A Simplified Thermal Model for Flat-Plate Photovoltaic Arrays

Martin K. Fuentes

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Sandia National Laboratories
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Martin K. Fuentes
Photovoltaic Systems Research Division
Sandia National Laboratories
Albuquerque, NM 87185

Abstract
Sandia National Laboratories is actively involved in the development of an accurate photovoltaic (PV) performance model, called PVFORM. A necessary part of this modeling effort is the prediction of the operating cell temperatures. This report describes a computer model that accurately predicts the cell temperature of a photovoltaic array to within 5°C. This thermal model requires a minimum amount of input and has been incorporated into PVFORM. The major input parameter to this model is the "Installed" Nominal Operating Cell Temperature or INOCT. The program uses INOCT to characterize the thermal properties of the module and its mounting configuration. INOCT can be estimated from the Nominal Operating Cell Temperature (NOCT) and the mounting configuration, or from cell temperature data from a fielded array.
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</tbody>
</table>
INTRODUCTION

Sandia National Laboratories is actively involved in modeling the electrical energy production of photovoltaic arrays in order to better evaluate the performance of existing arrays and predict the performance of theoretical ones. Any such model must obtain or calculate the three major parameters that are used to determine the array output power at a particular instant in time. These parameters are the plane of array insolation, module operating characteristics, and the average cell temperature. The model presented in this report can be used to calculate the average cell temperature of a flat-plate array so that it can be used in accurate energy predictions. This thermal model has been incorporated into PVFORM, a small but accurate PV performance model developed at Sandia National Laboratories.

The thermal model was designed to use as few data inputs as possible, making the code easier to use and reducing the probability of improper values being inputted by the user. The required inputs include the plane of array insolation, ambient temperature, wind speed, average array height above ground, anemometer height, and the "Installed" Nominal Operating Cell Temperature (INOCT). INOCT is defined as the cell temperature of an installed array at NOCT conditions (800 W/m² insolation, 20°C ambient temperature, and 1 m/sec wind speed). It differs from the JPL standard, the NOCT temperature, in that the mounting configuration is accounted for only with INOCT. The NOCT temperature is applicable only for open circuited, rack mounted modules.

The thermal model uses INOCT to estimate the heat gain and the convection and radiation losses at NOCT conditions. The model then varies the values of these parameters according to the variation in the environmental conditions. For instance, from INOCT the model obtains the convective coefficient at a wind speed of 1 m/sec. Because the laminar convective coefficient varies with the square root of the wind speed, we can obtain the proper convective coefficient at any wind speed in the laminar region. Similarly, the model is capable of predicting the heat gain and convective and radiation losses at any environmental condition. The model also incorporates a thermal capacitance to simulate the natural temperature lag of a typical module.

Three of the remaining input parameters can be obtained from meteorological data: plane of array insolation, ambient temperature, and wind speed. In fact, the plane of array insolation does not appear in most meteorological data tapes, but it can be obtained by using direct normal and horizontal insulations and an insolation model such as the one in PVFORM. The remaining
other input parameters are the array and anemometer height above ground. They are used to adjust the wind speed to the array height.

**ACCURACY OF THE THERMAL MODEL**

Several comparisons were made between the model and actual field data. Appendix C contains 41 plots displaying these comparisons. In every case, the error is less than 5°C. Listed in Table 1 are the INOCTs and the weighted uncertainties of the model for several prototypes at the Southwest Residential Experiment Station (SWRES). The uncertainties were weighted with insolation because PV energy predictions are more sensitive to errors at high insolation levels than at low insolation levels. In each case, the uncertainty is less than 4°C, and typically is around 2.5°C.

The results shown in Table 1 and in Appendix C demonstrate that the accuracy of this model is more than adequate for most PV applications. To obtain better results, one would have to characterize the geometry of the array and the thermal conductances of the module and its surroundings. Such an effort is difficult and would decrease the error only to ±3°C. The advantage of this model is that the thermal properties of the module and its mounting configuration are characterized by one value, INOCT. A more detailed model would require extensive input, which would increase the possibility that the user would input improper values.

Table 1: INOCTs and the weighted uncertainties of the thermal model for various prototypes at the SWRES.

<table>
<thead>
<tr>
<th>Prototype</th>
<th>INOCT (°C)</th>
<th>Uncertainty (±°C)</th>
<th>Number of Records</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE</td>
<td>65.2</td>
<td>1.8</td>
<td>1257</td>
</tr>
<tr>
<td>Solarex</td>
<td>58.3</td>
<td>2.3</td>
<td>1256</td>
</tr>
<tr>
<td>Arco</td>
<td>53.0</td>
<td>2.5</td>
<td>1259</td>
</tr>
<tr>
<td>ARTU</td>
<td>51.8</td>
<td>3.6</td>
<td>1271</td>
</tr>
<tr>
<td>BDM</td>
<td>51.6</td>
<td>2.8</td>
<td>1176</td>
</tr>
<tr>
<td>Westinghouse</td>
<td>49.4</td>
<td>2.6</td>
<td>1266</td>
</tr>
<tr>
<td>TEA</td>
<td>45.8</td>
<td>2.4</td>
<td>1252</td>
</tr>
<tr>
<td>Tri-Solar</td>
<td>44.8</td>
<td>2.4</td>
<td>1177</td>
</tr>
<tr>
<td>XT at 0 SOH</td>
<td>65.8</td>
<td>1.6</td>
<td>455</td>
</tr>
<tr>
<td>XT at 1 SOH</td>
<td>59.8</td>
<td>1.6</td>
<td>434</td>
</tr>
<tr>
<td>XT at 3 SOH</td>
<td>51.2</td>
<td>1.8</td>
<td>428</td>
</tr>
<tr>
<td>XT at 6 SOH</td>
<td>48.1</td>
<td>1.8</td>
<td>480</td>
</tr>
<tr>
<td>XT at 9 SOH</td>
<td>46.1</td>
<td>1.9</td>
<td>443</td>
</tr>
</tbody>
</table>

As with any model, certain assumptions that may not apply to every application are written into this model. For instance, the model assumes a fixed absorptivity for all modules, but not all modules have the same absorptivity. Because of the way the model is written, these differences do not affect the results significantly. The model is given the exact cell temperature at NOCT conditions, i.e. INOCT, and the model determines the difference between the cell temperature and INOCT from the difference between the environmental conditions and NOCT conditions. Thus if the model is high in its absorptivity, it will be low in its convection and radiation so that the equations will balance at the NOCT conditions. This may cause some error when the environmental conditions diverge from the NOCT conditions, but the error is typically small.
DERIVATION OF THE THERMAL MODEL

Energy Balance Solution

A PV module can be modeled as a single lump of solid material at a uniform temperature $T_c$ (Figure 1). The module receives heat in the form of insolation, $S$, and loses heat in the form of convection to ambient, $T_a$, and radiation to the sky and ground, $T_s$ and $T_g$. The energy balance is displayed in the equation below:

$$hc \cdot (T_c - T_a) + \varepsilon \cdot \sigma \cdot (T_c^4 - T_s^4) + \varepsilon \cdot \sigma \cdot (T_c^4 - T_g^4) - \alpha \cdot S + m \cdot c \cdot \frac{dT_c}{dt} = 0. \quad (1)$$

Figure 1: Schematic depiction of the simplified thermal model.

We can linearize this equation by noticing that the radiation terms can be expanded:

$$(T_c^4 - T_s^4) = (T_c^2 + T_s^2) \cdot (T_c + T_s) \cdot (T_c - T_s). \quad (2)$$

Since the product $(T^2 + T_s^2) \cdot (T + T_s)$ changes less than 5% for a 10°C variation in $T_c$, we can consider this product to be nearly constant. By doing so, the radiation terms in equation 1 become linear, and the equation can be easily solved. After solving for $T_c$, we can reevaluate the value of this constant and then solve for $T_c$ again. A nearly exact solution can be obtained after 5 iterations. We can simplify the heat balance equation by defining a radiation coefficient, $h_r$:

$$h_r = \varepsilon \cdot \sigma \cdot (T_c^2 + T_s^2) \cdot (T_c + T_s) \quad (3)$$

$$h_r = \varepsilon \cdot \sigma \cdot (T_c^2 + T_g^2) \cdot (T_c + T_g). \quad (4)$$
We can also assume that the insolation varies between time steps in a linear fashion:

\[ S = S_0 + \Delta S \cdot t/\Delta t. \]  

(5)

This is done so that the insolation profile is modeled as a continuous function, rather than as a step function. A step function is not a realistic depiction of the insolation profile over time, and leads to an additional error in the calculation of \( T_c \). The resulting heat balance is displayed below:

\[
hc \cdot (T_c - T_a) + hr_s \cdot (T_c - T_s) + hr_g \cdot (T_c - T_g) - \alpha \cdot (S_o - \Delta S \cdot t/\Delta t) + m \cdot c \cdot \frac{dT_c}{dt} = 0. 
\]

(6)

We can now obtain an explicit expression for \( T_c \) (Equation 7) by integrating equation 6:

\[
T_c = \frac{(hc \cdot T_a + hr_s \cdot T_s + hr_g \cdot T_g + \alpha \cdot S_o + \alpha \cdot \Delta S / L) \cdot (1 - e^L) + \alpha \cdot \Delta S}{hc + hr_s + hr_g} + T_c_0 \cdot e^L. 
\]

(7)

\( T_c_0 \) is the module temperature at the start of the time step and \( L \) is determined using

\[
L = - \frac{(hc + hr_s + hr_g) \cdot \Delta t / (m \cdot c)}. 
\]

(8)

In general terms, \( 1/L \) is the capacitance of the module. It is that factor which characterizes the thermal lag of a module.

In equation 7, we either know or can obtain a value for every parameter on the right hand side of the equation. We determined \( T_c_0 \) from our calculation for the last time step. We are given \( T_a \), and with it, we can estimate \( T_s \), and thus also \( hr_s \). But because \( hr_s \) also varies with \( T_c \), for which we are solving, we have to iterate our solution. \( S_o, \Delta S, \) and the time step are available as input data. The overall convective coefficient, \( hc \), is the sum of the top and bottom convective coefficients. We can determine the top side convective coefficient with very little difficulty, but the coefficient for the bottom side will have to be approximated using the top side convective coefficient and \( \text{INOCT} \). We can estimate \( T_s \) from the module and ambient temperatures, and thereby also determine \( hr_g \). We can estimate values for the absorptivity, emissivity, and thermal mass from known properties of modules.

Convective Coefficient on the Top Surface of the Module

The convective coefficient is highly dependent upon the profile of the air near the surface of the module. This profile can be either laminar, turbulent, free, or any combination of the three. Therefore, we must use convective coefficient equations for all three regions as well as for any transition or mixed regions. At the SWRES, a structured experiment was conducted to determine the top side convective coefficient. Several modules were mounted on a roof and insulated underneath. The top side convective coefficients were determined for a wide range of wind speeds and compared to predictions from published equations. E. M. Sparrow proposed equation 9 for the laminar convection in the environment, and it was found to closely approximate the actual convective coefficients:
The standard convection equation for laminar flow over a flat plate (Equation 10) is 9% higher than the equation proposed by Sparrow, and predicts coefficients that are slightly higher than the data.

\[ \text{St} \cdot \text{Pr}^{0.67} = 0.86 \cdot \text{Re}^{-0.5} \quad \text{Re} < 1.2 \cdot 10^5 \]  

(9)

For turbulent convection, the only applicable equation is the standard equation for turbulent flow over a flat plate:

\[ \text{St} \cdot \text{Pr}^{0.4} = 0.031 \cdot \text{Re}^{-0.2} \quad \text{Re} > 1.2 \cdot 10^5 \]  

(10)

This equation predicts coefficients that are slightly higher than the data obtained at the SWRES. If we decrease this equation by the same 9% that we found for laminar flow, we obtain an equation that fits the data adequately:

\[ \text{St} \cdot \text{Pr}^{0.4} = 0.028 \cdot \text{Re}^{-0.2} \quad \text{Re} > 1.2 \cdot 10^5 \]  

(11)

The length scale for the Reynolds number in equations 9, 10, 11, and 12 is the hydraulic diameter of the module. Most modules have dimensions of 0.3 x 1.2 meters, and therefore a hydraulic diameter of approximately 0.5 m.

For free convection, G. C. Vliet's equation was found to fit the data adequately:

\[ \text{Nu} = 0.21 \cdot (\text{Gr} \cdot \text{Pr})^{0.32} \]  

(13)

The Grashof number in equation 13 contains the sine of angle of inclination. A tilt angle of 30° is assumed in the model.

There are two transition regions between the free, laminar, and turbulent regions. The region between the laminar and turbulent regimes can be modeled as an abrupt change at \( \text{Re} = 1.2 \cdot 10^5 \) without incurring any severe penalty. But the region between the free and laminar regions needs to be modeled as a gradual transition. The method for modeling this transition was first determined by Churchhill (1977), and then supported by Ruckenstein (1978), Shenoy (1980), and Siebers (1983). They all determined that the mixed convective coefficient can be obtained by taking the cube root of the cubes of the free and forced convective coefficients:

\[ h_{\text{mix}}^3 = h_{\text{free}}^3 + h_{\text{forced}}^3 \]  

(14)

This method was substantiated with test data from the SWRES.

Heat Loss from the Bottom Surface of the Module

The convective coefficient on the bottom surface of the module cannot be precisely modeled without a complete description of the geometry under the array. The convective coefficient, for example, would be much less for a two inch standoff mounted array than it would be for a rack mount. The effect of the different mounting configurations can be approximated, though, by scaling the bottom side convective coefficient to the top side, and determining the scaling factor using INOCT.
INOCT is the cell temperature at very specific environmental conditions (800 W/m² insolation, 20°C ambient, 1 m/sec wind speed). The radiation loss to the sky and the convection from the top surface of the module at NOCT conditions can be estimated. The remaining heat loss is due to the convection from the back side of the module and the radiation to the ground or roof. Thus we can determine the amount of heat transfer through the bottom of the module using INOCT.

It is assumed that the ground or roof temperature is somewhere between ambient temperature and the module temperature. For a rack mount, the convective coefficient under the module is approximately equal to that on top of the module and the ground or roof temperature would be equal to ambient. We can consider the rack mount as the ideal case for maximum heat transfer. If the situation would be any less than ideal, it is assumed that the radiation and convection under the module would be penalized equally. We can calculate this penalty by using the energy balance equation at NOCT conditions:

\[
\alpha \cdot S - h_c \cdot (T_{INOCT} - T_a) - h_r \cdot (T_{INOCT} - T_s) = h_c \cdot (T_{INOCT} - T_a) + h_r \cdot (T_{INOCT} - T_g) .
\]  

(15)

We can denote R as the ratio of the actual to ideal heat loss from the back side convection and radiation:

\[
R = \frac{h_c \cdot (T_{INOCT} - T_a) + \epsilon \cdot \sigma \cdot (T_{INOCT}^4 - T_g^4)}{h_c \cdot (T_{INOCT} - T_a) + \epsilon \cdot \sigma \cdot (T_{INOCT}^4 - T_a^4)} .
\]  

(16)

Substituting the numerator in equation 16 for the left hand side of equation 15 yields an equation for R that can be readily evaluated at NOCT conditions:

\[
R = \frac{\alpha \cdot S - h_c \cdot (T_{INOCT} - T_a) + \epsilon \cdot \sigma \cdot (T_{INOCT}^4 - T_s^4)}{h_c \cdot (T_{INOCT} - T_a) + \epsilon \cdot \sigma \cdot (T_{INOCT}^4 - T_a^4)} .
\]  

(17)

After obtaining the ratio, R, we can determine the convective coefficient under the module and the ground or roof temperature:

\[
h_c = R \cdot h_c
\]  

(18)

\[
T_g = \left[ T_{INOCT}^4 - R \cdot (T_{INOCT}^4 - T_a^4) \right]^{0.25} .
\]  

(19)

These equations, again, are applicable only at NOCT conditions. For all other environmental conditions, the bottom side convective coefficient is considered to be proportional to the top side convective coefficient. Therefore, we can calculate \( h_c \) in the same manner as in equation 18. The total convective coefficient, \( h_c \), is just the sum of the top and bottom convective coefficients.

To determine the ground or roof temperature at other environmental conditions, it was assumed that the ground or roof temperature is always between the ambient and module temperatures, and can be scaled as a ratio of these temperatures (Equation 18). Thus, the ratio, \( R_g \), is assumed to be constant for all environmental conditions:

\[
T_g = T_a + R_g \cdot (T_c - T_a) .
\]  

(20)
$R_g$ is determined at NOCT conditions using equations 19 and 21:

$$R_g = \frac{T_g - Ta}{T_{INOCt} - Ta}.$$  \hspace{1cm} (21)

In our numerical solution, the ground temperature now varies with the module temperature, for which we are solving. Therefore, we will have to iterate the solution of module temperature in order to obtain an appropriate ground temperature.

The Wind Speed at the Module Height

The wind speed at the array height is usually lower than the given wind speed in the input data. TMY data tapes contain wind speeds that are applicable only where the anemometer was placed, 30 feet above the ground. The variation of wind speed with array height is best modeled with the following equation:

$$w = w_r \cdot (y/yr)^p.$$  \hspace{1cm} (22)

Equation 22 is a simple power law relationship with the value of $p$ dependent upon the type of air flow and obstructions in the area. Turbulent flow in a wind tunnel follows this power law profile with $p$ being equal to 1/7. In the open country, the wind speed follows the same equation, but $p$ is equal to 1/5. In the city, wind speed profiles are harder to obtain, but equation 22 can be used with a value of 1/3 for $p$. Since most photovoltaic installations are not in the middle of a city nor in a wind tunnel, the value of $p$ that the model uses is 1/5.

Sky Temperature

The prediction of the sky temperature depends on many factors that cannot be used as input to a simple thermal model. The sky temperature is dependent upon the ambient temperature, humidity, amount of cloud cover, type of cloud cover, and elevation. Of these dependencies, only the ambient temperature is readily available. In 1963, Swinbank proposed equation 23 as a suitable sky temperature equation for clear sky conditions:

$$T_s = 0.0552 \cdot Ta^{1.5}.$$  \hspace{1cm} (23)

He apparently averaged out the effects that humidity and elevation have on sky temperature. This equation, though, is not applicable during cloudy days. During days with complete cloud cover, the sky temperature will approach that of ambient. Thus we can expect that the average sky temperature would be somewhere between ambient and the value Swinbank's equation would predict. The average amount of cloudiness across the United States can be estimated using the clearness index. The average clearness index for 68 cities across the United States is 0.61. If we assume that a perfectly clear day has a clearness index of 0.90, then we can assume the cloudiness and haziness causes a 32% decrease in the horizontal insolation. We might also assume that the cloudiness and haziness causes the sky temperature to be 32% closer to ambient on the average day than what it would be during clear days.
Thus we can modify Swinbank's equation to account for the average cloudy day in the United States:

\[
Ts = 0.68 \cdot (0.0552 \cdot Ta^{1.5}) + 0.32 \cdot Ta .
\]  

(24)

Absorptivity and Emissivity

The absorptivity in this analysis is defined as that fraction of the array plane insolation that is converted into thermal energy in the module. In terms of the reflectivity, \( r \), and the module efficiency, \( \eta \), the absorptivity, \( \alpha \), can be calculated using the following equation:

\[
\alpha = (1 - r) \cdot (1 - \eta) .
\]

(25)

The wavelength spectrum for the reflectivity covers the whole solar spectrum (below 3.5 microns), and is not limited electrical response spectrum of a PV cell. Table 2 shows reflectivities and emissivities of four different modules. A typical module has a reflectivity of approximately 0.10, and since typical efficiencies are on the order of 0.08, the model uses 0.83 as its absorptivity.

Table 2: Overall reflectivities and emissivities of four PV modules.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Reflectivity</th>
<th>Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARCO</td>
<td>0.09</td>
<td>0.87</td>
</tr>
<tr>
<td>Solarex</td>
<td>0.15</td>
<td>0.83</td>
</tr>
<tr>
<td>Motorola</td>
<td>0.07</td>
<td>0.83</td>
</tr>
<tr>
<td>GE</td>
<td>0.09</td>
<td>0.86</td>
</tr>
<tr>
<td>Average</td>
<td>0.10</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The wavelength spectrum for the emissivity is the same as the thermal radiation spectrum of an object at 40°C (above 3.5 microns). A typical value for the emissivity of a module is 0.84.

The Thermal Mass of the Module

The thermal mass per unit area of a module, \( m \cdot c \), is required in the model to simulate the thermal lag of a typical module. An exact value for \( m \cdot c \) is not required, because variations of 50% in the value of \( m \cdot c \) will not appreciably change the results of the model. The thermal mass per unit area of four different modules are shown in Table 3.

Table 3: Thermal mass per unit area of four PV modules.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>( m \cdot c ) (J/m(^2)°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARCO</td>
<td>8,600</td>
</tr>
<tr>
<td>Solarex</td>
<td>13,000</td>
</tr>
<tr>
<td>Motorola</td>
<td>9,300</td>
</tr>
<tr>
<td>GE</td>
<td>12,900</td>
</tr>
<tr>
<td>Average</td>
<td>11,000</td>
</tr>
</tbody>
</table>
The average thermal mass is 11,000 J/m²°C. For direct and some standoff mounts, however, the thermal mass of the module is affected by the mass of the roof. Since these types of mounts typically have rather high INOCTs, we can tie the thermal mass of the module to its INOCT. The method for doing this in the model is displayed in following equations:

\[
\begin{align*}
    m \cdot c &= 11,000 \\
    m \cdot c &= 11,000 \cdot [1 + (\text{INOCT} - 48)/12] \\
    \text{INOCT} &\leq 48°C \\
    \text{INOCT} &> 48°C \\
\end{align*}
\] 

(26) 

(27)
INSTALLED NOMINAL OPERATING CELL TEMPERATURE

Estimating INOCT from NOCT and Mounting Configuration

As noted earlier, INOCT or the "Installed" Nominal Operating Cell Temperature is the cell temperature of an installed array at NOCT conditions. It differs from the JPL standard, the NOCT temperature, but INOCT can be obtained using the NOCT temperature and the mounting configuration. The determination of INOCT is critical in order to use the thermal model.

At the Southwest Residential Experiment Station (SWRES), a structured experiment was conducted to characterize the thermal behavior of a PV array under different mounting schemes. The experiment varied the standoff height of the array in an attempt to simulate three different mounting configurations. The minimum standoff height of zero inches simulated a direct mount; the 9 inch standoff height approximated a rack mount, and the remaining heights depicted various types of standoff mounts. The modules were manufactured by Motorola Corp. and had a NOCT temperature of 49°C. The results of the experiment are shown in Table 4. According to these results, INOCT for direct mounts are 17° to 20° higher than NOCT. Rack mount can expect to have INOCTs about 3° lower than NOCT. INOCTs for standoff mounts are -1°C to 11°C higher than NOCT temperatures.

Table 4: Variation of INOCT with Standoff height. The standoff height is measured from the roof to the module frame.

<table>
<thead>
<tr>
<th>Standoff Height (inches)</th>
<th>INOCT (°C)</th>
<th>INOCT - NOCT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.†</td>
<td>68.1</td>
<td>20</td>
</tr>
<tr>
<td>0.</td>
<td>65.8</td>
<td>17</td>
</tr>
<tr>
<td>1.</td>
<td>59.8</td>
<td>11</td>
</tr>
<tr>
<td>3.</td>
<td>51.2</td>
<td>2</td>
</tr>
<tr>
<td>6.</td>
<td>48.1</td>
<td>-1</td>
</tr>
<tr>
<td>9.</td>
<td>46.1</td>
<td>-3</td>
</tr>
</tbody>
</table>

†Insulation was placed under the modules to simulate a worst case situation.

Table 5: Comparison of INOCT and NOCT.

<table>
<thead>
<tr>
<th>Prototype</th>
<th>INOCT (°C)</th>
<th>NOCT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE</td>
<td>65.2</td>
<td>58.‡</td>
</tr>
<tr>
<td>Solarex</td>
<td>58.3</td>
<td>49.</td>
</tr>
<tr>
<td>Arco</td>
<td>53.0</td>
<td>56.‡</td>
</tr>
<tr>
<td>ARTU</td>
<td>51.8</td>
<td>46.</td>
</tr>
<tr>
<td>BDM</td>
<td>51.6</td>
<td>49.</td>
</tr>
<tr>
<td>Westinghouse</td>
<td>49.4</td>
<td>46.</td>
</tr>
<tr>
<td>TEA</td>
<td>45.8</td>
<td>49.</td>
</tr>
<tr>
<td>Tri-Solar</td>
<td>44.8</td>
<td>--</td>
</tr>
</tbody>
</table>

‡NOCT was obtained while the module was direct mounted.

INOCTs were obtained from the different prototypes at the SWRES and were compared to their NOCT temperatures (Table 5). TEA is the only rack mount,
and as predicted its INOCT is 3°C lower than the NOCT temperature. The GE prototype is the only real direct mount, and its INOCT is about 18°C above typical NOCT temperatures. The NOCT temperature listed for the GE module is unusually high because the module was mounted as a direct mount when the NOCT temperature was determined.

The three standoff mounts also have INOCTs that can be predicted from the results of the standoff height experiment. BDM has a standoff height of 5 inches, but obstructions under the array effectively reduce this height to 3 inches. Thus we would expect its INOCT to be about 2°C higher than its NOCT temperature, and in fact, it is about 2.6°C higher. The Solarex prototype has a standoff height of about 2 inches. We would thus expect its INOCT to be about 54°C, or 5°C above its NOCT temperature. In this case, though, we are 4°C too low, which is a result of the channeling under the array. This channeling blocks the east-west winds from cooling the underside of the modules. The ARCO prototype is also a channeled standoff mount with a standoff height of 6 inches. The entrance and exit, though, are only 4 inches wide, which effectively reduces the standoff height to 4 inches. Thus we would expect an INOCT of 47°C. If we apply the same 4°C penalty for the channeling, we obtain 51°C, which is very close to the actual INOCT of 51.8°C.

Table 7 summarizes the method for estimating INOCT from NOCT and the mounting configuration.

Table 7: Method for obtaining INOCT from NOCT and the mounting configuration.

<table>
<thead>
<tr>
<th>Mounting Configuration</th>
<th>INOCT Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rack Mount</td>
<td>INOCT = NOCT - 3°C</td>
</tr>
<tr>
<td>Direct Mount</td>
<td>INOCT = NOCT + 18°C</td>
</tr>
<tr>
<td>Standoff/Integral</td>
<td>INOCT = NOCT + X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W (inches)</th>
<th>X(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>-1</td>
</tr>
</tbody>
</table>

where W is standoff, entrance, or exit height/width, whichever is minimum. Add 4°C if channeled.

Determining INOCT from Test Data

The most accurate method for determining INOCT is to use the program "INOCT.for" (Appendix B) and actual cell temperature data from the array in question. "INOCT.for" uses the array data and the thermal model to determine the best INOCT value. The program assumes an INOCT of 48°C, and then runs the thermal model on all the data. The error between the actual and predicted values is weighted with insolation, because the error during high insolation periods has greater impact on the accuracy of PV energy predictions than error during low insolation periods. The bias in the weighted error is added to the INOCT value, and the thermal model is run on all the data again. This
process is repeated until the bias is less than 0.1°C. Since the program uses the thermal model to determine INOCT, the thermal model is most accurate when it uses an INOCT value from this program.

The input to "INOCT.for" is almost identical to that used for the thermal model. "INOCT.for" does not require an INOCT value as input, but it does require actual cell temperatures along with the environmental conditions (insolation, ambient temperature, wind speed, and time). The program was designed to be run on a microcomputer, but it can also be run on larger machines. The amount of time the program takes to run depends on the amount of environmental and cell temperature data it is required to analyze (there is no limit to the number of records that it can analyze). The best results are obtained when the number of data records exceed 500. The user should be sure to check for anomalies in the data. Data obtained during rainy or snowy days should be omitted.

SUMMARY

The cell temperature of a photovoltaic array can be accurately modeled with the simple program described in this paper. The program, "Therm.for", is accurate to within 5°C and requires a minimum amount of input. The major input parameter is the "Installed" Nominal Operating Cell Temperature or INOCT. The program uses INOCT to characterize the thermal properties of the module and its mounting configuration. The value of INOCT can be estimated from the NOCT temperature and the mounting configuration (refer to Table 7), or from cell temperature data and the "INOCT.for" program.
MOMENCLATURE

$\alpha$  - Absorptivity of the module below 3.5 microns
$\sigma$  - Boltzman's constant $= 5.669 \cdot 10^{-8}$ W/m$^2$·°K$^4$
$\epsilon$  - Emissivity of the module above 3.5 microns
$\eta$  - Module efficiency
$\rho$  - Density of air
$\nu$  - Kinematic viscosity of air
$c$  - Overall specific heat of the module (J/kg·°K)
$D_h$  - Hydraulic diameter of the module (m)
$g$  - Gravitational constant $= 9.8$ m/sec$^2$
$Gr$  - Grashof number $= g \cdot (T - T_a) \cdot D_h^3 / \nu^2 / T$
$h$  - Convective coefficient (W/m$^2$·°K)
$hc$  - Overall convective coefficient of the module (W/m$^2$·°K)
$hc_B$  - Convective coefficient on the bottom of the module (W/m$^2$·°K)
$hc_T$  - Convective coefficient on the top of the module (W/m$^2$·°K)
$hr_s$  - Radiative coefficient to the sky (W/m$^2$·°K)
$hr_g$  - Radiative coefficient to the roof or ground (W/m$^2$·°K)
$INOCT$  - Installed Nominal Operating Cell Temperature (°K)
$k$  - Conductivity of air
$m$  - Mass of the module per unit surface area (kg/m$^2$)
$L$  - Inverse of the thermal capacitance of the module
$NOCT$  - Nominal Operating Cell Temperature (°K)
$Nu$  - Nusselt number $= h \cdot D_h / k$
$p$  - Power law coefficient of the wind
$Pr$  - Prandtl number $= 0.71$ for air
$r$  - Reflectivity of the module
$R$  - Ratio of bottom side heat transfer to top side
$R_s$  - Ratio of ground temperature over ambient to module temperature over ambient
$Re$  - Reynolds number $= w \cdot D_h / \nu$
$S$  - Insolation (W/m$^2$)
$S_o$  - Insolation from the last time step (W/m$^2$)
$\Delta S$  - Change in insolation over the time step (W/m$^2$)
$SOH$  - Standoff height (inches)
$St$  - Stanton number $= h / (\rho \cdot c \cdot w)$
$t$  - Time (sec)
$\Delta t$  - Time step (sec)
$Ta$  - Ambient temperature (°K)
$Tc$  - Cell temperature (°K)
$Tc_o$  - Cell temperature from the last time step (°K)
$TINOCT$  - Installed Nominal Operating Cell Temperature (°K)
$T_g$  - Roof or ground temperature (°K)
$Ts$  - Sky temperature (°K)
$w$  - Wind speed at module height (m/sec)
$wr$  - Wind speed at anemometer height (m/sec)
$y$  - Height of module (m)
$yr$  - Height of anemometer (m)
REFERENCES


24 Swinbank, W. C., Long-Wave Radiation from Clear Skies Q. J. Royal Meteorological Society, vol 89, 1963


31 Wen, L., An Investigation of the Effect of Wind Cooling on Photovoltaic Arrays DOE/JPL-1012-69, March 1982


APPENDIX A

The program below is the thermal model. It is written in Fortran 77 and can be easily run on a microcomputer. If it is run on a microcomputer, it is strongly recommended that a math coprocessor be installed in the computer.

THIS IS A VERY SIMPLE THERMAL MODEL FOR FLAT PLATE PV MODULES. THIS MODEL IS BASED ON THE "INSTALLED" NOCT TEMPERATURE. IT SCALES THE OVERALL CONVECTIVE COEFFICIENT FROM THE NOCT CONDITION TO THE DESIRED ENVIRONMENT AND THEN ESTIMATES THE OTHER THERMAL PARAMETERS TO OBTAIN THE CELL TEMPERATURE.

NEEDED INPUT:
FROM SCREEN
INOCT TEMPERATURE (C)

FROM A DATA FILE
FIRST RECORD - MODULE HEIGHT, ANEMOMETER HEIGHT (M)
SUBSEQUENT RECORDS - DATE (YYDDD), TIME (H), POA INSOLATION (W/M2), AMBIENT TEMP. (C), AND WIND SPEED (M/SEC).

OUTPUT TO A FILE:
DATE (YYDDD), TIME (H), POA INSOLATION (W/M2), AMBIENT TEMP. (C), WIND SPEED (M/SEC), AND CELL TEMPERATURE (C).

PROGRAM THERM
CHARACTER infile*15,outfile*15
DATA BOLTZ/5.669E-8/,EMISS/0.84/,ABSORP/0.83/,xlen/0.5/
DATA CAP0/11000./

OPENING THE INPUT AND OUTPUT FILES
PRINT *," INPUT THE NAME OF THE INPUT DATA FILE : ",READ(*,'(A)')INFILE
OPEN(1,FILE=INFILE,STATUS='OLD')
PRINT *," INPUT THE NAME OF THE OUTPUT FILE : ",READ(*,'(A)')OUTFILE
OPEN(2,FILE=OUTFILE,STATUS='NEW')

READING THE inoct
PRINT *," INPUT NOCT : ",READ *,TINOCT
TINOCT=TINOCT+273.15

CONVECTIVE COEFFICIENT AT NOCT
WINDMOD=1.
TAVE=(TINOCT+293.15)/2.
DENSAIR=0.003484*101325./TAVE
VISAIR=0.24237E-6*TAVE**0.76/DENSAIR
CONDAIR=2.1695E-4*TAVE**0.84
DETERMINING THE GROUND TEMPERATURE RATIO AND THE RATIO OF THE TOTAL CONVECTION TO THE TOP SIDE CONVECTION.

\[
\text{BACKRAT} = \frac{\text{ABSORP} \times 800. - \text{EMISS} \times \text{BOLTZ} \times (\text{TINOCT}^4 - 282.21^4) + \text{HCOND}}{\left(\text{HGROUND} + \text{HCOND}\right) \times (\text{TINOCT} - 293.15)}
\]

\[
\text{TGROUND} = \left(\text{TINOCT}^4 - \text{BACKRAT} \times (\text{TINOCT}^4 - 293.15^4)\right)^{0.25}
\]

\[
\text{IF}(\text{TGROUND} > \text{TINOCT}) \text{TGROUND} = \text{TINOCT}
\]

\[
\text{IF}(\text{TGROUND} < 293.15) \text{TGROUND} = 293.15
\]

\[
\text{CONVRAT} = \frac{\text{ABSORP} \times 800. - \text{EMISS} \times \text{BOLTZ} \times (2 \times \text{TINOCT}^4 - 282.21^4 + \text{TGROUND}^4)}{\text{HCOND} \times (\text{TINOCT} - 293.15)}
\]

ADJUSTING THE CAPACITANCE OF THE MODULE BASED ON THE INOCT

\[
\text{CAP} = \text{CAP0} \times \left(1 + \frac{\text{TINOCT} - 293.15}{12}\right)
\]

INITIAL VALUES

\[
\text{SUN0} = 0.
\]

\[
\text{TIME0} = 0.
\]

\[
\text{DATE0} = 0.
\]

\[
\text{TMODO} = 293.15
\]

\[
\text{N} = 0
\]

READING THE DATA

\[
\text{REWIND 1}
\]

\[
\text{READ}(1,\*) \text{HITEMOD, HITEANE}
\]

\[
3 \text{ READ}(1,*, \text{END}=20) \text{DATE, TIME, SUN, TAM} \text{, WINDANE}
\]

\[
\text{N} = \text{N} + 1
\]

\[
\text{DTIME} = \text{TIME} - \text{TIME0} + 24 \times (\text{DATE} - \text{DATE0})
\]

\[
\text{TAMB} = \text{TAMB} + 273.15
\]

\[
\text{SUN} = \text{SUN} \times \text{ABSORP}
\]

SKY TEMPERATURE

\[
\text{TSKY} = 0.68 \times (0.0552 \times \text{TAMB}^{1.5}) + 0.32 \times \text{TAMB}
\]

WIND SPEED AT MODULE HEIGHT

\[
\text{IF}(\text{WINDANE} \lt 0.) \text{WINDANE} = 0.
\]

\[
\text{WINDMOD} = \text{WINDANE} \times (\text{HITEMOD} / \text{HITEANE})^{0.2} + 0.0001
\]

OVERALL CONVECTIVE COEFFICIENT

\[
\text{TMOD} = \text{TMOD}
\]

DO 10 J = 1, 10
TAVE=(TMOD+TAMB)/2.
DENS AIR=0.003484*101325./TAVE
VIS AIR=0.24237E-6*TA VE**0.76/DENS AIR
COND AIR=2.165E-4*TA VE**0.84
REYNOLD=WIND MOD*X LEN/VISA IR
HFORCE=0.8600/REYNOL D**.5*DENS AIR*WIND MOD*1007./0.71**.67
if(REYNOLD.GT.1.2E5)HFORCE=0.0282/REYNOL D**.2*
+ DENS AIR*WIND MOD*1007./0.71**0.4
GRASHOF=9.8/TAVE*ABS(TM O D-TAMB)*XLEN**3/VISA IR**2*0.5
HFREE=0.21*(GRASHOF*0.71)**0.32*COND AIR/XLEN
HCONV=CONVRAT*(HFREE**3+HFORCE**3)**(1/3.)

C SOLVING THE HEAT TRANSFER EQUATION
C
HSKY=EMIS S*BOLTZ*(TMOD**2.+TSKY**2.)*(TMOD+TSKY)
TGROUND=TAMB+TGRAT*(TMOD-TAMB)
HGROUN D=EMISS*BOLTZ*(TMOD**2.+TGROUND**2.)*(TMOD+TGROUND)
EIGEN=(HCONV+HSKY+HGROUND)/CAP*DTIME*3600.
EX=0.
IF(EIGEN.GT.-10.)EX=EXP(EIGEN)
TMOD=TMOD+EX+((1.-EX)*(HCONV*TAMB+HSKY*TSKY+HGROUND*TGROUND
+ +SUNO+(SUN-SUNO)/EIGEN)+SUN-SUNO)/(HCONV+HSKY+HGROUND)
10 CONTINUE
C
C MAKING THE NEW VALUES THE OLD VALUES FOR THE NEXT TIME STEP
C
TMODO=TMOD
SUNO=SUN
TIMEO-TIME
DATEO-DATE
C
C OUTPUT
C
WRITE(2,400)DATE,TIME,SUN,TAMB-273.15,WINDANE,TMOD-273.15
400 FORMAT(F6.0,F6.2,F7.1,F7.2,F6.2,F7.2)
GOTO 3
20 RETURN
END
APPENDIX B

This program can be used to determine the Installed Nominal Operating Cell Temperature from field data. It is written in Fortran 77 and can be easily run on a microcomputer. If it is run on a microcomputer, it is strongly recommended that a math coprocessor be installed in the computer.

C THIS PROGRAM COMPUTES THE "INSTALLED" NOCT TEMPERATURE FROM FIELD DATA.
C IT MATCHES THE ACTUAL THERMAL BEHAVIOR OF AN ARRAY WITH THE RESULTS FROM
C A SIMPLIFIED THERMAL MODEL REQUIRING THE INOCT AS INPUT. IT ITERATES
C INOCT TO PROVIDE THE BEST MATCH BETWEEN THE MODEL'S RESULTS AND THE
C ACTUAL THERMAL BEHAVIOR. THE BEST ESTIMATE FOR INOCT IS WEIGHTED WITH
C INSOLATION, SO THAT THE LEAST ERROR OCCURS AT HIGH INSOLATION LEVELS.
C
C NEEDED INPUT FROM A DATA FILE
C FIRST RECORD - AVERAGE MODULE HEIGHT, ANEMOMETER HEIGHT (M)
C SUBSEQUENT RECORDS - DATE (YYDDD), TIME (H), POA INSOLATION (W/M2),
C AMBIENT TEMP. (C), AND WIND SPEED (M/SEC).
C
C OUTPUT TO THE SCREEN:
C THE INSTALLED NOMINAL OPERATING CELL TEMPERATURE (C)
C
C PROGRAM INOCT1
CHARACTER YES*1, DATAFILE*15
DATA BOLTZ/5.669E-8/, EMISS/0.84/, ABSORP/0.83/, XLEN/0.5/
DATA CAP0/11000. /

C FIRST ESTIMATE OF INOCT
1 TINOCT=48.4273.15
C
C OPENING THE DATA FILE
C
PRINT *, ' INPUT THE NAME OF THE DATA FILE : '
READ(*, '(A)') DATAFILE
OPEN(1, FILE=DATAFILE)

C CONVECTIVE COEFFICIENT AT NOCT
C
2 WINDMOD=1.
TAVE=(TINOCT+293.15)/2.
DENS AIR=0.003484*101325./TAVE
VISAIR=0.24237E-6*TAVE**0.76/DENS AIR
CONDAIR=2.1695E-4*TAVE**0.84
REYNOLD=WINDMOD*XLEN/VISAIR
HFORCE=0.8600/REYNOLD**0.5*DENS AIR*WINDMOD*1007./0.71**0.67
GRASHOF=9.8/TAVE*(TINOCT-293.15)*XLEN**3/VISAIR**2*0.5
HFREE=0.21*(GRASHOF*0.71)**0.32*CONDAIR/XLEN
HCONV=(HFREE**3+HFORCE**3)**(1/3.)

C DETERMINING THE GROUND TEMPERATURE RATIO AND THE RATIO OF THE TOTAL
CONVECTION TO THE TOP SIDE CONVECTION.

\[
\begin{align*}
\text{HGROUN} &= \text{EMISS} \times \text{BOLTZ} \times (\text{TINOCT}^2 + 293.15^2) \times (\text{TINOCT} + 293.15) \\
\text{BACKRAT} &= (\text{ABSORP} \times 800 - \text{EMISS} \times \text{BOLTZ} \times (\text{TINOCT}^4 - 282.21^4) - \text{HCONV} \\
& \quad \times (\text{TINOCT} - 293.15)) / ((\text{HGROUN} + \text{HCONV}) \times (\text{TINOCT} - 293.15)) \\
\text{TGROUND} &= (\text{TINOCT}^4 - \text{BACKRAT} \times (\text{TINOCT}^4 - 293.15^4))^{0.25} \\
& \quad + (\text{TINOCT} - 293.15) / ((\text{HGROUN} + \text{HCONV}) \times (\text{TINOCT} - 293.15)) \\
\text{IF} & (\text{TGROUND} \geq \text{TINOCT}) \text{TGROUND} = \text{TINOCT} \\
\text{IF} & (\text{TGROUND} \lt 293.15) \text{TGROUND} = 293.15 \\
\text{TGRAT} &= (\text{TGROUND} - 293.15) / (\text{TINOCT} - 293.15) \\
\text{CONVRAT} &= (\text{ABSORP} \times 800 - \text{EMISS} \times \text{BOLTZ} \times (2 \times \text{TINOCT}^4 - 282.21^4 \\
& \quad - \text{TGROUND}^4)) / (\text{HCONV} \times (\text{TINOCT} - 293.15)) \\
\end{align*}
\]

ADJUSTING THE CAPACITANCE OF THE MODULE BASED ON THE TINOCT

\[
\begin{align*}
\text{CAP} &= \text{CAP} \times (1. + (\text{TINOCT} - 321.15) / 12.) \\
\end{align*}
\]

INITIAL VALUES

\[
\begin{align*}
\text{BIAS} &= 0. \quad \text{STDEV} = 0. \\
\text{SUNTOT} &= 0. \\
\text{SUNO} &= 0. \\
\text{TIMEO} &= 0. \\
\text{DATEO} &= 0. \\
\text{TMODO} &= 293.15 \\
\text{N} &= 0 \\
\end{align*}
\]

READING THE DATA

\[
\begin{align*}
\text{REWIND 1} \\
\text{READ(1,*),HITEMOD,HITEANE} \\
3 \text{ READ(1,*),END=20) DATE,TIME,SUN,TAMB,WINDANE,TACTUAL} \\
\text{N=N+1} \\
\text{DTIME = TIME - TIMEO + 24.* (DATE - DATEO)} \\
\text{TAMB = TAMB + 273.15} \\
\text{TACTUAL = TACTUAL + 273.15} \\
\text{SUN = SUN \times ABSORP} \\
\end{align*}
\]

SKY TEMPERATURE

\[
\begin{align*}
\text{TSKY} &= 0.68 \times (0.0552 \times \text{TAMB}^{1.5}) + 0.32 \times \text{TAMB} \\
\end{align*}
\]

WIND SPEED AT MODULE HEIGHT

\[
\begin{align*}
\text{IF(WINDANE.LT.0.) WINDANE = 0.} \\
\text{WINDMOD = WINDANE \times (HITEMOD/HITEANE)^{0.2+0.0001}} \\
\end{align*}
\]

OVERALL CONVECTIVE COEFFICIENT

\[
\begin{align*}
\text{TMOD} &= \text{TMODO} \\
\text{DO 10 J=1,10} \\
\text{TAVE} &= (\text{TMOD} + \text{TAMB}) / 2. \\
\text{DENS} &= 0.003484 \times 101325. / \text{TAVE} \\
\text{VISAIR} &= 0.24237 \times 6 \times \text{TAVE}^{0.76} / \text{DENS} \\
\end{align*}
\]

21
CONDAIR=2.1695E-4*TAVE**0.84
REYNOLD=WINDMOD*XLEN/VISAIR
HFORCE=0.8600/REYNOLD**.5*DENSAIR*WINDMOD*1007./0.71**.67
if(REYNOLD.GT.1.2E5)HFORCE=0.0282/REYNOLD**.2*
+DENSAIR*WINDMOD*1007./0.71**.4
GRASHOF=9.8*TAVE*ABS(TMOD-TAMB)*XLEN**3/VISAIR**2*0.5
HFREE=0.21*(GRASHOF*0.71)**0.32*CONDAIR/XLEN
HCONV=CONVRAT*(HFREE**3+HFORCE**3)**(1/3.)

SOLVING THE HEAT TRANSFER EQUATION

HSKY=EMISS*BOLTZ*(TMOD**2.+TSKY**2.)*(TMOD+TSKY)
TGROUND=EMISS*BOLTZ*(TMOD**2.+TGROUND**2.)*(TMOD+TGROUND)
EIGEN=-(HCONV+HSKY+HGROUND)/CAP*DTIME*3600.
EX=0.
IF(EIGEN.GT.-10.)EX=EXP(EIGEN)
TMOD=TMODO+EX+((1.-EX)*(HCONV+HKS0Y+HGROUND+TGROUND
+GROUNO+(GROUNO+GROUNO)/EIGEN)+GROUNO+(GROUNO+GROUNO)/EIGEN)+GROUNO+(GROUNO+GROUNO)/EIGEN)

10 CONTINUE

MAKING THE NEW VALUES THE OLD VALUES FOR THE NEXT TIME STEP

TMODO=TMOD
SUNO=SUN
TIMEO=TIME
DATEO=DATE

CALCULATING THE BIAS AND STANDARD DEVIATION

BIAS=BIAS+(TMOD-TACTUAL)*SUN
STDEV=STDEV+(TMOD-TACTUAL)**2*SUN
SUNTOT=SUNTOT+SUN
GOTO 3

20 CONTINUE
BIAS=BIAS/SUNTOT
STDEV=(STDEV/SUNTOT)**0.5
TINOCT=TINOCT-BIAS
IF(ABS(BIAS).GT.0.02)GOTO 2

OUTPUT

WRITE(*,'(/,lx,A)')DATAFILE
WRITE(*,400)TINOCT-273.15,STDEV,CONVRAT,TGRAT

400 FORMAT(
+  ' INSTALLED NOMINAL OPERATING CELL TEMPERATURE = ',F4.1,'°C',
+  ' WEIGHTED UNCERTAINTY OF THE MODEL = ',F4.1,'°C',
+  ' RATIO OF TOTAL CONVECTION TO TOP = ',F5.2,
+  ' RATIO OF GROUND TO CELL TEMP ABOVE AMBIENT = ',F5.2,'//
  CLOSE(1,STATUS='KEEP')

C ANOTHER RUN?

PRINT *, 'ANOTHER RUN WITH A DIFFERENT INPUT FILE? : '
READ(*,'(A)')YES
IF(YES.EQ.'Y' .OR.YES.EQ.'y')GOTO 1

RETURN
END
APPENDIX C

This a collection of 41 plots of actual and predicted cell temperatures from several prototypes at the Southwest Residential Experiment Station (SWRES). All the predictions were made with the thermal model using the INOCT values presented in this paper.

Figure C-1: Actual and predicted cell temperatures from the BDM prototype at the SWRES on June 5, 1982.
Figure C-2: Actual and predicted cell temperatures from the BDM prototype at the SWRES on September 14, 1982.

Figure C-3: Actual and predicted cell temperatures from the BDM prototype at the SWRES on December 17, 1982.
Figure C-4: Actual and predicted cell temperatures from the TEA prototype at the SWRES on June 26, 1982.

Figure C-5: Actual and predicted cell temperatures from the TEA prototype at the SWRES on September 16, 1982.
Figure C-6: Actual and predicted cell temperatures from the TEA prototype at the SWRES on December 18, 1982.

Figure C-7: Actual and predicted cell temperatures from the TEA prototype at the SWRES on March 13, 1983.
Figure C-8: Actual and predicted cell temperatures from the Tri-Solar prototype at the SWRES on June 26, 1982.

Figure C-9: Actual and predicted cell temperatures from the Tri-Solar prototype at the SWRES on September 16, 1982.
Figure C-10: Actual and predicted cell temperatures from the Tri-Solar prototype at the SWRES on December 18, 1982.

Figure C-11: Actual and predicted cell temperatures from the Tri-Solar prototype at the SWRES on March 9, 1983.
Figure C-12: Actual and predicted cell temperatures from the ARTU prototype at the SWRES on June 26, 1982.

Figure C-13: Actual and predicted cell temperatures from the ARTU prototype at the SWRES on September 19, 1982.
Figure C-14: Actual and predicted cell temperatures from the ARTU prototype at the SWRES on December 17, 1982.

Figure C-15: Actual and predicted cell temperatures from the ARTU prototype at the SWRES on March 11, 1983.
Figure C-16: Actual and predicted cell temperatures from the ARCO prototype at the SWRES on June 5, 1982.

Figure C-17: Actual and predicted cell temperatures from the ARCO prototype at the SWRES on September 16, 1982.
Figure C-18: Actual and predicted cell temperatures from the ARCO prototype at the SWRES on December 18, 1982.

Figure C-19: Actual and predicted cell temperatures from the ARCO prototype at the SWRES on March 11, 1983.
Figure C-20: Actual and predicted cell temperatures from the Westinghouse prototype at the SWRES on June 26, 1982.

Figure C-21: Actual and predicted cell temperatures from the Westinghouse prototype at the SWRES on September 19, 1982.
Figure C-22: Actual and predicted cell temperatures from the Westinghouse prototype at the SWRES on December 17, 1982.

Figure C-23: Actual and predicted cell temperatures from the Westinghouse prototype at the SWRES on March 9, 1983.
Figure C-24: Actual and predicted cell temperatures from the Solarex prototype at the SWRES on June 5, 1982.

Figure C-25: Actual and predicted cell temperatures from the Solarex prototype at the SWRES on September 16, 1982.
Figure C-26: Actual and predicted cell temperatures from the Solarex prototype at the SWRES on December 18, 1982.

Figure C-27: Actual and predicted cell temperatures from the Solarex prototype at the SWRES on March 11, 1983.
Figure C-28: Actual and predicted cell temperatures from the GE prototype at the SWRES on June 26, 1982.

Figure C-29: Actual and predicted cell temperatures from the GE prototype at the SWRES on September 16, 1982.
Figure C-30: Actual and predicted cell temperatures from the GE prototype at the SWRES on December 18, 1982.

Figure C-31: Actual and predicted cell temperatures from the GE prototype at the SWRES on March 9, 1983.
Figure C-32: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on August 1, 1984. SOH = 9 inches.

Figure C-33: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on August 2, 1984. SOH = 9 inches.
Figure C-34: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on June 22, 1984. SOH = 6 inches.

Figure C-35: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on June 27, 1984. SOH = 6 inches.
Figure C-36: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on July 21, 1984. SOH = 3 inches.

Figure C-37: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on June 22, 1984. SOH = 3 inches.
Figure C-38: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on July 12, 1984. SOH = 1 inch.

Figure C-39: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on June 13, 1984. SOH = 1 inch.
Figure C-40: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on July 1, 1984. SOH = 0 inches.

Figure C-41: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on June 2, 1984. SOH = 0 inches.
Beckwith Electric Company
Attn: R. W. Beckwith
11811 62nd St. N.
Largo, FL 33543

Big Island Solar
790 Leilani Street
Hilo, HI 96720

Black & Veatch (2)
Attn: Sheldon Levy
Larry Stoddard
11401 Lamar Avenue
Overland Park, KS 66211

Blueprint Associates Ltd.
Attn: Art Dickerson
245 Hacienda Avenue
San Luis Obispo, CA 93401

Boeing Computer Services
Attn: Henry Mayorga
565 Andover Park West
Tukwila, WA 98188

Charles Brent
Box 5172
Hattiesburg, MS 39406

Cal State Polytechnic University
Attn: William B. Stine
School of Engineering
3801 West Temple Avenue
Pomona, CA 92768-4062

Cal Poly State University
Attn: Prof. Art Dickerson
El/EE Dept.
San Luis Obispo, CA 93407

California Institute
of Technology
Attn: Marc A. Nicolet
Electrical Engineering Dept.
116-81
Pasadena, CA 91125

California Micro Utility
Attn: Rick Rodgers
Fort Cronkhite
Bldg. 1065
Sausalito, CA 94965

Cal Tran
Attn: Roy Mode
1120 N Street
Sacramento, CA 95814

Carbone Investment
Management Corp.
Attn: Robert C. Carbone
636 Trigo Lane
Paso Robles, CA 93446

Carolina Power & Light Co.
Attn: Kent Hoffman
P. O. Box 1551
Raleigh, NC 27602

CBNS
Attn: Leonard S. Rodberg
Queens College, CUNY
Flushing, NY 11367

Centre of Energy Studies
Attn: J. C. Joshi
Indian Institute of Technology
Hauz Khas, New Delhi - 110016
INDIA

Chevron Research (4)
Attn: John Cape
L. Fraas
Larry Partain
E. E. Spitler
P. O. Box 1627
Richmond, CA 94802

City of Austin Electric Utility (2)
Attn: John Hoffner
David C. Panico
P. O. Box 1088
Austin, TX 78767

City of Palo Alto
Attn: Scott Akin
Utilities Department
P. O. Box 10250
Palo Alto, CA 94303

Cochise Engineering Consultants
Attn: Bruce Johnson
822 Calle Jinete
Sierra Vista, AZ 85635
Georgia Power Company  
Attn: Jim Benton  
107 Technology Parkway  
Norcross, GA 30092  

Gould Research Center  
Attn: Roland Christen  
40 Gould Center  
Rolling Meadows, IL 60008  

Walt Hart  
5741 S. Jasmine  
Englewood, CO 80111  

Dale E. Haskins  
P. O. Box 6  
Tijeras, NM 87059  

Graham Hatfield  
8402 Magnolia, Suite H  
Santee, CA 92071  

Hawaii Natural Energy Institute  
Attn: Art Seki  
University of Hawaii at Manoa  
2540 Dole St.  
Honolulu, HI 96822  

Helionetics  
Attn: Larry Suelzle  
DECC Div.  
17312 Eastman St.  
Irvine, CA 92714  

Hirst Company  
Attn: Carrol Cagle  
P. O. Drawer 1926  
Albuquerque, NM 87103  

Mr. G. Hoffman  
Tuev Rheinland  
Box 101750  
500 Cologne  
WEST GERMANY  

Hughes Aircraft Corporation  
Attn: John Ingersoll  
Bldg. E11 - M/S V123  
P. O. Box 902  
El Segundo, CA 90245  

Hughes Research Labs (3)  
Attn: R. Knechtli  
S. Kamath  
R. Loo  
3011 Malibu Canyon Road  
Malibu, CA 90265  

IEEE Standards Dept.  
Attn: Robert J. Klein  
345 E. 47th St.  
New York, NY 10017  

Illuminated Data, Inc. (3)  
Attn: Jerry Winker  
Virgil Erbert  
John Doherty  
P. O. Box 751  
Albuquerque, NM 87103  

Independent Power Company  
P. O. Box 649  
N. San Juan, CA 95960  

Integral Energy Systems  
425 Spring Street  
Nevada City, CA 95959  

Integrated Power Corp.  
Attn: Doug Danley  
Systems Engineering Manager  
7524 Standish Pl.  
Rockville, MD 20855  

Inter-Island Solar Supply  
345 N. Nimitz Highway  
Honolulu, HI 96817  

Intersol Power Corporation (4)  
Attn: Derek C. Cass  
Nicholas J. Ganiaris  
John Sanders  
Juris Berzins  
11901 W. Cedar Avenue  
Lakewood, CO 80228
McDonnell Douglas (2)
Attn: David A. Carey
Ken Stone
5301 Bolsa Avenue
Huntington Beach, CA 92647

McFall-Konkel & Kimball
Attn: Robert E. Sidwell
2160 South Clermont St.
Denver, CO 80222

McGraw Hill
607 Boylston Street
Boston, MA 02116

Meridian Corporation (6)
Attn: George C. Royal
Bradley MacAleer
Lawrence T. Slominski
Deborah Eskenazi
Robert V. Russo
Anil Cabraal
5113 Leesburg Pike
Suite 700
Falls Church, VA 22041

Meyer Company
Attn: Joe Meyer
104 Lewan Circle
Longview, TX 75604

Midwest Research Institute
Attn: Matthew Imamura
425 Volker Vlvd.
Kansas City, MO 64110

MIT Lincoln Laboratory
Attn: George Turner
Box 73
Lexington, MA 02173

Mobil Solar Corporation (2)
Attn: Anthony Norbedo
Bob Hammond
16 Hickory Drive
Waltham, MA 02254

Mohawk Valley Community College
Attn: Timothy J. Schwob
Division of Technology & Business
1101 Sherman Drive
Utica, NY 13501

Monroe and Associates
Attn: David A. Carey
5301 Bolsa Avenue
Huntington Beach, CA 92647

Motorola
Attn: Keith Kingston
GED
8201 E. McDowell
Scottsdale, AZ 85252

NASA, HQ
Attn: John Loria
Code RET-1
Washington, DC 20546

NASA/Lewis Research Center (2)
Attn: Manju Goradia
Henry Curtis
c/o Dr. David Brinker
M/S 302-1
21000 Brookpark Rd.
Cleveland, OH 44135

NASA/Space Tech. Center
Attn: Wayne Hudson
KAFB
Albuquerque, NM

National Technical Systems (2)
Attn: Tomasz Jannson
David Pelka
12511 Beatrice St.
Los Angeles, CA 90066

New Mexico Solar Energy Institute (2)
Attn: Chuck Whitaker
Paul Hutchinson
P. O. Box 3SOL
Las Cruces, NM 88003

New Shelter Home Magazine
9317 Shoshone
Albuquerque, NM 87111

New York Power Authority
Attn: Mark Kapner
10 Columbus Circle
New York, NY 10019

Northern Arizona University
Attn: Jerry Hatfield
NAU Box 15600
Flagstaff, AZ 86011
Old Dominion University  
Attn: Dr. A. Sidney Roberts, Jr.  
Norfolk, VA  23508

ONSITE Energy  
Attn: R. Alan Cowan  
P. O. Box 9217  
838 S. W. 1st, Suite 520  
Portland, OR  97204

Ontario Research Foundation  
Attn: John Savage  
Sheridon Park  
Mississauga, Ontario  
CANADA Postal Code L5K1B3

Pacific Gas and Electric  
Attn: Chuck Whitaker  
3400 Crow Canyon Rd.  
San Ramon, CA  94583

Pacific Gas and Electric  
Attn: J. W. Maitland Horner  
77 Beale Street  
San Francisco, CA  94106

Pacific Gas and Electric (3)  
Attn: Stephen L. Hester  
Kay Piror  
Tom Hoff  
3400 Crow Canyon Road  
San Ramon, CA  94583

Pacific Inverter  
Attn: James A. Ross  
8480 Cliffridge Lane  
La Jolla, CA  92037

Gary Parker, GPL  
P. O. Box 306  
La Canada, CA  9011

Philadelphia Electric Co.  
Attn: Donald Fagnan  
Research and Testing Division  
2301 Market Street  
Philadelphia, PA  19101

Photovoltaic Energy Systems, Inc.  
Attn: Paul D. Maycock  
2401 Childs Lane  
Alexandria, VA  22308

Photovoltaics Int’l Magazine  
Attn: Mark Fitzgerald  
2250 N. 16th Street  
Suite 103  
Phoenix, AZ  85006

U. S. Photovoltaic Corp.  
Attn: John Evans  
3022 Feiler Place  
San Diego, CA  92123

Photowatt (2)  
Attn: William Taylor  
Mike Keeling  
2414 W. 14th Street  
Tempe, AZ  85281

The Potomac Edison Company  
Attn: Paul H. Stiller  
Downsville Pike  
Hagerstown, MD  21740

Public Service Company of NM (3)  
Attn: Howard A. Maddox  
Don Martinez  
R. Frank Burcham  
Alvarado Square, MS 0202  
Albuquerque, NM  87158

Public Service Electric & Gas (3)  
Attn: Paul P. Perkins  
Harry T. Roman  
John L. Del Monaco  
80 Park Plaza, T16A  
P. O. Box 570  
Newark, NJ  07101

Purdue University (3)  
Attn: Richard Schwartz  
Mark Lundstrom  
Jeff Gray  
School of Electrical Engineering  
West Lafayette, IN  47907

Rainmaker Cooling, Inc.  
Attn: Leonard R. Bachman  
1518 Castlerock  
Houston, TX  77090
Regional Economic Research
Attn: Steve Ettinger
3911 California St.
San Diego, CA 92110

Research Triangle Institute
Attn: Mike LaMorte
Box 12194
Research Triangle Park, NC 27709

Rockwell International Corporation
Rocketdyne Division
Attn: T. C. Evatt
6633 Canoga Avenue
Canoga Park, CA 91304

Rodgers & Company
2615 Isleta Blvd., SW
Albuquerque, NM 87105

Sab Nife Inc.
Attn: Arne O. Nilsson
George Washington Highway
P. O. Box 100
Lincoln, RI 02865

SAIC
Attn: Richard Sterrett
MS #5
P. O. Box 2351
La Jolla, CA 92038

Salt River Project
Attn: Gary L. Powell
P. O. Box 1980
Phoenix, AZ 85001

San Diego Gas & Electric (2)
Attn: Don E. Fralick
Eric Pulliam
110 W. "A" Street
P. O. Box 1831
San Diego, CA 92112

San Luis Valley Solar Energy Assn.
Attn: Tom Enos
512 Ross Ave.
Alamosa, CA 81101

SERA Solar Corp. (3)
Attn: Larry Anderson
Lee Christel
James Gibbons
3151 Jay Street
Santa Clara, CA 95054

Scientific Analysis, Inc.
Attn: John Allen Gunn
4249 Lomac Street
P. O. Box 3112
Montgomery, AL 36109

Michael Sheffer, PE
10004 Guadalupe Trail
Corrales, NM

Six Rivers Solar, Inc.
818 Broadway
Eureka, CA 95501

SMUD (2)
Attn: D. H. Thorpe
Dave Collier
6201 S Street
Sacramento, CA 95825

SOHIO (3)
Attn: Ron Cull
Steve Fairbanks
Art Nagel
4440 Warrenville Ctr. Rd.
Cleveland, OH 44128

Solac Builders
1610 Hoffman, NE
Albuquerque, NM 87110

The Solar Connection
Attn: Michael Orians
P. O. Box 1138
Morro Bay, CA 93442

Solar Design Associates
Attn: Steven J. Strong
Conant Road
Lincoln, MA 01773

Solar Electric Systems, Inc.
Attn: Steve Verchinski
Southwest Independent
Power Producers Assn
2700 Espanola, NE
Albuquerque, NM 87110

Solar Electric Specialties
P. O. Box 537
Willits, CA 95490
Stanford University (3)
Attn: Young Kwark
Ron Sinton
Richard Swanson
McCullough 206
Stanford, CA 93405

Stanford University
Attn: Albert Keicher
Member, Technical Staff
SLAC, P. O. Box 4349
Stanford, CA 94305

Star Light Energy
Attn: J. Furber
135 Shadow Brook Lane
Ben Lomond, CA 95005

Stone & Webster Engineering (2)
Attn: John V. Burns
Duncan Moodie
P. O. Box 2325
Boston, MA 02107

Stone & Webster Engineering (4)
Attn: Don McCabe
H. L. Guard
D. W. Hooker
R. R. Henss
P. O. Box 5406
Denver, CO 80217

Strategies Unlimited
Attn: Robert V. Steele
201 San Antonio Circle
Suite 205
Mountain View, CA 94061

SUNY Albany
Attn: Richard Perez
ASRC
1400 Washington Ave.
Albany, NY 12222

Sunnyside Solar
Rt 4, Box 295
West Brattleboro, VT 05301

Swedish State Power Board
Development
Attn: Dr. Bjorn Karlsson
Alvkarleby Laboratory
S-810 71 Alvkarleby
SWEDEN

3T Takanaya, Inc.
Attn: Terry Kunimune
DBA Neo Energy, Inc.
6058 San Fernando Rd.
Glendale, CA 91202

Tennessee Valley Authority
Attn: Joan M. Wood
217 Power Building
Solar Electric Section
Chattanooga, TN 37401

Tennessee Valley Authority (2)
Attn: Sharon Ogle
Barnabas Seaman
1S 72A Signal Place
Chattanooga, TN 37402

Tennessee Valley Authority
Attn: Jeff Jansen
Solar Group
Architectural Design Branch
400 Commerce Ave.
Knoxville, TN 37902

Tennessee Valley Authority
210 Power Building
Attn: David J. Chaffin
Chattanooga, TN 37401

The 12 V Shoppe
1927 W. Thunderbird Road
Phoenix, AZ 85023

TRW
Attn: Robert Patterson
One Space Park
Redondo Beach, CA 90278

Uhl and Lopez Engineers, Inc.
Attn: David A. Penasa
213 Truman NE, Box 8790
Albuquerque, NM 87198

Unica Corporation
Attn: Dietrich Grable
50 Oakdale Ave.
San Rafael, CA 94901

United Energy Corporation
Attn: John K. MacKay
420 Lincoln Centre Dr.
Foster City, CA 94404