DOE/NASA/20485-79/2
NASA TM-79163

A METHOD FOR CORRELATING PERFORMANCE DATA OF A TERRESTRIAL SOLAR CELL ARRAY

Frederick F Simon
National Aeronautics and Space Administration
Lewis Research Center

May 1979

Prepared for
U.S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Distributed Solar Technology

NOTICE

1 Report No NASA TM-79163	2 Government Accession No	3 Recipient s Catalog No
4 Title and Subtitle A METHOD FOR CORRELATING PERFORMANCE DATA OF A TERRESTRIAL SOLAR CELL ARRAY		5 Report Date May 1979 6 Performing Organization Code
7 Author(s) Frederick F Simon		8 Performing Organization Report No E-023 10 Work Unit No
9 Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11 Contract or Grant No 13 Type of Report and Period Covered Technical Memorandum
12 Sponsoring Agency Name and Address U S Department of Energy Division of Distributed Solar Technology Washington, D C 20545		14 Sponsoring Agency ~~Code~~ Report No DOE/NASA/20485-79/2

15 Supplementary Notes

Prepared under Interagency Agreement DE-A101-79ET20485

16 Abstract

An analytical method is proposed for characterizing array power output, in the region of maximum power, as a function of environmental variables The purpose of the correlation is to provide a way of evaluating the output of an array under environmental conditions that differ from those encountered during testing Power data obtained at one location can be used to predict array performance at other locations

17 Key Words (Suggested by Author(s))	18 Distribution Statement
Terrestrial solar cell array Power correlation	Unclassified - unlimited STAR Category 44 DOE Category UC-63

19 Security Classif (of this report)	20 Security Classif (of this page)	21 No of Pages	22 Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service Springfield Virginia 22161

NASA-C-168 (Rev 10-75)

DOE/NASA/20485-79/2
NASA TM-79163

A METHOD FOR CORRELATING PERFORMANCE DATA OF A TERRESTRIAL SOLAR CELL ARRAY

Frederick F. Simon
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

May 1979

Prepared for
U. S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Distributed Solar Technology
Washington, D. C. 20545
Under Interagency Agreement DE-AI01-79ET20485

N79-26503 #

E-023

SUMMARY

Equations are proposed for characterizing photovoltaic array power output as a function of environmental variables. The equations are applicable to photovoltaic arrays having a parallel arrangement of series linked solar cells. This method will meet the need for correlating experimental array power data in order to use such correlations for design purposes.

Power data correlating equations are developed by employing the classic solar cell diode equation. Photovoltaic array power variables are open-circuit voltage, cell temperature, and short-circuit current. These variables are related to environmental variables such as ambient temperature, solar irradiance, and wind. For validation, a correlation test was performed using the Department of Energy/Lewis Research Center (DOE/LeRC) Systems Test Facility array. The correlations presented should have general applicability for similar systems at other locations.

1.0 INTRODUCTION

There is a need for equations that will characterize photovoltaic array power output in terms of environmental factors of wind, ambient temperature, the total solar irradiance reaching the array, sun position with respect to the array, and reflective properties of the ground. This report presents a photovoltaic array power correlation method that characterizes power output with respect to environmental factors for photovoltaic arrays having a parallel arrangement of series linked solar cells. The characterization of array power output in terms of environmental variables should provide a useful tool for the following:

(1) Use of array power data, obtained in one geographical location, for the prediction of array power output in the region of maximum power at other geographical locations.

(2) Assessment of the effect of array electrical malfunctions, aging, dirt, snow, and ground reflection on power output.

(3) Prediction of array power for variations in array configuration and size.

Array power output may be characterized by the familiar I-V curve. A resulting difficulty with this approach is the need for many I-V curves for characterizing array output under changing environmental conditions. Furthermore, the I-V curve approach contains more information than is required for correlating array power output with environmental conditions. Three points on the I-V curve often suffice to characterize array output; namely, short-circuit current, open-circuit voltage, and array voltage at the maximum power point.

An analytical array power correlation is developed using the classic solar cell diode equation. The power correlation can be given in terms of open-circuit voltage, cell temperature, and short-circuit current. These variables are related to the environmental variables of solar irradiation, wind, and ambient temperature. The array power equations developed in this report are applicable at or in the region of the maximum power output of a solar cell array.

The solar cell array in the DOE/LeRC Systems Test Facility (STF) was used to experimentally test and evaluate the suitability of the proposed power correlation. The STF was built at the Lewis Research Center for the Department of Energy to test "breadboard" photovoltaic systems, subsystems, and components. A description of STF is given in reference 1.

This report contains a summary of the correlation equations developed, examples of the application of these equations to the data of the STF array, and an evaluation of the performance of the correlation equations. Full development of the correlating equations is given in appendixes A, B, and C. Application of the technique described is based on the use of a calibrated reference cell with the same characteristics as the array being studied. Use of the reference cell is described in appendix A.

2.0 SUMMARY OF POWER EQUATIONS

The analytical relationship between the power output of a solar cell array and the variables of solar irradiance, ambient temperature, and wind is derived in appendixes A, B, and C. A summary of the resulting equations follows.

2.1 Power Output of an Array Consisting of a Single Type of Solar Cell (Type j)

$$P = a^* I_{rc} K M_j A_{c,j} V \left[1 - e^{-(b\Phi/n_{c,j})} \right] \tag{1}$$

where

$$\Phi = \frac{V_o - V}{T_{c,j}}$$

and

P	array power, watts
a^*	short-circuit current constant of proportionality for a single cell and type at standard sun conditions, amps/mw
I_{rc}	total solar irradiance determined with a reference cell, mw/cm^2 (includes ground reflection)
K	factor which accounts for array surface film effects, dimensionless ($0 \leq K \leq 1$)
M_j	total number of cell series strings of type j
$A_{c,j}$	area of one solar cell of type j, cm^2
V	array voltage at or near maximum power, volts
b	constant, ^{o}K, volts
V_o	array open circuit voltage, volts
$T_{c,j}$	cell temperature of type j, ^{o}K
$n_{c,j}$	number of cells in a series string of type j

2.2 Power Output of an Array Consisting of More Than One Type of Solar Cell (Types X, Y, Z)

$$P = \overline{a}^* I_{rc} \overline{K} M \overline{A}_c V \left[1 - e^{-(\text{[illegible]}/\overline{T}_c)} \right] \tag{2}$$

where

$$M = \sum_{j=x,y,z} M_j \tag{2a}$$

$$\overline{A}_c = \frac{1}{M} \sum_{j=x,y,z} M_j A_{c,j} \tag{2b}$$

$$\overline{\Phi} = (V_o - V)/\overline{T}_c \tag{2c}$$

$$\overline{T}_c = \frac{\sum_{j=x,y,z} n_{c,j} M_j T_{c,j}}{\sum_{j=x,y,z} n_{c,j} M_j} \tag{2d}$$

$$\overline{n}_{c,j} = \frac{\sum_{j=x,y,z} n_{c,j} M_j}{\sum_{j=x,y,z} M_j} \tag{2e}$$

$\overline{a}^*$ = short-circuit current constant of proportionality for an average cell area at standard sun conditions, amps/mw

$\overline{K}$ = factor which accounts for average array surface film effects of different cell types, dimensionless $(0 \leq K \leq 1)$

Cell Temperature

$$T_{c,j} = c_o I_{rc} + T_a$$
$$c_o = f(T_{c,j} - T_a, \text{ wind velocity}) \tag{3}$$

Open-Circuit Voltage

$$V_o = n_{c,j} A_{o,j} \left[1.092 - T_{c,j} \left(m LN \left(\frac{I_{rc}}{T_{c,j}^3} \right) + b_o \right) \right] \tag{4}$$

$A_{o,j}$ = cell constant of type j, dimensionless

m, c_o, b_o = constants determined from experimental data

T_a = ambient temperature, ^oK

In the case of an array with mixed cell types, cell temperature ($T_{c,j}$) to be used in equation (4) is the cell temperature of the type with the highest open-circuit voltage.

For the case of a photovoltaic array of a single cell type equation (1) states that array power is a function of solar irradiance (I_{rc}) as measured by a calibrated reference cell, the number of series strings (M), the area of one solar cell area (A_c), the array voltage at or near maximum power (V), the array open-circuit voltage (V_o), the cell temperature (T_c), and the number of solar cells in a series string (n_c). Equation (2) is similar except for use of average variables where appropriate. The constants (a*, b, and K) in equations (1) and (2) can be evaluated from experimental data as shown in section 3.0. The constants (M) and (n_c) are determined from knowledge of the array configuration. The constant (K) takes into account the effect on array power of the condition of the array surface (dirt, etc.). In equations (3) and (4), the measured variables of cell temperature and open-circuit voltage are related to the environmental variables of solar irradiance and ambient temperature. With equations (1) through (4), the array power may be related to the environmental variables.

3.0 APPLICATION OF EQUATIONS TO THE STF ARRAY

A photograph of STF solar cell modules mounted on four-by-eight foot panels is shown in figure 1. Figure 2(a) is an electrical schematic which shows the interconnections of solar panels into series strings and figure 2(b) describes the solar cell equivalent circuit. Power obtained from three solar cell types (X, Y, Z), arranged as shown in figure 2(a), is fed to the facility control room which contains instrumentation for measuring array voltage, current and other variables related to the array power. Table 1 contains the sample power data used for the purpose of demonstrating the use of the derived power equation (eq. (2)) for correlating data and for predicting array power.

The approach to be taken for correlating the array power data of table 1 is to rearrange equations (2) and (4) in such a manner so as to permit a determination of the correlating constants (a*, K, and b) in equation (2), and (m) and (b_o) in equation (4).

3.1 Determination of Constants m and b_o (eq. (4))

Table 2 contains the array open-circuit voltage data for type y solar cell. Type y data is used because this type of cell has the highest open-circuit voltage of the example power data (table 2) for the three types of solar cells which make up the array. As shown in appendix C (eq. (C-7)), equation (4) may be linearized into an expression of the form:

$$\omega = m\psi + b_o \tag{5}$$

where

$$\omega = \left(1.092 - \frac{V_o}{n_{c,j}A_{o,j}}\right)\Big/ T_{c,j} \tag{5a}$$

$$\psi = LN\left(I_{rc}/T^3_{c,j}\right) \tag{5b}$$

As shown in appendix C and table 2, array open-circuit voltage is a function of total solar irradiance (I_{rc}) and cell temperature ($T_{c,j}$). Expressing the open-circuit data in the manner of the functional relationship given by equation (ω) should result (as shown in appendix C) in a linear correlation. An example of how the basic data of table 2 is put into the form of omega (ω) and psi (ψ) follows·

<u>Input Data</u>

$n_{c,y}$ = 576; number of type Y cells in series

$A_{o,y}$ = 2.7 (see appendix B, eq. (B-5a))

$T_{c,y}$ = 320.85 ^{o}K

I_{rc} = 85.2 mw/cm^2

V_o = 290.0 volts

Substitution of the above values in equations (5a and 5b) results in the following:

$\omega = 2.82\times10^{-3}$

$\psi = -12.87$

Continuing the above calculation for the rest of the open-circuit voltage data of table 2 results in values of omega (ω) and psi (ψ) which are plotted as shown in figure 3. The correlation of figure 3 encompasses open-circuit voltages which range from 260 to 330 volts, cell temperature range of 265° to 324° K, and total solar irradiance range of 2 mw/cm^2 to 106 mw/cm^2. The constants from figure 3 are as follows:

$m = -0.19\times10^{-3}$

$b_o = 0.52\times10^{-3}$

As indicated by equation (C-5), the constant (m) should remain independent of the age of the array. The constant (b_o) will vary with the array age due to its dependence on amount of solar radiation which is effectively transformed into array current. Since the array current is affected by such things as surface dirt, the value of the constant (b_o) will have to be periodically determined from experimental open-circuit voltage data.

3.2 Determination of the Constant (b) (eq. (2))

Equation (2) may be put into a format for correlating array current data in such a way to determine the constant (b). To do this equation (2) is changed into a form involving current by substitution of the following relationships for current and short-circuit current derived in appendix A:

$$i = P/V \tag{6}$$

$$i_{sc} = \bar{a}^*\overline{K}\overline{A}_c M I_{rc} \tag{7}$$

The resulting equation for array current is as follows:

$$i = i_{sc}\left[1 - e^{-(b\overline{\Phi}/\overline{n}_c)}\right] \tag{8}$$

i = array current, ampts

i_{sc} = array short-circuit current, amps

Equation (8) is rearranged as follows:

$$\bar{\Phi} = \frac{\bar{n}_c}{b} \gamma \tag{9}$$

where

$$\bar{\Phi} = \frac{V_o - V}{\bar{T}_c} \tag{9a}$$

$$\gamma = LN \left[\frac{1.0}{1.0 - \frac{i}{i_{sc}}} \right] \tag{9b}$$

To determine the constant (b), the power data (table 1), the open-circuit voltage correlation (fig. 3), and the short-circuit current correlation (fig. 4) are used. An example of the use of this data is as follows:

From the first line of power data of table 1 we have

$T_{c,x} = 298.6^{\circ}$ K	$n_{c,x} = 525$	Series cells per string
$T_{c,y} = 312.2^{\circ}$ K	$n_{c,y} = 576$	
$T_{c,z} = 306.6^{\circ}$ K	$n_{c,z} = 528$	
$I_{rc} = 83.0$ mw/cm^2	$M_x = 24$	Number of series strings
$V = 241.8$ volts*	$M_y = 3$	
$i = 19.80$ amps	$M_z = 12$	
*Corrected for line loss	$A_o = 2.7$	

Use of the above data and the equation for the average temperature (eq. (2d)), figures 3 and 4 give the following:

$\overline{T}_c$ = 302.3° K (eq. (2d))

V_o = 292.7 volts (fig. 3)

$\overline{\Phi}$ = 0.168 (eq. (9a))

i_{sc} = 22.0 (fig. 4)

i/i_{sc} = 0.90 (i from table 1)

γ = 2.30 (eq. (9b))

By continuing the above computational approach for the power data of table 1, values of phi ($\overline{\Phi}$) and gamma (γ) are calculated which then are plotted as shown in figure 5. The reciprocal of the slope of figure 5(a) is equal to 13.1 ($b/\overline{n}_c = 13.1$). Since $\overline{n}_c$ is calculated from equation (2e) to be 530, then the value of b is 6974.

3.3 STF Array Power Correlation

Having determined the above information, of the constants (m), (b_o), and (b), a correlation of array power is possible by using equation (2). Equation (2) is rearranged as follows:

$$\frac{P}{\mu} = \overline{a}^* \overline{K} I_{rc} \tag{10}$$

where

$$\mu = \left[1.0 - e^{-(b/\overline{n}_c)(V_o - V/\overline{T}_c)}\right] M \overline{A}_c V \tag{10a}$$

The experimental power data (table 1) is placed in the form of equation (10) as follows:

Step (_): The basic power data is obtained from table 1 and the above derivations. Using the first line of data as an example we have the following values.

$P = iV = 19.8 \times 241.8 = 4.79$ kW (from table 1, V corrected for line loss)

$\overline{T}_c = 302.3^{\circ}$ K (eq. (2d))

$I_{rc} = 83.0$ mw/cm^2

$M = 39$ (sum of $M_x + M_y + M_z$ strings in series from table 1)

$\overline{A}_c = 35\ 01$ cm^2 (eq. (2b))

$V = 241.8$ volts (from table 1, corrected for line drop)

Step (2): Determine open-circuit voltage from figure 3 or equation (4).

$V_o = 292.7$ volts

Step (3): Calculate (μ) using equation (10a) where $b/\overline{n}_c = 13.1$ as determined from figure 5(a).

$\mu = 2.936\times10^{5}$ cm^2-volt

Step (4): Determine ratio of power (eq. (10) and table 1)

$P/\mu = 0.0163$ w/cm^2-volt

Step (5). Repeat steps 1 - 4 for all power data of table 1 and plot modified power (P/μ) as a function of total solar irradiance (fig. 6).

Plotting the left side of equation (10) as a function of the total solar irradiance gives a linear correlation having a slope of a^*K (fig. 6) equal to 2.06×10^{-4} amp/mw With the values of the constants $\overline{a}^*$, $\overline{K}$, and b determined, equation (2) may be expressed as follows for the power data of table 1.

$$P = (2\ 06\times10^{-4})I_{rc}VM\overline{A}_c\left(1.0 - e^{-(6974/\overline{T}_c)\overline{\Phi}}\right) \tag{11}$$

where

$$\bar{\Phi} = \frac{V_o - V}{\bar{T}_c}$$

3.4 Array Power Prediction Approach

Equation (11) was determined using photovoltaic power data obtained in Cleveland, Ohio. Equation (11) may be used for predicting array power in Cleveland or in other areas having different environmental conditions. An outline of the prediction approach is as follows:

Step (1): Determine the configuration constants for a given array - M, $\bar{n}_c$, or n_c and $\bar{A}_c$ or A_c (eqs. (2a), (2b), and (2e)).

Step (2): Establish the operating voltage level - V.

Step (3): Determine from weather tapes or measurements the variables I_{rc} and T_a.

Step (4): Calculate the cell temperature (T_c) using equation (3).

Step (5): Calculate the open-circuit voltage (V_o) from the value of the cell temperature (T_c) and the total solar irradiance (I_{rc}) by using equation (4).

Step (6): In case of an array containing mixed cell types, calculate the average cell temperature ($\bar{T}_c$) using equation (2d).

Step (7): Calculate array power using equation (11).

The data of table 1 (for Cleveland) may be used as an example of the above calculation steps to see how well the predicted power compares with actual power. For this example the cell temperatures are already given so there is no need for equation (3). Following the above steps of 1-3 and 5-7 for the conditions of table 1 results in values of predicted power which are given in table 3. A plot comparison of the predicted versus actual power is given in figure 7. The deviation of predicted power from actual power for the present example shows an average deviation of ±4.2 percent.

4.0 CONCLUSIONS

Photovoltaic array power data correlating equations have been developed that permit characterization of array power output in terms of environmental variables. These power correlations permit the prediction of photovoltaic array power in different locations for arrays having parallel arrangements of series strings.

For a given array configuration, the controlling variables in the power correlation are solar irradiance, open-circuit voltage, and cell temperature. An analytical expression is given for correlating open-circuit voltage in terms of solar irradiance and cell temperature. The cell temperature is determined, for a given wind condition, from an accepted correlation of cell temperature as a function of ambient temperature and solar irradiance.

The environmental data required for prediction of power using the equations recommended in this paper are ambient temperature and total solar irradiance in the plane of the photovoltaic array. With these inputs the prediction of array power can be made with reasonable accuracy. The sample calculation in this paper gave an average deviation for predicted versus measured power of ±42 percent.

Since the power correlation was tested for a limited range of environmental conditions for one given array series-parallel configuration, further tests of these equations need to be performed for correlating experimental power from photovoltaic arrays of different configurations in different geographic areas having wide differences in climate. Simple modifications of the present equations can also be made to include other array series-parallel configurations and these modified equations can then be tested for their potential to correlate experimental power data.

The use of a calibrated reference solar cell for measuring solar irradiance is an important aid in the correlation of solar cell array power, because a reference cell compensates for the spectral and angular response effects of the array.

5.0 NOMENCLATURE

a	array short-circuit constant of proportionality, amps/mw
A_c	individual solar cell area, cm^2
A_o	cell constant, dimensionless
b	constant in diode equation, ^oK/volt

c_o	constant in cell temperature correlation equation, $^oK/mw/cm^2$
C	velocity of light, 2.99793×10^{10} cm/sec
b_o	open-circuit voltage correlating constant
E_g	cell energy gap, joules
h	Plank's constant, 6.6254×10^{-27} cm/sec
i'	array current flux, $amps/cm^2$
i	array current, amps
i_L	light generated current, amps
i_D	solar cell diode current, amps
i_o	saturation current of p-n junction, amps
I	solar irradiance determined with a black body receiver (including ground reflection), mw/cm^2
I_{rc}	total solar irradiance determined with a reference solar cell, mw/cm^2
k	Boltzmann constant, 1.3806×10^{-23}, joule/^oK
K_r	ground reflection factor, dimensionless
K	array surface film factor, dimensionless
ℓ	proportionality constant, dimensionless
M	total number of cell string arrangements
m	open-circuit voltage correlating constant
n_c	number of cells in a series string
P	array power, watts
q	electronic charge, 1.602×10^{-19} coulomb
R_s	cell series resistance, ohms
$S(\lambda)$	cell spectral response, electrons/photon
T_a	ambient temperature, ^oK
T_c	cell temperature, ^oK
T_r	reference temperature, ^oK
V	array voltage, volts

V_c	individual solar cell voltage, volts
V_d	solar cell diode voltage, volts
V_o	array open-circuit voltage, volts
V_{oc}	individual solar cell open-circuit voltage, volts
α	solar cell absorptance for direct radiation, dimensionless
$\overline{\alpha}$	solar cell absorptance for diffuse radiation, dimensionless
τ	solar cell cover transmittance for direct radiation, dimensionless
$\overline{\tau}$	solar cell cover transmittance dor diffuse radiation, dimensionless
θ_i	solar incident angle with respect to normal to panel, dimensionless
λ	wavelength of light
β	voltage temperature coefficient, volt/^{o}K cell

Subscripts:

d	diffuse component of solar irradiance
D	direct component of solar irradiance
j	single solar cell type; j = x, y, or z
max	maximum
rc	reference solar cell
x	cell type x
y	cell type y
z	cell type z
sc	short-circuit
T	total

Superscripts:

*	standard conditions of spectrum and incident angle
—	average condition

TABLE 1. - SAMPLE POWER DATA FOR ONE DAY FOR THE PHOTOVOLTAIC ARRAY OF THE SYSTEMS TEST FACILITY

Module type X containing 24 series strings with 525 cells per string, each cell having area 20.3 cm^2
Module type Y containing 3 series strings with 576 cells per string, each cell having area 49.5 cm^2
Module type Z containing 12 series strings with 528 cells per string, each cell having area 60.8 cm^2

$$\bar{A}_c = 35.0 \text{ cm}^2$$

$$\bar{m}_c = 530 \text{ cells/string}$$

$T_{c,x}$	$T_{c,y}$	$T_{c,z}$	i, amps	V, volts	I_{rc}, mw/cm^2
Degrees centigrade					
25.60	39.20	33.60	19.80	240.20	83.00
25.50	39.30	33.80	19.80	240.70	83.50
26.10	40.20	35.00	17.90	253.70	84.20
26.50	40.20	35.00	21.20	222.40	85.40
25.20	41.30	43.40	21.50	232.80	88.70
23.40	41.30	40.10	21.20	231.80	88.50
15.80	40.00	36.80	21.80	236.60	91.10
15.20	42.00	41.20	25.20	231.20	101.10
15.00	41.80	39.80	24.60	226.20	97.70
15.10	41.50	37.80	20.80	251.10	90.70
15.10	41.40	37.40	22.40	234.80	90.40
16.50	41.00	36.10	22.90	240.10	95.10
16.70	40.90	36.60	22.60	233.00	93.20
9.20	30.00	22.80	11.90	262.50	56.30
9.20	25.40	21.00	11.60	259.60	52.60
26.30	39.80	34.60	12.20	273.80	85.90
26.40	39.90	34.90	12.20	273.40	84.30
15.50	41.30	35.10	18.60	266.90	103.10
15.80	41.30	37.10	9.30	288.30	93.40

TABLE 2. - SAMPLE STF ARRAY OPEN-CIRCUIT VOLTAGE DATA TAKEN ON SEVERAL DAYS

$n_{c,y} = 576$

$A_{o,y} = 2.7$

STF array open-circuit voltage, V_o, volts	Cell temperature, $T_{c,y}$, ^oK	Total solar irradiance, I_{rc}, mw/cm^2
290.0	320.85	85.2
303.0	315.15	105.2
298.0	323.95	101.0
301.0	321.15	100.0
294.0	320.45	84.5
307.0	312.95	85.6
309.0	314.85	103.8
307.0	309.35	67.4
314.0	308.75	93.4
310.0	310.45	93.9
299.0	308.15	39.9
260.0	264.95	1.5
328.0	270.55	30.0
330.0	285.35	51.8
315.0	305.65	80.3
304.0	300.75	70.0
317.0	308.35	90.2
307.0	318.25	105.6
320.0	290.15	41.8
314.0	280.05	14.6

TABLE 3. - PREDICTED POWER USING EQUATION (11) COMPARED WITH SAMPLE POWER DATA OF TABLE 1

Actual power, kW	Predicted power, kW	Deviation, percent
4.79	4.73	-1.3
4.80	4.76	-.8
4.57	4.35	-4.8
4.75	4.77	+.4
5.04	4.94	-2.0
4.95	4.94	-.2
5.19	5.31	+2.3
5.87	5.83	-.7
5.61	5.56	-.9
5.26	4.81	+10.5
5.30	5.09	-4.0
5.54	5.51	-.5
5.42	5.37	-.9
3.14	3.41	+8.6
3.03	3.46	+14.2
3.36	3.33	-.9
3.35	3.02	-9.9
4.99	5.60	+12.2
2.67	.79	-70.6
		Average deviation neglecting extreme data point = ±4.2 percent

6.0 REFERENCES

1. Forestieri, A.; et al.: ERDA/Lewis Research Center Photovoltaic Systems Test Facility. NASA TM X-73641, 1977.

2. Terrestrial Photovoltaic Measurement Procedures. ERDA/NASA/1022-77/16, NASA TM-73702, 1977.

3. Dave, J. V.; Braslau, N.: Importance of the Diffuse Sky Radiation in Evaluation of the Performance of a Solar Cell. Sol. Energy, vol. 18, no. 3, 1976, pp. 215-223.

4. Weizer, V. G.: Consideration of Design and Calibration of Terrestrial Reference Solar Cells. Terrestrial Photovoltaic Measurements, II, ERDA/NASA/1022-76/4, NASA CP-2010, 1976, pp. 203-222.

5. Rauschenback, H. S.: Solar Cell Array Design Handbook, Vol. 1. (JPL SP 43-38, Vol. 1, Jet Propulsion Lab.; NASA Contract NAS7-100.) NASA CR-149364, 1976, p. 9.2-1.

6. Stultz, J. W.; Wen, L. C.: Thermal Performance Testing and Analysis of Photovoltaic Modules in Natural Sunlight. JPL Rep.-5101-31, Jet Propulsion Lab., 1977.

7. Spring, K. H., ed.: Direct Generation of Electricity. Academic Press, 1965.

8. Hovel, H. J.: Solar Cells, Vol. 11. Semiconductors and Semimetals, R. K. Willardson and A. C. Beer, eds., Academic Press, 1975, p. 176.

APPENDIX A - ANALYTICAL RELATIONSHIP OF ARRAY SHORT-CIRCUIT CURRENT TO THE TOTAL SOLAR IRRADIANCE MEASURED BY A REFERENCE SOLAR CELL

The short-circuit current of a solar cell is proportional to the intensity of solar irradiance. It is also a function of the solar spectrum and the angle of incidence between the sun and the solar cell. Therefore, if solar irradiance is measured with a black body receiver (e.g., pyranometer) information on incident angle and spectrum is required for a complete correlation of solar cell short-circuit current.

The measurement approach used to compensate for incident angle and spectrum is the use of a calibrated reference solar cell for the measurement of total solar irradiance. Such a cell is calibrated under conditions of zero solar incident angle and collimated sun passing through a clear sky (ref. 2). The reference cell is made from the same material as the photovoltaic array being tested and is placed at the same tilt angle as the array. This appendix develops the analytical expression for the relationship which exists between the array short-circuit current (when measured under other than standard conditions of 100 mw/m^2 and 28^{o} C) and the solar irradiation measured by use of a reference solar cell calibrated at standard conditions. Such a relationship is needed as a step in developing a complete analytical expression for correlating the power output of an array, under nonstandard conditions, to the output of a reference cell calibrated at standard conditions.

Reference 2 gives the requirements for the calibration of a reference cell under clear sky conditions. To permit a comparison between the conditions of calibration and the nonstandard conditions encountered by the array, the equations of Dave and Braslau (ref. 3) are useful. These equations are for the light generated current of a solar cell, which for the present purpose, assuming negligible cell series resistance, can be used to determine the short-circuit current of a cell under nonstandard solar environments.

A reference cell calibrated under standard conditions (ref. 2) has a short-circuit calibration constant which is expressed as follows:

$$a^*_{rc} = i'_{sc,*rc}/I^*_D \qquad \text{(A-1)}$$

where

a^*_{rc} = reference cell calibration constant, amps/mw

$i'_{sc,*rc}$ = reference cell short-circuit current flux at standard conditions of spectrum and incident angle

I^*_D = direct component of solar irradiance determined with a black body receiver at standard conditions of spectrum and incident angle

By the use of the equations of reference 3 for light generated current a^*_{rc} may be expressed as follows:

$$a^*_{rc} = \frac{q}{hC} \frac{\psi^*_{rc}}{I^*_D} \tag{A-2}$$

where

$$\psi^*_{rc} = \int_0^\infty \tau_{rc}(\lambda^*, \theta_i = 0)\alpha_{rc}(\lambda^*, \theta_i = 0)S_{rc}(\lambda^*)\lambda^* I_D(\lambda^*)d\lambda^* \tag{A-3}$$

q = electronic charge, coulomb

h = Plank's constant, erg/sec

C = velocity of light, cm/sec

τ_{rc} = reference cell cover transmitted for direct irradiation, dimensionless

λ^* = light wavelength at standard sun conditions, cm

θ_i = solar incident angle

α_{rc} = solar cell absorptance for direct irradiation of reference cell, dimensionless

$S_{rc}(\lambda^*)$ = reference cell spectral response at standard sun conditions, electrons/photon

Equation (A-2) states that the calibration constant (a^*_{rc}) of the reference cell is determined at conditions of standard spectrum (λ^*), standard solar incident angle ($\theta_i = 0$) and standard direct solar irradiance (I^*_D).

When the reference solar cell is used to measure total solar radiation (I_T) under conditions of variable solar spectrum, variable solar incident angle and ground reflection, the following equations for the calibration constant are applicable:

$$a_{rc} = i'_{sc,rc}/I_T \tag{A-4}$$

I_T = total solar irradiance measured with a black body receiver (pyranometer)

a_{rc} = calibration constant for a reference cell at nonstandard conditions

The calibration constant can also be expressed as:

$$a_{rc} = \frac{q}{hC} \frac{\psi_{rc}}{I_T} \tag{A-5}$$

where the parameter ψ_{rc} applies to variable condition of spectrum (λ) and incident angle (θ_i) for a reference cell as follows:

$$\psi_{rc} = \int_0^\infty \Big[K_{r,D}(\lambda)\tau_{rc}(\lambda,\theta_i)\alpha_{rc}(\lambda,\theta_i)S_{rc}(\lambda)\lambda I_D(\lambda)d\lambda + K_{r,d}(\lambda)\overline{\tau}_{rc}(\lambda)\overline{\alpha}_{rc}(\lambda)S_{rc}(\lambda)\lambda I_d\, d\lambda\Big] \tag{A-6}$$

$K_{r,D}$ = ground reflection factor for direct component of solar irradiation, dimensionless

$K_{r,d}$ = ground reflection factor for diffuse component of solar radiation, dimensionless

$\overline{\tau}_{rc}$ = reference cell cover transmittance for diffuse irradiation, dimensionless.

The calibration constant as expressed by equation (A-4) is not a true constant, but is a function of the solar spectrum (λ) and solar incident angle (θ_i). Employing the method used to obtain the short-circuit correlation constant of the solar cell (eq. (A-1)) to the solar cell array being measured results in the following relationship:

Array at Standard Sun Conditions

$$a^* = i'_{sc^*}/I^*_D \tag{A-7}$$

or

$$a^* = \frac{q}{hC}\frac{\psi^*}{I^*_D} \tag{A-8}$$

where

$$\psi^* = \int_0^\infty \tau(\lambda^*, \theta_i = 0)\alpha(\lambda^*, \theta_i = 0)S(\lambda^*)\lambda^* I_D(\lambda^*)d\lambda^* \tag{A-9}$$

Equation (A-8) states that the calibration constant of the array (a^*) is determined at conditions of standard spectrum (λ^*), standard solar incident angle ($\theta_i = 0$) and standard direct solar irradiance (I^*_D).

In practice, of course, a photovoltaic array operates under variable solar conditions. The short-circuit current of the array may be expressed as follows:

Array at Nonstandard Sun Conditions

$$i'_{sc} = aI_T K \tag{A-10}$$

or

$$i'_{sc} = \frac{q}{hC}\psi K \tag{A-11}$$

where

$$\psi = \int_0^\infty \Big[K_{r,D}(\lambda)\tau(\lambda, \theta_i)\alpha(\lambda, \theta_i)S(\lambda)\lambda I_D(\lambda)d\lambda + K_{r,d}(\lambda)\bar{\tau}(\lambda)\bar{\alpha}(\lambda)S(\lambda)\lambda I_d(\lambda)d\lambda\Big] \tag{A-12}$$

K = array surface film factor, dimensionless

Equations (A-1) and (A-4) are the basic reference cell performance equations for both standard and nonstandard solar conditions. Similarly, equations (A-7) and (A-10) are the basic array performance equations for both standard and nonstandard solar conditions. What remains, is to develop an expression for the relationship between the reference cell output and the array output.

Relationship Between Reference Cell Output and Array Output

The first step is to establish the relationship between the standard and nonstandard conditions for array short-circuit current flux (i'_{sc}). By combining equations (A-8) and (A-11) as follows then,

$$i'_{sc} = a^*\left(\frac{I^*_D}{I_T}\right)\left(\frac{\psi}{\psi^*}\right)I_T K \qquad \text{(A-13)}$$

The reference solar cell is used to measure the total solar irradiance (I_{rc}) which reaches the solar array. This value (I_{rc}) can be different than the total solar irradiance measured with a black body receiver (I_T) as previously explained. The procedure for determining the value of the total solar irradiance (I_{rc}) using a reference cell is to measure the current output and to employ the calibration constant (a^*_{rc}) determined at standard conditions using equation (A-1). The resulting value for I_{rc} is as follows:

$$I_{rc} = i'_{sc,rc}/a^*_{rc} \qquad \text{(A-14)}$$

The relationship between the reference cell total irradiance (I_{rc}) and that of a black body instrument (pyranometer) is determined from a combination of equations (A-14) and (A-15). The resulting equation is as follows:

$$I_{rc} = \frac{a_{rc}}{a^*_{rc}} I_T \qquad \text{(A-15)}$$

or by substituting for a_{rc} and a^*_{rc} with equations (A-2) and (A-5) the following is obtained:

$$I_{rc} = \left(\frac{\psi_{rc}}{\psi^*_{rc}}\right)\left(\frac{I^*_D}{I_T}\right)I_T \qquad \text{(A-16)}$$

Substituting in the equation for the array short-circuit current (eq. (A-13)) for the value of the total solar irradiation (I_T) from equation (A-16) results in the following:

$$i'_{sc} = a^* \left(\frac{\psi}{\psi^*}\right)\left(\frac{\psi^*_{rc}}{\psi_{rc}}\right) I_{rc} K \tag{A-17}$$

Inspection of equations (A-3), reference cell at standard conditions, and (A-9), array at standard conditions, for ψ^*_{rc} and ψ^* indicates thest values would be equal if the array and reference cell were made of the same material and had the same spectral response. Similarly, inspection of equations (A-6), reference cell at nonstandard conditions, and (A-12), array at nonstandard conditions, for ψ_{rc} and ψ indicates that these quantities also would be equal if the array and reference cell were made of the same cover material and had the same spectral response. It is possible to simplify equation (A-17) by matching the reference cell with the array such that the spectral (S(λ)) response of each is proportional and the angular ($\tau\alpha$) response of each is proportional. This is expressed as follows:

Standard conditions	Nonstandard conditions	

$$\frac{S_{rc}(\lambda^*)}{S(\lambda^*)} = \frac{S_{rc}(\lambda)}{S(\lambda)} = \ell_0 \tag{A-18}$$

$$\frac{(\tau^*\alpha^*)_{rc}}{\tau^*\alpha^*} = \frac{(\tau\alpha)_{rc}}{\tau\alpha} = \ell_1 \tag{A-19}$$

with these substitutions in equations (A-3), (A-9), (A-6), and (A-12), the following identifies are obtained:

$$\frac{\psi^*_{rc}}{\psi^*} = \ell_0 \ell_1 \tag{A-20}$$

$$\frac{\psi_{rc}}{\psi} = \ell_0 \ell_1 \tag{A-21}$$

By substitution of equations (A-20) and (A-21) in equation (A-17), equation (A-17) is simplified as follows:

$$i'_{sc} = a^* I_{rc} K \qquad \text{(A-22)}$$

or in terms of cell area

$$i_{sc} = a^* I_{rc} K A_c \qquad \text{(A-23)}$$

Equation (A-22) is the desired expression for correlating short-circuit current because the short-circuit current is expressed in terms of a true constant (a^*) that is related to a standard clear day sun condition. This relationship is possible when a calibrated reference solar cell is used for measuring total solar irradiance (I_{rc}).

8.0 APPENDIX B - DERIVATION OF PHOTOVOLTAIC ARRAY POWER CORRELATION

In appendix A, the equation was developed for array short-circuit current as a function of the total solar irradiance measured with a reference solar cell (eq. (A-23)). This relationship is required in what follows so as to permit developing an expression for array power in terms of total solar irradiation for a limited portion of the I-V characteristic curve around the maximum powerpoint.

Figure 2(b) is the equivalent circuit for a solar cell having series resistance and large or infinite shunt resistance. A voltage balance for the circuit of figure 2(b) (ref. 5) results in the following equation:

$$i_j = i_{L,j} + i_{o,j}\left[1.0 - e^{\frac{q(V_c + i_j R_{s,j})}{kA_{o,j}T_{c,j}}}\right] \tag{B-1}$$

i_j	cell current of cell type j, amps
$i_{L,j}$	light generated current of cell type j, amps
$i_{o,j}$	saturation current of p-n junction of cell type j, amps
$A_{o,j}$	cell constant of type j
$R_{s,j}$	series resistance of cell type j, ohms
V_c	cell voltage, volts

To transform equation (B-1) into a form useful for the insertion of experimental data such as power, voltage and solar irradiation we use the following conditions:

$$V_c = 0;\ i_j = i_{sc,j} \qquad \text{Short-circuit current}$$

$$V_c = V_{oc};\ i_j = 0 \qquad \text{Open-circuit current}$$

Substituting the above conditions into equation (B-1) results in the following:

Short-Circuit Condition, $V_c = 0$

$$i_{sc,j} = i_{L,j} + i_{o,j}\left[1.0 - e^{\frac{q(i_{sc,j}R_{s,j})}{kA_{o,j}T_{c,j}}}\right] \tag{B-2}$$

Open-Circuit Condition, $i_j = 0$

$$0 = i_{L,j} + i_{o,j}\left[1.0 - e^{\frac{qV_{oc,j}}{kA_{o,j}T_{c,j}}}\right] \tag{B-3}$$

Combining equations (B-1) and (B-3) results in the following:

$$i_j = i_{sc,j}\left[\frac{e^{\frac{qV_{oc,j}}{kT_{c,j}A_{o,j}}} - e^{\frac{q(V_c+i_jR_s)}{kT_{c,j}A_{o,j}}}}{e^{\frac{qV_{oc,j}}{kT_{c,j}A_{o,j}}} - e^{\frac{qi_{sc,j}R_{s,j}}{kT_{c,j}A_{o,j}}}}\right] \tag{B-4}$$

$V_{oc,j}$ cell open-circuit voltage of type j, volts

$i_{sc,j}$ cell short-circuit current of type j, amps

Since equation (B-4) is intended only for use in the region around the maximum power point the equation can be simplified by neglecting the series resistance since in the practical application of power near or at the maximum power condition the values of V_{oc} and V_c are greater than $i_{sc}R_s$ by an order of magnitude. Therefore equation (B-4) is simplified as follows:

$$i_j = i_{sc,j}\left[1.0 - e^{-\frac{q(V_{oc,j}-V_{c,j})}{kT_{c,j}A_{o,j}}}\right] \tag{B-5}$$

Equation (B-5) analytically describes the region of the I-V curve that offers maximum or near-maximum solar cell power (fig. B-1). For a given value of short-circuit current ($i_{sc,j}$), cell temperature ($T_{c,j}$), and open-circuit voltage ($V_{oc,j}$), equation (B-5) gives the relationship between current (i_j) and cell voltage ($V_{c,j}$) as shown in figure B-1. Since cell temperature, short-circuit current, and open-circuit voltage are functions of the ambient temperature and solar irradiation, equation (B-5) gives the electrical properties of the solar cell as the cell encounters different environmental situations.

Equation (B-5) may be rearranged in terms of the constant ($A_{o,j}$) as follows:

$$A_{o,j} = \frac{V_{oc,j} - V_{c,j}}{T_{c,j}} \frac{q}{k} \frac{1}{LN\left(\dfrac{1.0}{1.0 - \dfrac{i_j}{i_{sc,j}}}\right)} \tag{B-5a}$$

For a type y solar cell, the constant $A_{o,y}$ may be determined using the following experimental data obtained for type y modules with the use of a pulsed simulator as the radiation source:

$i_{max,y}$ = 1.197 amps

$i_{sc,y}$ = 1.377 amps

$V_{oc,y}$ = 0 571 volts

$V_{max,y}$ = 0.427 volts

$T_{c,y}$ = 301^{o} K

Substitution of the above values in equation (B-5a) gives the following value for the constant $A_{o,y}$.

$$A_{o,y} = 2.7 \tag{B-5b}$$

To transform equation (B-5) for a single cell to an equation describing the array of figure 2(a), the following equations are applicable:

$$i = M_j i_j \tag{B-6a}$$

$$i_{sc} = M_j i_{sc,j} \tag{B-6b}$$

$$V = n_{c,j} V_{c,j} \tag{B-6c}$$

$$V_o = n_{c,j} V_{oc,j} \tag{B-6d}$$

V_o	array open-circuit voltage, volts
M_j	total number of cell strings for type j
i	array current, amps
i_{sc}	array short-circuit current, amps
V	array voltage, volts
$n_{c,j}$	number of cells in a series string for type j

Equations (B-6a) and (B-6b) state that the array current is the summation of the individual series string current. Equation (B-6c) assumes the individual cell voltages to be equal so that cell voltage is simply total voltage divided by the number of cells in a series string.

Substitution of equations (B-6a), (B-6b), (B-6c), (B-6d), and (A-23) into equation (B-5) results in the following equation:

$$P_j = a^*KM_jA_{c,j}I_{rc}V\left[1.0 - e^{-\frac{b\Phi}{n_{c,j}}}\right] \tag{B-7}$$

where

$$\Phi = (V_o - V)/T_{c,j}$$

$$b = q/kA_{o,j}$$

Equation (B-7) is the power equation for a photovoltaic array which contains one type of solar cell and is applicable to array characteristics in the region of maximum power. Use may be made of equation (B-7) by using the theoretical values for (a*) and (b) and setting (K) equal to 1 or a value that allows for degradation. The above approach will give theoretical power value in the region of maximum power. The intent is to use equation (B-7) with experimentally determined values of (a*), (K), and (b).

For an array having mixed cell types, a modification of equation (B-7) is required. The approach is to determine average values for the cell temperature ($\overline{T}_c$), the cell area ($\overline{A}_c$), and the number of cells per series strings ($\overline{n}_c$). In the case of $\overline{T}_c$ and $\overline{n}_c$ averages need to be determined which permit an accounting of the effect that cell temperature has on array voltage The average cell area is derived by assuming equal current flux for all the cell types which make up the array

The string voltage change due to cell temperature change may be expressed as a linear function of temperature change as follows·

$$\Delta V_j = \beta n_{c,j}(T_r - T_{c,j}) \tag{B-8}$$

β voltage temperature coefficient, volt/^oK cell

T_r reference temperature, ^oK

Since the voltages across each string are all equal, equation (B-8) may be expressed as follows.

$$\Delta V = \frac{\beta}{\sum_{j=x,y,z} M_j}\left[\sum_{j=x,y,z} n_{c,j} M_j (T_r - T_{c,j})\right] \tag{B-9}$$

or in terms of average array cell temperature ($\overline{T}_c$) and average number of cells per series string, equation (B-9) is expressed as follows:

$$\Delta V = \frac{\beta}{\sum_{j=x,y,z} M_j}\left(\sum_{j=x,y,z} M_j\right)(T_r - \overline{T}_c)\,\overline{n}_c \tag{B-10}$$

By defining the average number of cells per series string as

$$\bar{n}_c = \frac{1}{\sum\limits_{j=x,y,z} M_j} \sum_{j=x,y,z} n_{c,j} M_j \tag{B-11}$$

and equating equation (B-10) to (B-8) results in the following expression for the average cell temperature:

$$\bar{T}_c = \frac{\sum\limits_{j=x,y,z} n_{c,j} M_j T_{c,j}}{\sum\limits_{j=x,y,z} n_{c,j} M_j} \tag{B-12}$$

The array current output (fig. 2(a)) is the sum of the current of the individual strings as follows:

$$i = \sum_{j=x,y,z} M_j i_j \tag{B-13}$$

Expressing (B-13) in terms of the current flux we obtain

$$i = \sum_{j=x,y,z} M_j i'_j A_{c,j} \tag{B-14}$$

Assuming that the current flux of the individual types to be equal results in the following:

$$\bar{A}_c = \frac{1}{M}\left[\sum_{j=x,y,z} M_j A_{c,j}\right] \tag{B-15}$$

Equations (B-15), (B-12), and (B-11) may be used to express the power equation (B-7) in terms of average variables. The result is as follows:

$$P = \bar{a}^* I_{rc} \bar{K} M \bar{A}_c V \left[1.0 - e^{-(b\bar{\Phi}/\bar{n}_c)} \right] \quad \text{(B-16)}$$

where

$$\bar{\Phi} = (V_o - V)/\bar{T}_c$$

$$\bar{A}_c = \frac{1}{M} \sum_{j=x,y,z} M_j A_{c,j}$$

$$M = \sum_{j=x,y,z} M_j$$

Equation (B-16) is the power equation in the region of maximum power for an array made up of series string arrangements of different cell type with each series string containing one type of solar cell (fig. 2). For a calculation of ideal power, theoretical values may be used for (a^*) and (b) where K is set equal to degradation factor. In this paper the interest is to use equation (B-16) for correlation of array power in the region of maximum power and by so doing obtain experimental values for the above constants.

In the derivations above it has been assumed that the cell temperature may be obtained by measurement or by calculation from knowledge of solar irradiance and ambient temperature. The cell temperature may be correlated in terms of the environmental variables of solar irradiation (I_{rc}) and ambient temperature (T_a) by the method outlined in reference 6. This may be expressed as follows:

$$T_{c,j} = c_o I_{rc} + T_a \quad \text{(B-17)}$$

$$c_o = f(T_{c,j} - T_a, \text{ wind velocity})$$

In equation (B-17), the value of c_o is essentially a constant for a given range of wind velocities and ambient temperature (see ref. 6 for details).

9.0 APPENDIX C - DERIVATION OF THE RELATIONSHIP BETWEEN OPEN-CIRCUIT VOLTAGE AND SOLAR IRRADIANCE AND CELL TEMPERATURE

Equations (B-16) and (B-7) require an input value of open-circuit voltage (V_o). Since open-circuit voltage is a function of solar irradiance and cell temperature, an expression for open-circuit voltage which can encompass both these variables is required. The open-circuit voltage can be solved for from equation (B-1) with series resistance neglected so as to permit a simplified expression for correlation purposes. The open-circuit voltage derived from equation (B-1) assuming zero series resistance is as follows:

$$V_{oc} = \frac{A_{o,j}k}{q} T_{c,j} \; LN\left[1.0 + \frac{i_{sc,j}}{i_{o,j}}\right] \qquad \text{(C-1)}$$

Since

$$V_o = n_{c,j} V_{oc}$$

<u>and</u>

$$i_{sc,j}/i_{o,j} >>> 1$$

Equation (C-1) may be written as follows:

$$V_o = \frac{n_{c,j}A_{o,j}k}{q} T_{c,j} \; LN\left(\frac{i_{sc,j}}{i_{o,j}}\right) \qquad \text{(C-2)}$$

The above expression can be expressed in terms of the variables of cell temperature and solar irradiance by making substitutions for the short-circuit current ($i_{sc,j}$) and the saturation current ($i_{o,j}$).

An expression for the saturation current ($i_{o,j}$) is derived in reference 7 as follows:

$$i_{o,j} = BT_{c,j}^{3} e^{-Eg/kT_{c,j}} \qquad \text{(C-3)}$$

B a constant

Eg cell energy gap, joules

The short-circuit current expressed by equation (A-23) may be stated in terms of the array short-circuit current for a given cell type as follows

$$i_{sc,j} = B_o I_{rc} \tag{C-4}$$

where

$$B_o = a^* K M_j A_{c,j}$$

Substituting equations (C-3) and (C-4) into equation (C-1) we obtain the following:

$$V_o = \frac{m_{c,j} A_{o,j} k}{q} T_{c,j} \; \mathrm{LN} \left[\frac{B_o I_{rc}}{B T_{c,j}^3 e^{-Eg/kT_{c,j}}} \right] \tag{C-5}$$

Equation (C-5) may be expressed as follows:

$$\omega = \frac{\frac{Eg}{q} - \frac{V_o}{A_{o,j} n_{c,j}}}{T_{c,j}} = -\frac{k}{q} \left[\mathrm{LN}\left(\frac{I_{rc}}{T_{c,j}^3} \right) + \mathrm{LN}\left(\frac{B_o}{B} \right) \right] \tag{C-6}$$

Equation (C-6) suggests the following open-circuit voltage correlating equation for silicon photovoltaic cells (Eg = 1.1 e.v , Eg/q = 1.092).

$$\omega = m\psi + b_o \tag{C-7}$$

where

$$\omega = \frac{1.092 - \frac{V_o}{n_{c,j} A_{o,j}}}{T_{c,j}}$$

ψ = $LN\left(I_{rc}/T^3_{c,j}\right)$

m = slope of correlating line

b_o = intercept of correlating line

The potential advantage of equation (C-7) for correlating open-circuit voltage is that it permits a two-variable correlation rather than the three-variable correlation which is normally required, as depicted by figure C-1. As an example of the use of equation (C-7), the data of reference 8 presented in the form of figure C-1 is given in table C-1. Table C-1 gives the basic data of reference 8 and the calculated data according to equation (C-7). The data correlation according to equation (8) for the data of reference 8 is given in figure C-2. A comparison of figure C-2 with figure C-1 demonstrates the value of the present approach which present a more general relationship for open-circuit voltage. A test of how well the data of reference 8 can be predicted from the correlation of figure C-2 is given in table C-2. Table C-2 indicates that the average deviation of the predicted open-circuit voltage from the experimental open-circuit voltage is less than ±1 percent.

TABLE C-1. - DATA OF REFERENCE 8 EXPRESSED IN THE MANNER OF EQUATION (7)

$n_c = 1.0$

Assume $A_o = 1.0$

Open-circuit voltage, V_{oc}, volts	Cell temperature, T_c, ^oK	Solar irradiation, I, mw/cm^2	$LN\left(\frac{I}{T_c^3}\right)$	$\frac{(1.092 - V_o)}{T_c}$
0.425	323	10	-15.03	2.07×10^{-3}
.55	273	10	-14.53	1.99
.63	233	10	-14.05	1.98
.52	323	100	-12.73	1.77
.63	273	100	-12.22	1.69
.72	233	100	-11.75	1.60

TABLE C-2. - COMPARISON OF PREDICTED AND EXPERIMENTAL VALUES OF OPEN-CIRCUIT VOLTAGES

Experimental open-circuit voltage, volts	Calculated open-circuit voltage, (fig. C-2), volts	Difference, percent
0.425	0.425	0
.55	.546	-.7
.63	.641	+1.8
.52	.526	-1.2
.63	.633	+.5
.72	.715	-.6

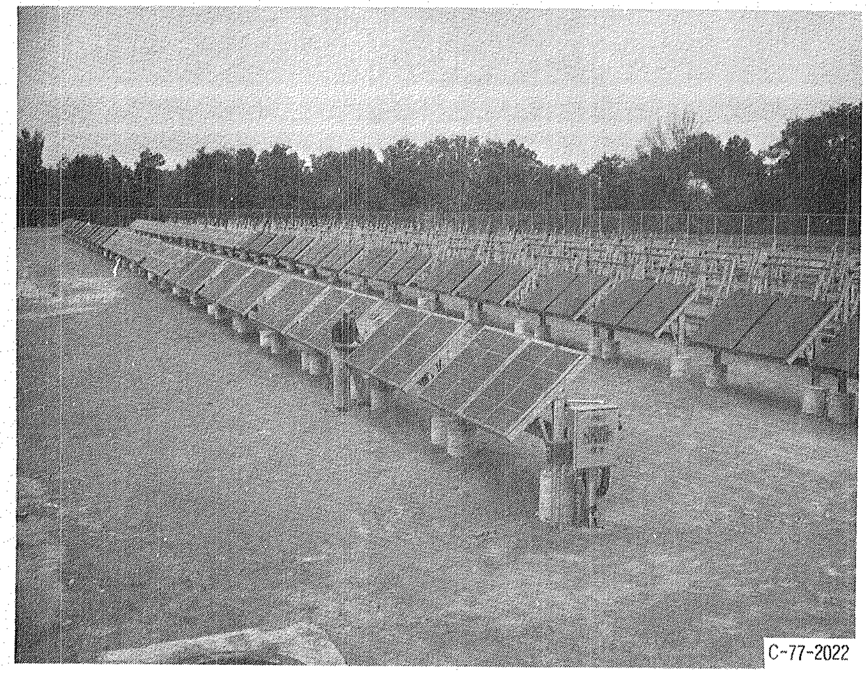
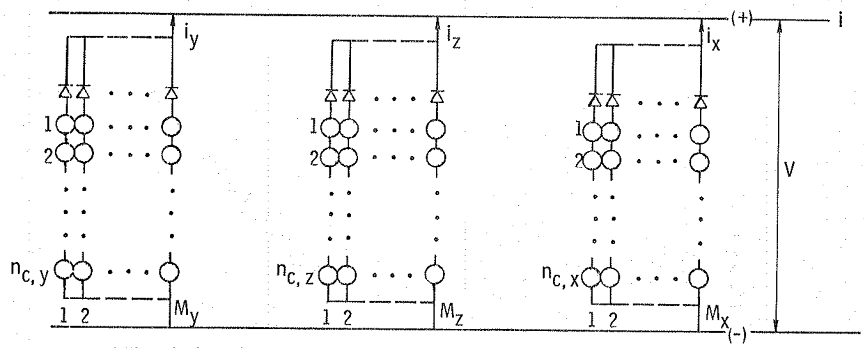
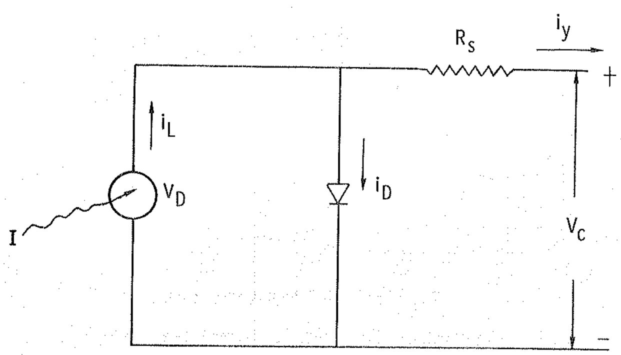


Figure 1. - DOE/LeRC Photovoltaic Systems Test facility (Solar Array Field).



(a) Electrical configuration of solar cell modules of DOE/LeRC Systems Test Facility.



(b) Solar cell equivalent circuit.

Figure 2. - Solar cell electrical circuit.

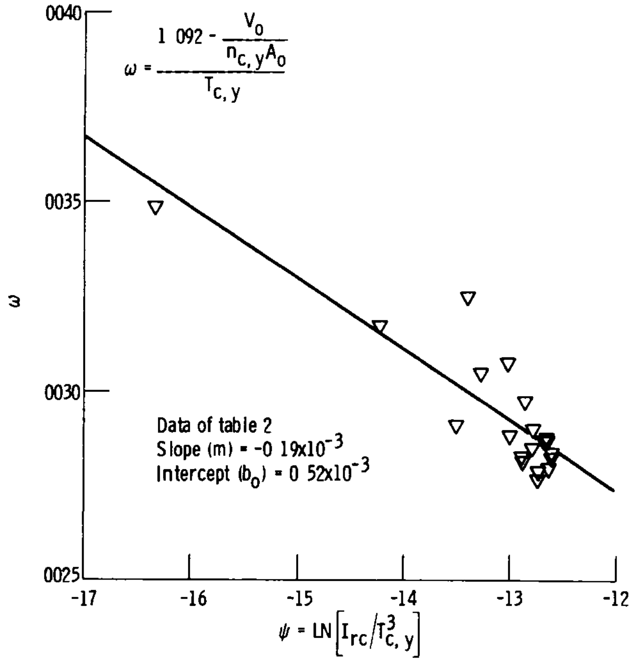


Figure 3 - Open circuit voltage correlation (Linearization of eq (4))

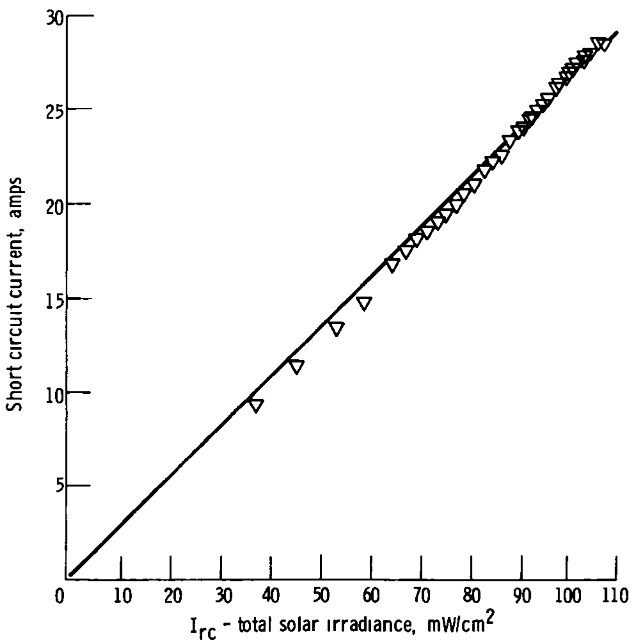


Figure 4 - Short-circuit current correlation

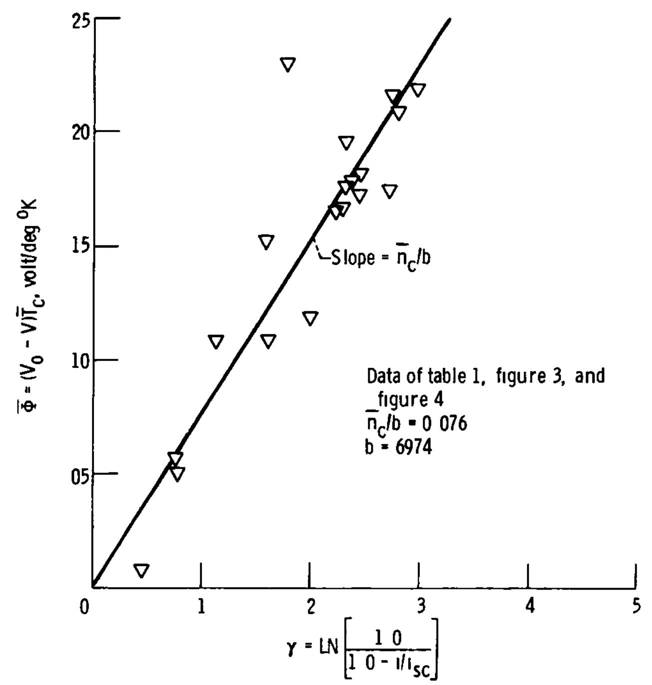


Figure 5 - Determination of the correlation constant

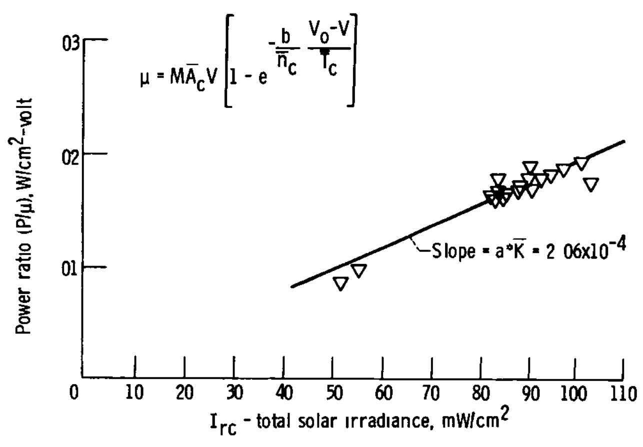


Figure 6 - Array power correlation

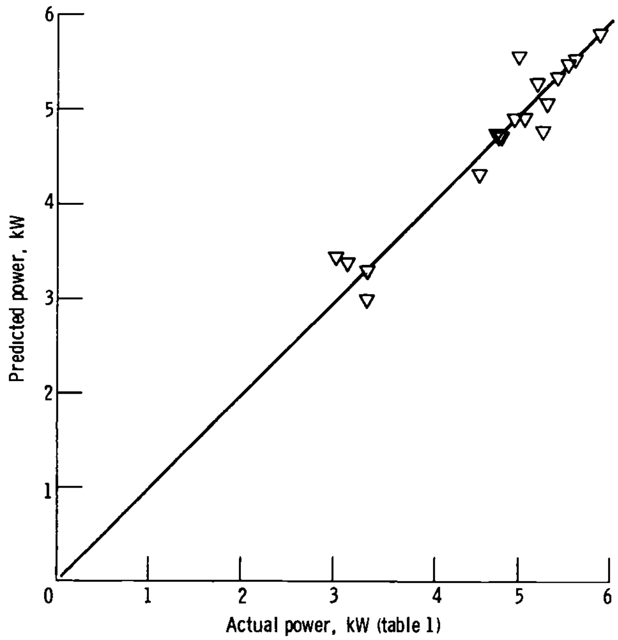


Figure 7 - Predicted versus experimental STF array power

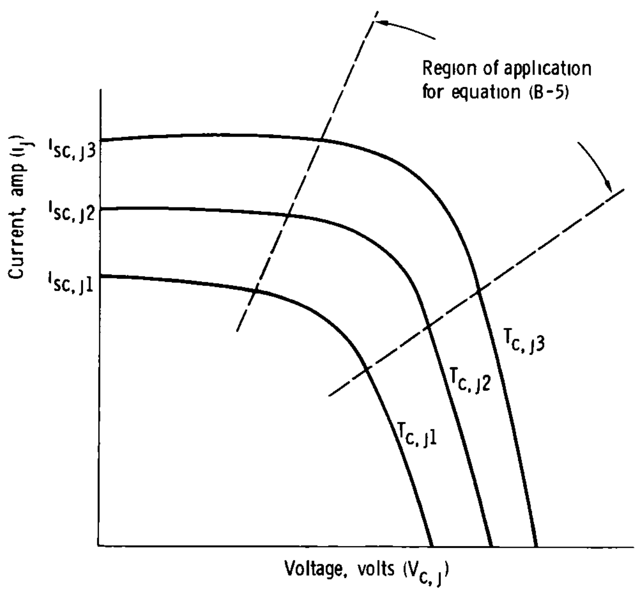


Figure B-1 - Region of application for array power equation

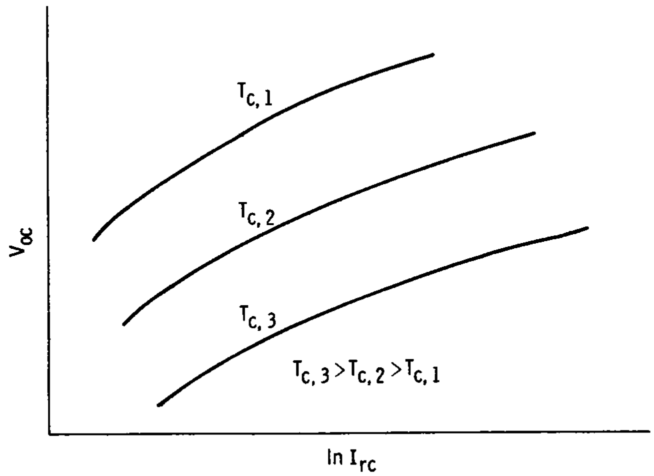


Figure C-1 - Relationship of open-circuit voltage to cell temperature and total solar irradiance

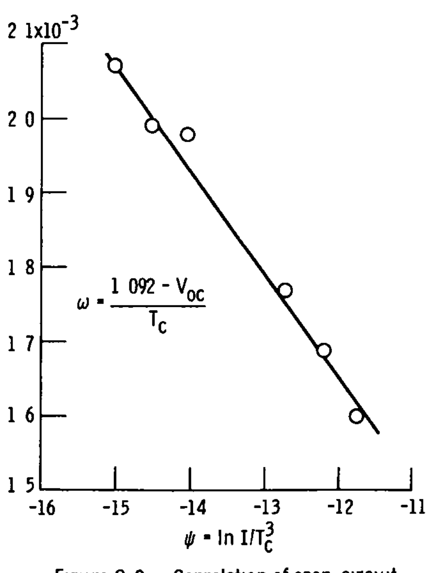


Figure C-2 - Correlation of open-circuit voltage data (ref 8) according to equation (C-6)

End of Document