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MARTIN MARIETTA

Determination of Effects of Atmospheric Contamination on Photovoltaic Cells in Concentrating Systems

S. I. Kaplan

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DETERMINATION OF EFFECTS OF ATMOSPHERIC CONTAMINATION ON PHOTOVOLTAIC CELLS IN CONCENTRATING SYSTEMS

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ABSTRACT

Three sets of single-crystal silicon photovoltaic (PV) cells were irradiated in a reflective concentrating solar collector at Oak Ridge National Laboratory (ORNL). The objective was to examine whether the effects of concentrated sunlight would affect airborne particulate material depositing on the cells or their cover glasses, causing removal-resistant layers that would seriously attenuate insolation reaching the cells. Four types of cell assembly specimens were deployed in each of the three sets: (1) coverglass clamped to face of PV cell, with embossed face of glass away from cell; (2) coverglass clamped to face of PV cell, with embossed glass surface toward cell; (3) cover glass spaced above cell with 1.6-mm air gap, with embossed side out; (4) cover glass spaced above cell with 1.6-mm air gap, with embossed side toward cell. The sets were exposed for periods of up to 162 days, between October 1962 and September 1963. The observed results were negative: no unusually adherent deposits were found, and the observed light attenuation was typical of that routinely observed in comparable exposure durations with nonconcentrating PV arrays.

In an auxiliary experiment, a silicon PV cell of construction similar to those in the main experiment was recovered, together with fragments of its surrounding pottant, from a damaged receiver used in a reflective solar concentrator at the array at Mississippi County Community College in Arkansas. These materials were subjected to x-ray spectrographic analysis to determine whether elemental silver had migrated from the collector grid of the cell into the adjacent pottant. The result was negative, supporting previous evidence from flat-plate arrays concerning the resistance of these cells to such damage. At the conclusion of the above test series, the concentrator assembly was transferred to the Florida Solar Energy Center.

INTRODUCTION

Background

This study was conducted at Oak Ridge National Laboratory (ORNL) in response to the deployment of test arrays of solar photovoltaic (PV) cells in optically concentrating mounts at locations outside the arid Southwest. Our concern was that humid weather and films of various airborne contaminants common to such areas might, upon intense solar exposure, affect PV cell behavior differently than would dry mineral dusts. The reasoning was that such atmospheric contaminants can (and probably do) deposit on the cyclically heated surfaces of PV cells operated outdoors unless these surfaces are hermetically sealed. If such cells are operated under optically concentrated sunlight, the enhanced energy flux incident upon the cells creates a potential for thermal- or photon-induced changes to the contaminant films. Such changes could affect the optical transmissivity of the contaminant films and possibly their adherence to the cover glass or antireflective coating of the PV cells, as well. Possible optically active contaminants could include industrial pollutants and natural materials such as pollens or pine oils.

Objectives

The initial objectives of the study were (1) to examine the effects on PV cell performance of extended exposure to atmospheric contaminants characteristic of populated areas in nonarid climates; (2) to identify any air contaminants which form films that significantly affect PV cell performance; (3) to determine the mechanism of, and means for counteracting, if possible, the effects produced by any such contaminants.

A subsequent objective was to explore briefly whether prolonged exposure to concentrated sunlight would enhance silver migration in PV cells employing Ti-Pd-Ag grid metallization and encapsulated in room temperature vulcanizing (RTV) silicone polymer.

EVOLUTION OF TEST FACILITY

Preoperational History

This project was authorized by the Distributed Solar Technology Division, U.S. Department of Energy (DOE), in June 1980. Extensive prior discussions were held by ORNL representatives with staff members of Sandia National Laboratory Albuquerque and with the Solar Energy Research Institute regarding the worth and feasibility of the study.

ORNL proposed to erect a linear parabolic reflecting concentrator on a two-axis tracking carriage to expose various configurations of solar PV cells simulating the arrangements used on existing or proposed concentrating arrays. In March 1981, after concurrence of the above organizations that the proposed approach was feasible, ORNL secured a suitable concentrating reflector assembly from Solar Kinetics, Inc., in Dallas, Texas, and contracted with Astro Works in White Rock, New Mexico, for a tracking mount. The vendor encountered unexpected difficulties in providing the required automatic tracking controls and in March 1982 shipped the mount to Oak Ridge with a manual drive only. A sun-following automatic drive control was obtained and subsequently fitted to the unit at ORNL.

Single-crystal silicon PV cells from Applied Solar Energy Corporation, AFG Sunadex cover glass, and DuPont Kapton electrical insulating film were obtained by ORNL for the test specimens. The PV cell assemblies were mounted on a liquid-cooled target bar (Fig. 1), which was aligned along the focus of the reflector (Fig. 2). Following the installation of the test apparatus on the roof of a laboratory building at ORNL in August 1982, the mirror alignment, tracking drive operation, and control system were checked while the PV cell assemblies were being fabricated. Initial testing of cells began in October 1982.

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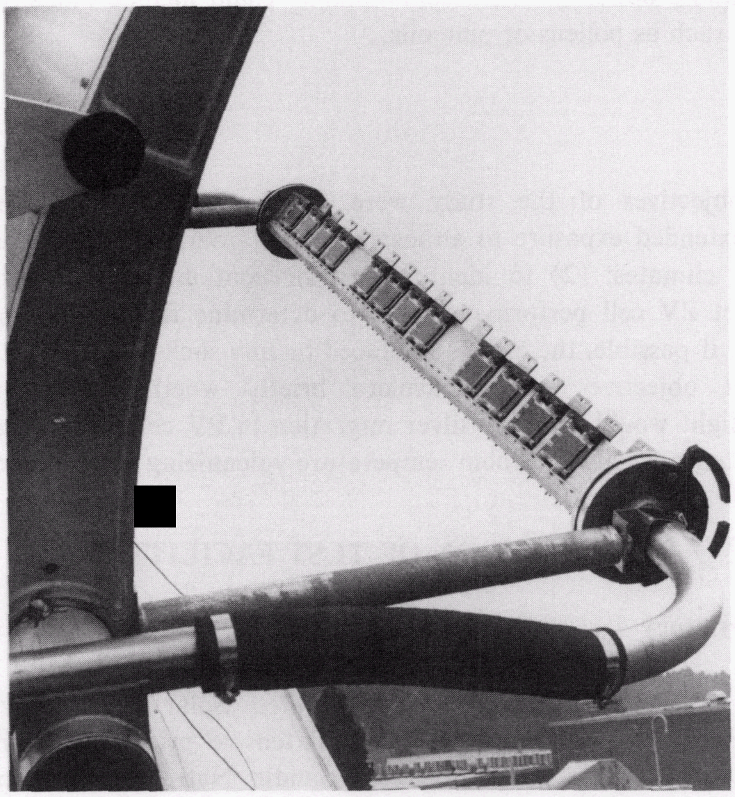

Fig. 1. Target assembly for photovoltaic cell testing.

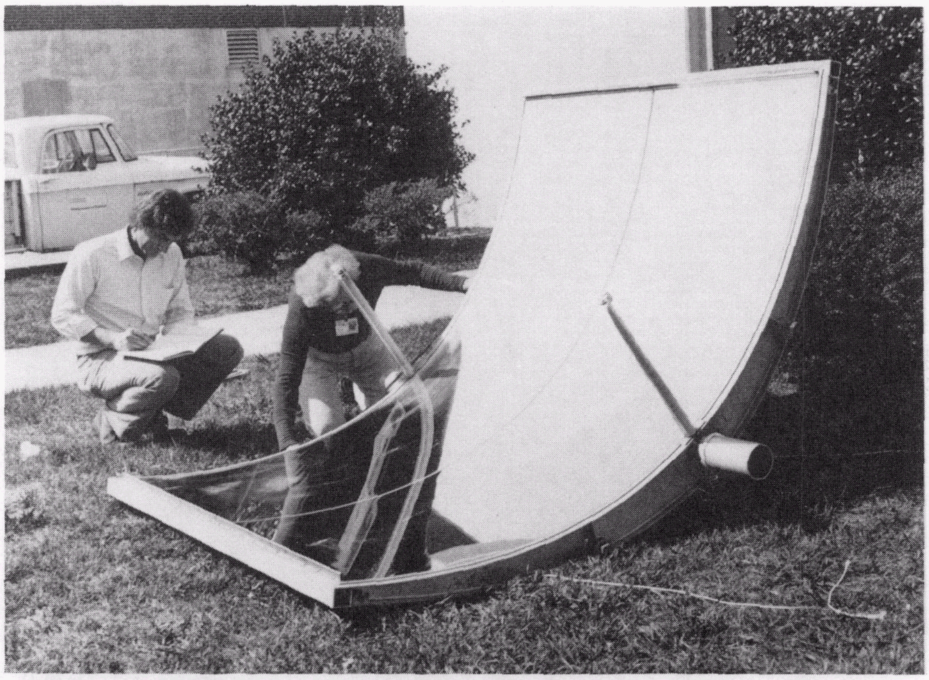

Fig. 2. Parabolic reflector for test assembly.

Equipment Design

Tracking Mount. The tracking mount (Fig. 3) consisted of a reflector support cradle mounted on a motor-driven, geared equatorial tracking drive that provided diurnal positioning. An automatic axis tilt drive that used a motor-driven lead screw provided seasonal declination adjustment. A Mann-Russell Mark IV Solar Tracker Module provided wake-up, solar image acquisition, shutdown, position reset, and emergency stowing signals for the positioning drives. Capabilities of the drive are detailed in Table 1.

Reflector. The reflector was a parabolic trough, fabricated from crescent-shaped aluminum ribs covered with a sheet aluminum skin, much like a section of aircraft wing. The concave side of the reflector was faced with two sheets of 0.076-cm (0.030-in.) untempered, polished glass, silvered on the rear surface. The glass was manufactured by Glaverbel (Belgium). The sheets of glass were cemented to thin steel backing sheets. These assemblies were sufficiently flexible so that they could be mounted on the reflector frame by springing them into the proper curved contour and then confining the edges of the sheet with bolted flanges along the ends of the reflector (Fig. 2). This mounting method placed all parts of the glass sheet into compression. Reflector details are summarized in Table 2.

Solar Receiver. The receiver or target bar was a liquid-cooled hollow aluminum weldment of square cross section, 10.2 × 10.2 × 120 cm (4 × 4 × 48 in). The ends were fitted with flanges to connect to flexible hoses for the coolant, and the interior contained a square filler block running down its length to form an annular coolant passage. The

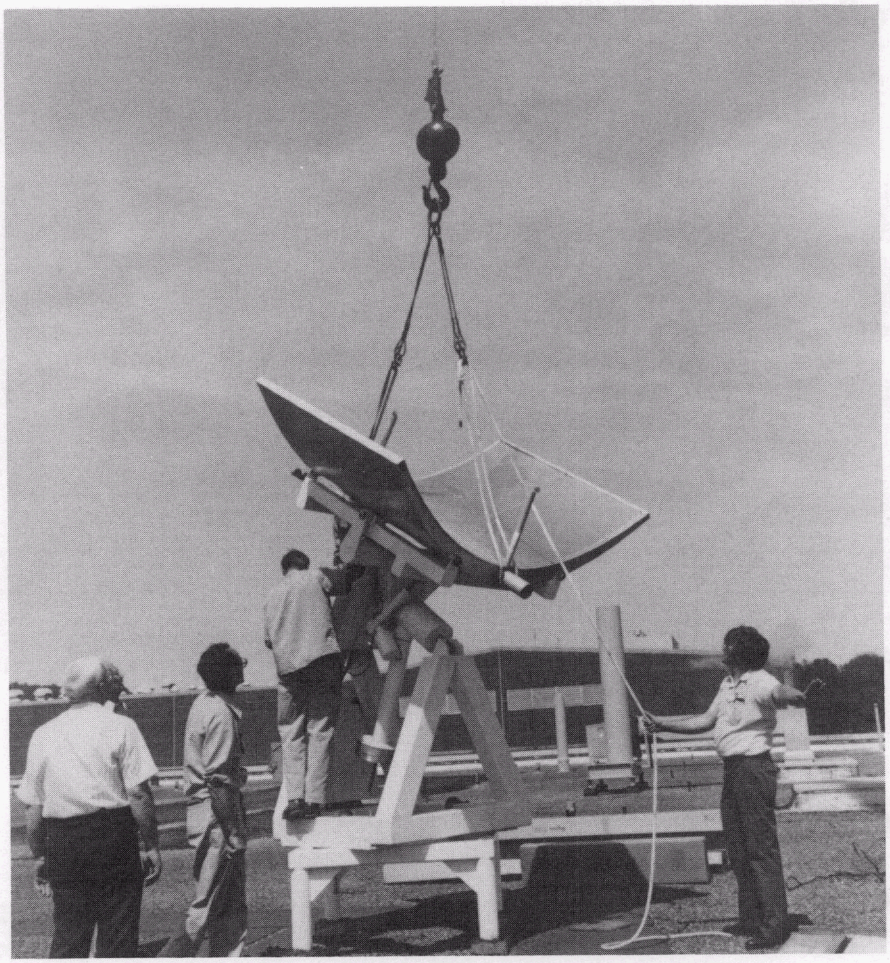

Fig. 3. Installation of test assembly on roof mount.

Table 1. Performance capabilities of solar tracking drive

Manual drive rates, rad/h	5.24, 20.9
Default tracking rate (sun obscured), rad/h	0.26
Tracking accuracy, rad	±0.0017
Tracking range, polar axis, rad	π (due east to due west)
Tracking range, declination axis, rad	1.13[a]
Stow position	Facing due east
Maximum wind speed for normal operation, m/sec (mph)	13.4 (30)
Maximum wind speed without mechanical damage, m/sec (mph)	40.2 (90)

[a]Pointing axis angle from 0.44 to $\pi/4$ rad (25° to 90° above horizon).

Table 2. Collector details

Reflector	
Collector manufacturer	Solar Kinetics, Inc.
Type	Parabolic trough; hollow monocoque construction; aluminum ribs and skin
Length along axis, cm	121.9
Chord, cm	213.4
Focal length, cm	56.3
Reflective surface	0.076-cm-thick glass sheet, untempered, polished, back-surface silvered; manufactured by Glaverbel (Belgium)
Target assembly	
Orientation	Along focal axis
Length, cm	120
Width, cm	10.2 × 10.2
Material	Black anodized aluminum
Number of specimen positions	34

surface of the receiver was anodized, for weather protection, and was tapped for retainer screws to hold the PV cell assemblies.

PV Cell Assemblies. The cells used for irradiation specimens were single-crystal n-p silicon cells with Ti-Pd-Ag collector grids and metallic backing, supplied by the Applied Solar Energy Corporation. The cell face dimensions were 45 mm long by 42 mm wide; the active cell width between collector buses was 36 mm. The cell design was optimized for concentrated sunlight at 30×.

Four types of assembly were constructed to simulate various types of cell mounting either potentially or actually in use by contemporary arrays:

Type A—Each cell was clamped against a 45- by 42-mm rectangle of 3.2-mm-thick Sunadex low-iron glass, with the heavily embossed side of the glass facing away from the cell.

Type B—Identical to type A, except that the heavily textured side of the cover glass faced the cell.

Type C—Cover glasses were suspended with a 1.6-mm clearance above bare cells by means of notched nylon spacers (Fig. 4). Type C assemblies oriented the cover glass with the heavily embossed side away from the cell.

Type D—Identical to type C, except that the heavily embossed cover glass side faced the cell.

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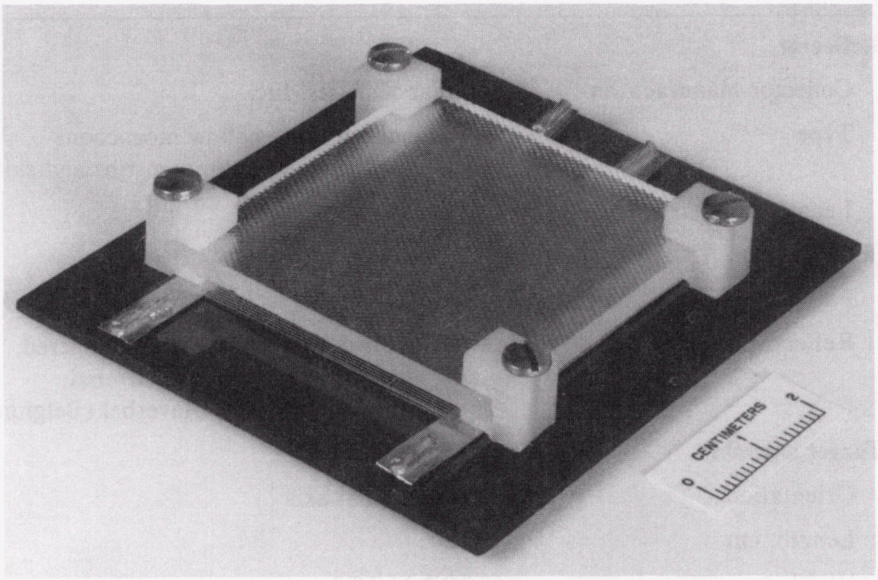

Fig. 4. Photovoltaic cell test assembly, type C.

Cell backings were electrically insulated from their aluminum mounting plates by a sheet of 0.05-mm Kapton inserted between the two faces. Thermal contact was maximized by applying ECCOTHERM TC-8M thermal grease at metal-metal and metal-Kapton interfaces. The mounting plates were attached to the receiver by screwed clamping flanges. Details of the cell and receiver assemblies are presented in Table 3.

Temperature Control Systems. Provisions were made to control the temperature of the receiver so that overheating of the cells would not occur. Figure 5 shows the schematic layout of the temperature control system employed for the test series at ORNL. Heat absorbed by the receiver coolant was rejected to an ORNL process cooling stream.

Before the ORNL cell tests and in anticipation of future tests at other locations, a package cooling loop was constructed for the test facility. This loop employed a fan coil unit to reject heat from the coolant to the surrounding air. The assembly was skid mounted and required only electric power for the circulating pump and cooling fan for operation.

EXPERIMENTAL PROGRAM

Simulation Parameters

Array Simulation. The cell mounts, types A through D as described above, were designed to simulate the type of cell exposure that would be encountered in various types of concentrating arrays in use. Thus, types A and B simulate linear reflector concentrating systems where the cells are protected by cover glasses in contact with the cell faces. Types C and D simulate some of the features of Fresnel lens concentrators in the event that cover

Table 3. Cell assembly details

Mounting plate	
Dimensions, mm	7.2 × 8.9 × 0.19
Material	Black anodized aluminum
Test cell	
Dimensions, mm	45 × 42 (36 mm active width)
Type	Single crystal silicon n-p
Cover glass	
Dimensions, mm	45 × 42
Material	3.2-mm-thick Sunadex glass
Kapton sheet thickness, mm	0.051
Stand-off distance for raised cover glasses, mm	1.6

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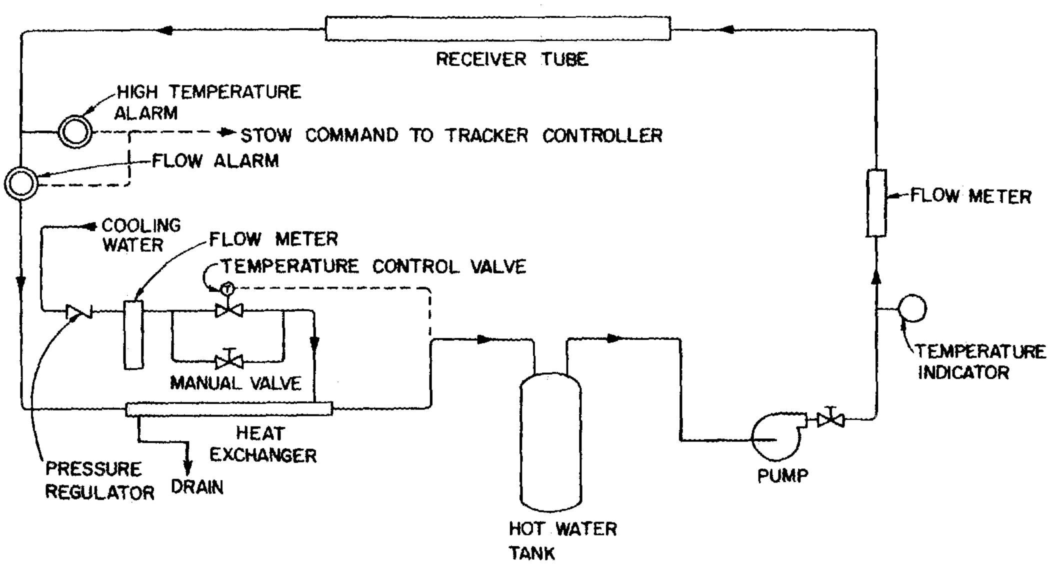

Fig. 5. Temperature control system for receiver tube.

glasses were not mounted. The cells in these arrays are frequently sheltered from direct weather by the lenses and housing, but the boxes are allowed to "breathe" through vent holes.

Environment. ORNL is located in a forested reserve but also exhibits urban atmospheric characteristics because of local coal-fired steam generation, numerous buildings, machinery, and vehicular traffic. Rainfall is in the 120 to 150 cm/year range, and the climate is moderately humid.

Procedure

The adopted exposure arrangement involved mounting three pairs of cells on the test bar, exposing them for either 1 month or (in the case of set 3) longer periods, and then removing and analyzing the cells. Typically, the pairs consisted of two type A, two type B, and one each of types C and D.

Calibration. Prior to exposure, calibration measurements were made on type A and B assemblies. The cells were exposed to a simulated AM 1 solar spectrum (type ELH lamp) at 0.100 W/cm^2 and 28°C; measurements were recorded for short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and maximum power output (P_{max}). Fill factor and specific power were then computed. The 1× concentration results thus obtained were reasonably consistent with the 30× concentration typical data supplied by the cell manufacturer (Fig. 6). External quantum efficiencies over the spectral range from 400 to 1100 nm were also determined, using beams of quasi-monochromatic light (Fig. 7). These were generated by optical filtration of the ELH lamp spectrum, using narrow-band (50-nm) interference filters.

Cover glasses were also checked to determine initial values and uniformity of transmissivity among samples. Using a reference PV cell as a photodetector, narrow-band spectral transmission measurements were made by taking the ratio of solar cell output with and without the cover plate in the optical path. Errors in these measurements were estimated not to exceed ±1%. The measured values (Fig. 8) essentially confirmed the performance reported by the manufacturer.

Cell Assembly Exposure Testing. After calibration checks, a set of specimens including types A, B, C, and D assemblies was clamped in place on the target bar and irradiated. After the test period was completed, this set was removed for inspection, and while the removed set was being inspected and retested, a second set was installed. Set 3 was also used in parallel with the others for part of the time to provide a longer continuous exposure run. Sufficient cooling was provided through the target bar to ensure that the cell base temperatures would not exceed 50°C. The actual temperature of the cells was allowed to float with the ambient weather conditions and time of day. At the end of the period, the measurements described under the previous heading "Calibration" were repeated, except that type A and B assemblies were not disassembled and measurements were made through the weathered, unwashed cover glasses. The cover glasses in type C and D assemblies were separated from their respective cells and separately measured. This provided not only an evaluation of the cells exposed to ambient air conditions but also a means of estimating whether any deterioration of type A or B performance was due to cell losses, glass transmission losses, or both. The individual irradiation periods varied from 5 to 21 weeks in length; total irradiation time undergone by each of the three sets is tabulated below.

Set number	Individual exposure time (days)	Total time (days)
1	45, 40, 69	154
2	84, 23, 55	162
3	147	147

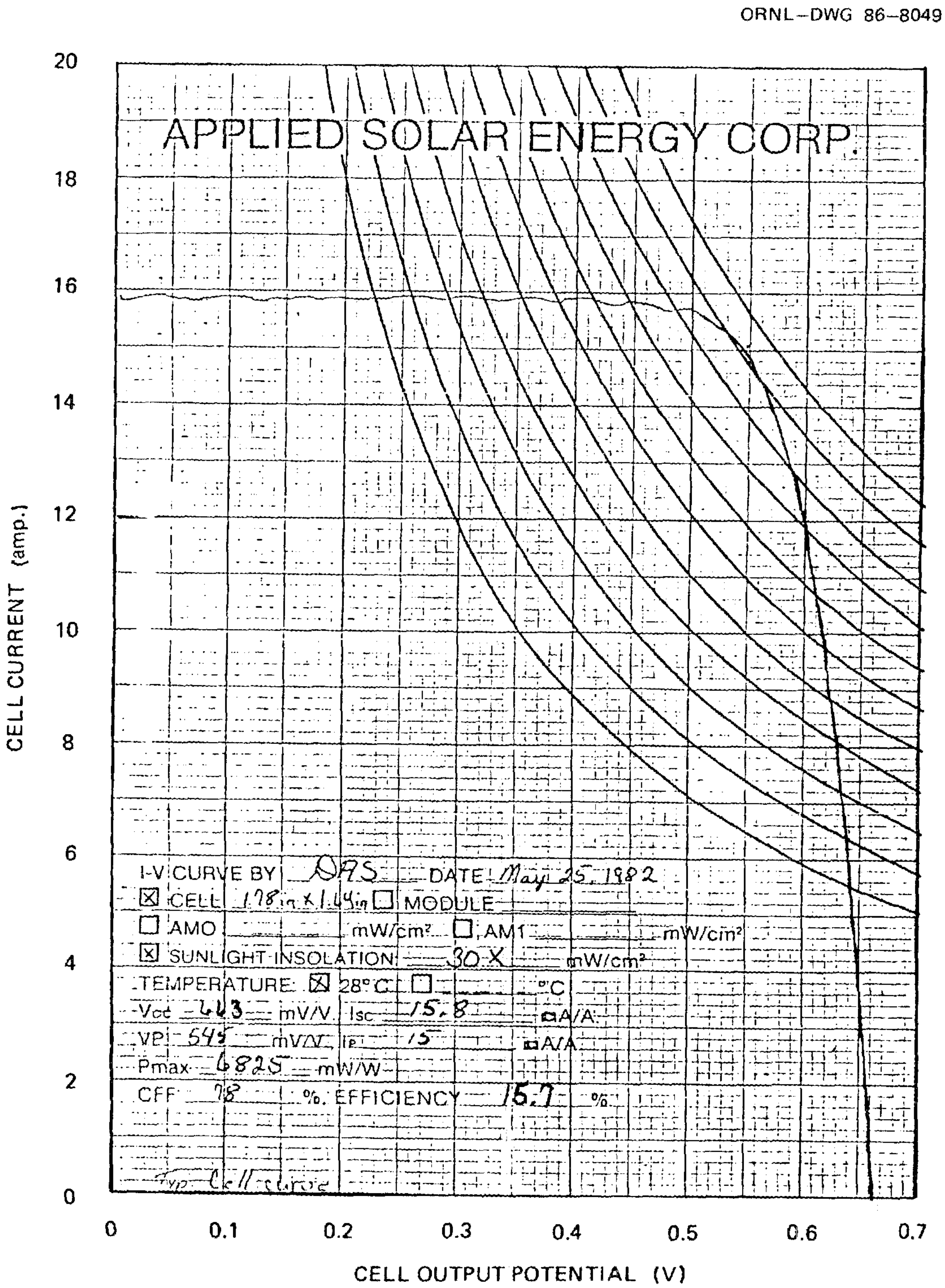

Fig. 6. Test data for typical photovoltaic cell as supplied by Applied Solar Energy Corporation.

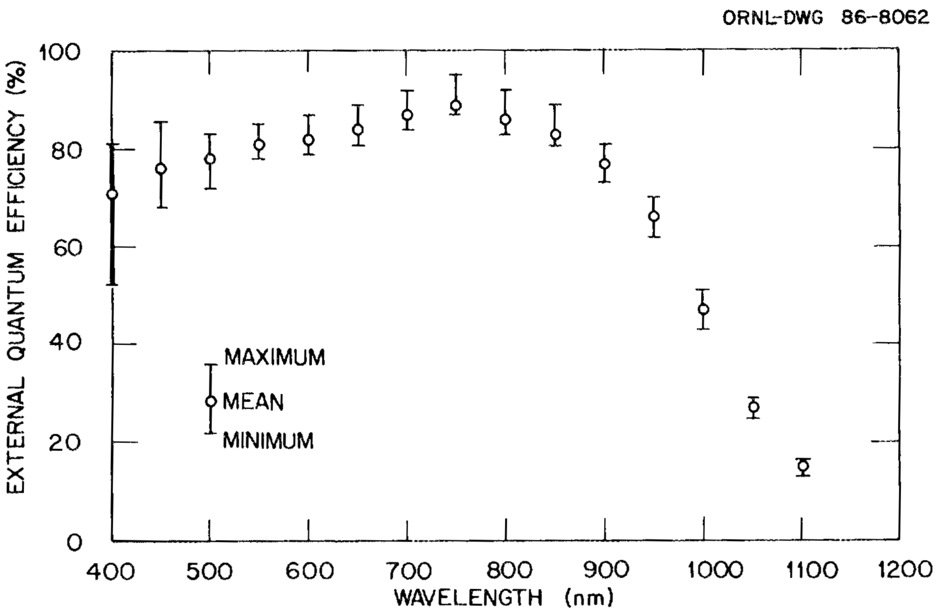

Fig. 7. Measured external quantum efficiency of typical cell assembly.

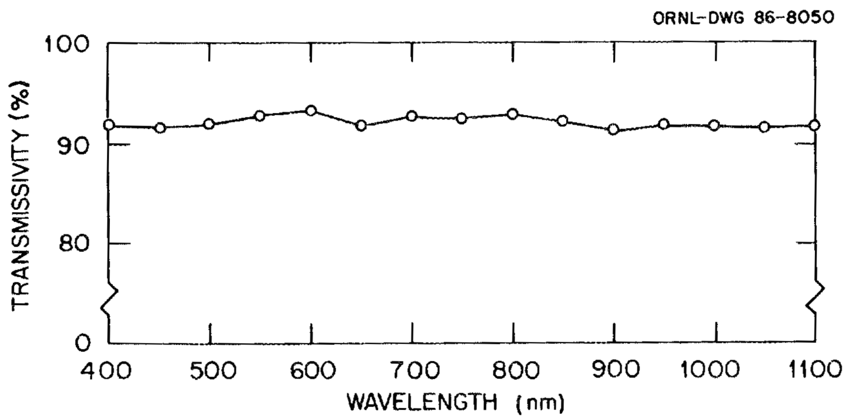

Fig. 8. Typical measured values for cover glass transmissivity.

RESULTS

Cell Assembly Performance

Table 4 presents the measured behavior of the PV cells before and after the irradiations. Results from the type A and B assemblies, where the cover glasses protected the cells from contact with the atmosphere, show some minor degradation of the power output, quite comparable with that seen for nonconcentrating PV systems.[1] The fill factor changes are essentially within the error band of the measurements (estimated at ±2%).

Table 4. Cell assembly performance before and after exposure

Cell assembly	Assembly type[a]	Calibration				Final			
		V_{oc},[b] mV	I_{sc},[c] mA	Fill factor	Specific power (mW/cm^2)	Fill factor	Change (%)	Specific power (mW/cm^2)	Change (%)
					Set 1				
LU-1	A	577	533	0.780	14.9	0.783	+0.4	14.6	−2.0
LU-3	A	581	536	0.777	15.0	0.778	+0.1	14.6	−2.7
LD-1	B	576	526	0.775	14.6	0.780	+0.6	14.9	+2.1
LD-3	B	570	531	0.768	14.4	0.775	+0.9	14.4	0.0
B-3	D	580	478	0.770	13.3	0.586	−23.9	7.04	−47.1
B-5	D	582	522	0.775	14.6	0.663	−14.5	11.3	−22.6
					Set 2				
LU-6	A	585	548	0.777	15.4	0.780	+0.4	14.1	−8.4
LU-7	A	588	545	0.775	15.4	0.778	+0.4	14.3	−7.1
LD-5	B	578	530	0.760	14.4	0.753	−0.9	13.7	−4.9
LD-6	B	579	535	0.745	14.3	0.724	−2.8	13.2	−7.7
B-31	C	585	512	0.785	14.5	0.721	−8.2	12.1	−16.6
B-32	D	585	548	0.777	15.4	0.780	+0.4	14.1	−8.4
					Set 3				
LU-4	A	580	537	0.777	15.1	0.775	−0.3	14.3	−5.3
LU-5	A	582	560	0.763	15.4	0.764	+0.1	14.0	−9.1
LD-2	B	576	530	0.780	14.8	0.784	+0.5	14.9	+0.7
LD-4	B	578	527	0.770	14.6	0.768	−0.3	14.2	−2.7
B-6	C	583	512	0.778	14.4	0.598	−23.1	9.1	−36.8
B-2	D	569	501	0.786	14.0	0.588	−25.2	3.3	−76.4

[a]A: cover glass touching cell with deeply textured side out; B: cover glass touching cell with deeply textured side in; C: cover glass spaced 1.6 mm above cell with deeply textured side out; D: cover glass spaced 1.6 mm above cell with deeply textured side in.

[b]Open-circuit voltage.

[c]Short-circuit current.

While this agreement does not guarantee that no cell degradation has occurred, the small deviation among the several cases implies that decreased output was chiefly caused by some uniform mechanism. The most obvious possibility is the reduced light transmission caused by the soiling of the cover glasses.

Type C and D assembly cells obviously experienced significant deterioration. This appears to have resulted from their relatively unprotected mounting configuration on the target bar. The major mechanism considered to be responsible for the damage was the accumulation of moisture in the gap between the cover glass and the cell. The cover glasses, spaced at 1.6 mm above the cells, apparently acted as a trap for moisture, instead of the desired simulation of a ventilated lens box, which is characteristic of refracting concentrators.

Cover Glass Performance. As noted earlier, the cover glasses from the type C and D assemblies were demounted and rechecked for optical transmissivity at the end of each set exposure. The results of these measurements over the period September 1982 to September 1983 are given in Table 5. The modest (2–9%) decrease in light transmission is consistent with that observed for cover glass material in nonconcentrating exposure,[2] indicating that no unusual soiling mechanisms were occurring. There is no significant difference evident between the behavior of the glasses with the deep embossing toward or away from the weather. While the question of relative dirt adhesion on stippled vs smooth surfaces has been raised with respect to the Georgetown University flat-plate array,[3] other observations[4] have detected no meaningful differences in this respect.

Related Testing

Silver Migration Test. One of the component tasks of this project was to obtain an additional check on the observed resistance to internal silver migration exhibited by RTV silicone polymer-encapsulated, single-crystal silicon PV cells, fabricated with Ti-Pd-Ag collector grid material. Originally, we planned to fabricate a specimen especially for this purpose; however, in the course of repairs to PV cell strings at the Mississippi County Community College (MCCC) PV system in Arkansas, a suitable cell specimen became available for this purpose. At the time of removal, the cell had accumulated over 1.5 years of exposure under concentrating conditions of up to 24×.

The cell, together with fragments of adjacent silicone pottant material, is illustrated in Fig. 9. In its original position in the MCCC receiver, there was a dc potential of ~230 V between the cell and the bare, grounded receiver frame 1.5 cm away. The cell potential was positive with respect to ground. X-ray spectrograms were made of the interconnector (a copper–tin alloy), the bus bar (a silver–tin alloy), the cover glass of the cell, and one edge of the Ti-Pd-Ag cell grid metallization. The results established the expected presence of silver in the bus bar and grid and likewise its absence in the interconnector and cover glass. Comparable analyses were performed on the fragments of pottant that had been in contact with the cell when it was mounted in its receiver; all of these latter results were negative for silver content.

CONCLUSIONS

Cell Assembly Tests. Environmental exposure tests were performed on single-crystal silicon PV cell assemblies irradiated with concentrated sunlight, over a total time period of approximately one year. Measurements during and following this period did not reveal any tendency for the production of unusually light-attenuating or especially adherent soiling deposits on the cover glasses of the assemblies. Mechanical clamping of the cover glasses against the cells was adequate to prevent moisture migration into the assemblies, as evidenced by the high residual power-producing capacity of the cells after irradiation. The attenuation of sunlight through the cover glasses was comparable with that observed in nonconcentrating PV cell arrays. The experiments intended to reproduce exposure conditions representative of refractive concentrator arrays were unsuccessful, because the

Table 5. Cover glass transmissivity

Wave length (nm)	Days of exposure with smooth side of coverglass															
	Up			Down			Up			Down			Up		Down	
	0	85	154	0	85	154	0	107	193	0	107	193	0	147	0	147
	Set 1						Set 2						Set 3			
402	0.928	0.891	0.846	0.928	0.891	0.859	0.932	0.902	0.912	0.926	0.917	0.876	0.923	0.917	0.923	0.891
453	0.912	0.888	0.849	0.913	0.900	0.849	0.932	0.905	0.899	0.927	0.913	0.882	0.923	0.927	0.918	0.893
502	0.919	0.894	0.868	0.906	0.905	0.868	0.932	0.910	0.896	0.932	0.912	0.902	0.926	0.932	0.913	0.907
548	0.935	0.909	0.881	0.917	0.911	0.880	0.935	0.914	0.926	0.922	0.911	0.938	0.917	0.934	0.921	0.894
602	0.929	0.904	0.876	0.911	0.918	0.885	0.939	0.911	0.892	0.943	0.915	0.892	0.938	0.933	0.917	0.900
652	0.919	0.910	0.892	0.927	0.917	0.898	0.935	0.917	0.892	0.935	0.918	0.906	0.913	0.936	0.920	0.900
703	0.938	0.914	0.892	0.917	0.917	0.897	0.929	0.919	0.895	0.931	0.912	0.926	0.932	0.937	0.923	0.908
750	0.929	0.913	0.896	0.922	0.901	0.898	0.928	0.917	0.896	0.936	0.907	0.914	0.928	0.939	0.922	0.905
801	0.925	0.910	0.898	0.919	0.914	0.908	0.936	0.907	0.911	0.939	0.914	0.907	0.938	0.935	0.924	0.893
853	0.922	0.915	0.894	0.917	0.923	0.908	0.927	0.919	0.910	0.923	0.919	0.918	0.923	0.936	0.912	0.906
903	0.937	0.914	0.894	0.923	0.917	0.904	0.926	0.910	0.893	0.922	0.910	0.910	0.909	0.937	0.908	0.900
952	0.924	0.914	0.895	0.908	0.917	0.903	0.923	0.917	0.904	0.922	0.910	0.907	0.919	0.931	0.913	0.907
1001	0.927	0.916	0.891	0.915	0.916	0.897	0.918	0.912	0.902	0.904	0.912	0.910	0.919	0.929	0.914	0.907
1053	0.927	0.912	0.900	0.901	0.918	0.900	0.913	0.919	0.918	0.921	0.912	0.909	0.915	0.929	0.916	0.901
1101	0.933	0.916	0.903	0.898	0.923	0.912	0.924	0.916	0.907	0.902	0.912	0.898	0.904	0.930	0.912	0.901

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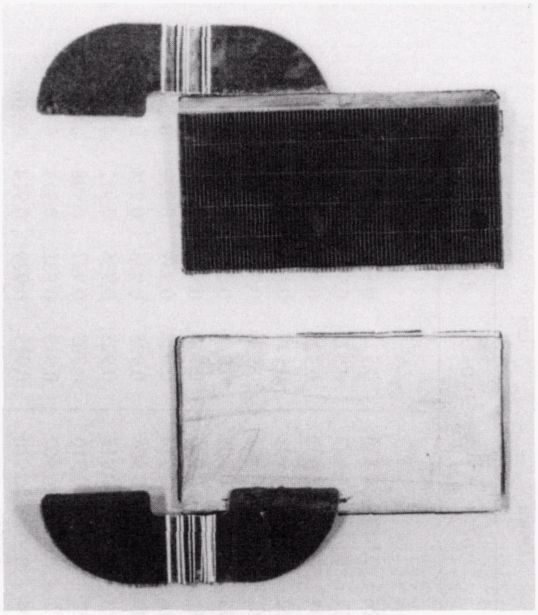

Fig. 9. Front and rear of Mississippi County Community College photovoltaic cell with attached interconnector.

sheltering scheme that was adopted apparently trapped moisture around the cells, producing unrepresentative conditions.

Silver Migration Test. An RTV silicone polymer-encapsulated, single-crystal silicon PV cell with silver-bearing metallization, recovered from the MCCC concentrating PV array, was spectroscopically examined for elemental silver in the surrounding pottant, with negative results. The finding supports previous observations in flat-plate systems, where the same type of encapsulant and metallization proved resistant to electrochemical migration of silver.

EXPLORATION OF FURTHER TEST OPTIONS

Following completion of the environmental exposures at ORNL, two other possibilities were reviewed with DOE concerning useful sites for studying possible anomalous depositions of airborne material: an airport site and a south-central industrial urban site.

Airport Site. During field tests of various solar arrays at airport sites, operating personnel identified hydrocarbon residues as a source of soiling on cover glasses and mirrors.[5] To explore a possible site for testing soiling by jet engine exhaust residues, we discussed with Atlanta airport officials the idea of locating the ORNL test apparatus at the airport for an extended period. At the Eleventh Concentrator PV Project Information Meeting in Albuquerque in December 1983, however, status reports were presented on arrays operating at Dallas, Albuquerque, and Phoenix airport sites. In subsequent questioning, the speakers indicated that any loss of array power attributable to airborne jet exhaust products was either undetectable or readily restorable by standard array surface cleaning techniques. On this basis, ORNL concluded, with DOE concurrence, that redeployment of the test unit at the Atlanta site would not be justified.

South Central Industrial Urban Site. ORNL reviewed annual reports of the U.S. Environmental Protection Agency[6,7] to identify cities in the selected region having significant industrial particulate emissions in their atmosphere. These were matched against the availability of a laboratory or university in the city that would provide a host site and operating services for the test apparatus.

Two sites were identified. However, at this stage in the evolution of concentrating PV arrays, it had become apparent that refractive concentrators were generally better suited than reflective systems for PV service and that the more westerly U.S. sites, with their low diffuse component of insolation, would be the economic choice for future concentrator PV systems. Therefore, this approach was discontinued.

FINAL DISPOSITION OF UNIT

In July 1984, the project was terminated. Because no opportunity for using the test apparatus in ORNL programs could be identified, other DOE program sites were approached, including Sandia National Laboratory Albuquerque, Solar Energy Research Institute, and Florida Solar Energy Center (FSEC). The unit was subsequently transferred to FSEC for use in outdoor irradiation tests of solar modules.

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