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Design of a 20 - KWp Photovoltaic Concentrator Experiment at Fauquier High School, Warrenton, Virginia

InterTechnology/ Solar Corporation

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Master

FINAL REPORT

Submitted To

THE UNITED STATES DEPARTMENT OF ENERGY
(Contract No. ET-78-C-04-4290)

DESIGN OF A 20-KWP PHOTOVOLTAIC
CONCENTRATOR EXPERIMENT

at

FAUQUIER HIGH SCHOOL
WARRENTON, VIRGINIA

18 October 1979

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I. INTRODUCTION AND SUMMARY

A. Brief System Description

Under U.S. Department of Energy Contract No. ET-78-C-04-4290, InterTechnology/Solar Corporation designed a photovoltaic concentrator system for Fauquier High School in Warrenton, Virginia, 40 miles west of Washington, D.C. The system provides both electrical energy from the photovoltaic modules and thermal energy from the cooling of those modules. DC electrical energy from the photovoltaic modules will be first converted to AC and then used to provide power for lighting in the vocational/technical building and the system control building.

Instead of being rejected, the thermal energy collected is stored in a 6500-gallon tank for use in the wintertime to provide heat for a greenhouse located adjacent to the array.

The photovoltaic system supplies 20 kWp of electrical power by means of 40 6' wide by 10' long parabolic-cylinder collectors mounted in a polar mode. The photovoltaic modules are located along the focal line of the collectors and connected to form two series strings of 108 1" x 1" cells. Each string of 108 cells operates at a nominal voltage of 53 volts. The 40 concentrating collectors are installed in eight rows of five collectors each as shown in Figure 1. The five collectors in a given row are connected in a series so that the total voltage from each row is 265 volts nominal. Electrical power from each string of five collectors is brought back via cables to the control building. In the control building, all eight rows are wired in parallel to provide an overall 265 volt nominal system with a maximum current of 80 amps. This power is fed into an inverter which provides single phase 277 volt AC power. The photovoltaic power is fed into a switching system to feed either photovoltaic power or utility power to nine 2 kW lighting circuits in the vocational technical school and to fan, pump and auxiliary loads in the control building.

CONTROL BUILDING

PHOTOVOLTAIC
CONCENTRATOR
ARRAY

FIGURE ES-1 ARCHITECT'S CONCEPT OF
PHOTOVOLTAIC SYSTEM AT FAUQUIER
HIGH SCHOOL

B. System Features

The special features of the ITC/Solar photovoltaic concentrator system are summarized in Table 1.

Of particular significance in this project is the advanced collector design which has been developed and incorporated by ITC/Solar. The main features of this advanced collector are the split parabola allowing for separate focal lines falling directly on the photovoltaic strings and the provision for sliding the receiver along the focal lines to compensate for seasonal end-loss effects. It is estimated that systems costs can be reduced on the order of 25-35% by utilizing these features.

C. Market Impact of System

ITC/Solar selected a school to demonstrate its system because photovoltaic systems are economically attractive where daytime electrical loads are high and there is no need to build expensive storage systems. Furthermore, the extremely large number of schools in the United States (greater than 200,000) make them an ideal target market for photovoltaic systems in terms of the potential thermal and electrical energy savings.

Table 1
SPECIAL SYSTEM FEATURES

<u>ITEM</u>	<u>COMMENTS</u>
<u>Technical</u>	
1. Advanced Collector Design	Split parabola and adjustable receiver can save up to 35% over conventional designs.
2. Size/Cost	Small system size allows DOE to test demonstrate a competitive technology (relative to 2 axis trackers for example) at a reasonable cost (<\$500,000)
3. Daytime Loads	Daytime electrical loads minimize necessity for expensive battery storage systems.
4. Incremental Loads	A large number of relatively small (~2 kW) loads allow for the maximum utilization of solar energy without the need for storage or energy rejection.
5. Proximity to Thermal Loads	Nearby location of large thermal loads (greenhouse) allow for economic usage of array heat which would be rejected otherwise. Relatively inexpensive thermal storage allows for nighttime usage of thermal energy when needed.
6. Switching Method	Method of switching represents important alternative to feeding power back to utility.
7. <u>Small</u> NiCd Storage System	Inclusion of a short term (15 min) NiCd storage system overcomes rapid switching problems all conversion schemes are subjected to during partly cloudy periods.
8. Minimal Interface Requirements	Simple electrical interface will minimize interruption of school operation if PV system has failures. Also, allows for short installation period for interface.
9. Each Collector has its own Tracking System	By including a self contained tracking system problems associated with gang tracking are avoided.

II. CONCEPTUAL SYSTEM DESIGN

A. Meeting DOE Objectives

To meet the Department of Energy's array price objective of \$2 per peak watt (1975 dollars) by 1982, well chosen and properly designed photovoltaic systems must be funded through normal construction industry channels. A range of state-of-the-art technology options, such as two-axis tracking and single-axis tracking systems, should be constructed to determine which of these systems will be most cost competitive and/or compatible with existing energy supply systems from both initial and life-cycle cost points of view. Construction of these systems on the buildings which represent large potential markets will allow for a full test of user acceptance and institutional/environmental issues. Construction of such photovoltaic systems should also be compatible with the operational patterns and energy objective of the site owner.

The 20 kWp photovoltaic concentrator system for the Fauquier High School fits well with the above Department of Energy objectives*. The state-of-the-art technology involved consists of a single-axis tracking parabolic cylinder with a concentrator ratio of 35 mounted in the polar mode. Several innovations in the collector allow for the significant reduction of system costs (on the order of 25-35%) in future systems of this type.

* Abstracted from National Photovoltaic Plan, Feb. 1978.

B. Block Diagram

The block diagram of the photovoltaic concentrator system conceived by ITC/Solar Corporation for Fauquier High School in Warrenton, Virginia, is shown in Figure 2.

As can be seen from the diagram, the system provides both electrical energy from the photovoltaic modules and thermal energy from the cooling of those modules. The DC electrical energy from the photovoltaic modules will be first converted to AC and then used to provide power for lights located in the vocational/technical school and for control building power. The rejected thermal energy will be stored in a 6500 gallon tank and used in the wintertime to provide heat for the greenhouse located near the array. All system components, including structures, collectors, cabling, piping, storage tank, batteries, controls, heat rejectors, instrumentation, electrical interface and thermal interface, are described in detail below.

C. Design

1. Overall Operation

The photovoltaic system provides a nominal 20 kWp of electrical power by means of 40 6' wide by 10' long polar-axis mounted parabolic-cylinder collectors. The photovoltaic modules are located along the focal lines of the collectors and connected to form 2 series strings of 108 1" x 1" cells. Each string of 108 cells operates at a nominal voltage of 53 volts.

The layout of the 40 concentrating collectors consists of rows of 5 collectors each. The 5 collectors in a given row are connected in series so that the total voltage from each row is 265 volts nominal. Electrical power from each string of 5 collectors is brought back via cables to the control building. In the control building, all 8 rows are wired in parallel to provide an overall 265 volt nominal system with a maximum current of 80 amps. This power is fed into an inverter

Figure 2
SYSTEM BLOCK DIAGRAM

to provide single phase 277 volt AC power. This photovoltaic power is fed into a switching system, which feeds either utility power or photovoltaic power to nine 2 kW lighting circuits and the control building. These lighting circuits supply power to lighting in the masonry and building trade shops of the vocational/technical school. Control building power is for pumps, fans, lighting and other auxiliary power requirements. Overall control of the system is provided by a micro-processor controller which determines photovoltaic power availability and load demand and, on the basis of this information, determines which of the various loads will receive photovoltaic power.

In order to avoid short-term switching and associated light flicker problems, a NiCd battery system is installed in parallel with the array. Only when the array voltage drops below a preset value do the batteries provide power to the system. Once the batteries are fully discharged, the photovoltaic system has top priority for recharging the batteries. In addition, the battery system supplies DC power to drive the tracking system.

To take advantage of the large amount of thermal energy which the system rejects to cool the photovoltaic modules, the system collects this thermal energy and stores it in a 6500-gallon storage tank. The energy in the storage tank then provides heating to a greenhouse located near the array. In the summer a heat rejector is used to dissipate thermal energy from collector cooling.

2. Site Plan and Structures

Figure 3 shows the location of all of the major system components and their relationship to each other. The land availability at the Fauquier High School dictates that the system be located on a portion of the grounds located behind the greenhouse and near the vocational/technical

FIGURE 3
LAYOUT SHOWING PHOTOVOLTAIC SYSTEM
IN RELATION TO SCHOOL BUILDINGS

school. Owing to the contours of the land and the existing facilities located nearby, the space available for collectors effectively limits the system to that shown in Figure 3. As can be seen in Figure 3, the relative location of the various facilities is well suited for this project. The greenhouse, which acts as a heat load for the rejected thermal energy in the wintertime, is directly adjacent to the site and does, therefore, require a minimal amount of piping runs. The vocational/technical school is located approximately 100 yards from the site, which means that losses in cabling are small. The top of the control house is on a level with the base of the collector rows and thus is partially underground, thereby reducing heating and cooling demands in the building. The control house contains the thermal storage tank, inverter, batteries, and all of the controls and instrumentation necessary for operation of the system. In addition, a small amount of work space is also provided in this building.

Structural elements within the system include concrete retaining walls because each of the rows is located 4 feet higher than the row in front of it (except for the last two rows, which have a smaller step and greater spacing). Other structural elements include those required for the control house, and the pads which will provide support for each of the 40 collectors.

3. The Collector

As previously mentioned, ITC/Solar is using a parabolic-cylinder type of collector mounted in a polar-axis mode. Originally it was intended to purchase an off-the-shelf collector from Acurex or Del-Jacobs. However, owing to difficulties in obtaining a suitable collector from these suppliers, ITC/Solar designed its own. One of the major design considerations for this collector was to avoid spill-over of the focused beam outside of the location occupied by the photovoltaic cells. To accomplish this, it was decided to split the standard parabola in such a way that separate focal

points for each half of the collector could be established. This is shown diagrammatically in Figure 4. The overall dimensions of the collector is 6 feet wide by 10 feet long. The receiver for this collector is located along the focal lines and has 2 separate strings of photovoltaic cells mounted on each focal line. The basic receiver is an aluminum extrusion which allows for mounting photovoltaic cells on the bottom sides and for snapping in copper tubing for cooling on the top sides.

The collectors are mounted in a polar-axis mode at a tilt angle of approximately 39 degrees. With this type of mounting a certain amount of end losses are encountered around the times of the summer and winter solstices owing to the paths of the light reflected from the ends of the reflector. In order to compensate for the end losses, ITC/Solar has provided for linear motion of the receiver along the axis of the collector, so that a twice-a-year adjustment allows for greater utilization of the reflected radiation.

Tracking of each collector is done individually rather than in a gang operation. A separate shadow band unit, DC power, and DC motor are provided for each collector to reduce maintenance. Small electrical junction boxes are located at each end of the collector. Thermal connections are made via insulated flexible metal tubing. The operating temperature of the collector is limited to somewhere in the neighborhood of 55°C.

In order to protect the receiver from open circuit or end-loss conditions, by-pass diodes are placed around groups of 5 cells in series, thus only 5 percent of the voltage is lost upon open-circuit or end-loss conditions occurring in a group.

REVISIONS					
NO.	DATE	BY			
1			SPLIT-PARABOLIC REFLECTOR		
2					
3			DRAWN BY AJD	SCALE	MATERIAL
4			CHK'D	DATE 10-17-18	DRAWING NO.
5			TRACED	APP'D	

4. Electrical Subsystem

It was previously mentioned that each collector has two strings of 108 cells connected in series with by-pass diodes around every 5 cells for protection against open circuit and shadowing effects. The two parallel strings of 108 cells are connected at the collector level to avoid problems associated with early morning and late afternoon shadowing, but are connected in series with the other four collectors in a given row. Thus, for each row there is a string from the left side of the receivers and a string from the right side of the receivers, each operating at a nominal 265 volts.

Each of the 8 rows of 5 collectors then have two strings running into the control room where they are connected into a junction box. In the control room each string has its own ammeter, blocking diode, and circuit breaker. On the output side of the circuit breakers, all 16 strings are connected in parallel.

The power is then fed into an inverter. The output of the inverter is single phase 277 volts AC. From the inverter, photovoltaic power is fed to a panel in the control room and also sent via underground cabling to a panel in the vocational/technical school. From the panel in the vocational/technical school, separate 277 volt single-phase lines are run for each load to a switching network. The switching circuit has photovoltaic power entering on one side of a switch and utility power entering on the other side. The lighting circuit is then connected to either photovoltaic power or utility power by the system controller depending upon load demand and photovoltaic power availability. Each switch is connected to the utility in its normal position; however, the controller uses a current sensor output to determine whether a load is calling for power at a given time, and if photovoltaic power is available for that load, it connects the switch to the photovoltaic system power line. Power to the load is then routed to the existing circuit breaker panel before being distributed to the load itself.

In the control building a similar arrangement is employed except that a step down transformer has been installed to give either 240 or 110 volts for operating pumps, fans, lighting and other similar equipment. The controller itself runs on utility power only.

Under partial sun conditions, problems could be encountered when the system switches rapidly between utility and photovoltaic power. These problems include light flicker, switch wearout and control difficulties related to the maximum power tracker. To avoid these problems, ITC/Solar has added a short-term NiCd battery capability to the system. When output from the array drops below a preset voltage, input to the inverter comes from the batteries for a period of up to 15 minutes. Once the batteries have been discharged beyond a certain voltage level, top priority is given to recharging the batteries with photovoltaic power before providing power to the other loads. The utility interface in this particular case is relatively simple since either a particular load is on utility power or it is on photovoltaic power. Thus, there is no chance that photovoltaic power will be fed back to the utility.

Because the system generates high-voltage DC power, safety precautions have been designed into the project. These include isolated positive and negative cables, weather-tight electrical connections, a fence located around the project and the use of underground cable where possible. In addition, a lightning rod is included at the north end of the array.

5. Thermal Subsystem

To optimize the electrical output of the array, the concentrating collectors must be cooled. Two copper tubes snap into the collector receiver and are connected in parallel at the top and bottom of the collector. A reverse-return piping system provides the ethylene glycol coolant to the collector.

Approximately one gpm of coolant flows through each collector. It is anticipated that under normal operating conditions a temperature rise of approximately 5° to 15°C will be experienced. The coolant is sent through a heat exchanger in the 6500 gallon thermal storage tank and heats water which may then be used for heating the adjacent greenhouse and the control building in the wintertime by means of fan coil units.

In the event that the temperature of the solar storage tank gets above approximately 50°C, heat is rejected from the system. A two-stage heat rejector operates mostly during the summertime when there is no other use for the collected heat. The heat rejector is over-sized so that the fan power can be reduced with a consequent reduction in the parasitic power requirements of the system. A sensor located on the output on each of the collectors determines if output temperatures are too high (>90°C) in which case the collectors are driven to their stow position.

To limit the stagnation temperatures within the receiver, the receiver itself is not insulated. However, to maximize the gain of thermal energy during the wintertime, the piping to and from the collector array is insulated. The storage tank is insulated with 6 inches of polyurethane.

6. Controls and Instrumentation

Table 2 indicates the various operational modes of the electrical and thermal systems. The basic parameters involved in the various modes are summer and winter operations and daytime and nighttime or cloudy period operations.

The controller used on this project is a micro-processor controller which performs the following functions:

TABLE 2
FAUQUIER HIGH SCHOOL SYSTEM MODE CHART

	WINTER		SUMMER	
	DAY	NIGHT/CLOUDY	DAY	NIGHT/CLOUDY
Electrical Subsystem	Provides Power to Lighting and Control Bldg. Loads	No Power Provided	Provides Power to Lighting and Control Bldg. Loads	No Power Provided
Thermal Subsystem	Provides Heat to Greenhouse as Required and Cools Array	Provides Stored Heat to Greenhouse as Required	Rejects Array Heat	Not in Operation

* includes power for driving the system, i.e. pumps, heat rejectors, tracking

1. Determine the existence of electrical loads,
2. Switch loads between photovoltaic and utility power,
3. Perform maximum power tracking for the system,
4. Determine which loads receive available photovoltaic power,
5. Determine when to shed the photovoltaic system in favor of the utility system.

The controller functions independently of the instrumentation package. In addition to the required Sandia instrumentation package, ITC/Solar intends to install an instrumentation package which allows for an on-site evaluation of various operational parameters associated with the system and also for diagnostic checking. The instrumentation package includes a complete weather station; sensors for sensing current and voltage at various points in the system, sensors which allow for the determination of temperatures at various points in the system, and power and energy meters to indicate the amounts of power and energy delivered to the various loads.

7. Site Compatibility

The system's basic load, electrical power, is primarily a daytime lighting load which fits well with the operation of the system during the daylight hours and allows for minimum storage. In addition, the location of the array near the greenhouse, which has a large heating load during winter months, allows for utilizing the tremendous amounts of thermal energy produced by the collectors. Since a heat rejection system would be required at any rate, the additional cost of a storage tank and the necessary controls for delivering heat to fan coil units located in the greenhouse is minimal and a payback period on the order of ten years or less is expected.

III. SYSTEM ANALYSIS

A. Weather Data

Concentrating solar collectors respond primarily to direct solar radiation. Since direct radiation totals are not available for the Warrenton, Virginia area, the ITC/Solar computer program synthesizes direct radiation values from total radiation data. The nearest station to Warrenton that has measured solar radiation for a long period of time is Washington, D.C., about 50 miles ENE of Warrenton. ITC/Solar has used the Washington, D.C. data collected by the U.S. Weather Bureau and published by Liu and Jordan (1967). The total radiation is broken into direct and diffuse components by a method to be described later.

Temperature data were obtained from the U.S. Department of Commerce publication, "Climatography of the United States No. 81", for the State of Virginia. ITC/Solar used the temperatures for Dulles Airport, in Chantilly, Virginia which is about 30 miles to the Northeast of Warrenton. The temperatures at Dulles and Warrenton usually agree closely. The insolation and temperature data are shown in Table 3.

B. Load Data

The electrical and heating loads are shown in Table 3. The lighting loads are measured values, the pump and controller load is estimated. The heating load for the greenhouse is not monitored separately, so it was estimated using a simple model. The heat gains and losses were calculated using as inputs the dimensions of the greenhouse, the U value of single pane plate glass, the same insolation data that was input to the simulation program, and degree-day-data for Dulles Airport.

TABLE 3

WEATHER AND LOAD DATA

<u>Month</u>	<u>Daily flux on Horizontal megajoules/sq metre</u>	<u>Mean ambient temperature, °C</u>	<u>Daily average heating load, megajoules</u>	<u>Peak Electric Demand, Kilowatts (Same demands all year)</u>		
				<u>Load No.</u>		
Jan.	7.18	0.1	3640.	1	2.0	Controls & pumps for Collector System
Feb.	10.23	1.0	2460.	2	2.3	
Mar.	14.24	5.4	1070.	3	2.1	
Apr.	18.16	11.7	0.	4	2.8	Lighting Loads
May	20.96	17.0	0.	5	2.3	
June	23.61	21.7	0.	6	2.6	
July	21.90	24.1	0.	7	2.3	
Aug.	19.43	23.1	0.	8	2.3	
Sept.	16.41	19.4	0.	9	2.2	
Oct.	21.29	13.1	0.	10	1.9	
Nov.	8.66	7.1	1460.			
Dec.	6.74	1.1	3440.			

C. Simulation Model

The computer program calculates photovoltaic and thermal performance by simulating the operation of the system hour-by-hour (or minute-by-minute, if necessary) for one year. The logic of the program is summarized in the flow chart (Figure 5). A description of the important subroutines follows.

SUNGWE - Calculates the extraterrestrial radiation for the given latitude and month.

WETHER - Generates the insolation values for each day of the month from the available monthly average daily radiation. Distribution functions describing the statistical distribution of daily radiation on the horizontal surface are used. The form of the distribution functions depends primarily on the parameter $\bar{K}_T$ (= the monthly average value of the fraction of extraterrestrial radiation that reaches the local ground level). $\bar{K}_T$ is calculated from the monthly average daily insolation. The distribution functions were obtained from solar radiation data for 27 localities in the United States.

TAMBI - Generates the daily range of ambient temperature for each day of the month, using input values of the average temperature range and a random number generator.

SUNGE0 - Determines the solar altitude, azimuth, and incidence angle of the beam radiation on the solar collector, for each day of the year. Input quantities required are the collector tilt and orientation angles, and the local latitude angle.

TAMB2 - Calculates the ambient temperature for the hour, based on the temperature range generated by TAMBI, and a fixed average curve of daily temperature variation.

Figure 5
Photovoltaic Program Flow Chart

FLUXPC - From a knowledge of daily total radiation, this subroutine generates the hourly direct and diffuse radiation on the tilted and horizontal surfaces. The time variation of the normal flux is given by (Meinel and Meinel, 1976).

$$\text{FLUX}_N = \exp(-0.357 \times (\sin \alpha)^{-0.678})$$

α is the solar altitude angle. The flux is normalized so that the area under the horizontal flux curve equals the total horizontal daily flux. The fraction of diffuse radiation is calculated:

$$\text{DIFFUSE} = \text{TOTAL} * (1.0045 + .04349K_T - 3.5227 K_T^2 + 26313K_T^3)$$

The diffuse is subtracted from the total; only the direct component is used in the simulation.

THETA - Calculates the incidence angle of the direct normal radiation on the collector. For polar mount, this is the solar declination angle.

ENDLOS - Calculates the illumination along the length of the receiver; the fully illuminated zone, the partially illuminated zone, and the dark zone.

SHADE - Calculates morning and evening shading of collectors by their neighbors. No row-to-row shading of polar mounted collectors is included.

POWRPV - Generates cell temperatures, calculates power output of shaded and unshaded single cells, using manufacturers efficiency curves. It determines number of cells which will be inactive due to end losses, and calculates power lost in the bypass diodes.

HYBRID - Since the output of the solar cells is a sensitive function of their temperature and the temperature rise through the receiver depends on the amount of solar energy going into electrical energy, the thermal and electrical calculations must be repeated until the temperature of the output fluid converges.

LOAD - Determines which loads get photovoltaic power in order of priority, so that maximum possible photovoltaic power is used in the loads. If there is not enough photovoltaic power to run the collector system, the collector system is not used.

HEATING - The hourly space heating loads are calculated from a knowledge of the daily total load and the distribution of heating load over the day. The solar contribution to the space heating is calculated.

OUTPUT - A sample of the annual summary output is given in the accompanying Tables 4 and 5.

D. System Performance Calculations

The output of the simulation program is reproduced in Tables 4 and 5. The total solar energy is the output of the photovoltaic cells. Not all of it can be delivered to the loads; loads seven through ten are zero on weekends, and the sun is up for longer than the loads are on in the summer. Each load gets either photovoltaic power or utility power, so there will always be some power left over that is insufficient to supply one more load. Also, there are times when the output of the collectors is so low that not even one load can be supplied. If there is not enough power to run load number one, the pumps and fans, the system is not run.

TABLE 4
ANNUAL SUMMARY OF ELECTRICAL SYSTEM PERFORMANCE

ANNUAL SUMMARY

COLLECTOR AREA = 827.99 SQUARE METRES
 NUMBER OF COLLECTOR ROWS = 5
 NUMBER OF COLLECTORS PER ROW = 8 8 8 8 8
 RECEIVER TUBE SPACING, METRES = 3.048
 LENGTH OF COLLECTOR AT NORTH OR EAST END WITH NO CELLS, METRES
 JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
 0.000 0.000 0.000 0.381 0.381 0.381 0.381 0.381 0.381 0.000 0.000 0.000
 NUMBER OF CELLS BYPASSED BY ONE DIODE = 10
 SPECIFIC WORKING FLUID FLOWRATE = 0.61360 KG/SEC-SQ METRE
 FLUID INLET TEMPERATURE = 50.00 DEG C
 STORAGE CAPACITY = 24.60 CUBIC METRES OF WATER
 NUMBER OF COLLECTORS HOOKED IN SEQUENCE IS 1

FLUXES IN KILOWATT-HRS/SQ METRE-MONTH, ELECTRIC ENERGY IN KW-HRS/MONTH

MONTH	TOTAL SOLAR ENERGY	SOLAR ENERGY NOT USED	SOLAR ENERGY TO LOADS	ELECTRIC LOAD	DIRECT FLUX COLLECTOR	FLUX ON RECEIVER	ELECTRICAL EFF.-%
1	1777.43	223.33	1549.10	6495.99	82.68	64.98	8.89
2	1987.40	266.00	1721.40	5800.00	104.49	75.30	8.53
3	2421.74	329.64	2101.10	6408.99	136.95	96.62	7.93
4	2506.00	379.00	2126.00	6177.00	147.93	98.93	7.60
5	2645.06	391.86	2253.20	6495.99	162.75	103.11	7.29
6	2827.31	406.81	2421.50	6177.00	178.96	110.42	7.08
7	2736.84	393.44	2343.40	6409.00	171.53	107.08	7.16
8	2684.23	357.93	2326.30	6495.99	159.49	105.50	7.55
9	2525.96	323.16	2202.80	6090.00	152.02	105.77	7.45
10	2475.47	294.37	2185.10	6495.99	137.90	99.28	8.06
11	2058.20	192.40	1865.80	6262.99	104.70	76.48	8.82
12	1745.06	235.86	1509.20	6322.00	85.18	62.43	9.19
TOTALS	28394.70	3780.00	24614.70	75631.95	1630.59	1105.91	7.81

FLUXES IN MEGAJOULES/SQ METRE-MONTH, THERMAL ENERGY IN MEGAJOULES/MONTH

	DIRECT FLUX COLLECTOR	THERMAL ENERGY	THERMAL EFF.-%	NUMBER OF HOURS LOADS GET SOLAR POWER										
				1	2	3	4	5	6	7	8	9	10	11
1	319.26	30785.54	43.24	172	146	118	92	73	45	19	6	2	9	0
2	376.16	36203.07	43.16	200	166	131	97	47	50	10	0	6	14	0
3	403.04	48510.71	44.12	246	201	174	130	94	45	19	0	2	19	0
4	532.56	49308.21	41.52	262	200	182	118	100	56	10	0	3	18	0
5	585.89	49094.09	37.58	280	210	186	138	106	50	8	0	10	10	0
6	644.25	53811.25	37.46	296	216	190	148	110	66	10	0	4	33	0
7	617.52	53787.90	39.06	288	206	188	143	103	63	22	0	5	19	0
8	574.16	55873.30	43.64	290	220	188	142	97	46	24	0	2	24	0
9	547.26	57128.93	46.81	260	202	181	118	112	60	14	6	2	23	0
10	494.45	51835.37	46.82	246	198	174	137	111	58	15	4	3	17	0
11	376.94	38939.00	46.23	176	168	153	109	89	49	36	4	4	22	0
12	306.65	29106.80	42.57	184	150	126	91	71	30	5	0	4	8	0
TOTALS	5870.13	554384.25	42.35	2920	2283	1991	1463	1153	610	186	20	47	216	0

TABLE 5
ANNUAL SUMMARY OF THERMAL SYSTEM PERFORMANCE

ALL LOADS AND SOLAR INPUTS ARE IN GIGAJOULES

MONTH	HEATG. LOAD	SOLAR INPUT FOR HEATG	TOTAL LOAD	% SOLAR
1	112.8	27.3	112.8	24.2
2	68.9	24.6	68.9	35.7
3	33.2	16.2	33.2	79.0
4	0.0	0.0	0.0	100.0
5	0.0	0.0	0.0	100.0
6	0.0	0.0	0.0	100.0
7	0.0	0.0	0.0	100.0
8	0.0	0.0	0.0	100.0
9	0.0	0.0	0.0	100.0
10	0.0	0.0	0.0	100.0
11	43.8	30.1	43.8	68.6
12	106.6	28.4	106.6	26.6

FLUXES IN MEGAJOULES/SQ METRE-MO., TANK LOSSES IN MEGAJOULES/MONTH

MONTH	FLUX ON HOR.	DIRECT ON TILTED	TANK LOSS	KTBAR	MIN. TANK TEMP	MAX. TANK TEMP	EFF.
1	219.2	319.3	829.7	0.458	26.	54.	38.4
2	287.1	376.2	774.9	0.492	28.	54.	29.3
3	428.3	493.0	850.0	0.508	28.	55.	23.8
4	533.4	532.6	860.4	0.520	47.	56.	0.0
5	641.5	585.9	767.7	0.529	49.	54.	0.0
6	700.9	644.2	639.2	0.570	49.	54.	0.0
7	670.8	617.5	605.3	0.544	50.	55.	0.0
8	590.8	574.2	628.7	0.535	50.	55.	0.0
9	478.0	547.3	690.7	0.547	49.	56.	0.0
10	370.1	496.5	853.2	0.541	49.	55.	0.0
11	252.7	376.9	719.5	0.515	28.	54.	35.8
12	204.7	306.6	801.7	0.474	26.	54.	41.5

SPACE HEATING LOAD= 365.33 GIGAJOULES/YEAR
HEAT LOSSES FROM THE TANK= 9.02 GIGAJOULES/YEAR
SOLAR SPACE HEATING= 136.61 GIGAJOULES/YEAR

FLUX ON HORIZONTAL= 5377.6 MEGAJOULES/SQ METRE-YEAR
DIRECT FLUX ON TRACKING PLANE= 5870.1 MEGAJOULES/SQ METRE-YEAR
SOLAR SPACE HEATING= 37.4 PERCENT

ANNUAL SOLAR INPUT TO TOTAL LOAD= 37.3922%
ANNUAL HEAT COLLECTION EFFICIENCY= 10.44%

The direct flux on the collector is the monthly total direct normal flux on the collector area times the cosine of the angle between the solar rays and the normal to the collector. For polar mount, this is the solar declination angle. The flux on receiver is the flux on the collector times the reflectivity of the trough, the fraction of the collector unshaded, and the ratio of the receiver length to the collector length. The electrical efficiency is the ratio of the total solar energy to the direct energy on the collector (direct flux times collector area).

The thermal energy is just the amount of heat produced by the sun on the receiver; of the 30.8 gigajoules produced in January, 27.3 went to heat the greenhouse, 0.8 was lost from the tank, and the rest was either rejected or resulted in a change in tank temperature over the month.

E. Solar Fractions

The total solar electrical energy delivered to the loads was 24615 kW-hrs; of this, $2 \text{ KW} \times 2920 \text{ hours} = 5840 \text{ kW-hrs}$ was used in powering the photovoltaic system, so 18775 kW-hrs is the total power delivered to the lighting loads. The total electric load is 75632 kW-hrs; of this, $2 \text{ kW} \times 4380 \text{ hours}$ is for powering the photovoltaic system. The solar electrical fraction is therefore $18755 \div 66872 = 28.1\%$. The solar heating fraction, as shown in the computer printout, Table 5, is 37.4%.

The solar energy going toward space heating is 136.61×10^9 joules per year, (table 5) which is 129.5×10^6 BTU. This is equivalent to 1444 gallons of fuel oil, using 138,000 BTU per gallon of oil and a furnace efficiency of 65%. At 80 cents a gallon for the oil, the cash value of the solar heating is \$1,155 per year. The electrical output of 18,775 kW-hrs would cost \$451 if purchased from the utility company at 2.4 cents a kilowatt-hour. It is noted that the thermal system saves significantly more dollars than the electrical system does.

F. Key Trade-Offs

The photovoltaic system simulation model that was described in the preceding sections was employed to study the effects on system performance of a number of system design parameters. Parameter variations that were studied included:

- Concentrator module spacing
- Coolant inlet temperatures
- Coolant flow rate
- Thermal conductance between cell and substrate
- Receiver heat loss coefficient

Some of the results of these analyses are shown in the following figures. Figure 6 shows the variation of total array output with reflector module spacing. The decrease in array output with decreased reflector spacing is due to shadowing in the morning and evening hours. The effect is most pronounced during the late spring and summer months when there are many daylight hours. Although the simulation indicated that spacing of over 12 feet would be desirable from the point of view of total array output, the limited amount of space at the proposed site dictated a smaller spacing.

The final spacing of 10 feet on center (the reflector is 6 feet wide) was selected on the basis of array output, site limitations and the need for access between reflectors for installation and maintenance.

The decrease in array output with coolant inlet temperature shown in Figure 7 results from the decrease in cell output voltage with increasing cell temperature. There are several factors which must be considered in optimizing the coolant temperature, which are:

- Array output power
- Array output voltage
- Thermal energy delivered to load
- Power required for heat rejection

The variation in array output power with temperature is about $-0.5\%/^{\circ}\text{C}$. The variation in array voltage with cell temperature is approximately the same. The inverter that was selected (Abacus Controls) has a very wide range of allowable input voltages (200 Volts to 320 Volts), but the use of batteries as backup to minimize transients imposes the requirement that the array operating voltage be above the nominal battery voltage. With an array voltage of 260 Volts at 55°C Cell temperature, a nominal battery voltage of 240 Volts, and a thermal conductance of $50 \text{ Watts/m}^2\text{-}^{\circ}\text{C}$ (referenced to reflector aperture area) we have for the maximum fluid temperature,

$$(T_{\max})_{\text{fluid}} = (T_{\max})_{\text{cell}} - \Delta T_{\text{cell to fluid}}$$

and $\Delta T_{\text{cell to fluid}} = \frac{600 \text{ Watts/m}^2}{50 \text{ Watts/m}^2\text{-}^{\circ}\text{C}} = 12^{\circ}\text{C}$, where the 600 Watts/m^2

represents the maximum expected thermal power absorbed by the cell. Also at an operating voltage of 240V the maximum cell temperature is given by

$$(T_{\max})_{\text{cell}} = 55^{\circ}\text{C} + \left(\frac{260 \text{ V.} - 240 \text{ V.}}{260} \right) / 0.005/^{\circ}\text{C} = 70.4^{\circ}\text{C}.$$

Thus,

$$(T_{\max})_{\text{Fluid}} = 70.4^{\circ}\text{C} - 12^{\circ}\text{C} = 58.4^{\circ}\text{C}$$

Fluid temperatures will be regulated at $50\text{-}55^{\circ}\text{C}$ by use of the heat rejector. In the wintertime, the heat load of the greenhouse will be sufficient to keep the fluid temperatures below 55°C . Since the greenhouse is maintained at approximately 50°F (10°C) at night, low storage tank temperatures can be effectively used for heating.

The variation of relative array electrical output with flow rate is shown in Figure 8. The decrease in array output with decreasing flow rate is due to the increase in average cell temperature due to an increase in fluid outlet temperature. The flow rate in the graph is shown as the thermal capacitance rate, $m C_p$, normalized to the array aperture area. The key factor here is the parasitic pump power required to generate the flow. The analysis is complicated by the fact that, for the flow rates and pressure drops under consideration, the pumps are driven by fractional horsepower motors and the overall efficiency of these pumps varies widely. A 1/2 hp pump was selected which will give a flow rate of 40 gpm (7 Btu/hr-ft^2) of 40% ethylene glycol/water. A higher flow rate of $10 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ would result in a 3/4 hp pump being required with no net increase in P.V. power delivered to the lighting load. Thermal capacitance rates below $7 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ would not yield any net increase in PV power due to the inefficiency of the smaller pumps. Also, there would be difficulty in maintaining a sufficiently high fluid film heat transfer coefficient at the low flow rates.

Another decrease in efficiency due to thermal effects is caused by the thermal resistance between the cell and the cooling fluid. The primary thermal resistance is due to the silicone adhesive between the cell and the aluminum substrate. The original silicone adhesive proposed by OCLI resulted in a calculated heat transfer coefficient, h , of $37 \text{ Watts/m}^2\text{-}^\circ\text{C}$. It can be seen from the figure that even a modest increase in h will result in a significant increase in array power output. Also, for a given inlet temperature, the output voltage will increase as h increases. After consultation with OCLI, they decided to switch to an RTV silicone adhesive with a higher thermal conductivity. The overall heat transfer coefficient is expected to be approximately $50 \text{ Watts/m}^2\text{-}^\circ\text{C}$ (based on array area). Because of the importance of achieving a high heat transfer coefficient, turbulators will be used in the coolant tubes to increase the fluid film coefficient.

The variations in the receiver heat loss coefficient, U_L , that were investigated resulted in very minor changes in the electrical output of the array. The thermal output does increase somewhat with decreasing U_L but it was found that the PV receiver is an adequate thermal receiver (for the low fluid temperatures that we use) without any need for insulation. For this reason, and to limit the rate of increase of stagnation temperature if the coolant flow stopped, thermal insulation was omitted from the receiver.

IV. PROTOTYPE PERFORMANCE

The reflector module was mounted on top of the ITC/Solar office building for testing. The split parabola alignment was found to be good with two beams being well centered on the V-receiver all along its length. The optical quality of the reflector was good with line widths at the focus of 3/8" to 1/2" (a line width of about 1/4" is the theoretical limit due to our 18" size). Some minor distortions in the image could be seen. These were due to slight distortions in the reflector contour at the location of the supporting ribs and to a wavy pattern that was intrinsic to the reflective film. The image quality could be studied quite easily by making a "photograph" of the beam using blueprint paper exposed for a few seconds and developed normally.

The tracking controls and mechanical drive train were found to work well. The 60/1 speed-reducer does, however, have some backlash which is enough to allow the beam to wander over the target under windy conditions. However, due to the 1" width of the PV cell, the beam always stays on the cells.

The PV cells produced by OCLI for the prototype receiver were individually tested before mounting on the ITC/Solar designed substrate. Figure 9 is a representative I-V curve for some of the cells. After the cells were tested, they were mounted on the receiver substrate and checked for continuity and breakdown voltage (1000 Volts). One side of the V-shaped receiver had cells, the other side was left bare for other testing. Before the receiver was shipped to ITC/Solar an outdoor test was run on the completed assembly. The results are shown in Figure 10.

Some of the results of the ITC/Solar testing of the receiver concentrator combination are presented in the I-V curves of Figure 11. Testing was carried out on both clear and partly hazy days. The data shown in the figure represent very clear days. The direct normal insolation levels were

Figure 9 Measured I-V Characteristics
for OCLI Concentrator Cells

Figure 10
I-V Curve For PV Receiver
≈ 1 Sun, 25°C
108 Cells

Fig. 11 - I-V Curves of the Prototype
Concentrating PV/Thermal
Collector.

determined using a silicone cell pyranometer with a shadow disk. The results are excellent with maximum output power ranging between 200 to 220 watts (for the single string) depending on inlet temperature. The curve fill factors ranged between 0.65 and 0.67 which is very close to the 0.68 fill factor that was measured for the individual cells in Figure 6. This result is quite impressive when one considers that the beam is actually concentrated on only half of the cell area.

During the testing program, an accidental loss of power to the cooling pump resulted in some delamination of the cells and cover glass. This occurred for over half the cells. In addition, some of the cover glasses cracked. The damage is thought to have been caused by the thermal shock that resulted when the coolant flow resumed. The receiver did have a high temperature protection device installed at that time. Since the pre-set temperature (190°F) of the protection device sensor was not reached, it is assumed that high temperature did not cause the damage.

The I-V curve taken on the next clear day after the delamination occurred is represented by the triangles on Figure 11. These days had approximately the same direct normal insolation. It is seen that there has been very little decrease in maximum power output and only a slight decrease in short circuit current.

The PV concentrator as a unit has performed reliably over a wide range of ambient temperatures and conditions. Based on the electrical tests made on the prototype, the original design rating of 500 watts per concentrator at 1000 W/m^2 and 100°F fluid temperature will easily be met.

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