NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-495

Solar Cell Performance as a Function of Temperature and Illumination Angle of Incidence

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FOREWORD

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

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CONTENTS

I. INTRODUCTION

The response of solar cells to non-normal illumination has been measured. The accurate measurement of this response in the usual solar cell laboratory is quite often complicated by light source difficulties. A solar simulator usually produces a divergent light beam so that rotating a solar cell or a panel of solar cells places a portion of the sample into a more intense beam and another portion into a less intense beam. If the sun is used as a source, one must take care to block sky radiation from the cells and to continually follow the sun as it moves across the sky.

A heliostat in the JPL Celestarium was available for performing pre-flight calibrations on the experimental solar panels to be flown on Applications Technology Satellite E (ATS-E). The heliostat produced an accurately parallel vertical beam inside a dark room with non-reflecting walls and ceiling. This source proved to be ideal for the required calibration runs, eliminating both light source deficiencies enumerated above. The results of this testing and a comparison with a simple theory are presented in this paper.

II. EXPERIMENTAL APPARATUS

Various types of solar cells were mounted on solar panels encompassing coverglasses ranging in thickness from 0.30 mm (12 mils) to 1.52 mm (60 mils). The cells were mounted on two different solar panels, 65 cells on a rigid aluminum honeycomb panel and 15 cells on a flexible Kapton panel. There were 13 types of solar cell/coverglass configurations. Each configuration was represented by a sample size of 5 cells. Data for 3 of the solar cell/coverglass configurations are reported here: 10 Ω-cm 0.30-mm (12 mil) cells with 0.51-mm (20 mil) coverglasses, 10 Ω-cm 0.30-mm (12 mil) cells with 0.15-mm (6 mil) coverglasses, and 2 Ω-cm 0.20-mm (8 mil) cells with 0.15-mm (6 mil) coverglasses. These cells were all mounted on the aluminum honeycomb panel. The 2 Ω-cm cells were solderless cells of Heliotek manufacture. The other types were solder-dipped cells manufactured by Centralab. Coverglass material was 7940 fused silica with ultraviolet filters and antireflection coatings. The coverglasses were mounted to the cells with RTV-602 silicone adhesive. During the Celestarium measurements, solar cell parameters measured were short-circuit current I_{sc}, open-circuit voltage V_{oc}, and during one run the entire I-V curve was recorded for each cell at each of the following angles of incidence: 0, 30, 45, 60, and 75 deg. Some information was gained regarding the equilibrium temperatures of the cells at these various angles of incidence by monitoring the output of thermistors mounted behind the cells. The intensity of the normally incident sunlight varied as the day progressed, and was monitored by JPL Balloon Flight Standard Solar Cell BFS 511. During the measurements reported here, the solar intensity at the test panels ranged from 68 to 74 mW/cm^2. The values for short-circuit current, maximum power P_{max}, and current at maximum power are corrected for temperature variations and compared with the cosine function and with a function representing solar energy transmitted through the coverglass. The values for open-circuit voltage are compared with values predicted from equations derived from the experimental data of other workers giving V_{oc} as a function of cell temperature and solar intensity.

III. EXPERIMENTAL PROCEDURE

The heliostat in the Celestarium facility was used to produce the parallel bundle of solar radiation. The heliostat consisted of a mirror which automatically tracked the sun and cast the reflected bundle of light onto a second fixed mirror. The second mirror was mounted in the ceiling of the Celestarium and, in turn, reflected the light bundle vertically downward onto the test area. Tracking accuracy was such that the bundle was vertical to within ±6 sec of arc after initial warm-up of the tracking electronics. The light bundle is approximately 24 in. in diameter.

The uniformity of the light bundle was measured by means of two solar cells. One cell, Balloon Standard BFS 511, was maintained at a fixed position, and a second Balloon Standard cell, BFS 510, was moved about the bundle as a probe. An intensity map of the bundle was constructed from this data. During subsequent measurements, the solar cells were positioned in the light beam, using the intensity map as a guide so that the intensity variation over the surface of the panel was no more than ±1.5%.

The panels were mounted on a dividing head capable of rotation about two axes. Special fixtures were constructed for mounting the panels on the dividing head which allowed the panels to be accurately adjusted perpendicular to the beam at the zero reference marks. The aluminum panel was rotated about only one axis for the measurements reported here. However, it was established that the axis of rotation made no difference in cell short-circuit current output (a function which varies linearly with light intensity) for rotation about either the dividing head axis or for a compound angle rotation.

Current-voltage (I-V) curves are taken of each cell using a variable resistive load and an X-Y plotter. I-V curves representative of each of the three cell/coverglass configurations reported here are shown in Figs. 1 through 3. These figures show I-V curves resulting from each of the five noted angles of incidence. The curves for each cell were taken in sequence, starting at 0 deg and proceeding through 75 deg. Noted on each curve are values of short-circuit current, maximum power point, and voltage and current at maximum power. Open-circuit voltage was read out separately on a digital voltmeter and is not shown on the curves.

Solar cell temperature and panel temperature were not controlled during these measurements, but were spot checked for a limited number of cells. Typical temperature variation with angle of incidence under our experimental conditions is shown in Table 1. Sufficient time was allowed at each angle for the panel and cells to attain thermal equilibrium. As these data show, there is approximately a 10°C drop in temperature in going from 0 to 75 deg incidence.

IV. DATA ANALYSIS

Data was taken from the I-V curves and processed with the aid of a computer. Statistical parameters have been calculated for I_{sc}, V_{oc}, current at maximum power, I_{mp}, voltage at maximum power, V_{mp}, and P_{max} for both absolute values and values normalized to the normal incidence data. Results of these calculations are presented in the Appendix (Table A-1).

The behavior of the solar cell parameters with angle of incidence was compared with the parametric data of Sandstrom (Ref. 1) and Yasui (Ref. 2) who measured the performance of several different types of solar cells under varying conditions of solar intensity and cell temperature.

Solar intensity incident on the solar cell surface decreases as the cosine of the angle of incidence. However, at large angles of incidence, a significant amount of solar energy is lost due to reflection from the front surface of the coverglass. Reflectance ρ, defined as the ratio of reflected intensity to incident intensity, can be calculated as a function of angle of incidence with the aid of the Fresnel formulas. The reflectance, neglecting the effect of the anti-reflective coating on the coverglass and considering only one reflective surface, is expressed as follows:

$$\rho(\theta) = 1/2\left[\frac{\tan^2(\theta - \theta')}{\tan^2(\theta + \theta')} + \frac{\sin^2(\theta - \theta')}{\sin^2(\theta + \theta')}\right] \qquad (1)$$

where θ and θ' are the angles of incidence and refraction, respectively (Refs. 3 and 4). From Snell's law

$$\theta' = \arc \sin \left(\frac{\sin \theta}{n}\right) \qquad (2)$$

where n is the index of refraction of the reflecting surface. For fused silica $n = 1.46$. As θ goes to zero, Eq. (1) has the limit

$$\lim_{\theta \to 0} \rho(\theta) = \frac{(n - 1)^2}{(n + 1)^2}$$

Energy transmitted through the coverglass can be described in terms of energy transmitted at $\theta = 0$ by

$$\frac{t}{t_0} = \frac{t(\theta)}{t(\theta = 0)} = \frac{1 - \rho(\theta)}{1 - \rho(\theta = 0)} \cos \theta \qquad (3)$$

and Fig. 4 depicts the functions $\rho(\theta)$ and t/t_0 calculated for $n = 1.46$. For comparison, cos θ is also shown. Some values of cos θ and t/t_0 are also given in Table 2. It can be seen that t/t_0 and cos θ are essentially the same at small angles and diverge approximately 5% at 60 deg.

Since I_{sc}, P_{max}, and I_{mp} are expected to depend linearly on the transmitted energy and not very strongly on cell temperature (Ref. 1), these experimental values are normalized to $\theta = 0$, and compared with cos θ and relative transmitted intensity t/t_0. Results of this comparison are shown in Table 3. Also shown are the percentage deviations of the experimental values from cos θ and t/t_0. As a general rule, the prediction given by t/t_0 is always better than cos θ at $\theta = 75$ deg, always better at $\theta = 60$ deg when predicting P_{max}, and better about half the time when predicting I_{sc} or I_{mp} at $\theta = 60$ deg. However, just using cos θ to predict these parameters at angles up to $\theta = 45$ deg is nearly always better.

The results are even better when the cell temperature change is accounted for. Sandstrom gives data (Ref. 1) directly applicable to the 2 Ω-cm 8-mil cells. Empirical fits to the Sandstrom data gave the following formulas, which predict I_{sc} and P_{max} as a function of both solar intensity and cell temperature:

$$I_{sc} = (0.870 + 0.000582\ T)\ I \qquad (4)$$

$$P_{max} = (0.440 - 0.00172\ T)\ I \qquad (5)$$

where I is illumination intensity in mW/cm^2 and T is temperature in degrees Celsius. These relationships can be applied in the temperature range $-20 < T < 60°C$ and over intensities from 5 to 250 mW/cm^2. They should not be regarded as highly accurate functions, but do represent an average behavior over the temperature and intensity range indicated. Temperature corrections using Eqs. (4) and (5) were made to the 2 Ω-cm I_{sc} and P_{max} data of Table 3 and the Appendix. The magnitude of the corrections, and comparison of corrected data to cos θ and t/t_0 is given in Table 4. The corrections to I_{sc} make no appreciable difference, but the corrections to P_{max} data are substantial and the t/t_0 function is seen to agree with the corrected data to better than 2% over all angles of incidence, which is approaching the measurement uncertainties.

Similar corrections may be made to the 10 Ω-cm cell data using the approximate relationships

$$I_{sc} = (1.004 + 0.000977\ T)\ I \qquad (6)$$

$$P_{max} = (0.465 - 0.002090\ T)\ I \qquad (7)$$

obtained from the parametric studies of Yasui (Ref. 2) on 10 Ω-cm, 2 × 2 cm Centralab cells 0.46 mm (18 mils) thick, and may not apply as well to cells 0.30 mm (12 mils) thick. Again the corrections to short-circuit current are negligible, but do tend to improve the agreement with the t/t_0 prediction. The corrections to maximum power are again sizeable, but the disparity with values of t/t_0 becomes greater. Figures 5, 6 and 7 show the normalized I_{sc}, I_{mp}, and P_{max} data plotted with the t/t_0 curve for all three cell/coverglass configurations. Data in these figures are uncorrected for temperature variations.

The values for V_{oc} do not change with tilt angle as fast as the values for current and power, because V_{oc} depends logarithmically on illumination intensity. V_{oc} does depend rather strongly on temperature. Data from Refs. 1 and 2 were used to formulate V_{oc} in terms of illumination and temperature. Two methods of predicting the V_{oc} performance were used. The first applied an intensity correction at constant temperature using

$$V_{oc} = A + B \log I \tag{8}$$

followed by application of a correction factor for temperature, usually called β, in the following equation:

$$V_{oc} = V_{oc_0} + \beta(T - T_0) \tag{9}$$

β is found to be quite constant over illumination intensities between 25 and 140 mW/cm^2. The coefficients A and B in Eq. (8) were found to have an approximately linear temperature dependence, so they were fit to the equations

$$A = A_1 + A_2T \tag{10}$$

and

$$B = B_1 + B_2T \tag{11}$$

which give Eq. (8) the form

$$V_{oc} = (A_1 + A_2T) + (B_1 + B_2T) \log I \begin{cases} -20 \le T \le +40°C \\ 25 \le I \le 250\,mW/cm^2 \end{cases} \tag{12}$$

Method II consisted of direct application of Eq. (12).

Method I, using Eqs. (8) and (9) was found to give better agreement with JPL experimental data when Eq. (8) was used with values of A and B appropriate to 40°C. Table 5 lists the values found for A, B, A_1, A_2, B_1, B_2, and β for both the 2 and 10 Ω-cm cells. A summary of the V_{oc} calculations using both methods I and II is given in Table 6. Note that both methods of data correction involve the absolute calculation of V_{oc}. No ratioing is done. As expected, the method I calculation is usually better, because method II involves fitting functions to data which, in turn, was derived from previous fits to experimental data. The calculations for the 2 Ω-cm cell are best, possibly because parametric data were available for the same cell thickness used in the experiment. Ten Ω-cm parametric data used was always for 0.46 mm (18 mil) cells while the JPL experimental cells were 0.30 mm (12 mils) thick.

V. CONCLUSION

It is found that silicon solar cell output can be predicted as the angle of incidence of solar illumination is varied within the limited illumination and temperature levels used here. The methods used in this paper are found to predict V_{oc} to accuracies better than 4%, I_{sc} to better than 6%, and P_{max} to better than 4% at all tilt angles up to and including 75 deg. At tilt angles smaller than 60 deg, prediction accuracy for P_{max} increases to 2%. Cell temperature information used in the work reported here was of unknown accuracy and may have been the major contributor to the discrepancy with prediction. No significant difference in off-axis solar cell performance between cells covered by 0.15-mm (6 mil) coverglasses and cells covered by 0.51-mm (20 mil) coverglasses was observed in these measurements.

REFERENCES

1. Sandstrom, J. D., "Electrical Characteristics of Silicon Solar Cells as a Function of Cell Temperature and Solar Intensity," Proceedings of the IECEC Conference, Boulder, Colo., August 1968.

2. Yasui, R. K., unpublished experimental data, Jet Propulsion Laboratory Photovoltaics Group, October 1970.

3. Sears, F. W., Optics, p. 174. Addison-Wesley Publ. Co., Reading, Mass., 1949.

4. Ross, R. G., Jr., "Solar-Panel Approaches for a Venus-Mercury Flyby," paper presented at the Space Technology and Heat Transfer Conference, Los Angeles, Calif., June 21 to 24, 1970.

Table 1. Thermistor temperature as a function of angle of incidence

Solar cells No. 70 - 74 Thermistor RT-15 Solar intensity = 65 mW/cm^2		
Pacific daylight time	Angle of incidence, deg	Temperature, °C
12:10	0	41.7
12:13	10	41.7
12:17	20	41.1
12:20	30	40.6
12:26	40	38.9
12:31	50	36.1
12:38	60	34.4
12:43	70	32.2

Table 2. Applicable values of cos θ and t/t_0

θ, deg	cos θ	t/t_0
0	1.00000	1.00000
30	0.86603	0.86474
45	0.70711	0.69998
60	0.50000	0.47540
75	0.25882	0.20246

Table 3. Average values of normalized short-circuit current, current at maximum power and maximum power with percentage deviations from cos θ and calculated transmitted energy

Angle of incidence θ	$\frac{I_{sc}}{I_{sc_0}}$	% Deviation from cos	% Deviation from t/t_0	$\frac{I_{mp}}{I_{mp_0}}$	% Deviation from cos	% Deviation from t/t_0	$\frac{P_{max}}{P_{max_0}}$	% Deviation from cos	% Deviation from t/t_0
10 Ω-cm, 0.30-mm cells, 0.51-mm coverglasses									
0	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00
30	0.878	+1.36	+1.51	0.886	+2.31	+2.46	0.886	+2.25	+2.40
45	0.732	+3.45	+4.51	0.717	+1.38	+2.41	0.710	+0.41	+1.43
60	0.497	-0.62	+4.52	0.494	-1.13	+3.99	0.485	-3.00	+2.02
75	0.222	-14.33	+9.52	0.215	-16.82	+6.34	0.201	-22.26	-0.62
10 Ω-cm, 0.30-mm cells, 0.15-mm coverglasses									
0	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00
30	0.871	+0.56	+0.71	0.859	-0.81	-0.66	0.866	-0.01	+0.14
45	0.713	+0.80	+1.82	0.704	-0.45	+0.56	0.704	-0.46	+0.55
60	0.490	-2.06	+3.01	0.481	-3.70	+1.28	0.472	-5.62	-0.74
75	0.213	-17.67	+5.25	0.203	-21.67	+0.14	0.191	-26.39	-5.90
2 Ω-cm, 0.20-mm cells, 0.15-mm coverglasses									
0	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00
30	0.872	+0.72	+0.87	0.873	+0.82	+0.97	0.868	+0.17	+0.32
45	0.709	+0.30	+1.32	0.705	-0.36	+0.66	0.690	-2.44	-1.45
60	0.487	-2.69	+2.34	0.480	-4.06	+0.90	0.464	-7.24	-2.44
75	0.217	-16.21	+7.12	0.211	-18.48	+4.22	0.192	-25.94	-5.32

Table 4. Temperature corrections applied to I_{sc} and P_{max} data for 2 Ω-cm 0.20-mm cells

Angle of incidence θ, deg	I_{sc}/I_{sc_0}	Temperature correction	Correction value[a]	% Deviation from cos	% Deviation from t/t_0
0	1.000	1.000	1.000	0.00	0.00
30	0.872	0.999	0.871	+0.57	+0.72
45	0.709	0.997	0.707	0.00	+1.00
60	0.487	0.995	0.485	-3.00	+2.02
75	0.217	0.993	0.215	-16.93	+6.19
Angle of incidence θ, deg	$\frac{P_{max}}{P_{max_0}}$	**Temperature correction**	**Correction value[b]**	**% Deviation from cos**	**% Deviation from t/t_0**
0	1.000	1.000	1.000	0.00	0.00
30	0.868	1.005	0.872	+0.69	+0.84
45	0.690	1.019	0.703	-0.58	+0.43
60	0.464	1.037	0.481	-3.80	+1.18
75	0.192	1.051	0.202	-21.95	+0.00

[a] I_{sc}/I_{sc_0} × temperature correction = correction value.

[b] P_{max}/P_{max_0} × temperature correction = correction value.

Table 5. Temperature and intensity correction coefficients

Cell type	A(40°C)	B(40°C)	A_1	A_2	B_1	B_2	β, mV/°C
2 Ω-cm, 0.20 mm	388.8205	72.72053	494	-2.6	63.85	+0.23121	-2.33
10 Ω-cm, 0.46 mm	394.0302	58.35	513	-2.97212	42.4	0.38329	-2.36

Values given are valid for $-20°C \le T \le +40°C$
$25 \le I \le 250$ mW/cm^2

Table 6. Comparison of measured and calculated values

Angle of incidence θ, deg	Cell temperature	Measured V_{oc}	Method I V_{oc}	% Deviation from measured	Method II V_{oc}	% Deviation from measured
10 Ω-cm, 0.30-mm cell, 0.51-mm coverglass (Cells 25 to 29)						
0	42	513.3	498.4	-2.91	497.5	-3.08
30	41	511.3	497.1	-2.79	496.1	-2.97
45	38	507.4	498.8	-1.70	497.7	-1.91
60	34	501.5	498.4	-0.61	497.7	-0.76
75	31	478.4	483.7	+1.15	484.7	+1.32
10 Ω-cm, 0.30-mm cell, 0.15-mm coverglass (Cells 40 to 44)						
0	42	515.7	497.3	-3.56	496.5	-3.73
30	41	512.9	496.0	-3.29	495.1	-3.48
45	38	508.8	497.7	-2.18	496.7	-2.38
60	34	500.1	497.4	-0.54	496.7	-0.68
75	31	476.4	482.9	+1.36	483.7	+1.54
2 Ω-cm, 0.20-mm cell, 0.15-mm coverglass (Cells 65 to 69)						
0	42	527.2	517.4	-1.86	519.6	-1.44
30	41	523.0	515.2	-1.50	517.2	-1.12
45	38	518.3	515.5	-0.56	517.1	+0.31
60	34	508.4	512.6	+0.82	513.8	+0.25
75	31	488.0	492.7	+0.96	494.4	+1.30

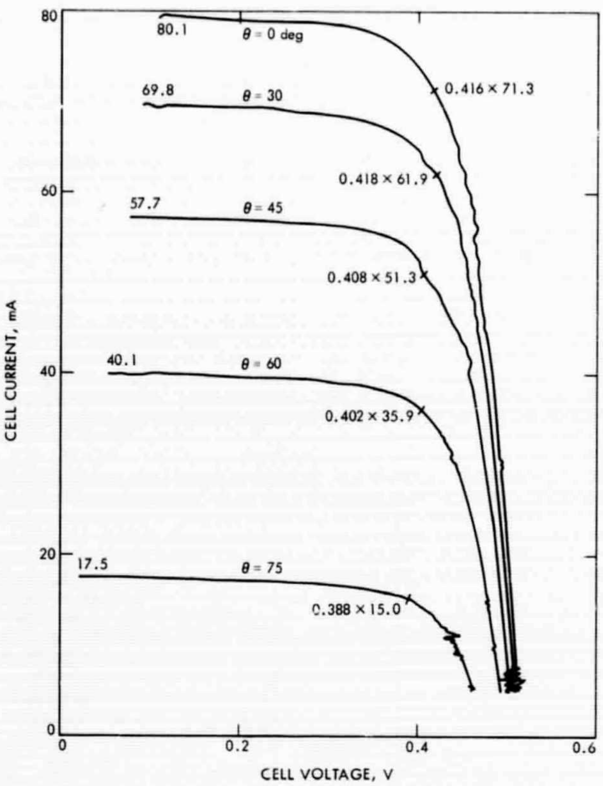

Fig. 1. I-V Curves as a function of angle of incidence for 10 Ω-cm 0.30-mm cell with 0.51-mm coverglass

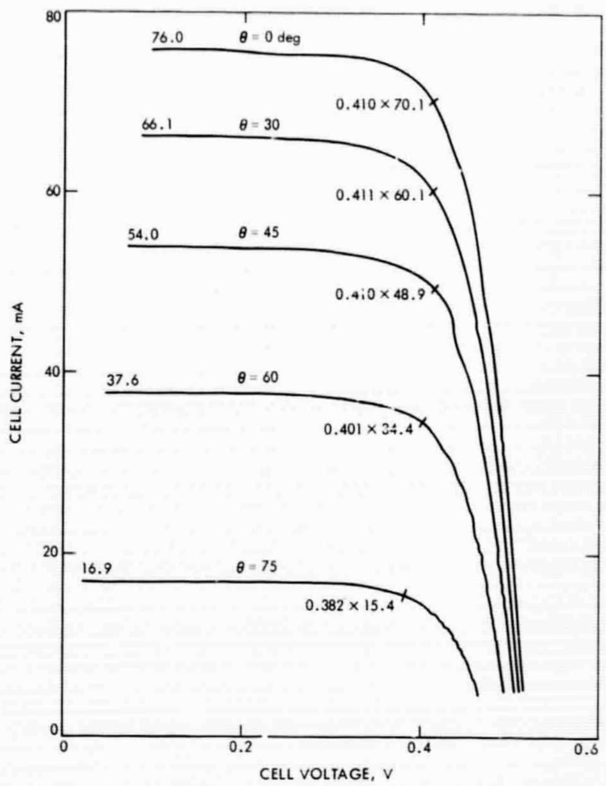

Fig. 2. I-V Curves as a function of angle of incidence for 10 Ω-cm 0.30-mm cell with 0.15-mm coverglass

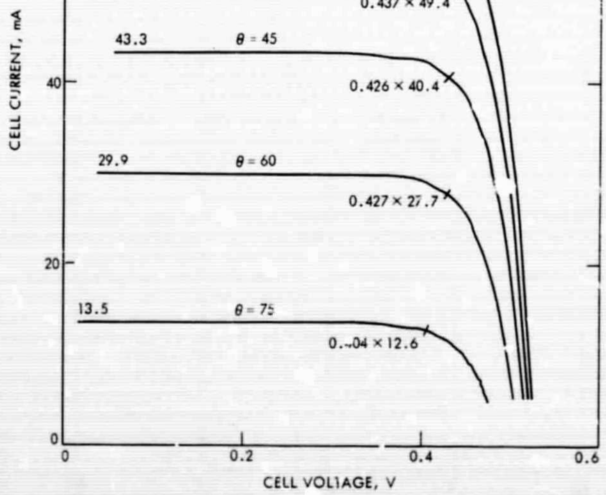

Fig. 3. I-V Curves as a function of angle of incidence for 2 Ω-cm 0.20-mm cell with 0.15-mm coverglass

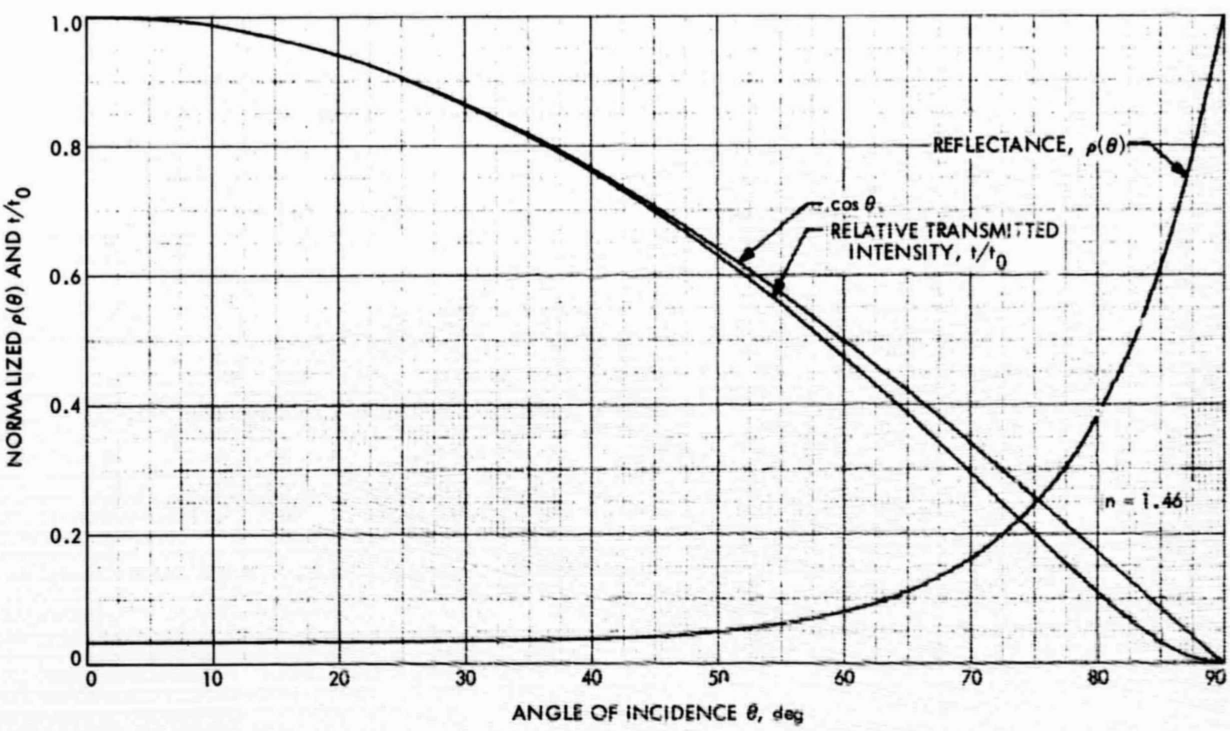

Fig. 4. Reflectance, relative transmitted intensity, and cosine functions versus angle of incidence

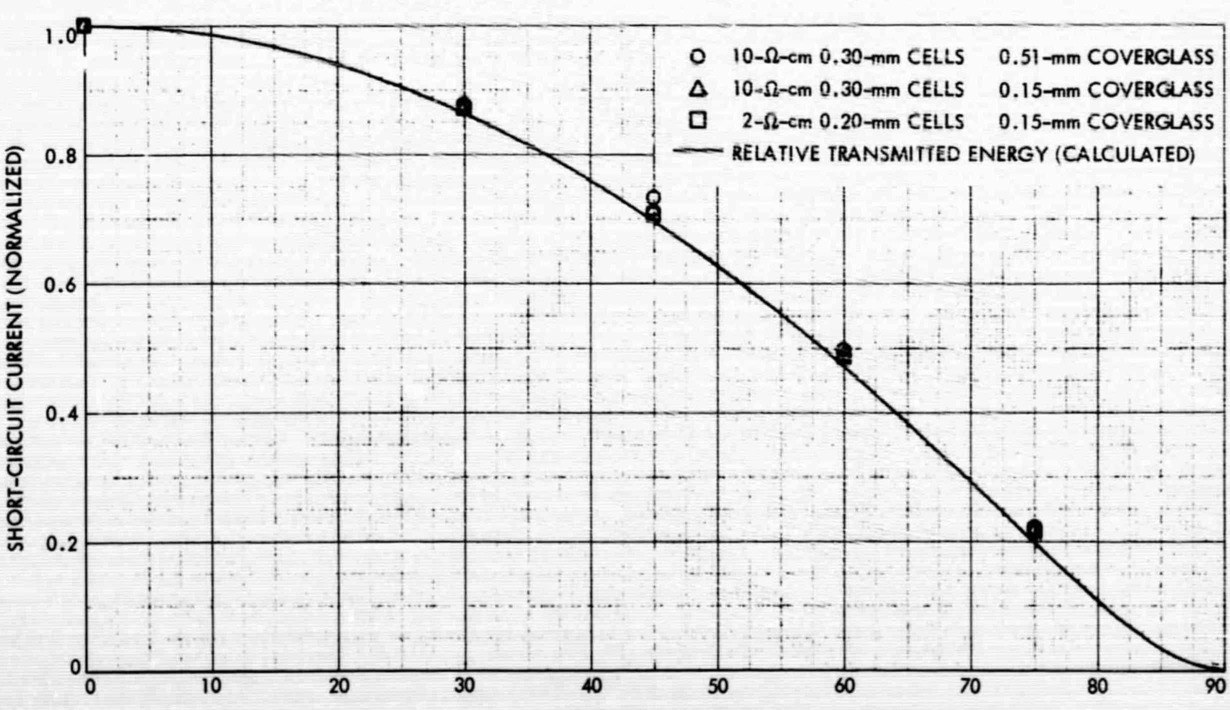

Fig. 5. Normalized short-circuit current versus angle of incidence

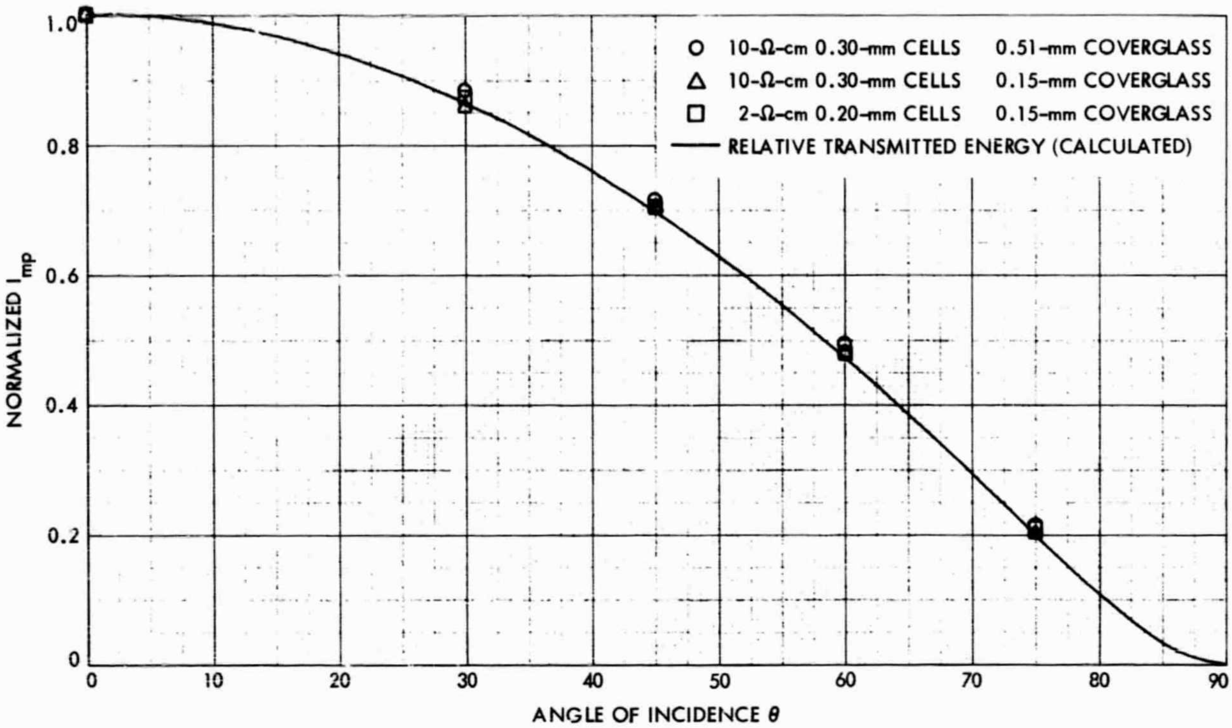

Fig. 6. Normalized current at maximum power versus angle of incidence

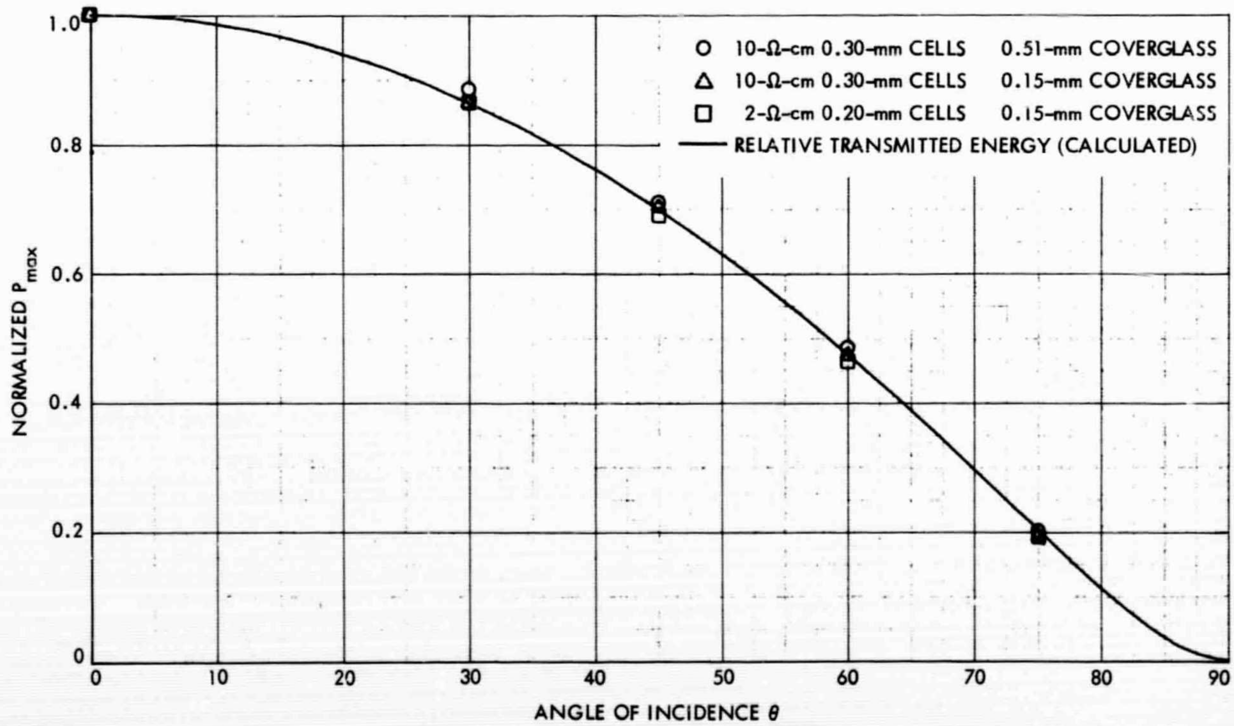

Fig. 7. Normalized maximum power versus angle of incidence

APPENDIX

SOLAR CELL PARAMETERS FOR ANGLE OF INCIDENCE

Table A-1. Calculated statistics of solar cell parameters for angle of incidence

ATS-E
10 OHM-CM, 0.30 MM CELL, 0.51 MM COVERGLASS

ANGLE OF INCIDENCE = 00 DEGREES

CELL NO.	ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
25	80.100	514.100	71.300	416.000	29.660
26	78.000	508.300	71.000	416.000	29.536
27	79.200	507.400	71.600	413.000	29.570
28	81.000	514.100	73.200	411.000	30.085
29	80.400	522.200	72.800	418.000	30.430
AVG.	79.740	513.320	71.980	414.800	29.856
VARIANCE	1.368	33.875	.932	7.700	.151
STD DEV	1.169	5.820	.965	2.774	.388
95 CON LIM	1.452	7.225	1.198	3.444	.482

ANGLE OF INCIDENCE = 30 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
25	69.800	.871410	507.900	.987940	61.900	.868162	418.000	1.004807	25.874	.872336
26	68.600	.879487	507.900	.998231	62.900	.885915	417.000	1.002403	26.229	.888045
27	69.500	.877525	505.100	.995467	64.200	.896648	403.000	.975786	25.872	.874937
28	72.000	.888888	513.500	.998832	64.700	.883879	410.000	.997566	26.527	.881729
29	70.100	.871890	522.000	.999617	65.200	.895604	425.000	1.016746	27.710	.910602
AVG.	70.000	.877840	511.280	.996017	63.780	.886042	414.600	.999462	26.442	.885530
VARIANCE	1.565	.000050	45.225	.000022	1.837	.000132	70.300	.000225	.576	.000233
STD DEV	1.250	.007102	6.724	.004780	1.355	.011496	8.384	.015000	.759	.015296
95 CON LIM	1.553	.008817	8.348	.005934	1.682	.014272	10.409	.018621	.942	.018989

Table A-1 (contd)

ATS-E
10 OHM-CM, 0.30 MM CELL, 0.51 MM COVERGLASS

ANGLE OF INCIDENCE = 45 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
25	57.700	.720349	504.800	.981910	51.300	.719495	408.000	.980769	20.930	.705658
26	56.300	.721794	505.300	.993121	51.400	.723943	411.000	.987980	21.125	.715242
27	56.900	.718434	502.100	.989554	50.600	.706703	406.000	.983050	20.543	.694725
28	59.000	.728395	507.100	.986383	53.200	.726775	412.000	1.002433	21.918	.728544
29	61.800	.768656	517.600	.991191	51.500	.707417	417.000	.997607	21.475	.705725
AVG.	58.340	.731526	507.380	.988432	51.600	.716867	410.800	.990368	21.198	.709979
VARIANCE	4.763	.000444	35.825	.000019	.925	.000086	17.700	.000087	.275	.000160
STD DEV	2.182	.021092	5.985	.004415	.961	.009326	4.207	.009348	.524	.012669
95 CON LIM	2.709	.026185	7.430	.005482	1.194	.011577	5.223	.011606	.651	.015729

ANGLE OF INCIDENCE = 60 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
25	40.100	.500624	499.000	.970628	35.900	.503506	402.000	.966346	14.431	.486561
26	38.800	.497435	499.900	.982507	35.000	.492957	405.000	.973557	14.175	.479922
27	39.900	.503787	497.400	.980291	35.900	.501396	408.000	.987893	14.647	.495326
28	40.800	.503703	501.900	.976269	36.600	.500000	406.000	.987834	14.859	.493917
29	38.500	.478855	509.100	.974913	34.500	.473901	414.000	.990430	14.283	.469366
AVG.	39.620	.496881	501.460	.976922	35.580	.494352	407.000	.981212	14.479	.485018
VARIANCE	.907	.000108	20.875	.000021	.687	.000146	20.000	.000113	.076	.000114
STD DEV	.952	.010410	4.568	.004655	.828	.012100	4.472	.010644	.276	.010712
95 CON LIM	1.182	.012924	5.672	.005779	1.028	.015022	5.552	.013214	.343	.013298

Table A-1 (contd)

ATS-E
10 OHM-CM, 0.30 MM CELL, 0.51 MM COVERGLASS

ANGLE OF INCIDENCE = 75 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
25	17.500	.218476	475.800	.925500	15.000	.210378	388.000	.932692	5.820	.196218
26	17.600	.225641	477.400	.938286	15.000	.211267	394.000	.947115	5.910	.200094
27	17.800	.224747	476.100	.938312	15.600	.217877	388.000	.939467	6.052	.204688
28	19.200	.237037	479.300	.932308	17.100	.233606	384.000	.934306	6.566	.218260
29	16.300	.202736	483.600	.926081	14.800	.203296	384.000	.918660	5.683	.186760
AVG.	17.680	.221727	478.440	.932098	15.500	.215285	387.600	.934448	6.006	.201204
VARIANCE	1.067	.000157	10.225	.000039	.890	.000131	16.800	.000109	.116	.000134
STD DEV	1.032	.012550	3.197	.006262	.943	.011470	4.098	.010467	.340	.011594
95 CON LIM	1.282	.015580	3.969	.007775	1.171	.014240	5.088	.012995	.422	.014394

Table A-1 (contd)

ATS-E
10 OHM-CM, 0.30 MM CELL, 0.15 MM COVERGLASS

ANGLE OF INCIDENCE = 00 DEGREES

CELL NO.	ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
40	76.000	518.200	70.100	410.000	28.741
41	75.500	523.400	69.000	422.000	29.118
42	74.800	511.300	69.100	413.000	28.538
43	73.800	516.900	67.200	416.000	27.955
44	74.300	508.600	68.700	407.000	27.960
AVG.	74.980	515.680	68.820	413.600	28.462
VARIANCE	.692	34.175	1.097	33.300	.255
STD DEV	.831	5.845	1.047	5.770	.505
95 CON LIM	1.032	7.257	1.300	7.164	.627

ANGLE OF INCIDENCE = 30 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
40	66.100	.869736	514.000	.991895	60.100	.857346	411.000	1.002439	24.701	.859437
41	66.000	.874172	522.000	.997325	59.500	.862318	424.000	1.004739	25.228	.866405
42	65.000	.868983	507.800	.993154	60.300	.872648	413.000	1.000000	24.903	.872648
43	64.400	.872628	515.500	.997291	57.000	.848214	427.000	1.026442	24.339	.870643
44	65.000	.868983	505.200	.993314	58.700	.854439	410.000	1.007371	24.067	.860737
AVG.	65.300	.870901	512.900	.994596	59.120	.858993	417.000	1.008198	24.647	.865974
VARIANCE	.530	.000005	44.000	.000006	1.792	.000084	62.500	.000111	.209	.000034
STD DEV	.728	.002371	6.633	.002539	1.338	.009186	7.905	.010558	.457	.005850
95 CON LIM	.903	.002944	8.234	.003152	1.661	.011405	9.814	.013107	.568	.007262

Table A-1 (contd)

ATS-E
10 OHM-CM, 0.30 MM CELL, 0.15 MM COVERGLASS

ANGLE OF INCIDENCE = 45 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
40	54.000	.710526	508.900	.982053	48.900	.697574	410.000	1.000000	20.049	.697574
41	54.100	.716556	519.500	.992548	48.500	.702898	426.000	1.009478	20.661	.709561
42	53.500	.715240	503.500	.984744	49.200	.712011	406.000	.983050	19.975	.699943
43	52.800	.715447	511.700	.989940	47.600	.708333	416.000	1.000000	19.801	.708333
44	52.800	.705882	500.400	.983877	48.000	.698689	410.000	1.007371	19.680	.703840
AVG.	53.440	.712730	508.800	.986632	48.440	.703901	413.600	.999980	20.033	.703850
VARIANCE	.393	.000020	55.375	.000019	.423	.000038	60.800	.000107	.144	.000026
STD DEV	.626	.004474	7.441	.004421	.650	.006200	7.797	.010385	.379	.005184
95 CON LIM	.778	.005555	9.238	.005489	.807	.007698	9.680	.012892	.471	.006435

ANGLE OF INCIDENCE = 60 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
40	37.600	.494736	499.800	.964492	34.400	.490727	401.000	.978048	13.794	.479955
41	37.200	.492715	510.500	.975353	33.200	.481159	419.000	.992890	13.910	.477738
42	36.500	.487967	494.900	.967924	33.700	.487698	398.000	.963680	13.412	.469985
43	36.200	.490514	503.800	.974656	32.200	.479166	410.000	.985576	13.202	.472255
44	36.100	.482620	491.500	.966378	32.200	.468704	399.000	.980343	12.847	.459491
AVG.	36.720	.489711	500.100	.969761	33.140	.481491	405.400	.980108	13.433	.471885
VARIANCE	.427	.000022	55.725	.000024	.918	.000073	80.300	.000116	.188	.000064
STD DEV	.653	.004698	7.464	.004947	.958	.008557	8.961	.010814	.434	.008012
95 CON LIM	.811	.005832	9.267	.006141	1.189	.010623	11.124	.013425	.539	.009947

Table A-1 (contd)

ATS-E
10 OHM-CM, 0.30 MM CELL, 0.15 MM COVERGLASS

ANGLE OF INCIDENCE = 75 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
40	16.900	.222368	477.800	.922037	15.400	.219686	382.000	.931707	5.882	.204683
41	16.200	.214569	485.200	.927015	13.800	.200000	398.000	.943127	5.492	.188625
42	15.900	.212566	473.400	.925875	14.600	.211287	386.000	.934624	5.635	.197474
43	15.800	.214092	477.900	.924550	13.100	.194940	391.000	.939903	5.122	.183225
44	15.100	.201871	467.500	.919189	12.900	.187772	387.000	.950859	4.992	.178545
AVG.	15.980	.213093	476.36[illegible]	.923733	13.960	.202737	388.800	.940044	5.425	.190510
VARIANCE	.427	.000053	42.475	.000009	1.093	.000163	36.700	.000056	.134	.000112
STD DEV	.653	.007338	6.517	.003146	1.045	.012772	6.058	.007513	.366	.010596
95 CON LIM	.811	.009110	8.090	.003906	1.297	.015857	7.520	.009327	.455	.013155

Table A-1 (contd)

ATS-E
2 OHM-CM, 0.20 MM CELL, 0.15 MM COVERGLASS

ANGLE OF INCIDENCE = 00 DEGREES

CELL NO.	ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
65	60.900	525.900	57.500	437.000	25.127
66	62.600	533.500	58.900	443.000	26.092
67	59.400	522.400	56.400	435.000	24.534
68	59.300	529.000	55.300	446.000	24.663
69	62.600	525.200	57.300	441.000	25.269
AVG.	60.960	527.200	57.080	440.400	25.137
VARIANCE	2.643	17.900	1.792	19.800	.379
STD DEV	1.625	4.230	1.338	4.449	.616
95 CON LIM	2.018	5.252	1.661	5.524	.764

ANGLE OF INCIDENCE = 30 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
65	53.300	.875205	522.600	.993725	49.400	.859130	437.000	1.000000	21.587	.859130
66	54.500	.870607	530.400	.994189	52.000	.882852	441.000	.995485	22.932	.878866
67	51.400	.865319	515.800	.987366	48.900	.867021	430.000	.988505	21.027	.857055
68	51.500	.868465	527.200	.996597	48.300	.873417	443.000	.993273	21.396	.867542
69	55.200	.881789	518.900	.988004	50.600	.883071	437.000	.990929	22.112	.875061
AVG.	53.180	.872277	522.980	.991976	49.840	.873098	437.600	.993638	21.811	.867531
VARIANCE	2.957	.000041	35.300	.000016	2.173	.000106	24.800	.000019	.545	.000091
STD DEV	1.719	.006422	5.941	.004080	1.474	.010329	4.979	.004407	.738	.009560
95 CON LIM	2.134	.007973	7.376	.005065	1.830	.012823	6.182	.005471	.917	.011868

Table A-1 (contd)

ATS-E
2 OHM-CM, 0.20 MM CELL, 0.15 MM COVERGLASS

ANGLE OF INCIDENCE = 45 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
65	43.300	.711001	517.500	.984027	40.400	.702608	426.000	.974828	17.210	.684922
66	44.600	.712460	525.800	.985567	41.800	.709677	433.000	.977426	18.099	.695657
67	42.000	.707070	508.700	.973774	39.600	.702127	425.000	.977011	16.830	.685986
68	41.900	.706576	524.100	.990737	38.800	.701627	442.000	.991031	17.149	.695334
69	44.400	.709265	515.400	.981340	40.500	.706806	430.000	.975056	17.415	.689176
AVG.	43.240	.709274	518.300	.983089	40.220	.704569	431.200	.979070	17.340	.689815
VARIANCE	1.633	.000006	47.750	.000038	1.252	.000012	46.700	.000046	.223	.000021
STD DEV	1.277	.002509	6.910	.006238	1.118	.003528	6.833	.006791	.473	.004596
95 CON LIM	1.586	.003116	8.578	.007745	1.389	.004380	8.483	.008431	.587	.005706

ANGLE OF INCIDENCE = 60 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
65	29.900	.490968	508.300	.966533	27.700	.481739	427.000	.977116	11.827	.470715
66	30.500	.487220	515.700	.966635	28.500	.483870	428.000	.966139	12.198	.467487
67	28.700	.483164	502.800	.962480	26.600	.471631	425.000	.977011	11.305	.460789
68	28.800	.485666	509.900	.963894	27.100	.490054	427.000	.957399	11.571	.469177
69	30.400	.485623	505.100	.961728	27.000	.471204	422.000	.956916	11.394	.459902
AVG.	29.660	.486528	508.360	.964254	27.380	.479699	425.800	.966916	11.659	.463814
VARIANCE	.743	.000008	24.450	.000005	.547	.000066	5.700	.000099	.130	.000066
STD DEV	.861	.002876	4.944	.002280	.739	.008157	2.387	.009966	.361	.008151
95 CON LIM	1.070	.003571	6.138	.002830	.918	.010127	2.963	.012375	.443	.010120

Table A-1 (contd)

ATS-E
2 OHM-CM, 0.20 MM CELL, 0.15 MM COVERGLASS

ANGLE OF INCIDENCE = 75 DEGREES

CELL NO.	ISC (MA)	ISC/ISCO	VOC (MV)	VOC/VOCO	IMP (MA)	IMP/IMPO	VMP (MV)	VMP/VMPO	PMAX (MW)	PM/PMO
65	13.500	.221674	487.600	.927172	12.600	.219130	404.000	.924485	5.090	.202582
66	13.400	.214057	491.900	.922024	12.000	.203735	410.000	.925507	4.920	.188558
67	12.600	.212121	485.300	.928981	12.000	.212765	397.000	.912643	4.764	.194179
68	13.000	.219224	489.900	.926086	11.900	.215189	402.000	.901345	4.783	.193960
69	13.600	.217252	485.400	.924219	11.700	.204188	387.000	.877551	4.527	.179185
AVG.	13.220	.216866	488.020	.925696	12.040	.211001	400.000	.908306	4.817	.191693
VARIANCE	.172	.000014	8.250	.000007	.113	.000046	74.500	.000392	.043	.000074
STD DEV	.414	.003848	2.872	.002683	.336	.006818	8.631	.019817	.207	.008604
95 CON LIM	.514	.004778	3.565	.003331	.417	.008465	10.715	.024603	.258	.010682