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Commercial Application of a Photovoltaic Concentrator System

Phase I - Final Report

(June 1, 1978 to February 28, 1979)

D. J. Anderson, E. R. Anderson, K. M. Bardwell,
G. J. Collaros, A. Fong, W. R. Kauffman,
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The BDM Corporation

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United States
Department of Energy

Albuquerque Operations Office
Albuquerque, NM 87115

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PHASE I FINAL REPORT
FOR THE PERIOD

1 JUNE 1978 - 28 FEBRUARY 1979

D. J. ANDERSON, E. R. ANDERSON,
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PREPARED FOR THE

U.S. DEPARTMENT OF ENERGY
DIVISION OF ENERGY TECHNOLOGY
UNDER CONTRACT ET-78-C-04-5313

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FOREWORD

This report, BDM/TAC-78-493-TR, is submitted to the Department of Energy, Albuquerque Operations Office through Sandia Laboratories, Albuquerque, New Mexico 87115, by The BDM Corporation, 2600 Yale Blvd. S.E., Albuquerque, New Mexico 87106. The report documents the design and analysis of a state-of-the-art photovoltaic concentrator system. The included effort was initiated based on an award from the PRDA-35 solicitation (Contract No. ET-78-C-04-5313) and was carried out over the period from 1 June 1978 to 28 February 1979. The program was directed by W. R. Kauffman under the cognizance of Mr. C. B. Rogers, the government technical representative (GTR). The principal BDM contributors to the program were D. J. Anderson, E. R. Anderson, K. M. Bardwell, G. J. Collaros, A. Fong, W. R. Kauffman, T. J. Lambarski, E. Merewether, M. L. Noss, R. Parsons, M. G. Semmens, and T. J. Stueber. This team was supported by a group of subcontractors identified within the body of the report.

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CHAPTER I
EXECUTIVE SUMMARY

A. INTRODUCTION

This report documents the design and analysis of the BDM CAPVC (Commercial Application of a Photovoltaic Concentrator) system. The information herein describes the preliminary design, prototype test and evaluation, system analysis, and final design of a large scale concentrating photovoltaic system. The resulting system is an experimental application which is intended to support the concept of future commercialization of PV (photovoltaic) systems. The approach utilized throughout the design was to achieve a quality system supportive of the overall goals of the DOE program at both minimum cost and risk.

B. APPLICATION DESCRIPTION AND RATIONALE

BDM selected the headquarters building for its Technology Applications Center in Albuquerque, New Mexico as the application for the CAPVC system. This building is planned as a new, attractive, and energy efficient complex which will house a full staff specializing in engineering, physical science, computer science, and policy studies.

The CAPVC solar system, a nominal 50-kW_p roof-mounted, single-axis tracking linear parabolic trough system, was designed to supply 12 percent of the building's electrical load and over 50 percent of the heating load. This system is planned to operate in a load-sharing augmentary role with the electrical utility. It will also operate experimentally as an active system wherein it will feed power back into the PNM (Public Service Company of New Mexico) utility grid on weekends and holidays. A roof-mounted system was selected because it provides security for the protection of the system as well as safety for personnel during operation, and eliminates additional costs and problems related to land use.

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The system was sized at 50 kW for two reasons. First, system analysis studies showed that the available roof area on the selected building could adequately accommodate this size system in an optimum manner. Second, it was determined that a 50 kW system was modular in size and scalable to larger systems and could provide an experiment at minimal cost while still providing a complete set of information supportive of the overall program goals.

The CAPVC building illustrated in figure I-1 is currently under construction. It will be a 72,000 square foot, three-story office building located near the Albuquerque International Airport. The actual location and plot plan are shown in figure I-2.

The Albuquerque location is ideal for a concentrator application because it takes advantage of the high direct solar insolation characteristic of the southwestern U. S. The location also provides high visibility to the general public and solar community with convenient access to DOE and Sandia Laboratory offices. Also, because BDM will occupy the building, our design staff will be able to maintain maximum control of operations during installation and system evaluation tasks. The staff was involved in the building design and has been able to implement building features which will facilitate efficient and clear interfaces between the building and CAPVC system.

BDM designed the building as a "showplace" for both the solar system and energy conservation. Both the total energy consumption and the peak load are predicted to be less than 50 percent of that required for a conventional office building. Energy conservation measures include designing the building with an internal mall to minimize the external wall and window areas, prefabricated walls using a concrete/insulation sandwich construction, double-pane windows with built-in reflective blinds, specially designed lighting under microprocessor control, and a variable air volume air conditioning system which uses outside air when an appropriate temperature differential exists. An added benefit is provided by the roof-mounted solar collectors which reduce the overall air conditioning requirements. The air conditioning load is the dominant load of any building in the

Figure I-1. BDM Office Building with CAPVC Array Installed

Figure I-2. The BDM CAPVC Site

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Albuquerque area. Estimates indicate that as much as 30 percent or more of the air conditioning load during the summer will come from "roof heating" during high insolation periods. About a third of the roof will be covered with collectors, so the building load will be consequently reduced.

The application of the solar system to a commercial office building is particularly important for the commercialization of photovoltaic systems. Office buildings represent a large demand for electrical and thermal power from utility systems. Over 260 million square feet of new office buildings requiring over 1,000 MW of power were started in the U.S. in 1978. These buildings will have roof areas which can be utilized for single axis tracking solar systems with little or no modification to the building structure. The CAPVC design could be readily extrapolated to a significant portion of the office construction market with concomitant energy savings. Further, office buildings are usually financed by large investors who have the capital to invest in solar systems but are generally reluctant because of the risk involved in undemonstrated applications. This is, of course, a significant impediment to the commercialization of solar systems. CAPVC was planned as an important step in providing information to financial institutions, which could in turn facilitate more traditional financing of solar systems, thus assisting in the overall commercialization of photovoltaics. Factors relating to the actual cost savings (capacity displacement as well as energy displacement, system reliability, and system salvage value) are all important factors to financial institutions and to utility firms as well.

C. PHOTOVOLTAIC POWER SYSTEM DESCRIPTION

The major subsystems of the CAPVC are the photovoltaic array, power conditioning, thermal system, and the control and data acquisition systems. The array is composed of the concentrator, receiver tube, and the PV cell and module. The power conditioning includes the inverter and the wiring and switchgear. The thermal system involves both a heat rejection circuit and a building heating circuit. Finally, the components of the control and data acquisition system are the control loops and the instrumentation transducers.

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Figure I-3 provides a block diagram showing these system components and the subcontractors responsible for the fabrication and installation of each of the subelements. Figure I-4 provides an overview description of each of the key components.

The collector system has 6720 square feet of aperture and utilizes a 90-degree rim angle trough fabricated from aluminum with monocoque construction for structural integrity. The layout of the array is shown in figure I-5. The PV cells are held on a receiver tube at the focal point of the trough. The receiver tube is V-shaped with a cell on each side of the V for optimal system performance. The linear parabolic trough was selected because of the high concentration ratio which the system would provide (with off-the-shelf technology), contributing to large economic advantages. The CAPVC system will operate with a concentration ratio of 35:1 (geometric) or 23.75 suns net. The receiver tube was designed so that 5-foot modules can be removed and replaced for easy maintenance during operation without having to break into the fluid system. The collector system and the receiver tube extrusions are to be fabricated and provided by Solar Kinetics. A photograph of the prototype CAPVC collector and receiver tube is shown in figure I-6.

The Solar Kinetics single-axis parabolic trough was selected for several reasons. First, it represents commercially available proven technology. Second, in tests at Sandia, it demonstrated superior performance and rugged reliable construction. Third, single-axis tracking is appropriate for roof mounting. Two-axis tracking would increase the system weight and the turning moment load imposed on the building roof structure. Finally, the single-axis tracking offers long-term economic benefits for photovoltaic commercialization. Inherently, a single-axis system will capture less energy (per unit area) than an equivalent two-axis system because of the cosine effect and end shadowing. However, the cost of the two-axis concentrator subsystem is substantially greater. On the other hand, the single-axis tracker is more sensitive to PV cell cost and, as PV cell costs decrease, the single-axis trough will rapidly become the more cost-effective system.

Figure I-3. CAPVC System Components and Team Members

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Figure I-4. Overview of CAPVC System Components

Figure I-5. CAPVC Array Layout

Figure I-6. T-600 CAPVC Photovoltaic Collector at the BDM Solar Test Facility

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The solar cells are single crystalline silicon cells with an active area of 1.75 cm by 6.48 cm per cell which maximizes the cells available from a boule. These cells were optimized for a net concentration of 23.75 suns. The cell manufacturer will provide the required 13,944 cells and mount the cells on the receiver tube subassemblies including all interconnection, bypass circuitry and encapsulation. Each of these cells are designed to operate with a minimum efficiency of 13.5 percent.

The electrical energy produced by the CAPVC system is converted to AC power by a DC/AC inverter. The power conditioning also includes the switch gear necessary to tie into the building bus and utility interface. The utility interface was designed by BDM and will be implemented by the Craddock subcontractors. Public Service Company of New Mexico was extensively involved in the phase I design and will review the actual utility interface, monitor harmonics, and participate in the test of the active CAPVC system.

The CAPVC photovoltaic modules are actively cooled. Therefore, a large quantity of low-grade thermal energy will be available to the building for heating. BDM in conjunction with the Craddock Development Company, which is responsible for the construction of the building, is providing the necessary hardware and sensible storage tanks to use this heat for building heating during the winter. The heat transport subsystem also includes a closed-circuit evaporative cooling tower.

D. SYSTEM DESIGN AND EVALUATION

BDM implemented an approach which involved detailed system analyses and prototype test and evaluation to provide an optimized PV system with proven components and maximum performance. The basic system analysis approach is shown in figure I-7. The NET-2 and SOLCEL computer codes were existing codes while SHADE, SHADE STRUCTURE, and the HP-9830 circuit analysis routines were developed during the CAPVC program. Also, modifications to SOLCEL allowed more accurate modeling of the CAPVC system.

The approach to the CAPVC system hardware design was to use only high performance, proven, state-of-the-art equipment. Where possible,

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Figure I-7. CAPVC System Analysis Approach and Interfaces

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commercial components were selected. In the area of the receiver tube assembly where no commercial product was available, an aggressive design approach yielded a prototype. This part, along with the balance of the CAPVC collector system, was fabricated during phase I and thoroughly evaluated in the BDM Solar Test Facility shown in figure I-8. As a result, the performance of all system elements has already been verified. Key results are presented in figure I-9.

The receiver tube met or exceeded all requirements for actively cooling the PV cells. The results provided in figure I-9(a) show the temperature gradient between the outer and inner receiver tube extrusions is approximately 15°F (at 5 GPM flow rate), which is identical to the analytically predicted value. This figure also shows the maximum cell temperature for the 5 gal/min design coolant flowrate to be approximately 150°F, which is the maximum operating cell temperature desired. For the design flowrate, a fluid temperature rise of 18 to 20°F can be expected for the 60-foot long receiver tube row, based on temperature rises of 6-7°F for the 20-foot prototype rows. A design value of 20°F had been predicted. The accompanying pressure drop for the 60-foot row would be 3 psid based on the measured pressure data. This low value results in low pumping requirements.

Figure I-9(b) presents the electrical output power for a 57-inch prototype PV module (1-cell string). The measured peak output was between 57 and 58 watts. This differed from the 74 watts projected for the final design for two reasons. The final design included both additional cell active area and additional collector aperture area. When these changes are accounted for, the measured value of 57.8 watts would project to 73.5 watts which is essentially identical to the analytically predicted value. This figure also shows the effect of temperature on the output power. Additional data validated the open circuit voltage degradation rate of approximately 2mV/°C. The cell output performance was shown to vary linearly with insolation as expected. The sensitivity of output power to collector cleaning was measured to be between 5 and 8 percent.

CAPVC LINEAR PARABOLIC TROUGH
CONCENTRATOR SYSTEM

CTR TERMINAL AND LINE PRINTER

PCM-12 MINICOMPUTER AND
DUAL FLOPPY DISC DRIVES

INSTRUMENTATION
RACK

Figure I-8. BDM Solar Test Facility

Figure I-9(a). Receiver Tube Temperature Gradients

Figure I-9(b). PV Module Electrical Performance

Figure I-9. Key Prototype Test Results

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The prototype PV modules were subjected to several months of winter conditions in Albuquerque and no degradation occurred. One module underwent temperature/humidity cycling at Sandia Laboratories and no performance degradation or physical damage was observed.

Alternative sources for much of the CAPVC hardware have been identified. Two key items where backup bids were obtained include the PV cell and inverter system. These options are to be exercised only if improvements in system performance and cost can be realized or if anticipated hardware delivery problems are encountered.

E. SYSTEM PERFORMANCE AND ATTRIBUTES

The CAPVC application demonstrates a substantial reduction in both electrical, peak demand, and energy requirements for a commercial office building. As illustrated in figure I-10, the conservation measures utilized in the design of the BDM/TAC office complex substantially decrease the demand profile from a typical commercial office building. Further reductions are realized in that the solar system for the CAPVC array will displace in excess of 12 percent (95.9 MWhr) of the annual electrical energy requirements of the building and up to 20 percent of the peak demand. As illustrated in figure I-10, there is a one-to-one positive correlation between the peak array output and the peak demand for an office building complex. This results in reducing the peak requirements of the utilities and thus enhances the economic aspects of the photovoltaic array system. This application represents a very large potential market and thus, these energy and peak demand savings can be substantial on a nationwide basis.

The cost of the PV power provided to the CAPVC building is another strong attribute of the system. The calculated cost per peak watt for the CAPVC application is illustrated in figure I-11 and compared with the DOE cost projections for uninstalled arrays. The estimated installed cost per peak watt of the array is \$5.67, slightly lower than the DOE cost projections for uninstalled arrays (see figure I-11). Further, it

Figure I-10. Projected CAPVC Building Load and Array Performance

Figure I-11. Projected CAPVC Array (Installed) Cost

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was determined that a learning curve factor of about 0.9 (large scale production estimates from Solarex and Solar Kinetics) can be anticipated for the CAPVC technology. Thus, as accumulated production increases, substantial reductions in the cost are projected. These projections are also shown in figure I-5 where the anticipated cost in 1975 dollars with an accumulative production of 10 MWp would be \$2.52 per peak watt installed. The time phase for the accumulative production, of course, is dependent on successful commercial applications such as CAPVC and in Federal Government policies. However, 1-megawatt production per year is well within the capability of the current photovoltaic industry.

F. OTHER ISSUES

Other issues with which the phase I design studies were concerned included:

- (1) Environmental and Institutional Analyses
- (2) Utilization of Phase I Experience to Develop QC/QA Plans for Phase II Fabrication and Installation
- (3) Development of an OT&E Plan for Phase III

In order to guarantee that no institutional barrier would affect the CAPVC system, a careful study was carried out to assess the specific impacts of codes and ordinances, financial and taxation policies, insurance and liability, and environmental considerations. The final design of the system was developed in a manner that assured compliance with each of these areas.

Experience gained in working directly with the system hardware in the BDM Solar Test Facility indicated that a stringent QC/QA program would be required in phase II to assure program success. The necessary QC/QA programs were developed as a part of the phase I effort. Specific attention was given to the areas of the concentrator and PV module.

To assure that the CAPVC design was capable of providing the operating and evaluation data required in the phase III assessment of the system, an OT&E (Operational Test and Evaluation) Plan was developed. This plan addressed the following key areas:

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- (1) System Performance
- (2) System and Subsystem Reliability
- (3) System Costs
- (4) Nontechnical Issues
- (5) System Potential for Cost and Performance Improvements

G. SUMMARY

In summary, the CAPVC system application involves the implementation of an advanced but highly reliable and economically attractive photovoltaic concentrator system. The application is on an attractive new office building which represents a large potential market. The CAPVC application can provide information which will be important to the future commercialization of photovoltaic and solar systems. The technology proposed for the application was developed and tested in a prototype system and can, therefore, be implemented with total confidence for success. The detailed design of the system, and the analysis and evaluation which have been conducted as part of phase I of the program, are described in detail in the following chapters.

CHAPTER II
SYSTEM DESIGN AND ANALYSIS

A. OVERVIEW

1. System Description

A schematic diagram of the 50 kW_p CAPVC system is provided in figure II-1. The photovoltaic concentrating array is a roof-mounted, single-axis linear parabolic trough, using single crystalline silicon photovoltaic cells. A total of 6,720 square feet of aperture is focussed on 13,944 PV cells. The photovoltaic system operates in parallel with the local utility in an augmentary loadsharing operating mode. The array is actively cooled and the thermal energy utilized for building heat during winter months.

The specific components of the CAPVC final design are enumerated in table II-1 along with the associated design and performance attributes.

Table II-2 presents a summary of the pertinent CAPVC system parameters which define the final design.

2. Systems Analysis Approach

It was the purpose of the system analysis portion of the CAPVC program to support system design and optimization and the prediction of system and component performance. This was accomplished through the use of hand calculations and either existing or developed computer software. The system analysis was part of a defined approach which carried the CAPVC design from preliminary to final design as shown in figure II-2.

Available information was collected from published documents and manufacturer's specifications, which was then used to develop a preliminary design. Information on the concentrator system and extrusion technology was gained from Solar Kinetics, Incorporated. Solarex Corporation provided information on cell performance while the inverter information was acquired from Westinghouse. Thermal system information was acquired from Bridgers and Paxton. With this information and general knowledge in the areas of available insolation and system integration, a proposed system was designed.

Figure II-1. CAPVC Block Diagram

TABLE II-1. CAPVC SYSTEM DESIGN ANALYSIS

COMPONENT	AREA OR CONSIDERATION	SELECTED CONFIGURATION	DESIGN CONFIGURATION	COMPONENT	AREA OR CONSIDERATION	SELECTED CONFIGURATION	DESIGN CONFIGURATION		
CONCENTRATOR	TYPE	LINEAR PARABOLIC TROUGH	COMMERCIALLY AVAILABLE FIELD TESTED SINGLE AXIS TRACKING	PV MODELS	LENGTH	58.5 INCHES	EASY MODULAR REPLACEMENT EASY ONE-MAN HANDLING FOUR PER 20-FOOT CONCENTRATOR FLEXIBILITY EASY SHIPPING/STORAGE ALLOWS FUTURE RETROFITS		
		90° RIM ANGLE 4-FOOT APERTURE	OPTIMUM RIM ANGLE LOW PROFILE MINIMIZES WIND LOADING		COMPONENT ARRANGEMENT	PROTECTION DIODES ON EACH MODULE	GUARANTEED PROTECTION EASY HANDLING ALLEVIATES END SHADOW PROBLEM		
		GEOMETRIC CONCENTRATION RATIO: 35 TO 1	SHORT FOCAL LENGTH WITH INCREASED ACCURACY DISTRIBUTED COLLECTOR WEIGHT			PV CELLS POSITIONED AND ENCAPSUALTED SO INTENSE LIGHT DOES NOT HIT EDGE METALLI- ZATION BUS	INCREASE IN CONVERSION EFFICIENCY (MIN. METALLIZATION SHADOW) INCREASED RELIABILITY OF METAL INTER- CONNECTS, PROTECTION DIODES, ETC.		
		NET CONCENTRATION RATIO: 23.75 TO 1	AT FOREFRONT OF PV CELL TECHNOLOGY MINIMIZES REQUIRED CELL AREA			EACH SIDE OF MODULES IS WIRED IN SERIES	MEETS SYSTEM VOLTAGE SPECS		
	MIRROR STRUCTURE	MONOCOQUE CONSTRUCTION ALUMINUM CASTINGS COVERED WITH AIRCRAFT GRADE ALUMINUM SKIN	STRONG (LOW STRUCTURAL FLEXURE) LIGHT WEIGHT RESISTANT TO HAIL DAMAGE QUALITY CONSTRUCTION			ELECTRICAL INTERCONNECTS	WIRING BETWEEN MODULES IS SIMPLIFIED WEATHERPROOF CONNECTOR SCHEME	WEATHERPROOF SYSTEM SIMPLE DISCONNECT FOR MAINTENANCE LOW COST HIGH RELIABILITY	
SUPPORT STRUCTURE	PYLONS MOUNTED TO INTEGRAL ROOF PLATE	SIMPLICITY, MAXIMUM STRUCTURAL STRENGTH							
REFLECTING SURFACE	FEK-244	HIGH REFLECTIVITY PROVEN WEATHERABILITY							
TRACKING SYSTEM	HYDRAULIC (SINGLE AXIS)	ACCURATE NO BACKLASH OR MECHANICAL SLOP WEATHER RESISTANT HIGH RELIABILITY/LOW MAINTAINABILITY ROOFTOP MOUNTABLE RAPID FOCUS-TO-STORED POSITION FOR SURFACE PROTECTION ANGULAR MISALIGNMENT COMPENSATION							
RECEIVER TUBE	TYPE	TRIANGULAR SHAPE	FLAT CELL MOUNTING SURFACE ALLEVIATES RECEIVER TUBE SHADOW ON CELLS COMPATIBLE WITH AVAILABLE COLLECTOR SYSTEM ALLOWS INTENSITY PROFILE OPTIMIZATION PROVIDES ADEQUATE ROOM FOR CELL MOUNTING, ELECTRICAL CONNECTIONS, AND DIODE PROTECTION	POWER CONDITIONING	OPERATING MODE	AUGMENTARY WITH UTILITY NO ELECTRICAL STORAGE	GOOD LOAD MATCHUP VIABLE OPERATING MODE BATTERY DEMONSTRATION NOT NECESSARY		
		STRUCTURE	2-PIECE CONCEPT: INNER COOLING TUBE REMOVABLE OUTER CELL MODULE ALUMINUM EXTRUSIONS		EASE OF TRANSPORTATION EASE OF INSTALLATION EASE OF MAINTENANCE AND REPAIR ALLOWS REMOVAL OF PV CELLS WITHOUT AFFECTING COOLING SYSTEM LIGHT WEIGHT RIGID-MINIMUM SAG EASE OF MANUFACTURING GOOD THERMAL CONDUCTIVITY	POWER CONDITIONING	MICROPROCESSOR CONTROLLED INVERTER	INPUT/OUTPUT PROTECTION ISOLATION OVERLOAD CAPABILITIES LINE OR SELF COMMUTATING PEAK POWER TRACKING PARALLEL OPERATION CAPABILITY	
						SWITCH GEAR	MANUAL SWITCHES	REDUCES COST MAINTENANCE SIMPLIFIES SYSTEM	
	COOLING	ACTIVELY COOLED	ASSURES ABILITY TO COOL CELLS MAXIMUM CELL TEMPERATURE CAN BE DEFINED AND MAINTAINED PROVIDES THERMAL ENERGY FOR BUILDING HEAT SMALLER REQUIRED AREA MINIMIZES SHADOW		UTILITY INTERFACE	ARRAY PARALLELS UTILITY AT BUILDING BUS WITH REVERSE POWER SENSING LOCKOUT	SIMPLIFIES UTILITY/CAPVC INTERFACE POSITIVE UTILITY/ARRAY SAFETY DISCONNECT		
				ETHYLENE GLYCOL/WATER MIX (50/50 BY WEIGHT) WITH NALCO 2755 INHIBITOR				GOOD HEAT TRANSFER CHARACTERISTICS NO FREEZING PROBLEMS COMPATIBLE WITH ALUMINUM WITH INHIBITOR FIELD TESTED AND PROVEN ALLOWS LOW PRESSURE SYSTEM	
		RECEIVER TUBE STAND	ADJUSTABLE WITH CUSTOMIZED MOUNTING BRACKET	ALLOWS OPTIMIZED FOCUSING ON PV CELLS BRACKET ALLOWS RECEIVER TUBE THERMAL GROWTH					
	PV CELLS	TYPE	SILICON CELL OPTIMIZED TO 23.75 SUNS	STATE OF THE ART TECHNOLOGY COMMERCIALLY AVAILABLE OPTIMUM CONVERSION EFFICIENCY (13.5% AT 131°F)	ARRAY	LAYOUT	ROOFMOUNT N/S ORIENTATION 3 APERTURE SPACING MODULAR	PROVIDES SYSTEM SECURITY/SAFETY MEETS BDM APPLICATION ELIMINATES LAND USE PROBLEMS MAXIMIZES SYSTEM OUTPUT PERFORMANCE GOOD ARRAY OUTPUT/LOAD MATCH OPTIMUM UTILIZATION OF ROOF AREA ALLOWS FLEXIBILITY AND EFFICIENCY IN SYSTEM LAYOUT SIMPLIFIES PLUMBING AND WIRING EXPANDABLE IN MODULAR UNITS TO LARGER SYSTEMS	
		GEOMETRY	2 x 6.48 CM SILICON 1.746 x 6.48 CM ACTIVE AREA	WIDTH OPTIMUM FOR CONCENTRATION WITH SELECTED CONCENTRATOR LENGTH OPTIMUM FOR OUTPUT VOLTAGE CONSIDERATIONS AND MAXIMUM FILL FACTOR		COOLING SYSTEM	HEAT REJECTION	CLOSED CIRCUIT EVAPORATIVE COOLING	ALLOWS USE OF COOLING FLUID OTHER THAN WATER ALLOWS COLLECTOR COOLING SYSTEM TO BE CLOSED LOOP COMMERCIALLY AVAILABLE IN PROPER SIZE MINIMIZES HEAT REJECTION COST
							BUILDING HEAT	INTERFACE WITH BDM PROVIDED HEATING SYSTEM	BDM FUNDED SYSTEM PROVIDES USABLE ENERGY
							INSTRUMENTATION AND CONTROL	DESIGN PHILOSOPHY	MODULAR CENTRALIZED DATA COLLECTION HANDWIRED SYSTEM CONTROL
SYSTEM STATE INDICATORS								COMMERCIAL SENSORS FOR PRESSURE, TEMP- ERATURE, WIND, SPEED, HUMIDITY POWER CONDITIONING INFORMATION FROM MICROPROCESSOR CONTROLLED INVERTER SYSTEM	INEXPENSIVE PROVIDES THOROUGH INFORMATION FOR SYSTEM ANALYSIS INFORMATION AVAILABLE FOR FAULT DETECTION
SAFETY SHUTDOWN	AUTOMATED SUBSYSTEM TO SHUT SYSTEM OFF AND STORE COLLECTORS IF DANGEROUS CONDITIONS OCCUR MANUAL SYSTEM SHUTDOWN	WILL MONITOR TEMPERATURES, FLOW RATES, ETC. INDIVIDUAL CONTROLS FOR EACH ARRAY PROTECT EXPENSIVE SYSTEM FROM DAMAGE SAFETY SWITCHES IN CONTROL ROOM AND ON ROOF CONTROL ALL ARRAYS							
SYSTEM DISPLAY PANEL	CUSTOM DISPLAY PANEL TO DEMONSTRATE SYSTEM OPERATION. WILL CONTAIN MANUAL SYSTEM CONTROLS WILL INCLUDE SYSTEM PICTORIAL I/V METERS, FLOW METERS, ETC.	PROVIDES VISUAL DISPLAY PROVIDES OPERATOR CONTROL							

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TABLE II-2. CAPVC SYSTEM PARAMETERS

<u>PARAMETER</u>	<u>DESCRIPTION</u>
Peak Output Power	47 kW
Operating Voltage	254 VDC
Operating Amperage	185 Amps
Aperture Dimension	48 inches (4 ft)
Total Collector Aperture Area	6720 ft ²
Collector Net Concentration Ratio	23.75
Number of Collector Modules	84
Collector Row Length	120 ft (6,20-foot modules)
Number of Collector Rows	14
Receiver Tube Length	1680 ft (TOTAL FIELD)
Coolant Flow Rate	5 GPM/ROW 140 TPM TOTAL
Coolant Inlet Temperature	90°F
Exit Temperature	110°F

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Figure II-2. CAPVC Design Development

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With the aid of hand calculations, computer modeling, and simulation, design definition and improvements were made where needed to maximize performance. The computer software used were NET-2, SHADE, SHADE STRUCTURE, SOLCEL and additional software developed on the HP-9830. NET-2 and the HP-9830 were used to analyze solar cell protection circuitry. The SHADE and SHADE STRUCTURE computer programs were used to analyze the array layout. The SOLCEL computer program was used to assess the overall system performance and costs.

The BDM Solar Test Facility was a vital part in the design and analysis of the receiver tube and solar cell performance validation. With this measured data, more credible performance projections of the CAPVC system performance were made.

Utilizing this approach to analyze the CAPVC system design and performance, BDM was able to develop an optimized and proven photovoltaic system.

3. Component Development

The approach to the CAPVC system design was to make maximum use of commercially available hardware. Table II-3 provides an overview of the major subsystem elements. With the exception of the receiver tube,

TABLE II-3. SUMMARY OF CAPVC COMPONENTS AND STATUS

<u>MAJOR SYSTEM COMPONENT</u>	<u>STATUS</u>
1. CONCENTRATOR SUBSYSTEM	COMMERCIALY AVAILABLE
2. RECEIVER TUBE AND MODULE SUBSTRATE	PROTOTYPE TESTED AND APPROVED
3. PV CELL	PROTOTYPE TESTED AND APPROVED
4. ASSEMBLED PV MODULE	PROTOTYPE TESTED AND APPROVED
5. POWER CONDITIONING (INVERTER AND SWITCH GEAR)	COMMERCIAL SYSTEM
6. HEAT TRANSPORT AND REJECTION SYSTEM	ALL COMMERCIAL COMPONENTS
7. INSTRUMENTATION SYSTEM (CONTROL AND DATA ACQUISITION)	COMMERCIAL COMPONENTS/ PROTOTYPE DEMONSTRATION

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the PV cell and the assembled module, all components are commercially available and proven products. Prototypes of those components which required development were fabricated during phase I and underwent extensive evaluation before they were approved for use in the CAPVC system. All prototype components have been tested and approved for production.

In order to maximize the confidence in the CAPVC phase II program, a scaled prototype of the collector system was fabricated during phase I and installed at the BDM Solar Test Facility in Albuquerque. See appendix A for a complete description of this facility. The prototype underwent extensive testing to confirm that the collector, cell, and receiver tube met minimum performance standards specified during system design. During the evaluation, the overall performance of the array was found to be well within the design range defined. Also, several lessons were learned which were used to enhance the performance and maintainability of the CAPVC concentrator system design. A summary of the test findings and design modifications which resulted from testing are shown in table II-4.

B. COMPONENT DESIGN AND ANALYSIS

The major components of the CAPVC system are as follows:

- (1) Photovoltaic Array
- (2) Power Conditioning
- (3) Thermal System
- (4) Control and Data Acquisition System

The photovoltaic array consists of the concentrator, receiver tube, and the photovoltaic cell and module. The array layout is of course a major consideration of this system. The key elements of the power conditioning include the operating mode, inverter, and wiring and switch gear. The thermal system involves both a heat transport and rejection system as well as a building heating system. The primary elements of the control and data acquisition system are the control loops and the transducers.

Each of these areas will be discussed in detail in the following sections. The format of the discussions is generally as follows:

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TABLE II-4. RESULTS OF PROTOTYPE TESTING

HARDWARE PERFORMANCE CONFIRMED ACCEPTABLE

CONCENTRATOR OPTICAL EFFICIENCY
CONCENTRATOR HYDRAULIC TRACKING SYSTEM ACCURACY
REFLECTIVE TROUGH CLEANING PROCEDURE
RECEIVER TUBE ALIGNMENT
RECEIVER TUBE/FLUID NON-CORROSIVE COMPATIBILITY
FILM COEFFICIENT/HEAT TRANSFER
SUBSTRATE ALIGNMENT AND SURFACE QUALITY
TWO PIECE RECEIVER TUBE HEAT TRANSFER/CELL COOLING
PV MODULE OUTPUT POWER, EFFICIENCY, I-V CHARACTERISTICS
EFFICIENCY AS A FUNCTION OF TEMPERATURE
CELL RELIABILITY
PV MODULE PRODUCTION, ASSEMBLY, AND ENCAPSULATION
PV MODULE WEATHERABILITY/TEMPERATURE-HUMIDITY CYCLING
COLLECTOR SYSTEM SAFETY CONTROLS
INSTRUMENTATION SENSING/CONTROL AND DATA ACQUISITION

DESIGN MODIFICATIONS RESULTING FROM PROTOTYPE TESTING

COLLECTOR TOLERANCE FACTORS
RECEIVER TUBE/PV MODULE CLAMPS
RECEIVER TUBE/SUBSTRATE INDEX FOR CELL ALIGNMENT
NO "TRIP RIBBON" FOR TURBULENT FLUID FLOW REQUIRED -- REDUCED PUMPING POWER

NO THERMAL GREASE REQUIRED FOR PV MODULE/RECEIVER TUBE CONTACT
LONGER PV CELL CUT FROM ORIGINAL WAFER -- HIGHER PACKING FACTOR AND REDUCED MATERIAL WASTE

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- (1) Design Consideration
- (2) Preliminary Design
- (3) Intermediate Design
- (4) Test and Evaluation and/or Systems Analysis
- (5) Final Design

The test and evaluation and system analysis discussions are included within each component area to assure a direct relation between the individual design configuration and the appropriate test and analysis information.

1. Photovoltaic Array

- a. Concentrator

- 1) Design Consideration

The CAPVC concentrator system includes the collectors, pylons, and tracking mechanisms. The collectors are reflecting surfaces designed to collect and focus direct solar insolation. These reflecting surfaces are rigidly supported by means of pylons and include tracking mechanisms which provide the means for tracking the sun.

The conceptual design of the CAPVC collector included the considerations of the collector configuration, type of tracking, concentration, size, layout, cost, performance, quality, maintainability, and reliability.

The requirements of the collector system were that it be flexible, efficient, and provide for the optimum utilization of available space and that it support the office building application. Early in the conceptual phase, a roof-mounted design was selected to provide maximum security and safety for both the system and the general public, reduce land use and materials costs, and take advantage of several other benefits such as reduced air conditioning loads during the summer. Since the majority of the roof area would be covered by collectors, a significant amount of the solar insolation that would have been absorbed by the roof would now be intercepted by the collectors.

In selecting a collector configuration, BDM investigated both Fresnel and parabolic trough collectors. Both of these configurations have high concentration levels, which are important for minimizing the required PV cell area. However, preliminary calculations indicated

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that collector systems requiring two axis tracking, as is the case for Fresnel concentrators, present wind loads exceeding the acceptable limits for a roof-mounted system. Also, single-axis tracking offers long-term economic benefits for photovoltaic commercialization. The single-axis system will capture less energy (per unit area) than an equivalent two-axis system because of the cosine effect and end shadowing, but the cost of the two-axis concentrator subsystem is substantially higher. The single-axis tracker is more sensitive to PV cell cost and therefore, as PV cell costs decrease, it will become the more cost-effective system. For these reasons, the horizontal linear parabolic trough (LPT) concentrator with single-axis tracking was selected as the conceptual configuration.

The size of the collector system was important as a structural design consideration. A low profile and low weight collector was deemed necessary, especially for roof-mounted arrays, to minimize the dead weight and wind load turning moment on the roof.

It was important to select a concentrator system from a category of commercially available and field tested collectors to assure system success within the program time frame. By the careful comparison of each of these designs in terms of cost, performance, quality, maintainability, and reliability, the best collector system could be chosen.

2) Preliminary Design

A study of available LPT collectors resulted in the preliminary selection of the 90° rim angle concentrating trough manufactured by Solar Kinetics. This collector was designated the T-500 and is shown installed in the BDM Solar Test Facility in figure II-3. This trough was selected for several reasons. First, it represents commercially available proven technology. Second, in tests at Sandia, it demonstrated superior performance and rugged reliable construction. Third, it met the CAPVC system requirements.

The T-500 concentrating collector has an aperture of 3.5 feet (42 inches) and a focal length of 10.5 inches. The 90° rim angle is optimum for LPT collectors as discussed in the Sandia report, SAND 74-0124. The relatively small aperture and accompanying short focal

Figure II-3. SKI T-500 Collector

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length result in high focusing accuracy and a low profile collector system. The collector height as tested was 61 inches. This collector design was wind tunnel tested, and the resulting aerodynamic coefficients have been used to predict maximum collector field lift and drag forces of 97,020 and 102,488 pounds, respectively. These loadings were well within the intended planned building specifications.

The structure of the T-500 collector consists of aluminum castings which form bulkheads covered by an aircraft grade aluminum skin. This is a lightweight and strong structure, which is very resistant to reflector surface deflection, which would cause variations in the light intensity profile at the receiver tube. The skin is resistant to hail damage and provides a good substrate for the optical quality acrylic coating. The acrylic coating currently being used for the T-500 is FEK-244 (manufactured by 3M) with an average specular reflectivity of 84 percent. Solar Kinetics has conducted weather testing on 3M reflective films for a total of 3 years with less than 4 percent specular loss and no other unsatisfactory degradation. Similar results have been obtained by 3M, who has tested the surface for a period of 11 years.

The tracking system for the T-500 is hydraulically actuated and has been chosen for several reasons. All mechanical tracking mechanisms will develop backlash when exposed to continuous wind buffeting. However, hydraulics eliminate this type of backlash as well as providing a light cushioning effect to sudden loads. The hydraulic system is also weather resistant, having no gears and chains exposed to the weathering environment. This tracking system is highly reliable and requires minimal maintenance. The T-500 tracking accuracy is 5 milliradians with a tracking rate of 0.1 RPM and a rate of 2 RPM to reach the protected stow position.

The tracking system is controlled by a differential shadow bar device. Tracking is achieved through the use of two light sensitive transistors positioned equally between a shadow bar. When the shadow bar is pointed directly at the sun, the shadow splits each transistor. As the sun moves, the shadow becomes unequal, and an electronic imbalance is sensed by the tracker control, causing a relay to be energized.

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This completes a circuit to the hydraulic fluid control valve, which directs pressurized fluid to the tracker drive, causing the collector to move until the shadow bar is again pointing at the sun. In this position, the tracker control is in dead band, and neither relay is activated. A dead band adjustment is provided which will change the sensitivity of the tracker - providing accurate tracking during clear days, but preventing searching during cloudy conditions. A time delay adjustment is also provided. Proper adjustment of these two pots provides accurate pointing and keeps the system in dead band during cloudy periods.

Limit switches are provided to prevent overtracking in the automatic mode. There are several conditions under which the collector is sent to the stow position; they are: PV cell over temperature, rain, nightfall, high winds and loss of flow. Any number of field contact closure devices can be used to open the circuit to the stow relay. When this occurs, the automatic tracker is de-energized, and a signal is initiated. The stow slave relay is energized when the stow relay loses its signal (open circuit), and the bypass valve is activated. This allows the hydraulic fluid to circumvent the adjustable flow control valve, and the collector is driven to the stow position at a rapid rate. Upon reaching stow, the stow limit switch opens the circuit to the stow slave relay coil, and the entire system is at rest. This method of stowing the collector is used as the automatic night stow through the use of a light switch. At dawn, the light switch closes the stow relay coil circuit, and the automatic tracker is again energized when the sunlight causes sufficient shadow differential on the light sensitive transistors. The system tracks to the west until dead band is reached and maintained during the day. At nightfall, the collector is sent to stow by the light switch. At any time during the day, should any of the stow hazard switches (light, temp., rain, flow, etc.) open the circuit, the collector will be driven to the stow position and remain until all switches are closed.

3) Component Test and Evaluation

BDM tested the T-500 collector extensively during phase I at the Solar Test Facility (figure II-4). The optical efficiency

Figure II-4. CAPVC Linear Parabolic Trough Concentrator System
Prototype Testing Setup

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and the tracking accuracy of the T-500 met all of the CAPVC system design specifications. The collector system was operated for several months, and no component failures were observed.

By utilizing electrical output from the prototype photovoltaic modules, it was determined that the mirror intercept factor was 87 percent, which was the design minimum. This factor was determined experimentally by focusing the incident light from the collector on the receiver tube and comparing projected electrical output to actual output. The collector focal point was verified to be 10.5 inches.

During the prototype evaluation, design modifications were recommended for the collector system which significantly improve the overall CAPVC design. The prototype T-500 collector reflective trough focusing tolerances were evaluated, and it was found that most of the trough provided the minimum optical efficiency specified for the design. However, a problem involving divergence of the reflective trough between bulkheads was identified. These prototype collectors had been expedited through fabrication to meet prototype delivery schedules. This problem was discussed with Solar Kinetics, Inc., the concentrator manufacturer (SKI), resulting in the definition of explicit trough tolerance requirements. BDM has also designed a device to measure the overall optical efficiency of the troughs as they are fabricated (see QC/QA, Chapter V). This quality control device will ensure that all troughs used in the CAPVC system will conform to minimal optical efficiencies.

BDM carried out the mirror cleaning procedures recommended by the collector manufacturer (Solar Kinetics) for maintaining a clean reflecting surface on its prototype collectors. This approach was found to be successful and will be utilized in maintaining the CAPVC collector field.

For typical soil conditions, SKI recommended periodic rinsing of the mirror surface with deionized water. City water can be used, but will result in some mirror spotting unless a special drying process is instituted. If weather conditions permit, exposing the mirror surface to mild rainfall will also reduce dust accumulations. Depending

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on conditions, the following detergent cleaning procedure should be used biannually or quarterly. Clean with a pressure washer with a nozzle pressure of 400-800 psi. The Malsbary C-310 is recommended. The detergent solution should be 0.1-0.3 percent active detergent at the washer nozzle. This detergent level creates a moderate sudsing action. Excessive detergent solution should be avoided. The detergent should be a nonionic biodegradeable type such as Union Carbide UCON 15-5-9, Rhom & Haas Triton X-100, or Jefferson Surfonic N-95. These detergent liquids are nondrying for thorough rinsing. Under no conditions should any detergent solution be allowed to dry on the mirror before rinsing. A deionized water rinse should immediately follow the pressure wash. SKI does not recommend any phosphate or silicate based detergent systems.

There should be no mechanical agitation of the mirror surface, i.e., no mopping or wiping of the mirror. In addition, the pressure wash spray should be kept near a 90-degree angle with the mirror and the spray not directed at low angles against the edges of the applied film. The water temperature should not exceed 120°F.

4) Final Design

The SKI T-600 collector was selected instead of the T-500 collector for the final CAPVC design. The T-600 with a 4-foot aperture (48 inches) provides almost 18 percent more energy at nearly the same cost as the T-500 with equal optical efficiency. The commercial availability, together with these performance and cost factors, resulted in the final selection of the T-600. In addition, BDM has since tested a T-600 collector at the Solar Test Facility (figure II-5) and has found that it conforms to the CAPVC specifications.

The T-600 linear parabolic trough is a tested production line item from Solar Kinetics. It is a slightly modified T-500. The basic collector structure is identical, with the exception of the T-600 bulkheads, which have been updated and improved.

The T-600 is manufactured from aluminum with the dimensions summarized in figures II-6 and II-7. The concentrator subassembly includes all elements identified in figure II-6. The T-600 has

Figure II-5. T-600 Collector

LIST OF ELEMENTS

1. A precisely constructed mirror surface is covered with metallized acrylic film, combining weather resistance and high reflectivity.
2. The parabolic contour of the cast aluminum ribs is N/C machine generated for an accurate focus.
3. An insulated flex hose allows rotation of the collector with unrestricted flow.
4. Self aligning sealed ball bearings absorb structural loads maintaining collector motion without binding.
5. A forged steel flange carries torsional loads into the collector structure. Allows mirror installation with eight bolts.
6. The steel support pylon is galvanized for corrosion protection.
7. Mounting studs are a standard pattern for each collector.
8. This load bearing joint* protects the collector structure from strains induced by misalignment from foundation shifts.

* PAT PENDING

T-600 SPECIFICATIONS

MODULE WIDTH	53.0 IN
MODULE LENGTH	20 FT
MIRROR WIDTH	48.0 IN
SOLAR AREA (FT ²)	80
REFLECTANCE	0.84
MAX VERT HEIGHT	55 IN
ROTATION AXIS HT	39 IN
TRACKING ANGLE	235°
STOW ANGLE	45°
SYSTEM WEIGHT	4.0 LB/FT ²

Figure II-6: T-600 Collector Detailed Specifications

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T-600 GENERAL LAYOUT

T-600 MIRROR ASSEMBLY
(ALUMINUM)

RECEIVER TUBE MOUNTING BRACKET ASSEMBLY
(ZINC PLATED)

DIM.	FT.
A	4.00
B	11.3.50
C	20.50
D	10.75

T-600-CAPVC SUB FIELD COLLECTOR ARRAY
(2 ROWS ONLY SHOWN)

- NOTES:
1. EACH ROW WILL CONSIST OF SIX, 20' LG., COLLECTOR MODULES
 2. SPACING BETWEEN ROWS WILL BE 12'
 3. COMPLETE ARRAY WILL CONSIST OF 14 ROWS

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LIST OF MATERIAL				
SOLAR KINETICS				
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T-600 COLLECTOR DETAILS				
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SCALE: SHEET 1 OF 1				
D SK-498				
APPLICATION				
HEAT ASS Y				

Figure II-7. T-600 Collector Details

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the same high focusing accuracy due to a relatively small aperture and accompanying short focal length as the T-500. The height of the collector is 65 inches, which provides a low-profile system consistent with the roof-mounted application. The results from wind tunnel tests have been used to predict T-600 aerodynamic coefficients which have been utilized to calculate maximum collector field lift, drag, and downward forces of 48,384, 120,400, and 139,776 pounds, respectively. These loadings, which include the collector system weight of 26,880 pounds, were incorporated in the design of the CAPVC building roof structure.

The key concentrator performance parameters continue to be optical efficiency, tracking accuracy, and durability. The specular reflectance of the trough is a minimum of 0.84 (new), and no more than 0.005 percent degradation per year is projected. The focusing accuracy of the trough provides an intercept factor of 0.87 when used with the CAPVC receiver tube subassembly. The tracking mechanism of the concentrator is the same as the T-500 and will provide accuracies within 5 milliradians. Further, the concentrator system has been designed for a minimum 20-year life.

The collector system is mounted to the CAPVC building roof with mounting plates which will be attached to the building roof structure (figure II-8) during construction of the building. This is accomplished by welding the plates to the reinforcing bars located in the roof beams. The collector support pylons are mounted on these bases with bolts which are welded to the plates as also shown in figure II-8. The SKI concentrator provides U-joints within the pylon bearing mounts of the mirror system. This is significant for a roof-mounted system since these U-joints allow slight shifting and movement of the roof without affecting the collector tracking ability.

Figure II-9 shows the collector pylon mounts in the Solar Test Facility. The drive, intermediate, and end pylons are indicated. The pylon mounting details are shown in figure II-10. Figure II-11 shows the drive pylon and attachment for the collector, and figure II-12 shows the pylon attachment point on the collector.

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26-79

Figure II-9. Collector and Mounting Pylons

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• END PYLON •
(STEEL, ZINC PLATE)

• DRIVE PYLON HOUSING •
(STEEL, ZINC PLATE)

• INTERMEDIATE PYLON •
(STEEL, ZINC PLATE)

• DRIVE PYLON MECHANICAL •
(STEEL, ZINC PLATE)

NO. REV'D	PART NO.	MATERIAL	DESCRIPTION	ITEM NO.
LIST OF MATERIAL				
DRAWN A	DATE 1/30/79	MATERIAL:	SOLAR KINETICS INC.	
CHECKED:		FINISH:	TITLE: T-600 PYLON DETAILS	
ENGINEER		TOLERANCES:	CODE IDENT. SIZE DWG. NO. REV.	
PROGRAM MANAGER Wayne L. Simpson	1/30/79	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES CONTRACT OR COST CENTER	D SK-496	
APPLICATION		SCALE	SHEET 1 OF 1	

Figure II-10. T-600 Pylon Details

Figure II-11. Drive Pylon Collector Attachment Point

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Figure II-12 T-500 Collector Showing Pylon Mounting Location

The hydraulic mechanisms used for the tracking system (pump, accumulator tank, and electronic controls) are to be housed in one of the two solar mechanical rooms located on the third floor of the CAPVC building. The pressurized hydraulic fluid is transmitted to the tracking pylons in high pressure hydraulic lines. The hydraulic accumulator is designed to have a capacity of fifteen gallons to assure that the complete array can be stowed in the event of a power failure. The tracking power requirements are minimal. A 3/4 horsepower pump, which operates intermittently, is all that is required to track the entire field.

b. Receiver Tube

1) Design Considerations

The receiver tube is a structural support which positions the photovoltaic cells in the focal zone of the concentrating collectors. Because of the high concentration ratio characteristic of the CAPVC design (35:1 geometric), active cooling of the cells is necessary. The receiver tube provides the required cooling which results in the collection of thermal energy that must be either utilized or dissipated.

The receiver tube conceptual design effort included the evaluation of structural, optical, and heat transfer considerations as well as ease of maintenance.

The primary structural requirement of the receiver tube is that it provide a rigid and uniform support for the PV cells. The receiver tube can have only minimal sag along its length in order to provide for even cell irradiation. Another requirement is that the receiver tube have adequate space for PV cell mounting, electrical connections, and protective diodes.

The optical requirement was that the receiver tube be designed to optimize the focusing of the sun's rays on the active area of the cell in a manner that would assure an optimal intensity profile. A shadow effect is caused by the receiver tube blocking a portion of the sun's rays and creating a shadow on the collector which is transmitted to the receiver tube. It was therefore necessary to place the PV cells on the receiver tube away from this shadowed area.

The receiver tube heat transfer must provide active cooling for controlling the PV cell temperatures to assure optimal electrical performance. This results in the requirement for the receiver tube and cooling system to have good overall heat transfer characteristics. To reduce parasitic pumping power requirements for the cooling system, it is also important that a low pressure system be designed.

The ease of manufacturing, installation, and maintenance of the receiver tube system is an important design consideration from an operational and cost standpoint. A final requirement is that the receiver tube be compatible with an existing concentrator system.

Since no commercially available receiver tube provided the necessary focal mounting and active cooling for the PV cells, the receiver tube was specially designed for the CAPVC program.

2) Preliminary Design

The preliminary receiver tube design (figure II-13) was configured to meet all of the previously discussed conceptual requirements. The receiver tube assembly was modular in nature and consisted of two aluminum extrusions and attachment brackets. The outer extrusion provided the mounting areas for the PV cells, PV cell interconnections, and protective diodes. The outer extrusion (PV module) was 40 inches long (maximum length set by the PV manufacturer at the time) and could be easily mounted to the inner extrusion which was designed to carry the cooling fluid and to be compatible with the T-500 collector (also chosen during the preliminary design).

The separate removable PV module was designed to allow for ease of production, transportation, installation, and maintenance. The two-piece approach allows the outer extrusion on which the PV cells are mounted to be easily removed for maintenance and repair without any need to break into the cooling system within the inner extrusion.

Both extrusions were made of aluminum for its light weight, rigidity, and good thermal conductivity, and because aluminum is easily extruded. Sufficient cross-sectional area was included to minimize sag in the receiver tube, thereby alleviating the problem of uneven cell

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DEVELOPMENT OF THE CAPVC RECEIVER
TUBE ASSEMBLY

INITIAL DESIGN

INTERMEDIATE DESIGN

FINAL DESIGN

Figure II-13. Development of the CAPVC Receiver Tube Assembly
II-37/II-33

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irradiation. The concept was modular in design to allow for ease of production, transportation, installation, and maintenance.

The triangular geometry provided structural rigidity, allowed the cells to be directly irradiated, and with selective mounting, alleviated any problem with the shadow caused by the receiver tube. This was accomplished by mounting the cells away from the receiver tube vertex area on which the shadow falls. The optimum cell location on the receiver tube was not determined during the conceptual phase, but was defined during the detailed design and evaluation effort.

The receiver tube was designed not only to provide the optimum mounting area for the PV cells, but for the active cooling necessary to maintain a maximum cell temperature of 150°F as well. The use of aluminum with good thermal conductivity provided good heat transfer by conduction from the PV cell area to the coolant. The addition of fins on the internal walls was included to increase the wetted perimeter of the coolant tube, thereby increasing the convection area for the coolant and increasing the cooling effectiveness. The requirement for fins was further studied during the detailed design of this component.

The two-piece extrusion concept introduces an additional interface in the transfer of heat from the PV cell to the cooling fluid. This interface is the contact resistance at the mating surface between the inner and outer extrusions. The resistance occurs because contact between the two extrusions is generally less than unity. The irregular contact of the two surfaces results in an impediment to the transfer of heat. It was determined that this area be very carefully studied in the detailed design phase of CAPVC and that actual test data concerning the transfer of heat in the area be obtained. Two backup configurations were defined for this design. The first involved the use of thermal grease in the contact area should additional heat transfer be required. If cell temperatures remain too high, a second alternate configuration would require the mounting of the cells directly to the inner extrusion, which would assure adequate cooling.

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Many heat transfer fluids were studied for this particular application, and the selection was narrowed to water, Therminol 55, and ethylene glycol/water mixes. Water would have been best from a heat transfer standpoint, but the problem of freezing made it unacceptable for this application. Experience in actual applications has shown that a water system cannot be effectively drained to prevent freezing, and once drained, it is difficult to refill the system without forming air locks. Therminol 55 has been used often in solar thermal applications, but its high viscosity at low temperatures (263 lb/hr ft @ 50°F) and low thermal conductivity (.073 Btu/hr ft °F @ 100°F) make it impractical for the relatively high level of heat transfer needed to maintain acceptable cell temperatures. Sufficient heat transfer with an adequate margin of safety was shown to be provided with a 50/50 ethylene glycol/water solution with a viscosity of 13.3 lb/hr ft at 50°F and a thermal conductivity of 0.245 Btu/hr ft °F at 100°F.

In order to eliminate corrosion within the inner aluminum extrusion cooling passage, a special inhibitor (NALCO 2755) was selected to be included as an additive to the cooling fluid. The NALCO 2755 was designed by the National Chemical Company for use in solar applications with the intent of inhibiting the corrosion of multimetallic closed systems. It maintains clean heat transfer surfaces through the incorporation of scale control agents and dispersants. It is specifically recommended for systems involving extensive aluminum surfaces and is compatible with ethylene glycol based antifreezes. Test results have shown that when NALCO 2755 is added to a cooling fluid in contact with aluminum, no corrosion occurs over an extended period of time.

3) Intermediate Design

A detailed design study of the preliminary receiver tube configuration resulted in the definition of an intermediate design which incorporated features to improve the compatibility of the receiver tube with the cell and its interconnects. This intermediate design was the prototype tested at BDM's Solar Test Facility during phase I of the CAPVC program and is shown in figure II-13.

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In selecting the actual dimensions for this design, it was necessary to provide sufficient mounting area for the cells, bypass diodes, and cell interconnects. It was also necessary to work closely with the extrusion manufacturer to assure a design which could be simply extruded to precise tolerances. The cell mounting area was not changed significantly from the initial design except for the addition of a notch in the busbar area of the cell to provide additional space for the cell interconnects. The vertical sides of the receiver tube were extended to provide adequate space for the mounting of the bypass diodes. The coolant channel size was optimized to provide an acceptable heat transfer coefficient at a reasonable pressure drop. The resulting size was somewhat constrained by the overall receiver tube configuration.

The attachment brackets were redesigned as a simple snap-on aluminum extrusion. The preliminary design which involved the use of thousands of small screws was not felt to be realistic and would involve too much time for removal and replacement. The bracket was extended to shade the bypass diode and cell interconnect areas.

The PV module (outer receiver tube extrusion) was lengthened from the preliminary design length of 40 inches to the prototype length of 57 inches in order to minimize the number of extrusions to be required in the CAPVC system. Discussions with the cell manufacturer indicated that an approximate length of 5 feet was the maximum practical production size.

Another noticeable change concerns the absence of fins in the coolant tube of the prototype inner extrusion. The effectiveness of the fins in the preliminary design was evaluated during the initial part of phase I by use of the fin equation. In practice, the addition of fins is hardly ever justified unless the value of the fin equation, $\bar{h}A/Pk$, is considerably less than unity. For the fin equation, the convective heat transfer coefficient is denoted by $\bar{h}$, the cross-sectional area of the fin denoted by A , the fin perimeter denoted by P , and the thermal conductivity of the fin material denoted by k . It was determined that the use of fins in the coolant tube would not significantly increase

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the cooling effectiveness, and for that reason, the fins were not included in the prototype design. However, the cooling effectiveness of the receiver tube without fins still had to be evaluated during testing.

To provide structural support for the CAPVC receiver tube, a standard Solar Kinetics thermal application receiver tube stand was redesigned to accommodate the triangular shape characteristic of the CAPVC configuration. This stand is shown in figure II-14. It includes the adjustment mechanisms necessary for the proper alignment of the receiver tube. The receiver tube can be positioned by means of focal point, lateral, and rotational adjustments as shown to provide for the optimum irradiation of the PV cells. The teflon holder is customized to the shape of the inner extrusion and supports the receiver tube assembly in a manner which allows it to expand thermally along its length. The maximum receiver tube growth for a 60-foot CAPVC thermal row was predicted to be 0.69 inches.

The original design called for receiver tube stands to be placed every 10 feet along the receiver tube length. Structural calculations showed considerable sag over the 10-foot expanse. Additional studies were carried out to improve the structural integrity such that the sag over the 10-foot length would be acceptable. No acceptable configuration was identified, and 5-foot intervals were then considered. With the standard receiver tube configuration, the longitudinal sag for a 5-foot span of the receiver tube was calculated to be a maximum of 0.006 inches, which was well within the acceptance limits. Thus, the 5-foot receiver tube stand interval was selected.

4) Component Test and Evaluation

The prototype receiver tube was evaluated extensively during phase I testing. Its structural rigidity, alignment, and cell mounting compatibility were carefully reviewed. The operation and maintainability of the three-piece extrusion was monitored closely, particularly in the attachment clip area. Of particular importance was the determination of the heat transfer performance of the design. In conjunction with the thermal studies, the fluid flow characteristics of the

Figure II-14. Receiver Tube Stand

system were also studied. Furthermore, the compatibility of the receiver tube stand was demonstrated.

The thermodynamic characteristics of the receiver tube cooling system were evaluated completely during the phase I testing. Of primary importance was the evaluation of the convective heat transfer coefficient. The predicted heat transfer coefficient was calculated by assuming fully developed turbulent flow heat transfer in a smooth tube. For this case, the following Dittus-Boelter equation is applicable:

$$Nu = 0.023 Re^{0.8} Pr^{0.4}$$

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where Nu is the Nusselt number, Re is the Reynold's number, and Pr is the Prandtl number. Since the definition of Nusselt number is

$$Nu = \frac{\bar{h}D}{k}$$

where $\bar{h}$ is the convective heat transfer coefficient, D is the hydraulic diameter, and k is the thermal conductivity of the fluid, the heat transfer coefficient, $\bar{h}$, can be expressed as the following:

$$\bar{h} = \frac{Nu k}{D} = \frac{0.023 k}{D} Re^{0.8} Pr^{0.4}$$

With the defined receiver tube coolant geometry and a design flow rate of 5 gal/min, a nominal heat transfer coefficient of 467 Btu/hr ft²°F was calculated. Utilizing this value, along with the appropriate boundary conditions in a heat transfer model, resulted in predictions of nominal and maximum cell temperatures of 140°F and 150°F, respectively. These are acceptable cell temperatures, and the purpose of demonstrating the thermal characteristics of the prototype receiver tube was to verify that these temperatures could be attained.

Further, consideration of the thermal and fluid flow test results would indicate whether the desired turbulent flow conditions existed. If turbulent flow were not attained, the projected temperatures would be exceeded for the given design conditions. Turbulent flow could then be attained by increasing the flow rate or utilizing a turbulence inducing flow ribbon, neither of which is desirable due to increased pumping power requirements.

If it were determined that turbulent flow had been obtained and cell temperatures were still too high, this would indicate significant contact resistance between the outer and inner extrusion. This resistance restricts the flow of heat trying to leave the cell area and pass into the cooling fluid medium. Increased heat flow could then be obtained by improving the thermal conductivity in the gap area through

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the use of a high conductivity thermal grease. Also, fins could be returned to the design in an attempt to further enhance the flow of heat into the coolant.

However, none of these enhancements were necessary as the test results showed average and maximum cell temperatures comparable to the predictions for the desired design conditions. Details of these results and representative test data are presented in the following discussions.

Fluid temperature as a function of receiver tube length is shown in figure II-15. For a flowrate of 5 gal/min along the 20-foot collector, a fluid temperature increase of 5 to 7°F (owing to normal experimental scatter) was observed. Therefore, for the 60-foot long CAPVC collector row with a design flowrate of 5 gal/min, a fluid temperature increase of 15 to 21°F (based on the experimental range of data from the 20-foot collector) can be expected, which is within the design limits. The coolant system was designed such that the coolant enters and exits the 60-foot collector row at 90°F and 110°F respectively, resulting in a 20°F coolant temperature rise.

The receiver tube radial temperatures as a function of flowrate are shown in figure II-16. This test series was conducted without thermal grease between the inner and outer extrusions. However, it can be observed that the maximum receiver tube temperature (which is representative of the maximum cell temperature) was maintained between 145°F and 160°F, an acceptable range. It is important to observe the varying degrees of sensitivity in the radial temperatures to the coolant flowrate. For example, increasing the coolant flowrate above the 5 gal/min design point does not significantly lower the receiver tube temperatures and would result in much higher pumping power requirements.

The receiver tube temperatures are also shown as a function of radial distance in figure II-17. This test series was also run without thermal grease between the inner and outer receiver tube extrusions and shows that the PV cell can be adequately cooled. The

II-46

Figure II-15. Fluid Temperature as a Function of Receiver Tube Length

RECEIVER TUBE RADIAL TEMPERATURES

Figure II-16. Receiver Tube Radial Temperatures

Figure II-17. Receiver Tube Temperature Gradients

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temperature gradient across the interface gap between the inner and outer extrusion as a function of coolant flowrate can be seen in figure II-18. The maximum observed gradient of 20°F is still within acceptable design limits. It was therefore concluded that thermal grease need not be used in the gap between the extrusions to maintain acceptable PV cell temperatures.

The thermal efficiency of the CAPVC receiver tube was determined to be approximately 65 percent. This value was calculated utilizing the preceding thermal results in a heat transfer analysis and includes the loss of the energy converted to electrical power.

The pressure results shown in figure II-19 were important in verifying that the CAPVC cooling system will be a low pressure design. It can be seen that a flowrate of 5 gal/min for a 20-foot collector results in a pressure drop of 1 psia or less. Therefore, for the 60-foot CAPVC collector row, a pressure drop of 3 psia would be expected for the design flowrate of 5 gal/min.

During the several months of operation, no corrosion developed either within the coolant tube or between the inner and outer receiver tube extrusions. In fact, the entire receiver tube assembly was in an exposed environment during the winter months, and no degradation in quality was observed. In addition, the PV module (outer extrusion including cells) underwent 30 severe temperature/humidity cycles (-30°F to 120°F) at Sandia Labs without any degradation in hardware quality or PV cell electrical output.

In maintaining the receiver tube assembly, it was continually demonstrated that the attachment clips holding the PV module to the heat transport receiver tube were not easily removed. This clip (the third aluminum extrusion) also included a shield which covered the outside of the receiver tube to protect the interconnect and bypass diode circuitry. However, it was observed that this shielding was not necessary due to the quality and coverage of the RTV encapsulation. Therefore, a new stainless steel clip was designed which could provide both the positive pressure contact between the two aluminum pieces and ease of removal.

09-II

Figure II-18. Interface ΔT

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Figure II-19. CAPVC Pressure Results

The receiver tube stand adjustments were utilized throughout phase I to study the alignment of the receiver tube. Achieving proper alignment proved to be no problem as the stand adjustments provided the necessary flexibility. The receiver tube sag between stands was measured using a 5-foot level and was found to be negligible, thus demonstrating the structural rigidity of the receiver tube assembly. The teflon holder portion of the stand was carefully inspected and adequate clearance to allow receiver tube thermal growth was noted.

It was observed during study of the prototype PV modules that the cells were not evenly mounted at their optimum locations. Discussions with the cell manufacturer who mounted the cells uncovered a production problem in that there was no way to guarantee accurate cell mounting on the prototype extrusion. To alleviate this problem, a definitive index point was added to the final design of the outer extrusion to assure that all cells are located 0.1 inches from the vertex (figure II-20).

When the 57-inch long outer extrusions with 22 (6 cm long) cells were mounted to the inner receiver tube extrusions at the concentrator focal point, it was quickly realized that an improved cell packing factor was desirable. The prototype configuration utilized only 90 percent of the available mirror area. To improve this utilization, the individual PV cell lengths were increased to the maximum possible length of 6.48 cm. The number of cells (22) was maintained due to operating voltage considerations. The outer receiver tube was increased in length to 58.5 inches to provide a substrate compatible with the longer cell string.

5) Final Design

The final receiver tube design (figure II-13) reflects the design modifications that were a direct result of the prototype testing. Three areas were updated from the intermediate design. These were the addition of the cell mounting index, the redesign of the attachment clips, and the increase in length of the outer extrusion from 57 to 58.5 inches. The details of the final design are shown in figure II-21.

II-53

Figure II-20. PV Cell Mounting Index Point

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The redesign of the attachment clip is the major change in the final design. Due to the inadequacy of the intermediate design aluminum clip, three aspects of the clip were changed. The use of aluminum for the clip material did not allow the required flexibility for both tight clamping and ease of installation. Stainless steel was chosen to replace the aluminum as it is more flexible, strong, and durable. As was discussed in the previous section, the shield portion of the clip was unnecessary and was therefore dropped from the design to facilitate handling of the clip as well as reduce weight. Finally, the length of the clip was reduced to 3 inches to make its installation easier. The resulting design is shown in figures II-21 and II-22. The CAPVC system requires 13,440 of these clamps, as they will be mounted continuously down the length of the receiver tube assembly to assure positive clamping and to block the direct path of dirt and moisture into the area between the two extrusions.

In order to support the overall CAPVC system, 1680 feet of receiver tube assembly will be required. There are 84 inner 6063-T5 aluminum extrusions each 20-feet in length. These extrusions would be heliarc welded on site to form 28, 60-foot rows. Standard pipe fittings are welded into these extrusions at both ends of each row to provide for hookup of the plumbing to the thermal subsystem (figure II-23). There are 336 outer 6063-T5 aluminum extrusions each 58.5 inches in length. Thus, for each 20-foot collector module, there are four outer extrusions. No additional surface preparation is required for the mounting of the PV cells. The extrusion tolerances were set according to the Aluminum Association Standard Tolerances.

The final receiver tube assembly design maintains all of the characteristics demonstrated by the intermediate design which were proven during the prototype testing, with the exception of the design improvements previously noted. Thus, although the receiver tube has an updated configuration, it is a proven design which meets all of the requirements of the CAPVC system.

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PROGRAM MANAGER			CODE IDENT.		
			52308		
			SIZE		
			02D001385		
			DWG. NO.		
			REV.		
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Figure II-22. Drawing of Clip Detail
II-59/II-60

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LIST OF MATERIAL				
DRAWN: G. AHASTEEN DATE: 1/27/73				
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Figure II-23. Return Pipe Assembly
II-61/II-62

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c. PV Cell and Module

1) Design Considerations

The CAPVC system design required the use of a concentrating photovoltaic cell. Communications with Sandia Laboratories regarding cell suppliers resulted in the identification of a concentrating cell design being developed under contract by Solarex, Inc. Further discussions with Solarex concerning this cell indicated that a similar design would be appropriate for CAPVC.

A cell design concept which became the baseline cell of the CAPVC system was generated in conjunction with Solarex. This cell was designed for mounting on the specially designed CAPVC receiver tube and several configurations were considered before the phase I concept was attained. The combination of the receiver tube and mounted cells was designated the PV module.

The phase I PV module design was then fabricated by Solarex and delivered to BDM for test and evaluation in its Solar Test Facility. Several months of testing were carried out to characterize the performance and operation aspects of the modules.

In a parallel effort to the testing, detailed circuit analyses were carried out to optimize the module circuitry. Specifically, the areas of cell shadowing and bypass diode protection were addressed. A newly generated Hewlett-Packard 9830 program and the NET-2 circuit analysis program were utilized in these analyses.

The information and results gained from the testing program and the analytical studies were used to optimize the PV cell and module configurations. This optimization resulted in the definition of a final CAPVC cell and module design.

2) Preliminary Design

Modifications were made in the initial cell design developed for Sandia by Solarex to optimize the design for the CAPVC system. This resulted in the design of a single crystalline Silicon cell with a microglass cover and physical dimensions which were 2 cm wide x 6 cm

long. The active area dimensions were 1.746 cm x 6 cm providing an active area of 10.48 cm². The projected power conversion efficiency was 13.5 percent at 55°C. The projected I-V characteristic of this cell when mounted in the CAPVC configuration is shown in figure II-24. The cell manufacturer estimated that the open circuit voltage of the cell would decrease at a rate of 2.1 mV/°C.

In order to assure an optimized cell design, BDM worked closely with Solarex to define the desired cell parameters. Definition of the expected illumination profile on the active area of the cell was analytically determined and is presented in figure II-25. This profile was used to provide an optimized metallization network to assure maximum efficiency in the gathering of the generated current.

The cells are mounted on both sides of the outer extrusion of the V-shaped CAPVC receiver tube assembly as shown in figure II-26. To ensure the focusing of the maximum amount of sunlight on the active area of the cell, careful positioning was achieved. A closeup photograph of the cell is presented in figure II-27.

The CAPVC modular receiver tube design concept required the definition of a finite length of outer extrusion on which the PV cells were to be mounted. Solarex indicated that for ease of cell mounting and shipping, a 40-inch long extrusion was optimum. The selection of this length resulted in three 40-inch long outer extrusions for each 10-foot long preliminary design mirror module. The 40-inch outer extrusion with cells mounted in place was designated as a PV module. Seventeen cells were to be mounted on each of these modules.

3) Intermediate Design

As the CAPVC system design progressed, further discussions with the cell manufacturer indicated that a longer PV module could be handled in the production process. Longer modules were desired to decrease the number of extrusions and connections in the system. The maximum length from a handling standpoint was determined to be approximately 5 feet. It was also necessary to have a module which could fit between the 5-foot spacing of the receiver tube stands. A length of

Figure II-24. Prototype CAPVC Cell I-V Curve

Figure II-25. Initial Cell Illumination Profile

78-493-TR

Figure II-26. PV Cell Mounting

Figure II-27. Photograph of CAPVC Prototype Photovoltaic Cell

57 inches was selected to allow for the longitudinal thermal expansion of the receiver tube and clearance around the support stand clamps. This longer module provided room for the mounting of 22 cells.

No changes in the cell design were made for the intermediate design of the PV module. The basic configuration of the receiver tube assembly and cell is shown in the photograph presented in figure II-28.

Considering this design, a 22-cell module at 55°C was projected to operate at 11.4 volts and 5.6 amps at peak power. This would produce a peak output power of 63.8 watts per module or 2.9 watts per cell.

Eight prototype intermediate design PV modules were fabricated by Solarex for test and evaluation in the BDM Solar Test Facility. An optimum design for the bypass diode circuitry had not been determined, and thus a conservative design was initiated. Two different protection schemes were provided for comparison as shown in figure II-29. A photograph of one of these modules is presented in figure II-30.

4) Prototype Test and Evaluation

The eight prototype PV modules were mounted in the test facility setup shown in appendices A and B. A complete current and voltage monitoring capability was provided as described in appendix B.

After receiving the first few receiver tubes from the cell manufacturer, it became evident that the method of encapsulating the cells on the outer extrusion needed improvement. Adequate protection of

Figure II-28. Receiver Tube Assembly/Cell Photograph

**FOUR EXTRUSIONS HAVE
THE FOLLOWING DIODE CONFIGURATION:**

**FOUR EXTRUSIONS HAVE
THE FOLLOWING DIODE CONFIGURATION:**

Figure II-29. Intermediate Design Prototype
Bypass Diode Configurations

Figure II-30. Module Photograph

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the cell and electrical interconnects was provided; however, the overall appearance of the module was not of high quality. The encapsulating process being utilized by Solarex was found to be unacceptable as it was very crude and did not provide a process which could be properly controlled and successively repeated. To demonstrate a process whereby the flow of the encapsulant could be regulated in a production manner, BDM developed a prototype Module Fabrication Fixture (see figure II-31). The fixture was sent

Figure II-31. PV Module Fabrication Fixture

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to Solarex for use in the fabrication of the remaining prototype modules. The modules resulting from the use of the fixture showed significant improvement in encapsulation quality. For phase II production of these modules, it was determined that a production fixture would be required.

Inspection of the prototype modules identified two other areas where improvements were necessary. The oxygen free copper cell interconnects used in the prototype were standard Solarex items utilized to meet stringent program time requirements. These interconnects were too large; therefore, custom fit (smaller) pieces were required for the finalized module design. It was also found during inspection of the modules upon arrival that several of them had cells which had become shorted to the substrate. The modules had been checked at the factory before shipping, and it was not clear as to the cause of the shorting. These modules were repaired, and it was determined that inspection of the module continuity must be made both before and after shipping.

Testing of the modules proceeded for several months with a large amount of data being gained. Both the electrical and thermal performance of the modules were characterized. Due to the large amount of information available, only a representative portion will be presented herein.

The effect of temperature on the open circuit voltage (V_{oc}) of the module is shown in figure II-32. The manufacturer had projected that the degradation of the open circuit voltage would occur at a rate of 2.1 mV/°C (1.167 mV/°F) per cell. These results show a very close correlation to the projected value.

The current-voltage characteristics (I-V curve) of the aggregate module is presented in figure II-33 at two different average cell temperatures. This curve is very characteristic of the projected performance. Note the shifting of the curve due to temperature.

Figure II-32. Temperature Effect on V_{oc}

57-INCH PV MODULE

Figure II-33. I-V Curve

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The power curve corresponding to the I-V results in figure II-33 is shown in figure II-34. Note the shifting of the peak power point due to temperature. The higher temperature results in reduced power as expected. These results along with additional data points also showed that the output performance between a clean and dirty mirror varied between 5 and 8 percent.

A linear relation was expected between peak output power and direct normal insolation. This was demonstrated in testing over a period of time as shown in figure II-35.

In order to assure that the PV module could endure severe weather cycling, a 57-inch prototype module was tested in the Sandia temperature/humidity cycling facility. As discussed in the receiver tube section, the module underwent 30 severe cycles (-30°F to 120°F) over the period of approximately 10 days. No physical changes in the cells or mounting were observed. The module was then remounted in the test facility and its output power measured. No performance degradation was discernable. Figure II-36 shows the before and after performance of the module.

Consideration of the expected performance of the PV module with the actual measured values showed that the cells and aggregated modules were performing exactly as predicted. Table II-5 presents a sample calculation comparing an actual data point measurement to the analytically predicted value.

5) Circuit Analysis

A circuit analysis study was carried out in order to provide a PV module with an optimized electrical circuit to assure maximum performance. The need for protecting each series string of cells against current transients and shadow induced reverse bias breakdown was identified in the early design phases. The placement of blocking diodes at one end of each string of cells was provided in the design to protect the string against current transients. Bypass diodes were identified as necessary to prevent reverse bias breakdown caused by cell failure or shadowing. The necessity for diode placement optimization resulted in a detailed systems circuit analysis. For the purpose of this analysis and the

57-INCH PV MODULE

Figure II-35. Peak Output Versus Insolation

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Figure II-36. Photovoltaic Module Output Before and After Temperature/Humidity Cycling

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TABLE II-5. SAMPLE CALCULATION

Conditions

$$\text{Insolation} = 895 \text{ W/m}^2$$

$$\text{Temperature} = 165^\circ\text{F} (74^\circ\text{C})$$

$$\text{Cosine Factor} = 0.9766$$

$$\text{Packing Factor} = 0.8055$$

$$\text{Area} = 0.289 \text{ m}^2$$

$$*\epsilon_{\text{CELL}} = 12.3\%$$

**Projected Findings

$$\epsilon_A = .84 \times .87 \times .123 \times \frac{615 \text{ mV} - 40 \text{ mV}}{615 \text{ mV}} \times .8055$$
$$= 0.0677$$

$$\text{Power} = 895 \frac{\text{W}}{\text{m}^2} \times .9766 \times 0.289 \text{ m}^2 \times 0.0677$$
$$= 46.69 \text{ W}$$

**Measured Power

$$\text{Power} = 47.0 \text{ W}$$

*No A-R microglass coating

**Because of symmetry, 1/2 aperture/22 cell string used for calculations and testing

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following discussion, the set of cells protected by a single bypass diode are referred to as a bypass group.

The purpose of the detailed analysis was to (1) optimize array performance, (2) quantify performance degradation, and (3) yield an appropriate final design. Although east-west, north-south and a combination of east-west, north-south oriented collectors were considered, the north-south orientation was determined as the optimum layout for the CAPVC system. The circuit analysis was carried out only for this final design configuration. The cell used in the analysis was the initial configuration with an efficiency of 13.5 percent at 55°C and an active area of 10.48 cm². The T-500 42-inch aperture, along with the intermediate design configuration of the module, were also included. Although this analysis was carried out for an intermediate design, careful consideration of the final design parameters indicated the results were still appropriate and were actually conservative.

Further input required included detailed insolation data, definition of shadow geometry, and detailed parameter data on the cells and diodes. Insolation data for the Albuquerque area was acquired from typical meteorological year SOLMET data from the National Climatic Center. This provided both insolation intensity and sun angles. Summer solstice, winter solstice, and equinox provide the maximum, minimum, and average insolation values for the year. Analysis utilizing the information from these three days was considered sufficient to study the seasonal performance variations for the array.

Parameters describing the cell and diodes were also determined. They characterize the forward, normal, and reverse operating conditions of the device. An HP-9830 data reduction program was developed to generate the normal conditions from the available I-V curves. Reverse conditions were defined by the manufacturer. The resulting parameters for the cell and bypass diodes are presented in table II-6.

A geometrical description of end shadowing is illustrated in figure II-37. Shadowing due to the gaps between collector modules is also represented by a similar geometry as shown in figure II-38. Figure II-39

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TABLE II-6. CELL AND BYPASS DIODE DATA

<u>CELL PARAMETERS</u>	
<u>Parameter</u>	<u>Value</u>
Series Resistance	4.47E-3 Ω
Shunt Resistance	20 Ω
Photocurrent	.289A/Sun
Saturation Current Constant	20A
Reference Temperature	332 $^{\circ}$ K
Emission Constant	.987
Temperature Coefficient	1.42E4 $^{\circ}$ K
Solar Input Power Constant	1047 mW/Sun
Power (Exponent) of Temperature	3.039

<u>BYPASS DIODE PARAMETERS</u>	
<u>Parameters</u>	<u>Value</u>
Bulk Resistance	5.36E-2 Ω
Saturation Current	2.18E-11A
Emission Constant	35.4 V $^{-1}$

illustrates the gaps that occur between the modules in the final design layout. To study performance of the array, the power lost as a result of end and gap shadowing must be determined.

Initial analyses studied the impact of end shadowing on a 20-foot string of cells, which represents the cells associated with a single collector section, which is the smallest modular array element appropriate for shadowing studies. The impact of aggregating the 20-foot collector section into 120-foot rows to represent the full array performance was studied with the addition of the resulting gap shadowing. This analysis showed that end and gap shadowing gave essentially the same performance efficiency. This is due to the similarity between the end and gap shadowing effects. Thus, the primary performance and circuit optimization studies carried out and documented in the following

Figure II-37. End Shadowing of a Collector

Figure II-38. Gap Shadowing Effects

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Figure II-39. Layout of One 120' Row of Collectors to Illustrate Gap Positioning

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discussions are based on a single end shadowed 20-foot cell string. The end versus gap shadowing results have been included as validation for this approach.

With the input parameters defined, the circuit analysis was carried out utilizing a two level approach. Detailed analysis of many bypass diode configurations were carried out with an HP-9830 program generated for modeling this phenomena. After narrowing down the possible configurations, the NET-2 circuit analysis program was used to verify the results. Brief descriptions of these programs are presented in appendix C.

In order to determine the amount of power lost due to end shadowing, a baseline HP-9830 computer run was made. This run simulated a fully illuminated array to determine the maximum power out of one string. These results were then compared to the results of end shadowing for each diode configuration studied.

The first assumption used in simplifying this analysis assumed a cell to be either illuminated or dark. This was based on the I-V characteristics for the CAPVC cell illustrated in figure II-24. If one cell of a string is operating at the peak power point and undergoes a small decrease in illumination, that cell quickly becomes reverse biased as if it were completely dark. The shadowed cell becomes reversed biased because the many unshadowed cells in the string determine the peak power current which remains relatively constant. The above assumption requires a means of determining when a cell is illuminated and when it is dark. Whenever the short circuit current of a cell became less than the peak power current for the rest of the string, then that cell was considered to be reverse biased. This is illustrated in figure II-40.

This second assumption (that peak power current is relatively unchanged by end shadowing) required that the analysis be carried out for a system where the number of shadowed cells is very small compared to the number of illuminated cells. In this analysis no more than 5 percent of the cells were shadowed at the same time. Since so few cells were shadowed, the peak power current of the shadowed cells did not decrease the peak power current of the string, therefore the peak power current for the string was considered to be a constant.

*Values used in prototype design.

Figure II-40. Comparison of Shadowed and Illuminated Cell I-V Curves to Show Shadowed Cell Operating in Reverse Bias Region

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The peak power current of the string was determined to be 93 percent of the short circuit current from the CAPVC cell I-V curve. Since current and insolation are directly proportional, a cell was considered to be completely illuminated if the average insolation on the cell was greater than or equal to 93 percent of the total available insolation. A cell was considered to be dark if the average insolation on the cell was less than 93 percent of the total available insolation. The insolation at the center of the cell was considered to represent the average insolation on that cell.

To identify the 93 percent illumination point consider the shadow illustrated in figure II-37. The receiver tube is completely illuminated from point C to point D and completely shadowed from point A to point B. The intensity of the partial shadow on the receiver tube varies between no illumination at point B to full illumination at point C. This variation in shadow intensity can be related to the position on the receiver tube by considering a cross section of the parabolic mirror as shown in figure II-37. The ray of light hitting at point E or F on the mirror will strike point C or D respectively on the receiver tube. A ray going through point G and hitting point H on the mirror will strike at point P on the receiver tube between B and C. Any rays striking the mirror between point G and F will miss the point P. Rays striking the mirror between points E and G will strike point P. Thus, the energy at point P is the energy striking between E and G. Since the insolation from the sky is uniformly distributed, the intensity at point P relative to an unshadowed point is the distance between E and G divided by the distance between E and F. Thus, the focal length at point H = $\sqrt{(EG)^2 + (GH)^2}$ can be found from the equation for the parabolic mirror and the intensity of the shadow at the point P.

Using a 42-inch aperture collector, and assuming a cell is shadowed if the average insolation on that cell is less than 93 percent of the total available insolation, gives a focal length of 49.61cm. The actual length of the shadow is then calculated using the equation: $d = F_d \tan \theta$. The angle θ varies as a function of both the azimuth and elevation angles of the sun. This data was acquired from SOLMET data

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tapes from the National Climatic Center. The relationship for the angle θ was found to be: $\theta = \sin^{-1} (\cos (\text{azimuth}) \cos (\text{elevation}))$.

The cells that were illuminated were considered to produce peak power. However, if the cell was shadowed, the power lost from that bypass group was considered to be twice the peak power out of that one cell. This resulted from the assumption that the forward voltage across the bypass diode was based on the difference in area, metalization and relative current directions for these devices.

The cross-sectional area of the bypass diode is 1/12 that of the cell. Since both devices must operate at the same current, a greater current density and junction voltage will be present in the bypass diode. The series resistance is affected by the difference in area and metalization patterns for the cell and the diode. The diode has a solid metal plate on the top and bottom, while the cell has a plate on the bottom but thin metal projections on the top. The increased metallization on the diode produces less series resistance while a smaller area results in a twelve-fold increase in series resistance for the devices. Figure II-41 illustrates these two devices and the current flow in each. This figure indicates that the external operating voltage for the cell is .535 volts, and the external operating voltage for the bypass diode is -1.07 volts. When calculating the external operating voltage of a forward biased cell, the current direction through this device is such that the voltage across the series resistance is subtracted from the junction voltage. However, for the diode, the voltage across the series resistance is added to the voltage of the diode. Therefore, based on differences in area, metalization and current direction for the CAPVC cells and diodes, the forward voltage of the diode was assumed to be twice the peak power voltage of the cell.

The physical PV module size (58.5 inches) presented a limitation for choosing the diode protection schemes. The arrangement of diodes had to be chosen to accommodate the 22 cells located on the outer PV extrusion. The 7 diode configurations studied were different possible ways to accommodate 22 cells. Another limiting factor for optimizing a protection scheme was the maximum allowable reverse voltage of 5 volts

*Values used in prototype design.

Figure II-41. Circuit Diagrams for CAPVC PV Cell and Bypass Diode to Show Difference in Operating Voltages

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specified by Solarex. As demonstrated in figure II-42, this indicated that only 6 cells may be in any one bypass group. Since bypass groups are not necessarily the same size, placing the smaller groups nearest the shadow would provide better protection for the module. The most cost effective design would favor one standardized protection scheme requiring the fewest number of bypass diodes.

After establishing these basic assumptions and derivations, this problem was solved using the HP-9830 program. Using the CAPVC cell parameters and SOLMET insolation data, the analysis was done for spring equinox, summer solstice and winter solstice. Table II-7 illustrates the effectiveness of each diode configuration. Little difference in performance was observed between the different configurations. Two of the protection schemes, one having one group of 4 cells and three groups of 6 cells and the other having two groups of 5 cells and two groups of 6 cells, were found to provide nearly the same performance while meeting the requirement to minimize the number of diodes. The smaller bypass groups were positioned nearest the shadow. Neither of these configurations would exceed the acceptable voltage level for the diode. Both would require one standard design of 4 diodes per 22 cells; thus, by minimizing the number of diodes, the design proves to be cost effective.

Further analysis was performed for these two diode configurations. For the scheme consisting of one group of 4 cells and three groups of 6 cells, the group of 4 cells nearest the shadow would provide only 18 percent of the nominal energy collected over a year by a nonshadowed bypass group. Similarly, for the scheme consisting of two groups of 5 cells and two groups of 6 cells, the first group of 5 cells in the southernmost module would provide only 24 percent of the nominal energy collected over a year by a nonshadowed bypass group. Table II-8 presents the results for these two bypass configurations and compares them to results for each design after the first bypass group in the southernmost module has been eliminated. These results indicate less than 2 percent decrease in average yearly output power between the design before and after eliminating the bypass group. This fact narrowed the

Figure II-42. Circuit Illustrating that 6 Cells are the Maximum Number of Cells in One Bypass Group to Limit Reverse Voltage to 5 Volts

TABLE II-7. COMPARISON OF THE ENERGY OUTPUT OF THE SEVEN
DIODE PROTECTION SCHEMES STUDIED

Protection Scheme Number	Number of Bypass Groups	Number of Cells Per Bypass Group	% of Total Available Insolation on Equinox	% of Total Available Insolation on Summer Solstice	% of Total Available Insolation on Winter Solstice	% of Total Available Insolation Average for One Year
1	2	11	87.46	98.44	85.24	91.96
2	3	6	92.29	99.04	81.31	93.61
	1	4				
3	2	6	92.29	99.04	81.31	93.61
	2	5				
4	5	4	94.21	99.28	82.42	94.15
	1	2				
5	11	2	93.07	99.52	78.43	93.07
6	2	5	93.25	99.19	82.27	93.73
	2	6				
7	1	4	94.21	99.28	80.70	93.79
	3	6				

TABLE II-8. COMPARISON OF ENERGY OUTPUT FOR TWO DIODE CONFIGURATIONS BEFORE AND AFTER ELIMINATING THE BYPASS GROUP NEAREST THE SHADOW

Protection Scheme Number	Number of Bypass Group	Number of Cells Per Bypass Group	% of Available Insolation on Equinox	% Available Insolation on Summer Solstice	% Available Insolation on Winter Solstice	% Available Insolation Average For One Year
1	2	5	93.25	99.16	82.27	93.73
	2	6				
2	1	5	94.33	93.46	84.55	91.99
	2	6				
3	1	4	94.21	99.28	80.68	93.79
	3	6				
4	3	6	95.44	94.48	82.96	92.53

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design choice to either a configuration of one group of 5 cells and two groups of 6 cells or a configuration of three groups of 6 cells for the southernmost module in each 20-foot collector section. Since these two designs were found to provide nearly the same performance, the configuration consisting of one group of 5 cells and two groups of 6 cells was chosen for the southernmost module since it required fewer cells and would produce a more cost effective system. The optimized diode protection would consist of four cell modules per 20-foot collector section. The southernmost module would consist of 17 cells protected by 3 bypass diodes. The bypass group nearest the shadow would consist of 5 cells, and the other two bypass groups would each contain 6 cells. The other 3 PV cell modules would each contain 22 PV cells protected by 4 bypass diodes (2 groups of 5 cells nearest the southern edge of the collector and 2 groups of 6 cells). This optimized protection scheme is illustrated in figure II-43.

The results from the preceding analysis were verified with the NET-2 circuit analysis program. This computer code includes models to analyze electrical and thermal transients in large photovoltaic array systems. Since the NET-2 analysis did not require the same simplifying assumptions used for the HP-9830 analysis, this second approach can be used to evaluate the assumptions used in the HP-9830 program. Both approaches utilized the same insolation, sun angles and cell parameters.

The same cell parameter data was input to the NET-2 program as was utilized in the HP-9830 analysis. The HP-9830 solutions were based on power equations whereas the NET-2 analysis used the voltage and current for its solutions.

Although both approaches implemented the same basic cell and insolation data, they were different in their bypass diode and shadow modeling techniques. The HP-9830 simulation assumed that the forward voltage of the bypass diode was twice the peak power voltage of a cell, independent of the current flowing in the bypass diode. NET-2 models the voltage and current characteristics of the bypass diodes internally using diode parameters, as discussed in appendix C, as inputs to the program.

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Figure II-43. Placement of PV Cell Modules and Bypass Diodes On the Receiver Tube

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Another major difference between the two problem approaches is the method of calculating the length and intensity of the end shadow. As discussed previously, the HP-9830 simulation assumed a cell was reverse biased if the short circuit current of that cell was less than the peak power current of the rest of the series string. Using this assumption and the CAPVC cell data, a threshold focal distance, F_d , of 49.61 cm was determined. The length of the shadow, $F_d \tan \theta$, was calculated using this threshold focal distance. A cell was considered to be completely shadowed if the length of the shadow included the location of the center of that cell. The NET-2 shadowing analysis did not require these same assumptions.

The model used for the NET-2 analysis is illustrated in figure II-44. It was not necessary to make any assumption to determine when a cell would become reverse biased. Since the NET-2 program performs its calculations in terms of voltages and currents, NET-2 determines whether each cell is forward or reverse biased after specifying the cell characteristics and system operating conditions. The shadowing effect along the length of a string of cells was input to NET-2 as a variation in insolation intensity on each PV cell element. This insolation intensity was calculated as a function of SOLMET insolation data, collector focal length, the location of the center of the cell, and the angle θ between the collector axis and the sun.

Before end shadowing effects could be determined, a run simulating a fully illuminated string was made to establish the maximum power out of one string. This run used the same NET-2 model described above without the variation of insolation intensity from cell to cell.

The NET-2 end shadowing analysis was performed only for the bypass diode configuration consisting of two groups of 5 cells and two groups of 6 cells. Results for the baseline and end shadowing NET-2 runs, and those corresponding results of the HP-9830 program are found in table II-9. The NET-2 analysis predicted a 5.3 percent loss, and the HP-9830 analysis predicted a 6.3 percent loss in annual array energy output due to shadowing. The agreement between these results indicates that either approach is adequate for the study of end shadowing

Figure II-44. Model used in NET-2 Analysis for Determining End Shadowing Effects

TABLE II-9. COMPARISON BETWEEN NET-2 AND HP-9830 ANALYSIS FOR OPTIMIZED DIODE
CONFIGURATION (2 GROUPS OF 5 CELLS AND 2 GROUPS OF 6 CELLS)

DAY OF YEAR	ARRAY OUTPUT ENERGY FOR FULLY ILLUMINATED ARRAY - NET-2 (kWh)	ARRAY OUTPUT ENERGY INCLUDING END SHADOWING - NET-2 (kWh)	ARRAY OUTPUT ENERGY FOR FULLY ILLUMINATED ARRAY - HP-9830 (kWh)	ARRAY OUTPUT ENERGY INCLUDING END SHADOWING - HP-9830 (kWh)
SPRING EQUINOX	224.08	210.46	225.60	210.36
SUMMER SOLSTICE	288.17	287.63	290.21	287.75
WINTER SOLSTICE	127.41	107.52	128.18	105.47

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effects. Results for both analyses are compared for the four bypass groups of one PV cell module in table II-10. The first bypass group is defined as the first group of five cells nearest the southern end of the cell module. The results indicate a close agreement between the analyses for the second, third and fourth bypass groups; however, there was a 12 percent difference in results between the two analyses for the first bypass group. The HP-9830 analysis predicted an annual energy output of 51.76 Wh whereas the NET-2 analysis predicted 78.6 Wh for the first bypass group. It was also determined that whenever this first bypass group became reverse biased in the NET-2 analysis, it would also become reverse biased in the HP-9830 analysis. This was found to be the case for all hours of all three of the days studied. Knowing that the first bypass group became reverse biased at the same time in both analyses suggested that the diode characteristics varied between the two analyses. These results indicated the diode parameters used in NET-2 characterized a better quality diode than the HP-9830 analysis. The diode modeled in the HP-9830 program represented realistic diode operation. The fact that these two analyses agreed so closely for the expected annual energy output provides evidence that the rest of the assumptions made for the HP-9830 analysis were very reasonable.

TABLE II-10. COMPARISON OF ANNUAL ENERGY OUTPUT FOR THE INDIVIDUAL BYPASS GROUPS IN ONE CELL MODULE

BYPASS GROUP NUMBER	HP-9830 ANALYSIS ANNUAL ENERGY OUTPUT (Wh)	NET-2 ANALYSIS ANNUAL ENERGY OUTPUT (Wh)
1	51.76	78.6
2	169.68	173.3
3	235.28	243.68
4	261.36	259.35

A final NET-2 shadowing analysis determined the effect of shadowing due to the 6-inch gaps between 20-foot collector

sections. This gap shadow, as illustrated in figure II-38, includes a variation in intensity along its length.

This problem was modeled using the previous NET-2 end shadow model with an additional shadow displaced 6 inches due to the gap. The effects of these two shadows were added together, multiplied with the insolation, and input to the PV cell model.

The results of the gap shadowing analysis are compared to end shadowing effects in table II-11. For this design, it can be seen that end and gap shadowing result in equal amounts of power loss from the array. Gap shadowing effects could be less than end shadowing effects if the illumination from the collector on the southern edge of the gap extended past one or more bypass groups on the collector to the northern edge of the gap. The longest shadow that the CAPVC system will experience is 80 cm long; this implies that the illumination from the neighboring collector extends 40 cm. In order to illuminate the closest bypass group, the illumination would have to extend 55 cm. Clearly, for the present CAPVC design, the gap shadow will affect the output power in the same manner as the end shadow.

6) Final Design

A final PV cell and module configuration was defined based on the test and evaluation and the circuit analyses completed during phase I.

The longitudinal packing factor of the Solar Test Facility installed cells was determined to be too low resulting in the non-utilization of approximately 10 percent of the collector mirror area. To improve this situation, the cell was lengthened. Additional cells could not be added due to open circuit voltage limits imposed by the inverter operating characteristics. A 7.62 cm (3-inch) diameter silicon wafer is used in the cell manufacturing process. Since two cells are cut from each wafer, the maximum cell length which could be attained was 6.48 cm. Using either larger wafers or one cell from each existing wafer would greatly increase the cost of the cells. This increased length cell significantly improved the overall packing factor.

The final cell design is presented in figure II-45. It has overall dimensions of 2 cm by 6.48 cm with an active area of

TABLE II-11. COMPARISON OF GAP SHADOWING AND END SHADOWING
ANALYSIS FOR OPTIMIZED DIODE CONFIGURATION

<u>DAY OF YEAR</u>	<u>ARRAY ENERGY OUTPUT FOR FULLY ILLUMINATED ARRAY NET-2 (kWh)</u>	<u>ARRAY ENERGY OUTPUT INCLUDING GAP SHADOWING NET-2 (kWh)</u>	<u>ARRAY ENERGY OUTPUT INCLUDING END SHADOWING NET-2 (kWh)</u>
SPRING EQUINOX	224.08	210.49	210.46
SUMMER SOLSTICE	288.17	286.22	287.63
WINTER SOLSTICE	127.41	108.33	107.52

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11.31 cm². The only difference from the initial cell is its length and the inclusion of AR coating on the cover glass. The cell provides a minimum bare cell conversion efficiency of 13.5 percent at 55°C. The final cell configuration will be utilized with the T-600 collector and will be irradiated with the intensity profile presented in figure II-46. The I-V characteristics for this final configuration are presented in figure II-47. Each cell produces 3.37 watts at the net concentration ratio of 23.75 and 1000 watts/m² insolation.

The final module design is presented in figure II-48. The length of the module was increased from 57 to 58.5 inches to provide room for the mounting of the longer cells. The cells are mounted with 1 mm spacing and occupy 57 of the 58.5 inches available. The remaining 1.5 inches allows for .75 inches on each end of the module for the module busbars to be installed. A 58.5 inch outer extrusion length allows 1.5 inches per module to clear the receiver tube stands and allow for thermal expansion of the assembly. The location of the cells on the module relative to the illumination of the receiver tube assembly is shown in figure II-49.

The cells are centered on the outer extrusion. Each outer extrusion is centered between two receiver tubes stands which are 60 inches apart. As indicated in figure II-50, the first receiver tube stand, placed on either side of the 12-inch gap, is placed 1 inch in from the edge of the mirror. The tracking mechanisms makes it inconvenient to place this receiver tube stand at the collector edge. The rest of the receiver tube stands are placed 60 inches apart, thus the last stand on each 20-foot collector section is placed on the pylon, 1 inch to the outside of the collector mirror. This arrangement of stands results in the first cell nearest the 12-inch gap being located 2.52 inches away from the edge of the mirror. The last cell in each 22-cell module is located .52 inches from the edge of the mirror. For the 17-cell modules, the cell closest to the 12-inch gap is located 15.4 inches from the collector's edge.

Figure II-46. CAPVC Projected Cell Intensity Profile

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Figure II-47. Projected I-V Curve for Solarex PV Cell (Active Area = 11.31cm²)

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- NOTES:
- 1. TO BE MOUNTED WITH A HIGHLY THERMAL CONDUCTIVE EPOXY, WHICH WILL ALSO PROVIDE ADEQUATE CELL STANDOFF VOLTAGE.
 - 2. THE P.V. MODULE ASSEMBLY WILL BE COMPLETELY ENCAPSULATED OVER THE INTERCONNECT & DIODE AREAS.
 - 3. FOR CELL DETAIL SEE SOLAREX DWG.#0743.

• P.V. MODULE •
SCALE: 1/4 SIZE

NO. REQ'D	PART NO.	MATERIAL	DESCRIPTION	ITEM NO.
LIST OF MATERIAL				
DRAWN C. AHASTEEN		DATE 1/30/79	MATERIAL:	
CHECKED:			FINISH:	
ENGINEER			TOLERANCES:	
PROJ. ENGR.			UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES CONTRACT OR COST CENTER	
PROGRAM MANAGER			CODE INVT.	
			SIZE	
			DWG. NO.	
			REV.	
			52308	
			D 02D0001383	
			SCALE:	
			SHEET	
			OF	

Figure II-48. Final PV Module Details
II-111/II-112

II-113

Figure II-49. Receiver Tube Assembly Showing Proper Positioning of PV Cell Relative to Solar Illumination

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Figure II-50. Cell Placement on Collectors II-115/II-116

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There are four cell modules for every 20-foot collector section. The southernmost cell module in each 20-foot section consists of 17 cells. These are protected by three bypass diodes (a group of 5 cells nearest the shadow and two groups of 6 cells). The remaining 3-cell modules consist of 22 cells. Each of these three modules are protected by four bypass diodes. There are two groups of 5 cells and two groups of 6 cells. The 5-cell bypass groups are positioned nearest the shadow. Six collector sections form a row, and their 24 PV modules are wired in series in the final design. This results in a row output operating voltage and current of 254 VDC volts and 6.61 amps. Fourteen rows comprise the array, and the overall operating voltage and current are 254 VDC and 185 amps respectively. Figure II-64 (page II-137) in the array layout section depicts this configuration.

Performance of the modules was based on the cell output characteristics. Each 22-cell module will produce 74.13 watts, and each 17-cell module will provide 57.1 watts at a net concentration ratio of 23.75 with 1000 w/m^2 insolation.

The cell modules provide 1500 VDC standoff between the PV cell and aluminum substrate while the thermal conductivity of the 5 mill thick potting compound is $0.013 \text{ w/cm}^2\text{-}^\circ\text{C}$. The completed PV module is designed to endure 20 years of winter temperature/humidity cycling with no performance degradation or physical deterioration.

d. Array Layout

1) Design Considerations

The array layout directly addresses the specific positioning of the photovoltaic concentrator in the CAPVC application. Three areas were addressed in order to determine the optimum system layout:

- (1) Shadowing of the array by external structures
- (2) Orientation of the collectors
- (3) Collector row spacing

Specific computer codes were utilized in each area to assure that the optimum condition was identified. In addition, considerations of available roof area and the optimization of the plumbing, electrical wiring, and control and instrumentation layouts were included in the definition of the final design configuration.

2) Array Shadowing

In order to determine if any planned or existing structures or natural obstacles would cast shadows on the array which would be unacceptable to its operation and performance, the program SHADE STRUCTURE was developed. The program runs on the Hewlett-Packard 9830 and can determine shadowing at any time during any day of the year.

Inputs to the program were defined in terms of the cartographic and topological geometry of the solar array and the obstacle which could shadow the array. The coordinate system used in the CAPVC analyses is illustrated in figure II-51. This figure shows the cartographical layout of the site. From the map, the positive Y-axis (north) was defined as the E 387 000 line, and the positive X-axis (east) was defined as the N 1 473 000 line. With this coordinate system, an x, y, and z (roof elevation) value is input for each obstacle under consideration. The width and length of the obstacle are also specified. Figure II-52 defines these input parameters for the CAPVC array and for both proposed and existing building sites.

A sample of the SHADE STRUCTURE output is shown in figure II-53. This is a typical shadow plot for one complete day of the

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Figure II-51. Shade-Structure Coordinate System

*Compiled by photogrammetric methods from aerial photographs taken December 2, 1972, by Bohannon Westman Huston & Assoc. Inc.

Figure II-52. Proposed and Existing Building Sites for Shadowing Analysis

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Figure II-53. Shadow Cast From Nearest Large Obstacle at Winter Solstice

year. This type of information was generated and compiled for all existing and planned structures for all seasons of the year. Figure II-54 presents the annual shadowing zone for the two existing structures nearest to the array. Figure II-55 presents the same information for the three nearest proposed buildings. The information shown in both figures is for sun elevations greater than 15 degrees. Shadows at less than 15 degrees are not presented, as intra-array shadowing becomes the major consideration for these sun angles.

Discussions with Craddock Development, who plan the major construction in the immediate area of the array, have not identified any proposed buildings beyond those considered by this analysis. Considering the available land spaces and the existing zoning, no additional shadowing problems are expected (see chapter IV for a discussion of the zoning regulations). As a point of reference, figure II-56 presents the heights of buildings on the land ridge to the south of the array which could cause some minimal array shadowing at the lowest sun angle of the year (winter solstice). These buildings could be constructed only if considerable zoning variances were allowed. Discussions with city officials indicate this to be an extremely unlikely possibility.

In summary, shadowing of the CAPVC array by external objects and structures is not a problem.

3) Array Orientation

CAPVC electrical performance was utilized as the key delineator for choosing the array orientation. Early in the program it had been felt that a combination NS/EW configuration (as shown in figures II-57 and II-58) could provide additional system information at a small sacrifice in array performance. The two NS/EW configurations shown are based on an early and final building design. After careful consideration of the PRDA objectives, it was determined that the orientation should be selected based on the system which provided the most energy with the best load/array output matchup.

The SOLCEL computer program was used to predict and compare the performance of NS/EW, all NS, and all EW configurations. A

Figure II-54. Annual Projected Shadowing from Nearest Existing Buildings

Figure II-55. Annual Projected Shadowing from Nearest Proposed Buildings

Figure II-56. Maximum Building Height Along Southern Ridge Before Array Shadowing Occurs at Winter Solstice

78-493-TR

Figure II-57. Preliminary NS/EW Collector Field Layout

Figure II-58. Intermediate NS/EW Collector Field Layout

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detailed description of how these performance predictions were derived is presented in chapter III. The results concerning orientation selection are presented in the following paragraphs.

Figure II-59 presents a comparison between the insolation available to the NS oriented array and the EW array. The monthly peaks of the projected BDM electrical load is presented on the same figure. The energy available to the NS orientation shows a good positive correlation with the peaks of the electrical load.

Figure II-60 gives an array output power comparison between the three orientations for a typical summer day. It is obvious from this result that the NS array provides the most energy during the summer when the CAPVC building requires the maximum electricity due to its air conditioning load.

Table II-12 shows the overall electrical output performance comparison of the three array orientations. (The NS values are slightly different than the results presented in chapter III, as the orientation study was completed for an earlier array configuration. The changes resulting in the final configuration did not affect these comparative results.) These results show that the NS orientation provides 9 percent more energy annually than does the EW array and 3 percent more than the combined array.

Based on a better load matchup and more energy available annually, the NS oriented array was selected as the final design configuration.

4) Intra-Array Spacing

In order to study intra-array shadowing for the purpose of selecting the appropriate row spacing for the CAPVC array, a computer program designated as SHADE was developed. SHADE calculates intra-array shadowing for fixed or single-axis tracking collectors at any orientation and inclination angle for any day and time of the year.

Figure II-61 illustrates the amount of solar insolation collected by a NS array as the collector row spacing varies from infinity to 1 aperture for a typical summer day. The energy output obtained by

II-129

Figure II-59. Comparison between EW and NS Oriented Collectors with the Projected CAPVC Building Peak Load Profile.

Figure II-60. Array Output Power Comparison Among Three Orientations for a Typical Summer Day

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TABLE II-12. COMPARISON OF THREE ORIENTATIONS UTILIZING SOLCEL

<u>TYPE OF ENERGY</u>	<u>ORIENTATION</u>		
	<u>EW</u>	<u>EW/NS</u>	<u>NS</u>
INSOLATION AVAILABLE (MWh)	1427.5	1427.5	1427.5
INSOLATION COLLECTED (MWh)	1107.8	1132.8	1157.8
END AND GAP SHADOW LOSS (MWh)	8.2	7.0	5.8
ARRAY POWER (MWh)	92.1	95.4	98.4
POWER SUPPLIED TO LOAD (MWh)	83.2	88.3	90.8

Figure II-61. Energy Collected by a NS Array at 4 Aperture Spacings for a Summer Day

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integrating the area under these curves and completing the analysis for all seasons of the year is shown in figure II-62. It was clear from this analysis that a 2-3 aperture spacing would be optimum for the CAPVC array.

The available roof area on the CAPVC building along with additional studies of solar array row spacing were considered in conjunction with the preceding results. This resulted in the selection of the 3-aperture spacing configuration as the optimum and most cost effective system.

5) Final Layout

The final CAPVC array layout is shown in figure II-63. This is a nominal 50 kW system laid out in a NS orientation with 3-aperture row spacing. There are 14 collector rows each comprised of 6, 20-foot collector modules resulting in a 120-foot row length.

Included in figure II-64 is a summary description of the array wiring and piping for the finalized design layout.

2. Power Conditioning

a. Operating Mode

1) Introduction

Power conditioning for the CAPVC system was developed by considering three major objectives. These included demonstrating the electrical operation of the CAPVC array, demonstrating the feasibility of connecting a photovoltaic array to a load and/or in parallel with a commercial utility, and identifying and characterizing the system operating modes and key interfaces. Understanding these objectives led to the following approach.

The system operating modes were defined to support the PRDA goals and requirements. Then key system and component interfaces were identified. Each operating mode was next evaluated by BDM and PNM, and the hardware and electrical schematics were specified to support the selected operating modes. Analyses of the resulting system were based on the use of an inverter to accept DC power from the solar array

Figure II-62. Inter-array Shadowing Effects of NS Oriented Array

Figure II-63. Final CAPVC Array Layout
II-135/II-136

Figure II-64. Final CAPVC Array Wiring and Piping

to produce usable AC power. The inverter was determined to be more efficient and less expensive than either an motor generator (MG) or an uninterruptable power system (UPS) as illustrated in figure II-65.

2) Preliminary Design

The preliminary design identified four system operating modes resulting in the power conditioning system layout shown in figure II-66. These four modes included:

- (1) Supply building loads solely by the photovoltaic power system.
- (2) Supply building loads with the photovoltaic power system operating in parallel with a 277 VAC 3 phase utility grid.
- (3) Provide load management while in parallel with the utility.
- (4) Supply the commercial utility grid with the output of the photovoltaic power system.

The first operating mode (supplying on-site loads solely with array power) was intended to demonstrate the effects of specific load transients on the array. This study considered loads ranging from a transient-sensitive computer facility to a print shop. However, the first stage of the inverter includes a filtering circuit. This circuit is illustrated in figure II-67. Any transients of higher than 1 kilohertz will be filtered out by the large capacitors. The lower frequencies will be of no interest since the control loop nominally operates at 1 kilohertz. Since the load transients will be filtered, this mode of operation was not warranted.

The second and third operating modes utilize the array power system operating in parallel with the utility. The power of the array is added to the utility power at the building bus. This augmentary mode can be implemented with or without load management. Load management provides a means of regulating the time of day in which the array power is supplied to the load. Figure II-68 illustrates this peak shaving of the load. Since the utility rate charged depends on the peak kilowatt demand for the months, it would follow that supplying power at the peak demand time each day would lower the monthly utility rates. This daily peak shaving would require microprocessor control and extensive battery storage.

Figure II-65. Efficiencies and Relative Cost of Power Conditioning System Alternatives

Figure II-66. Schematic of Preliminary Power Conditioning/Distribution System

Figure II-67. Block Diagram of the Inverter Preregulator
Illustrating Frequency Filtering

Figure II-68. Typical Summer Day Peak Load and Collector Profile Illustrating Peak Shaving

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The equipment required for load management would add considerable cost to the CAPVC system, and therefore this mode of operation was carefully studied. Battery storage operations have been well characterized in many field installations such as missile silos, and thus further demonstration in the CAPVC system was not felt to be a necessary requirement. Further, the extensive data acquisition capabilities of CAPVC would provide enough information to predict fully how load management could have been accomplished without any additional expenditure for batteries or load management control equipment. It was therefore decided that demonstration of load management in the CAPVC system was unnecessary and not cost effective for the tight PRDA funding levels known to exist.

Supplying power from the array into the utility grid was the final operating mode considered for the CAPVC system. The preliminary design included automatic switches to provide energy to the utility grid whenever it was available. After discussions with PNM, it was decided to operate in the feedback mode only under the supervision of both BDM and PNM personnel. This special feedback mode involves disconnecting the array from the building load and directing power back onto the utility line. Since this would be a special experiment, it would not warrant the expensive automatic switches (manual switches will be used) specified in the preliminary design.

There were at least two reasons for not supplying feedback power onto the PNM line automatically. Until satisfactory procedures have been demonstrated, PNM was concerned with the operational safety aspects of a system on their line which they are not able to totally control. Also, PNM was concerned with the waveform quality of the generated power. Performing these special feedback experiments would enable both BDM and PNM to study the waveform quality and technical feasibility of the reverse power flow conditions and, as a result, set the stage for more automated interactions in future systems.

3) Final Design

After studying each of the proposed preliminary design operating modes, it was clear that only one primary mode was necessary for the characterization of the CAPVC system. This mode is

augmentary load sharing with the commerical utility, PNM. Special feed-back experiments will be included but are supplementary to the overall system operation. Figure II-69 is a block diagram of the final design of the power conditioning distribution system required to support the selected mode.

b. Inverter

During phase I, Westinghouse was identified as the supplier of the inverter. This inverter was designed specifically for solar applications for DC to AC conversions. Initially it was designed to produce 120/208 VAC. During the design phase, Westinghouse developed an option providing an inverter with output of 277/480 VAC. This option was selected for the CAPVC system since the building service will require 277/480 VAC. The addition of this option eliminated the necessity of a voltage step-up transformer at the output of the inverter which was included in the preliminary design.

There is some question whether the Westinghouse prototype system will become a production unit within the CAPVC time frame because of issues involving nonrecurring costs. However, BDM has identified, solicited and received bids from two additional inverter sources. Both Delta Electronic Control and Windworks, Inc., have off-the-shelf inverters which, although not optimized for PV systems, can satisfy the CAPVC requirements without component development. If the issue concerning the Westinghouse inverter is not resolved, an inverter will be selected from the above alternatives.

Performance and engineering specifications presented in the following sections will specifically address the Westinghouse inverter. However, should the Delta or Windworks inverter be chosen, they will be required to meet the same performance and engineering specifications to ensure system integrity and power quality.

The Westinghouse inverter (shown in figure II-70) is capable of performing under a continuous 50 kVA load with an overload capability of 100 kVA for 5 seconds. A block diagram of the inverter is presented in figure II-71. The inverter accepts inputs from the PV array

Figure II-69. Schematic of Final Power Conditioning/
Distribution System

Figure II-70. Westinghouse Inverter

Figure II-71. Block Diagram of Westinghouse/CAPVC Inverter

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with a voltage range of 200 to 300 VDC. The inverter's preregulator feeds a power modulator which free runs for stand-alone power or is synchronized to the line for parallel connections to augment the utility. The output is 60 Hz, 277/480 VAC, three-phase power. The efficiency at 100 percent load is 92.5 percent. The inverter is line commutated and incorporates a peak power tracker to maximize power output of the PV array. The inverter output is protected against over-and-under-voltage, overcurrent and abnormal frequency. Input and output filtering are provided to suppress EMI inputs, distortion of the output, and RF signal propagation by the inverter. Paralleling inductors at the output of the inverter assures an output phase that is slightly advanced and power shares with PNM. Power quality is enhanced by proper phase control in the power modulator and output filtering.

Additional specifications for the inverter are included in table II-13.

Instrumentation voltages are brought out to a connector for monitoring current and voltage, DC at the input and three-phase AC at the output. If the output current exceeds 60 amperes, the inverter will shed the load after 5 seconds.

The possibility that the inverter might not start up due to overvoltage was investigated. If the input voltage to the inverter drops below 200 or exceeds 350 VDC, the inverter input contactor opens and the inverter shuts down. On a cold (0°F), windy morning, the array open circuit voltage would not exceed 350 VDC, and start-up is not a problem. Conversely, the array is actively cooled such that the voltage could never drop below 200 VDC.

c. Electrical Wiring and Switchgear

The building electrical distribution and switchgear for the final design are shown in figures II-72 and II-73. Each schematic includes a list of components. Table II-14 lists component specifications for the CAPVC power conditioning and switchgear.

1) Collector Electrical Layout

Figure II-74 shows that each of the 14 collectors contains 2 strings of series connected PV cells. Each string carries a

TABLE II-13. WESTINGHOUSE INVERTER SPECIFICATIONS

Type: AVI-503A

Part Number: 947F901-2

Rating: 50 kVA Continuous, 100 kVA for 5 seconds

Output: 60 Hz, three-phase, four-wire, 277/480 volts

Efficiency at 0.9 Power Factor: Under 5% load, 59.3%
 Under 25% load, 87.5%
 Under 100% load, 92.5%

THD (Total Harmonic Distortion) less than 5%

Input: 200 to 300 V_{OC} (up to 350 VDC with slight deviation to specifications)

Output Protection: Over/Under Voltage
 Over Current
 Abnormal Frequency

Utility Tie: Synchronized with utility line
 Voltage variation + 10% - 15% (balanced or unbalanced)
 Phase angle ± 10 degrees

Mechanical & Environmental: 24-inch standard rack on 4-inch castors
 28.3 inches wide, 30.3 inches deep, and
 91 inches high, including castors
 Total weight: 1830 pounds
 Ambient temperature: -10 to +45° Celcius
 Relative humidity: up to 96% noncondensing
 Barometric pressure: 790 to 520 mm of
 Mercury

Other: Solar array peak power tracking
 Automatic start and utility grid paralleling

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REVISIONS
1 2/21/77

PROJECT DATE DRAWN CHECKED
SHEET E-11

78-94

- GENERAL NOTES:
- A. ALL CONDUCTORS SHALL BE #12 THW UNLESS NOTED OTHERWISE ON DRAWING.
 - B. ALL CONDUCTORS SHALL BE COPPER. NO SUBSTITUTES.
 - C. ALL CONDUIT SHALL BE A MINIMUM OF 1/2" UNLESS NOTED OTHERWISE ON DRAWING.

- CONSTRUCTION NOTES:
- 1 5 #12-3/4"C.
 - 2 6 #12-3/4"C.
 - 3 7 #12-3/4"C.
 - 4 8 #12-3/4"C.
 - 5 9 #12-1"C.
 - 6 10 #12-1"C.
 - 7 11 #12-1"C.
 - 8 12 #12-1"C.
 - 9 13 #12-1"C.
 - 10 14 #12 - 1-1/4"C.
 - 11 SAFETY SWITCH, WESTINGHOUSE #RMU-261, 600 VDC, 2 POLE, 30 AMP, MD, NEMA 3R, FUSIBLE WITH TYPE "R" FUSE CLIPS, FUSE AT 15 AMPS WITH BUSSMAN "LPS-R" FUSES.
 - 12 J-BOX - 6" x 6" x 4", CAST WITH MUBS. WEATHERPROOF.
 - 13 J-BOX - SIZE AS REQUIRED. WEATHERPROOF.
 - 14 SAFETY SWITCH, WESTINGHOUSE #RMU-261, 600 VDC, 30 AMP, MD, NEMA 3R, NON-FUSIBLE.
 - 15 J-BOX - 8" x 8" x 4", CAST WITH 1 - 1" HUB PER SIDE. LEAVE 6 FOOT OF SLACK INSIDE OF J-BOX. WEATHERPROOF.
 - 16 1 - 7 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774, AND 2 - 2 PAIR TWISTED & SHIELDED 22 GAGE - 1"C.
 - 17 2-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2 - 2 PAIR TWISTED & SHIELDED 22 GAGE - 1 1/2"C.
 - 18 3-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 1 1/2"C.
 - 19 4-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 1 1/2"C.
 - 20 5-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 2"C.
 - 21 6-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 2"C.
 - 22 7-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 2"C.
 - 23 8-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 2 1/2"C.
 - 24 9 - 9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 2 1/2"C.
 - 25 10-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 3"C.
 - 26 11-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 3"C.
 - 27 12-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 3"C.
 - 28 13-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774 & 2-2 PAIR TWISTED & SHIELDED 22 GAGE - 3"C.
 - 29 14-9 PAIR TWISTED & SHIELDED 22 GAGE BELDEN #8774, & 4-2 PAIR TWISTED & SHIELDED 22 GAGE - 3"C.
 - 30 2 PAIR TWISTED SHIELDED #22-1/2"C.
 - 31 JUNCTION OR PULL BOXES, ONE SIZED FOR THE DC POWER WITH 2 COPPER BUSSES WITHIN WITH LUM FOR 14 #12 AND 1 #4/0 ON EACH BUS. STAMP ONE BUS - AND THE OTHER - THE OTHER J-BOX SHALL BE SIZED FOR THE CONTROL CABLES INDICATED AND SHALL HAVE 2-3" C. FROM THE BOX TO THE CONTROL ROOM ON THE FIRST FLOOR.
 - 32 MOUNT RECEPTACLE ON PARAPET, UP 12" ABOVE ROOF.
 - 33 MOUNT RECEPTACLE ON PYLON SUPPORT FOR SOLAR COLLECTORS, UP 12" ABOVE ROOF.

SKETCH "B"
NOT TO SCALE

NOTE
LIGHTING PROTECTION SYSTEM
GENERAL: PROVIDE AND INSTALL A COMPLETE MASTER LABEL LIGHTING PROTECTION SYSTEM AS DESIGNED AND MANUFACTURED BY THE LIGHTING PROTECTION COMPANY OF ST. PAUL, MINNESOTA AND A-C LIGHTING SECURITY INC.
NOTE: EXCLUDES LIGHTING PROTECTION SYSTEM.
ALL ITEMS & WORK SHOWN ON THIS SHEET SHALL BE SUBMITTED AS A SEPARATE CONTRACT BID PRICE. THIS PRICE SHALL INCLUDE CONDUIT & WIRE TO FIRST FLOOR.

ROOF - ELECTRICAL PLAN
SCALE 3/8" = 1'-0"

Figure II-73. Electrical Roof Plan
II-153/II-154

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TABLE II-14. POWER CONDITIONING AND SWITCH GEAR

NO.	PART NO.	DESCRIPTION	SPECIFICATIONS
42	G.E. CO. IN3671A, RA	BLOCKING DIODES	12A RATING, 1.0V MAX @ 6A
14	WESTINGHOUSE RHF-261	FUSIBLE SAFETY SWITCH	2 POLE, 30A, 600V, HEAVY DUTY, NEMA 3R FUSIBLE WITH CLASS R FUSE CLIPS
14	BUSSMAN LPS-R	FUSES	15A, CLASS R
14	WESTINGHOUSE RHU-261	NON-FUSIBLE SAFETY SWITCH	2PAK, 30A, 600V, HEAVY DUTY, NEMA 3R, NON-FUSIBLE
14	CIRCLE A-W	JUNCTION BOXES	6" X 6" X 4", CAST WITH HUBS, WEATHERPROOF
28	CIRCLE A-W	JUNCTION BOXES	SIZE PER 13 ON FIGURE II-73, WEATHERPROOF
14	CIRCLE A-W	JUNCTION BOXES	8" X 8" X 4", CAST WITH 1-1" HUB PER SIDE FOR INSTRUMENTATION CABLES, WEATHERPROOF
1	CIRCLE A-W	JUNCTION BOX	PULL BOX ON ROOF FOR CONDUCTORS-SIZE PER 31 ON FIGURE II-73, WEATHERPROOF
1	CIRCLE A-W	JUNCTION BOX	PULL BOX ON ROOF FOR INSTRUMENTATION CABLES - SIZE PER 31 ON FIGURE II-73, WEATHERPROOF
1	CIRCLE A-W	JUNCTION	12" X 12" X 4" D., J. BOX IN INSTRUMENTATION ROOM FOR CONDUCTORS
1	CIRCLE A-W	JUNCTION BOX	24" X 24" X 6" D., J. BOX IN INSTRUMENTATION ROOM FOR INSTRUMENTATION CABLES
1	WESTINGHOUSE HF-463-N	FUSIBLE SAFETY SWITCH	100A, 600V, 3POLE, 4WIRE, SOLID NEUTRAL, HEAVY DUTY, FUSIBLE WITH CLASS R CLIPS, NEMA 1
1	BUSSMAN LPS-R	FUSE	90A, CLASS R
1	WESTINGHOUSE RHU-463	NON-FUSIBLE SAFETY SWITCH	100A, 600V, 3POLE, 4WIRE, SOLID NEUTRAL, HEAVY DUTY, NON-FUSIBLE, NEMA 3R
28	DALE LA9B3A	SURGE ARRESTERS	SPARK GAP ARC-OVER VOLTAGE FACTORY ADJUSTABLE FROM 400-4500 VDC. TOLERANCES = 20% TO 10% AMBIENT OPERATING TEMPERATURE RANGE -55°C TO +72°C.
3	WESTINGHOUSE CSF	CURRENT TRANSFORMERS	1200:5 RATIO
3	WESTINGHOUSE TYPE CW	REVERSE POWER RELAYS	3 PHASE APPLICATION
3	WESTINGHOUSE CV-1	LOSS OF VOLTAGE RELAYS	3 PHASE APPLICATION
1	WESTINGHOUSE EHB-3090 WITH SHUNT TRIP	CIRCUIT BREAKER	MOLDED CASE, 100A FRAME, 3POLE, 600V, 90A TRIP, WITH SHUNT TRIP UNIT
3	WESTINGHOUSE EMP	POTENTIAL TRANSFORMERS	2:41 RATIO, GENERAL PURPOSE
1	WESTINGHOUSE 947F901-2	INVERTER	200-300 VDC INPUT; 50kW; 60 Hz, 3PHASE, 4WIRE, 277/480 V OUTPUT
1	WESTINGHOUSE RHF-467-N	SERVICE DISCONNECT SWITCH	800A, 600V, 3POLE, 4WIRE, SOLID NEUTRAL, HEAVY DUTY, FUSIBLE WITH CLASS L CLIPS, NEMA 3R
1	BUSSMAN KRP-C	FUSE	700A, CLASSL

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- NOTES:
- 1. EACH PV STRING IS 120' LONG AND IS TERMINATED WITH 6' PICTAILS OF #14 AWG. THE PV STRINGS ARE ROOF MOUNTED IN 14 N-E COLLECTORS. EACH COLLECTOR HAS TWO STRINGS, SAFETY SWITCHES, FUSES, SPARK GAPS AND PROTECTION DIODES.
 - 2. JUNCTION BOXES AND CONDUIT PROVIDED PER BUILDING CONTRACTOR SCHEMATICS USING STANDARD UL APPROVED COMPONENTS FOR RATING SHOWN. BUILDING ELECTRICIANS FOR WILL PULL CABLES AND DO ALL WIRING UP TO AND INCLUDING SAFETY SWITCHES. BDM TECHNICIANS WILL WIRE COLLECTORS, DIODES AND INVERTER.
 - 3. THE 14 COLLECTORS ARE TIED TOGETHER ON THE ROOF AND BUSSED DOWN TO THE CAPVC INVERTER. DOTTED LINES INDICATE JUNCTION BOXES.
 - 4. MARK WITH "DANGER-CHECK FOR VOLTAGE". OPENING SAFETY SWITCHES ISOLATE COLLECTORS BUT DO NOT REMOVE POWER.
 - 5. ALL VOLTAGES AND CURRENTS SHOWN ARE MAXIMUMS.
 - 6. NO EARTH GROUND SHALL BE BROUGHT INTO THE CAPVC BUILDING. ALL EXTERNAL EARTH GROUND ARE AT THE PNM SERVICE DROP.

NO. REQ'D	PART NO.	MATERIAL	DESCRIPTION	ITEM NO.
1	947F901-2 OR EQUIVALENT		CAPVC INVERTER, W.E.C	3
28	LA9B3A		SURGE ARRESTER	2
42	1N3871A RA OR EQUIVALENT		BLOCKING DIODES, C.E. CO.	1
LIST OF MATERIAL				
DRAWN: G. AHASTEEN		DATE: 7/26/79	2800 YALE BLVD., S.E., ALBUQUERQUE, NM 87108	
CHECKED:				
ENGINEER:				
PROJ. ENGR.:				
PROGRAM MANAGER:			TITLE: CAPVC SYSTEM ELECTRICAL SCHEMATIC	
			CODE IDENT. 52308 SIZE D DWG. NO. 02D001275 REV.	
NEXT ASSY.			SCALE: SHEET 1 OF 1	
APPLICATION				

Figure II-74. CAPVC System Electrical Schematic
II-157/II-158

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6-foot pigtail on each end. These are routed into junction boxes provided by the building contractor. At the positive north side of each collector, blocking diodes are connected to each string; the strings are interconnected and provided with a fuse and isolating switch. At the negative south end, the pigtails are interconnected and provided with another isolating switch so that both ends can be isolated.

The array is protected from lightning transients by placing spark gaps at both ends of each collector. The spark gap near the positive end of the collector is placed between the cathode of the blocking diode and ground. The spark gap near the negative end of the collector is connected between the terminal and ground. Since the PV strings are not grounded, there must be a spark gap on each collector end to provide a path to ground for any surge transients encountered. Under transient surge conditions, the 400 VDC spark gap will not breakdown until it reaches 800 volts. Using a spark gap on both collector ends requires the blocking diodes to withstand up to 1600 V to assure complete transient protection.

The power cables are routed through conduit to a junction box at the west end of the array. Here the cables from the collectors are interconnected and bused into the building. The switches, fuses, junction boxes and conduit will be installed by the electrical contractor. Blocking diodes and spark gaps will be installed by BDM. All wiring up to the diodes will be done by the electrical contractor. Connections and wiring of the collectors will be accomplished by BDM technicians.

2) Switchgear

The switchgear design was developed by BDM in conjunction with Westinghouse Engineering Services, PNM, and Zerwer Engineering (the electrical engineers for Craddock Development Corporation).

Switches are provided on each end of each of the 14 collectors for complete isolation of individual collectors to facilitate fault location, characterize efficiency degradation, and perform maintenance without a complete shutdown.

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As shown in the detailed power conditioning diagram in figure II-75, a reverse power sensing circuit is provided which breaks the CAPVC line to provide positive shutdown in the event of a utility power outage. This was a safety requirement requested by PNM. The circuit has reverse power and loss-of-voltage sensing relays.

Figure II-76 is a block diagram of the reverse power sensing circuit. Current transformers on each leg of the three phase bus couple reverse power signals into three reverse power relays. Reverse power on any one phase causes the three circuits on the PV line to open. Power transformers couple loss of voltage into corresponding relays for redundant operation. Following a power outage, PNM will attempt to reclose the line at various intervals up to 120 seconds. The reverse power sensing circuit permits manual closure once PNM power has returned.

A PV lockout switch is provided for the PNM troubleshooter so that he or she can cut off the PV line from the main bus and building loads to assure safe working conditions. A load release switch in the building allows the collectors and inverter to be disconnected from the building bus.

Considerable thought was given to the possibility of insuring that the CAPVC system continue providing power to selected loads during a PNM power outage. This would involve much additional switchgear, and it could not be guaranteed to operate since, without battery storage, the inverter could shutdown if collectors stowed due to adverse weather conditions. Therefore, it was decided that parallel operation with the utility was sufficient, and the stand alone mode was not warranted.

The special experiment to evaluate the feasibility of powering the PNM grid from the CAPVC system is performed by shutting down all loads with the exception of the CAPVC control and monitoring circuits and jumping the reverse power sensing junction box to feed the PNM transformer. This will provide BDM and PNM with information to help define an acceptable operational mode with utilities in future PV applications. However, since this will be a special experiment, the additional permanent switchgear to bypass the reverse power sensor was not warranted.

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Figure II-75. Detailed Power Conditioning and Switching Block Diagram

Figure II-76. Block Diagram of Reverse Power Sensing Circuit

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3. Thermal System (CAPVC Heat Rejection and Building Heating)

a. Design Consideration

The CAPVC thermal system includes the heat rejection circuit as well as the building heating circuit. The heat rejection circuit provides the necessary active cooling for the receiver tube-mounted photovoltaic cells. The building heating circuit provides supplementary building heat utilizing the available thermal energy collected in the CAPVC heat rejection circuit.

Photovoltaic systems with high concentration ratios require active cooling of the cell area. Since minimized cell temperatures are desired, low-grade thermal energy is produced. This thermal energy can be utilized if it is practical and cost effective.

The heat rejection circuit is a requirement for the CAPVC system in order to maintain the desired inlet cooling temperature throughout the year. Utilization of the low-grade thermal energy is not a requirement, and the CAPVC design considered several different configurations in this area as the thermal system design progressed through the phase I detailed design studies. Ultimately, it was decided to use the thermal energy for building heating during the winter months.

b. Preliminary Design

The schematic for the preliminary design of the CAPVC thermal system is shown in figure II-77. This concept involved utilization of the thermal energy for building heating. The main components of the heat rejection circuit were the pump, the fluid cooler, and the piping to and from the collector field. The building heating circuit was provided by the (hot working fluid) coil in the building air handler duct. The working fluid would normally circulate between the collectors and the heat rejection unit. However, when building heat was needed, this heated fluid would be circulated through a special coil (heat exchanger) in the forced air heating system.

The fluid cooler for the heat rejection circuit was selected as a closed circuit evaporative cooler. Initially, a Baltimore Aircoil unit was chosen. This configuration provides easily maintainable

78-403-TR

Figure II-77. Schematic of Preliminary Design for the CAPVC Thermal System

heat rejection rates at a reasonable cost from a commercially available and proven piece of machinery. Trade-offs existed between the total cooler capacity (i.e., initial cost) and the fluid flow rate. Differences in the initial cost of evaporative coolers in the range of sizes required for the CAPVC system were small, and optimization efforts were not considered until the phase I detailed design effort. However, the evaporative cooler size was optimized for the final design.

The closed circuit evaporative cooler was selected instead of a cooling tower design because of the type of working fluid required for this application, namely a solution of 50/50 ethylene glycol/water. It was not practical to evaporate and discharge this fluid from the cooling tower to the atmosphere. An intermediate heat exchanger between the (ethylene glycol/water) working fluid and the (water) cooling tower would solve the problem, but would result in decreased efficiency as well as increased system cost and complexity. Water could not be used as the working fluid because of air lock, drainage, and freezing problems. Figure II-78 describes the operation of the particular heat rejection unit.

In the preliminary design, several uses were considered for the low-grade thermal energy. Since Albuquerque has a high air conditioning load and a comparatively low heating load, both absorptive and Rankine cooling cycles were considered. However, because the working fluid would reach maximum temperatures of only 115°F (preliminary design), it was considered economically inadvisable to employ thermal air conditioning systems. A low-grade energy source would require special equipment, such as a templier (heat pump), an expensive device that amplifies the low-grade thermal energy to a more usable heat source. Further, BDM believed that the expenditure of resources to design a thermal air conditioning system (that could use low-grade heat) did not relate directly to the original PRDA objective. Therefore, thermal air conditioning was eliminated as a viable system because of excessive cost and complexity. On the other hand, a standard forced air heating unit can utilize the low-grade thermal energy coming from the array without the need for a templier. The building heating circuit requires the interface heat

(HEAT REJECTION RATE CAN BE VARIED)

Figure II-78. Closed Circuit Evaporative Cooler

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exchanger, pipes, pump, coils, and associated controls, but its total cost is still much less than that of the thermal air conditioning system. Therefore, the building heating circuit was selected as an optional system for CAPVC.

c. Intermediate Design

The intermediate design of the thermal system for CAPVC eliminated the use of the low-grade thermal energy. Careful studies predicted that the CAPVC building heating requirements would result in a cost of less than \$1000 per year. With this minimal requirement, a cost effective system could not be defined as a viable part of the CAPVC system. Much thought was given to providing the system strictly for the value of the information which could be gained concerning system thermal performance. Consideration of the overall goals of the PRDA procurement indicated strongly that unless the thermal system could be shown as cost effective, it should not be considered as part of the DOE funded elements of the CAPVC system. It was then decided that the building heating portion of the design would be dropped and attention focused on the heat rejection circuit. Figure II-79 is a schematic of this intermediate design.

This design concept was carried throughout the major portion of the phase I design.

d. Component Test and Evaluation

During phase I testing at BDM's Solar Test Facility, the components of the CAPVC heat rejection circuit were tested and evaluated. The components of the heat rejection circuit which were evaluated included the fluid pump, fluid cooler (heat rejection unit), expansion tank, and plumbing. The coolant plumbing is visible entering and exiting the receiver tubes (mounted at the focal point of the collectors) of the prototype collector set-up shown in figure II-80. The heated coolant fluid exits the receiver tube and is piped directly to the mechanical pad. The mechanical pad (figure II-81) supporting the fluid cooler and pump is located at ground level. The heated coolant from the collectors is piped through the expansion tank, pump, and fluid cooler. The pot feeder is used for adding more coolant or inhibitors.

- $T_{\text{FLUID IN}} = 115^{\circ}\text{F}$ OR OPTIMALLY MINIMIZED (PUMPING POWER)
- $T_{\text{FLUID OUT}} = 90^{\circ}\text{F}$ OR MINIMUM BASED ON $T_{\text{WET BULB}}$

Figure II-79. Intermediate Thermal Energy System Design

Figure II-80. CAPVC Parabolic Trough Concentrator System Cooling Circuit T-500

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Figure II-81. Solar Test Facility Mechanical Pad

The heat transport system underwent extensive testing for several months and met or exceeded all design specifications. The coolant fluid (50/50 ethylene glycol/water with NALCO 2755 inhibitor) performed flawlessly. The inspection of fluid samples confirmed the correct specific gravity (i.e., the proper mixture of ethylene glycol/water) and visual clarity (i.e., fluid was free of particulate matter). A visual inspection of the inside of the receiver tubes also showed no sign of corrosion. The fluid cooler and pump operated as expected with no down time and provided adequate cooling for the PV cells.

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In summary, the cooling circuit was a dependable, easily controlled, and maintained system with low pumping power requirements. The entire system consists of off-the-shelf and proven hardware, thus ensuring a high-level of success for this subsystem.

e. Final Design

Additional considerations for the utilization of the low-grade thermal energy for building heating were carried out during the latter part of the phase I design. Because of the valuable information that could be gained from the operation of such a system, BDM decided to fund the construction of a building heating circuit which was compatible with the heat rejection circuit. This system remains non-cost effective, but will provide valuable operational experience.

Before a final decision was made, it was necessary to study the trade-off between the CAPVC electrical output and useful thermal energy, both of which are directly related to the coolant temperature. As the coolant temperature is increased to provide useful thermal energy, the average PV cell temperature, which is 130°F if a building heating circuit is not in use, rises to 140°F when the circuit is included in the design.

The projected annual CAPVC DC power is 103.2 MWh for an average operating PV cell temperature of 130°F. Further, the projected DC power (PV cell temperature, 130°F) for the four winter months, (Nov., Dec., Jan., Feb.) is 22.1 MWh.

However, when the building heating circuit is used for those four winter months, a displacement of 2.1 percent (500 kWh) in DC power results. Based on the entire year, this displacement in DC power amounts to only 0.5 percent. Offsetting the displacement of DC power is the acquisition of useful thermal energy at the rate of 8.34×10^5 Btu/day or a total of 2.93×10^4 kWh for the four month period. These calculations are based on a thermal water storage tank capacity of 10,000 gal and a useful temperature gradient of 10°F between the tank and the heating coil. Therefore, the CAPVC system would be displacing 500 kWh in DC power for four months, but it would be acquiring 2.93×10^4 kWh in thermal energy

during that time. This represents a net power gain of 2.88×10^4 kWh. Since a net power gain is realized, the building heating circuit was included as an integral part of the final CAPVC design.

All of the components required to provide the CAPVC thermal system are commercially available and proven and will comply with all ASME, ASHRAE, and other applicable codes and standards. The design features and detailed components of the heat rejection circuit will be discussed first, followed by the discussion of the building heating circuit.

1) Heat Rejection Circuit

The final heat rejection circuit design is shown schematically in figure II-82. This figure illustrates many of the circuit's design features. The plumbing of the collector field is modular in design, whereby the coolant enters at each end (north and south) of the 14, 120-foot collector rows and is collected at the midspan of each of the rows. This system simplifies plumbing, minimizes pumping pressure head, and maximizes flexibility, accessibility, and ease of maintenance. For example, the coolant pressure drop across each 60-foot collector row at 5 gal/min is 3 psia, and the total pumping power required for the entire system is only 0.6 kW. The coolant system flowrate is defined for a single optimum design condition (140 gal/min system total, 5 gal/min per 60-foot collector row), and it will not be varied during operation. The system is flow balanced by adjusting the valves and measuring the flow at each end of a 60-foot row. A complete description of this system is presented in figures II-83 through 86.

The CAPVC array plumbing (figure II-84) consists of black steel piping. The north and south collector rows are fed by supply manifolds that taper from 4-inch to 1-inch diameter pipe. The supply and return manifolds both pass through the roof directly over the third floor equipment room in which the pump is located. The piping to the evaporative cooler is routed to ground level through the solar chase on the east side of the building (figure II-86). All solar water piping will be proven tight at a hydrostatic pressure of 120 psia.

3-20' COLLECTOR
MODULES

Figure II-82. CAPVC Heat Rejection System

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EQUIPMENT SCHEDULE											
SYMBOL	DESCRIPTION										
①	COOLING TOWER: Factory assembled and insulated, closed circuit cooling tower, sectional counter flow, blow-through design, centrifugal fan, hot dipped galvanized steel construction. Pan section shall include access doors, strainer, water bleed line valve, 115 volt electric water level control system, manual drain valve and automatic vacuum breaker. The fan motor shall include a 1.15 service factor, mounted on adjustable motor base and driven with a V-belt designed for not less than 150% of the motor nameplate horsepower. The unit shall include removable coil section, open type water distribution system, removable eliminators, low leakage insulated discharge dampers having less than 1% leakage at 3" w.g., spray pump, and pan heater. The spray pump shall be centrifugal, close coupled, bronze fitted with mechanical seals and shall deliver 3 gpm minimum of water per sq. ft. of unit cross section. The pan heater shall be electric with water tight junction box, control thermostat set for 40°F, and low water cut-out relay. The discharge damper, spray pump, and fan shall operate in sequence as indicated by the control diagrams. Baltimore Aircoil Model VXI-36-2, 440 volt, 3 phase, 60 Hz, capacity as scheduled below.										
	Symbol	GPM	EWT	LWT	P.D. Ft.	Amb. W.B. Temp. °F	CFM	Air P.D. In. w.g.	Fan HP	Spray Pump HP	Pan Heater KW
	1	140	110°F	90°F	2	68°	22,000	0.375	15	1.0	6.0
②	END SUCTION PUMP: Horizontal, close coupled, end suction, cast iron bronze fitted with casing rings, shaft sleeves and mechanical seal. The casing shall be vertically split with a minimum working pressure of 125 psig. Impeller shall be single suction enclosed type of bronze construction. Shaft shall be high strength SAE 1045 carbon steel. Bearing frame shall be cast iron construction provided with catch basin reservoir with tapped drain hole to collect and pipe away mechanical seal leakage. Furnish one spare mechanical seal. Motor shall be for use with 440 volt, 3 phase, 60 hz power. Weinman Series 300, 2-1/2" K. Capacity as scheduled below.										
③	Symbol	GPM	Head (Ft.)	Motor HP	RPM	Fluid					
	2	140	62.0	5	1750	50% Ethylene Glycol					
	3	140	60.0	5	1750	Water					
④	EXPANSION TANK: Pressurized diaphragm type, ASME certified and stamped for 125 psig water working pressure. Tank shall be horizontal and shall contain a flexible diaphragm securely sealed within the tank permanently separating the 15 psig air charge from the system fluid. Furnish line size air purger and float type air vent with a shut-off valve between purger and air vent. Extrol size AX-15.										
⑤	FLOW MEASURING STATION: The flow measuring station shall consist of a ball valve and orifice. The ball valve to be teflon seated tight shut-off type with stem seal and tamper resistant locking device. Orifice to be calibrated and color coded with quick disconnect valves at the meter fittings, and shall have a chained metal tag showing orifice size, 5 gpm and meter reading for 5 gpm. Unit shall be rated for 250°F and 150 psi. Gerand Engineering Co. size 1". Capacities as indicated on the drawings.										
⑥	VENTURI FLOW METER: Furnish unit complete with quick disconnect valves, portable master meter and safety shut-off valves. Venturi shall be one piece brass screwed connection. The unit shall be designed such that a flow rate of 140 gpm will be between 10 and 40 inches of water pressure differential. Rinco Engineering size 3" - 750.										
⑧	ETHYLENE GLYCOL MAKE-UP UNIT: Ethylene glycol make-up system including "Lobec" positive displacement gear pump model 4LAL, complete with base plate, motor, coupling, and suitable for use with ethylene glycol, capacity of 9 gpm at 30 psig, 1/3 horsepower, 120 volt, single phase, 60 Hz, 1750 rpm, 32 gallon solution tank - 18" diameter x 30" high ±, differential pressure switch to start pump at 25 psi and stop at 30 psi, with 120 volt solenoid valve interlocked with pump.										
⑨	HEAT EXCHANGER: Water to ethylene glycol, shell and U-tube design, removable tube bundle 125 psig, steel shell with cast iron head, 3/4" O.D. copper tubes, steel tube sheets, baffles and spacers, solar water 50% ethylene glycol in tubes, with supports, furnish complete calculations showing heat transfer surface and complete dimensional drawings. Fouling factor 0.0005 both shell and tube side. Tube side in at 110°F - out at 100°F, 14.0 ft. P.D., 140 gpm. Shell side in at 92°F - out at 100°F, 18.0 ft. P.D., 140 gpm, 187 sq. ft. of surface area. Omega 2U-10-78. 800 lbs.										
⑩	WATER LEVEL CONTROLLER: Displacement type liquid level controller suitable for use in water at 120°F and 100 psig. Controller with two SPST mercury switches, 13 amp rating, 120 volt, single phase, 60 Hz. Controller shall have 4", 125 lb. cast iron flange for mounting, type 304 stainless steel displacers, switch enclosure shall be waterproof NEMA enclosure. Magnetrol Model A-103F (tandem), or approved equal.										
⑫	SOLAR WATER STORAGE TANK: 30 psig working pressure, plasite finish inside, with all necessary connections for filling, manual gauging, venting, tank water supply and return connections, and access manhole located near the top of tank. The tank shall contain 5,000 gallons of water, 8 ft. diameter x 14 ft. long. Tank will be used in the vertical position.										
⑬

Figure II-83. CAPVC Thermal System Sheet 1

SOLAR COLLECTOR PIPING PLAN
SCALE: 3/32" = 1'-0"
(ROOF ABOVE THIRD FLOOR)

	PROJECT NO.	CAPVC THERMAL SYSTEM		JOB NO.
	REVISIONS			8979 / 1
				DRAWN BY
				CHECKED BY
				R.E.S.
				DATE
		BRIDGERS & PAXTON CONSULTING ENGINEERS, INC.		SHEET
		ALBUQUERQUE, NEW MEXICO		32

Figure II-84. CAPVC Thermal System - Sheet 2
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	PROJECT NO.	CAPVC THERMAL SYSTEM		JOB 2276 / 6
	REVISIONS			OWNER B.O.P.
		BRIDGERS & PAXTON CONSULTING ENGINEERS, INC. ALBUQUERQUE, NEW MEXICO		CONTRACT R.O.B.
				DATE
				SHEET 34

Figure II-86. CAPVC Thermal System - Sheet 4

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All of the pipes are insulated with 1-1/2-inch Johns-Manville flamesafe AP-T fiberglass sectional pipe insulation with a pressure sensitive closure system. In addition, pipes exposed to the weather are finished with a 0.016-inch smooth aluminum jacket with a 60-pound Kraft paper vapor barrier and connected with a modified S-lock equal to Premetco "Loc-Jack" z-crimps. All piping is rigidly supported by pipe stands or hangers where necessary.

The heat exchanger unit is a factory assembled and insulated closed circuit evaporative cooler, designated as a Baltimore Aircoil Model VXI-36-2. The cooler is located at ground level on the east side of the building away from interference with other mechanical equipment. A heat rejection rate of 1.2 million Btu/hr, based on a coolant temperature difference of 20°F, is provided by the fluid cooler. The cooler is designed to cool the collector coolant from 110°F to 90°F (ambient wet bulb temperature, 68°F).

The pump for the heat rejection circuit is a Weinman Series 300 end suction pump with a head of 62.0 feet (50 percent ethylene glycol) for a flowrate of 140 gal/min. The pump is located in the third floor equipment room for convenience and protection from the elements (figure II-84).

The heat transport fluid is a 50/50 ethylene glycol/water mixture with NALCO 2755 inhibitor and with a freezing point of -33°F. The ethylene glycol makeup system includes the "Lobee" positive displacement gear pump model 4LAL complete with base plate, motor, and coupling.

The expansion tank is an Extrol size AX-15. It is a pressurized diaphragm type which is ASME certified and stamped for 125 psig of water working pressure.

Locations for flow measurements of the system are shown in figures II-83 and II-84. A flow measurement station consists of a ball valve and orifice and is a Gerand Engineering Company size 1 inch. The Venturi flow meter is a Rinco Engineering size 3-inch-750, designed so that it will read between 10 and 40 inches of water pressure differential for a flowrate of 140 gal/min.

2) Building Heating Circuit

The simplified schematic of the CAPVC building heating circuit (figure II-87) shows that this system is entirely separate from the heat rejection circuit. When the building heating system is not in use, the CAPVC working fluid never enters the interface heat exchanger. The building heating system maintains a building temperature of 55°F after working hours and provides building preheat in the mornings of the winter months. During the day, the building heating circuit will be running simultaneously with the CAPVC system when the storage tanks are in need of charging to a maximum temperature of 100°F. When the tanks are fully charged, the system will shut off. The building heating system will next be activated when a demand is made for building heat or when the tanks need to be recharged, and this can occur simultaneously on cold winter mornings. Although the primary source of building heat comes from the use of electric radiant panels throughout the building, it is intended that the supplementary solar building heat will decrease the conventional power usage by one-half.

The primary components of the building heating system are the heat exchanger, the hot water coils, the storage tanks, and the pump. A detailed description of this system is also shown in figures II-83 through II-86). The following discussion identifies each of the key elements of the design.

The ethylene glycol/water to water heat exchanger is an Omega 2U-10-78 and is located in the third floor equipment room for convenience and protection from the elements. The heat exchanger provides a heat rejection rate of 0.6 million Btu/hr based on a coolant flowrate of 140 gal/min and a coolant temperature difference of 8°F.

The primary plumbing (figure II-83) consists of 4-inch diameter schedule 40 black steel pipe. The piping can be joined by welding or by screw joints. All exterior and exposed pipes will be insulated with 1-1/2 inch thick Johns-Manville Flame-Safe AP-T fiberglass sectional pipe insulation with a pressure sensitive closure system.

Figure II-87. Solar Building Heating System

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The thermal storage consists of two 5,000 gallon water storage tanks which are located in the mall area of the building (figure II-86). The tanks are uninsulated and will radiate heat to the mall area of the building as well as store thermal energy for use in the heating coils. The tanks have the capacity to store 0.83 million Btu per day based on an increase of water temperature of 10°F. Each tank is ASME-certified and stamped for 30 psig water working pressure. The tank pressurization is provided by a nitrogen bottle and regulator (set at 25 psig). The water level controller for each of the two storage tanks is a Magentrol A-103F (tandem) model.

The heating circuit pump is a Weinman Series 300 end suction pump with a head of 60-feet of water for a flowrate of 140 gal/min. The pump is located in the third floor equipment room. Flow measurements are provided by a Venturi flow meter (Rinco Engineering size 3-inch-750) designed such that the meter will read between 10 and 40 inches of water pressure differential for a flowrate of 140 gal/min.

The two hot water coils (figure II-83), which provide building heating, are located in the main air handler ducts. The coils are operated by automatic thermostatic controls whenever the return air temperature is below 55°F.

4. Controls and Instrumentation

a. Introduction

The goal of the CAPVC Phase II instrumentation and control system design was to provide industrial level controls and instruments which may be utilized with minimum operator intervention. This assures the safe and efficient utilization of a PV collector electrical power generation system in an industrial environment. The design optimizes the use of closed loop monitoring systems and is not dependent upon the existence of a computer based control and data acquisition system for its operation.

The phase II design is based on an extension and, in some cases, a simplification of the design and philosophy followed by BDM in the design and operation of its Solar Test Facility (STF). The phase II design is thus a product of actual test and evaluation experience.

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The following discussions address the finalized designs of the arrays, control systems, data acquisition and transducers. In each of these areas, the phase II design considerations and final configuration are presented. Where appropriate, the experience gained in BDM's STF is referenced.

Figure II-88 is a block diagram of the Phase II CAPVC Control and Data Acquisition System. This block diagram is oriented to show the measurements to be recorded, the measurement locations, and the key system interfaces.

b. Control System

The areas of the CAPVC experiment which required specific control systems included:

- (1) Collector tracking
- (2) Coolant flow
- (3) Heat rejection
- (4) Inverter

In addition, control of the safety aspects of the system must be maintained. The support of these control areas was provided through the institution of a communications system and the provision of a control center which serves as the nerve center for the array.

1) Tracking

The CAPVC collector system was designed with a closed loop shadow bar tracking unit for tracking the sun's movement across the sky. The system was designed with the primary manual enable and control circuits at the control center with additional manual controls at the tracker control box on the collector drive pylon. These controls allow a manual override of the tracking system to permit driving of the collector to any desired nontracked position including stow. System wake-up and shutdown are controlled by a light sensor which activates/deactivates the shadow bar tracker sensing unit. Tracking of the collector system using the shadow bar tracker is completely automatic, requiring only the initial setup to assure that accuracy is maintained at all sun angles.

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Figure II-88. CAPVC Control and Data Acquisition System Diagram

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Shadow bar tracking was utilized during prototype testing in the Solar Test Facility and was found to be accurate, simple, reliable, and cost effective. It was observed that care and experience must be utilized when adjusting the manually-set circuit sensitivity. If not properly set, an oversensitive system will hunt excessively during partly cloudy conditions, and an undersensitive system will not track accurately.

2) System Coolant Flow

Coolant flow in the collector system was designed to be controlled at two levels. Total system flow is controlled by an adjustable valve at the coolant pump outlet. This valve can be manually adjusted, but has been designed with an initial setting to provide a total system flow of 140 gal/min. Changes in this setting will be required only if the system design flow rate is found to provide inadequate cell cooling. In this case, the total flow will be slightly increased until adequate cooling is attained. This main control valve is intended to be optimally adjusted to the finalized configuration.

A second level of flow control is provided at the collector row level. It is required that the flow into each of the 28 cooling circuits be the same. This is accomplished with adjustable valves at the inlet to each of the collector cooling rows. Balancing of the flow will be achieved during initial setup and will have to be changed only if the total system flow is adjusted. Periodic checks will be performed to assure that the flow remains balanced. Additional valves were included at the outlet of each circuit to allow an individual row to be isolated for maintenance, without having to shut down the entire coolant system.

Coolant pump control is a simple on/off switch which was designed into the control center system.

Applicable Solar Test Facility experience reflected in the final design primarily included operation and control of a closed circuit coolant system with the flexibility of variable flow. An understanding of the pumping characteristics of the system was also directly applicable.

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3) Heat Rejection

The controls for the heat rejection unit are included in the off-the-shelf Baltimore Aircoil unit. The internal controls include individual pump and fan switches along with a temperature control unit, which is set for the desired coolant outlet temperature. An overall on/off switch for the unit is provided in the CAPVC control room.

4) Inverter

The inverter control electronics are internal to the device, and the inverter turns on automatically when it is receiving an appropriate level of power from the array. The unit is located in the control room with its own switches and displays, and thus no additional controls are necessary. A disconnect is included should the inverter require maintenance.

5) Control Center

The CAPVC Control Center was designed to provide a central point for data acquisition, control, and power generation.

Figure II-89 is a conceptual layout of the control center. The Control Center was designed for optimum system operation and ease of viewing to facilitate tours and demonstrations conducted concerning the CAPVC system. The objective of the center's design was to situate the control center equipment such that it may be visible and in close proximity to the status panel during tours and briefings.

Figure II-90 is a conceptual depiction of the CAPVC Control Center Status Panel. This is modeled after industrial status and control panels wherein the function being monitored is schematically presented on the panel for ease of operation and status identification.

Figure II-91 is a schematic representation of the data, control, and power cabling and its distribution after leaving the Control Center junction boxes. The ODAS will interface with the data and control lines at their interface with the control and status panels.

6) Safety

BDM's concern for industrial safety in the final design was addressed in two areas - operator and visitor safety, and equipment and facility safety.

• FLOOR PLAN •
SCALE: 1/2" = 1'-0"

• SECTION A-A •
SCALE: 1/2" = 1'-0"

• SECTION B-B •
SCALE: 1/2" = 1'-0"

• FRONT ELEVATION •
SCALE: 1/2" = 1'-0"

NO. REV'D	PART NO.	MATERIAL	DESCRIPTION	ITEM NO.
LIST OF MATERIAL				
DRAWN: DUBEN	DATE: 1-26-79	MATERIAL:	2800 YALE BLVD., S.E., ALBUQUERQUE, NM 87108 TITLE: CAPVC CONTROL CENTER	
CHECKED: D	1-26-79	FINISH:		
ENGINEER: DUBEN	1-27-79	TOLERANCES:		
PROJ. ENGR.				
PROGRAM MANAGER: <i>Walter Kaufman</i>	1/30/79			
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES CONTRACT OR COST CENTER			CODE IDENT. 52308	REV.
NEXT ASSY.			SIZE D	DWG. NO. 02D001377
APPLICATION			SCALE: AS NOTED	SHEET 1 OF 1

Figure II-89. CAPVC Control Center

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NO. REQ'D		PART NO.	MATERIAL	DESCRIPTION	ITEM NO.
LIST OF MATERIAL					
DRAWN: DUBEN		DATE: 1-25-79	<div> 2800 YALE BLVD., S.E., ALBUQUERQUE, NM 87108</div>		
CHECKED: [Signature]		1-26-79			
ENGINEER: DUBEN		1-27-79			
PROJ. ENGR.					
PROGRAM MANAGER: [Signature]		1/31/79	TITLE: COLLECTOR ARRAY GRAPHIC PANEL CAPVC		
			TOLERANCES:		
			UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES CONTRACT OR COST CENTER		
NEXT ASSY.			CODE IDENT. 52308	SIZE D	DWG. NO. 02D001376
APPLICATION			SCALE: 1/4" = 1'	SHEET 1	OF 1

Figure II-90. CAPVC Control Center Status Panel

(32) BUFFERED ALARM DATA FROM APS* INCLUDES :

- (28) SUBFIELD OVERTEMP
- (1) COOLANT PUMP PRESSURE LOSS
- (1) EMERGENCY STOW ACTIVATION
- (1) WEATHER STOW COMMAND
- (1) HYDRAULIC PUMP PRESSURE LOSS

NO. REQ'D	PART NO.	MATERIAL	DESCRIPTION	ITEM NO.
LIST OF MATERIAL				
DRAWN: C. AHASTEEN	DATE: 1/28/79	MATERIAL:	 2800 YALE BLVD., S.E., ALBUQUERQUE, NM 87108 TITLE: CAPVC CONTROL CENTER CABLING	
CHECKED:		FINISH:		
ENGINEER:				
PROG. ENGR.:	1-30-79			
PROGRAM MANAGER:	1/30/79		UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES CONTRACT OR COST CENTER	
NEXT ASSY.		CODE IDENT. 52308	SIZE D	DWG. NO. 02D001378
APPLICATION		SCALE:	SHEET 1 OF 1	

Figure II-91. CAPVC Control Center Cabling
II-197/II-198

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a) Operator and Visitor Safety

Personnel and operator safety can be ensured by (1) restricting access to only those BDM employees who have been thoroughly trained in the system and certified for access to the Control Center or Array Site during operation, and (2) by ensuring that no visitors are allowed into the Control Center or Array Site unless accompanied by a CAPVC certified BDM employee. This was achieved in the design through the definition of cypher locks at the Control Center and Array Site access doors. The code for these doors will be periodically changed and be issued only to those BDM employees with authorized access.

Appropriate operator and visitor safety was carefully defined and then successfully demonstrated in the operation of the Solar Test Facility during prototype testing. The lessons learned from this experience were included in the final design of CAPVC and will be valuable in the operation of the larger but similar system.

b) Equipment and Facility Safety

Individual, closed loop, monitoring and alarm systems are included in the final design of each subsystem to prevent damage to the array or the facility if the subsystem fails. These systems sense status or transducer data coming from the array or its subsystems. In the event a potentially harmful situation is realized, the subfield or entire array is shut down and stowed. This information will be transmitted to the Control and Status Panel where orderly shutdown may be affected or the automatic command overridden if, in the judgment of the operator, the fault situation may be explained by activity in other areas of the CAPVC system. Table II-15 itemizes the physical event which will result in subfield, full array, or support system shut down or in a warning indication to the Control Center.

7) Communications

The final CAPVC design includes intercom headset jacks at the base of the central collector support pylons and at the various subsystem and machine room locations to assure complete control of the system, and to facilitate maintenance activities.

TABLE II-15. AUTOMATIC SAFETY SYSTEM

<u>Symptom</u>	<u>Override Capability</u>	<u>Action</u>	<u>Comment</u>
Loss of PNM AC Power	No	Inverter Off Stow Full Array	Initiated by overload on inverter Initiated by power switch drop out on hydraulic accumulator
Loss of Coolant Pump Pressure	Yes	Stow Full Array Shut off coolant pump	Energizes master stow relay Trips AC solenoid to coolant pump
Subfield Array Overtemp	Yes	Stow row containing sub- field array	Row is stowed by sensing subfield array outlet surface temp above 200°F
Wind or Precipitation	Yes	Stow Full Array	Full array is stowed in winds exceeding 70 mph or in the event of precipitation
Loss of Hydraulic Pressure	No	Warning to control Cut AC power to hydraulic pump	Indicates loss in ability to track or stow Indicates possible break in hydraulic line
Heat Exchanger Fan or Pump Failure	Does Not Apply	Warning indi- cator to control center	Indicates potential high coolant temp resulting in high array temperature

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In the operation of the STF, walkie-talkies were used as communication devices but were not altogether convenient, and thus a hard wire system was chosen as an improvement.

c. Data Acquisition

The final system design philosophy utilized by BDM totally separates the control and operations functions of the CAPVC system from data acquisition, analysis, and recording. In phase II, DOE will provide the data acquisition system with government furnished equipment (GFE), along with such peripheral devices as are required for the programming and operation of the ODAS; and, DOE will additionally provide such recording devices as are appropriate to their data, data management, and data access requirements.

The Department of Energy will also provide, as part of the ODAS, such signal conditioning devices as required to record the data which DOE and BDM agree is necessary for the successful operation of the Phase II and Phase III Applications Experiment. The signal conditioning devices required by BDM for system control will be specified and provided by BDM.

The data system and data file organization for phase II will be such that the Contractors Data Reduction Center may either request that recorded data be provided periodically on the GFE provided media or that the current data files be accessed via a dial-up MODEM. In this event, operating system software will be provided by the Data Reduction Center. This software will locate the data files of interest and transmit these data to the requesting agency. To the extent that MODEM's and/or Data Access Arrangement (DAA) devices are required, these will be provided by the Contractors Data Reduction Center.

d. Transducers

The transducers which form the basis of the data acquisition and control systems provide measurements of system coolant flow, temperature, and pressure as well as photovoltaic cell temperature, current and voltage. The AC power supplied by the utility and array are also monitored. Evaluation of the system, as well as the definition of

certain system safety parameters, depend on the monitoring of pertinent weather information. These transducers provide the level of information for both optimum system control as well as the satisfaction of the acquisition of data as defined by the uniform data collection requirements provided by DOE.

Table II-16 itemizes the measurements to be made during phases II and III of the CAPVC program.

Table II-17 provides specification and delivery data for the sensors to be used in phase II and III of the CAPVC demonstration program.

Figure II-92 presents the layout of the control and instrumentation system including the definition of the pertinent transducer locations.

1) Flow

The CAPVC design specifies the use of the Annubar probe with a National Semiconductor differential pressure transducer. This is based on the successful use of this equipment in the Solar Test Facility. Alternate flow measuring systems are still being evaluated which show promise as wide range linear measurement systems. The measurement of flow is, of course, critical to both the system operation and the characterization of the system heat transfer characteristics.

2) Temperature

The final design provides photovoltaic cell surface temperature measurements at the end of each of the 28 collector cooling rows. In addition, 28 coolant outlet fluid temperatures will be measured for continued correlation with the cell surface temperature measurements. Experience with the STF has shown that a total of four inlet coolant temperatures will be sufficient to characterize the collector coolant row inlet temperatures (28). Fluid temperatures on the heat exchanger and cooling tower systems will be measured for thermal energy computations.

All temperature monitors will be resistance temperature devices (RTD's). Experience with the STF indicates that a four wire Kelvin-type measurement will provide higher accuracy when utilizing the

TABLE II-16. CAPVC DATA MEASUREMENTS

CATEGORY	ITEM	MEASUREMENT	QUANTITY	Requirement Reference	Comment
Array and Subsystem Performance	1	Array Subfield Current	14	II.I.2 Page 22	Performance & Quality Control
	2	Array Field Voltage	2	II.I.3 Page 22	Same as Inverter Input Voltage II.II.1 Page 22
	3	Array Field Current	1	II.I.4 Page 22	Same as Inverter Input Current II.II.2 Page 22
	4	Subrow Surface Temperature	28	II.IV.8.1 Page 23	Subarray Safety - Overtemp Alarm
	5	Inlet Coolant Temperature	4	II.IV.8.2 Page 23	One at Each End of Two Inlet Manifolds Also Heat Exchanger Outlet Temp.
	6	Outlet Coolant Temperature	28	II.IV.8.3 Page 23	Subfield Array Performance
	7	Coolant Flow Rate	1	II.IV.8.4 Page 23	Array Performance, Efficiency, Safety
	8	Main Coolant Supply Pressure		BDM Requirement	System Safety -- Flow Loss Alarm
	9	Heat Exchanger Coolant Inlet Temp	1	II.VI.1 Page 24	H.E. ⁺ Efficiency, Maintenance (Provided by Builder)
	10	Heat Exchanger Coolant Outlet Temp	1	II.VI.2 Page 24	H.E. ⁺ Efficiency, Maintenance
	11	Potable Water Storage Temp	4	II.VI.7 Page 24	Status, System Safety
	12	Potable Water Inlet Temperature	1	II.VI.3 Page 24	Measure Energy Transfer to storage tanks
	13	Potable Water Outlet Temperature	1	II.VI.4 Page 24	Measure Energy Transfer to storage tank
	14	Heat Rejection Coolant Inlet Temperature	1	II.VI.5 Page 24	Measure Rejected Energy
	15	Heat Rejection Coolant Outlet Temperature	1	II.VI.6 Page 24	Measure Rejected Energy
AC Power System Performance	16	Inverter Output Voltage (3 Legs)	3	II.II.3 Page 22	Array/Inverter Efficiency & Performance
	17	Inverter Output Current (3 Legs)	3	II.II.4 Page 22	Array/Inverter Efficiency & Performance
	18	Inverter Output VARS, KWHRS	1	II.II.5 Page 22	Array/Inverter Efficiency & Performance
	19	Combined Load Voltage (3 Legs)	3	BDM Requirement	Total Building Load Measurement
	20	Combined Load Current (3 Legs)	3	BDM Requirement	Total Building Load Measurement
	21	Combined Load VARS, KWHRS	1	BDM Requirement	Total Building Load Measurement

*Requirements Reference From Table II of "Uniform Data Requirements and Data Collection Techniques"

⁺H.E. - Heat Exchanger

TABLE II-17. SPECIFICATION AND DELIVERY DATA FOR CAPVC SENSORS

DELIVERY (WEEK)	DESCRIPTION	MANUFACTURER	MODEL	TOTAL QUALITY	RANGE	OUTPUT
5	Fluid Temp	MINCON	S54 with F140 Fitting	42	0 to 150°F	676 Ω @ 25°C $\pm$ 0.5%
5	Surface Temp	MINCON	S1183BX	28	0 to 200°F	604 Ω @ 0°C $\pm$ 0.5%
8	Fluid Pressure	National Semi- Conductor	LX1720QF	1	0 to 100 psig	2.5 to 12.5 V
8	Differential Pressure	National Semi- Conductor	LX1701DDF	1	-5 psid to +5 psid	7.5 $\pm$ 5.0 V
6	Array Subfield Current	Dale	Precision Resistors	14	0 to 14A/0.05 Ω $\pm$ 0.5%	0 to 0.7 V: 14A
6	Array Field Current	Dale	Precision Resistors	1	0 to 190A/0.01 Ω $\pm$ 0.5%	0 to 1.9 V: 190A
-	Array Field Voltage	-	-	2	0 to 350 V _{DC}	Voltage to GFE ODAS
16	AC Voltage	SANGAMO	45461	6	480 V _{AC}	GRAPHIC
16	AC Amperage	SANGAMO	39172	6	0 to 100 A _{AC}	GRAPHIC
20	kWHRS, VARS	SANGAMO	58891	1	0 to 100 kW 0 to 200 KVARs	GRAPHIC
20	kWHRS, VARS	SANGAMO	58891	1	0 to 600 kW 0 to 1200 KVARs	GRAPHIC

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long wire runs required to go from the roof to the GFE data acquisition system. Since the GFE data acquisition system is capable of four wire resistance measurements, it will be used to make the temperature measurements.

The exception to the above measurements will be the output surface temperature measurements. Since these signals are to be used in the safety control system, the output of these RTD's will be buffered and amplified on the roof. A single ended voltage, proportional to the resistance (temperature) of the RTD, will be routed to the GFE data acquisition system for measurement.

3) Pressure

The final design includes the measurement of the main coolant supply pressure at the coolant pump discharge. This pressure will be used for closed loop warning of abnormal pump or fluid path operation, as interpreted through the high or low pump discharge pressure. Coolant flow problems in the individual collector coolant rows (28) will be detected through the closed loop safety circuitry associated with the collector outlet temperature. This is a simplification over the BDM STF installation, where four fluid pressure measurements were used to characterize the system.

4) Current

Fourteen subfield current measurements have been identified. In this case, a subfield is defined as a complete 120-foot collector row consisting of two parallel PV strings. The two strings are not identified independently since they are wired together at the end of the collector row. The measurements are designed to be made utilizing current shunts in the main DC power junction box at the array site. A total array field current is measured using a current shunt at the input to the inverter in the Control Center. The output current of each subfield array has a current shunt to ground so that a single ended voltage measurement across the shunt will be made. A single wire from each current shunt is brought down from the roof to the GFE data acquisition

system. All measurement lines are shielded to reduce noise pickup. The total current measurement shunt is floating and therefore requires a differential voltage measurement across the shunt. A shielded twisted pair is run from the roof to the GFE data acquisition system for this measurement.

Each array row contains two PV cell rows. These are located on two adjacent portions of the collector tube. To allow electrical isolation of a collector, a switch has been placed in the power circuit at each end of each row.

The STF utilized an identical approach to current measurement which proved simple and successful, and thus provides a high degree of confidence in this design.

5) Voltage

The CAPVC has been designed such that all array subfields are in parallel. Thus, the array subfield voltages are all equal and are additionally identical to the array field voltage. The array subfield currents will therefore be used in conjunction with the array field voltage to monitor the power developed by each subfield array. To account for line losses, a second array field voltage measurement was included in the Control Center at the input to the inverter.

Voltage measurements at the specified points are made using the GFE data acquisition system voltage measurement capability. Since the GFE data acquisition system is capable of voltage measurements to 1000 volts, no preconditioning is necessary. A single wire from the measurement point (plus the ground wire) is brought down from the roof to the GFE data acquisition system.

Experience in direct voltage measurements was obtained in the operation of the STF where single wire (plus ground) voltage measurements were made directly by the data acquisition system.

6) AC Measurements

The final design provides for measurements of the AC power system associated with the CAPVC building at three locations: 1) at the PNM supply to the building, 2) at the array inverter output,

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and 3) downstream of the point at which the inverter output is joined to the PNM supply. Total building load will be measured in that way, and the allocation of this load between the two power sources and any associated losses will also be measured. Instruments have been defined and include commercial grade chart recording meters for AC volts, amperage, kilowatt hours and VARS.

7) Weather Station

A complete GFE weather station will be provided by the Department of Energy. The instrumentation and control systems of CAPVC have provided for the inclusion of this addition in their designs. Complete information on this system has not been made available. However, through experience gained in operating the STF weather station, it is expected that this system will include the following items:

- (1) Pyranometer (total hemispherical insolation)
- (2) Pyrhelimeter (direct insolation)
- (3) Ambient temperature
- (4) Wind velocity and direction
- (5) Barometric pressure
- (6) Relative humidity
- (7) Rain indication

CHAPTER III
SYSTEM PERFORMANCE PROJECTIONS

A. APPROACH AND RATIONALE

The primary objectives of the system performance analysis were to, 1) predict array system performance, 2) predict percent of load displaced and 3) predict the cost of power from the array. In order to meet these objectives, the operational aspects of the CAPVC system were completely defined. Once this was accomplished, the system was analyzed using a computer simulation program.

The key elements of the CAPVC system which were addressed in the analysis included weather, electrical load, collector orientation, shadowing, component definition, and operation and performance. Each of these areas were carefully defined during the initial stages of the analysis.

The performance and cost projections were then carried out using the SOLCEL* computer code. SOLCEL is a computer simulation code which was selected for the CAPVC program system analyses because of its ability to simulate photovoltaic systems. Due to certain unique features of the CAPVC design, it was necessary to implement some code modifications to assure accurate modeling of the system.

B. SOLCEL

The SOLCEL computer program was used to project the CAPVC arrays' performance. SOLCEL was specifically designed for photovoltaic systems analysis and design optimization. This capability is ideally suited for analyzing the CAPVC performance. SOLCEL simulates the PV system by modeling each component, collector orientation, cell temperature, cell efficiency, power conditioning, etc. It is driven by hourly data of insolation and electrical load. SOLCEL essentially tries to meet the

*Photovoltaic Systems Analysis Program - SOLCEL Author J. K. Linn, SAND 77-1268, August 1977.

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load each hour with all of the available insolation. Then after a year of simulation, it lists out the performance statistics.

The CAPVC system has some unique characteristics in its design which necessitated the development of additional models in SOLCEL. These models are end shadowing and the Westinghouse inverter. Also, modifications were necessary to improve output, to improve the heat transfer model, and to add the applicable utility rate structure in SOLCEL. These areas are discussed in more detail in the following paragraphs.

The end shadow model was developed to simulate the effect on electrical performance of diode circuitry protection as the end shadow (or gap shadow) passes over several cells on a receiver tube. Figure III-1 illustrates this phenomena. This end shadow model represents shadowing at either the end of a collector row (end shadow) or the shadow caused by gaps between adjacent collector mirror modules (gap shadow). Both situations are represented by an identical equation and thus can utilize a single model. As the sun angle varies from the normal to the collector, a shadow is cast on the receiver tube. This shadow varies in intensity depending on the focal length. Figure III-2 shows the incident light profile on the receiver tube caused by end and gap shadowing. The equation defining this phenomena is discussed in detail in appendix D. The impact of this phenomena on the system performance is discussed in the section on SOLCEL results.

The existing inverter model was modified with an inverter algorithm developed by Westinghouse to represent their 50kW inverter, which was included in the CAPVC system design. The new algorithm was input to improve and update the existing SOLCEL algorithm specifically for this application. It should be noted that the current algorithm in SOLCEL did not include parasitic losses at low efficiencies which has been included in the new model. A further description of the model is provided in appendix D.

In order to model the heat transfer accurately, the convection coefficient was adjusted until the cells were performing at the cell temperatures measured by the Solar Test Facility. This required several runs with SOLCEL to determine a similar heat transfer coefficient.

Figure III-1. Illustration of End Shadowing of a Collector

Figure III-2. End and Gap Shadowing

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With the added software changes, additional output printing was added to SOLCEL to improve debugging and readability. A plot package was also added. These provided access to more information defining the CAPVC system performance.

Software was added to model the utility rate schedules from PNM. This provided a way to determine the cost to the user of the energy displaced by the array.

With the preceding modifications, the load data and the insolation data, SOLCEL was used to determine the performance and cost of power from the CAPVC system. In summary, these new model changes improved SOLCEL's capability to more accurately model a line focus concentrator system.

C. DATA REQUIREMENTS

1. BDM Building Electrical Load Profile

With no measured data available from the building upon which the array will be located, a significant effort was made to characterize and model the electrical load profile for this new building. Figure III-3 illustrates the three basic steps used to generate 365 days of electrical load.

The first step in generating a load profile was to find available measured data for an office building of a similar size and structure. The Public Service Company of New Mexico (PNM) had measured power data (kW at 15 minute intervals for 365 days) for nine office buildings in the Albuquerque area. The Plaza Del Sol National Bank (PDS) building was chosen as having the best daily load profile match-up to our load. Additionally, PNM put a Westinghouse Research package on our present building for a period of two months to record electrical power consumption at 15 minute intervals. This data was collected and put on magnetic tape and sent to our computer for reduction. Figure III-4 illustrates a comparison between BDM's present load and PDS's load profile. BDM's current load shows a very high base load at night but this will be reduced with a microcomputer system controlling lighting, heating and air conditioning loads in the new building. Since the amplitude of the peaks are not the same, the

- OBTAIN LOAD AND PEAK DEMAND INFORMATION ON SIMILAR BUSINESS ENVIRONMENTS

- USE TRANE CODE TO SIMULATE COOLING AND HEATING LOAD

- GENERATE FACTORS TO TRANSFORM PDS DEMAND CURVE TO CAPVC DEMAND CURVE

- CAPVC LOAD PROFILE (365 RECORDS)

Figure III-3. CAPVC Projected Building Load Profile Analysis

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Figure III-4. Comparison of PDS and BDM Load Profiles in September

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amplitude of the peak and the nighttime base load were scaled to represent the characteristics of the proposed CAPVC building.

The second step was to determine how to scale the PDS load profile to be utilized in approximating the BDM load profile. This was done by acquiring data to determine what the monthly peak loads are. Monthly peak loads were acquired from PNM for the present BDM building. These peaks were scaled up to the new building by compiling an equipment schedule for the present and new building. Table III-1 shows how the building loads were scaled by using the equipment schedules and square footage ratios between the buildings. This peak for the CAPVC building was used to scale up the peak loads from the present building. This produced a peak of 376.5 kW for the year. Since it was not expected that the heating and air conditioning loads would scale linearly, due to the energy conservation features included in the new building, another approach was taken. The TRANE computer code was run to model the new building load with all of the energy saving features. Table III-2 illustrates the results from this analysis. This approach reduced the projected peak load to 330 kW. This load analysis was combined with the billing loads peak to generate the projected peak loads of the CAPVC building. Figure III-5 illustrates the resultant monthly peak loads.

The final step combined the measured PDS data with the monthly CAPVC peak loads by scaling the measured data each month. This was done so that each month would have a corresponding peak load that was equivalent to the monthly peak loads shown at the bottom of Table III-2. The base load was also input for nights, half the day on Saturday and all day Sunday.

The base load was established by adding a minimal air conditioning load, a pumping and fan power for heating requirements from storage, and by adding a small percent for lighting and miscellaneous loads.

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TABLE III-1. EQUIPMENT SCHEDULE FOR BDM BUILDINGS

LOAD AND SCALE FACTORS FROM BUILDING 1
TO CAPVC BUILDING

LOAD	FACTOR	BLDG 1 (25,480 SQ. FT.)	CAPVC BLDG (70,000 SQ. FT.)
1) LIGHTING	.92 W/SQ.FT.	23.4 kW	64.4 kW (57.3)*
2) HEATING/AIR COND.	8.17 W/SQ.FT.	208.2 kW	572 kW (405)**
3) HOT WATER HEATING	.000392 W/SQ.FT.	10.0 kW	27.5 kW
4) COMPUTER EQUIP.		5.98 kW	9.66 kW
5) PUBLICATIONS			
a) PRESS ROOM		34 kW	51 kW
b) TYPEWRITERS		10.125 kW	27.84 kW
c) PHOTOLAB		11.6 kW	17.4 kW
6) EMPLOYEE LOUNGE		1.64 kW	2.5 kW
7) ELEVATORS		0	40.0 kW
	MAX PEAK POSSIBLE LOAD FACTOR	304.986 kW (X .59)	638.2 kW X .59
	PEAK	180.0 kW	376.5 kW

* COMPUTED WITH AN 11 PERCENT ENERGY SAVINGS FACTOR

** COMPUTED WITH A 30 PERCENT ENERGY SAVINGS FACTOR

TABLE III-2. RESULTS OF THE TRANE COMPUTER CODE

ELECTRICAL EQUIPMENT SCHEDULE FOR THE TRANE CODE	MONTH OF YEAR											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
115 TON CHILLER			44.5	62.5	81.8	93.2	101.6	90.0	83.5	66.6		
CHILLED WATER PUMP			3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3		
CONDENSER FANS			8.3	12.5	12.5	12.5	12.5	12.5	12.5	12.5		
CONTROLS	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
ELECTRIC RADIATION	73.1	47.1	29.3	9.4						11.3	27.3	61.4
SUPPLY FAN	21.2	25.2	27.5	33.3	26.3	28.8	30.2	26.8	26.4	23.9	25.5	22.4
RETURN AIR FAN	4.4	5.2	5.5	6.3	5.4	5.7	6.0	5.4	54.0	4.9	5.2	4.7
LIGHTS	98.0	98.0	98.0	98.0	98.0	98.0	98.0	98.0	98.0	98.0	98.0	98.0
MISCELLANEOUS	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0
TOTAL PEAK LOAD	275.0	254.0	295.0	304.0	306.0	302.0	330.0	315.0	308.0	299.0	235.0	265.0
NIGHT TIME BASE LOAD	7.3	5.0	3.5	2.6	2.4	2.5	2.5	2.4	2.4	3.3	5.1	7.6
SCALED BILLING STATEMENT PEAKS FROM BDM BUILDING 1	264.0	244.0	211.0	267.0	304.0	277.0	330.0	320.0	287.0	287.0	241.0	264.0
MONTHLY PEAK LOADS USED TO SCALE THE PDS LOAD	270.0	249.0	295.0	304.0	304.0	299.0	330.0	318.0	298.0	293.0	238.0	265.0

Figure III-5. Monthly Projected Peak Load

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This work resulted in generating 365 daily projected load profiles for the CAPVC building, which include all of the energy saving features designed into the building. Figure III-6 illustrates a typical daily peak load for the CAPVC building.

2. Weather Data

Weather data was acquired from the Sandia tape library of SOLMET typical meteorological year data. This data for one year (12 typical months) was derived from 26 years of measured data (weather conditions and available insolation) for the Albuquerque area. This data was used as the input for the SOLCEL computer program to calculate the power available from the array.

3. System Description

The CAPVC system design characteristics were described in detail for SOLCEL input in order to simulate the PV system. Major system data inputs included:

- Array orientation
- Concentrator geometry
- PV Cell geometry (active area)
- Cell temperature
- Cell efficiency
- Thermal cooling system
- Inverter efficiency
- Diode protection scheme

Final performance projections were based on the final system design as described in detail in chapter II of this report.

D. SYSTEMS ANALYSIS RESULTS

1. System Performance

Extensive system performance studies of the CAPVC system were carried out throughout the phase I design effort. A significant portion of this work was directed towards the selection of the optimum array

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Figure III-6. Typical Daily Peak Load

orientation. The results of these studies are presented in section II.B.1.d. The following discussion addresses the final system design, which includes the selection of an all north/south array.

Figure III-7 illustrates the performance of the all N/S array on a sunny day in the summer. This plot shows 15 percent peak shaving and a 15 percent load displacement. However, this system does not necessarily shave peaks all the time as shown in the results presented in figure III-8. Actually it was projected that the array would shave 8 out of 12 monthly peaks. The overall annual performance of the array is illustrated in table III-3 where approximately 12 percent of the annual load was displaced by the CAPVC array. Based on the PV power supplied by the system versus the insolation collected, it can be observed that the overall efficiency of the collectors, which includes optical efficiency, cell efficiency, and packing factor, was 7.8 percent.

Based on results from the Solar Test Facility, the overall array efficiency was calculated to be 7.53 percent as shown in table III-4. These results also predicted a peak power output from the array of 47 kW. This corresponds to the peak shown in figure III-7 from SOLCEL results of 48 kW. Both sets of figures from the Solar Test Facility and SOLCEL are within 4 percent of each other and show good agreement.

2. Cost Projections

a. Cost Of Electricity From The Utility Company

Before considering the cost of power from the CAPVC system, a reference point was derived by calculating the cost of energy from the utility power company (Public Service Company of New Mexico, PNM). This was accomplished by incorporating three utility rate schedules from PNM into SOLCEL. The first is the current rate schedule being used by BDM. The second schedule is a proposed seasonal variation in peak demand charge and energy charge. The third schedule is a proposed time of day pricing. All three schedules contain five basic charges.

- (1) Monthly system charge - \$10/month.
- (2) Peak demand charge - \$3.85/kW peak.
- (3) Energy charge - 1.4¢/kWh.
- (4) Fuel and purchase power cost adjustment - table III-5.
- (5) Cost of service index adjustment - table III-5.

Figure III-7. Typical Summer Day Peak Load and Collector Profile

Figure III-8. Partial Peak Shaving

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TABLE III-3. FINAL SOLCEL RESULTS

	POWER (MWH)
AVAILABLE INSOLATION	1631.6
INSOLATION COLLECTED	1323.4
END AND GAP SHADOWING	3.2
ARRAY POWER	103.2
PV SYSTEM POWER SUPPLIED	95.9
INTERNAL POWER REQUIRED	3.0
TOTAL LOAD FOR CAPVC BUILDING	789.9

TABLE III-4. ARRAY EFFICIENCY CALCULATIONS WITH SOLAREX CELLS

$$\epsilon_A = \epsilon_R \times \epsilon_I \times \epsilon_{CELL} \times \epsilon_T \times PF$$

where

ϵ_A = Array Efficiency

ϵ_R = Specular Reflectance = 0.84

ϵ_I = Intercept Factor = 0.87

ϵ_{CELL} = Cell Efficiency (Microglass and Conversion)
= 12.54% @ 55°C

$$\epsilon_T = \text{Temperature Effect} = \frac{V_{OC}(@ 55^\circ\text{C}) - (T_0 - 55^\circ\text{C})(2.1 \text{ mV})}{V_{OC} @ 55^\circ\text{C}}$$

PF = Overall Packing Factor = .870 (22 Cell Module)
(Includes shadow area at V of receive tube) = .672 (17 cell module)

POWER = Insolation (D.N) x Cosine Factor x A_{AP} x ϵ_A

$\frac{22 \text{ Cell Module}}{(1/2 - \text{Aperture})}$

$\frac{17 \text{ Cell Module}}{(1/2 - \text{Aperture})}$

$\epsilon_A = 7.98\%$

$\epsilon_A = 6.17\%$

$P_{22} = 1000 \text{ w/M}^2 \times 1.0 \times .929 \text{ m}^2 \times 0.0798$
= 74.13 watts

$P_{17} = 1000 \text{ w/M}^2 \times 1.0 \times 929 \text{ m}^2 \times 0.0617$
= 57.32 watts

No. of 22 cell modules = 504

NO. of 17 cell modules = 168

$$\epsilon_A = \frac{7.98(504) + 6.17(168)}{672} = 7.53\%$$

Total Array Power (Peak) = 46.99 kW_p
= 47.0kW_p

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TABLE III-5. ESTIMATED ADJUSTMENT FACTORS

FUEL ADJUSTMENT FACTORS FORECAST

	FACTOR \$/kwh
SEPTEMBER - DECEMBER 1978 AVERAGE	\$.009764
AVERAGE FACTOR FOR 1979	\$.009976

COST OF SERVICE INDEX FACTOR FORECAST

<u>MONTHLY FACTOR APPLIED</u>	FACTOR \$/kwh
JULY 1978	\$.012329
AUGUST 1978	.010390
SEPTEMBER 1978	.010390
OCTOBER 1978	.010390
NOVEMBER 1978	.011210
DECEMBER 1978	.011210
JANUARY 1979	.011210
FEBRUARY 1979	.017010
MARCH 1979	.017010
APRIL 1979	.017010
MAY 1979	.020730
JUNE 1979	.020730
JULY 1979	.020730
AUGUST 1979	.021690

All listed costs are for the current schedule. With this utility rate schedule, SOLCEL was used to read the load data and calculate the total cost of energy consumed from the utility for the CAPVC Building. Table III-6 illustrates the cost comparison between three utility rate structures and it gives a base by which a comparison can be made between the cost of power from the utility and the cost of power from the CAPVC system. It also shows how much the total displaced energy would cost.

b. Cost Of Energy From CAPVC Array

The cost of power from the CAPVC array was determined for both utility and private ownership. This was accomplished using the ERDA/EPRI cost model* included in SOLCEL, which is commonly used for utility ownership calculations, but which can also be modified to handle other types of ownership by changing the appropriate input parameters.

The DOE provided utility ownership cost input parameters, which were somewhat different than the actual values which would define ownership by PNM. A comparison of these input parameters along with a definition of the private ownership parameters is presented in table III-7. The private ownership inputs were modified from the PNM numbers to reflect a local corporation's financial status. Note that a tax credit was included in the corporation input.

Computer runs were made for each of these cases and the results are presented in table III-8. It should be noted that in generating these values, SOLCEL makes the assumption that the annual load and insolation data are the same for the life of the system.

* "The Cost of Energy from Utility-Owned Solar Electric Systems," JPL 5040-29, ERDA/JPL-1012-76-3, June 1976.

TABLE III-6. COMPARISON OF UTILITY RATE SCHEDULES (1979 DOLLARS)

	COST OF ELECTRICAL POWER FOR CAPVC BUILDING	COST OF POWER DISPLACED IN FIRST YEAR
PRESENT UTILITY RATE SCHEDULE	6.14¢/kWh	\$5,864
SEASONALY ADJUSTED SCHEDULE	6.05¢/kWh	\$5,778
SEASONAL AND TIME OF DAY ADJUSTED	6.33¢/kWh	\$6,045

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TABLE III-7. INPUT PARAMETERS TO THE ERDA/EPRI
COST METHODOLOGY

INPUT PARAMETERS	DOE	PNM	PO*
SYSTEM OPERATING LIFETIME	20	20	20
ANNUAL "OTHER TAXES" AS A FRACTION OF CAPITAL INVESTMENT	.02	.03	.03
ANNUAL INSURANCE PREMIUMS AS A FRACTION OF CAPITAL INVESTMENT	.0025	.0025	.0025
EFFECTIVE INCOME TAX RATE	.50	.3312	.3312
RATIO OF DEBT TO TOTAL CAPITALIZATION	.5	.5	.75
RATIO OF COMMON STOCK TO TOTAL CAPITALIZATION	.4	.35	.25
RATIO OF PREFERRED STOCK TO TOTAL CAPITALIZATION	.10	.15	-
ANNUAL RATE OF RETURN ON DEBT	.10	.09	.09
ANNUAL RATE OF RETURN ON COMMON STOCK	.12	.14	.20
ANNUAL RATE OF RETURN ON PREFERRED STOCK	.10	.09	-
RATE OF GENERAL INFLATION	.07	.07	.07
ESCALATION RATE FOR CAPITAL COSTS	.07	.07	.07
ESCALATION RATE FOR OPERATING COSTS	.07	.07	.07
ESCALATION RATE FOR MAINTENANCE COSTS	.07	.07	.07
BASE YEAR FOR CONSTANT DOLLARS	1975	1975	1975
ESCALATION RATE FOR FUEL COSTS	.10	.10	.10
FIRST YEAR OF COMMERCIAL OPERATION	1980	1980	1980
TAX CREDIT	-	-	.10

*PRIVATE OWNERSHIP

TABLE III-8. COST OF ELECTRICAL POWER FROM A UTILITY
OWNED OR PRIVATELY OWNED ARRAY

CAPVC CURRENT COST OF ELECTRICAL POWER

	<u>BASE YEAR</u>	<u>LEVELIZED BUSBAR ENERGY COST (¢/kwh)</u>	<u>BUSBAR ENERGY COST AT BEGINNING OF OPERATION(¢/kwh)</u>
PNM PARAMETERS	1975	94.3	52.2
DOE PARAMETERS	1975	97.5	53.0
PO PARAMETERS	1975	87.4	48.7

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CHAPTER IV INSTITUTIONAL/ENVIRONMENTAL ASSESSMENT

A. INTRODUCTION

During the phase I CAPVC program and the parallel development of BDM's Solar Test Facility, BDM has addressed the institutional and environmental issues which would have an impact on the CAPVC phase II and III programs. The specific impacts on the CAPVC of codes and ordinances, financial and taxation policies, insurance and liability, and environmental effects were assessed to guarantee that no institutional barriers were present. Each issue was examined from two aspects - first the direct impacts on the CAPVC program were determined, then the potential impacts on the long-term commercialization of PV systems were examined. The CAPVC program can make a substantial contribution to future PV applications by providing information on specific issues that may have impact on policy development. The major institutional interactions, impact areas, and CAPVC contributions are presented in figure IV-1. Data collected through operation and evaluation will be used to address these institutional concerns.

Federal, state, and local governments have a key role in encouraging commercialization through legislation and incentives. Figure IV-2 details the states which have passed legislation relating to solar energy. The State of New Mexico has been one of the leaders in the development of solar legislation.

National standards and professional organizations are also involved. These and the other factors which will affect commercialization of PV systems are discussed in each section.

B. CODES AND ORDINANCES

Codes, ordinances and standards will play a crucial role in the commercialization of PV systems. Insurance companies and financial institutions rely on codes, ordinances, and standards for guidelines in

Figure IV-1. Institutional Interactions

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STATE ACTS RELATING TO SOLAR ENERGY 1974 - 77	TAX INCENTIVES			EASEMENTS & ZONING	STANDARDS AND/OR CERTIFICATION	CODE PROVISIONS	PROVIDE STATE PROMOTION, INVESTIGATION OR R & D	STATE BUILDINGS TO USE SOLAR	LIFE CYCLE COST ANALYSES AND FEASIBILITY OF NON- FOSSIL FUEL IN STATE OWNED/ASSISTED BUILDINGS	SOLAR LOANS	UTILITIES & SOLAR
	REAL PROPERTY	INCOME	SALES								
Alabama											
Alaska		★							•		
Arizona	•		★				•				
Arkansas		★					•				★
California	★	•			★	•	•	★	★		•
Colorado	•	★		•			•		•		
Connecticut	•		★		•						
Delaware											
Florida					•	•	•		•		
Georgia	•		•				•				
Hawaii	•	•					•		★		★
Idaho		•									
Illinois	•						★		★		★
Indiana	•										
Iowa							•	★			
Kansas	★	•		★					•		
Kentucky							•				
Louisiana											
Maine	★		★				•				
Maryland	•			★			•				
Massachusetts	•	•							•	★	
Michigan	•		•				•				
Minnesota					•				★	★	
Mississippi											
Missouri											
Montana	•	★					•				
Nebraska									★		
Nevada	★						•				
New Hampshire	•										
New Jersey	★				★						
New Mexico	★	•	★	★	★	★	★	★	•	★	★
New York	★				★		•				
North Carolina	★	★					•		•		
North Dakota	•	★		★							
Ohio							•				
Oklahoma		★							★		★
Oregon	•	★		•	★		★			★	
Pennsylvania											
Rhode Island	★						•				
South Carolina											
South Dakota	•										
Tennessee											
Texas	★		•				★		★		
Utah							★				
Vermont	•										
Virginia	•				★		•				
Washington	★				★		•		•		
West Virginia											
Wisconsin		★			★						
Wyoming											
Totals	27	16	6	6	11	2	25	2	15	3	5

• 1974 - 1976 LEGISLATION

SOURCE: CENTER FOR BUILDING TECHNOLOGY -MBS

★ 1977 LEGISLATION

Figure IV-2. State Acts Relating to Solar Energy

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the assessment of risk. Designers and manufacturers rely on them for systems development guidelines. Users rely on them as indicators of product reliability and safety. Legal institutions will rely on system compliance with codes, ordinances, and standards to protect consumers and establish both product and professional liability.

1. Codes

The effects of codes, ordinances, and standards on the design and acceptance of distributed PV systems is not yet thoroughly understood, due to the limited number of systems that have been fielded. Although much work has been done in the solar thermal area, limited assessment has been done for PV systems. While model codes and standards exist for thermal systems, their applicability to PV systems is limited because of the electrical aspects and very distinct differences in physical composition. It is essential that these issues and impacts are addressed early to minimize future conflicts and enhance commercialization.

Even though many of these issues are specific to a locality, a large number of local and national organizations are involved, and the trends in national, state, and local adoption and enforcement need to be identified. Model codes are developed by national code-writing organizations, such as those listed in figure IV-3. They are adopted or modified by local governmental bodies to suit regional requirements. As such, the codes define the actual system construction requirements, designating minimum standards. For a system to become operational, it must be inspected by a local official and found to be in compliance with the applicable code. Although several of the model code-writing bodies have addressed solar thermal issues, no national model photovoltaic codes exist.

BDM addressed the existing code requirements in the design of its CAPVC project and STF (Solar Test Facility). In these designs, BDM followed the applicable codes of the State of New Mexico to insure compliance. These included the Uniform Building Code, the Uniform Plumbing Code, and the Uniform Solar Plumbing Code. In the final design of the system, BDM incorporated the requirements of the National Fire Protection Association for fire protection and NEMA standards for electric motors.

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CODE	SOURCE
THE UNIFORM BUILDING CODE (UBC)	INTERNATIONAL CONFERENCE OF BUILD- ING OFFICIALS WHITTIER, CALIFORNIA
THE NATIONAL BUILDING CODE (NBC) AND THE FIRE PREVENTION CODE	RECOMMENDED BY THE AMERICAN INSURANCE ASSOCIATION
THE SOUTHERN STANDARD BUILDING CODE (SSBC)	SOUTHERN BUILDING CODE CONGRESS BIRMINGHAM, ALABAMA
THE BASIC BUILDING CODE (BBC) THE BASIC FIRE PREVENTION CODE THE BASIC HOUSING CODE	BUILDING OFFICIALS AND CODE ADMINISTRATORS INTERNATIONAL CHICAGO, ILLINOIS
THE NATIONAL FIRE CODES AND THE NATIONAL ELECTRICAL CODES	INTERNATIONAL FIRE PROTECTION ASSOCIATIONS NFPA BOSTON, MASSACHUSETTS
THE UNIFORM PLUMBING CODE AND THE UNIFORM SOLAR PLUMBING CODE	INTERNATIONAL ASSOCIATION OF PLUMBING AND MECHANICAL OFFICIALS, LOS ANGELES, CALIFORNIA

Figure IV-3. Model Codes and Code Writing Organizations

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The electrical and plumbing systems of the STF were inspected by local building inspectors and found to be in compliance with applicable codes. The STF uses the same collector and similar wiring and plumbing schemes as will be used in the CAPVC.

Codes may also require that licensed electricians and plumbers install PV systems. This will lead to the involvement of unions in insuring that the systems they install are approved for safety by a national certification organization such as UL.

2. Ordinances

Ordinances can affect a wide range of issues involving the design, installation, and operation of PV systems. Issues such as solar access, aesthetics of collectors, licensing and certification, and zoning must be considered.

Solar rights, or access to solar energy, is a relatively new legal problem. A number of methods have been suggested for providing access to solar energy for solar collector owners. These include easements, restrictive covenants, transferable development rights, prior appropriation, shade control, municipal acquisition of solar rights, permit systems, nuisance law, and zoning.

Zoning is presently emerging as the principal long-term tool for the protection of solar access. The Environmental Law Institute has prepared a comprehensive study of the solar rights problem. It is highly favorable to zoning. In addition, at least three model solar zoning ordinances have been written. The first was done by Owen et al. and is part of a report entitled "Santa Clara, California, Community Center, Commercial Solar Demonstration: Legal Alternatives, Implications, and Financing of Solar Heating and Cooling by a Municipal Corporation," available from NTIS under the number SAN/1083-76/1. The second was prepared by the City Planning Commission of Los Angeles as City Plan Case No. 26110, dated January 13, 1977. The third was prepared by Einsenstadt, Long and Utton and is NMEI Report No. 76-103. It is available from the New Mexico Energy Institute, University of New Mexico, Albuquerque, and will soon appear in the Urban Law Annual.

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Some communities already have solar zoning in place. These include Davis and Century City (California); Colorado Springs, Pitkin County, and Indio (Colorado); and Los Alamos (New Mexico). Other communities are giving it serious consideration: Santa Clara and Los Angeles (California), Toronto (Ontario, Canada), and Albuquerque (New Mexico).

BDM examined state and local regulations governing zoning, solar access, and aesthetics for effects which would have impact on the CAPVC program. The State of New Mexico has passed legislation (NM Statutes 70-8-1 to 70-8-5, the Solar Rights Act) which declares the right to solar energy as a property right and recognizes the precedence of prior appropriation, that is, of first possession of that right. In addition, the City of Albuquerque is considering proposed zoning regulations to protect solar access by limiting the height and placement of structures. The regulations would establish planes at 30- and 45-degree angles above the horizontal and along boundaries or centerlines which are north, east, or west of premises respectively (See figure IV-4, which shows the current zoning regulations.). By attending zoning meetings and providing comments on the approach, BDM has been working directly with City zoning officials in the development of these regulations.

Protection of solar access is also determined by the location of the CAPVC building. BDM's new office headquarters complex, which will house the CAPVC experiment, is located in a 60-acre industrial park owned by the Craddock Development Corporation. Craddock, a team member of the CAPVC program, has agreed to protect solar access by the placement of structures within the park. The BDM complex will occupy approximately 12.0 acres in the park; figure IV-5 shows the location of the building. BDM's location is enclosed entirely within the industrial park and does not border the residential area to the northwest or the commercial areas to the northeast.

In addition, BDM has conducted a thorough computer analysis using the Shade Structures Program to determine whether or not any objects external to the array, such as proposed buildings within the park or bordering the area, would cast shadows during any time of the year. There is no shadowing problem throughout the year from existing or planned structures.

height REGULATIONS in: R-2

IV-8

Figure IV-4. Current Zoning Regulations

all numbers except the 26 feet can vary depending on lot size and location

Figure IV-5. Location of CAPVC Site and Current Zoning

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Standards are set at the national level by organizations such as those listed in figure IV-6. The effectiveness of these standards is contingent upon industrial and consumer acceptance. Standards may adversely affect the PV market when serious delays are experienced in certifying a design or meeting an excessive requirement, which adds to system cost. The recent Department of Housing and Urban Development experience is a good example of the effect that time delays have on Federal incentive programs. A limited number of testing laboratories were designated to certify collectors. The volume of request for certification overwhelmed the system.

Although no standards have yet been developed for PV systems, much work has been done in the solar heating and cooling area. The published solar heating and cooling standards and performance criteria are detailed in figure IV-7 and have been included in this report for reference.

C. FINANCIAL AND TAXATION POLICIES

The effects of financial policies of institutions and the taxation policies of national, state, and local governments are primarily applicable to the long-term commercialization of photovoltaic systems, and will be discussed with their specific impact on CAPVC.

1. Financial

The availability of financing is a critical issue for the commercialization of PV systems, since residential, commercial, and industrial users will be dependent upon commercial loans for the substantial portion of funds for these systems. The identification of risk is a key concern, of course, of all lending institutions; and, although financing criteria have been established for a wide range of consumer and industrial loans where the risks are well established, financial institutions have no historical basis for assessing the risks of PV systems because of the limited number of systems which have been fielded. Consequently, in financing PV systems, a greater portion of risk will be transferred to the loan applicant, resulting in higher percentage interest

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ORGANIZATION	RESPONSIBILITIES
AMERICAN NATIONAL STANDARDS INSTITUTE - ANSI	COORDINATES ACTIVITIES OF OTHER STANDARD ORGANIZATIONS.
AIR CONDITIONING AND REFRIG- ERATION INSTITUTE - ARI	FORMED ARIF (AIR CONDITIONING AND REFRIG- ERATION INSTITUTE FOUNDATION) FOR DEVELOPING PROCEDURES FOR CERTIFYING COLLECTORS UNDER NBS CONTRACT.
SOLAR ENERGY INDUSTRIES ASSOCIATION - SEIA	FORMED SEREF (SOLAR ENERGY RESEARCH EDU- CATION FOUNDATION) FOR ADMINISTERING THE ABOVE CERTIFICATIONS UNDER DOE CONTRACT.
AMERICAN SOCIETY FOR HEATING REFRIGERATION AND AIR CONDI- TIONING ENGINEERS - ASHRAE	DEVELOPED METHODS FOR TESTING SOLAR COLLEC- TORS AND THERMAL STORAGE ASHRAE-93-77 AND 94-77.
AMERICAN SOCIETY FOR TESTING MATERIALS - ASTM	DEVELOPED PERFORMANCE TESTS FOR MATERIALS AND COMPONENTS.
NATIONAL BUREAU OF STANDARDS - NBS	GOVERNMENT LABORATORIES WHICH INITIATE STANDARDS AND TESTING PROCEDURES SUCH AS INTERIM PERFORMANCE CRITERIA FOR DOE AND MINIMUM PROPERTY STANDARD FOR HUD.
UNDERWRITERS LABORATORIES INC. - UL	IS DRAFTING SAFETY STANDARDS FOR COLLECTORS.
AMERICAN SOCIETY OF MECHANICAL ENGINEERS UNITED ENGINEERING CENTER - ASME	DEVELOPING TEMPERATURE AND PRESSURE STANDARDS FOR PIPING AND PRESSURE VESSELS.
SHEET METAL AND AIR CONDITION- ING CONTRACTORS NATIONAL ASSOCIATION - SMACNA	DEVELOPED INSTALLATION STANDARDS FOR AIR COLLECTORS.
INTERNATIONAL ASSOCIATION OF PLUMBING AND MECHANICAL OFFICIALS - IAPMO	ISSUED UNIFORM SOLAR ENERGY CODE WHICH HAS BEEN ADOPTED BY SEVERAL JURISDICTIONS AS PLUMBING CODE FOR INSTALLING LIQUID COLLECTORS.

Source: National Solar Heating and Cooling Information Center.

Figure IV-6. Solar Standards Organizations

ASHRAE Standard 93-77, METHODS FOR TESTING THE THERMAL PERFORMANCE OF SOLAR COLLECTORS. ASHRAE, 345 East 47th Street, New York New York 10017.

ASHRAE Standard 93-77, METHODS OF TESTING THERMAL STORAGE DEVICES BASED ON THERMAL PERFORMANCE. ASHRAE, 345 East 47th Street, New York, New York 10017.

FLORIDA SOLAR ENERGY CENTER TEST METHODS AND MINIMUM STANDARDS FOR SOLAR COLLECTORS. Florida Solar Energy Center 300 State Rd. 401, Cape Canaveral, Florida 32920 (November, 1976).

HEATING AND AIR CONDITIONING SYSTEMS INSTALLATION STANDARDS FOR ONE AND TWO FAMILY DWELLING AND MULTIFAMILY HOUSING INCLUDING SOLAR. Sheet Metal and Air Conditioning Contractors' National Association, Inc. 8224 Old Courthouse Road, Tysons Corner, Vienna, Virginia 22180. (Third Edition, February 1977).

INTERIM PERFORMANCE CRITERIA FOR SOLAR HEATING AND COMBINED HEATING AND COOLING SYSTEMS AND DWELLINGS. Prepared for the U.S. Department of Housing and Urban Development by the National Bureau of Standards. Available from GPO. SD Catalog No. C13.6/2:504.

INTERIM PERFORMANCE CRITERIA FOR SOLAR HEATING AND COOLING SYSTEMS IN COMMERCIAL BUILDINGS. Prepared for U.S. Energy Research and Development Administration by the National Bureau of Standards. NBS Report NBSIR 76-1187 (November 1976). Available from NTIS. Order No. PB 262 114.

INTERMEDIATE MINIMUM PROPERTY STANDARDS SUPPLEMENT - SOLAR HEATING AND DOMESTIC HOT WATER SYSTEMS. Prepared for the U.S. Department of Housing and Urban Development by the National Bureau of Standards (1977). Available from GPO, SD Catalog No. 4930.2.

INTERMEDIATE STANDARDS FOR SOLAR DOMESTIC HOT WATER SYSTEMS/HUD INITIATIVE. Prepared for the U.S. Department of Housing and Urban Development by the National Bureau of Standards. NBS Report NBSIR 77-1272 (July 1977). Available from NTIS. Order No. PB 271 758.

PROVISIONAL FLAT PLATE SOLAR COLLECTOR TESTING PROCEDURES. Prepared for the Department of Energy by the National Bureau of Standards. NBS Report NBSIR 77-1305 (October 1977). Available from NTIS. Order No. Pb 272 500.

UNIFORM SOLAR ENERGY CODE. International Association of Plumbing and Mechanical Officials, 5032 Alhambra Ave., Los Angeles, California 90032.

Source: National Solar Heating and Cooling Information Center.

Figure IV-7. Solar Heating and Cooling Published Standards, Codes, and Performance Criteria

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rates and greater collateral requirements. Since the market for PV systems in resale has not been established, the applicant must possess other assets.

Individual institutions will assess the risk in making loans based upon the amount of loan, the financial stability of the borrower, the collateral offered, the purpose of the loan, insurance requirements, and repayment schedules. The overriding criterion which can currently be established in the financing of PV systems is the ability of the borrower to repay the loan.

Solar thermal energy is the subject of widespread publicity and discussion in the financial community. Some financial institutions, having recognized the public relations value of being involved in this highly exposed activity, have actively pursued the residential market. Loan policies for solar thermal systems, unheard of a few years ago, are becoming more widespread, and some banks (such as San Diego Federal in California) have even developed system qualification criteria for approving loans. Items considered, for example, are the number of systems installed successfully, guarantees, independent evaluation of the effectiveness and life expectancy of the system, and payback periods.

Solar home-improvement loans and loans for new construction are now being serviced by major banking groups, such as the Bank of America in California. Terms available range from 10-1/4 percent to 19-3/4 percent, with payments of up to 60 months for home improvements. First National Bank of Arizona's loan policy on new construction equipped with solar systems is that the cost of the home should not exceed 10 percent more than its cost without the system.

Although institutions such as San Diego Federal offer reductions in their normal interest rates for solar loans, it currently appears that the most common practice is to treat solar thermal loans as normal home-improvement loans. The First National Bank of Arizona has informed BDM that its policy is to first review the anticipated payback period and, if it is five years or less, to approve the loan subject to its established criteria for home-improvement loans. If the payback period exceeds five years, the bank advises against installation of the system.

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Photovoltaic systems have not yet become common enough for financial institutions to develop specific policies to handle loan requests. The First National Bank of Arizona stated flatly that PV systems are not viable at this time. BDM's bank, the First American Bank of Virginia, has no experience with PV systems and no established guidelines. The Navy Federal Credit Union, one of the largest in the nation, stated in preliminary discussions that although it has no established position with respect to PV systems, it would be willing to loan up to \$20,000, subject to the same criteria as any other loan for business improvement or home improvement.

BDM discussed system financing with large institutional lenders which finance Craddock projects and with local banks which also provide construction loans. BDM contacted Craddock's financial officer to discuss the financing of building projects. Craddock finances its projects through major national lenders such as insurance companies and local institutions, depending upon the size of the project. Major national lenders expressed an interest in funding projects like CAPVC to demonstrate their corporate commitment to an important national policy. BDM contacted a Senior Vice President at Albuquerque National Bank to discuss local funding. The local institution was not concerned with the PV portion of the new building project and was only concerned with the soundness of the building construction loan.

In developing funding for photovoltaic system manufacturers, many financial institutions were unaware of the aspects of the PV market and regarded funding requests with no special considerations. Although experience data are limited because of the few requests for funding, it appears that the tendency is to examine commercial PV loan requests through data contained in balance sheets and profit and loss statements exclusively, and to ignore completely issues such as changing technology, the effects of the Federal Government's position on photovoltaics, and the potential equity in PV systems.

2. Taxation

Taxation policies are equally important in providing incentives for commercialization. Tax incentives can be adopted by a large number of

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local and state governments, in addition to federal legislation. A wide range of tax incentives may be adopted by each jurisdiction. The central problem surrounding tax legislation is first to summarize the existing legislation and tax incentive options, and then to assess the effectiveness of the available incentives.

When a loan application is considered by a financial institution, the ability of the borrower to repay the loan is the major factor evaluated. In situations involving loans for solar energy systems, however, items to be considered include not only the financial stability and income level of the applicant, but also potential savings in utility bills and the effects of income tax credits and other tax incentives on the ability to repay.

Tax legislation is currently viewed as both a mechanism for funding government activities and as a tool for implementing governmental policies and national objectives. As such, tax laws are a reflection of the basic character of the law-making bodies and the impact of special interest groups on the decision process.

With the current emphasis on the development of renewable energy sources, the solar energy field has been the object of numerous efforts to encourage development through tax legislation. The recently passed Federal Energy Act provides some tax incentives for solar equipment. This is actually not a single act, but a combination of several acts. While copies of these Acts are presently difficult to obtain, BDM has a copy of the House-Senate Conference Report concerning the Energy Tax Act of 1978 (Report No. 95-1324, Senate, 95th Congress, 2nd Session), which is purported to be the same as the Act recently signed by President Carter. The Conference Report provides tax credits of 30 percent for solar equipment expenditures of \$2,000 or less made for residential use, and a credit of 20 percent for expenditures between \$2,000 and \$10,000. Businesses would receive a 10 percent investment tax credit for solar equipment, in addition to the 10 percent that they could claim before passage of the Act.

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BDM contacted the County Assessors Office and the State Bureau of Revenue to examine the applicability of property tax and income tax incentives for solar systems. At the present time New Mexico does not have a property tax exemption. Discussions with the Bureau of Revenue indicated that the PV system would be treated as a normal HVAC system for tax assessment. New Mexico has, however, recently adopted income tax credits for the installation of solar systems, including PV (72-15A-11.3). The credit applies against personal income tax. Any resident may claim a tax credit not to exceed \$1,000 in an amount equal to 25 percent of the cost of equipment used in the taxpayer's principal residence for solar heating or cooling. The person furnishing the equipment must provide the taxpayer with an accounting of the cost. Fifty-five percent of the invoice cost of photovoltaic equipment is eligible for the solar tax credit. This percentage was determined by the State from data provided by Public Service Company of New Mexico; the data indicated that 55 percent of the electrical energy used in a home is used for space heating and heating of domestic hot water. The cost of collectors and control equipment is also eligible.

Other state legislatures have also been active in passing tax laws to encourage solar energy development. Figure IV-2 shows the states which have enacted solar energy tax incentives (as of 1977) which affect income tax, property tax, and sales tax. The National Solar Heating and Cooling Information Center released a compendium of state solar legislation, which is accurate as of July 1978. The list includes a brief description of financial incentive statutes passed by 39 states. These incentives fall into the following broad categories: deductions or credits for state income tax purposes, exemption of solar equipment from sales taxes, exemption of solar equipment from ad valorem property taxes or a reduction in the assessed value of such equipment, enabling legislation to permit municipalities or counties to reduce the assessed value of solar equipment, changes in banking law to encourage financing of solar equipment, exemption from use taxes, and providing solar equipment loans for veterans.

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The specific terms of these financial inducements vary widely from state to state, as does the length of time that each financial inducement will stay in effect.

D. INSURANCE AND LIABILITY

The issues of insurance and liability are central to the rapid commercialization of PV systems. These issues affect designers, manufacturers, institutions, and users of photovoltaic systems, ultimately affecting price and acceptance of PV systems. Insurability is a key question in assessing a request for a loan.

1. Insurance

Insurance can always be purchased to cover any item from loss or to cover the damage to persons or property which might result. The key issue in insurability is the institution's assessment of risk, which affects the cost of premiums and the type of coverage offered. The availability of insurance and the cost of premiums will affect the perception of risk by financial institutions and end users, and ultimately the market for photovoltaic systems. Photovoltaic systems are currently viewed by the insurance industry as an unknown risk. Since the reduction of loss is the industry's central concern, a system's compliance with national codes and standards is a critical indication to insurers of product risk.

Insurance can be purchased to protect the value of the system, and against damage which might result to persons or property. Different coverages and premiums will apply to different applications, whether residential, commercial, industrial, or required to protect against liability. As with any new technology with unknown operating characteristics and hazards, and items not standardized, the insurance industry views PV systems as exceptions requiring special policies, premiums, and design review by its engineering specialists. This will lead to high premiums until the operating characteristics and hazards are known and the risk distributed over many policy-holders to reduce the potential of loss.

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A review and analysis of the insurance and liability coverage required for the CAPVC was conducted by BDM and its insurance carrier, Commercial Union Assurance Company. Detailed discussions were held to assess CAPVC insurability, estimate the adequacy of BDM's coverage, identify additional coverage options, and estimate premium costs. Loss-prevention representatives from Commercial Union visited BDM's Solar Test Facility and conducted an analysis to determine system insurability. Commercial Union will also review the final CAPVC system design.

The insurance industry's perception of risk (affecting premium costs) is dependent upon its familiarity with PV systems. The participation of Commercial Union in the program will affect the commercialization of PV systems by increasing the experience of the industry with PV systems, reducing the perceived risks for insurance, and ultimately lowering premium costs. The review of the CAPVC program included a detailed inspection of the STF for design hazards according to the standards published by the American Insurance Association. A special pressure-relief valve was suggested by the Commercial Union representative and incorporated into the system. Commercial Union estimated premium costs to insure the existing arrays on the STF and related equipment at approximately \$500 to \$600 per year. Coverage was available under existing boiler machinery and electrical equipment policies. BDM has approximately \$50,000 invested in its system.

BDM is contractually required to carry specific levels of insurance coverage. Current coverage meets or exceeds the levels specified in the phase I contract for workman's compensation, employer liability, and general bodily injury (figure IV-8). Commercial Union, BDM's insurance carrier, has agreed to review the detailed CAPVC design to determine the coverages for phase 2. BDM and Commercial Union have identified additional coverage required for product and professional liability.

2. Liability

Product and professional liability is an important concern to manufacturers, designers, and sellers, since all may be held liable for injury to the person or property of a buyer or third party. Liability can be established due to negligence, breach of an expressed or implied

CERTIFICATE OF INSURANCE			
	LIMITS OF LIABILITY IN THOUSANDS		
TYPE OF INSURANCE		EACH OCCURRENCE	AGGREGATE
GENERAL LIABILITY COMPREHENSIVE FORM PREMISES-OPERATIONS CONTRACTUAL INSURANCE INDEPENDENT CONTRACTORS PERSONAL INJURY	BODILY INJURY	\$1,000	\$1,000*
	PROPERTY DAMAGE	\$100	\$100
	*APPLIES TO PRODUCTS, COMPLETED OPERATIONS, HAZARDS		\$1,000 PERSONAL INJURY
AUTOMOBILE LIABILITY COMPREHENSIVE FORM OWNED HIRED NON-OWNED	BODILY INJURY (EACH PERSON)	\$500	
	BODILY INJURY (EACH OCCURRENCE)	\$1,000	
WORKER'S COMPENSATION AND EMPLOYER'S LIABILITY	STATUTORY \$100 EACH ACCIDENT		

Figure IV-8. Insurance Carried

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warranty, or strict liability in tort. These are complex issues subject to frequent litigation. In these cases, negligence, a violation of duty to use due care in manufacturing and preparing a product for market, and the fact that the product was the proximate cause of injury or damage must be proven. Manufacturers, designers, and sellers must be conscious of their duty to exercise reasonable care in the design, test, and inspection of a product, and to warn users of any dangers inherent in product use. Reasonable care is defined as care commensurate with the risk of product-caused harm. These, however, are only general legal guidelines.

The insurance company's assessment of the risk of product-caused harm is the central criterion in determining rate structures. For high-risk items, insurance companies cannot cover potential losses themselves and must utilize industry-wide coverage pools to fully cover expected liability. The premiums for this coverage will be very expensive. The product liability premium coverage for the CAPVC experiment will be approximately two percent of the contract value annually. This is coverage only for the specific experiment, and the cost is an indicator of the insurance company's risk assessment.

In addition to product-caused damage, manufacturers, designers, and sellers may be sued for damages if the performance of a system does not conform with contract provisions, warranties, and advertising practices. These issues relate to consumer protection and can be divided into quality of installation and components, conformance of the system with contract provisions, warranties, and advertising practices.

Promises of system performance made at the time of sale, or performance of the system specified in the written contract document may lead to suits if the customer does not think the system is performing as promised. Photovoltaic system output will vary with time, as component aging will cause decline in system performance. While the measurement of system performance is straightforward, the manner in which performance is specified in a contract may not be.

If a warranty is given at the time of sale, the same problems arise in measuring system performance. The Solar Energy Industries Association has published guidelines for solar warranties. Editorials on

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the question of warranties have appeared in Solar Engineering and Solar Age. The fourth-cycle HUD Program for heating and cooling is requiring a five-year warranty on materials and workmanship. Warranty requirements also have a definite impact on the price of equipment.

The Solar Energy Industry Association has recently published guidelines for solar advertising, sales, and product representation standards. The publication summarizes the guidelines of the Federal Trade Commission to prevent a costly investigation and litigation, as well as adverse publicity which would affect not only the company involved, but the entire industry.

Consumer confidence in photovoltaic systems and the industry is promoted by attention to these problems.

Liability can also be established by a system's failure to comply with established codes and standards. By protecting against hazards, codes and standards play a central role in establishing insurability. The background for a hazards assessment of solar thermal systems was developed by the American Insurance Association, Engineering and Safety Service, which has published a special hazards bulletin. The American Insurance Association also publishes the National Building Code. The bulletin, entitled Solar Energy Systems Z-70, discusses the various aspects of solar energy systems (thermal only), the components, precautions, structural considerations, valves and controls, and other safety concerns. This publication is used by insurance company loss-prevention representatives as a guideline in reviewing solar systems. Many insurance companies have loss-prevention programs to assist manufacturers and designers in reducing accidents and eliminating health and safety hazards.

The hazards bulletin relies on the following codes: (1) National Building Code, 1976 Edition; (2) NBSIR 76-1187, Interim Performance Criteria for Solar Heating and Cooling Systems in Commercial Buildings; (3) ANSI 13.1-1976, Scheme for the Identification of Piping Systems; and (4) NFPA No. 78, Lightning Protection Code. Since this is distributed industry-wide and is a key document in hazards review, a similar document needs to be developed for PV systems.

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The American Insurance Association is one of the central national professional associations in the insurance industry. The National Fire Protection Association and various engineering and safety organizations such as the American Society of Safety Engineers are also key groups.

E. ENVIRONMENTAL AND OTHER ISSUES

As the numbers of installed photovoltaic systems increase, numerous environmental and other concerns are likely to arise. The designers, users, financiers, insurers, and governmental reviewers will be able to function more efficiently and encourage commercialization as information becomes available on the requirements for site-specific environmental impact statements and the specific effects of such factors as toxic material hazards, safety, reflected light, RF interference and other factors. These factors and other site-specific impacts were examined for the CAPVC program to insure that no hazards exist.

The federal government or local jurisdictions can require an EIS (Environmental Impact Statement) for projects which would have a significant impact on the environment (e.g., a nuclear power plant) or an Environmental Assessment for intermediate cases when an EIS is not required.

In general, the larger the proposed system and the more it involves construction on previously undisturbed land, the greater the chance that an EIS will be required. Large ground-mounted systems can have significant ecological impacts (such as increased run-off, microclimatic effects due to heat rejection) and pose additional safety hazards.

Separate from the Federal Government requirements, some states and local governments have adopted analogous regulations requiring environmental impact studies for proposed projects which need some type of state or local government approval for funding. The criteria for determining whether environmental impact studies are needed varies among the different jurisdictions.

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1. Airport Impacts

The CAPVC project will be located approximately 0.5 miles from the Albuquerque International Airport. The location is in a non-ILS (Instrument Landing System) area and is not under any approaches to major runways. BDM has reviewed the proposed location of the project and systems characteristics with the FAA (Federal Aviation Administration) and the City of Albuquerque Aviation Department. The primary concerns of these agencies are the height of building structures and the potential for interference with ILS (Instrument Landing Systems). The height of the building - three stories - poses no hazard to approaching aircraft. The RF interference problem is discussed in the following paragraph. BDM is filing a notice of proposed construction or alteration within the vicinity of an airport (FAA Form 7460-1) with the FAA to allow a formal review of the project. The location of the CAPVC experiment in relation to the Albuquerque International Airport and runways is shown in figure IV-9.

2. Electromagnetic Interference

The location of the experiment in close proximity to a major airport raises the question of potential EMI (electromagnetic interference) with navigation and communications equipment. BDM has examined the potential of the system for emitting radio frequency electromagnetic radiation from the power conditioning system and from the arrays themselves.

The CAPVC system has been modeled as an RC transmission line to determine if it could act as a source of EMI in the vicinity of sensitive equipment. The RC transmission line included a detailed model of the equivalent resistances and capacitances associated with each of the PV cells. The transmission line, composed of 498 individual cells representing one string, was modeled on the NET-2 network analysis computer code. The most likely mechanism for high-frequency noise to be injected into the PV array is the switching of load transients in the inverter. Since the inverter is shielded in a metallic container and housed in a facility built of reinforced concrete, direct radiation from the inverter would be extremely small. However, such transients may propagate through the

Figure IV-9. CAPVC in Relation to the Albuquerque International Airport and Runways

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system wiring to the PV strings mounted over the parabolic reflectors and, hence, could conceivably radiate directly into space. While parabolic dish antennas are commonplace and quite effective as directional antennas, parabolic troughs are never used as antennas because of the loss and lack of two-dimensional directivity. Nevertheless, it is worthwhile to determine the power transfer of a string of PV cells as proposed for CAPVC to determine the operating characteristics of the string at high frequencies.

The power loss in dB, defined as

$$\text{Power loss} = 20/\log_{10} \frac{\text{Power Out}}{\text{Power In}}$$

is presented in figure IV-10 for frequencies ranging from 10 kHz to 10 GHz. It is clear that the string greatly absorbs the higher frequency components and thus would function poorly as an excitation or feed element of the reflector as an electromagnetic source. If the string is assumed to be a perfect radiator, figure IV-10 can be used to determine the input power required to produce 0.1 watt of radiated output. Devices radiating below 0.1 watt are not regulated by the FCC. In the 1 to 10-GHz range, (the ILS band) it would take approximately 10^{50} watts of input signal to obtain 0.1 watt output radiated power. This is clearly not a feasible level of input power to the string. Even at 10 kHz, it would require about 1 kW of input power to produce 0.1 watt output from a single string. Therefore, due to the poor antenna characteristics of parabolic troughs and the high power levels required, EMI is not a practical concern for CAPVC.

3. Reflection Hazards

Distributed photovoltaic systems are often perceived to have the potential for creating both hazardous and nuisance reflection exposure to workers, visitors, and/or people in the neighborhood of the systems. Possible hazards include both direct exposure of people and secondary effects such as creating fires or hot surfaces. In addition, concentrated

Figure IV-10. Frequency Response

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or reflected sunlight might affect pilots, automobile drivers, and neighbors to the extent that accidents might occur.

The collector proposed for the CAPVC is the SKI parabolic trough concentrating solar collector. This collector has a focal length of 10.5 inches and focuses all incident light on the receiver tube assembly. There are no reflection hazards beyond the focal point.

Observation experiments of the reflectivity of the SKI collectors currently in place at the BDM Test Facility have been conducted to assess reflection hazards. Figure IV-11 shows the SKI collector (in tracking mode) facing the observer. The observation experiments resulted in the conclusion that there are no reflection hazards beyond the focal point of the collector.

Aesthetically, the collectors currently installed at the BDM STF have an attractive, cleanly designed appearance. Due to the contour of the terrain, the roof of the STF and the collectors are clearly visible from the street level (Yale Blvd.). The collectors are not distinguishable by the casual observer from existing rooftop equipment. The arrays for the CAPVC building will be located on the roof of a three-story building and will not be readily visible from street level.

4. Material Toxicity

The only potentially toxic material used in the system is the ethylene glycol/water mixture used for cooling the cells. Ethylene glycol is toxic only if swallowed. Handling the mixture requires only a thorough washing of exposed skin. This substance has been in use at the STF for several months, allowing BDM to develop procedures for its use. Separate systems are maintained for potable water and the plumbing heat transfer medium. This is in compliance with established codes and safety standards. In addition, the contents of the piping system carrying the heat transfer fluid will be clearly marked with the type of solution and the first aid measures required to be taken in the event of accidental exposure.

5. Safety

System safety is an important concern of many institutions and can directly influence the commercialization of photovoltaic systems

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Figure IV-11. Reflection Observation (Collectors in Operation - Pointed at Observer at 160 Yds.)

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through the cost of insurance premiums. All existing operational and maintenance hazards must be identified during the design phase to insure that proper protective measures are incorporated. In the operations phase all hazards not eliminated through design must be identified, warnings posted, protective devices required, and procedures established to eliminate exposure.

BDM conducted a hazards analysis of the Solar Test Facility, which clearly marked all operation hazards and developed procedures for requiring protective devices and controlling access. These procedures will be expanded for the CAPVC program. All the hazards of the STF have been assessed. All high-voltage areas are marked with warning signs, and wiring and cabling are protected. Built-in automatic safety devices have been installed in the equipment room to prevent accidental electric shock from the equipment rack. A sensor has been installed on the roof access hatch to shut down operation if unauthorized access occurs. All personnel are required to wear eye protection and other protective devices when working on the equipment. A safety rail has been included on the perimeter of the roof. These procedures will be expanded for CAPVC. Access will be controlled by cypher locks with limited distribution of codes. Similar operational hazards will be clearly marked and protective devices required.

6. Other Concerns

Some other, not so obvious, environmental factors may exist which affect the design and acceptance of such systems. The early identification of such factors and the development of recommended ways of eliminating or mitigating their adverse effects would contribute to the development of photovoltaic systems applications. During Phase II and III, BDM will maintain a recording system to document any additional problems which arise.

One additional area examined which was found to create no environmental impacts was the heat exchanger and cooling system. The heat exchanger is a closed circuit evaporative cooling tower which will

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be located at ground level away from any interference with other mechanical equipment. The system will utilize a Baltimore Aircoil cooler and reject heat at a rate of 1.2 million BTU/hr. This system is analogous to normal building evaporative air conditioning and has a heat rejection rate equivalent to normal air conditioning heat rejection units.

F. PUBLIC INFORMATION

BDM recognizes that one of the key elements in securing institutional acceptance of photovoltaic systems is public awareness. As such, BDM has encouraged representatives of governmental and private institutions to visit the STF and will continue this policy with CAPVC.

BDM has incorporated a CAPVC Visitors' Center into the design of its new building. The Center is on the first floor and will contain displays on system operation. The instrumentation display and control room will be in a glass-enclosed room to control access but permit visual inspection when CAPVC personnel are not available to conduct a guided tour. An artist's conception of the Visitors' Center is shown in figure IV-12.

Articles on CAPVC have been published in the Albuquerque Journal and company publications such as the BDM Review. BDM sponsored a tour of the STF as part of its groundbreaking ceremonies for the new building. U.S. Senator Harrison Schmitt; the Secretary of the New Mexico Department of Energy and Minerals, Nick Franklin; the Mayor of Albuquerque, David Rusk; and other representatives from city and county government and the Chamber of Commerce attended the groundbreaking as special guests (figure IV-13). This public-awareness campaign will be continued through the future phases of CAPVC.

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Figure IV-12. CAPVC Visitors' Center

Figure IV-13. BDM Groundbreaking Ceremonies for CAPVC Building and Solar Test Facility

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CHAPTER V FABRICATION AND INSTALLATION

A. OVERVIEW OF THE APPROACH

During the development of the Solar Test Facility, BDM gained considerable experience in the requirements necessary to ensure a quality system. As problems were recognized, solutions were developed which required procedures to be followed during the fabrication and installation of the components of the system. It was recognized to ensure that these procedures were followed and that all specifications were met, certain QC/QA (Quality Control and Quality Assurance) procedures must be developed and implemented during the fabrication and installation of these components during phase II. These procedures will be discussed in this chapter.

It should be noted that while developing the Solar Test Facility, procurements were made from several organizations. BDM interacted with them to develop some of the procedures to be described herein.

In developing the plan for the fabrication and installation of the various components, the procurement process was determined to be rather straightforward. However, the need for backup hardware supply sources and the need for competitive component costs were realized. As a result, a procurement approach was developed as part of the phase I effort.

B. QUALITY CONTROL AND QUALITY ASSURANCE PROCEDURE

1. The Photovoltaic Array

Specific measurements are required in several areas during the fabrication and installation procedures to ensure the integrity of the CAPVC system. The specific component fabrication or installation tasks which will include QC/QA measurements are: 1) Linear Parabolic Trough (LPT) Hardware Fabrication, 2) Receiver Tube Extrusion Fabrication, 3) Linear Parabolic Trough Installation, 4) PV Cell and PV Cell Module Fabrication, and 5) PV Module Installation.

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Solar Kinetics Incorporated (SKI) of Dallas, Texas, is the fabricator of the LPT hardware which includes the reflective trough, the collector pylons, and the hydraulic actuator assembly. SKI is also the fabricator of both the fluid-carrying receiver tube structure and the PV module substrate aluminum extrusion.

During phase I the reflective trough focusing tolerances were evaluated. It was found that most of the prototype troughs provided the minimum optical efficiency specified during the design. However, a potential problem involving divergence of the reflective trough between bulkheads was identified. This problem was discussed with SKI and explicit trough tolerances have been specified. BDM has designed a device to measure the overall optical efficiency of the troughs as they are fabricated. This quality control device will ensure that all troughs used in the CAPVC system design will conform to minimum optical efficiencies.

Also recognized during phase I evaluation was the importance of closely controlling the receiver tube and the PV module substrate dimensions. This would ensure the proper mating of the two, so that adequate thermal contact would be made. It was also important that the length of the receiver tube be the same as the 20-foot collector, since three were to be joined together to make up the 60-foot coolant rows. And finally, it was recognized that the receiver tube must be straight and without significant sag to ensure even cell irradiation.

As a result of this experience, BDM has specified the fabrication procedures required for each of these components. These procedures are shown in figure V-1 along with the specific QC/QA tasks which will be accomplished (QC/QA tasks shown in diamond elements).

In the fabrication of the collector pylons and hydraulic tracking system, SKI must check the specifications of the completed products against design specifications and verify the logic of the hydraulic actuator system to insure proper wiring. Each of these tasks must be documented and forwarded to the BDM staff. The fabrication of the linear parabolic reflecting surface requires the most stringent QC/QA controls. In this process, SKI, after receiving the bulkheads and raw materials

Figure V-1. Fabrication and QC/QA Procedure for CAPVC Linear Parabolic Trough

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from suppliers, must verify and inventory the materials and run a template check on the bulkheads to insure that they conform to the correct parabolic shape. Then, SKI would fabricate the trough and, during fabrication, again use a parabolic template to check conformity to the parabolic shape. After the trough has been completed, SKI would calibrate the overall optical efficiency of the trough.

The assurance of the optical efficiency of the LPT is one of the most critical issues that must be executed by the QC/QA task team. The focused illumination is the most critical interface of the CAPVC system design. Therefore, the BDM staff has designed the Focused Illumination Integration Fixture (FIIF) (illustrated in figure V-2) to allow a highly reliable check on the optical quality of the trough by its manufacturer. Basically, the fixture involves an inverted fixed LPT with a light source at the focal point. This trough is suspended above the test fixture where each production trough would be placed as it comes out of the assembly process. The test fixture also includes a receiver tube assembly at the focal point of the trough being tested. A module with previously calibrated photovoltaic cells would be moved up and down the receiver tube and the power output calibrated against a predetermined acceptable level. This calibration would involve careful manufacturing of a trough, and testing it in actual sunlight to ensure that its optical properties are such that the minimum acceptable power would be realized from each module. Tolerances would then be set for power from each module in an artificial environment in the FIIF, and each trough would be tested against an acceptable level before being prepared for shipment. The acceptable level established by BDM is 74 watts per 22-cell string. This is required to achieve the designed peak system output of 47 kW. When the calibrated measurements in the FIIF indicate that insufficient light is being focused onto the PV test module, the trough would be rejected. At this point, SKI would identify manufacturing flaws and correct them in the assembly process.

SKI is also responsible for the fabrication of the receiver tube extrusions. Each receiver tube must first be checked against design

Figure V-2. Focused Illumination Integration Fixture

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dimensions. The second QC/QA check on each of the aluminum extrusions is a "pull check" - an inspection to ensure that the receiver tubes are straight and are free of twists and misalignments. The final check on each receiver tube piece would be after the cutting or sawing procedure. The length of each module or 20-foot receiver tube would be checked to ensure that it is within tolerances. On the inner receiver tube, which carries the fluid, the interconnection fixtures are welded into place; after welding, a weld inspection would take place.

After these fabrication procedures and QC/QA checks, the trough hardware and receiver tubes would be shipped to the CAPVC site in Albuquerque. On arrival, each item would be inspected; all SKI-prepared material trace sheets and specification sheets would be reviewed when provided by SKI. As the troughs are being installed at the CAPVC site, each trough would be double checked by the QC/QA staff to insure that the troughs are 1) level and 2) aligned north/south, and that 1) the receiver tubes are at the focal point of the trough, and 2) all troughs track properly through a 270-degree arc. Each of these QC/QA checks would be included in the appropriate documentation.

The remaining QC/QA areas involve the fabrication of the PV cell and the PV module. The manufacturing procedures in the QC/QA task are diagrammed in figure V-3. The QC/QA task performed by the cell manufacturer would begin with the receipt of the raw materials required to fabricate the cells. They must ensure that all materials meet specified standards and are free from flaws and damage sustained in shipment.

The cells are then fabricated and each cell must be subjected to an electrical test under a 20-sun illumination to check the peak power output of the cell. Acceptable cells would be grouped into a bin for use in the module fabrication. In addition to the peak power check, the QC/QA manager would be responsible for visually inspecting all cells to make sure they are free from radial cracks, star cracks, or any other incipient cell flaw which would impair the performance of the cell.

The cells would then be covered with microglass, potted, interconnected, and encapsulated into the PV module on the aluminum substrate

Figure V-3. Fabrication and QC/QA Procedure for Receiver Tube/
PV Model Substrate/PV Model (Completed)

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provided by SKI. During phase I development, BDM recognized a need for a means to encapsulate the cells onto the substrate which would yield a quality product. BDM therefore designed a jig to accomplish the encapsulation, which was shown to give the desired results and to be applicable for use during the manufacturing process. Such a jig should be used. At this time, the module must undergo a visual inspection as well as stringent electrical tests to ensure the minimum 1500-volt DC standoff capability of the module. Also, bypass diodes and other electronic devices must be checked prior to module buildup to insure that no bad devices are included in the PV modules. After the PV module has been completed, it would once again undergo a visual inspection and would then be placed in front of an artificial light bank, and a reference I-V curve would be determined for the module to test the I-V performance of the interconnected cells. The PV modules would then be packaged and shipped to Albuquerque, where, upon receipt, they would be inventoried and once again visually inspected and a quick "short check" (i.e. short to substrate) would be performed by the BDM QC/QA staff to ensure that no damage has occurred in shipping and that minimum standoff voltage is still inherent in the PV module. The modules would then be installed in the CAPVC collector system and, as each series string of modules is interconnected, a reference I-V curve would be determined by the BDM staff to ensure the integrity of the collector performance.

At the completion of these processes, the QC/QA task leader would have enough documentation to trace all materials within the CAPVC array and to trace quality control checks which have been performed throughout the fabrication and installation procedure.

2. Power Conditioning

The inverter, switchgear, and associated equipment involved in the CAPVC design are off-the-shelf items, requiring no component development. Experience during phase I indicated that no special procedures were required during fabrication or installation to meet the CAPVC requirements.

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3. Thermal System

All of the components required to provide the heat rejection circuit for CAPVC are commercially available and proven, and will comply with all ASME, ASHRAE, and other applicable codes and standards. Also, all of the components required for the building circuit are commercially available and proven, and compatible with the CAPVC heat rejection circuit. These components will also meet or exceed ASME, ASHRAE, and other applicable standards, while meeting the design requirements of the system.

4. Control And Data Acquisition

All components and equipment required for control and data acquisition are off-the-shelf items. The experience BDM has had with the Solar Test Facility conducted during phase I has demonstrated that BDM has the expertise to integrate such a system for CAPVC. Therefore, no special procedures during installation are recommended.

C. PROCUREMENT PLAN

The need for backup hardware supply options was thoroughly addressed during phase I in order to assure timely delivery and competitive costs for each of the CAPVC system components. A procurement strategy was developed which included "work-around" options which will result in timely hardware delivery and low-bid cost effective selection. This approach is defined in figure V-4. The three major components to be procured are the collector system, the PV cells and modules, and the inverter. The only sole-source procurement will involve the concentrating collector. Solar Kinetics is currently the only source which can provide a collector to meet the CAPVC system requirements. Procurement of the PV cells and modules will be based on cost and performance evaluations. Likewise, the procurement of the inverter will be based on cost, delivery, and performance evaluation.

Figure V-4. Procurement Strategy for Phase II Fabrication and Installation

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D. SCHEDULE AND TASKS

Completion of a plan for the fabrication and installation of the CAPVC components required the identification of the specific tasks involved and a time phasing of these tasks into an overall program approach. Table V-1 presents a task breakdown of the fabrication and installation effort and figure V-5 is a modified PERT chart which describes the integration of the activities required to complete the CAPVC system.

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TABLE V-1. BREAKDOWN OF FABRICATION
AND INSTALLATION TASKS

1.0	PROCUREMENT	2.4.4.2	Liquid/Liquid Heat Exchangers	4.4.2.1	Sensors & Controls	6.2.1	Reflecting Trough
1.1	Specification Final Review	2.4.4.3	Sensible Storage	4.4.2.2	Tracking Hydraulic Power Supply	6.2.1.1	Bulkhead Templet Check
1.2	Procurement Package Preparation	2.4.4.4	Pump, Controls, and Plumbing	4.4.2.3	Coolant Pumps	6.2.1.2	Reflecting Surface Templet Check
1.2.1	Collector Subsystem	2.5	Instrumentation System Preparation	4.4.2.4	Cooling Tower	6.2.1.3	Reflecting Surface Alignment Check
1.2.2	Receiver Tube & PV Module Substrate Extrusion	2.5.1	Weather Instrumentation Platforms	4.4.2.5	Weather Instrumentation	6.2.1.4	Optical Efficiency Check
1.2.3	PV Cells & PV Module Fabrication	2.5.2	Instrumentation Cable Conduit Installation	4.5	Power Conditioning and Switching Gear	6.2.2	Collector Pylon Specification Verification
1.2.4	Electrical Contractor Services	2.6	CAPVC Roof and Roof Access Preparation	4.5.1	Inverter Installation	6.2.3	Hydraulic Actuator Assembly Logic Verification
1.2.5	Power Conditioning & Switch Gear	2.6.1	Stairway Access (Completed)*	4.5.2	Switching Gear Installation and Check	6.3	Receiver Tube and PV Module Substrate
1.2.5.1	Inverter	2.6.2	Access Security Control System Installation	4.5.3	Disconnect System Installation and Check	6.3.1	Die Dimension Check
1.2.5.2	Switchgear	2.6.3	Roof Parapet (Completed)*	4.5.4	Transformer Installation	6.3.2	Alignment (Pull) Check
1.2.6	Heat Transport and Rejection Subsystem	2.6.4	Safety Equipment & Warning Sign Installation	4.5.5	Building Power Supply Connections	6.3.3	Length Check
1.3	Materials Purchase Order Preparation	2.7	Lightning Protection System	4.6	Heat Transport and Rejection System	6.4	PV Module
1.3.1	Instrumentation Sensors	2.7.1	Collectors	4.6.1	Piping and Manifolding	6.4.1	Component Test
1.3.2	Control Hardware	2.7.2	Ground Connections	4.6.1.1	Piping Installation	6.4.1.1	PV Cell IV Check
1.3.3	Cabling and Wiring	3.0	FABRICATION & TRANSPORTATION	4.6.1.2	Insulation	6.4.1.2	Bypass Diode Check
1.3.4	Display Panel Hardware	3.1	Fabricate Collector Subsystem	4.6.2	Cooling Tower Installation	6.4.2	PV Module
1.3.5	Control Room Equipment and Hardware	3.1.1	Collecting Trough	4.6.3	Circulating Pump	6.4.2.1	Visual Inspection
1.4	DOE Purchase Approval Cycle	3.1.2	Pylons (Standard & Tracking)	4.6.4	Chemical Feed System	6.4.2.2	Continuity and Short-Circuit Check
1.5	Implement Hardware Procurement Procedures	3.1.3	Tracking/Hydraulic System	4.6.5	Fluid System Pressure and Flow Checks	6.4.2.3	Module IV Check
1.6	Procurement Monitoring and Control	3.1.4	RTS Stands	4.7	Instrumentation and Control System	6.5	Collector System Installation
1.6.1	Fabrication & Shipment	3.2	Receiver Tube & PV Module Substrate Extrusion	4.7.1	Sensor Installation	6.5.1	Visual Inspection
1.6.2	Services	3.2.1	Heat Transport Tube	4.7.1.1	Surface Temperature Installation	6.5.2	Collector Level Check
1.6.3	Materials Acquisition	3.2.2	PV Module Substrate	4.7.1.2	Fluid Temperature Installation	6.5.3	North/South Alignment Check
1.6.4	Assembly and Installation	3.2.3	Receiver Tube Clamps	4.7.1.3	Electrical System Sensors Installation	6.5.4	Focus Check
1.7	Receipt Inventory and Inspection	3.3	PV Cells and Modules	4.7.1.4	Fluid Flow Sensors Installation	6.5.5	Tracking/Rotation Check
2.0	SITE PREPARATION	3.3.1	Fabricate PV Cells	4.7.1.5	Pressure Sensors Installation	6.6	PV Module Subassembly Installation Checkout
2.1	Collector Site Preparation	3.3.2	Diodes, Interconnects, and Encapsulation	4.7.1.6	Control Sensors Installation	6.6.1	Visual Inspection
2.1.1	Collector Roof Mounts (Completed)*	3.3.3	PV Modules	4.7.2	Weather Station Installation	6.6.2	Short Circuit Check
2.1.2	Tracking System Hardware	3.4	Inverter	4.7.3	Instrumentation Wiring and Connections	6.6.3	Operational IV Curve for Each Module String
2.1.2.1	Hydraulic Power Supply Pads	3.5	Display Panel	4.7.4	System Control Loops	6.7	Subsystem Checkout Verification
2.1.2.2	AC Power Supply	4.0	ASSEMBLY, INSTALLATION, AND CHECKOUT	4.7.5	Microprocessor/Computer Installation	6.8	QC/QA Documentation
2.2	DC Power Cabling Preparation	4.1	Collector Subsystem	4.7.5.1	Hardware	7.0	DATA COLLECTION AND DOCUMENTATION
2.2.1	Cabling and Conduit Installation	4.1.1	Pylons	4.7.5.2	Software	7.1	Develop Specific Logs/Requirements
2.2.2	Junction Box Installation	4.1.2	Troughs	4.7.6	Display Panel Installation	7.1.1	Costs
2.3	CAPVC Control/Display Room Preparation	4.1.3	RTS Stands	5.0	OPERATION AND SYSTEM VALIDATION	7.1.2	Schedules
2.3.1	Building Electrical Bus Interconnect Installation	4.1.4	Tracking Subsystem	5.1	Collector Tracking Accuracy	7.1.3	Maintenance
2.3.2	Room Preparation for Inverter & Switchgear	4.2	Heat Transport and Receiver Tube	5.2	Receiver Tube Heat Transfer Check	7.1.4	Operations
2.3.3	Room Preparation for Microprocessor & Signal Conditioners	4.2.1	Heat Transport Tube Installation	5.3	Current Voltage and Photovoltaic Power Check	7.1.5	Safety
2.3.4	CAPVC Display Panel Installation	4.2.2	Coolant Connections	5.4	Inverter Validation	7.1.6	Other
2.3.5	CAPVC Room Security System Installation	4.3	PV Modules	5.4.1	Makeup	7.2	Establish Review and Reporting Procedures
2.4	Heat Transport Subsystem Preparation	4.3.1	Module Installation	5.4.2	Harmonics	7.3	Prepare System Descriptions
2.4.1	Heat Transport & Rejection System	4.3.2	J-Box Installation	5.4.3	Efficiency	8.0	LEGAL AND INSTITUTIONAL FACTORS
2.4.1.1	Pad Installation and Construction	4.3.3	Electrical Connections	5.5	Heat Transport Subsystem	8.1	Verify Phase I Analysis
2.4.1.2	AC Power Supply System Installation	4.3.4	Continuity Checks	5.5.1	Thermal Energy to Building	8.1.1	Codes, Ordinances
2.4.2	Fluid Circulating Pump Preparation	4.3.5	IV Measurements	5.5.1.1	Flow Controls	8.1.2	Finance, Taxation
2.4.2.1	Mechanical Pad Construction	4.4	Electrical Cabling and Wiring	5.5.1.2	Temperature Controls	8.1.3	Insurance Liability
2.4.2.2	AC Power Supply	4.4.1	DC Power Networks	5.5.2	Heat Rejection Efficiency	8.1.4	Environment
2.4.3	Mechanical Room Preparation	4.4.1.1	Power Bus to J-Box Connections	5.6	Control Loop Validation	8.2	Data Collection/Documentation
2.4.3.1	Heat Exchanger	4.4.1.2	Continuity Checks	6.0	QUALITY CONTROL/QUALITY ASSURANCE	8.3	Information Distribution
2.4.3.2	Pump	4.4.1.3	Power Disconnects	6.1	Material Certification of All Components		
2.4.4	Building Heating System Installation	4.4.2	AC Power System	6.2	Collector System		
2.4.4.1	Liquid/Air Heat Exchangers

Figure V-5. CAPVC Phase II PERT Diagram

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CHAPTER VI PHASE III OPERATION AND EVALUATION PLAN

A. INTRODUCTION

Phase III operation and evaluation of the CAPVC system will commence upon completion of phase II fabrication and installation, and will continue on a yearly basis for a period to be determined by the Department of Energy. Evaluation of the CAPVC will be on a system and subsystem level, including the subsystems: concentrator, receiver tube, PV cell and module, power conditioning, thermal system, and control and data acquisition system. The phase I design specifications and BDM's photovoltaic data collection and analysis experience with the Solar Test Facility have led to the development of the operation and evaluation plan for phase III. This chapter presents the methodology and evaluation techniques to be exercised during phase III.

B. OVERVIEW OF EVALUATION APPROACH

1. Purpose of Phase III Operation and Evaluation

The general purposes of phase III are: long-term monitoring and thorough evaluation of the CAPVC system and subsystem performance and reliability; establishment of the projected cost and utility impact of the system; assessment of the impact and problem areas of nontechnical issues on system design, installation, and operation; and acquisition of data to meet the evaluation and DOE requirements. In addition, an operation and maintenance manual is to be prepared for the CAPVC system within the first 90 days of phase III.

2. Analysis Overview

The key questions and issues to be addressed through the evaluation effort are:

- (1) How well does the system perform?
- (2) How reliable are the CAPVC system and subsystems?

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- (3) Does the CAPVC system offer potential for long range, improved concentrator performance and decreased costs?
- (4) What are the system costs?
- (5) What are the nontechnical issues that could have a significant impact on the commercial application of photovoltaic concentrator systems?

The general purpose and key questions and issues to be addressed through phase III define three major analysis areas involved in the CAPVC system evaluation: technical, nontechnical, and economic. An additional area of the evaluation concerns the assessment of the CAPVC/utility interface. This assessment will also include technical, nontechnical, and economic analyses, but is considered to be a separate area. An overview of the evaluation methodology to be used in phase III is presented in figure VI-1. This figure presents the various subanalysis phases which comprise the major analysis areas, with their interrelation in the overall CAPVC system evaluation. These phases are discussed in detail in following sections.

Results from the technical and economic evaluations will be combined to produce an overall measure of system capability, such as cost per peak kW, for optimal, standard, and projected operating conditions and costs. These measures, along with the commercial impact of nontechnical issues and utility interfaces, will provide the means to assess the overall system capability and cost-effective energy source potential.

Data to support phase III evaluation will be carefully collected and processed to ensure the validity of analysis results. Operational data will be collected through instrumentation built directly into the system and from daily operating logs. Maintenance and cost data will be recorded in maintenance logs and expense ledgers, respectively.

3. Evaluation Objectives

The major objective to be accomplished through technical evaluation is the determination of the operational effectiveness and suitability of the CAPVC system and subsystems, including operational performance and reliability, availability, and maintainability. Specific components subject to degradation will be identified, and the effect of that degradation

Figure VI-1. Overview of Phase III Evaluation Methodology

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on system performance will be determined. Through performance evaluation and system design review, technical problem areas and methods of solution or alternate approaches will be identified.

Economic evaluation of the CAPVC system will first involve the development of a detailed cost structure. This cost structure will then be input to existing or BDM-developed cost models to determine and forecast system cost per unit energy. An important factor in life cycle costing is the acquisition and/or determination of accurate reliability and maintainability (R&M) parameters and costs for input into the cost structure and cost model. The R&M parameters will be obtained through the detailed R&M analysis within the technical evaluation and will be sensitive to minor changes in system design. The system operation and maintenance (O&M) cost will then be derived along with the capital investment cost and input to the cost models. Further objectives of the economic evaluation are to determine the significant cost drivers to the projected system cost and to identify possible enhancements or alternatives which could decrease system cost.

The major objectives to be accomplished through evaluation of nontechnical issues influencing the CAPVC will be recording and analysis of the data gathered on the impacts of those issues and documentation of the results. These issues can be divided into the three major areas of environmental, institutional, and safety (although these areas are not self-contained). Results from this evaluation will be used to verify the phase I Institutional/Environmental Analysis and indicate further areas which have impact on the CAPVC. The summary and documentation of the phase III nontechnical evaluation will be available to assist institutions in decision making which may affect the commercialization of PV systems.

Three basic objectives will be addressed through the evaluation of the CAPVC/utility interface. The first objective is to determine the technical interaction feasibility and requirements, including protective switches and utility devices. The second is to determine and research the factors affecting the concept of distributed PV generating systems. The final objective is to determine the impact of commercial PV systems

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on utility rate structures. A special experiment will be included in this evaluation, involving the direct feedback of PV generated power into the utility. This experiment will demonstrate the feasibility of direct power feedback and the utility interface involved.

C. TECHNICAL EVALUATION PLAN

Technical evaluation will be performed during phase III to determine the operational effectiveness and suitability of the CAPVC system and subsystems. An initial technical evaluation of the system will be ongoing throughout a phase III checkout period scheduled for the first month of phase III operation. This checkout stage will involve the initial quantification of system and subsystem performance to estimate preliminary performance criteria. All phases of data acquisition and processing will be exercised to ensure they are functioning appropriately. Statistical summaries of the transducer data collected through this period will also be evaluated to determine that the data sampling interval is adequate, based on the variability of the data. High variability in certain parameter observations may indicate that a shorter sampling interval is required to more accurately assess that variability. Conversely, low variability would indicate that a longer sampling interval would be adequate, and thus save computer storage space.

The detailed phase III technical evaluation is divided into the areas of operational performance evaluation and reliability, availability, and maintainability analyses. Acquired data for these areas will be evaluated quarterly and will be appropriately documented to provide a constant flow of useful information concerning system operation and performance.

1. Operational Performance Evaluation

The basic objective of the CAPVC operational performance evaluation is to characterize system and subsystem performance during optimal, standard, and long-term operating conditions. This characterization will be accomplished through a series of engineering and statistical analyses on a system and subsystem level.

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a. Subsystem Performance Evaluation

Characterization of most of the CAPVC subsystems will be accomplished through performance-monitoring and observation; little analysis will be required. The intent of subsystem performance monitoring will be to determine whether the subsystems are performing up to preliminary specifications and how long-term operation affects those subsystems in terms of degraded performance. The fluid pump will be evaluated through the monitoring of coolant flow rates and supply pressures. Coolant inlet and outlet temperatures will indicate the performance of the heat exchanger. The thermal storage tank performance will be evaluated through inlet, outlet, and storage temperatures. Inverter efficiency will be monitored and calculated from the input and output voltage and current. The power consumption of the thermal pump, hydraulic tracking pump, and heat rejection unit will also be evaluated to determine the system utility power requirements.

It should be mentioned that the intent of performance monitoring and evaluation described above will not be to monitor the system components for problems and safety factors indicating possible system shutdown. In the event that a harmful situation is realized, system shutdown will occur automatically, via the safety control system.

An important aspect of the subsystem performance evaluation is to determine and understand the relationship between cell and coolant temperature through long-term operation. The heat transfer between coolant and cells is vital to cell safety and optimum system operation. A goal of the heat transfer characterization is to assure that an appropriate coolant temperature can be defined as a safety limit for cell protection. If the Δt (difference in cell and coolant temperature) calculations do not deviate significantly from what would be considered safe, then an optimal coolant temperature, which maximizes cell efficiency while remaining in the cell safety region, will be determined. Degradation of the heat transfer over time would indicate some resistance has developed. This degradation will be carefully evaluated and, if significant, included in the determination of an appropriate coolant monitoring temperature. The heat transfer will be calculated using the 28

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subarray cell temperatures, 4 array coolant inlet temperatures, and 28 array coolant outlet temperatures which are automatically recorded.

Results from the subsystem operational performance evaluation will be documented and will include graphical representations displaying time dependencies and degradation. Conclusions and results, coupled with a design review, may indicate areas for possible improvement or alternatives, which will be addressed.

b. System Performance Evaluation Methodology

The primary measures of system performance are the electrical and thermal energy output of the CAPVC. These measures will be characterized through standard descriptive statistical procedures which include descriptive statistics (means, standard deviations, and confidence intervals) and graphical representations (histograms and variable plots) of power output corresponding to time, insolation, etc. The dependence of power output on a number of factors will be investigated and described further through use of the general linear model technique. Linear models are common statistical tools in data analysis and include the techniques known as regression analysis, analysis of variance, and analysis of covariance. These methods are used to describe the relationship between a response (dependent) variable and quantitative and/or qualitative (independent) variables.

c. Specific Analyses

Because of the large amount of data to be collected and the long time span of the operation period, numerous analyses will be performed for specific time intervals and times of day, e.g., peak power output per day for a particular season of the year. The response and independent variables listed in table VI-1 below will be analyzed through the linear model techniques discussed. Possible categorical levels of the independent variables are also listed. This breakdown of the independent variable measurements will be used to form an analysis of variance model to discover which variables most significantly influence power output.

TABLE VI-1. CAPVC SYSTEM VARIABLES

<u>RESPONSE (DEPENDENT)</u>	<u>INDEPENDENT</u>	<u>LEVELS</u>
1. Electrical Power Output	1. Array Efficiency	Low, Med, High
2. Thermal Power Output	2. Insolation	Low, Med, High
3. Array Efficiency	3. Weather Condition	Clear, Hazy
4. Cell Temperature	4. Cell Temperature	Low, Med, High
	5. Time of Day	Before 10, 10-2, After 2
	6. Time of Year	4 Seasons

Appropriate intervals specifying the levels of the independent variables will be determined after early-on data screening. The independent variable levels may be reduced further to two levels per variable. This would form a 2^6 factorial design for an initial analysis. From there, analysis of the significant contributors to a response variable will consist of fitting regression models to the actual independent variable measurements. It is to be expected that time of day and year will be highly significant to power output. Analysis of covariance will be used to fit separate regression models for each configuration of the levels of the two time variables. These results will be analyzed in detail to discover trends and any power output degradation over time. Note that array efficiency and cell temperature are listed as both response and independent variables. Remaining independent variables may influence these two variables, and analysis will also be performed to determine the extent of that influence.

Projecting the system's power output performance for an extended life cycle will be important in determining the energy potential of PV systems. Changes in PV technology will be incorporated and estimated for input into sensitivity analyses and forecasts to understand the system's long-range potential and the advances that would contribute to that potential. These projections will be accomplished through extrapolation, engineering forecasting techniques, and the predictive regression equations derived.

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Although the CAPVC system does not have energy storage capability, the feasibility of energy storage and peak shaving will be analyzed. The average daily building load and array energy output match-up will be derived and the energy available for storage determined. The cost effectiveness of storing energy during off-peak hours and using stored energy during peak hours will then be assessed through economic evaluation.

Results from the system performance analysis will be in the form of instantaneous and average annual electrical and thermal energy produced by the system, overall array efficiency, and system electrical and thermal efficiencies. Graphical displays relating time and weather effects on these parameters will be produced. The analysis of variance tables and the regression and prediction equations derived will be presented with full rationale.

Data which support the system performance analysis are the array field voltage and current; subarray cell temperatures; coolant inlet, outlet, and storage temperatures (to calculate thermal energy); the inverter output voltage and current; and the combined load voltage and current. These data are recorded automatically through sensors and transducers.

2. Reliability, Availability, and Maintainability Analyses

Reliability, availability, and maintainability (RAM) are key parameters in evaluating the performance, cost effectiveness, and suitability of the CAPVC system. Detailed logs will be maintained throughout the phase III program to acquire the data necessary for deriving these parameters.

a. Reliability

Reliability refers to a measure of system susceptibility to failure. Estimates of CAPVC system and subsystem reliabilities will be based on the failure experience during phase III operation. Failure data will be collected on specially designed forms. The elapsed operating hours and failure information will be used to calculate MTBF (mean-time-between-failures) for systems and subsystems through the equation

$$\text{MTBF} = \frac{\text{total operating hours}}{\text{number of failures}}$$

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This definition may be applied at any level of system detail, depending on the number and complexities of failures. Estimates for more general levels of aggregation are then developed through use of the series/parallel reliability network formulae. It should be noted that the term "failure" is subject to several definitions. For the CAPVC evaluation, failures will be given a wide interpretation to include wear-outs and maintenance-induced problems.

The reliability data and results will serve as inputs into the system availability calculation and the determination of operation and maintenance costs. The significant level of detail to which failure data will be collected will allow the determination of which system components are the major causes of system downtime and which are the primary contributors to high maintenance costs. These components may be singled out as candidates for design modifications to improve reliability, with the intent of reducing life cycle costs.

The CAPVC reliability analysis will have two distinct sub-analysis stages. The first stage analysis will utilize the failure data from the CAPVC operation as it is currently configured throughout the operation period. The second stage analysis will use the collected data and results from the first stage as a basis for extrapolation to estimate the "mature system" reliabilities. Basic projection techniques that assess reliability as a function of time, experience with the system, and "burn in" (initial operating period in which failures may occur due to lack of familiarity with the system) of the hardware will be employed.

b. Maintainability

Maintainability is a measure relating the ease with which system and subsystem failures are corrected. The necessary information to determine system requirements for both scheduled and unscheduled maintenance actions will be acquired and derived from the maintenance data collected during phase III CAPVC operation and evaluation. Data items to be collected include: date, operating hours until failure (both cumulative and since last failure), component(s) that failed, man-hours to repair; expertise required to repair, description of corrective action, and materials consumed during repair (including replaced parts).

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The collected raw data will be summarized and reduced into measures such as MTTR (mean-time-to-repair) for the various components, and system-level measures such as the mean scheduled maintenance interval. The bulk of this data reduction will be accomplished through descriptive statistical techniques including means, standard deviations, confidence intervals, and frequency distributions. In addition to summarizing or characterizing the CAPVC system and subsystem maintenance behavior, predictions of steady-state mature system maintenance requirements will be produced. These projections allow for a more realistic assessment of the maintainability of commercial PV system applications.

c. Availability

Availability is a measure relating the likelihood that a system is operational at any instant in time. CAPVC system availability will be an important factor in the top-level evaluation of system capability. The results from the reliability and maintainability analyses are used in the evaluation of system availability which, in conjunction with the system operational performance evaluation, is used to determine the operational effectiveness and suitability of the CAPVC system. Availability is defined as:

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MDT}}$$

where MTBF = mean-time-between-failures, and
MDT = mean-down-time.

Mean-down-time includes MTTR and the time associated with logistic delays, system start-up, etc. The definition of availability may vary between applications which incorporate maintenance actions being performed during inoperative hours, such as nighttime or cloudy day maintenance actions on the CAPVC system, or continued system operation in degraded states. The CAPVC availability analysis will not be limited to a single equation, and the selection of which equation(s) to use will depend on the extent to which the system is subject to the situations discussed above.

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Availability measures the extent of hardware readiness. Environmental effects, such as weather delays, will be treated as external factors to the availability calculation, but will be incorporated into the evaluation. Similarly, the availability analysis will accommodate the fact that the system may continue to operate in the presence of certain modes of degradation. Failure of some system components, such as the coolant pump or tracking system, would be considered a catastrophic failure and result in a system shutdown. Other failures, such as a malfunctioning PV cell or natural degradation of the reflective surface, may result only in degradation to the total system performance. Under these circumstances, the system may continue to operate, either by choice or due to lack of detection of a failure arising between scheduled maintenances. Accounting for the system operation in degraded states into the availability measure is difficult. Estimation techniques incorporating these effects exist and will be researched during the evaluation.

As in the reliability analysis, two separate availability evaluations will be performed. The first considers the CAPVC system as it performs during the evaluation period. The second will involve availability determination based on extrapolation to the system performance that may be expected from a mature operating system. The SOLMET weather tapes will be used to access the long-term weather conditions for these projections.

d. Data Requirements

The RAM analysis data requirements will be collected on special operation and maintenance logs, with the following data items to be recorded: 1) date, 2) time, 3) failed component, 4) description of failure and result on system (shutdown or continued operation), 5) man-hours for repair or replacement (duration and number of people), 6) materials consumed in repair (solvents, grease, solder, etc.), 7) spares required, 8) skill level of person(s) required, 9) repair details, and 10) downtime.

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D. ECONOMIC EVALUATION PLAN

1. Overview

The phase III evaluation plan includes an economic assessment of the CAPVC system. This analysis will consider the cost of the system, as configured at the start of phase III, and a forecast of costs attainable in the future, given increased commercial application of system components and technological advances. Costs will be developed for each element of the system life, including design and development, hardware procurement and installation, and operation and maintenance (O&M). Procurement costs encompass the costs for special servicing and maintenance equipment, spares, repair handbooks, and training courses (if any), as well as the primary system equipment. An overview of the economic analysis is provided in figure VI-2.

The goal of the economic analysis will be to collect extensive cost, reliability, and maintainability data on the CAPVC for input to a cost model. The model will then be used to derive the costs needed to compute a levelized busbar energy cost and an overall system ownership cost for use in evaluating the economic feasibility of this PV application, and for uniform comparison with other systems and energy alternatives. After baseline estimates are established, analyses will be performed to examine the economic possibilities available from a mature PV system.

2. Cost Breakdown Structure Development

The first step in the phase III economic evaluation will be the development of a CBS (cost breakdown structure). Careful development of the CBS will assure that all costs are accounted for and that no double counting of costs is possible. Each element of the system life cycle will be included in this chart of accounts. The detailed reliability and maintenance analysis results will be used to obtain accurate information relating system O&M costs for both the phase III period and projected system life cycle. O&M costs are often the most unknown and underestimated costs in an economic evaluation. As part of the CBS, costs will be categorized as relevant system costs or special, one-time costs for this

Figure VI-2. Cost Methodology Flow

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application. This breakdown will provide the special costs enabling the accurate cost accounting for phases II and III of the CAPVC and the relevant costs to be used in the determination of life cycle costs for commercial PV systems. Some of the items in the CBS are depicted in figure VI-2.

3. Cost Model Development

The cost model refers to a set of accounting equations that translate resources into costs. Elements of the CBS will be aggregated into appropriate blocks to form inputs to the cost model. The model then applies inflation and discounting factors to develop a cost measure for the system, one which facilitates comparison with other PV systems and energy alternatives.

There exists several cost models that provide a framework for this analysis. The basic model developed by the Jet Propulsion Laboratory for DOE/EPRI is outlined in the report, "The Cost of Energy from Utility Owned Solar Electric Systems." Two additional models, SOLCEL and BUCKS, have been developed to incorporate and expand on the EPRI method. These existing models provide a basis for the economic assessment of the CAPVC. In addition BDM has developed the ECON1 cost model program which also implements the EPRI algorithms.

During the phase III evaluation, extensive data on system reliability, maintainability, and operations will be collected. This information will be used as input to the calculation of O&M costs at the detailed component level, and this calculation will require new modeling efforts. This detailed approach will allow for increased visibility into the system elements that drive the O&M costs. Once these "drivers" have been isolated, possible design corrections or alternatives may be considered and the O&M costs re-estimated for input into the model.

In addition to evaluating the then current phase III CAPVC system, cost modeling will be performed to assess its economic capability for projected future R&M conditions. This analysis implies the need for the costing of the forecasted system reliability and maintainability to mature system operation. The cost predictions will be tailored to the peculiar system elements. "Off-the-shelf" components may exhibit little

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change in costs with increased reliability, while advanced components will likely undergo considerable R&M advances with significant changes in costs.

Finally, cost projections will be required to estimate the economic impacts of anticipated technology advances, widespread commercialization of PV energy systems, and the resulting mass production of system components. These forecasts will be based on analogy with the improvements experienced in similar technologies and the formal forecasting techniques in the literature.

4. Data Requirements

The economic evaluation will require the acquisition and reduction of a considerable amount of detailed system data, including purchase costs of the system hardware, installation costs, failure data, maintenance repair times, maintenance materials consumed during repair and their costs, operating hours, etc. A variety of methods will be used to capture this data. Procurement costs will be based on purchase and expense ledgers; labor logs will be maintained for recording the costs of installation, checkout, and start-up; and the special log forms previously mentioned will record the operating hours, conditions, modes of degradation, and maintenance actions.

The raw cost data and results from the RAM analysis will require manipulation for input into the accounting equations forming the cost model. Descriptive statistical techniques form the primary data reduction method. Examples are the MTBF and MTTR measures from the R&M analysis for specific components and the average materials costs per repair measure.

5. Analysis Procedures

Once the cost model has been fully developed and the input data are assembled, several analyses will be conducted. A baseline cost analysis will be performed using the manipulated cost and R&M data collected on the phase III CAPVC system.

Results from these analyses will include estimates of the levelized busbar and private ownership costs for the CAPVC, assuming no improvements in technology, reliability, etc., over the projected system

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life. In addition, since the model will function at a detailed level, sensitivity analyses will be executed to indicate the cost driving components of the system. These elements will then be subject to critical study to determine alternatives for the reduction of costs, such as reliability improvement, lower unit costs, etc.

Another major analysis will consider the effects of system improvements that are likely by the mid 1980's. An improvement in levelized busbar costs and private ownership costs may result through increased commercialization of system elements, technology advances that increase reliabilities and/or reduce costs, or changes in government regulations or tax policies that promote solar concepts. A related analysis will consider the reduction in costs that result from mature system operation. In this case, the projected steady-state R&M values and costs will be used, as opposed to the prototype phase III experience.

Further results will be obtained from sensitivity studies for the above projected conditions. By systematically examining the effects of variations in baseline and projected parameters, the system variables that exert the greatest leverage on costs will be determined. Because of the inherent uncertainty in baseline parameters and projections, sensitivity analyses will enhance evaluation results, especially if they indicate that results are relatively unaffected by parameter variations.

E. EVALUATION OF NONTECHNICAL ISSUES

The evaluation of the impacts of nontechnical issues on the CAPVC will provide information on factors which may be critical to the future commercialization of PV technology. Environmental issues to be evaluated include collector reflection, RF interference, toxic materials, and human factors. Institutional issues of importance are the legal, financial, tax, insurance and liability, and sociopolitical factors involved in PV system operation. Results from hazards analyses and determined operational safety requirements are the safety issue factors that affect system design, operation, and maintenance.

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BDM has evaluated these issues in the preliminary phase I Environmental/Institutional Analysis (chapter IV). The key issues identified during phase I will be examined using the actual data obtained through phase III operation. More accurate and/or updated information on the impacts of the above-mentioned issues on the CAPVC will be acquired, evaluated, and documented.

Results of the technical and economic evaluations of the CAPVC will be utilized to address the nontechnical aspects of the PV application. Any nontechnical issues which affect system fabrication and installation during phase II will be documented and included in the phase III evaluation. The CAPVC program can make a substantial contribution to future PV applications by providing information on specific issues that may have an impact on policy development. The required data, results, specific evaluation areas, and major institutional concerns to be addressed are presented in figure VI-3.

To promote the solar energy industry, representatives of various institutions will be encouraged to visit the CAPVC facility to facilitate a first-hand understanding of the system. Loan officers, property appraisers, insurance loss prevention analysts, building and zoning officials, and other institutional decision makers will be given the opportunity to gain a valuable perspective on PV applications. This interaction should stimulate understanding and confidence in the commercialization of PV systems.

As mentioned above, the operational performance and cost data and the results from technical and economic evaluations will be acquired, summarized, and evaluated for their impact on nontechnical issues. In addition, data will be collected for each occurrence of a nontechnical factor affecting the system operation. These factors include accidents; natural damage; CAPVC/utility interface; conclusions reached regarding liability, insurance, and legal issues; and other pertinent factors. The complete data collection will be accomplished through the data acquisition plan which includes the existing BDM Management Information System and special logs. The pertinent data and evaluation results will be summarized

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Figure VI-3. Evaluation of Nontechnical Issues

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and made available for the evaluation of these results by government agencies, financial institutions, insurance companies, utilities, and commercial users.

F. EVALUATION OF UTILITY INTERFACE

The factors involved in the technical, nontechnical, and economic CAPVC system/utility interfaces form another area that significantly affects the future commercialization of PV technology and its cost-effective energy source potential. Goals of this phase III evaluation are to determine how the utility perceives the system and the interactions between the two.

Technical interactions between the CAPVC and the utility include the protective and normal switch gear involved with the parallel system and utility power feed to the building bus, the necessary disconnect safety switches for servicemen, and other required utility devices for load monitoring and rate determination. A protective switch which will avoid system power feedback into the utility bus will be installed during phase II. Evaluation will determine whether the system switch gear are performing as planned and that no problems occur, i.e., that no unintended power feeds back into the utility. Technical problems will be pinpointed and alleviated.

Anticipating the future widespread commercialization of PV systems, the utility interface with a large number of systems, as opposed to the special CAPVC arrangement, will be assessed. The concept of feeding the power generated by these systems back into the utility will be investigated to determine how the utility would handle the situation and whether the concept is more of a problem than it is beneficial. Utility impact on power generation building plans and rate structures for the large number of systems will be evaluated. A special experiment, scheduled during phase III, will support this evaluation. The experiment involves the planned feedback of CAPVC generated power back into the utility grid. The experiment will be exercised in conjunction with the utility to

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determine whether the power can be fed back to the utility in sufficient quantity and quality to be useful.

The impact of solar generated power on the utility rate structure and the impact of modified rate structures on future PV systems will be investigated. Before system operation begins, meetings with the utility will take place to determine whether they will set up a separate rate structure for the CAPVC. This, in turn, will affect the life cycle cost of the system and its long range cost effectiveness potential. Peak shaving and time of day pricing will also affect utility rates and pose a problem in the utility's accounting for the amount of peak load shaved. With a large number of systems involved in peak shaving, the peak may even shift to a different time of day. This investigation will require close work with the utility to provide for the evaluation of these factors and their impact on PV systems.

Information and data for the assessment of utility impact will be recorded in special log books which will address any problem areas. The rate structure impacts will be folded into the economic analysis. In addition, results from phase III evaluation will be provided to PNM to determine whether they have any new impact on rate structures.

G. OPERATION PLAN

The CAPVC system will be operated by BDM during the phase III period. Throughout system design, the intent has been to keep the system operation as simple as possible. Daily start-up and shutdown will be automatic and require no supervision. Poor weather conditions and/or any component malfunctions that necessitate shutdown will be automatically sensed through instrumentation linked to the system and result in automatic shutdown. Warning lights on the system control panel will indicate the cause of any shutdowns. Thus, system operation responsibilities will basically involve only the monitoring of system operation and instrumentation data acquisition, manual data recording in operation and maintenance logs, and scheduled and unscheduled maintenance duties. One of the tasks

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of phase III will be the production of a detailed operation and maintenance manual, to be completed 90 days from the start of phase III.

Key personnel required during day-to-day system operation are a test engineer and a data technician. Data technician responsibilities involve system monitoring during operation, daily upkeep of the operating and maintenance logs, assistance with operating the computer data peripherals and data reduction, observing and recording any system shutdowns and component failures, and simple scheduled and unscheduled maintenance actions. The engineer will be in charge of overall system operation and the data technician will report to him should any problems arise. Duties of the test engineer involve the organization of all aspects of system operation, including the detailed maintenance actions, scheduling and ordering of replacement parts or spares, and the timely progression of phase III evaluation procedures.

The efficient completion and recording of all scheduled and unscheduled maintenance actions will directly influence system operation evaluation. Scheduling of required maintenance will be accomplished after the system has been fully operational for the first 2 months of phase III and the repair requirements have been determined. Foreseen scheduled maintenance actions include mirror cleaning; the cleaning and deaeration of the coolant fluid; normal maintenances required for the upkeep of the hydraulic system in the tracking unit, pumps, and heat rejection unit; and the overall system inspection including control panel interfaces and data recording instrumentation.

BDM has established security and safety procedures for controlling access and protecting individuals and equipment during phase III operation. Entry to the control room and array areas, controlled by the use of cypher locks, will be restricted to CAPVC personnel only. CAPVC personnel will escort all visitors and nonprogram individuals for tours of the facility.

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H. PHASE III DATA ACQUISITION

Listed in table VI-2 are the technical, economic, and nontechnical data which will be collected through and during system operation; the source and frequency of the data collected; and the type of record which will be kept.

Careful attention has been paid to acquire all DOE required data where appropriate to this application. Data items listed in table VI-2 and the subset of data to be recorded via instrumentation during system operation, detailed in table VI-3, together fulfill the specifications in the "Uniform Data Requirements and Data Collection Techniques," section V of the Phase I Contractor Initiation document. All transducer data will be sampled at 2-minute intervals, thus providing adequate data to be averaged across the minimum sampling intervals specified by DOE. Logs will be kept current, and all data will be furnished in accordance with the required DOE schedule. A sample unscheduled maintenance log is presented in figure VI-4.

Once the GFE Onsite Data Acquisition System and peripherals have been specified and the DRC (Data Reduction Center) requirements determined, data management plans will be determined to facilitate the phase III data analysis plan. Specifics which require attention include the transducer data storage medium, its compatibility with computer systems which have data analysis packages (statistical programs, SOLCEL, etc.) required for phase III evaluation, and the reduced data format provided by the DRC.

I. TASK BREAKDOWN AND SCHEDULE

Specific phase III tasks have been carefully derived and scheduled to insure complete and timely CAPVC operation and evaluation. The phase III task breakdown and schedule of key milestones are presented in tables VI-4 and VI-5 respectively.

TABLE VI-2. PHASE III DATA ACQUISITION

<u>DATA ITEM</u>	<u>DATA TO BE COLLECTED</u>	<u>SOURCE/FREQUENCY</u>	<u>TYPE OF RECORD</u>
1. PURCHASED EQUIPMENT COSTS	COSTS OF ALL EQUIPMENT DATE OF ORDER DATE OF RECEIPT	BDM PURCHASE ORDER MATERIAL INSPECTION RECEIVING REPORT	SPECIAL LOG
2. CAPITAL AND CONSTRUCTION COSTS	INSTALLATION LABOR MATERIAL	SUBCONTRACTOR INVOICES BDM PURCHASE ORDERS	SPECIAL LOG
3. PERFORMANCE DATA	TRANSDUCER DATA LIST, SEE TABLE VI-3	TRANSDUCER RECORDED EVERY 2 MINUTES	COMPUTER FILE STORAGE
4. METEOROLOGICAL DATA	ITEMS IN DOE REQUIREMENTS	GFE WEATHER STATION, RECORDED EVERY 2 MIN.	COMPUTER FILE STORAGE
5. OPERATION CHARACTERISTICS	DAY AND TIME NOTICE OF COMPONENT DEGRADATION OR FAILURE RESULT ON SYSTEM (CONTINUED OPERATION OR SHUTDOWN) CAUSE AND DURATION OF DOWN TIME OR DEGRADED OPERATION TYPE OF EQUIPMENT FAILURE CAUSE OF EQUIPMENT FAILURE LENGTH OF TIME IN SERVICE	EACH OCCURRENCE	DAILY OPERATING LOG
6. MAINTENANCE, REPAIR, CLEANING	DAY AND TIME DESCRIPTION OF MAINTENANCE ACTION MAN-HOURS REQUIRED MATERIALS CONSUMED SKILL LEVEL REQUIRED COSTS OF LABOR, REPLACEMENTS, MAINTENANCE EQUIPMENT, AND MATERIALS	AS CONDUCTED, SCHEDULED AND UNSCHEDULED	MAINTENANCE LOG
7. SAFETY	OPERATION AND MAINTENANCE ACCIDENTS--TYPE, CAUSE, HAZARD, CORRECTION REQUIRED	EACH OCCURRENCE	ACCIDENT LOG
8. NONTECHNICAL CONSIDERATIONS	ENVIRONMENTAL, INSTITUTIONAL AND SAFETY IMPACTS AND RESULTS	EACH OCCURRENCE, MEETINGS	SPECIAL LOG
9. UTILITY INTERFACE	IMPACT ON RATES, LOAD SHARING, SWITCHING PROCEDURES	PLANNED MEETINGS, EACH OCCURRENCE OF PROBLEMS	SPECIAL LOG
10. INVERTER OUTPUT HARMONIC CONTENT	INVERTER OUTPUT PHASE ANGLE	SPECIAL MEASUREMENTS	SPECIAL LOG

TABLE VI-3. TRANSDUCER SAMPLED DATA ITEMS

<u>CATEGORY</u>	<u>ITEM</u>	<u>MEASUREMENT</u>	<u>QUANTITY</u>	<u>COMMENT</u>
Array and Subsystem Performance	1	Array Subfield Current	14	Performance & Quality Control
	2	Array Field Voltage	2	Same as Inverter Input Voltage
	3	Array Field Current	1	Same as Inverter Input Current
	4	Subrow Surface Temperature	28	Subarray Safety - Overtemp Alarm
	5	Inlet Coolant Temperature	4	One at Each End of Two Inlet Manifolds Also Heat Exchanger Outlet Temperature
	6	Outlet Coolant Temperature	28	Subfield Array Performance
	7	Coolant Flow Rate	1	Array Performance, Efficiency, Safety
	8	Main Coolant Supply Pressure	1	System Safety -- Flow Loss Alarm
	9	Heat Exchanger Coolant Inlet Temp	1	H.E.* Efficiency, Maintenance (Provided by Builder)
	10	Heat Exchanger Coolant Outlet Temp	1	H.E.* Efficiency, Maintenance
	11	Potable Water Storage Temp	4	Status, System Safety
	12	Potable Water Inlet Temperature	1	Measure Energy Transfer to Storage Tanks
	13	Potable Water Outlet Temperature	1	Measure Energy Transfer to Storage Tanks
	14	Heat Rejection Coolant Inlet Temperature	1	Measure Rejected Energy
	15	Heat Rejection Coolant Outlet Temperature	1	Measure Rejected Energy
AC Power System Performance	16	Inverter Output Voltage (3 Legs)	3	Array/Inverter Efficiency & Performance
	17	Inverter Output Current (3 Legs)	3	Array/Inverter Efficiency & Performance
	18	Inverter Output VARS, KWHRS	1	Array/Inverter Efficiency & Performance
	19	Combined Load Voltage (3 Legs)	3	Total Building Load Measurement
	20	Combined Load Current (3 Legs)	3	Total Building Load Measurement
	21	Combined Load VARS, KWHRS	1	Total Building Load Measurement

*H.E. - Heat Exchanger

OPERATIONAL DETAILS					REPAIR DETAILS				
DESCRIPTION OF FAILED COMPONENT S/N	DATE AND TIME OF FAILURE	DETERMINED CAUSE OF FAILURE	EFFECT ON SYSTEM OPERATION	CUMULATIVE OPERATING HOURS UNTIL FAILURE	MAN-HOURS FOR REPAIR	SKILL LEVEL REQUIRED	REPAIR ACTIVITY PERFORMED	MATERIALS CONSUMED, COSTS	SYSTEM AVAILABLE DOWN-TIME

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Figure VI-4. Sample Unscheduled Maintenance/Repair Actions Log Sheet

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TABLE VI-4. PHASE III TASK BREAKDOWN

Task 1.1	<u>PV-C SYSTEM OPERATION AND MAINTENANCE</u>
1.1.1	Operation and Maintenance of System Elements
1.1.1.1	Day-to-Day Operation
1.1.1.2	Scheduled Maintenance of Subsystems
1.1.1.3	Unscheduled Maintenance of Subsystems
1.1.2	Site Maintenance
1.1.2.1	Structural Integrity Checks
Task 1.2	<u>SYSTEM DATA ACQUISITION</u>
1.2.1	Implement Data Acquisition Plan
1.2.1.1	Acquire Operational Performance Data
1.2.1.2	Acquire Maintenance Action Data
1.2.1.3	Acquire Economic Data
1.2.1.4	Acquire Information on Nontechnical Impacts
1.2.1.5	Acquire Information on Utility Impact
1.2.2	Data Verification
1.2.3	Data Storage and Documentation
1.2.4	Data Reduction
Task 1.3	<u>SYSTEM ANALYSIS AND EVALUATION</u>
1.3.1	One Month Check-Out
1.3.1.1	Initial Performance Quantification
1.3.1.2	Establishment of Preliminary Performance Criteria
1.3.2	Technical Performance Evaluation
1.3.2.1	Assessment of Operational Performance
1.3.2.2	Reliability, Availability, and Maintainability Evaluation
1.3.3	System Economic Evaluation
1.3.3.1	Development of Cost Breakdown Structure
1.3.3.2	Model Operation and Maintenance Costs
1.3.3.3	Life Cycle Cost Analysis
1.3.4	Evaluation of Nontechnical Impacts
1.3.4.1	Environmental Issues
1.3.4.2	Institutional Factors
1.3.4.3	Safety Factors
1.3.5	Evaluation of Utility Interface
1.3.5.1	Technical Interaction
1.3.5.2	Distributed Generation Concept
1.3.5.3	Rate Structure Impact
1.3.5.4	Direct Power Feedback Special Test
1.3.6	System Design Review
1.3.6.1	Identification of Component and Design Problems
1.3.6.2	Determination of Solutions or Alternative Approaches
Task 1.4	<u>REPORTING AND DOCUMENTATION</u>
1.4.1	Preparation of O&M Manual
1.4.2	Preparation of Monthly Interim Reports
1.4.3	Preparation of Final Report
Task 1.5	<u>TECHNICAL/PUBLIC LIASON</u>
1.5.1	Conduct Briefings for the Technical Community
1.5.2	Conduct Briefings, Provide Illustrative and Operational Displays for Public Awareness
1.5.3	Provide Interchange with Institutional and Research Organizations

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TABLE VI-5. SCHEDULE OF KEY MILESTONES

<u>MILESTONE</u>	<u>MONTHS FROM PROGRAM START</u>
1. PREPARATION OF DATA LOGS	1
2. COST BREAKDOWN STRUCTURE	1
3. PERFORMANCE/ECONOMIC MODEL CHART	1
4. INITIAL PERFORMANCE EVALUATION AND DOCUMENTATION	1
5. OPERATING AND MAINTENANCE MANUAL	3
6. QUARTERLY PERFORMANCE EVALUATION AND DOCUMENTATION	QUARTERLY
7. REPORTS	
TECHNICAL PROGRESS AND MANAGEMENT	MONTHLY
FIRST YEAR REPORT	12
FINAL REPORT	24
8. EXTENDED OPERATION & SUMMARY REPORTS	24 TO 60

The initial months of phase III will require concentrated effort to prepare for the evaluation program. Preparation of the data logs and cost breakdown structure will be accomplished within the first month of the program. The system performance, economic analysis, and statistical computer program will also be installed and checked out during the first month of phase III. The initial system performance will then be evaluated and documented, and will serve as a reference for all subsequent evaluation and analysis. By the end of the third month, a complete operation and maintenance manual will be provided for use throughout the program.

After the initial preparation, all operation, data acquisition, maintenance, and liason will progress in a continous, parallel manner. Summary evaluation will be performed on a quarterly basis. The results of these analyses will be included in the monthly documentation. Complete, comprehensive reports will be provided at the end of each year of

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phase III operation. After the conclusion of phase III, the CAPVC system will be maintained and operated by BDM, and summary performance reports will be provided for a period of 5 years.

APPENDIX A
SOLAR TEST FACILITY DESCRIPTION

The BDM Solar Test Facility (STF) is located atop a BDM-occupied office building in the Newport Industrial Park, in Albuquerque, New Mexico. The rooftop site was chosen to avoid solar shadowing from nearby buildings and geographical features and for security reasons. There is ample space to allow for future facility expansion.

The STF was built for component development and prototype testing of CAPVC subsystems. It is designed for acquisition and analysis of electrical, thermal, flow, pressure, and meteorological data. There are three main functional and physical areas: (1) collector area, (2) mechanical area, and (3) control and data acquisition area. The collector and mechanical area are shown in figure A-1 while the control and data acquisition area is presented in figure A-2.

The collector area is located on the rooftop. It is comprised of two linear parabolic trough (LPT) concentrators with photovoltaic receiver tubes, collector drive and support pylons, collector tracking sensors, hydraulic pump unit, instrumentation junction boxes, and meteorological sensors. A flexible mounting system was incorporated to examine both east-west and north-south collector orientations. The LPT concentrators were manufactured by Solar Kinetics, Incorporated (SKI) of Dallas, Texas. Both concentrators are 20-feet in length, one continuous and one divided into two ten-foot sections for examining the effects of concentrator gap spacing on receiver tube performance. The concentrators track only in the vertical plane normal to the concentrator axis.

The concentrator tracking system is hydraulically actuated. A hydraulic pump charges an accumulator reservoir which supplies pressure to drive a piston in the tracking drive pylon without constantly running the pump when minor tracking corrections are required. The pump runs only when the accumulator pressure drops below a preset level.

The tracking system is controlled with a shadow bar differential light sensor and control relays which open fluid valves and allow the

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TRACKING LINEAR PARABOLIC
TROUGH SOLAR COLLECTOR

THREE PIECE EXTRUDED
ALUMINUM RECEIVER TUBE

HEAT EXCHANGER, PUMP, AND
THERMAL EXPANSION TANK

WIND SPEED AND
DIRECTION SENSORS

TRACKING DIRECT NORMAL
SOLAR RADIATION DETECTOR
(PYRHELIOMETER)

RAIN DETECTOR

STF LOCATION

TOTAL HEMISPHERICAL SOLAR
RADIATION DETECTOR (PYRANOMETER)

Figure A-1. BDM Solar Test Facility Collector and Mechanical Areas

CRT TERMINAL AND LINE PRINTER

PCM-12 MINICOMPUTER AND
DUAL FLOPPY DISC DRIVES

INSTRUMENTATION
RACK

CONTROL AND INSTRUMENTATION ROOM

Figure A-2. BDM Solar Test
Facility and Data Acquisition Area

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hydraulic system to drive the concentrator. While tracking, the concentrator is aligned in a plane formed by the sun and the concentrator axis. Pointing accuracy of the tracking system is within five milliradians (less than one-third of a degree), while the instantaneous field-of-view of the collector is approximately two degrees.

All receiver tube instrumentation is connected to the control and data acquisition area at the junction boxes. This allows maximum flexibility in sensor placement and reconfiguration and expedites troubleshooting.

Meteorological instrumentation includes ambient temperature, wind speed and direction, precipitation, total hemispherical solar radiation (pyranometer) and direct solar radiation (pyrheliometer) sensors. These are also connected to the data acquisition system.

The mechanical pad area is located at ground level on the south side of the building on which the collectors are mounted. This area contains the coolant fluid pump, thermal expansion tank, pot feeder, air trap, pressure relief valves, and the heat rejection unit. Standard plumbing connects the collectors to the mechanical pad area.

The pump is a low-temperature centrifugal model rated at 10 gallons per minute (GPM) at 170 feet of head. The flow rate can be continuously adjusted by means of a butterfly throttling valve. Flow rate is measured directly on an analog meter connected to an in-line differential pressure sensor.

Thermal expansion of the fluid is absorbed by a pressurized, bladder-type expansion tank, connected to the coolant fluid line. An in-line air trap prevents buildup of bubbles in the coolant fluid and vents the air to the atmosphere. A pressure relief valve prevents excessive buildup of pressurization in the coolant fluid due to blockage or excessive thermal expansion. A pot feeder is included for the addition of chemicals to the system.

Heat rejection from the coolant fluid loop is accomplished by a closed-circuit evaporative cooling tower. A standard line, off-the-shelf

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cooling tower (Baltimore Aircoil) was specially modified to allow heat rejection rates from 180 to 2600 BTU/min. This was done by installing extra inlet and outlet taps on the closed-loop serpentine coil of the heat exchanger. Manifolding was added to the main inlet and outlet lines to allow a wide selection of heat rejection rates.

The control and data acquisition area is located indoors at ground level (see figure A-2). The control rack, minicomputer, disk drives, terminals, and plotter are located in this area, which also serves as a visitor's center with informative displays.

Primary control of the concentrators and electrical systems is accomplished from the control rack. Individual concentrators can be raised or stowed, and modules of photovoltaic cells can be activated for examination of electrical characteristics. Hazard indicators are also located in the control rack as well as hazard overrides for trouble-shooting. The collectors will stow automatically under conditions of excessive coolant fluid temperature, loss of coolant fluid flow, excessive wind, or precipitation. These safety features were incorporated primarily for protection of the hardware. Personnel protection is provided by a limited access entry to the control room and stairway leading to the rooftop. The mechanical pad area is enclosed by a chain link fence with a locked gate.

All signals from the electrical, thermal, pressure, and meteorological sensors located throughout the system are connected to a 96-channel signal conditioning unit in the control rack. Here the analog signals are conditioned to a uniform voltage range and converted from analog to digital format.

The digital signals from the signal conditioning unit are interfaced to the minicomputer, which executes the data acquisition and reduction programs, and displays the data on either the cathode ray tube (CRT) or the line printer.

Program execution is controlled from the CRT terminal. The real-time output of the test data is available on the CRT. Hard copy data can be produced on the line printer.

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Computer programs and test data are stored on a dual floppy-disk drive. Floppy disks lower the execution time for large programs and enhance the storage capacity of the computer. Stored data can be retrieved for post-test data reduction.

The line printer also has the capability, through an integral acoustic coupler, to access larger mainframe computers for the purpose of greater computing power or peripheral options. The line printer also has a dual cassette tape drive for program and data storage and functions as a backup terminal for the CRT.

A digital plotter is connected to the computer system for use in data display.

A visitors center is also located in the control and data acquisition area. Various displays of system components are included as well as pictures of the full-scale subsystems. A visitors log is maintained.

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APPENDIX B

SOLAR TEST FACILITY TEST SETUP FOR CAPVC

The Solar Test Facility was highly instrumented to provide for prototype test and evaluation of CAPVC system components. The included instrumentation was designed primarily for the thermal and electrical characterization of the photovoltaic receiver tube assembly. A description of the transducers and their locations is presented in figure B-1.

Objectives of the heat transfer and flow characterization tests were to determine the temperature profile of the receiver tube in both the axial and radial directions and to study the fluid pressure and temperature distributions.

The electrical characterization tests were designed to measure output performance, determine the current-voltage relationships of the photovoltaic cells, study end-shadowing effects, examine bypass diode network behavior and configurations, and to study the reaction of the system to transients.

The overall system performance was determined from results of the above testing for use in extrapolation to the full-scale system.

Surface temperature sensors consist of a wire-wound resistance element thermistor, laminated into a flat configuration between thin layers of flexible insulation. They provide fast, accurate sensing of surface temperatures from -148°F to $+446^{\circ}\text{F}$. Accuracy is ± 1 percent of the resistance value. Surface temperatures were sensed at 16 positions along the receiver tubes of the solar collectors.

Fluid temperatures were measured using tip-sensitive probe-type resistance temperature detectors inserted directly into the stream of the coolant fluid at eight positions throughout the fluid loop (see figure B-2). Six of the probes are located at the four ends and two midpoints of the two receiver tubes while the other two probes are located at the inlet and outlet of the heat rejection unit (BAC). The fluid temperature probes are accurate within ± 0.5 percent of the resistance value over the range of -148°F to $+466^{\circ}\text{F}$.

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SOLAR TEST FACILITY INSTRUMENTATION

SURFACE TEMPERATURES (16)

**FLUID TEMPERATURES (6)
+ BAC (2)**

PRESSURES (4) + ΔP (1)

VOLTAGE MONITORS (24)

CURRENT MONITORS (8)

Weather Station

• DENOTES A SENSOR LOCATION

Figure B-1. CAPVC Instrumentation Locations

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Absolute fluid pressures are sensed at the four ends of the two receiver tubes (figure B-2) to determine pressure differentials across each receiver tube for determination of pumping losses. The pressure transducers are solid state devices measuring zero to thirty pounds per square inch absolute (PSIA) pressure with an accuracy within ± 0.1 PSIA.

Coolant fluid flow rate is measured with an in-line differential pressure sensor connected to an analog meter reading directly in gallons per minute (GPM). Flow rate is adjustable from zero to 15 GPM by means of a butterfly throttling valve.

Photovoltaic cell output voltages are sensed at twenty-four locations along the receiver tubes. Cell output currents are measured at eight positions.

Both the solar direct and total (direct + diffuse) radiation are measured. A clock-driven tracking pyrheliometer measures the direct component while a horizontally-mounted stationary total hemispherical pyranometer measures the total radiation. Measurements are accurate to within ± 0.5 percent.

Other environmental instrumentation includes ambient temperature, wind speed and direction, and a precipitation detector.

All signals from the electrical, thermal, pressure, and environmental sensors are hard wired to a 96-channel analog signal conditioner located in the control rack in the ground-level control and data acquisition area. The signal conditioner provides a reference voltage for the resistive sensors, and scales all signals to a range of 0 to 10 volts DC. The conditioned signals are wired to a switching matrix which feeds a ten-bit (one in 2^{10} resolution) high-speed analog-to-digital (A/D) converter.

A 12-bit minicomputer receives the output of the A/D converter and displays the data on the line printer or the cathode-ray tube (CRT) terminal. The mini computer uses high-level BASIC software for executing the data acquisition and reduction programs, with program execution controlled from either the CRT or the line printer. Programs and test data are stored on floppy disks in a dual floppy disk drive.

Figure B-2. Coolant Fluid Temperature and Pressure Probe Installations

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The current and voltage outputs of all or part of the photovoltaic array can be selectively connected, by means of a patch panel, to the control rack for detailed examination of the electrical output characteristics. Photovoltaic modules can be electrically connected in numerous series and parallel configurations. Purely capacitive loads of 2.1 to 33.6 microfarads can be applied to simulate battery storage and to examine transient effects on the system output. A constant voltage load can also be applied for obtaining output current versus voltage curves and for determining peak power outputs, as shown in figure B-3. Any combination of purely resistive, purely capacitive, and constant voltage loads may be applied to any portion of the photovoltaic array.

Post-test data reduction has been accomplished by retrieving the stored data from the floppy disk, and displaying the reduced data on either the CRT, line printer, or digital plotter. More extensive data reduction can be accomplished through an acoustic coupler located on the line printer, which can access larger mainframe computers with more powerful computing abilities and output options.

Figure B-3. Photovoltaic Cell Characteristic Curves

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APPENDIX C CIRCUIT ANALYSIS PROGRAMS

A. INTRODUCTION

Circuit analysis studies were carried out in the CAPVC program utilizing the NET-2 program and a simplified approach implemented on the HP-9830. This appendix presents a basic description of the NET-2 program, including a description of the PV cell and junction diode models utilized in the analysis. It also includes a description of the HP-9830 program.

B. NET-2

The NET-2 Network Analysis Program is a general-purpose digital computer program which solves the nonlinear time domain response and the linearized small signal frequency domain response of an arbitrary network described to the program. It is capable of handling a variety of network components and can be applied to problems arising in several engineering fields, including electronics, control systems, heat transfer, mechanical structures and systems, systems of nonlinear equations, and digital logic. The network elements may be freely intermixed, permitting interdisciplinary problems to be solved. NET-2 is also able to perform parameter variation studies, statistical studies, and network performance optimization.

NET-2 is capable of a wide range of analyses. Any physical occurrence which can be defined in terms of a network equivalent can be modeled at either the component or system level. Applications of this code include the modeling of illumination and load transients, fixed and propagating shadows, photovoltaic cell parameter optimization, collector design trade-offs, component and system thermal design studies, power conditioning design studies, and many other types of analyses limited only by the user's imagination.

The photovoltaic portions of the CAPVC system were modeled as networks. A network consists of a set of elements interconnected through a set of

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network nodes. The network can be described by individually describing each element and how it connects to the network node system.

The description of each network element requires specification of the element type, the names of the nodes to which it is connected, and the values to be attached to the parameters which control the element behavior. Values may be described either numerically or symbolically in terms of other quantities unless otherwise noted.

For more detailed discussions concerning NET-2 and its use in modeling photovoltaic systems, consult "Photovoltaic Transient Analysis Program User's Guide," which was prepared by BDM for Sandia Laboratories (SAND-78-7038).

The two elements of primary interest in the circuit analysis optimization and performance studies were the cell and the diode. The following two sections describe the models that represent these elements.

C. PV CELL MODEL

The PV cell model represents the basic unit for which the user has I-V curves, either a single PV cell or a module composed of many series/parallel PV cells. This model is based on an Ebers-Moll formulation, which assumes that the distributed cell characteristics can be modeled with lumped elements. This is an approximation which will satisfy almost all cases. If a more exact formulation is required, the user can approximate a distributed model by placing two or more basic PV cells in parallel. The PV cell model was developed to provide a means of analyzing the electrical response of PV cells to insolation and load transients in typical circuit configurations.

The model parameters are determined from PV cell measurements and are accurate within the range of the measurements. The measurements can be made by the user on specific devices, or they can consist of specification sheet data supplied by the vendor.

The Ebers-Moll model of the PV cell is shown in figure C-1. The output is defined by the equations:

Figure C-1. PV Cell Model

$$I_{PV} = I_P - I_D - C_J \frac{dV_D}{dt} - \frac{V_D}{R_{SH}}$$

$$V_{PV} = V_A - V_K = V_D - I_{PV}R_S$$

R_S represents the series resistance of the material and causes the output voltage to deviate from the junction voltage at high photocurrents. R_{SH} represents the shunt resistance. This accounts for the leakage current which is linear with voltage. A small value of shunt resistance will allow some of the current from the photocurrent generator to leak through it, reducing the current available at the output. NET-2 actually uses $1/R_{SH} = G$, the conductance, in its equations.

The internal power dissipation is calculated using $P = K_{SC}S - I_{PV}V_{PV}$ where K_{SC} = solar input power conversion constant, which is proportional to the cell area illuminated.

The Ebers-Moll model is a lumped approximation of distributed phenomena. Therefore, I-V and time response curves generated from the model will not exactly match measured curves. However, the formulation will be satisfactory for 99 percent of the applications. If closer matching of measured curves is required, the PV cell can be modeled with two or more Ebers-Moll diodes in parallel. This will, of course, also make the model parameters more difficult to calculate.

The model can be simplified if the user's application does not require the full complexity. The time dependence of the photocurrent generator can be eliminated and the steady state photocurrent can be simplified by setting some of the constants equal to zero. Methods for simplifying the capacitance terms can also be devised.

The preferred method for obtaining the parameters for the standard diode equation and the series resistance, R_S , is from dark forward bias I-V curves. These parameters can also be obtained from illuminated I-V curves.

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The parameters for the reverse breakdown current in the diode current equation can be determined from reverse breakdown data.

The cell parameters listed below were specific for the CAPVC cell.

SPECIFIC CAPVC CELL PARAMETERS

<u>Parameter</u>	<u>Equation Symbol</u>	<u>Value</u>
Series Resistance	R_S	$4.47E-3\Omega$
Shunt Conductance	G	.05 mhos
Photocurrent Generation Constant	I_{po}	.289A/sun
Saturation Current Constant	I_S	$20A/^{\circ}K^P$
Reference Temperature	T_R	$332^{\circ}K$
Emission Constant	M	.987
Temperature Constant	α	$1.42E4^{\circ}K$
Solar Input Power Constant	K_{SC}	1047mW/sun
Power (Exponent) of Temperature	P	3.039

The remaining parameters used to model a PV cell were values for typical Solarex cells. These are included in the following list:

REMAINING CELL PARAMETERS

<u>Parameter</u>	<u>Equation Symbol</u>	<u>Value</u>
Breakdown Constant	A	$15 V^{-1}$
Breakdown Constant	B	1
Transition Capacitance at $V=0$	C_o	1.5f
Nonlinear Effects Coefficient	C_S	$0.0 \text{ sun } ^{\circ}K^{-1}$
Nonlinear Effects Coefficient	C_{ST}	$0.0 (\text{sun } ^{\circ}K)^{-1}$
Nonlinear Effects Coefficient	C_T	$0.0 ^{\circ}K^{-1}$
Nonlinear Effects Coefficient	C_{TT}	$0.0 ^{\circ}K^{-2}$
Junction Grading Constant	N	.5
Minority Carrier Lifetime	T	5E4ns

REMAINING CELL PARAMETERS (Concluded)

<u>Parameter</u>	<u>Equation Symbol</u>	<u>Value</u>
Breakdown Voltage	V_B	-35V
Contact Potential	V_Z	1.1V
Diffusion Capacitance Constant	W	$2E-5ns^{-1}$
Reference Insolation	S_R	1 sun
Charge/Boltzmann Constant	Q/K	$1.16E4 \text{ } ^\circ K/V$

D. JUNCTION DIODE MODEL

The NET-2 junction diode model was used to characterize the bypass diodes. This model may be considered to be either Ebers-Moll or charge control in form, since these are merely equivalent ways of representing the same equations. The Ebers-Moll form was chosen for this analysis.

The model exhibits normal forward conduction and reverse cutoff behavior. Storage time effects are included.

The model does not include junction breakdown at large reverse voltages. Conductivity modulation of the base region is not included.

The diode model is represented by the equivalent circuit shown in figure C-2.

Figure C-2. Junction Diode Equivalent Circuit.

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The diode parameters listed below were determined from data for the specific diode being used for CAPVC.

<u>Parameter</u>	<u>Equation Symbol</u>	<u>Value</u>
Bulk Resistance	R_b	$5.36E-2\Omega$
Saturation Current	I_s	$2.18E-11A$
Emission Constant	θ	$35.4 V^{-1}$

~~The remaining diode parameters~~ are typical values for silicon rectifiers.

<u>Parameter</u>	<u>Equation Symbol</u>	<u>Value</u>
Transition Capacitance at $V=0$	C	5pf
Ohmic Leakage Admittance	G_c	$1E-6mmhos$
Photocurrent Constant	I_{p1}	0 pc/pj
Photocurrent Constant	I_{p2}	0 ma $\sqrt{ns}$ /pj
Saturation Current		
Damage Constant	K_{IS}	0 neut $^{-1}$
Bulk Resistance		
Damage Constant	K_{Rb}	0 neut $^{-1}$
Diffusion Capacitance	K_w	0 neut $^{-1}$
Damage Constant		
Grading Constant	N	0.3
Minority Carrier Lifetime	T	0ns
Contact Potential	V_z	1V
Diffusion Capacitance Constant	W	.1ns $^{-1}$

E. HP9830 CIRCUIT ANALYSIS PROGRAMS

The circuit analysis utilizing the HP9830 consisted of two separate programs. The first program determined the peak power out of the north-south oriented array at each hour of the day for summer solstice, winter

solstice and spring equinox. The second program determined the effectiveness of the different bypass diode configurations.

The peak output power for each hour of the day was a required input to the second program. The peak power was determined by sweeping the voltage across the string. At each voltage the cell operating current was calculated using the following equation:

$$I = I_{SC} * S - I_{ST} (e^{\frac{\theta V}{V_0}} - 1)$$

In this equation, S represents terrestrial insolation in suns, V_0 is the voltage across the string; and I_{ST} , the saturation current, and θ , an emission constant, are aggregated parameters representing a series string of cells. I_{SC} in the above equation is the short circuit current of the string at 1 sun terrestrial. From the operating current of the string, the operating voltage was calculated using the following equation:

$$V = V_0 - IR_S$$

where R_S represents the aggregated series resistance of the string. These cell parameters were determined by using the manufacturer's I-V curve of the cell and the equations previously developed for the NET-2 circuit analysis.

The second HP9830 program determines the effectiveness of various diode configurations. Inputs required for this program included the peak output power of a cell at each hour of the day, insolation data and sun angles. The bypass diode was modeled by assuming that the power lost from the bypass group when a cell became shadowed was twice the peak power out of an illuminated cell. This program calculates the length of the shadow as discussed in chapter II-B.1.c. and determines the power supplied by each bypass group and by a complete string of cells.

APPENDIX D
SOLCEL MODIFICATIONS

A. END AND GAP SHADOWING

End shadowing as illustrated in figure D-1 is a geometric problem. It is necessary to calculate the length of the shadow, which is in turn used to calculate the power degradation of the system. This shadow also varies in intensity. The following algorithm was derived for SOLCEL to determine the region on the receiver tube which has less than 100 percent illumination.

Figure D-2 illustrates the equation for a parabola with a focus at (0,p).

$$y = \frac{x^2}{4p}$$

To determine what the approximate distance from the end of the receiver tube is for a specified percent of illumination, the following two assumptions were made.

- (1) With a 90° rim angle, 100 percent illumination would start at the point where all 90° or $x = 2p$ is illuminated.
- (2) The distance from the mirror surface to the receiver tube is used to determine the distance from the end for a specified percent of illumination. This distance from the mirror to the receiver tube is the same as the distance from the mirror to the directrix, figure D-2.

$$y = \frac{x^2}{4p} + p$$

p = focal length of collector

One hundred percent illumination is at $x = 2p$. Therefore, the distance from the receiver tube for 90 percent illumination would be:

$$y = \frac{(.9(2p))^2}{4p} + p$$

Figure D-1. Receiver Tube End Shadowing

Figure D-2. Parabolic Parameters

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The next step is to calculate the distance from the end of the receiver tube to the point where insolation reaches 90 percent illumination. Another assumption is made. When the angle of radiation is 90° (figure D-1), the difference between the normal to the mirror at $x = 0$ and solar radiation is zero. As this angle goes to 90° , the angle between the normal from mirror at $x = 2p$ and radiation varies from 45° to 90° . Because of this similar variation in angles there is also a similar variation in distance down the receiver tube, zero to infinity. Therefore, the distance between the mirror and receiver tube is used with the angle between solar radiation and collector axis to calculate the distance from the end of the receiver tube for a given percent of insolation.

$$D = y/\tan \theta$$

y = distance between receiver tube and mirror at end of collector

θ = angle between radiation and collector axis

D = the distance from the end of the receiver tube

To calculate overlapping illumination from an adjacent collector (gap shadow), use the following equations. The percent changes for the first equation

$$y = \frac{((1-P)(2p))^2}{4p} + p$$

P = percent of illumination

p = focal length of collector

$$D = y/\tan \theta \quad G$$

G = gap between collectors

This yields the gap shadow. The illumination from both collectors may add at certain points. If the end shadow length is less than the gap shadow length, then both illuminations add.

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B. WESTINGHOUSE INVERTER ALGORITHM

The SOLCEL computer program required two algorithms for calculating the efficiency of the dc to ac inverter. The following equation calculates inverter efficiency as a function of ac power out.

$$F = L/R$$

F = ratio of load (L) to inverter (R) rating

This ratio can be tested to determine if the inverter is in an overload condition. Then the efficiency of the inverter is

$$E = \frac{L}{1.0509L + 673}$$

L is the output AC power from the inverter. The second form of this equation was to calculate the efficiency as a function of the input DC power

$$F = \frac{A}{1.0509R + 673}$$

A is the input DC power to the inverter, and R is the rating of the inverter. The efficiency was calculated with

$$E = \frac{1. - \left(\frac{673}{A} \right)}{1.0509}$$

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