will include both alphanumeric and graphic information as described above in the list of DACS functions. This device will provide the flexibility inherent in a software-generated display which can respond rapidly to changing conditions and which allows modifications and additions to be conveniently made.

In summary, the DACS configuration proposed here is a reliable, flexible approach which provides significant capabilities for implementation, operation, modification, and expansion of DACS functions.

The DACS software tasks listed above in Section 4.6.2.1 will be developed solely by RTI. The software development will be started immediately when Phase II begins. Source text entry and program testing can be started on RTI's existing PDP-11/60; consequently, software development will not be held up by the DACS computer delivery. The more

important tasks for measurement, control, and status display will be developed within the first three months of Phase II so that they can be used in the checkout of the arrays, the batteries, and the power conditioning equipment soon after each is installed. The initial versions of all the software tasks will have been completed within the first six months of Phase II, and final testing and modifications will proceed in phase with PVCS hardware testing. The DACS computer hardware delivery is 90 days ARO. Measurement instrumentation deliveries are 90-120 days ARO.

4.7 ON-SITE DATA ACQUISITION SYSTEM (ODAS)

4.7.1 GENERAL DESCRIPTION

The ODAS system will be government furnished equipment (GFE); however, RTI will be responsible for providing the sensor inputs, as discussed in Section 4.6.1. In addition, RTI will be responsible for implementing all of the ODAS software except that used in the transmission of the recorded data to the proposed National Data Reduction Center (via telephone data line). The following sections discuss design features to be provided in the ODAS, the ODAS software, and an example configuration of the ODAS which would offer much hardware and software compatibility with the proposed DACS configuration.

4.7.2 ODAS DESIGN FEATURES

The GFE ODAS will perform the following functions:

- Scan selected analog and digital inputs. Scan rates and scale factors must be independent and programmable
- For each input, record the value on a bulk storage medium at a specified recording interval. Scan rates will generally be much higher than the data recording rates; therefore, a moving average value of the input must be recomputed at each scan so that the recorded value will be the average of the sampled values since the last recording. Recorded values must be associated with time and sensor identification.

- Store recorded data for several days, compress, and transmit it to the National DRC via dial-up modem.
- On request, transmit data to the DACS via serial link. (This data may not include data required for control in the DACS which must be acquired directly by the DACS).
- Some limited analyses may be performed.
- Provide hard-copy and CRT display (independent of DACS hardware) of both real-time and stored data.
- Operation must resume automatically on recovery from power failure

4.7.3 ODAS SOFTWARE

To implement the functions listed in Section 4.7.2, the proposed ODAS software modules are the following:

- Measurement and Control Related Tasks
 - Analog Input Scan
 - Analog Input Scaling and Limit Checking
 - Analog Input Response (moving average computation)
 - Digital Input Scan and Response
- Information Storage, Transmission, and Retrieval Tasks
 - Storage of ODAS Information
 - Information Transmission to the RTI DACS
 - Information Transmission to National Data Reduction Center
- Demand Initiated CRT or Terminal Printer Output Tasks
 - Production Status
 - System Status (of measurements)
 - Subsystem Status (more detail)
- Miscellaneous Tasks
 - System Initialization
 - Parameter Modification (e.g. scan rates, etc.)
 - Power Recovery

These software modules are, with few exceptions, a subset of those required for the DACS (listed in Section 4.6.2.1). All of the programming for the ODAS will be in FORTRAN. The analog and digital I/O functions will be handled by the ISA-standard, FORTRAN-callable subroutines for those functions.

4.7.4 ODAS HARDWARE

The ODAS computer system is not to be procured by RTI because it is GFE. However, since the functional requirements of the ODAS and the DACS are similar, a possible ODAS configuration is illustrated (Figure 4-22) which would provide a high degree of software and hardware compability between the ODAS and DACS. Such an ODAS configuration would reduce the software development effort, the spare parts cost, and the hardware check-out effort. All of the components illustrated in Figure 4-22 are manufactured by Digital Equipment Corporation (DEC) except the auto-answer modem which is a Comdata product. The ODAS component descriptions and part numbers are listed below in Table 4-15.

Table 4-15. ODAS COMPONENTS LIST FOR COMPATIBLE ODAS SYSTEM

Quantity	Model Number	Description
1	SM-30LLB-BA	Packaged System Including: <ul style="list-style-type: none"> - PDP 11/34 CPU - Dual Removable 5 MB Disk Drives and Control (RL11/RL01) - 64K Words Parity MOS Memory - VT100 Alphanumeric CRT - RSX-11M Real-time Operating System - Real-time Clock
1	H775-CA	Battery Backup for MOS Memory
1	DZ11-A	EIA 8-line Serial Multiplexer
1	LA36-CE	30 CPS Printing Terminal
1	LAXX-KG	LA36 EIA Adapter
1	BC03M-25	25' Null Modem Cable to Connect DZ11-A Port to the LA36
1	BC05D-25	25' Modem Cable to Connect DZ11-A Port to Comdata Modem
1	T212A	Comdata Modem, Bell 212A Compatible
1	QP230-AQ	FORTTRAN IV
1	NCS11-AA	Industrial Control Subsystem
1	NAD-IA	8-Channel, Wide-range A/D Converter
1	NDC-IB	16-bit Digital Input Module
5	NMX-IA	16-Channel A/D Multiplexer

Figure 4-22. Compatible ODAS Configuration

4.7.5 ODAS PROCUREMENT AND DELIVERY

As indicated previously, the ODAS computer hardware is GFE, and RTI is therefore not responsible for its procurement. However, if a system should be selected such as that illustrated in Figure 4-22, the delivery by DEC would be approximately 90 days ARO. The ODAS measurement sensors, like those of the DACS, would be delivered in 90-120 days ARO.

The software development schedule for ODAS would essentially be the same as that described for the DACS in Section 4.6.2.3. However, if the selected ODAS system requires software which is not compatible with that to be developed on the DACS, additional software effort will be required.

5.0 SYSTEM DESIGN

The purpose of this chapter is to summarize the final system design as it has evolved, independent of the many design variants that have been considered. Thus, the system requirements are reviewed in Section 5.1; the design parameters are reviewed in Section 5.2; and the system description is reviewed in Section 5.3. Finally, in Section 5.4 the estimated costs of the system are reviewed. It may be noted that the cost of the array hardware is less than 40 percent of the installed cost of the system. This is characteristic of most photovoltaic systems; that is, the cost of erecting the system and integrating it with loads is an inescapable, large portion of the total system cost and will not be affected by lower cell or array costs.

The high proportion of the total cost that is not related to the array may be somewhat lower in the future since the present design costs include special engineering, software development, installation, and management costs that could be reduced by advancements in system design and packaging techniques.

Through the studies, analyses, and simulations previously described, a high level of credibility has been established for the final system design. However, it is expected that the experiment will provide results that will lead to modified designs for future similar applications. For example, it is expected that predictions of array power output, while accurate for the typical meteorological year data and design parameters used, will vary considerably in practice. Array output will be increased by use of cells that exceed the design efficiencies, by cell temperatures lower than the design values used, and by acquisition of the sun at lower elevation angles. Deviation of insolation from that of the typical year is to be expected with a direct effect on array output. Similar deviations are to be expected for other subsystems. In particular, the specified system loads could differ markedly from the simple load model used in the design. An important purpose of the experiment is to acquire the data that will allow more precision in future system designs.

The control system has been designed to provide considerable flexibility in operation of the system and in acquisition of data. This is

consistent with the range of performance variances inherent in the design and in the desirability for obtaining data on different operating modes. Software-imposed modifications of system operation should be easily implemented.

5.1 SUMMARY OF SYSTEM REQUIREMENTS

Ultimately, the requirements of RTI's Photovoltaic Concentrator System (PVCS) are derived from the overall objective of the PVCS applications experiment. From the overall objectives of the experiment, the more specific system design objectives result, and this set of design objectives then become the basis for the specific requirements that are placed on the system configuration, components, control techniques, and operational procedures.

5.1.1 OVERALL EXPERIMENTAL OBJECTIVES

The overall objectives of the RTI-PVCS were previously discussed in Section 2.2. For convenience, Table 2-1. is repeated below as Table 5-1.

Table 5-1. OBJECTIVES OF RTI/PVCS EXPERIMENT

DOE	To design and implement a photovoltaic concentrator system experiment in a realistic operational configuration so as to acquire technical data on the performance of such systems and non-technical data on the viability of such systems, and to do so with a cost-effective experiment.
RTI	To implement a solar photovoltaic system powering an energy-conservative RTI building so as to provide visible evidence of commitment to energy research.
Project Team	To design, fabricate, install, and operate a solar photovoltaic concentrator system that is reliable and representative of state-of-the-art technology, that serves a significant portion of the energy needs of a representative building, and that has a potential for long-term use as an energy devices/components/systems research vehicle.

5.1.2 SYSTEM DESIGN OBJECTIVES

To accomplish the overall objective of the PVCS experiment listed in Table 5-1, RTI has designed a PVCS which is responsive to the set of more specific design objectives listed in Table 5-2.

Table 5-2. RTI-PVCS DESIGN OBJECTIVES

-
- The design should be competitive, demonstrating the application of reliable state-of-the-art technologies.
 - Within the bounds of necessary constraints, the design should provide the maximum energy efficiency.
 - The system should be capable of consistently reducing the utility power consumption during utility peak-demand periods.
 - In terms of both the utility's load-management strategy and the technological constraints of interfacing with the utility, the system design should have a high degree of compatibility with the utility.
 - The capacity of the system should be significant with respect to both the intended load and the anticipated future applications.
 - The loads to be supplied by the PVCS should be selected such that the performance of the system in meeting those loads can be readily analyzed.
 - In order that a large percentage of the available PVCS power can be utilized, the system and the intended loads should be well matched.
 - To provide a high degree of operational flexibility, and to thereby enable evaluation of several operational strategies, the design should include a flexible data acquisition and control system.
 - To ensure that the PVCS has a useful life beyond the operation phase of PRDA-35, system components should be selected and configured in such a manner that components capacities and functions can be readily enhanced.
-

5.1.3 SPECIFIC SYSTEM REQUIREMENTS

From the design objective listed in Table 5-2, and from other design consideration, a set of specific design requirements can be derived. Table 5-3 lists the major design requirements for the RTI PVCS.

Table 5-3. SPECIFIC SYSTEM REQUIREMENTS

Load Selection:

- Primary Load that is Measurable and Reasonably Predictable
- Alternative Load used when PVCS Power exceeds Primary Load
- Significant Portion of Building Electrical Load
- Good Match with Diurnal Nature of PVCS Power
- Efficient Utilization of PVCS Power

Array:

- Capacity Compatible with Primary Load
- Reasonable Efficiency/Cost Trade-offs for Optics, Cooling, and Tracking
- Concentrator Adaptable to Retrofit with High-Concentration Cells and Liquid Cooling
- Modular Design for Ease of Expansion
- Passive Cooling for Each Concentrator
- Two-Axis Tracking
- Siting near PVCS Loads
- Low Shading Losses and Efficient Land Utilization
- Easily Maintainable
- Lightning Protection
- Acceptable Appearance

Power Conditioning and Distribution:

- Capacity Compatible with Primary Load
- Maximum-Power-Tracking, Synchronous Inverter
- Flexible, Safe Utility Interface, Providing Full Backup for the PVCS
- Alternate Inverter Control Methods: Output Power and Output Voltage (Isolated from Utility)
- High-Voltage Inverter Input to Reduce Array and Field Distribution Losses
- Reliable, Maintainable Equipment
- Safe, Conventional Distribution Hardware
- Battery Charge Rate Adjustable

Battery Storage:

- Discharge Rate Compatible with Primary Load
- Ampere-Hour Capacity Compatible with Primary Load Integrated over Utility Peak-Demand Period
- Conventional, Reliable Design
- Series-String Cell Voltage Compatible with Array Output Voltage Range and Inverter Input Voltage Specification
- Easily Maintainable
- Reasonable Floor-Space and Ventilation Requirements
- Reasonable Expected Cell Life

Table 5-3. (Continued)

Data Acquisition and Control (DACS):

- Analog & Digital Input/Output Capability for Control Functions
 - Direct and Supervisory Control of Array, Power Conditioning, and Power Distribution
 - Supervision and Documentation of PVCS Operational Modes
 - Local, Serial Data Link with GFE On-Site Data Acquisition System (ODAS)
 - Operation of Interactive PVCS Operator's Terminal
 - Operation of Interactive Display in Visitors' Center
 - Alarm-Limit and Reasonableness Checks on Critical Measurements
 - Reliable, Flexible DACS Hardware and Software
 - Applications Software Coded in FORTRAN by RTI Systems Engineers
 - Independent, GFE ODAS for DOE-Specified Measurement, Recording, and Data-Transmission Functions
-

5.2 SPECIFICATION OF DESIGN PARAMETERS

The general approach in the design effort was described in Section 2.0 as follows:

- Identify Experiment Options, Attributes, and Trade-offs
- Specify System Load Characteristics
- Select General System Approach
- Simulate System Performance
- Evaluate Costs
- Select Specific Experiment and System Design
- Specify System Components
- Iterate These Steps to Obtain Optimum Design

The specific design requirements listed in Table 5-3 influenced many decision steps in this iterative design process. The final RTI PVCS design configuration includes an array of 100 kW nominal peak capacity, a battery with a capacity of 1000 kWh, and a 100 kW utility-synchronous inverter (which incorporates the maximum-power tracking function). The battery is disconnected during maximum-power operation; it is connected to the array/inverter bus only for discharge or for PV charge. The PVCS will

drive both the lights and service loads of the new engineering building's east wing. When necessary, utility power will be used overnight to charge the battery sufficiently to supply the lighting load (as the primary load) during utility peak demand periods, if the array output is insufficient to do so. The east wing lighting load is projected to be 34 kW during working hours and 1.7 kW during nonworking hours.

When this system is simulated using Nashville TMY data to drive the simulation, the accumulated annual energy flows that result are as shown in Figure 5-1. Monthly variation of the array output and energy used for battery charging are shown in Figure 5-2. It is interesting to note that only a small percentage of the array output is stored in the battery system, indicating that the diurnal characteristic of the PVCS output is well matched with that of the available loads.

5.3 SYSTEM DESCRIPTION

The basic configuration of the final system design is illustrated in Figure 5-1. The characteristics and specifications for each of the major subsystems are illustrated in Table 5-4.

Table 5-4. PVCS CHARACTERISTICS AND SPECIFICATIONS

LOADS:

- Primary Load:
East Wing Lighting, (working hours) 34 kW
(nonworking hours) 1.7 kW
- Alternative Load:
Service, (working hours) 60 kW
(nonworking hours) 30 kW
- Alternative Load:
West Wing Lighting (working hours) 34 kW
(nonworking hours) 1.7 kW

ARRAY:

- Concentrator Modules per Array 240
- Panels per Array 20
- Concentrator Modules per Panel 12

Table 5-4 (Continued)

● Maximum Peak Power Output	9,576 watts
(for ambient temp. = 28°C, direct-normal insolation = 1000 w/M ²)	
● Number of Arrays in Field	10
● Turning Diameter of Array	82 feet
● Diameter of Support Rail	58 feet
● Maximum Height of Array	10 feet
● Total Weight of Array	15,250 pounds
● Maximum Operational Windspeed	30 mph
● Tracking System	active sun sensor with open-loop backup
● Diameter of Module	30 inches
● Maximum Power Output (module)	39.9 watts
● Voltage at Maximum Power (module)	1.94 volts
● Current at Maximum Power (module)	20.6 amperes
● Cell Type	Silicon
● Cell Diameter	3 inches
● Cell Cooling	Passive
● Optical System	Cassegrain
● Cell Efficiency (Nominal)	14%

POWER CONDITIONING:

Inverter:

● Capacity	100 kW
● Efficiency (Loading > 30%)	90%
● Input Voltage	0-650 VDC
● Output Voltage	208/120 VAC
● Type	12-step, 3-phase
● Frequency Stability	0.1%
● Lowest Harmonic	11th
● Maximum-Power Tracker Slew Frequency	1 KHz

Charger:

● Capacity	100 kW
● Efficiency (Loading > 30%)	90%
● Type	phase-controlled
● Output Voltage	528-622 VDC
● Float Charger Voltage	2.20V/cell
● Equalization Voltage	2.65V/cell
● AC Input Voltage	208V, 60Hz
● Voltage Regulation	+1%
● Output Current Limiting	120% rated load

Table 5-4 (Continued)

Battery:

● Capacity	1,000 kWh
● Number of Cells	240
● Cell Voltage - Nominal	2.00 volts
Low	1.85 volts
High	2.65 volts
● Type	Lead/Acid
● Acid Specific Gravity	1.25
● Normal Discharge Depth	75%
● Estimated Life	6 years
● Weight	129,600 lbs
● Floor Space	1,000 ft
● Ventilation	3,000 cfm

Data Acquisition and Control:

● Analog Input Channels	72
● Digital Input Channels	64
● Analog Output Channels	4
● Digital Output Channels	32
● Digital Processor	DEC PDP-11/34
● Real-Time Executive	RSX-11M
● Applications Software Processor	FORTRAN
● Main Memory	64K words
● Disk Memory (Removable)	10M Bytes
● Operator Terminal	VT100 CRT
● Hard Copy Terminal	LA36 DECwriter
● Serial Multiplexer (EIA-RS232)	DZ11-A
● Visitors' Center Display	Ramtek Micrographics

Figure 5-1. Annual Power Flow in RTI PVCS System

Figure 5-2. Energy Flow in Photovoltaic System

5.4 SYSTEM COST CONSIDERATIONS

5.4.1 GENERAL CONSIDERATIONS

The total cost of the PVCS described in this report is estimated to be approximately \$2.8 million (\$28 per watt). Included are costs of all hardware, software, and facilities required to operate, control, and house the system. The costs of features which reflect the experimental, prototype nature of the system are also included. These additional costs include computer-graphic display for a visitors' center and monitoring instrumentation beyond that required in similar future operational systems. The capacity of the system has a large impact on costs; however, the cost per watt does not vary linearly with system size (although it may in some future, production-driven environment). For the present, nonrecurring development costs have a large impact on the system costs. Table 5-5 presents a convenient categorization of the PVCS costs.

Table 5-5. ESTIMATED PVCS COSTS

ITEM NUMBER	ITEM DESCRIPTION	COST	PERCENT OF TOTAL
1	PVC Arrays, Related Services	\$1,119,000	40.0
2	Power Conditioning, Related Services	165,000	6.0
3	Batteries, Related Services	183,000	6.5
4	Array System Construction/Assembly	323,000	11.5
5	Electrical System Hardware and Construction	378,000	13.5
6	Data Acquisition and Control System	70,000	2.5
7	Visitors' Center and Facilities Costs	40,000	1.5
8	Management, Software Development, and Implementation Costs	442,000	15.0
9	Engineering Services/Design & Construction	98,000	3.5

The cost estimates shown in Table 5-5 are for a well designed, well engineered, aesthetically pleasing facility. Cost estimates for site preparation, construction of foundations, and assembly of arrays were prepared by an experienced architectural and engineering firm, and these estimates reflect conformance to good engineering practices and all applicable codes. Reasonable allowances for inflation factors are included. Thus, actual costs should compare well with the estimates. Furthermore, the proposed PVCS facility should be a reliable, flexible system suitable for many years of service in both experimental and applications services.

5.4.2 ARRAY COSTS

Item 1 in Table 5-5, the PVC array cost, is a dominant factor representing 40 percent of the total cost and is more than twice the cost of any other single item. The array costs are strongly affected by the size of the system. The array costs tabulated in Table 5-5 reflect an assumption on the part of Motorola that a larger number of arrays will be acquired during the PRDA-35 related procurement. (Fifty-nine arrays are proposed for the Arizona Public Service Co. system.) Thus, the nonrecurring costs associated with the design and development of the arrays are spread over a larger number of arrays. If much larger numbers were acquired, the nonrecurring costs would be less significant, and the array costs would vary somewhat linearly with the size of the system.

5.4.3 POWER CONDITIONING COSTS

Costs associated with item 2 of Table 5-5, the power conditioning apparatus, will vary nonlinearly with the system capacity. These costs include some nonrecurring development costs which would become less significant if either additional units or a larger unit were acquired. (The development effort reflects the inclusion of a maximum-power tracker in the interver system and the necessity of accepting a wide-range, nonstandard DC input voltage.)

5.4.4 BATTERY COSTS

The costs of the batteries, item 3 in Table 5-5, are not solely and directly related to PV array design capacity. In fact, the system could be operated without batteries; however, the performance capability would certainly be reduced. The ampere-hour capacity of the batteries will strongly influence costs. Battery design capacity is specified to be sufficiently large to displace the primary load from the utility during peak periods and is related to the PV array capacity only in the sense that both the array capacity and the battery capacity are dependent on the magnitude of the primary load.

5.4.5 CONSTRUCTION COSTS

The cost of the array construction and assembly, item 4 of Table 5-5, includes site preparation, construction of the foundation for the rail system, and personnel barriers. These costs vary directly with the system capacity; however, a "learning-curve" factor should lead to cost reduction as a percent of the total cost in similar future systems as contractors gain experience with PVCS installations.

The electrical system construction, item 5 of Table 5-5, is another large cost item that varies in a somewhat complex way with the system size and with unique features of the installation. A portion of the costs, i.e., the inter- and intraconnection of the arrays, varies directly with the number of PVC arrays in an installation. Between the point that the arrays are paralleled and the interface with the power inverter, the system costs are relatively insensitive to capacity. Cable and switchgear capacities vary, but installation costs do not vary significantly in proportion to capacities.

The sum of items 4 and 5 represents 25 percent of the total system cost. These items represent the on-site construction, assembly, and installation of the PVCS. A portion of these costs, perhaps as much as 8 to 10 percent, is relatively insensitive to the system capacity. The remainder is proportional to capacity; however, there will be some per-watt cost advantages gained with either larger or expanded systems.

5.4.6 OWNER-RELATED COSTS

The costs related to the data acquisition and control system, item 6 in Table 5-5, are relatively constant. These costs represent an extensive monitoring, data acquisition, and control capability that could be expanded for larger installations for relatively little cost. The visitors' center display costs that are included here can be considered fixed costs, independent of the system size and features.

Item 7 of Table 5-5 is strongly affected by RTI cost sharing. Generally, it represents the cost of housing batteries, power inverter, computer, other related apparatus, and the visitors' accommodations. It is largely independent of the system capacity and can vary widely with optional building features.

Other owner-related costs, item 8 in Table 5-5, includes overall management of the Phase II effort. It also includes negotiation for and management of subcontracts, procurement, participation in in-plant and on-site testing of components to specifications, and inspections for quality control. It also includes the development of computer software for the implementation of data acquisition, experimental protocol, and control strategies for the operation of the PVCS. Personnel training for maintenance of the system and some minor installation activities are also included, for example, the installation and maintenance of the GFE meteorological station and the GFE ODAS. These are relatively fixed costs and would not vary significantly with the system capacity.

5.4.7 COSTS OF ENGINEERING SERVICES

Engineering services are design and construction, item 9 of Table 5-5, are included to assure that the construction and assembly are of a top professional quality. This item provides for the participation of an experienced architectural and engineering firm in all aspects of the Phase II implementation, including design finalization, expertise in fabrication and assembly, adherence to local codes, and professional quality in construction practices. These are relatively fixed costs and should not vary significantly with changes in system capacity.

5.4.8 CONCLUSIONS

These system cost considerations strongly suggest that a significant reduction in the per-watt costs (from the \$28 per watt in this case) can be achieved in future installations. It is not realistic to estimate the cost of a system of a significantly different capacity at this time. (All components were not quoted for different capacities.) The experience of manufacturing the various components, constructing the foundation, and installing the components and wiring should provide additional information needed to accurately make such estimates. However, it is reasonable to state that the cost per watt for future comparable systems will certainly be less than that for the systems now being designed.

6.0 OPERATION AND EVALUATION PLAN

The third phase of the Photovoltaic Concentrator Application Experiment includes the system operation, data collection, and evaluation activities. The objective of these activities is to acquire data on the operational performance of the system and on the success of the system in meeting its design objectives. These data are expected to be complete and comprehensive so that they may be applied in subsequent technical and policy decisions relative to future experimental or operational photovoltaic concentrator systems. For the RTI system, the objectives of the Phase III effort are specifically to characterize the:

- solar energy available to the system
- natural environmental factors that impact system performance
- performance of the photovoltaic concentrator array
- performance of the control system
- efficiency and reliability of the overall system
- system effectiveness in meeting the load for which it is designed
- value of the photovoltaic power supplied to the load
- economics of the system
- impact of the battery system on performance
- relative merits of different control strategies
- efficacy of load sharing with utility
- maintenance requirements for the system
- operational impacts of system

The plan presented for Phase III is directed to acquisition of these data. The design of the RTI system provides an opportunity for operation in several modes and with various load configurations. Because of this, a two-year duration for Phase III has been designed and is described in the following paragraphs.

6.1 DOE UNIFORM DATA REQUIREMENTS

The DOE Uniform Data Requirements for the Photovoltaic Concentrator Applications Experiment constitute a minimum set. These hard data are obtained from transducer outputs sensed by the DOE-supplied, On-Site Data Acquisition System (UDAS) and are to be processed and archived by a DOE data reduction center. The initially defined hard data set is given in Table 6-1. Hard data are to be supplemented by soft data on the system

Table 6-1. UNIFORM DATA REQUIREMENTS - TRANSDUCER BASED DATA

Class	Parameter	Recording Interval
Meteorological	Total horizontal radiation	10 min.
	Direct normal radiation	10 min.
	Wind speed and direction	30 min.
	Barometric pressure	30 min.
	Ambient air temperature	30 min.
	Relative humidity (dew point)	1 hour
	Precipitation	1 hour
	Reference solar cell (Isc)	10 min.
System		
	Array-field voltage and current	10 min.
	Array-subfield voltage and current	10 min.
	Array-field energy	Daily
	Inverter input voltage and current	10 min.
	Inverter output voltage, current, and power	10 min.
	Solar cell operating temperature*	30 min.
	Battery voltage and current	
	Battery cell temperature*	10 min.
	Load voltage and current	30 min
	Power source	30 min. and when changed
	Load power or phase angle	30 min.
	Load energy	1 hour
	Tracking state (tracker-desteer)	when changed
	System state (on-off)	when changed

*For these parameters, only selected units will be monitored.

and its performance that are acquired during all phases of the experiment and recorded in the contractor reports and system operating log. These soft data types are listed in Table 6-2.

In considering additional hard data that may be archived through ODAS, RTI recommends data on the array, the system configuration as determined by control system mode, the battery charging power, and on the loads being served. A list of potential added transducer data is given in Table 6-3.

Table 6-2. UNIFORM DATA REQUIREMENTS - SOFT DATA

Data Type	Report Interval
Site description	One time
Equipment costs	One time
Capital and construction costs	One time
Construction schedule	One time
Schedule for cleaning, maintenance, calibration, and repair	Initial and each occurrence
Unscheduled maintenance	Each occurrence
System downtime	Each occurrence
Equipment failures	Each occurrence
Pre-operational testing/checkout	One time
Environmental effects	When appropriate
Utility interface	When appropriate
Safety considerations	One time
System schematic	One time
Harmonic content of inverter output	Every six months
Battery state-of-charge	Weekly
System description	One time

Table 6-3. POTENTIAL ADDITIONAL ODAS DATA

Type	Recording Interval
For one selected array:	10 min.
Array tracking angle, azimuth and elevation	
Cell mount temperature	
Module cover temperature	
Reflector surface temperature	
Module internal air temperature	
Array frame structural deflections	
Battery charge state	30 min.
Battery charger output power	30 min.
Battery connection state	When changed
Control system operating mode	When changed
Loads - Lighting system	10 min.
Other lighting circuits	10 min.
Service circuits	10 min.
HVAC	10 min.
Utility voltage	10 min.
Total utility power to facility	10 min.

Additional data that will be collected by RTI's Data Acquisition and Control System (DACS) are itemized in Table 4-10. These data are required for system control and for the analytical outputs specified in the following sections.

6.2 DATA ACQUISITION PLAN

The objectives of the data acquisition phase of the experiment can be divided into two sets. One set of objectives is attained by operation of the photovoltaic concentrator system in any mode available while acquiring data on the environment, the array and inverter performance, and the associated control and operational parameters. This first set of data provides a basis for evaluation of the specific array design, solar energy availability of the locale, and operational attributes of photovoltaic concentrators. In addition, the opportunity is available to attain a second, and equally valuable, set of objectives relating to the use of the electrical energy produced by the system. This set of objectives responds to questions on the proportion of a given load that can be supplied by the output of the photovoltaic concentrator array, the value of the energy storage relative to overall system performance, the economic advantage in displacing utility loads with photovoltaic power in peak demand periods, the performance of the system in a demand-reduction operational mode, and the extent to which the system can attain stand-alone operation for a given load. The operational modes that provide the basis for answering these questions are given in Table 6-4 and the proposed schedule of data acquisition is given in Table 6-5. As seen in the schedule, the primary mode of operation (Mode 1) is continued through a full year of operation in order to provide a data base for thorough evaluation. The three additional modes are each run for four one-month periods. This schedule provides for operation in all four seasons of the year with each period being of sufficient duration to minimize start-up transient effects and to average effects of extended cloudy periods.

During the data acquisition phase, measurements from the system transducers previously identified and from the meteorological station will

Table 6-4. Operating Modes and Objectives

System Configuration Mode 1 Time-of-day

Objective - To determine system performance when it is operated so as to completely remove the lighting load from the utility during peak demand periods.

Description - During peak demand periods, power for the lighting load is obtained from the array. When the array output is inadequate, the battery is connected and furnishes power as required up to the full lighting load. When array output exceeds the lighting load, it supplies alternate loads.

During off-peak periods, array output is used to charge the battery to 40 percent of capacity and to supply the lighting and alternate loads. Power in excess of that required by the loads is used to charge the battery up to its full capacity. The battery is not connected to the system in off-peak periods except when being charged by the array and during utility power interruptions. As needed, the battery is charged at night to bring its charge state to 40 percent of its capacity before each operating day.

Mode 2 Demand reduction

Objective - To determine system performance when it is operated so as to reduce the peak demand for the entire facility load.

Description - The array output supplemented by the battery as required will be used to reduce the daily demand peak of the facility by 250 kWh. This will be done by establishing a utility demand level that, by using the PVCS system, will not be exceeded. This level will be based on actual load data obtained in Mode 1 operation. All demand in excess of that level will be met by the array output or by use of the battery. Array power that is excess to this requirement will be used to recharge the battery and supply the facility loads.

Mode 3 Parallel battery

Objective - To determine system performance when the battery is connected in parallel with the array.

Description - In Mode 1, the battery is disconnected from the array except when power is required from it or when it is being charged by the array. This permits peak power tracking of the array. In this Mode 3, the battery will remain in the system at all times.

Mode 4 Isolated load

Objective - To determine system performance in satisfying a dedicated load.

Description - The east wing lighting load, estimated to be over 350 kWh per day, will be separated from the other facility loads and supplied by the array output directly and through the battery to the full extent of the available PVCS power. When power is not available from the array or battery, it will be supplied by the utility. The battery charge state will be maintained so that 40 percent of its capacity is available at the beginning of each peak power period in order to avoid demand on the utility.

be archived in digital format by the Data Acquisition and Control System (DACS). These extensive data will be available to carry out the analysis task described in the following section.

Table 6-5. DATA ACQUISITION SCHEDULE

System Operating Mode	Month of Phase III						
	6	9	12	15	18	21	24
1	-----						
2			--	--	--	--	
3			--	--	--	--	
4			--	--	--	--	

6.3 ANALYSIS

Both technical and economic analyses will be performed on a DEC PDP-11/60 computer, connected to the DACS via a serial communications link. This interconnection facilitates a variety of analyses, off-line storage of data, and the use of PDP-11/60 peripherals such as digital plotters. The analytical plan is carefully constructed to provide results for application to planning, designing, and constructing future solar energy systems and to policy decisions relative to application of photovoltaic concentrator systems. An outline of the proposed analyses is given in the following paragraphs. These are associated with the two sets of objectives defined in Section 6.2, i.e., one set for general analyses that apply to all modes of operation and one set which analyzes the effects of different modes of operation. The general analyses are described in Table 6-6. A number of the defined objectives for the experiment are met by routine processing and analysis of the archived data. For example, the insolation and environmental history of the site is obtained routinely, and array and system productivity can be presented in a variety of ways by simple manipulation of transducer data. Such routine data analyses are

not tabulated. The tabulated analyses require combinations of data, external information, and models that provide a higher level of knowledge from the experiment data acquisition phase.

Table 6-6. GENERAL ANALYSES - ALL MODES OF OPERATION

Analysis	Dependent Parameters	Independent Parameters
Cell, subarray, and array performance	Voltage Current Power Efficiency	Time Ambient temperature Wind speed and direction Atmosphere obscurants Insolation Tracking accuracy System dysfunctions
Tracking system performance	Deviation of tracking angles	Elevation/azimuth angles Time
Inverter performance	Efficiency	Input power Time
Battery performance	Efficiency (losses) Use level	Input power Output power Cell temperature Time
System performance	Proportion of loads supplied by solar energy directly and through battery System efficiency and reliability	Utility energy demand Inverter energy, in/out Battery energy, in/out Array energy Lighting system energy Alternate load energy Time System dysfunctions and degradation

The analyses of cell, subarray, and array performance are, in general the same as those performed in our system simulation studies. Among other things, these analyses will indicate the accuracy and applicability of the derived conceptual models when compared to the real operating system.

Consequently, the analyses will enable selection of more precise model forms and model parameters. These improved models can be directly applied for performance prediction in the DACS and will be useful in designs and analyses of other systems using similar components. In addition to specific operating characteristics of the concentrator solar cells individually and arrayed, these analyses will relate the performance of the reflux-type cell-cooling module, the changes in the optical efficiency of the concentrators, and the performance variances experienced as a result of environmental factors. The tracking system, inverter, and battery analyses are similar in intent, i.e., to confirm or to improve our conceptual model of their performance. The general system performance analysis is a measure of the overall performance independent of the mode of operation.

In contrast to general analyses, the specialized analyses listed in Table 6-7 are dependent on the operating mode. Each of these analyses would apply to each of the four operating modes for a total of 20 analyses. For example, the value of the energy derived from solar conversion should be different for each of the four operating modes. The system figure-of-merit is based on a utilization factor defined as the product of the fraction of the array output used by the load and the fraction of the load provided by the array output. In all of the operating modes, it is expected that all of the array output will be used, but not all of it will be used by the lighting system, the primary load. Thus, for the primary load, the first term in the utilization factor is low (simulation indicates about 60 percent), but for the total load, it is high, approaching 1. On the other hand, the second term, the fraction of the load provided by the array output, is much higher for the primary load than for the combined loads. These differences become even greater if the primary load is defined as the east wing lighting load during only the peak demand period.

Analyses of the system figure-of-merit for the different operating modes and different loads will lead to identification of the optimum load for the system, i.e., the maximum utilization factor.

The system output as measured by the value of the energy derived from solar conversion is also dependent on operating mode. Simulation has indicated that the greatest value is obtained in Mode 1 with a time-of-day rate structure. The simulation, however, is conservative in its estimates

TABLE 6-7 SPECIALIZED ANALYSES - MODE DEPENDENT

Analyses	Dependent Parameters	Independent Parameters
System figure-of-merit	Utilization factor	The independent parameters listed below are required for most of the analyses in this table.
System energy output	Value of energy derived by solar conversion	Time Insolation Array output power
System economics	Ratio of present and projected system costs to present and projected value of produced energy	Battery input Battery output Inverter output Lighting load Alternative loads Utility demand
Storage economics	Calculated incremental benefit of battery	System mode Rate structures System costs
System design	Sensitivity of performance parameters to design parameters	Discount rates Projected rate structures Projected system costs

of load variations, and the results must be considered to be tentative until confirmed by the experiment. The most pertinent modes of operation are Mode 1, Time-of-day, and Mode 2, Demand reduction.

The system economics are based on initial system costs, operating costs, and system productivity. Simulations have been based on RTI's analysis program which compares life-cycle system costs to the value of the energy produced based on utility rate structures. In order to ascertain the system economics fully, different scenarios based on present and projected rates will be analyzed. It is accepted that present solar cell costs and utility rates do not now provide acceptable economic conditions for photovoltaic systems. These analyses will utilize actual system

operating parameters in the various operating modes as well as projected system costs to ascertain the break-even conditions for system operation:

Simulations have not yet provided a definitive basis for economic optimization of the energy storage subsystem, the battery. The size of the battery is based on system operational considerations, not economic factors. An alternative to the battery is to use the utility as a full-load reserve; however, this approach does not allow the PVCS system to displace peak demand. The battery provides the capability for consistently displacing utility power from the peak period or for reducing demand peaks regardless of variations in insolation. Data being acquired on the PVCS system will permit realistic calculations of the marginal value of the battery to the PVCS system and thus will provide a basis for deciding whether to use battery storage in future systems.

Our simulations of overall system performance are based on assumptions of the size and diurnal variations of various loads. While these assumptions are based on sound engineering data, they are basically conservative. They assume that the lighting system is used at full capacity and that service loads follow a regular pattern. Actual performance of the system will, however, be measured relative to the real loads experienced. The question then arises as to the effect on performance, as measured by system figure-of-merit and productivity, of variations in general design parameters such as array size, battery capacity, and control strategy as well as component parameters such as optical efficiency, solar cell efficiency, cell operating temperature as regulated by the reflux-type cell coolers, and the power transmission and conditioning designs.

These descriptions are intended to describe the general nature of the analyses to be performed in Phase III of the experiment. It is expected that actual operation of the PVCS will lead to a variety of other analyses and that the results will provide definitive guidance to future policy on the role of photovoltaic concentrator systems, in particular, and on the role of photovoltaic systems, in general.

6.4 NON-TECHNICAL ISSUES TO BE RESOLVED IN PHASE III

The nature of the RTI experiment minimizes the impact of non-technical issues during the data acquisition phase of the experiment. Almost all of the issues in this category relate to acceptance of the PVCS system, perceptions of its value, and impacts of the system. Issues are listed in Table 6-8.

RTI, as owner and operator of the system, will be evaluating its operation carefully so as to be in a position to decide on its operation beyond the period of the experiment. Germane to this evaluation will be both technical and non-technical factors with, economics being a prime non-technical factor for this decision. Opportunities to employ the system for further research purposes will be an equally important factor. In this respect, the system has been designed to allow retrofit for thermal energy storage and for more efficient solar cells and the loads are compatible with such applications.

Table 6-8. NON-TECHNICAL ISSUES

-
- Will the owner/user of the system perceive the PVCS as providing an acceptable level of service and not being an undesirable intrusion on its campus?
 - Does the PVCS system establish a practical basis for a future economically viable system?
 - Does the public coming in contact with the system perceive it as being of real value as a response to energy needs?
 - Will the PVCS be maintained in operation beyond the 24-month data acquisition phase?
 - Are there undesirable environmental, safety, nuisance, or other impacts of the system?
 - Does the local utility view the system as desirable for further application in its service area?
-

APPENDIX A

RELIABILITY AND MAINTAINABILITY FEATURES
OF EXIDE POWER CONVERSION EQUIPMENT

The following discussion is adapted from technical literature describing Exide power conversion equipment.

A.1 INDICATION AND CONTROL FEATURES

A fundamental requirement of good reliability and maintainability is that the equipment design must include a sufficient number of indication and control devices. Table A-1 lists Exide's standard meters, indicators, and controls which will be included in the power conditioning equipment to be supplied to RTI:

Table A-1.

LOCAL INDICATORS AND CONTROL DEVICES IN POWER CONDITIONING EQUIPMENT	
<u>Controls</u>	<u>Meters</u>
AC Input Breaker	AC Input Voltage
DC Battery Breaker	AC Input Current
AC Output Breaker	Battery Current (zero-center)
UPS Module On	Elapsed Time
UPS Module Off	AC Output Voltage
Input Current Limit Adjust	AC Output Current
DC Voltage Adjust	DC Voltage
AC Output Voltage Adjust	
Alarm Unstore	<u>Alarm Indicators</u>
Lamp Test	Charger Fuse Blown
Horn Silence	Charger Logic Failure
Transfer to Bypass	Charger Overtemperature
	Battery Ground
	Battery Discharge
<u>Status Indicators</u>	Battery Undervoltage
AC Input Breaker Open	Inverter Fuse Blown
AC Input Breaker Closed	Inverter Overtemperature
DC Battery Breaker Open	Inverter Logic Failure
DC Battery Breaker Closed	Inverter Output Overload
AC Output Breaker Open	Fan Failure
AC Output Breaker Closed	Capacitor Fuse Blown
UPS Module On	Oscillator Failure
UPS Module Off	Power Supply Failure
UPS Module OK	Load Division Trouble
UPS Module Alarm	DC Undervoltage Trip
UPS Module Tripped	DC Overvoltage Trip
Sync to Utility	Inverter Leg Failure
Voltage Difference	AC Undervoltage Trip
System Bypass Breaker Open	AC Overvoltage Trip
System Bypass Breaker Closed	Frequency Control Failure
	Sync Trouble
	Power Sync Trip
	Signal Sync Trip
	Static Switch Failure

A.2 MALFUNCTION DETECTION

The circuits which decide when to disconnect a failing module are vitally important in assuring isolation of a failing inverter and thus overall system integrity. The approach to the selection and design of the malfunction detection circuits was as follows:

1. All failure detection circuits will be totally internal to the UPS module. Any external sensing raises the possibility of disconnecting a good inverter from the load due to a failure elsewhere in the system.
2. As far as possible, all failures will be sensed when they occur so that the module will be disconnected before the output power can degrade.
3. In cases where multiple inverters are paralleled, the failure detectors will sense internal parameters (e.g., D.C. link voltage, voltage drop across fuses, logic signals) rather than output terminal parameters (output voltage, current and power flow) to avoid any possibility that the power flow disturbance caused by one inverter's malfunction will falsely trigger another inverter's logic. Where output terminal parameters must be sensed, the trip signal resulting will be intentionally delayed to allow the more selective protections to act first.

The malfunction detection circuits which disconnect a module from the loads include the following:

- Control Power Supply Failure
- Frequency Reference Failure
- Logic Failed Detector (sequence detector)
- D.C. Link Voltage Out of Limits
- Inverter Thyristor Fuse Blowing
- Internal Fault Detection
- Voltage Regulator Failure (output overvoltage and undervoltage sensing biased by load sharing signals)

A.3 FAILURE ANNUNCIATION

When a failure occurs and, in the case of a major failure, the failed module has been removed from the load, the next objective is to alert the operating personnel that a failure has occurred. This is accomplished both audibly and visually, either at the module and/or at one or more remote locations. Two summary visual alarms will be provided at the remote monitor, one for major alarms and one for minor alarms. At each module, the following failure modes are annunciated visually:

Charger Fuse Blown	Power Supply Failure
Charger Logic Failure	Load Division Trouble
Charger Overtemperature	DC Undervoltage Trip
Battery Ground	DC Overvoltage Trip
Battery Discharge	Inverter Leg Failure
Battery Undervoltage	AC Undervoltage Trip
Inverter Fuse Blown	AC Overvoltage Trip
Inverter Overtemperature	Frequency Control Failure
Inverter Logic Failure	Sync Trouble
Inverter Output Overload	Power Sync Trip
Fan Failure	Signal Sync Trip
Capacitor Fuse Blown	Static Switch Failure
Oscillator Failure	

Whenever appropriate, the indicators incorporate memory, which requires manual operation of an "unstore" switch to erase. The lights are backed up by the control supply; so even if all power to the module is cut off, the alarm lights will continue to identify the cause of the problem.

Exide's new logic failure sensing and protection circuit is of particular value. The "Logic Failed Detector" is a unique circuit which samples the inverter logic circuit outputs right at the SCR gates themselves to determine whether the actual firing follows a correct "legal" pattern. If a logic failure occurs within 1.5 milliseconds or less, a trip signal is generated causing immediate removal of SCR gating followed by module shutdown and the visual/audible alarms. The speed with which the Exide logic failure trip is generated enables disconnection from the critical bus before degradation of the UPS output.

A.4 TROUBLESHOOTING

The power conditioning design is modular in layout. A built-in test equipment (BITE) PC board is available with the system logic as optional equipment and will be included in the RTI system. In addition, the alarm/annunciation system is arranged so as to pinpoint the failure and minimize the trouble "find time."

Practically all trouble corrections can be effected by simply locating and replacing the faulty module. The Exide equipment is designed so that this can be accomplished very easily and quickly.

The inverter leg is particularly noteworthy since, in most instances, its replacement will correct a problem. All the inverter legs are identical and completely interchangeable with each other in each UPS module. Charger thyristors are similarly packaged.

Most other replaceable subassemblies are in the logic category and consist of printed circuit cards which are mounted together in a single "card cage," mounted conveniently at eye level. Two boards provide complete annunciation. All potentiometer adjustments can be made from the front while the system is operating.

The BITE board permits several preventative maintenance checks.

1. A stepped wave simulator circuit is provided to aid in locating inverter output section timing malfunctions.
2. Test pattern generators are included to aid in detecting logic card failures.
3. An indicator light panel identifies failed component/subassembly.
4. Logic cards have numerous test terminals to facilitate speedy repair.

Emphasis is on subassembly substitution to get the system back on line; component replacement is then done at leisure, off line. The maintainability analysis of the module shows an MTTR (Mean Time To Repair) of .674 hour and a maximum time to repair of 6.284 hours.

A.5 MECHANICAL DESIGN

The physical package of the standard Exide UPS modules has proven to be very practical and successful and will be followed in the RTI system. The design involves the use of special 14-gauge steel frame cabinets, tailored to permit sufficient latitude to achieve an optimum balance among mechanical, electrical, and thermal objectives in the physical layout. It avoids the disadvantages incident to rack and drawer construction for high powered electronic equipment.

The design features mechanical simplicity in which the entire volume devoted to the charger and to the inverter, respectively, are free of vertical partitions. From top to bottom there are three distinct zones provided. At the top is found the signal and logic circuitry. At the bottom are the heavy power handling parts such as power transformers and large wiring, bus, filters, etc. In the middle, between the logic and power areas, are the power switching assemblies (inverter legs, etc.) which are thus ideally located to perform their interfacing job between logic and power. Some of the advantages of this arrangement are:

- a. The vertical isolation between power and logic shortens vertical wiring and avoids intermixing power and logic wiring, thus avoiding internal feedback and susceptibility problems.
- b. Horizontal power flow via bus and large wiring is not inhibited by barriers. Power wiring is very short and direct.
- c. The weight of the larger parts is distributed over the cabinet base area. The center of gravity is kept low and the components requiring the greatest lift and reach for maintainability are the lightest and smallest ones.
- d. Thermal design is simplified. Cooling air introduced at the bottom moves vertically upward and out through redundant fans mounted in the legs. Series SCR cooling air circuits wherein the cooling air for one leg is preheated by another are completely avoided in this design. Instead, the inverter legs and static switch thyristor assemblies are arranged side by side all at the same level. The open design and lack of series air circuits means more uniform SCR thermal margins throughout, lower total fan power requirements and high efficiency.

A.6 EXIDE POWER CONVERSION SYSTEMS SPECIFICATION SHEETS

The attached Exide publications (spec sheet, data sheet, and typical one-line drawing, AEA 100 004) describe Exide's standard 100 KW UPS.

Exide

BackUpTM power systems

100 KW (125 KVA) Uninterruptible Power System

Each standard system is complete and includes:

UPS module(s) containing rectifier/charger & inverter
Static Bypass Switch (Non-Parallel Configuration)
Battery Bank
Input, Output, Battery Breakers (molded case)

Ambient Temperature: (Operating) 0°C to 40°C
(Non-operating)
-20°C to 70°C

Relative Humidity: 0 to 95 percent

Heat Rejection: 46,500 BTU/hr. at rated load

88% @ full load

88% @ 75% load

87% @ half load

*Measured by dividing KW output of inverter by KW input of charger.

INPUT

Voltage: 208 or 480 or 600 VAC + 10%
-15% 3 phase, 3 wire

Frequency: 60 Hz $\pm$ 5%

Power Factor: .9 lag @ nominal conditions

Walk-in: 15 seconds to full load

Current Limit: Adjustable (125% max.)

Two standard settings

Total Current

Distortion: 10% max.

OUTPUT

Rating: 125 KVA @ .8 p.f.
112 KVA @ .9 p.f.
(most computers)
100 KVA @ 1.0 p.f.

Voltage: 208 or 480 or 600 VAC 3 phase
3 or 4 wire

Regulation: $\pm$ 1% { (a) 0 to 100% load
(b) 0° to 40°C ambient temp.
(c) min. to max. volts DC

Transient Response: $\pm$ 8% { (a) 50% step load change
(b) transfer of rated load to alternate source
(c) removal of a parallel module

 $\pm$ 1% { (d) loss of AC input
(e) retransfer of 100% load from alternate source

Transient Recovery: to $\pm$ 2% within 25 milliseconds
 $\pm$ 1% within 50 milliseconds

Harmonic Distortion: 5% total, 3% single harmonics

Line Drop Compensation: 0 to 5% adjustable

Frequency: Nominal: 60 Hz
Regulation: $\pm$.06 Hz
Line Sync Range: $\pm$.5 to 1.0 Hz adjustable
Slew Rate: 1 Hz per second

Current: Overload: 125% for 10 minutes
Current Limit: 150% for 30 seconds
Fault Clearing: 300% for 10 cycles

SECTION 74.10

Input ammeter with selector switch
Input voltmeter with selector switch
Battery charge/discharge zero center ammeter
DC voltmeter
Output voltmeter with selector switch
Output ammeter with selector switch
Elapsed time meter
Module status register

Ventilation: Forced air—redundant blowers
Throw-away filters changeable from
outside of cabinet

Cable Entry: Top or bottom entry

Weight: Approx. 6200 lbs.

Modules may be installed back-to-back or side-to-side.

Type: Lead Acid

Protection Time: 15 minutes standard

Floor Space: Approx. 100 square feet

Weight: Approx. 11,000 lbs.

Reverse Transfer (Non-parallel)
Parallel for Capacity
Parallel Redundant

Additional Metering
50 Hz Input and/or Output Units
Separate Battery Disconnect Switch
Bypass Transformer (only if input voltage is different
from output)
Remote Status Monitor Panel
Internal Diagnostics Module
Internal Control Power Battery
Interface to IBM Power Warning Feature
Input Filter (5% input current distortion)
Automatic Equalize Charge Timer

EXIDE POWER SYSTEMS DIVISION

ESB INCORPORATED

RALEIGH, N. C. 27604

100 KW SYSTEM DATA SHEET

System Output Rating 125 KVA at 0.8 PF
111.1 KVA at 0.9 PF
100 KVA at 1.0 PF

System Efficiency 88% @ 0.9 pf lagging
at full load.

Nominal service voltages available	volts phases neutral ground	120/208vac 3 1 1	208vac 3 0 1	277/480vac 3 1 1	480vac 3 0 1
A. AC input to UPS	nominal current maximum current duration of max. current		350 438 Note 1		152 190 Note 1
B. Ratings of protec- tive components	(Input) CB1 (Output) FU2 (Output) CB2 (Bypass) CB3 (Battery) FUB (Battery) CBB	600 600/NA 600/NA 800A 600/NA	600/600 800A 600/NA	400/300 300 400/NA 400/NA 800A 600/NA	400/300 800A 600/NA
C. AC output to critical load 125 KVA	nominal current maximum current duration of max. current	347 434 10 Min.		150 188 10 Min.	
D. AC input to bypass section 125 KVA	nominal current maximum current duration of max. current	347 Note 2		150 Note 2	
E. DC input to inverter	nominal voltage 270 VDC maximum voltage 294 VDC minimum voltage 190 VDC	nominal full load current 400 ADC maximum current 569 ADC			

NOTE 1. Determined by size of battery and degree of discharge.

NOTE 2. Determined by bypass branch protective device.

TYPICAL ONE LINE				
EXIDE REVERSE				
TRANSFER SYSTEM				
UPS				
SIZE	AEA	100	004	

N27263

APPENDIX B

LIGHTNING PROTECTION SYSTEM

B.1 PROTECTION SYSTEM DESIGN

The J. E. Sirrine Company drawing (No. R-1319-EP-5) on page B-3 illustrates the lightning protection system design. The computer program used to design the grounding system is described on page B-4.

B-3

PARTIAL PLOT PLAN
UNDERGROUND GRID SYSTEM

DETAIL EPS-1

SECRET

1° 10' 0"

TYPICAL GROUND CONNECTION

DETAIL EP5-2

AND CABLE TO BE CONNECTED
AS SHOWN TYPICAL BOTH SIDES
THREE PLACES EACH SIDE

CHD CABLE TO BE BROUGHT UP
THRU CONCRETE MD AND INSULATED
WELDED TO STEEL FRAME
CABLE TO HAVE SPECIAL
BANK TO ALLOW RETENTION OF
TRACKING ARRAY

NOTES

1 ALL SMD WIRE TO BE TWO GAGE COPPER

2 ALL CONNECTIONS & SPLICES TO BE BROSHEWELC WELDS

TRACKING ARRAY GROUNDING SCHEME

DETAIL EP5-3

LIGHTING ROD INSTALLATION

NY 4

[illegible]

DEAL

J. L. 'N' DE COMPANY

NORTH CAROLINA DIVISION
SALISBURY NORTH CAROLINA

DESK TYPING	SCALE GRAPHIC
DL TYPING	DATE 1-24-79
CL C/D	CHARGE
APP.	PLS
	MAILED

DRAWING TITLE

SOLAR ARRAY
GROUNDING PLAN

PHOTOVOLTAIC CONCENTRATOR
APPLICATIONS EXPERIMENT
R.T.I. ENGINEERING BLDG.
RESEARCH TRIANGLE PARK, NC

CLIENT DRAWING NUMBER

OFFICE DRAWING NUMBER
R-1319-EP-5 RO

B.2 GROUNDING DESIGN CALCULATIONS

Application No.: 5199 Application Name: GRID Group Code: Electrical
Program Title: Grounding Grid Design Language: Fortran
Operation Mode: Batch Author or Source: D.W. Scarboro - DP

Description:

GRID is used to calculate the resistance in ohms to earth of any configuration of a grounding grid and/or ground rod. Maxwell's method of images is used. The conductors in the grid must have uniform radius. Insulated conductors are not considered. The program calculates the charge and capacitance on the grid's conductors and uses this to calculate the resistance to ground of the grid. Meshed configurations are permitted. All conductors must intersect at multiples of ninety (90) degrees.

Input:

The location (coordinates, length, and depth) of the conductors must be given. The resistivity of the soil must also be known.

Output:

The output includes an echo print of all input data. The step potentials of each grounding grid is given. Finally, the resistance from the grid to earth is given.

Billing:

GRID is billed by unit pricing, based on the number of conductors in the grid.