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A Simplified Thermal Model for Flat-Plate Photovoltaic Arrays

Martin K. Fuentes

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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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INTRODUCTION

Sandia National Laboratories is actively involved in modeling the electical 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/m^2 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 similate 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 insolations 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.

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

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 Tc (Figure 1). The module receives heat in the form of insolation, S, and loses heat in the form of convection to ambient, Ta, and radiation to the sky and ground, Ts and Tg. The energy balance is displayed in the equation below:

$$hc\cdot(Tc - Ta) + \epsilon\cdot\sigma\cdot(Tc^4 - Ts^4) + \epsilon\cdot\sigma\cdot(Tc^4 - Tg^4) - \alpha\cdot S + m\cdot c\cdot\frac{dTc}{dt} = 0 \ . \qquad (1)$$

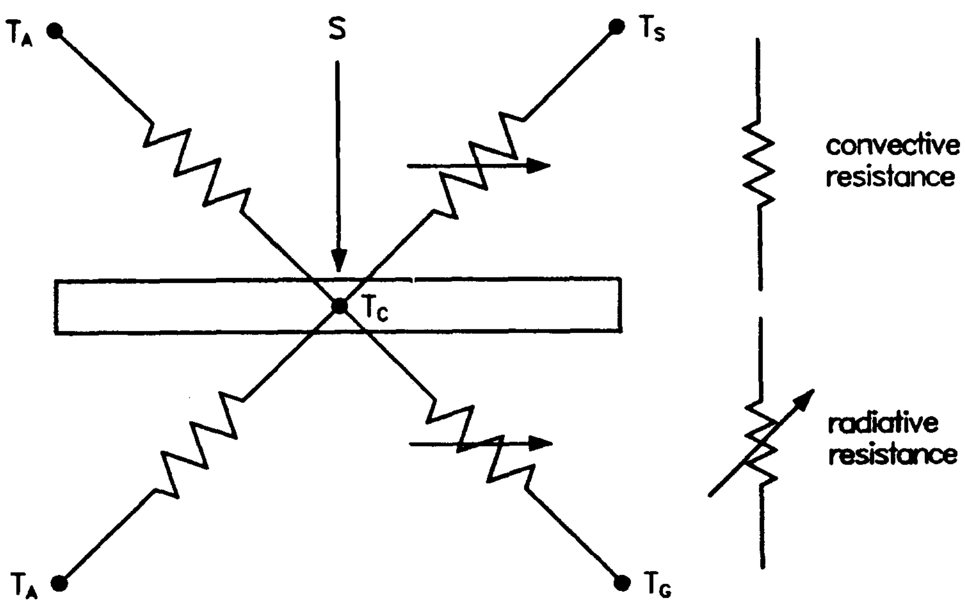

Figure 1: Schematic depiction of the simplified thermal model.

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

$$(Tc^4 - Ts^4) = (Tc^2 + Ts^2)\cdot(Tc + Ts)\cdot(Tc - Ts) \ . \qquad (2)$$

Since the product $(T^2 + Ts^2)\cdot(T + Ts)$ changes less than 5% for a 10°C variation in Tc, 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 Tc, we can reevaluate the value of this constant and then solve for Tc again. A nearly exact solution can be obtained after 5 iterations. We can simplify the heat balance equation by defining a radiation coefficient, hr:

$$hr_s = \epsilon\cdot\sigma\cdot(Tc^2 + Ts^2)\cdot(Tc + Ts) \qquad (3)$$

$$hr_g = \epsilon\cdot\sigma\cdot(Tc^2 + Tg^2)\cdot(Tc + Tg) \ . \qquad (4)$$

We can also assume that the insolation varies between time steps in a linear fashion:

$$S = S_o + \Delta S \cdot t/\Delta t \ . \tag{5}$$

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 Tc. The resulting heat balance is displayed below:

$$hc \cdot (Tc-Ta) + hr_s \cdot (Tc-Ts) + hr_g \cdot (Tc-Tg) - \alpha \cdot (S_o - \Delta S \cdot t/\Delta t) + m \cdot c \cdot \frac{dTc}{dt} = 0 \ . \tag{6}$$

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

$$Tc = \frac{(hc \cdot Ta + hr_s \cdot Ts + hr_g \cdot Tg + \alpha \cdot S_o + \alpha \cdot \Delta S/L) \cdot (1 - e^L) + \alpha \cdot \Delta S}{hc + hr_s + hr_g} + Tc_o \cdot e^L \ . \tag{7}$$

Tc_o is the module temperature at the start of the time step and L is determined using

$$L = - (hc + hr_s + hr_g) \cdot \Delta t/(m \cdot c) \ . \tag{8}$$

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 Tc_o from our calculation for the last time step. We are given Ta, and with it, we can estimate Ts, and thus also hr_s. But because hr_s also varies with Tc, for which we are solving, we have to iterate our solution. S_o, ΔS, 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 INOCT. We can estimate T_g 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:

$$St \cdot Pr^{0.67} = 0.86 \cdot Re^{-0.5} \qquad Re < 1.2 \cdot 10^5 \ . \tag{9}$$

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.

$$St \cdot Pr^{0.67} = 0.94 \cdot Re^{-0.5} \qquad Re < 1.2 \cdot 10^5 \tag{10}$$

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

$$St \cdot Pr^{0.4} = 0.031 \cdot Re^{-0.2} \qquad Re > 1.2 \cdot 10^5 \ . \tag{11}$$

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:

$$St \cdot Pr^{0.4} = 0.028 \cdot Re^{-0.2} \qquad Re > 1.2 \cdot 10^5 \ . \tag{12}$$

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:

$$Nu = 0.21 \cdot (Gr \cdot Pr)^{0.32} \ . \tag{13}$$

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 $Re = 1.2 \cdot 10^5$ 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 Churchchill (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:

$$h^3_{Mixed} = h^3_{Free} + h^3_{Forced} \ . \tag{14}$$

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/m^2 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:

$$\alpha \cdot S - hc_T \cdot (T_{INOCT} - Ta) - hr_s \cdot (T_{INOCT} - Ts) = hc_B \cdot (T_{INOCT} - Ta) + hr_g \cdot (T_{INOCT} - Tg) \quad (15)$$

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

$$R = \frac{hc_B \cdot (T_{INOCT} - Ta) + \epsilon \cdot \sigma \cdot (T_{INOCT}^4 - Tg^4)}{hc_T \cdot (T_{INOCT} - Ta) + \epsilon \cdot \sigma \cdot (T_{INOCT}^4 - Ta^4)} . \quad (16)$$

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:

$$R = \frac{\alpha \cdot S - hc_T \cdot (T_{INOCT} - Ta) + \epsilon \cdot \sigma \cdot (T_{INOCT}^4 - Ts^4)}{hc_T \cdot (T_{INOCT} - Ta) + \epsilon \cdot \sigma \cdot (T_{INOCT}^4 - Ta^4)} . \quad (17)$$

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

$$hc_B = R \cdot hc_T \quad (18)$$

$$Tg = [T_{INOCT}^4 - R \cdot (T_{INOCT}^4 - Ta^4)]^{0.25} . \quad (19)$$

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 hc_B in the same manner as in equation 18. The total convective coefficient, hc, 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:

$$Tg = Ta + R_g \cdot (Tc - Ta) . \quad (20)$$

R_g is determined at NOCT conditions using equations 19 and 21:

$$R_g = \frac{Tg - Ta}{T_{INOCT} - Ta} \quad . \tag{21}$$

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:

$$w = wr \cdot (y/yr)^p \quad . \tag{22}$$

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 can not 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 is readily available. In 1963, Swinbank proposed equation 23 as a suitable sky temperature equation for clear sky conditions:

$$Ts = 0.0552 \cdot Ta^{1.5} \quad . \tag{23}$$

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:

$$Ts = 0.68 \cdot (0.0552 \cdot Ta^{1.5}) + 0.32 \cdot Ta \ . \quad (24)$$

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, η, the absorptivity, α, can be calculated using the following equation:

$$\alpha = (1 - r) \cdot (1 - \eta) \ . \quad (25)$$

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.

Manufacturer	Reflectivity	Emissivity
ARCO	0.09	0.87
Solarex	0.15	0.83
Motorola	0.07	0.83
GE	0.09	0.86
Average	0.10	0.84

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·c, is required in the model to similate the thermal lag of a typical module. An exact value for m·c is not required, because variations of 50% in the value of m·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.

Manufacturer	m·c ($J/m^2 {}^\circ C$)
ARCO	8,600
Solarex	13,000
Motorola	9,300
GE	12,900
Average	11,000

The average thermal mass is 11,000 $J/m^2{}^\circ C$. 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:

$$m \cdot c = 11{,}000 \qquad T_{INOCT} \leq 48^\circ C \qquad (26)$$

$$m \cdot c = 11{,}000 \cdot [1 + (T_{INOCT} - 48)/12] \qquad T_{INOCT} > 48^\circ C \; . \qquad (27)$$

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 similate three different mounting configurations. The minimum standoff height of zero inches similated 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.

Standoff Height (inches)	INOCT (°C)	INOCT - NOCT (°C)
0.†	68.1	20
0.	65.8	17
1.	59.8	11
3.	51.2	2
6.	48.1	-1
9.	46.1	-3

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

Table 5: Comparison of INOCT and NOCT.

Prototype	INOCT (°C)	NOCT (°C)
GE	65.2	58.‡
Solarex	58.3	49.
Arco	53.0	56.‡
ARTU	51.8	46.
BDM	51.6	49.
Westinghouse	49.4	46.
TEA	45.8	49.
Tri-Solar	44.8	--

‡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.

Rack Mount	INOCT = NOCT - 3°C
Direct Mount	INOCT = NOCT + 18°C
Standoff/Integral	INOCT = NOCT + X

W (inches)	X(°C)
1	11
3	2
6	-1

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.

NOMENCLATURE

α	- Absorptivity of the module below 3.5 microns
σ	- Boltzman's constant - $5.669 \cdot 10^{-8}$ $W/m^2 \cdot °K^4$
ϵ	- Emissivity of the module above 3.5 microns
η	- Module efficiency
ρ	- Density of air
υ	- 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 - $g \cdot (T-Ta) \cdot D_h^3/\upsilon^2/T$
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_g	- Radiative coefficient to the sky ($W/m^2°K$)
hr_s	- 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_g	- Ratio of ground temperature over ambient to module temperature over ambient
Re	- Reynolds number - $w \cdot D_h/\upsilon$
S	- Insolation (W/m^2)
S_o	- Insolation from the last time step (W/m^2)
ΔS	- 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)
Δt	- Time step (sec)
Ta	- Ambient temperature (°K)
Tc	- Cell temperature (°K)
Tc_o	- Cell temperature from the last time step (°K)
T_{INOCT}	- Installed Nominal Operating Cell Temperature (°K)
Tg	- 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)

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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.

```
C  THIS IS A VERY SIMPLE THERMAL MODEL FOR FLAT PLATE PV MODULES.
C  THIS MODEL IS BACED ON THE "INSTALLED" NOCT TEMPERATURE. IT
C  SCALES THE OVERALL CONVECTIVE COEFFICIENT FROM THE NOCT CONDITION
C  TO THE DESIRED ENVIROMENT AND THEN ESTIMATES THE OTHER THERMAL
C  PARAMETERS TO OBTAIN THE CELL TEMPERATURE.
C
C  NEEDED INPUT:
C    FROM SCREEN
C      INOCT TEMPERATURE  (C)
C
C    FROM A DATA FILE
C      FIRST RECORD  -  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 A FILE:
C    DATE (YYDDD), TIME (H), POA INSOLATION (W/M2), AMBIENT TEMP. (C),
C    WIND SPEED (M/SEC), AND CELL TEMPERATURE (C).
C
C
      PROGRAM THERM
      CHARACTER infile*15,outfile*15
      DATA BOLTZ/5.669E-8/,EMISS/0.84/,ABSORP/0.83/,xlen/0.5/
      DATA CAPO/11000./
C
C  OPENING THE INPUT AND OUTPUT FILES
C
      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')
C
C  READING THE inoct
C
      PRINT *,'INPUT INOCT : '
      READ *,TINOCT
      TINOCT=TINOCT+273.15
C
C  CONVECTIVE COEFFICIENT AT NOCT
C
      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
```

```
      REYNOLD=WINDMOD*XLEN/VISAIR
      HFORCE=0.8600/REYNOLD**.5*DENSAIR*WINDMOD*1007./0.71**.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
C  DETERMINING THE GROUND TEMPERATURE RATIO AND THE RATIO OF THE TOTAL
C  CONVECTION TO THE TOP SIDE CONVECTION.
C
      HGROUND=EMISS*BOLTZ*(TINOCT**2.+293.15**2.)*(TINOCT+293.15)

      BACKRAT=(ABSORP*800.-EMISS*BOLTZ*(TINOCT**4-282.21**4)-HCONV
     +       *(TINOCT-293.15))/((HGROUND+HCONV)*(TINOCT-293.15))
      TGROUND=(TINOCT**4-BACKRAT*(TINOCT**4-293.15**4))**0.25
      IF(TGROUND.GT.TINOCT)TGROUND=TINOCT
      IF(TGROUND.LT.293.15)TGROUND=293.15
      TGRAT=(TGROUND-293.15)/(TINOCT-293.15)
      CONVRAT=(ABSORP*800.-EMISS*BOLTZ*(2*TINOCT**4-282.21**4
     +        -TGROUND**4))/(HCONV*(TINOCT-293.15))
C
C  ADJUSTING THE CAPACITANCE OF THE MODULE BACED ON THE INOCT
C
      CAP=CAPO
      IF(TINOCT.GT.321.15)CAP=CAP*(1.+(TINOCT-321.15)/12.)
C
C  INITIAL VALUES
C
      SUNO=0.
      TIMEO=0.
      DATEO=0.
      TMODO=293.15
      N=0
C
C  READING THE DATA
C
      REWIND 1
      READ(1,*)HITEMOD,HITEANE
    3 READ(1,*,END=20)DATE,TIME,SUN,TAMB,WINDANE
      N=N+1
      DTIME=TIME-TIMEO+24.*(DATE-DATEO)
      TAMB=TAMB+273.15
      SUN=SUN*ABSORP
C
C  SKY TEMPERATURE
C
      TSKY=0.68*(0.0552*TAMB**1.5)+0.32*TAMB
C
C  WIND SPEED AT MODULE HEIGHT
C
      IF(WINDANE.LT.0.)WINDANE=0.
      WINDMOD=WINDANE*(HITEMOD/HITEANE)**0.2+0.0001
C
C  OVERALL CONVECTIVE COEFFICIENT
C
      TMOD=TMODO
      DO 10 J=1,10
```

```
      TAVE=(TMOD+TAMB)/2.
      DENSAIR=0.003484*101325./TAVE
      VISAIR=0.24237E-6*TAVE**0.76/DENSAIR
      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**0.4
      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.)
C
C  SOLVING THE HEAT TRANSFER EQUATION
C
      HSKY=EMISS*BOLTZ*(TMOD**2.+TSKY**2.)*(TMOD+TSKY)
      TGROUND=TAMB+TGRAT*(TMOD-TAMB)
      HGROUND=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*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 ITTERATES
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
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 CAPO/11000./
C
C  FIRST ESTIMATE OF INOCT
C
    1 TINOCT=48.+273.15
C
C  OPENING THE DATA FILE
C
      PRINT *,' INPUT THE NAME OF THE DATA FILE  : '
      READ(*,'(A)')DATAFILE
      OPEN(1,FILE=DATAFILE)
C
C  CONVECTIVE COEFFICIENT AT NOCT
C
    2 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
      REYNOLD=WINDMOD*XLEN/VISAIR
      HFORCE=0.8600/REYNOLD**.5*DENSAIR*WINDMOD*1007./0.71**.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
C  DETERMINING THE GROUND TEMPERATURE RATIO AND THE RATIO OF THE TOTAL
```

```
C  CONVECTION TO THE TOP SIDE CONVECTION.
C
      HGROUND=EMISS*BOLTZ*(TINOCT**2.+293.15**2.)*(TINOCT+293.15)

      BACKRAT=(ABSORP*800.-EMISS*BOLTZ*(TINOCT**4-282.21**4)-HCONV
     +       *(TINOCT-293.15))/((HGROUND+HCONV)*(TINOCT-293.15))
      TGROUND=(TINOCT**4-BACKRAT*(TINOCT**4-293.15**4))**0.25
      IF(TGROUND.GT.TINOCT)TGROUND=TINOCT
      IF(TGROUND.LT.293.15)TGROUND=293.15
      TGRAT=(TGROUND-293.15)/(TINOCT-293.15)
      CONVRAT=(ABSORP*800.-EMISS*BOLTZ*(2*TINOCT**4-282.21**4
     +        -TGROUND**4))/(HCONV*(TINOCT-293.15))
C
C  ADJUSTING THE CAPACITANCE OF THE MODULE BACED ON THE INOCT
C
      CAP=CAPO
      IF(TINOCT.GT.321.15)CAP=CAP*(1.+(TINOCT-321.15)/12.)
C
C  INITIAL VALUES
C
      BIAS=0.
      STDEV=0.
      SUNTOT=0.
      SUNO=0.
      TIMEO=0.
      DATEO=0.
      TMODO=293.15
      N=0
C
C  READING THE DATA
C
      REWIND 1
      READ(1,*)HITEMOD,HITEANE
    3 READ(1,*,END=20)DATE,TIME,SUN,TAMB,WINDANE,TACTUAL
      N=N+1
      DTIME=TIME-TIMEO+24.*(DATE-DATEO)
      TAMB=TAMB+273.15
      TACTUAL=TACTUAL+273.15
      SUN=SUN*ABSORP
C
C  SKY TEMPERATURE
C
      TSKY=0.68*(0.0552*TAMB**1.5)+0.32*TAMB
C
C  WIND SPEED AT MODULE HEIGHT
C
      IF(WINDANE.LT.0.)WINDANE=0.
      WINDMOD=WINDANE*(HITEMOD/HITEANE)**0.2+0.0001
C
C  OVERALL CONVECTIVE COEFFICIENT
C
      TMOD=TMODO
      DO 10 J=1,10
      TAVE=(TMOD+TAMB)/2.
      DENSAIR=0.003484*101325./TAVE
      VISAIR=0.24237E-6*TAVE**0.76/DENSAIR
```

```
      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**0.4
      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.)
C
C  SOLVING THE HEAT TRANSFER EQUATION
C
      HSKY=EMISS*BOLTZ*(TMOD**2.+TSKY**2.)*(TMOD+TSKY)
      TGROUND=TAMB+TGRAT*(TMOD-TAMB)
      HGROUND=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*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  CALCULATING THE BIAS AND STANDARD DEVIATION
C
      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
C
C  OUTPUT
C
      WRITE(*,'(/,1x,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
C  ANOTHER RUN?
C
      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.

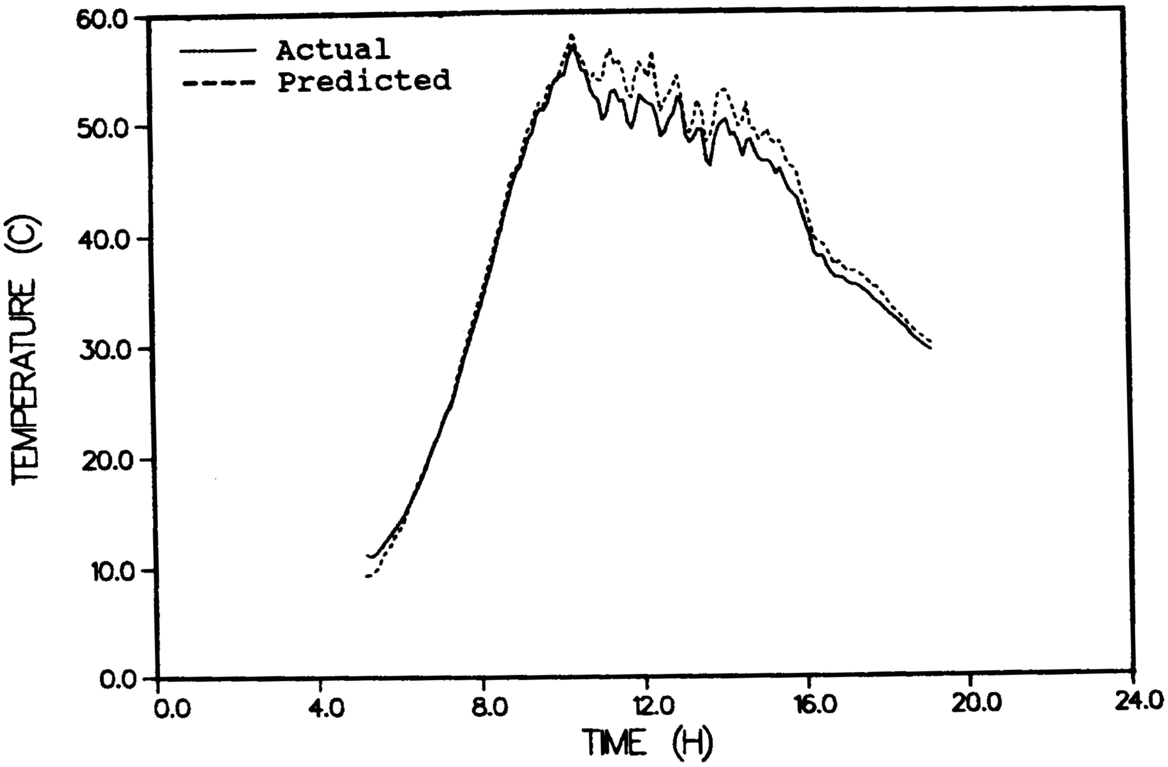

Figure C-1: Actual and predicted cell temperatures from the BDM prototype at the SWRES on June 5, 1982.

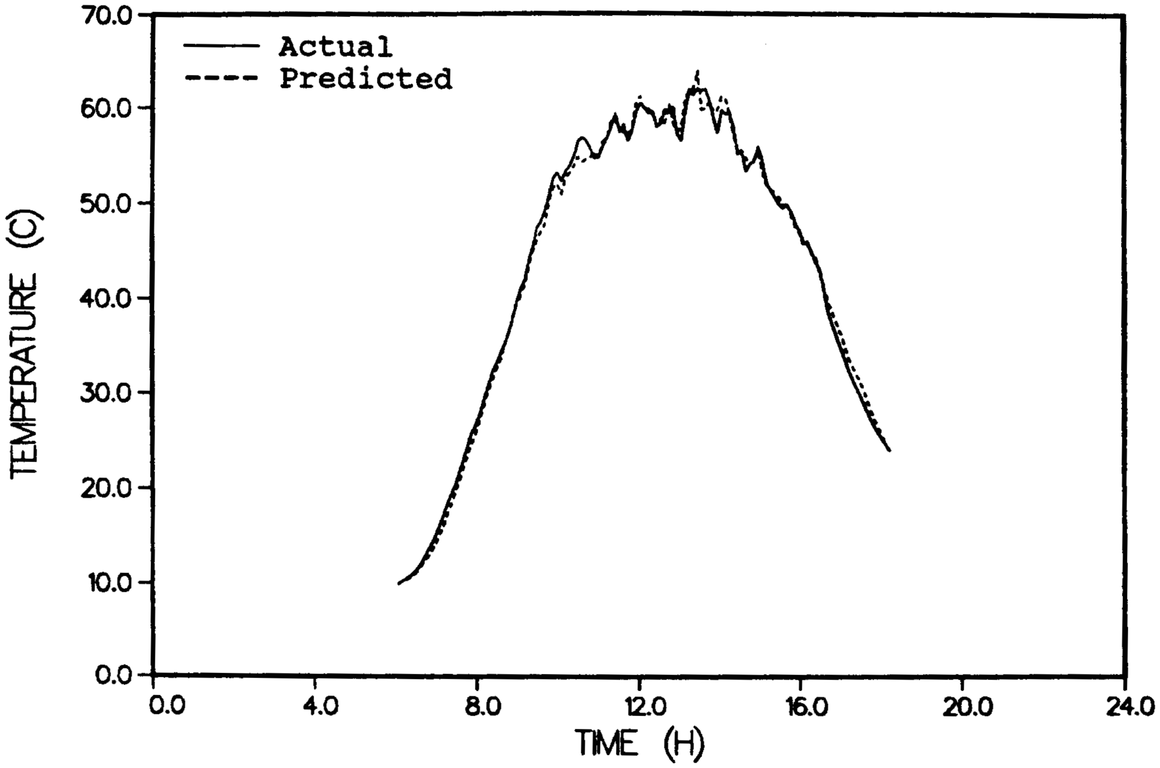

Figure C-2: Actual and predicted cell temperatures from the BDM prototype at the SWRES on September 14, 1982.

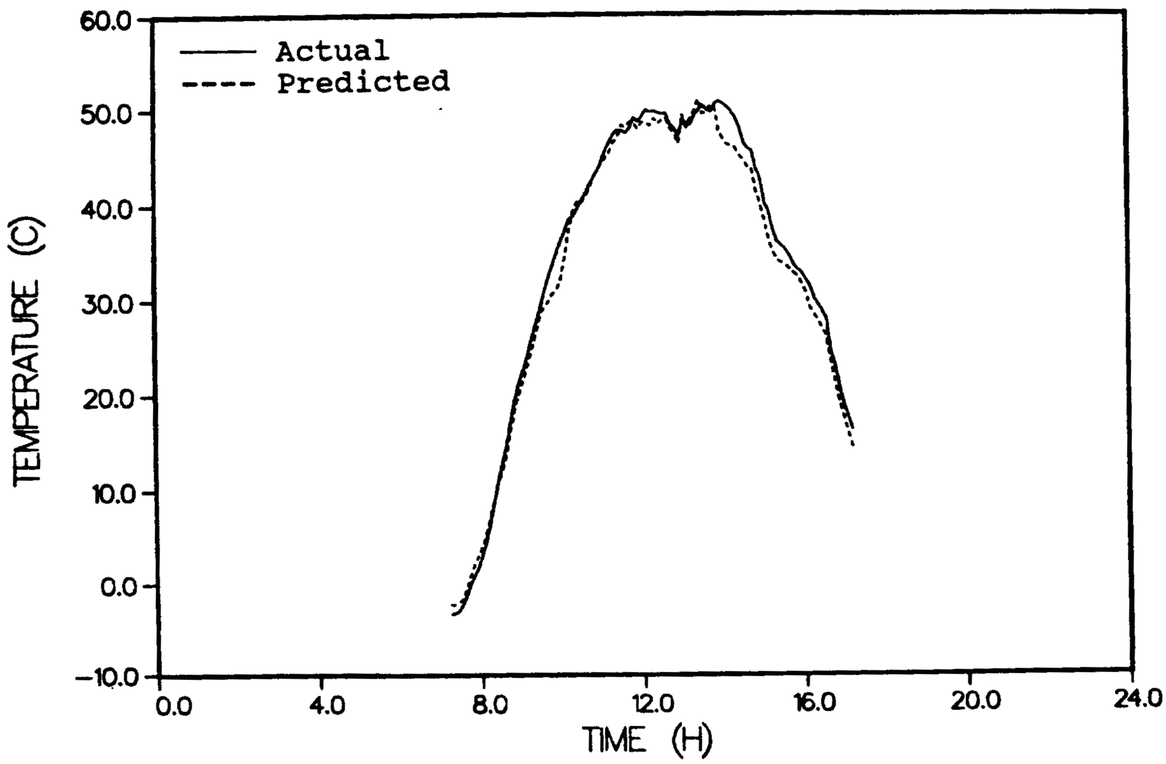

Figure C-3: Actual and predicted cell temperatures from the BDM prototype at the SWRES on December 17, 1982.

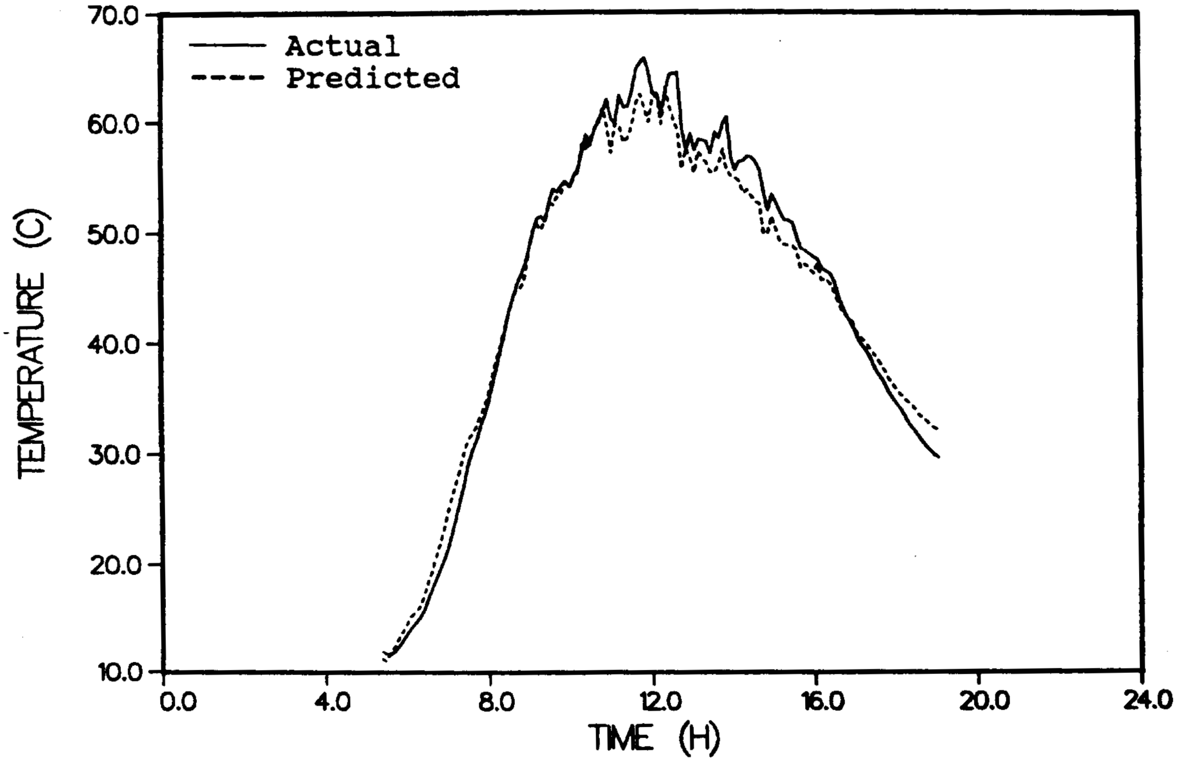

Figure C-4: Actual and predicted cell temperatures from the TEA prototype at the SWRES on June 26, 1982.

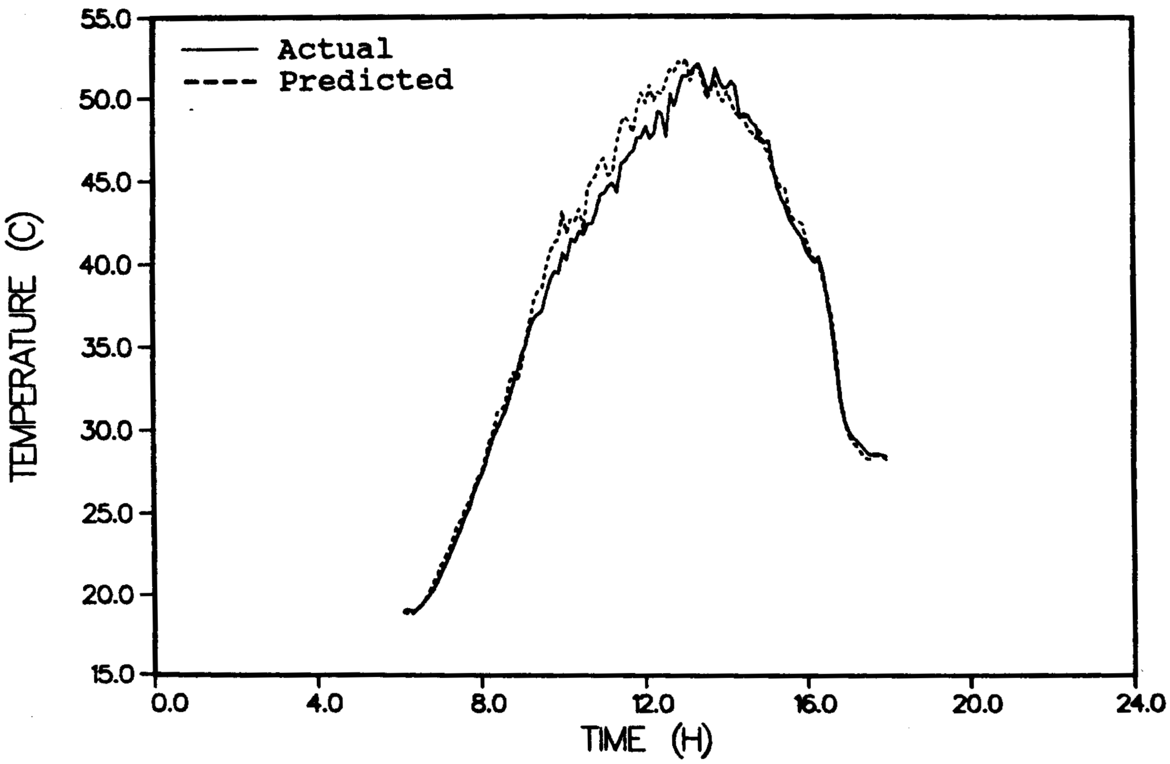

Figure C-5: Actual and predicted cell temperatures from the TEA prototype at the SWRES on September 16, 1982.

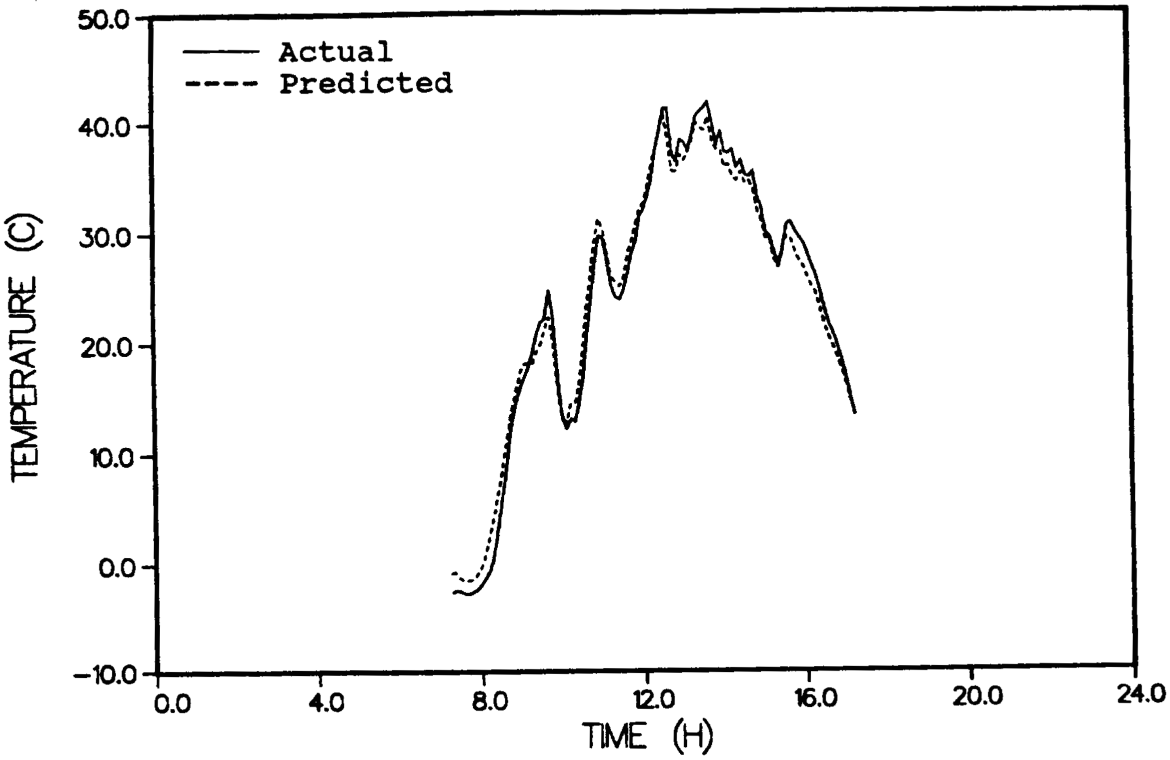

Figure C-6: Actual and predicted cell temperatures from the TEA prototype at the SWRES on December 18, 1982.

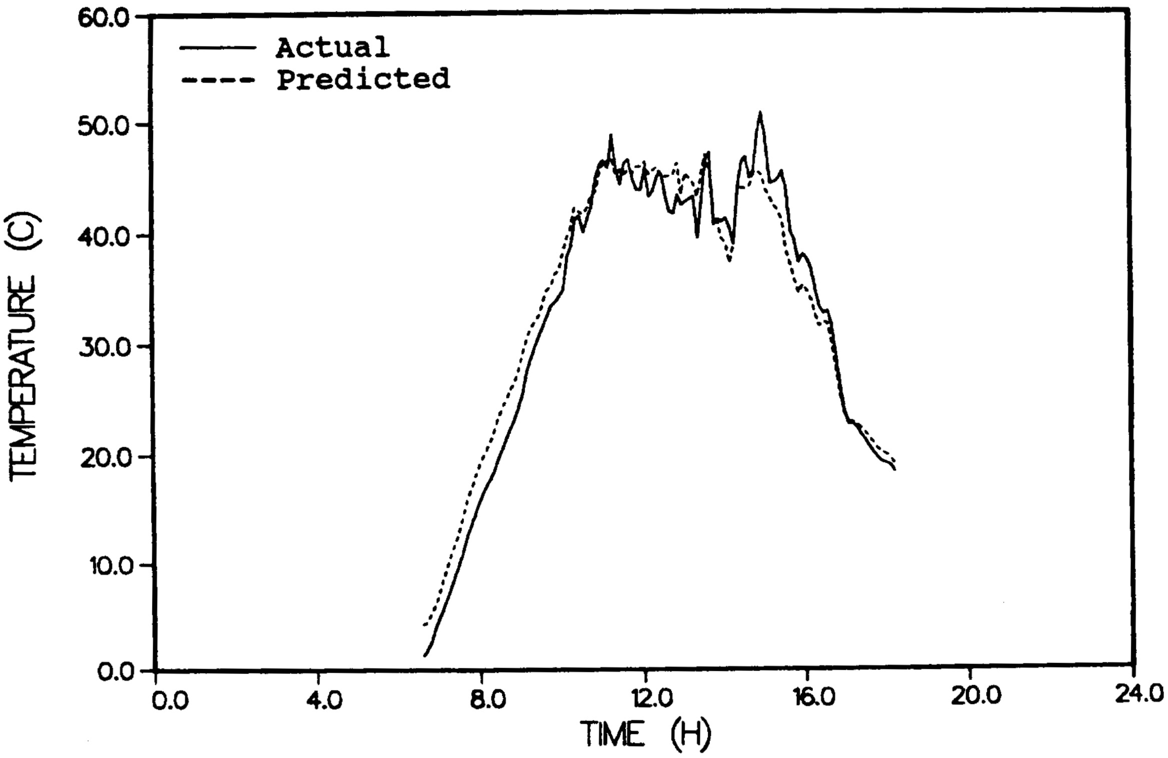

Figure C-7: Actual and predicted cell temperatures from the TEA prototype at the SWRES on March 13, 1983.

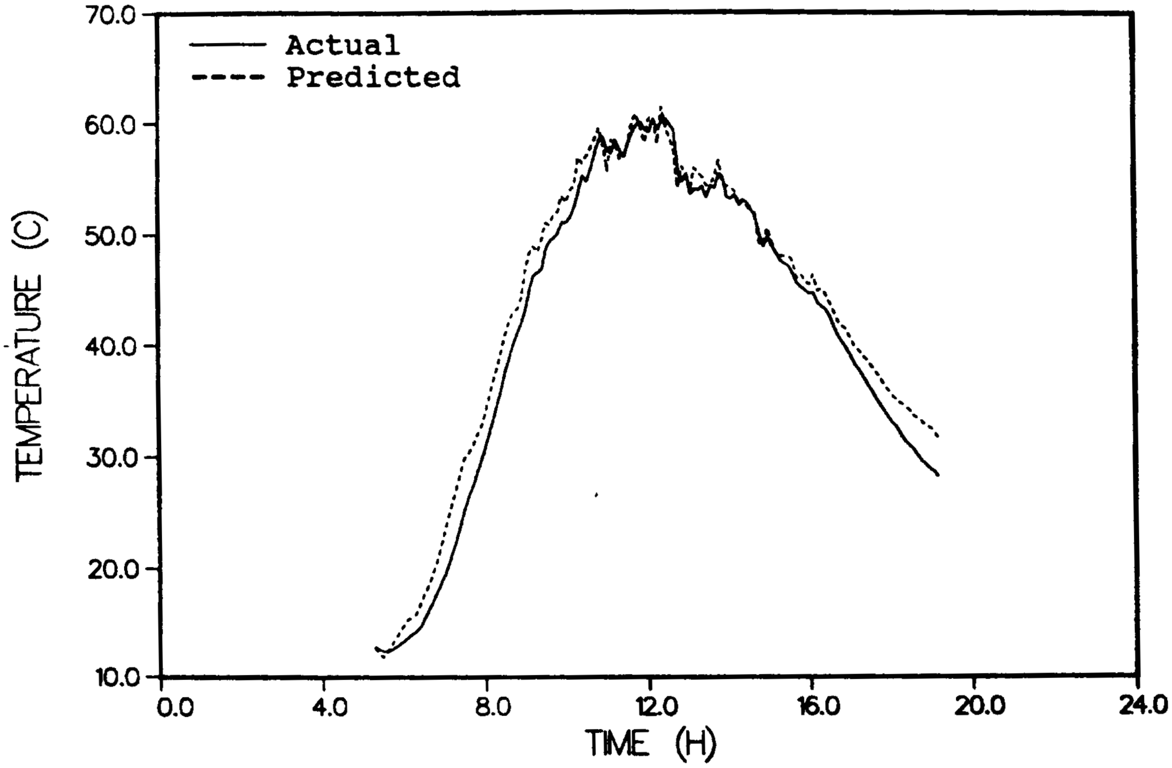

Figure C-8: Actual and predicted cell temperatures from the Tri-Solar prototype at the SWRES on June 26, 1982.

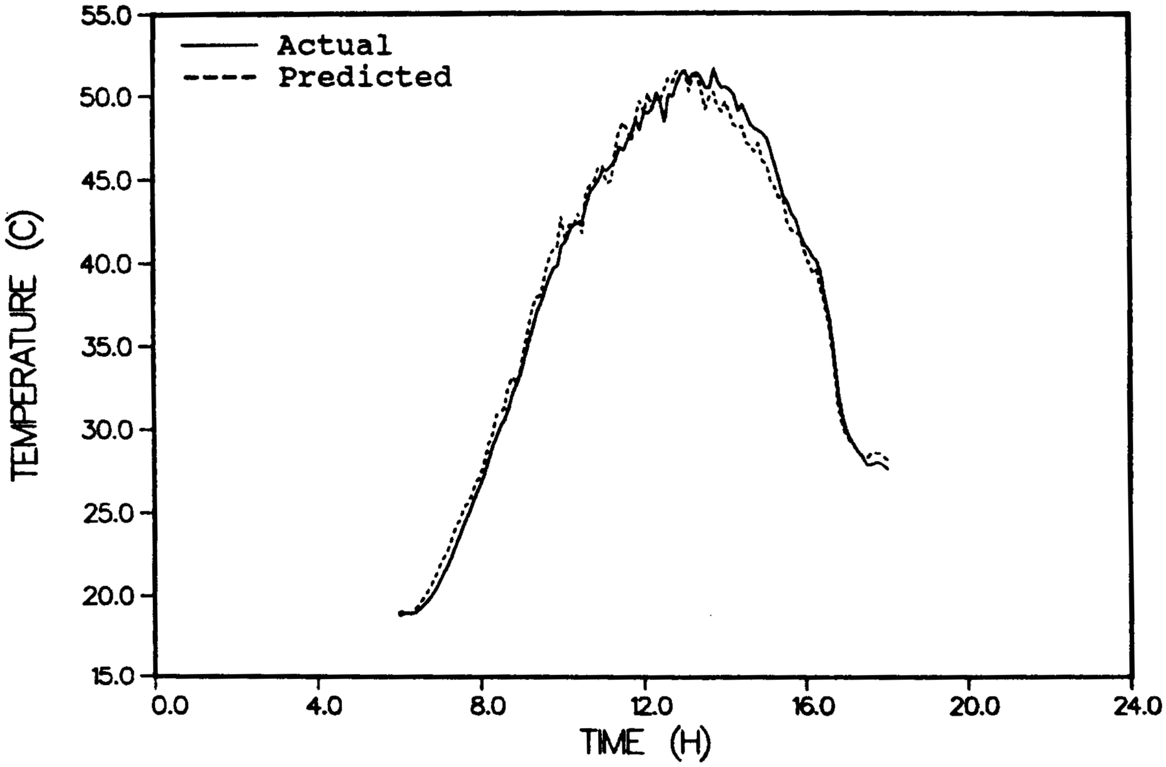

Figure C-9: Actual and predicted cell temperatures from the Tri-Solar prototype at the SWRES on September 16, 1982.

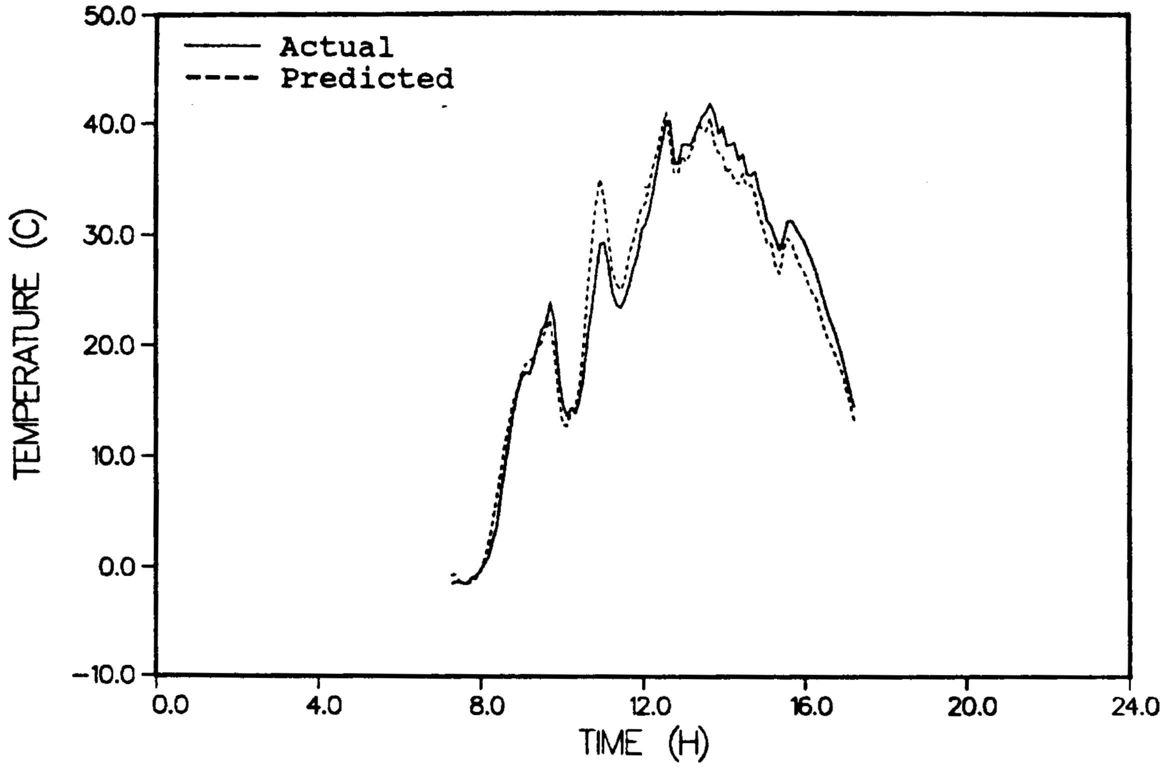

Figure C-10: Actual and predicted cell temperatures from the Tri-Solar prototype at the SWRES on December 18, 1982.

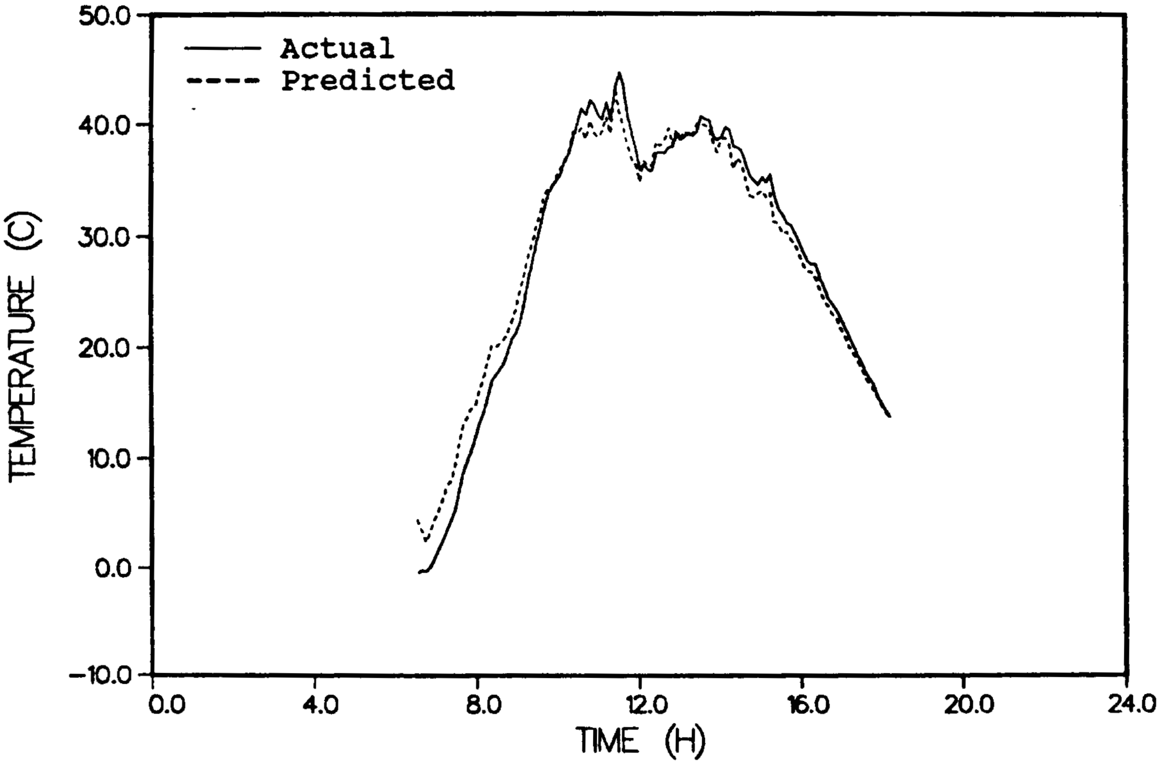

Figure C-11: Actual and predicted cell temperatures from the Tri-Solar prototype at the SWRES on March 9, 1983.

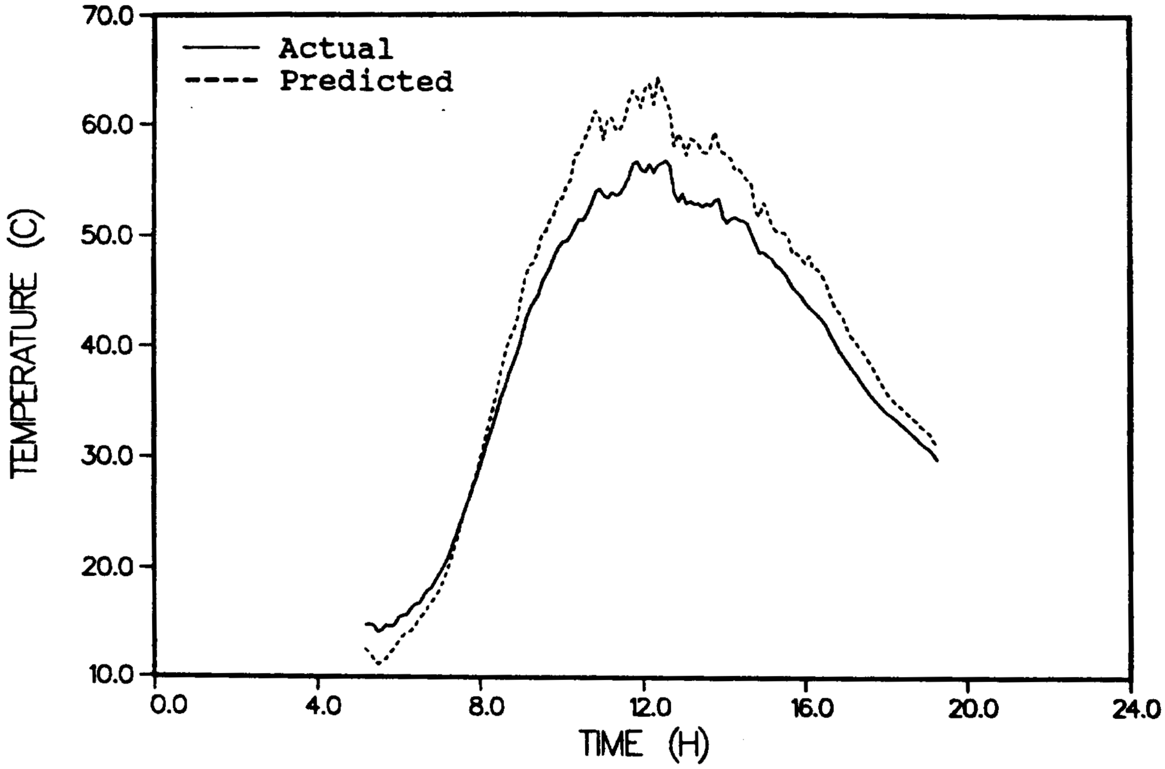

Figure C-12: Actual and predicted cell temperatures from the ARTU prototype at the SWRES on June 26, 1982.

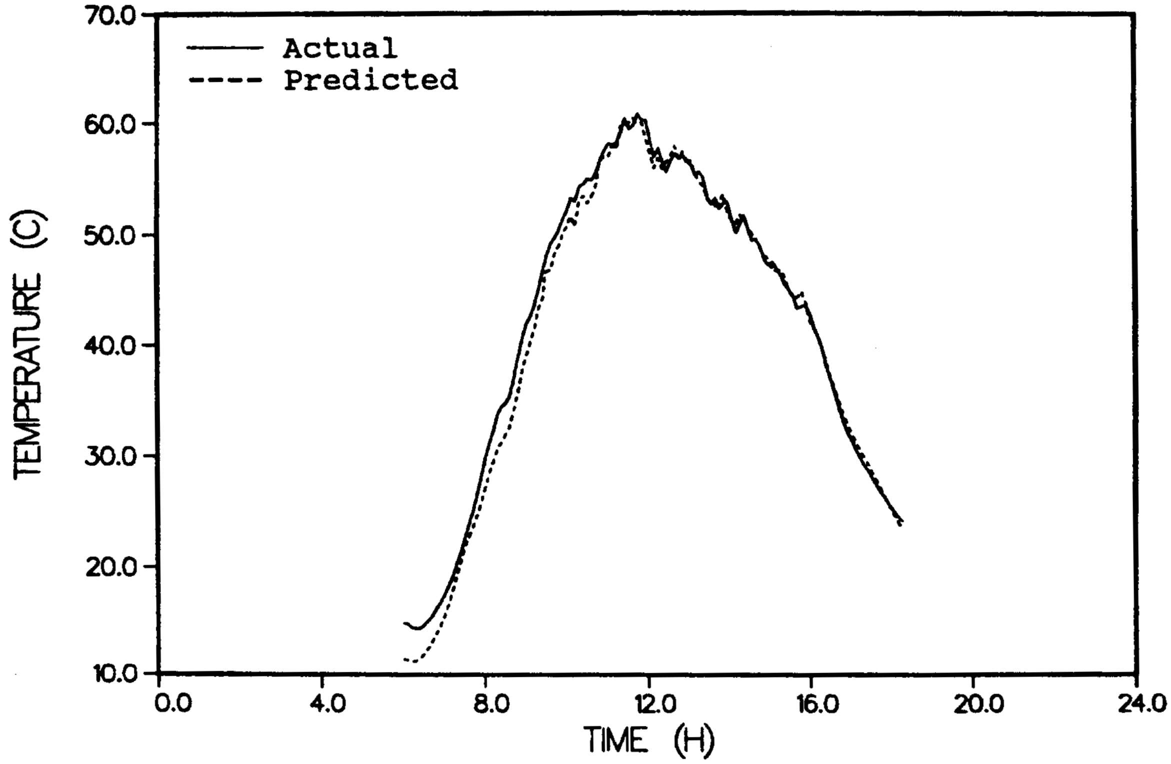

Figure C-13: Actual and predicted cell temperatures from the ARTU prototype at the SWRES on September 19, 1982.

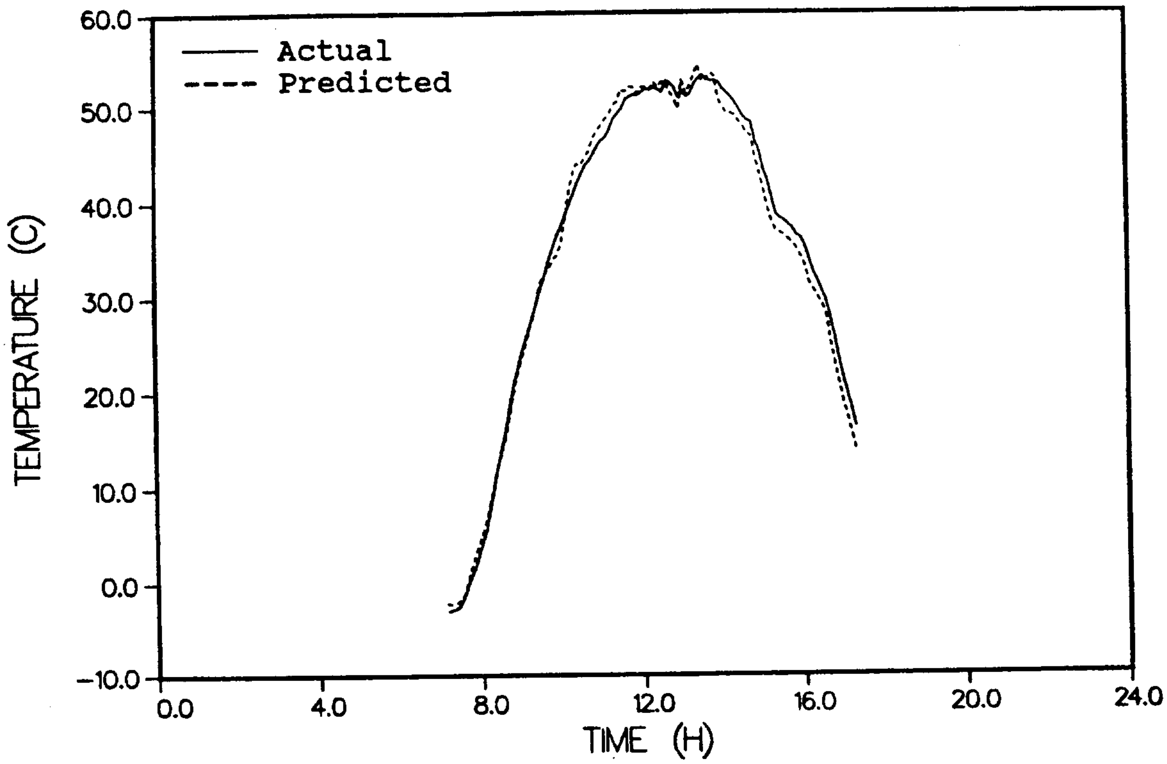

Figure C-14: Actual and predicted cell temperatures from the ARTU prototype at the SWRES on December 17, 1982.

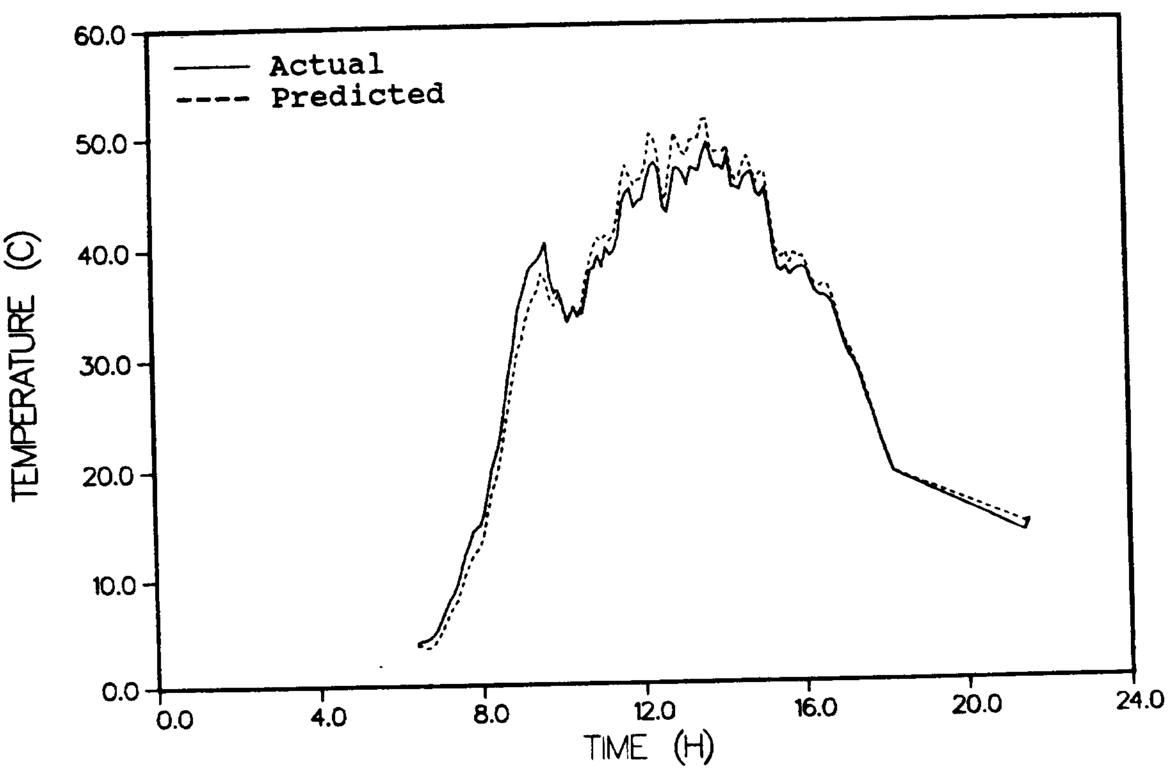

Figure C-15: Actual and predicted cell temperatures from the ARTU prototype at the SWRES on March 11, 1983.

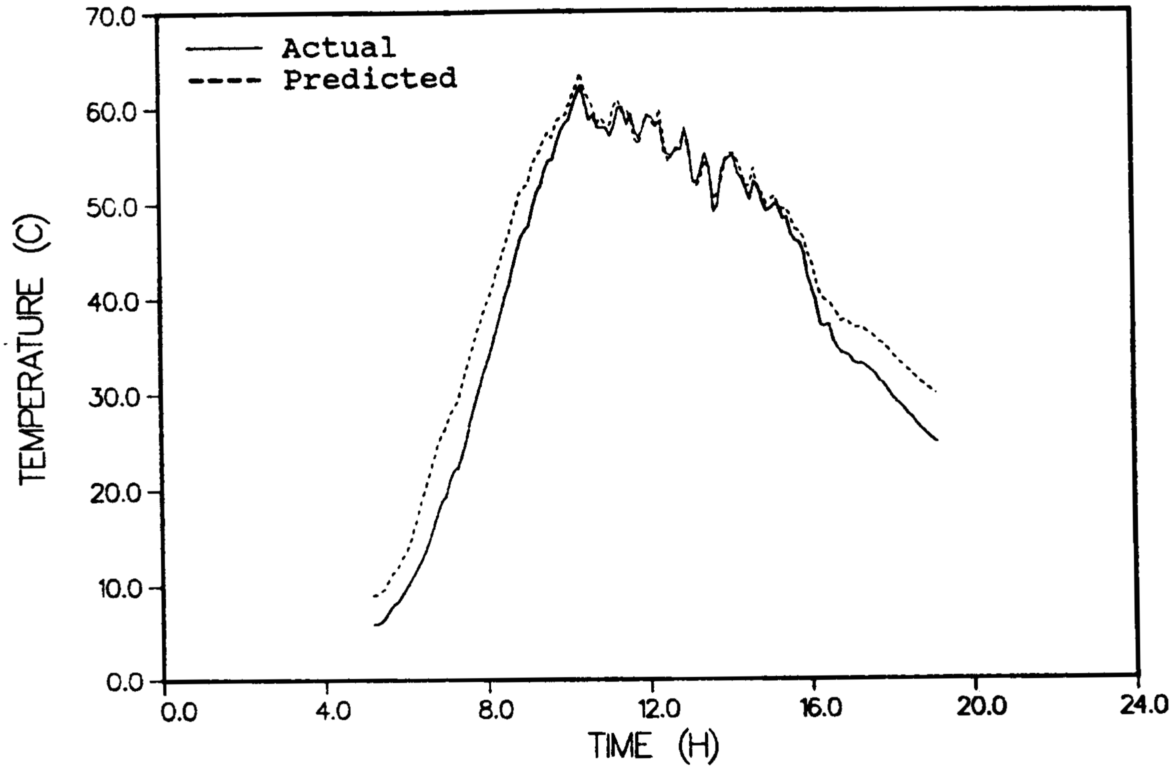

Figure C-16: Actual and predicted cell temperatures from the ARCO prototype at the SWRES on June 5, 1982.

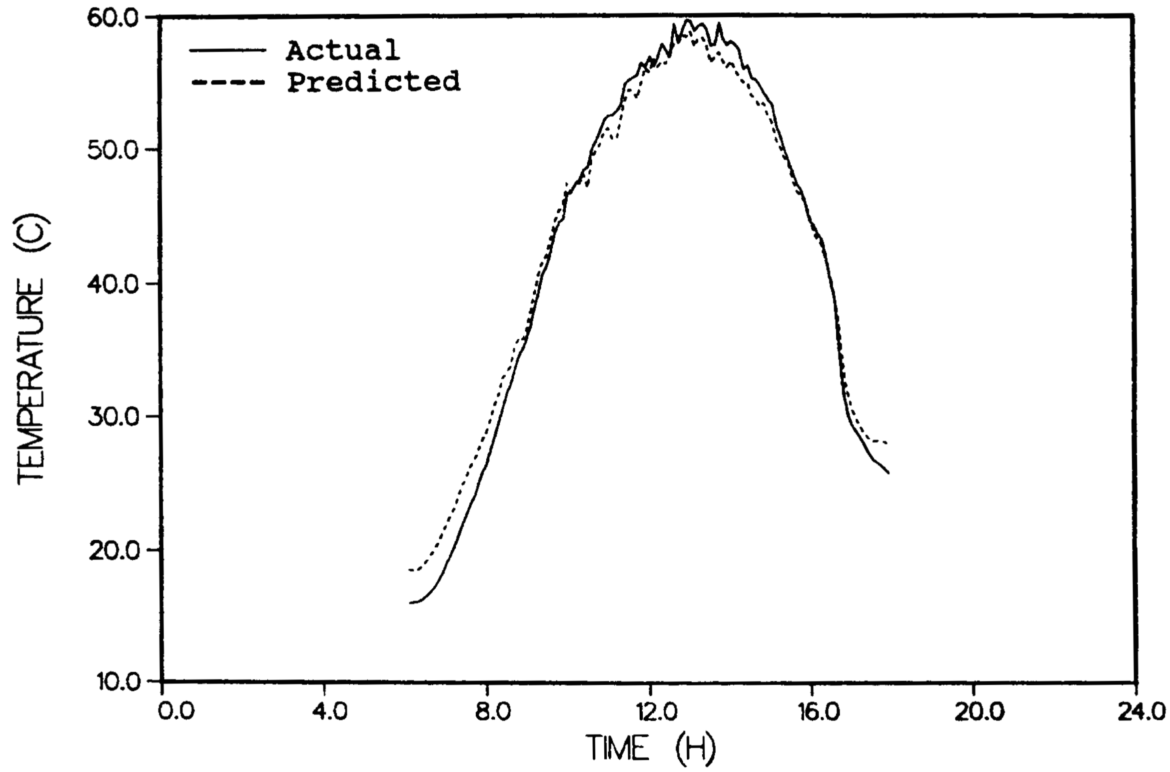

Figure C-17: Actual and predicted cell temperatures from the ARCO prototype at the SWRES on September 16, 1982.

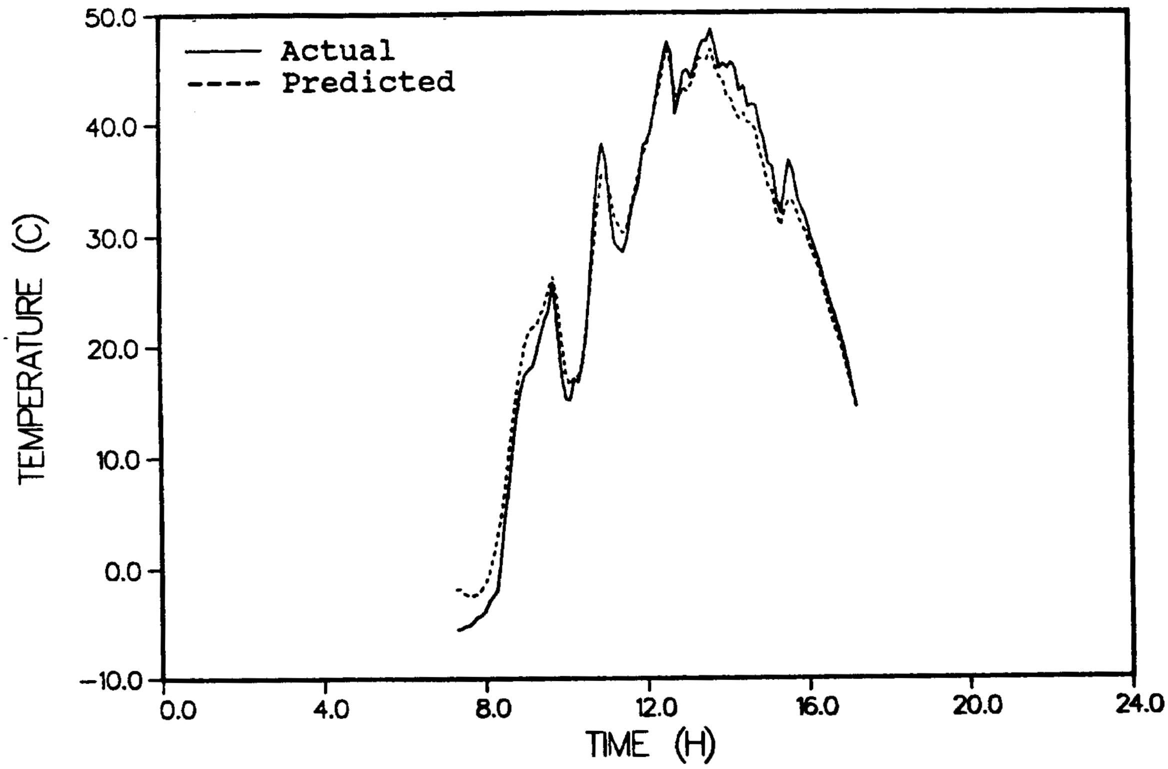

Figure C-18: Actual and predicted cell temperatures from the ARCO prototype at the SWRES on December 18, 1982.

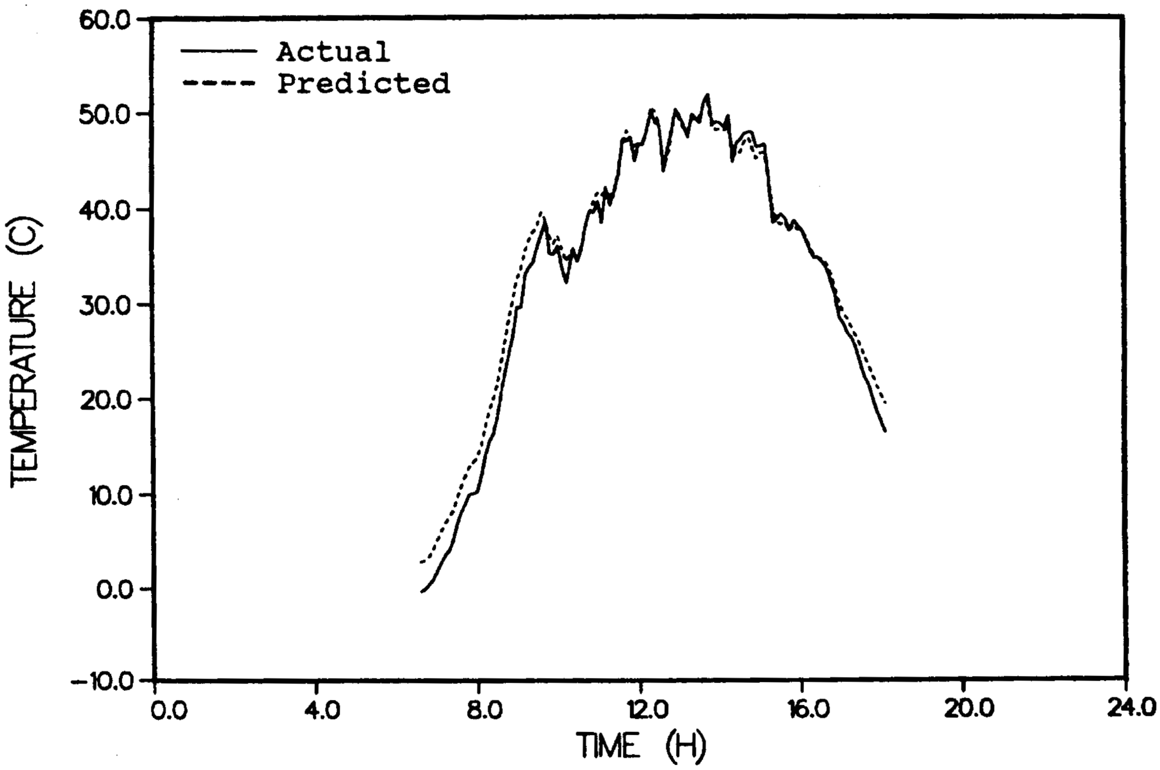

Figure C-19: Actual and predicted cell temperatures from the ARCO prototype at the SWRES on March 11, 1983.

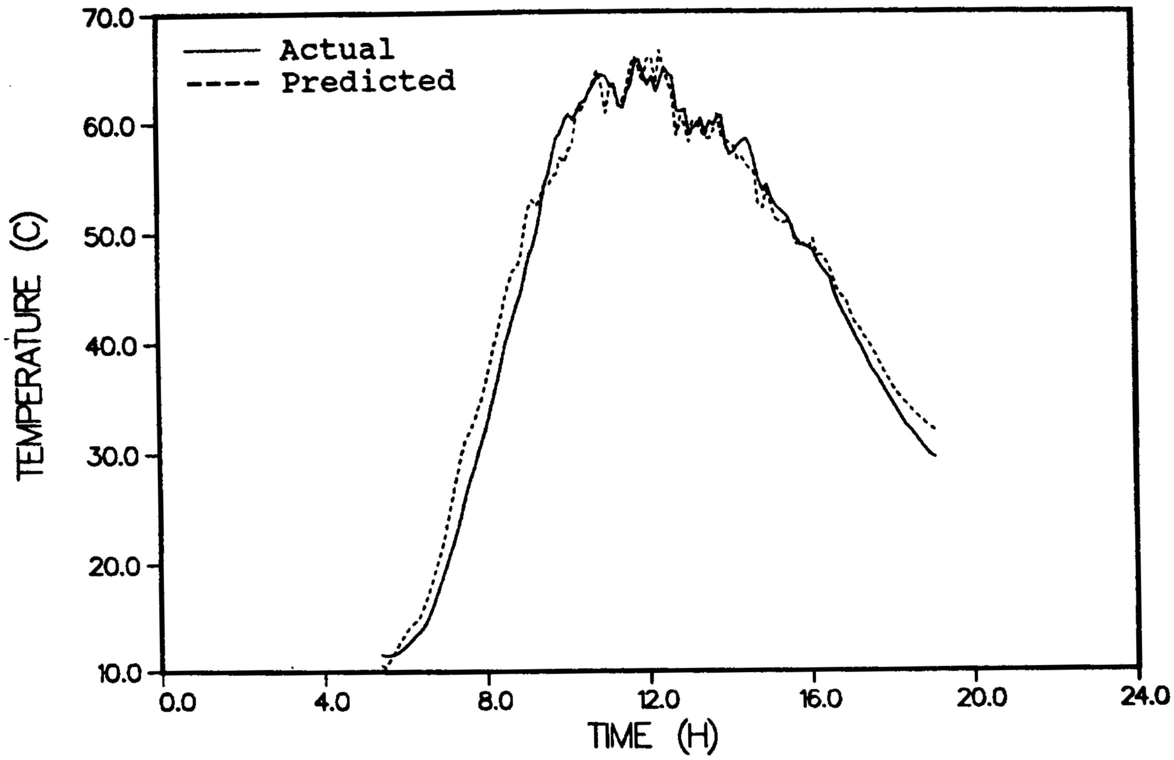

Figure C-20: Actual and predicted cell temperatures from the Westinghouse prototype at the SWRES on June 26, 1982.

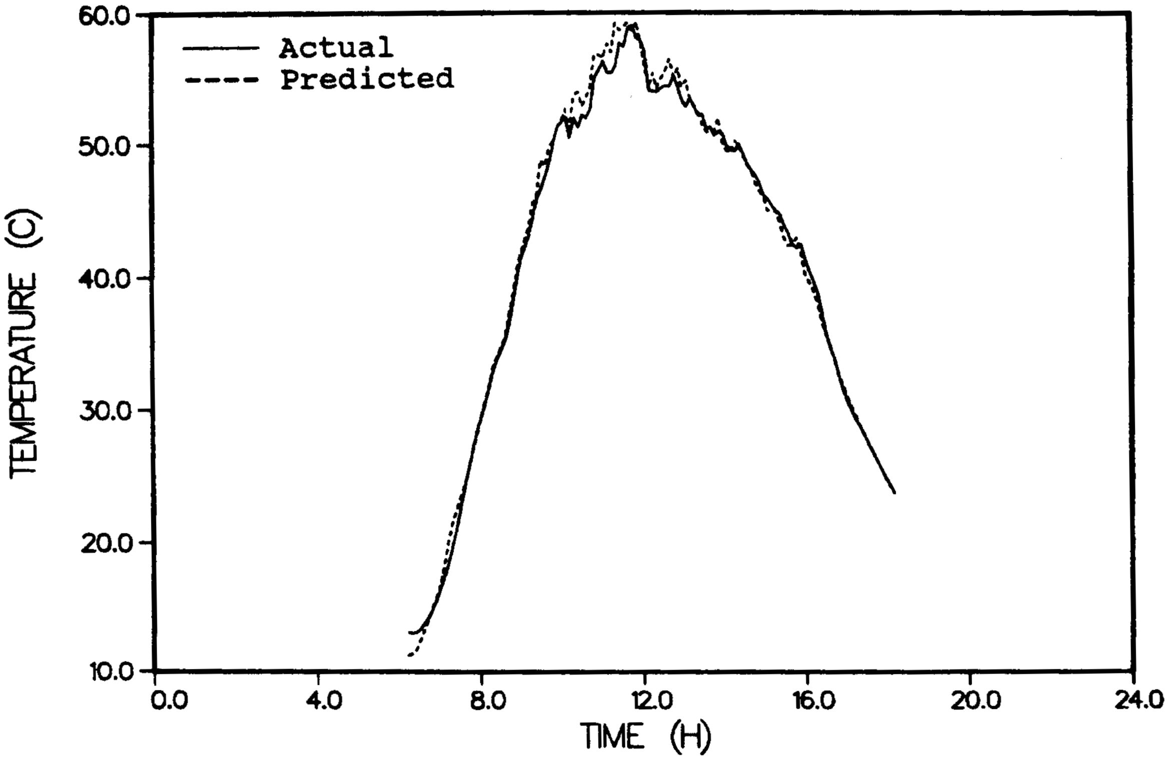

Figure C-21: Actual and predicted cell temperatures from the Westinghouse prototype at the SWRES on September 19, 1982.

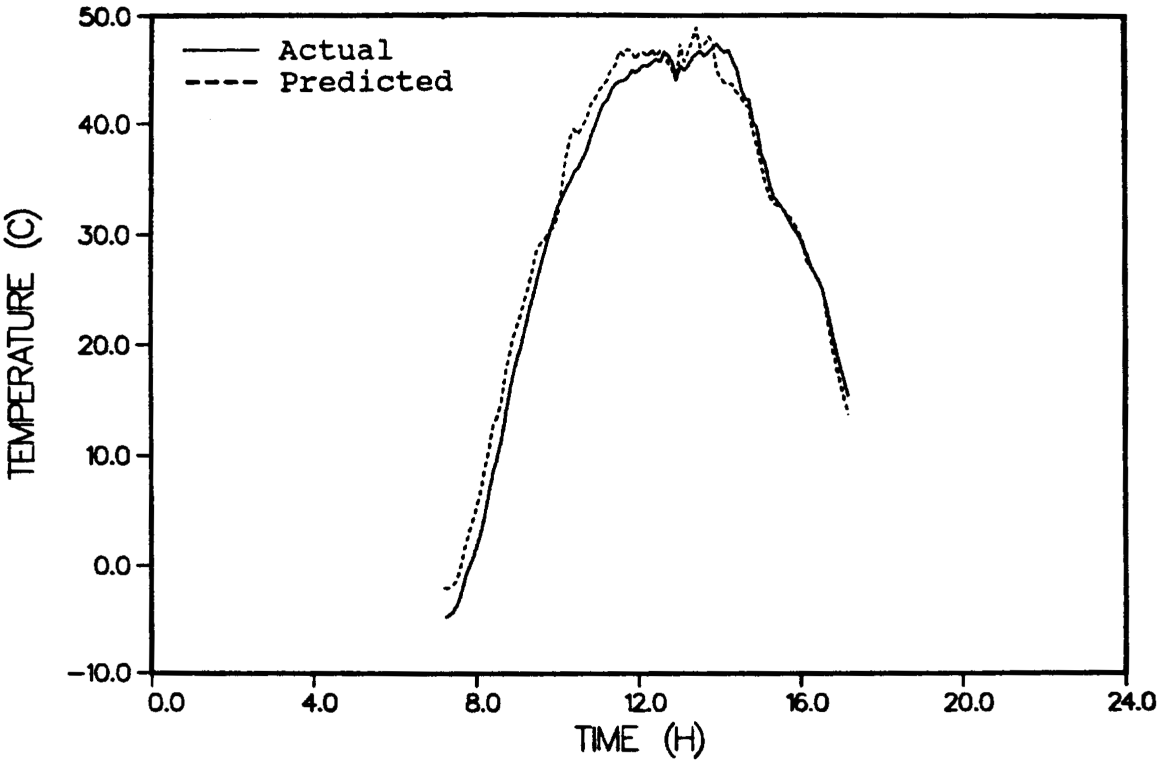

Figure C-22: Actual and predicted cell temperatures from the Westinghouse prototype at the SWRES on December 17, 1982.

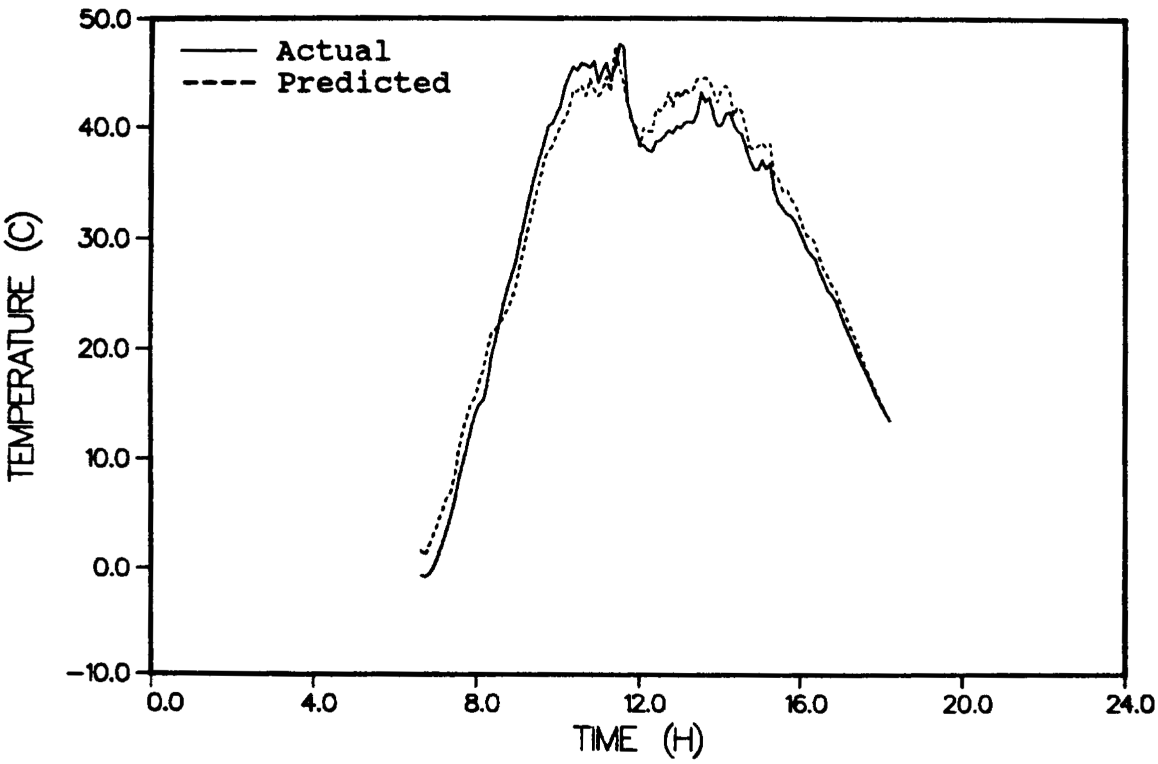

Figure C-23: Actual and predicted cell temperatures from the Westinghouse prototype at the SWRES on March 9, 1983.

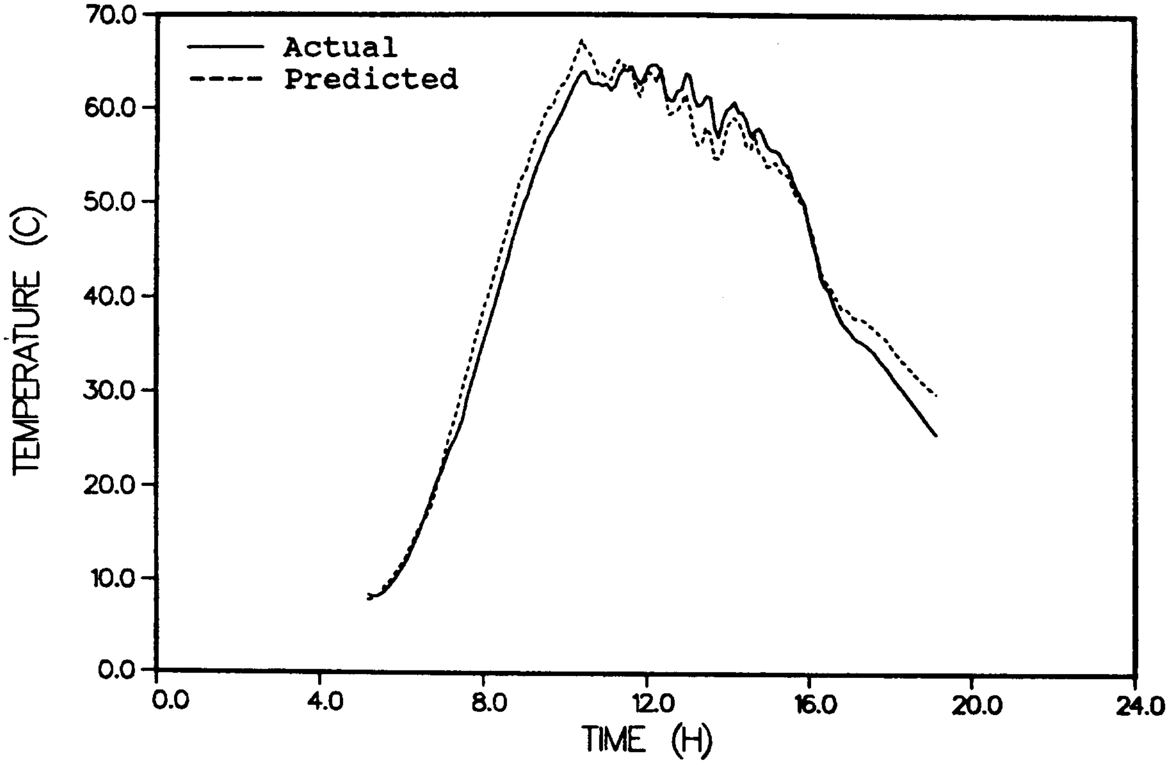

Figure C-24: Actual and predicted cell temperatures from the Solarex prototype at the SWRES on June 5, 1982.

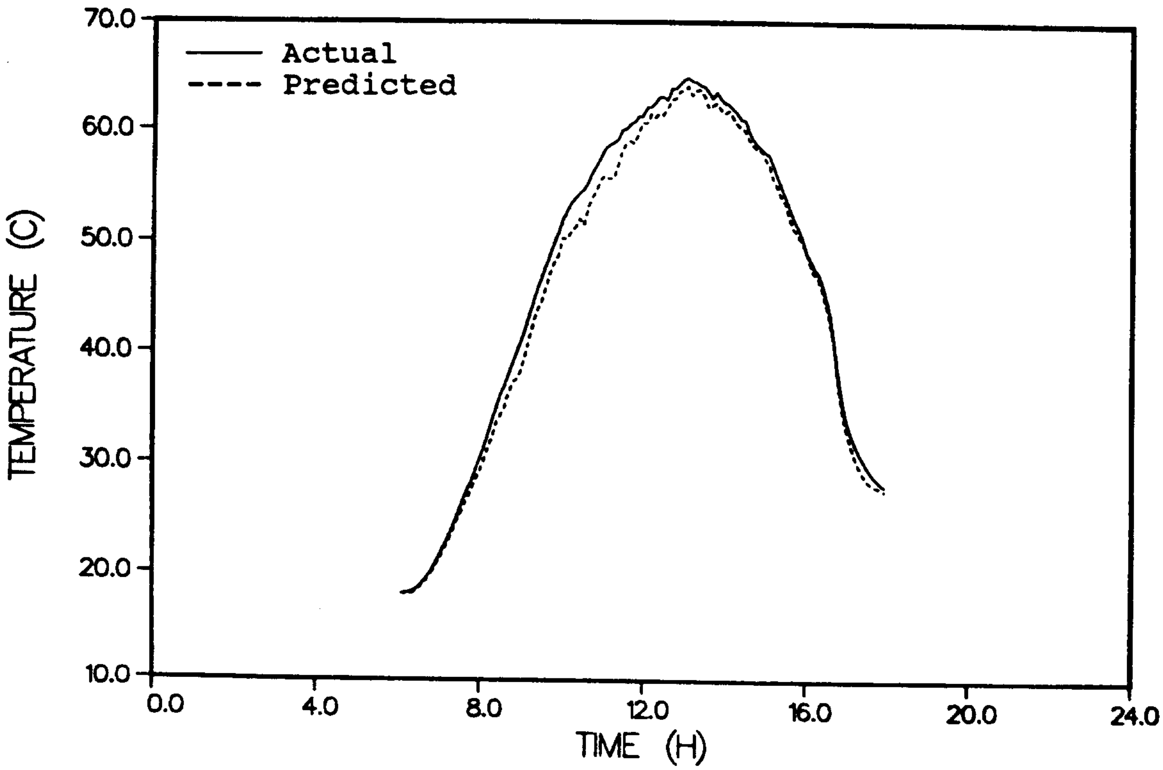

Figure C-25: Actual and predicted cell temperatures from the Solarex prototype at the SWRES on September 16, 1982.

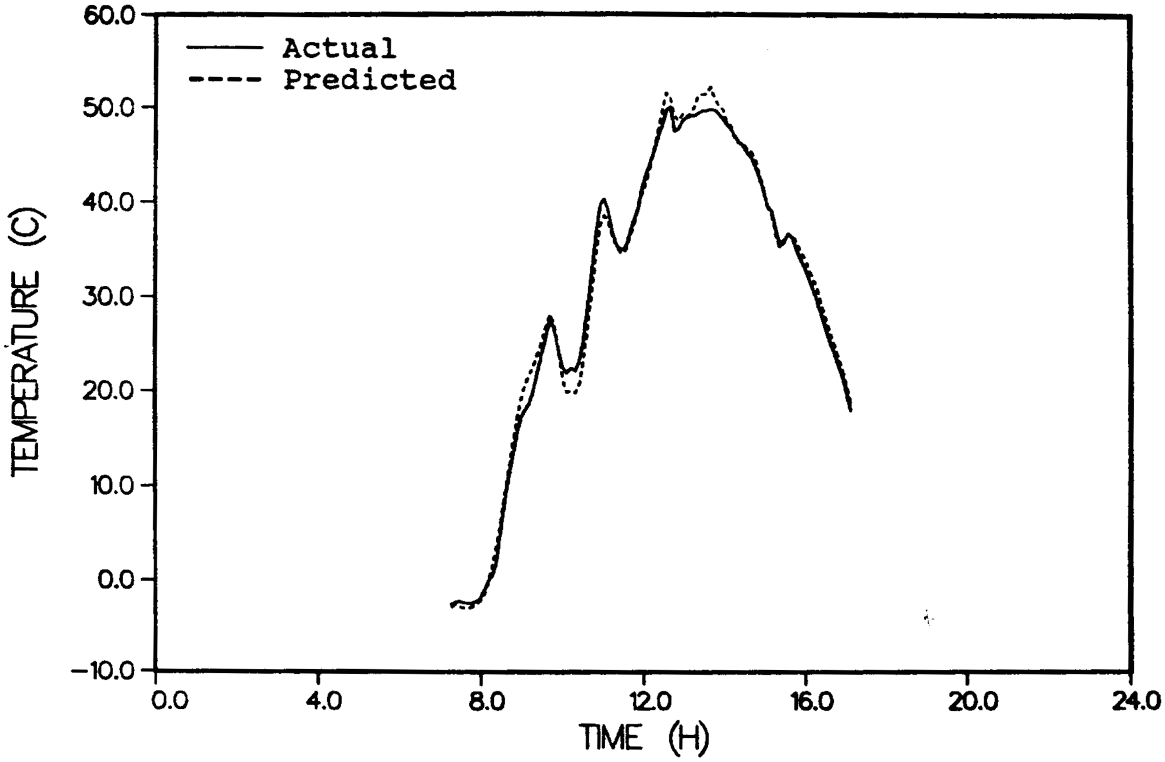

Figure C-26: Actual and predicted cell temperatures from the Solarex prototype at the SWRES on December 18, 1982.

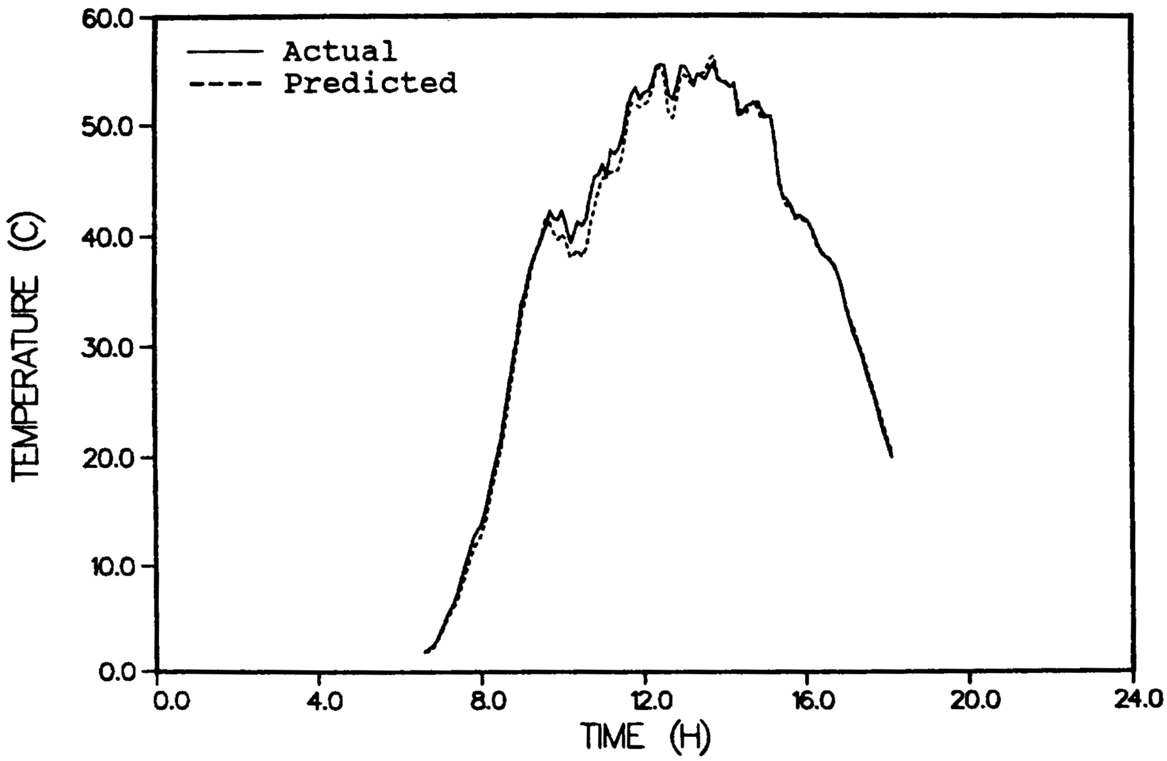

Figure C-27: Actual and predicted cell temperatures from the Solarex prototype at the SWRES on March 11, 1983.

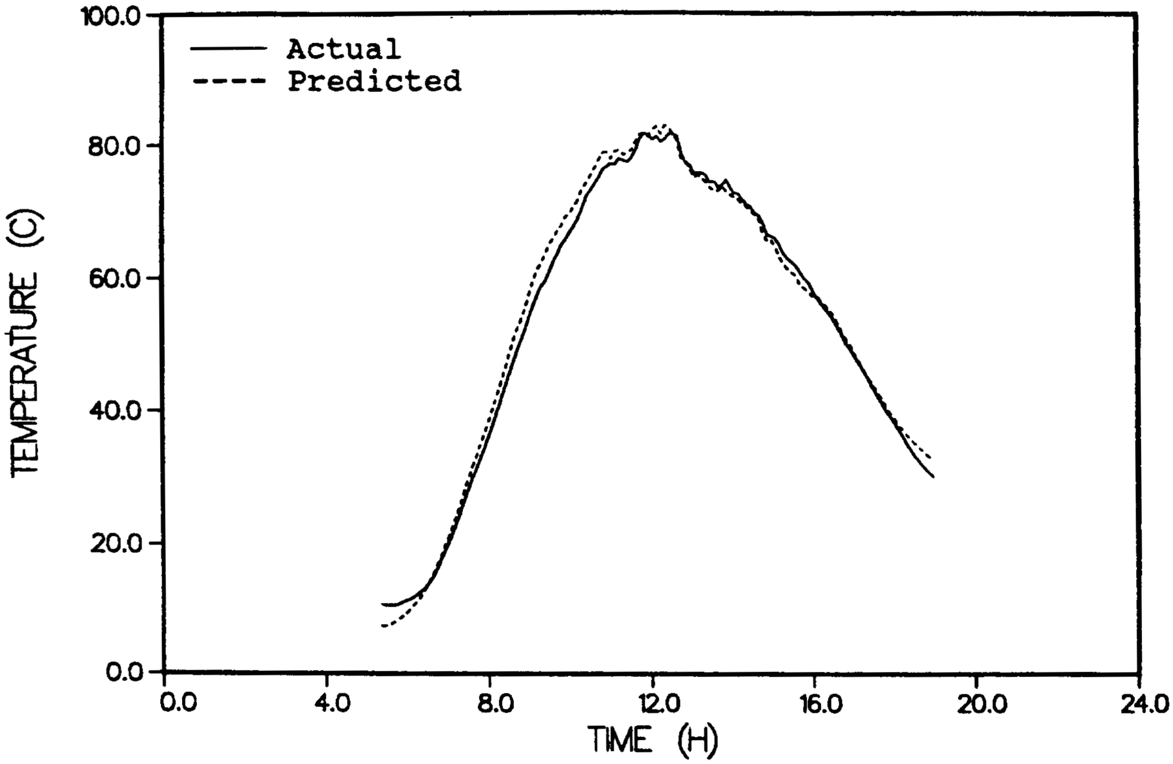

Figure C-28: Actual and predicted cell temperatures from the GE prototype at the SWRES on June 26, 1982.

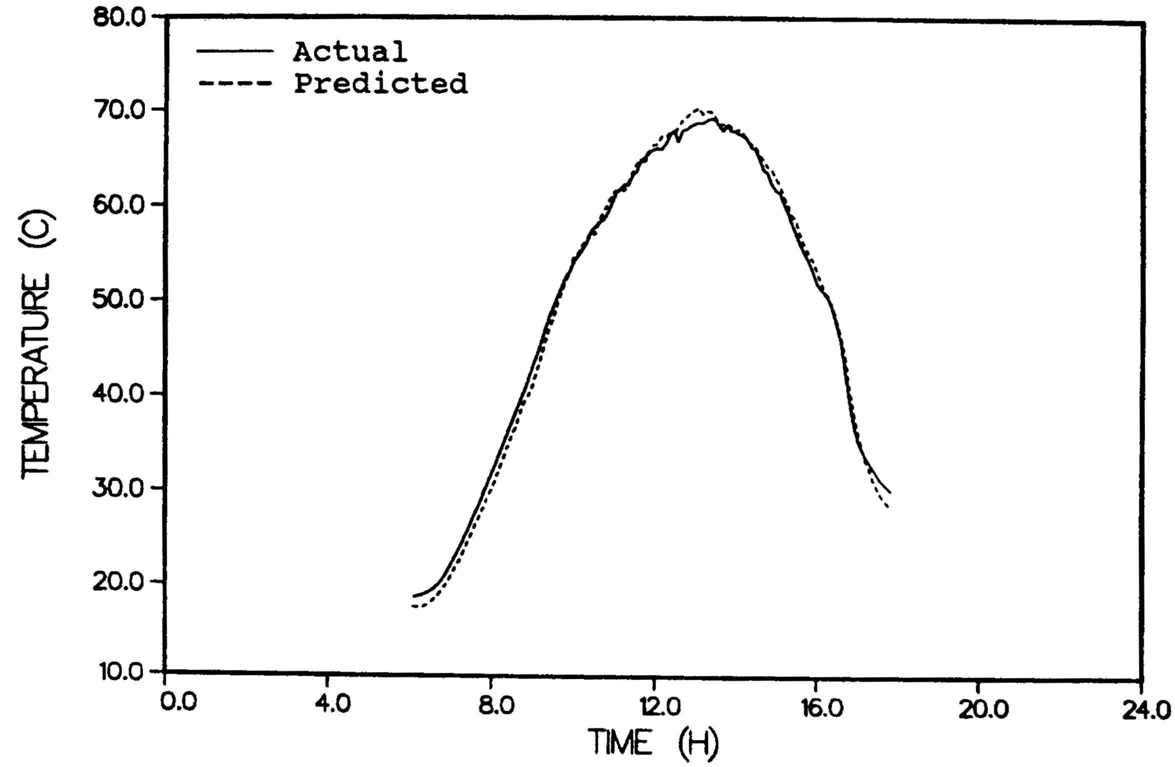

Figure C-29: Actual and predicted cell temperatures from the GE prototype at the SWRES on September 16, 1982.

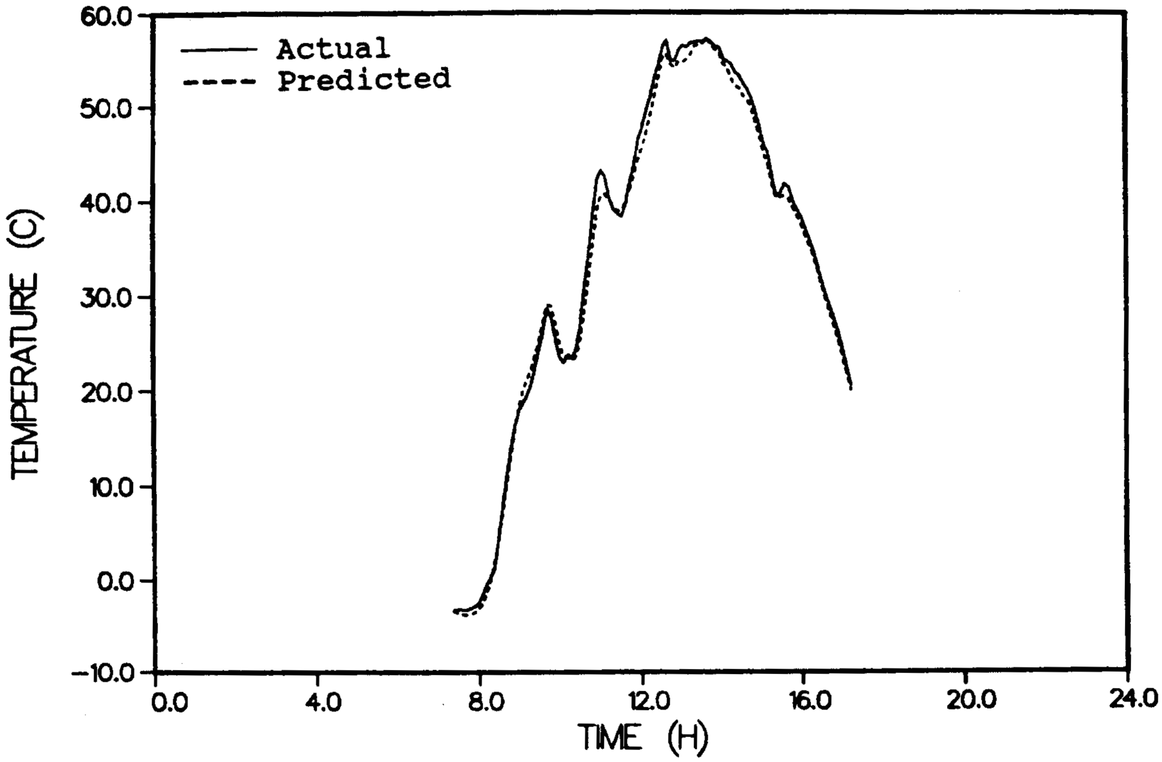

Figure C-30: Actual and predicted cell temperatures from the GE prototype at the SWRES on December 18, 1982.

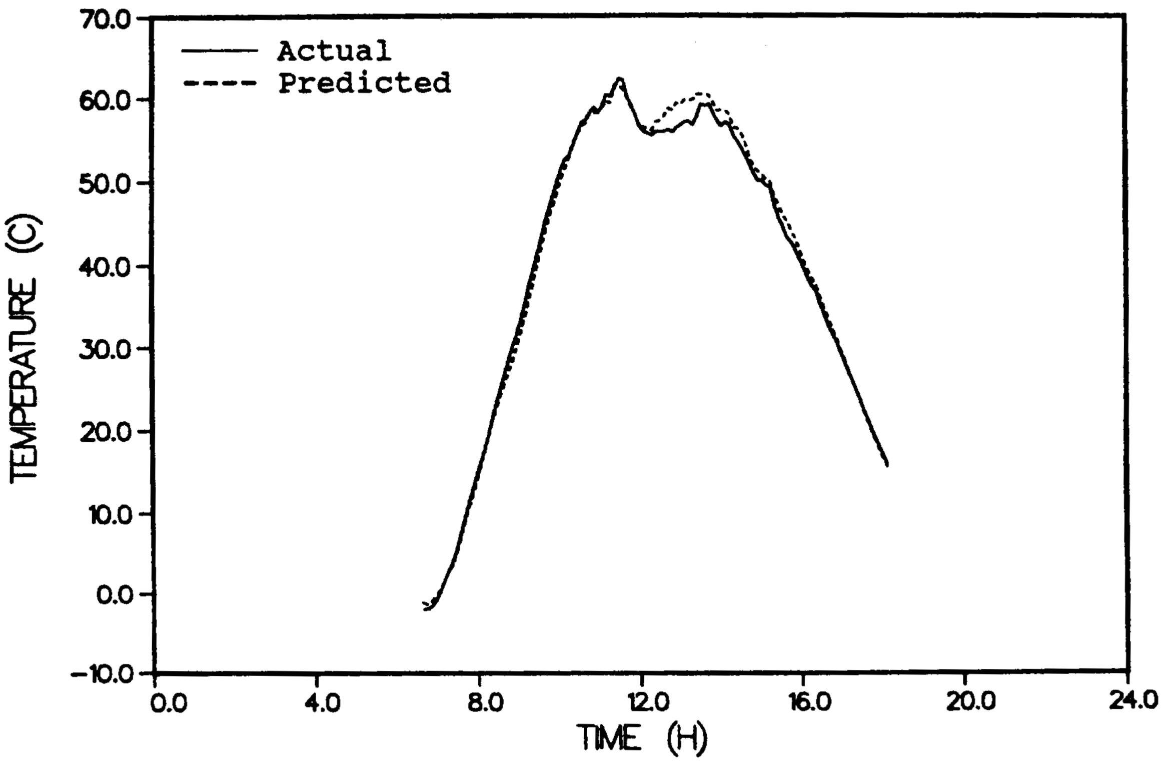

Figure C-31: Actual and predicted cell temperatures from the GE prototype at the SWRES on March 9, 1983.

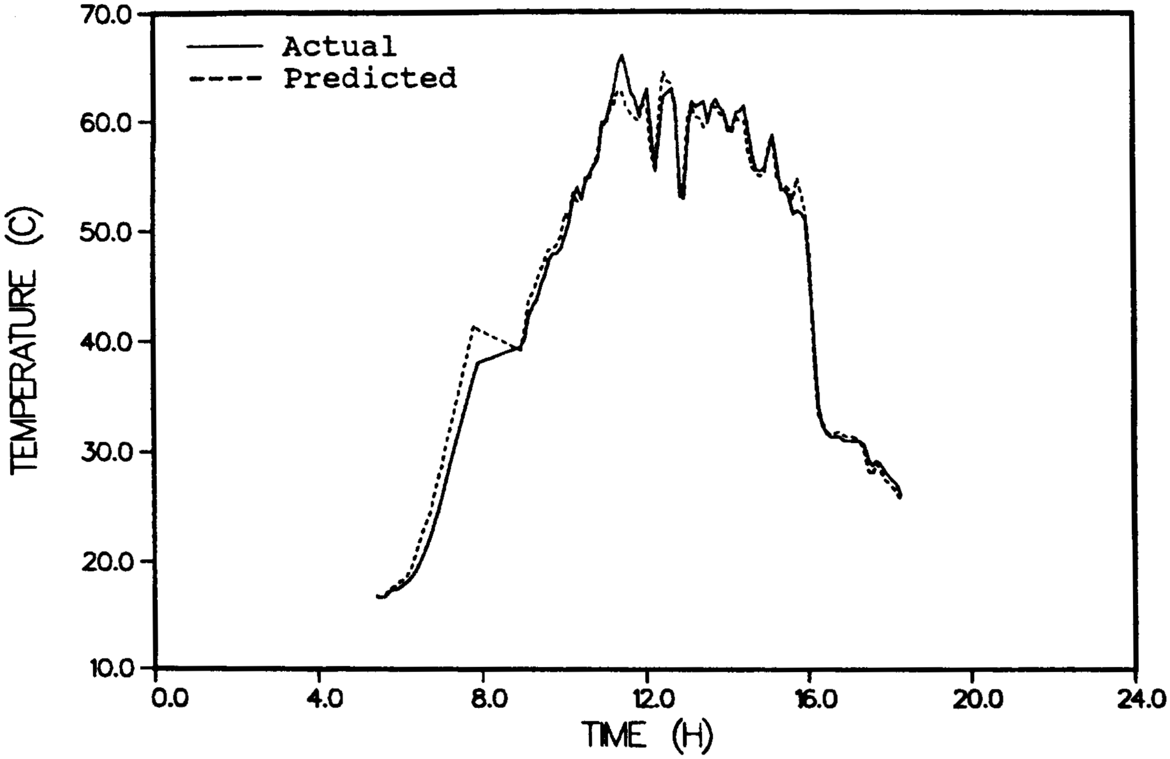

Figure C-32: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on August 1, 1984. SOH = 9 inches.

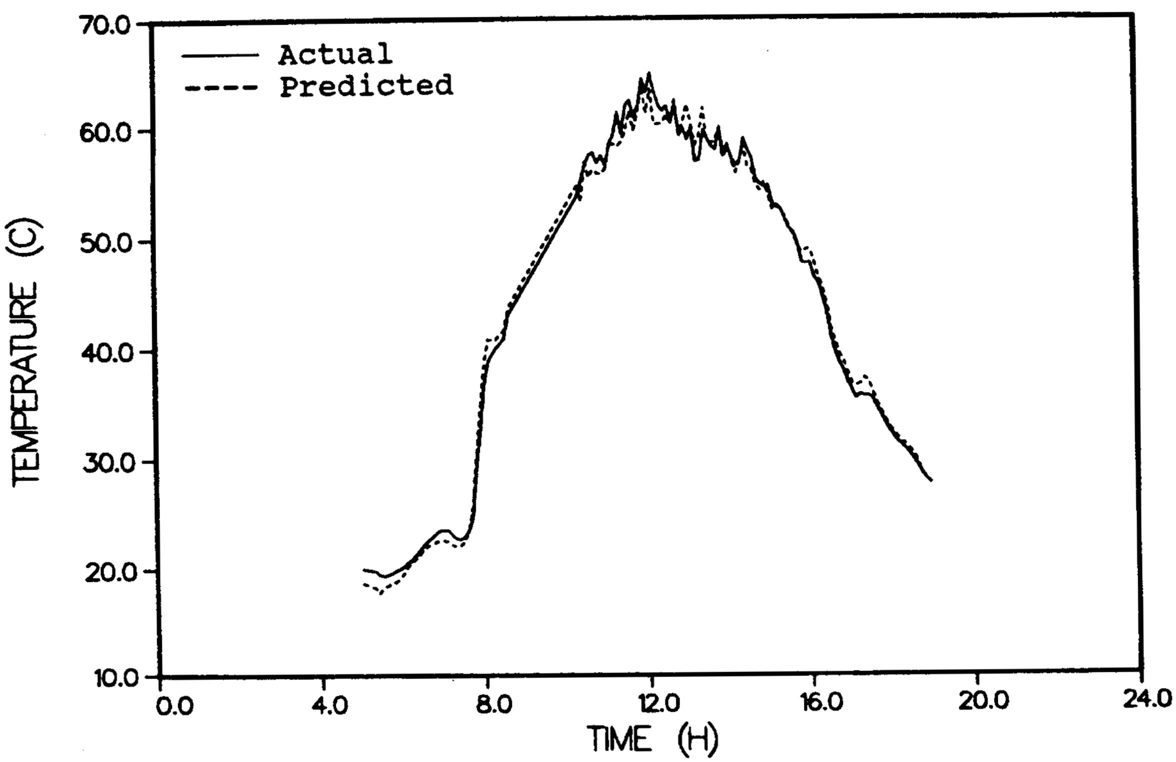

Figure C-33: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on August 2, 1984. SOH = 9 inches.

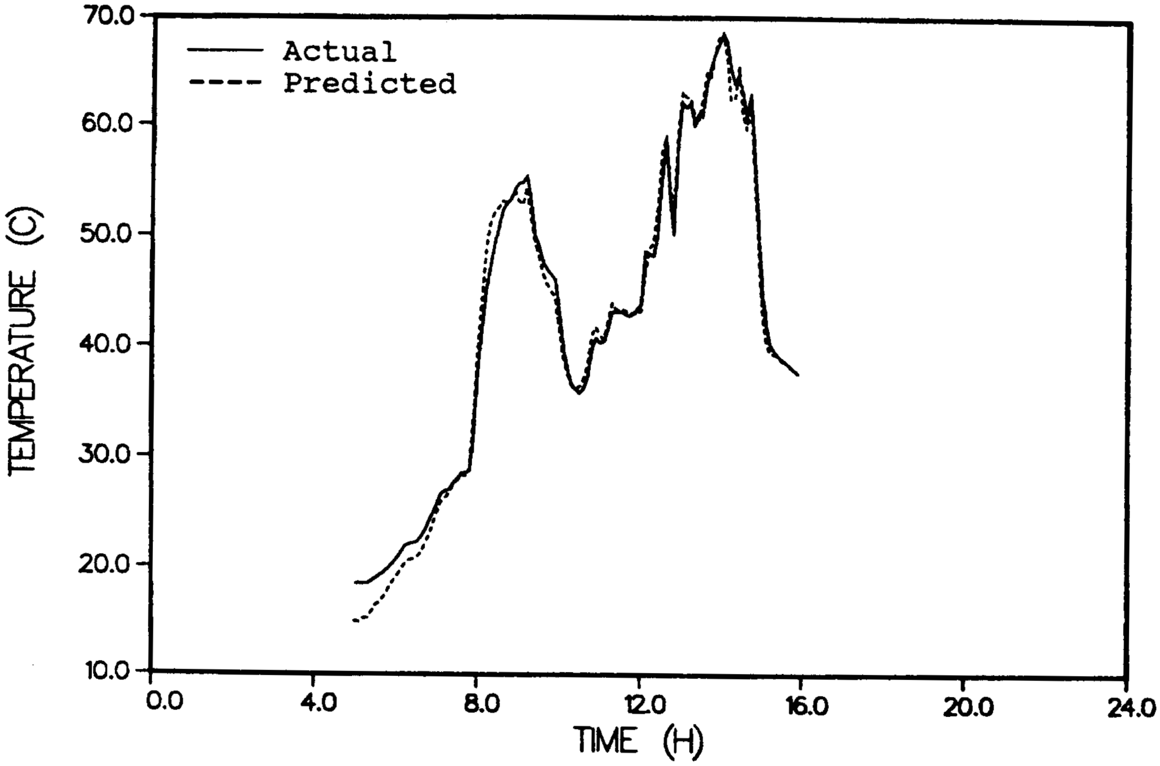

Figure C-34: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on June 22, 1984. SOH = 6 inches.

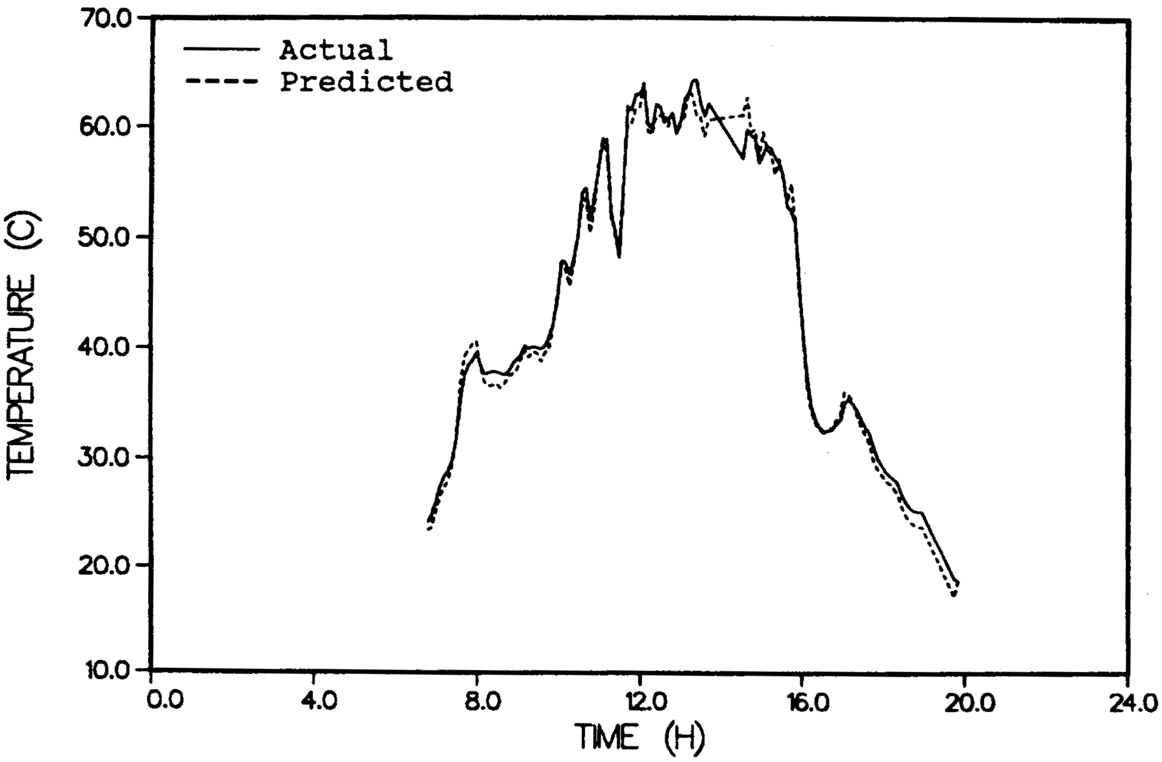

Figure C-35: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on June 27, 1984. SOH = 6 inches.

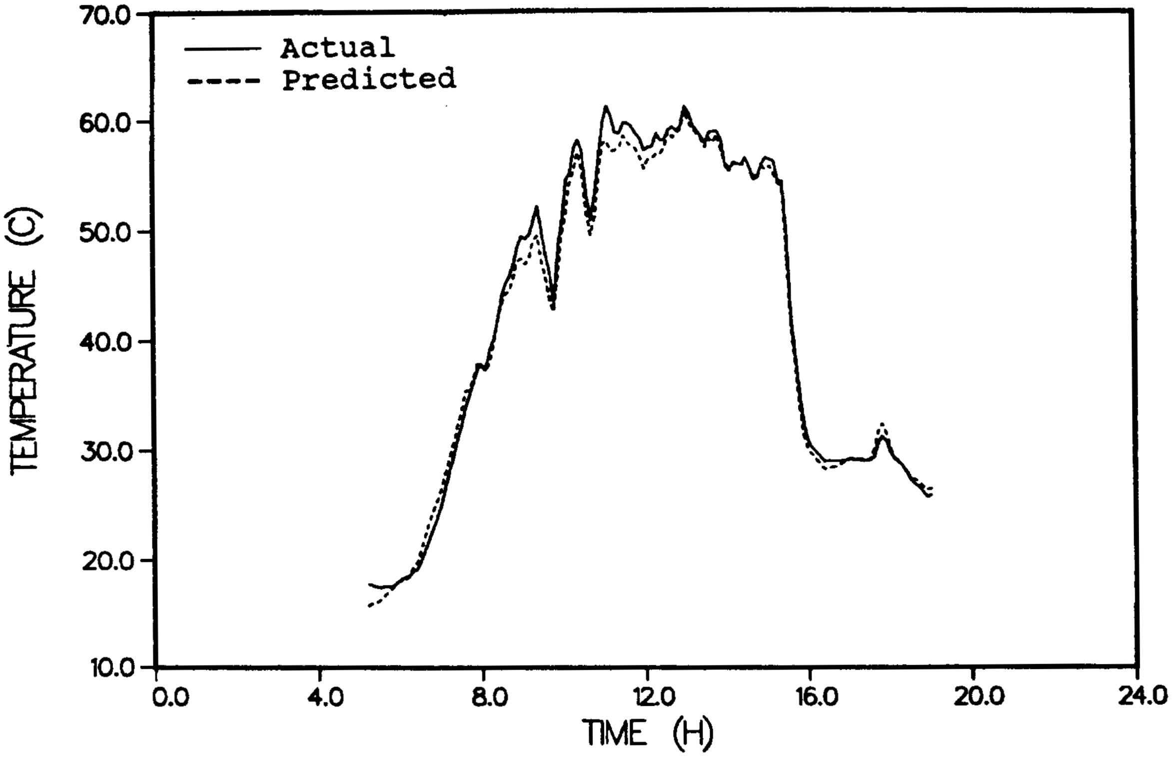

Figure C-36: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on July 21, 1984. SOH = 3 inches.

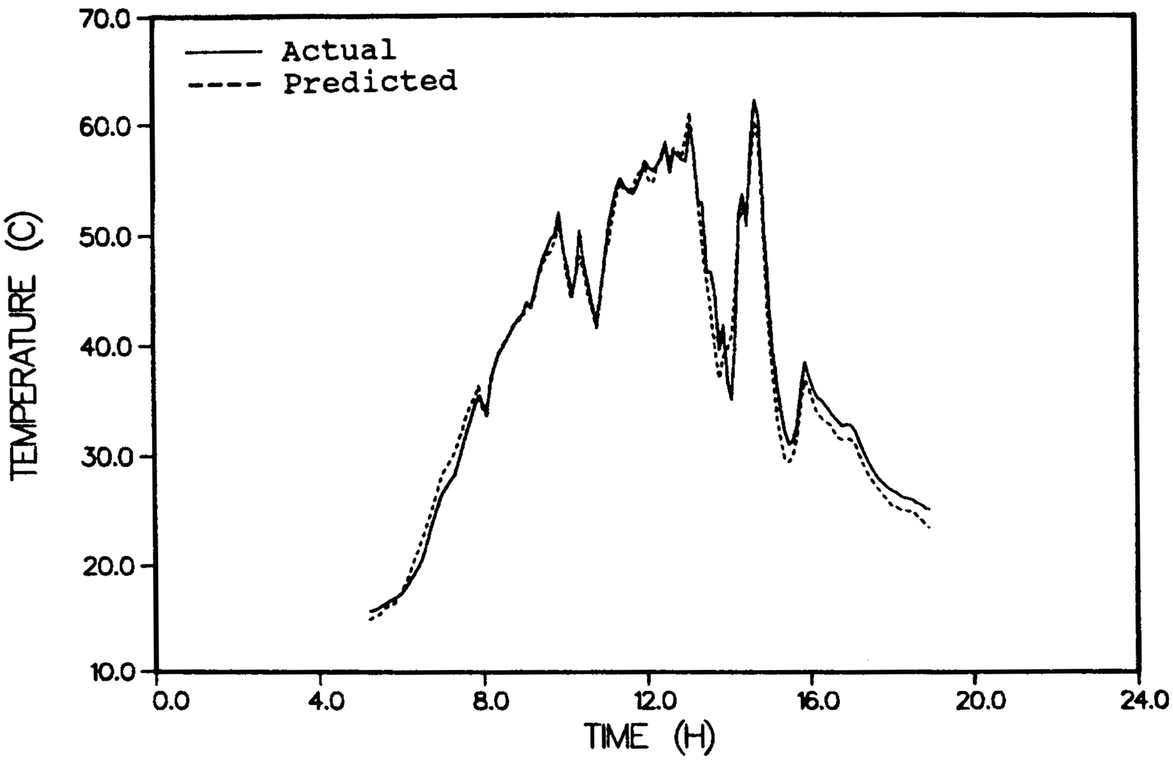

Figure C-37: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on June 22, 1984. SOH = 3 inches.

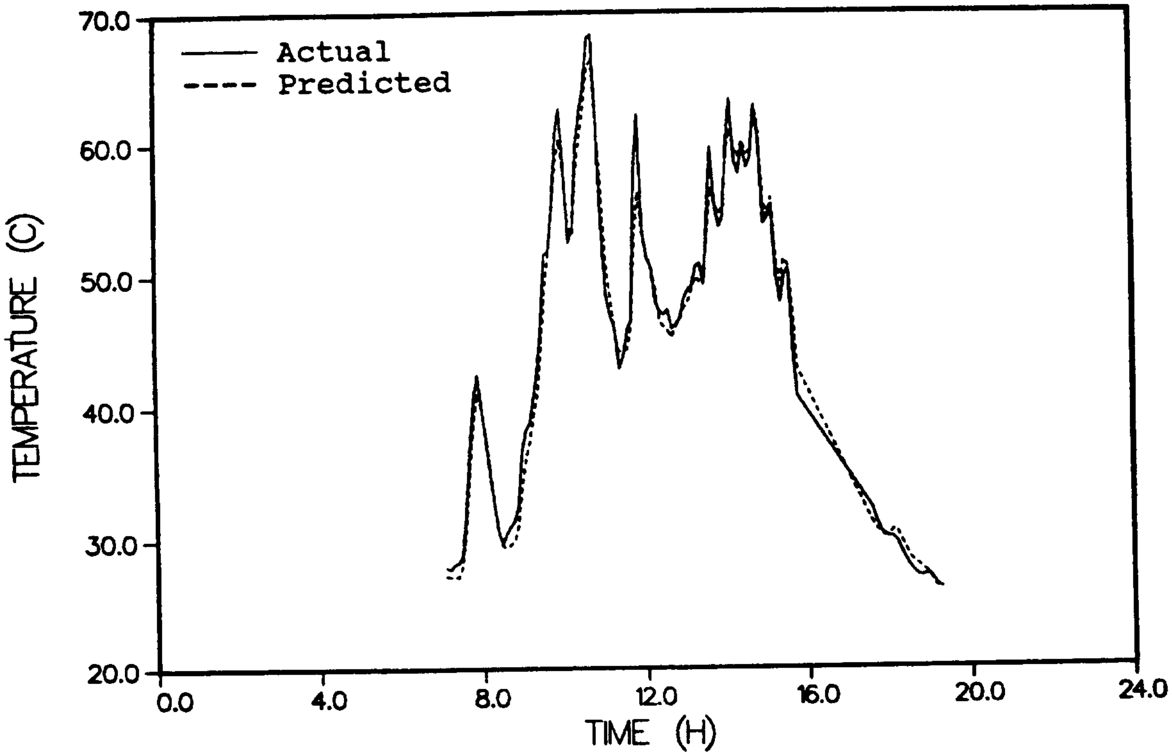

Figure C-38: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on July 12, 1984. SOH = 1 inch.

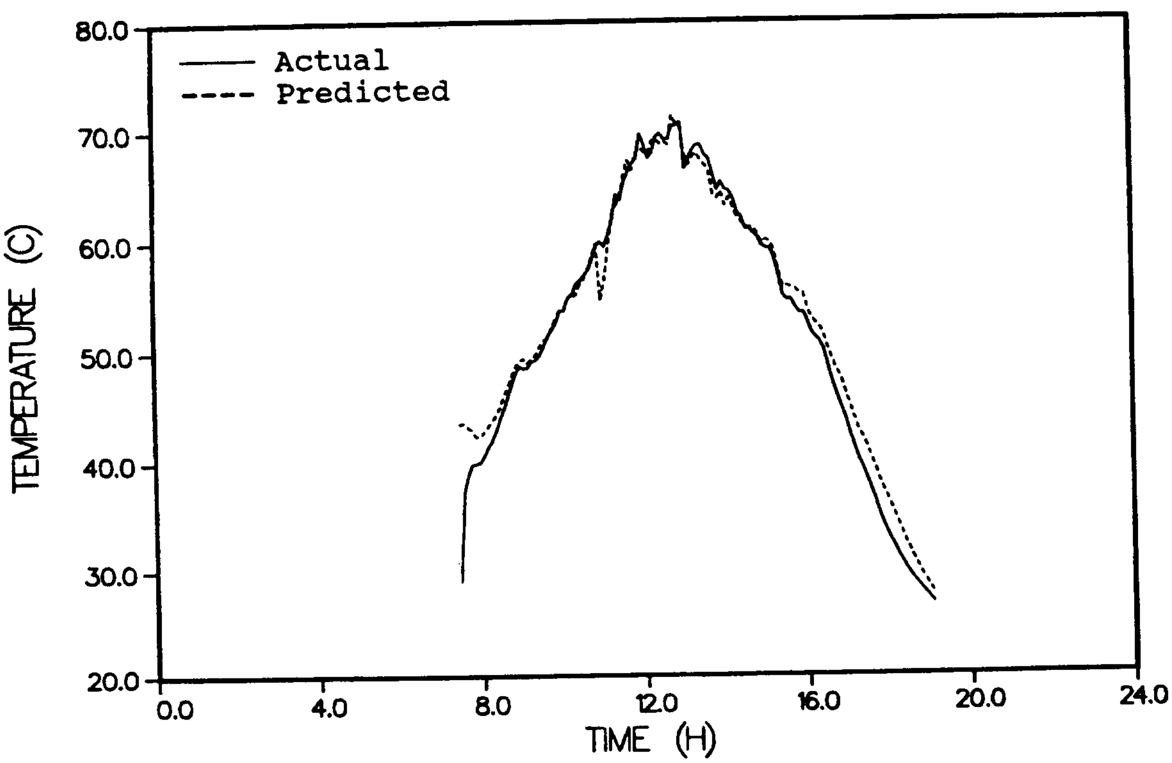

Figure C-39: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on June 13, 1984. SOH = 1 inch.

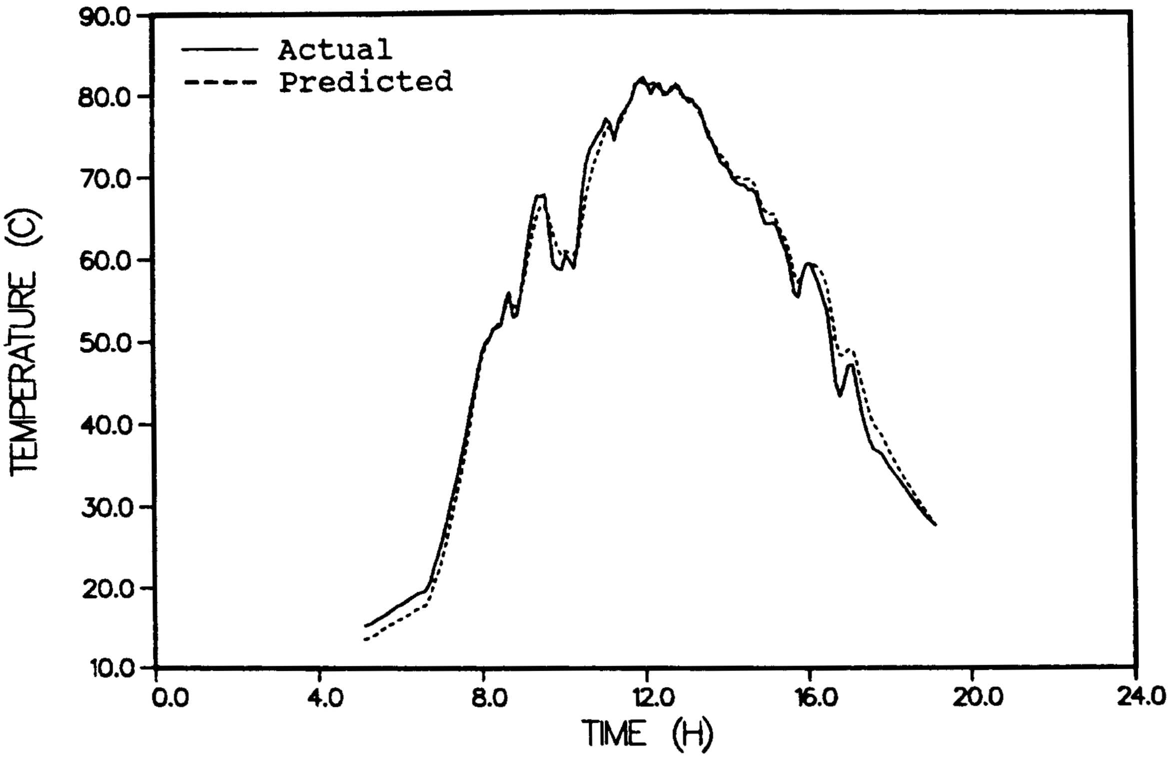

Figure C-40: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on July 1, 1984. SOH = 0 inches.

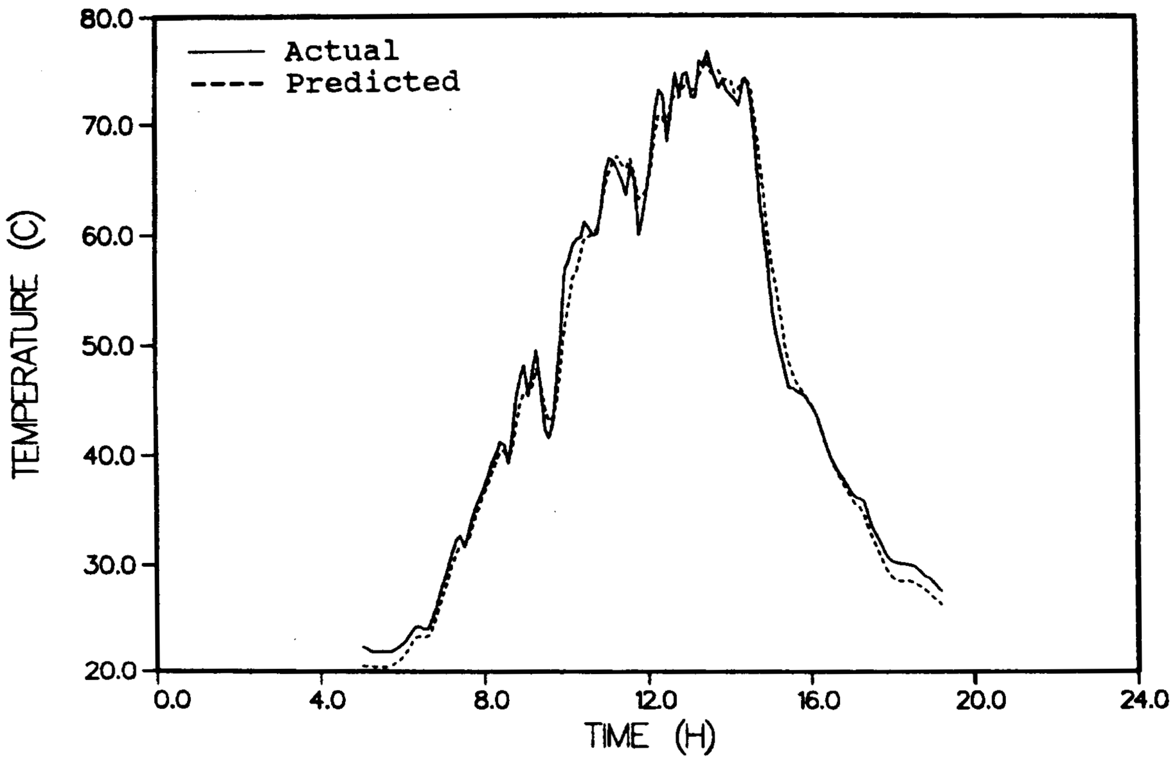

Figure C-41: Actual and predicted cell temperatures from the Flexible Testbed at the SWRES on June 2, 1984. SOH = 0 inches.

Distribution:

Acheval Wind Electronics Corp. (2)
Attn: Donald W. Bingley
James C. Wood
361 Aiken St.
Lowell, MA 01854

Acurex Corporation
Attn: Les Doss III
555 Clyde Avenue
P. O. Box 7555
Mountain View, CA 94039

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Attn: Dan Rosen
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485 Clyde Avenue
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Aerospace Corporation
Attn: Edward J. Simburger
2350 E. El Segundo Blvd.
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20442 Sun Valley Drive
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11536 Gondola Drive
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Alabama Power Co.
Attn: John T. Bambarger
600 North 18th St.
P. O. Box 2641
Birmingham, AL 35291-0650

Alpha Solarco
Attn: Don Carroll
1014 Vine St., Ste. 2530
Cincinnati, OH 45202

Alternative Sources Energy
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Milaca, MN 56353

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4440 Del Monte
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15407 Stonewood Terrace
Sherman Oaks, CA 91403

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9937 Jefferson Blvd.
Culver City, CA 90232-3591

Applied Solar Energy Corp. (4)
Attn: Frank Ho
Ken Ling
Kou-I Chang
Jawahar Tandon
15251 E. Don Julian Road
City of Industry, CA 91746

ARCO Power Systems
Attn: Floyd Blake
Suite 307
7061 S. University Blvd.
Littleton, CO 80122

ARCO Solar, Inc. (3)
Attn: James C. Arnett
Ken W. Mitchell
Gary Shushnar
9351 Deering Street
P. O. Box 2105
Chatsworth, CA 91313

ARCO Solar, Inc. (4)
Attn: Ray Kosanke
Charles Gay
Henry Yoo
Library
9351 Deering Street
Chatsworth, CA 91313

Arizona Public Service
Attn: Pete Eckert
P. O. Box 21666, Sta. 4160
Phoenix, AZ 85036

Arizona Solar Energy Commission
Attn: Robert L. Sears
Executive Tower Room 502
1700 W. Washington
Phoenix, AZ 85007

Arizona State University
Attn: Dr. Mehdi N. Bahadori
College of Architecture and
Environmental Design
Tempe, AZ 85287

Arizona State University
Attn: Charles Backus
College of Engineering
Tempe, AZ 85281

Asian Institute of Technology
Attn: Dr. F. Lasnier
Division of Energy Technology
G.P.O. Box 2754
Bangkok 10501
THAILAND

Auburn University
Attn: Ali F. Imece
Electrical Engineering Dept.
Auburn, AL 36849

Auroville International USA
Attn: Joel Goodman
P. O. Box 162489
Sacramento, CA 95816

Backwoods Cabin Electric Systems
8530 Rapid Lightning Creek Road
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Attn: Bradley E. O'Mara
7745 E. Redfield Rd. #600
Scottsdale, AZ 85260

Battelle Columbus Laboratories (2)
Attn: Donald C. Carmichael
Gerald T. Noel
505 King Avenue
Columbus, OH 43201

Ray Bahm & Associates
Attn: Ray Bahm
2513 Kimberly Court NW
Albuquerque, NM 87130

Herman G. Barkmann
Mechanical Engineer
107 Cienega
Santa Fe, NM 87501

Ron Bayes
4040 Morningstar Drive
Salt Lake City, UT 84117

The BDM Corporation (2)
Attn: Tim Lambarski
William Schwinkendorf
1801 Randolph Road SE
Albuquerque, NM 87106

The BDM Corporation
Attn: Alan Brune
8200 Mopac Expressway
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Tukwila, WA 98188

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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

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822 Calle Jinete
Sierra Vista, AZ 85635

Colorado Mountain College
Attn: Steve McCorney
Solar Program
3000 County Road 114
Glenwood Springs, CO 81601

Commission of the European Communities
Attn: Dr. G. Riesch
Joint Research Centre
Ispra Establishment
21020 Ispra (Varese)
ITALY

Jim Cullen
Jim Cullen Associates
P. O. Box 732
Laytonville, CA 95454

Cyro Industries
155 Tice Blvd.
Woodcliff Lake, NJ 07675

Delta Solar
Attn: Leon Wahler
1148 W. Fremont
Stockton, CA 95203

Dennis A. DeHaven Associates, Inc.
Attn: Dennis A. DeHaven
11 South Middletown Rd.
P. O. Box 1790
Media, PA 19063

El Paso Electric
Attn: Margaret Andriola Danao
P. O. Box 982
El Paso, TX 79960

U. S. Department of Energy (5)
Attn: A. D. Krantz
V. N. Rice
R. H. Annan
M. Prince
L. Herwig
Forrestal Bldg. - Rm. 5B066
1000 Independence Ave. SW
Washington, DC 20585

U. S. Department of Energy
Attn: Gary G. Hoffman
Western Area Power Administration
P. O. Box 3402
Golden, CO 80401

U. S. Department of Energy (3)
Albuquerque Operations Office
Attn: D. C. Graves
Joe Weisiger
D. L. Krenz
P. O. Box 5400
Albuquerque, NM 87115

U. S. Department of Energy
Attn: John Hanson
Nuclear & Geosciences Div.
P. O. Box 5400
Albuquerque, NM 87115

Design Collaborative Southwest
Attn: Marc Schiff, AIA
105 4th Street SW
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Attn: George Bolling
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DeVry Institute of Technology
Attn: Anthony Meola
2149 West Dunlap Ave.
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EG&G (5)
Attn: Karl McAllister
Gary Galbraith
Kurt Snyder
Winston Boyer
Bill Boyson
2450 Alamo SE
Albuquerque, NM 87119

Electric Power Research Institute (4)
Attn: John Schaefer
Ralph Ferraro
Roger Taylor
Ed DeMeo
P. O. Box 10412
3412 Hill View Avenue
Palo Alto, CA 94303

Electric Sun Systems
4501 E. Seneca
Tucson, AZ 85712

Energy Associates
Attn: Walter Adams
5109 Royene NE
Albuquerque, NM 87110

Energy, Inc.
Suite 101
5345 Wyoming Blvd. NE
Albuquerque, NM

Energy Engineering, Inc.
4616 McLeod Rd. NE
Albuquerque, NM

ENTECH, Inc. (3)
Attn: Mark O'Neill
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P. O. Box 612246
DFW Airport, TX 75261

Fred C. Fehrer
885 Northampton Drive
Palo Alto, CA 94303

James Ferrari
1589 Territory Trail
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Max Findell
836 Rio Arriba Ave., SE
Albuquerque, NM 87123

Edward J. Fitzpatrick
195 New Road
Southampton, PA 18966

Florida Power and Light
Attn: Gary L. Michel
P. O. Box 14000
Juno Beach, FL 33408

Florida Power & Light Corp.
Attn: Robert S. Allan
P. O. Box 14000
700 Universe Blvd.
June Beach, FL 33408

Florida Solar Energy Center (2)
Attn: Henry M. Healey
Dr. Gobind H. Atmaram
300 State Road 401
Cape Canaveral, FL 32920

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General Electric Company
Attn: P. C. Bogiages
Corporate R&D
P. O. Box 8 (KW, D286)
Schenectady, NY 12301

Georgia Institute of Technology
Attn: Sheldon M. Jeter
School of Mechanical Engineering
Atlanta, GA 30332

Georgia Institute of Technology
Attn: Dr. George J. Vachtsevanos
School of Electrical Engineering
Atlanta, GA 30332

Georgia Power Co.
Attn: Fred Krause
7 Solar Circle
Shenandoah, GA 30265

Georgia Power
Attn: Clayton Griffin
P. O. Box 4545
Atlanta, GA 30302

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
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DECC Div.
17312 Eastman St.
Irvine, CA 92714

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P. O. Drawer 1926
Albuquerque, NM 87103

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

Hughes Aircraft Corporation (3)
Attn: John A. Castle
George Naff
Neil Marshall
P. O. Box 9399
Bldg. A1 M/S 4C843
Long Beach, CA 90810-0399

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

Iowa State University
Attn: A. G. Potter
215 Coover Hall
Ames, Iowa 50010

Jacksonville Electric Authority
Attn: George S. Rizk
233 West Duval St.
Jacksonville, FL 32202

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Attn: Bob Martin
251 South Lake Avenue
Pasadena, CA 91101

L. W. James & Associates
Attn: L. James
1525 E. County Road 58
Fort Collins, CO 80524

Dr. Osamah Jamjoom
P. O. Box 8372
Jeddah
Kingdom of SAUDI ARABIA

Jet Propulsion Laboratory (3)
Attn: Russell S. Sugimura
L. Wen
Melvin Smoker
Mail Stop 507/201
4800 Oak Grove Drive
Pasadena, CA 91109

Jet Propulsion Laboratory (2)
Attn: W. Callaghan
M. Leipold
MS 502/414
4800 Oak Grove Drive
Pasadena, CA 91109

Johnson Controls, Inc.
Attn: Dr. Kathryn R. Bullock
P. O. Box 591
Milwaukee, WI 53201

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Solar Systems Division
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William Lamb Co.
Attn: Joel Davidson
10615 Chandler Blvd.
N. Hollywood, CA 91601

Lambert Technologies Corp.
Attn: John MacKay
4847 Mercury Street
San Diego, CA 92111

Norbert Larusch
700 Lomas Blvd. NE
Albuquerque, NM

Leedshill-Herkenhoff
Attn: Steve Koffman, AIA
500 Copper Avenue NW
Albuquerque, NM 87102

Lifeline Solar, Inc.
Attn: Ron Green
9550 Warner Avenue
Suite 201
Mountain Valley, CA 92708

Martin Marietta Energy
Systems, Inc.
Attn: Stephen I. Kaplan
P. O. Box Y
Oak Ridge, TN 37831

Martin Marietta (2)
Attn: H. C. Wroton
D. Hughes
P. O. Box 179
Denver, CO 80201

Massachusetts Institute
of Technology
Attn: Louis Bucciarelli
E51-201B
Cambridge, MA 02139

McCree Solar Consultants
Attn: Mark Cree Jackson
1816 Summit Drive
West Lafayette, IN 47906-2232

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
Rt. 4, Box 7B
Santa Fe, NM

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
Mississanga, 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 Firor
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 19011

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

Photocomm, Inc.
7735 E. Redfield Road
Scottsdale, AZ 85260

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

Solar Energy Research Institute (5)
Attn: Richard DeBlasio
Jack Stone
R. Hein
Donna Hawkins
Cecile Leboeuf
1617 Cole Blvd.
Golden, CO 80401

Solar Energy Research Inst. (2)
Attn: Library
1536 Cole Blvd., Bldg. #4
Golden, CO 80401

Solar Kinetics, Inc.
Attn: David L. White
10635 King William Dr.
Dallas, TX 75220

Solarex Corporation (2)
Attn: Ramon Dominguez
Eric E. Daniels
1335 Piccard Drive
Rockville, MD 20850

Solarex Corporation (4)
Attn: Richard Keller
Ted Blumenstock
Daniel Bumb
Jeff German
6510 W. 91st Avenue, Suite 102
Denver, CO 80030

Solarize, Inc.
Attn: John Berdner
1450 Harbor Blvd.
Suite D
West Sacramento, Ca 95691

Solar Products
HC 30, Box 890
Prescott, AZ 86301

Solar Systems Design, Inc.
RD 1, Box 462A
Voorheesville, NY 12186

Solavolt International (2)
Attn: Bill Bailey
Paul Garvison
P. O. Box 2934
Phoenix, AZ 85062

Solarwest Electric
232 Anacapa Street
Santa Barbara, CA 93101

Solar Works
Attn: Paul Wilkins
Rt 2, Box 274
Santa Fe, NM 87501

Southern California Edison (4)
Attn: Nick Patapoff
Thomas J. Ardizzone
Bill Rothenbuhler
Spencer Carlisle
Research and Development
P. O. Box 800
Rosemead, CA 91770

Southern Company Services, Inc. (2)
Attn: J. Timothy Petty
J. Grott
P. O. Box 2625
Birmingham, AL 35202

Sovonics Solar Systems
Attn: Ronald C. Cull
4440 Warrensville Center Rd.
Cleveland, OH 44128

Spectrolab (3)
Attn: Jan Smith
Ron Diamond
J. Minahan
12500 Gladstone Avenue
Sylmar, CA 91342

Spire Corporation (6)
Attn: Steve Hogan
S. Tobin
R. Little
M. Spitzer
M. Nowlan
S. Rechtoris
Patriots Park
Bedford, MA 01730

Springborn Laboratories, Inc.
Attn: Bernard Baum
Enfield, CT 06082

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
58 Oakdale Ave.
San Rafael, CA 94901

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

University of Alabama JEC
Attn: Leonard Adcock
Test Facility
Huntsville, AL 35899

University of Arizona
Attn: Adrian Tylin
Department of Nuclear Engineering
Engineering Bldg., Room 104
Tucson, AZ 85721

University of Arizona
Attn: Francisco Luttmann
Nuclear and Energy Engineering
Tucson, AZ 85721

University of Arizona
Attn: Donald E. Osborn
College of Engineering
Solar and Energy Research Facility
Harvill Bldg. Box 11, Room 151
Tucson, AZ 85721

University of Cape Town
Attn: Dr. A. A. Eberhard
Energy Research Institute
Private Bag
Rondebosch 7700
SOUTH AFRICA

University of Chicago
Attn: Joseph O'Gallagher
5640 S. Ellis Avenue
Chicago, IL 60637

University of Delaware
Attn: Allen M. Barnett
Electrical Engineering Dept.
Newark, DE 19711

University of Kansas
Attn: Dave Martin
2291 Irving Hill Dr.
Campus West
Lawrence, KS 66045-2969

University of Lowell
Attn: Stuart L. Frye
One University Ave.
Lowell, MA 01854

University of New Mexico
Attn: Dr. W. A. Gross
Dept. of Mechanical Engr.
Albuquerque, NM 87131

University of New Mexico
New Mexico Engr. Res. Inst. (2)
Attn: G. Leigh
J. Fernandez
Campus Box 25
Albuquerque, NM 87131

University of Queensland
Attn: Peter Jolly
SERC
St. Lucia, Queensland
AUSTRALIA

University of Texas at Arlington
Attn: Jack Fitzer
Electrical Engineering Dept.
Arlington, TX 76019

University of Wisconsin
Attn: Prof. J. D. Wiley
Dept. of Electrical Engr.
Madison, WI 53706

University of Wisconsin
Attn: Dr. Sandy Klein
Dept. of Mechanical Engineering
Madison, WI 53706

US Army Corps of Engineers
Attn: Linda Lawrie
P. O. Box 4005
Champaign, IL 61820

Varian Associates (4)
Attn: C. Hamaker
N. Kaminar
G. Virshup
J. Werthen
611 Hansen Way - K-219
Palo Alto, CA 94303

Virginia Polytechnic Institution
Attn: Saifur Rahman
Electrical Engineering Dept.
Blacksburg, Va 24061

Virginia Power Co. (2)
Attn: J. W. Greene
Wendy Thompson
P. O. Box 26666
Richmond, VA 23261

George Warfield
RD 2, Box 264
Vergennes, VT 05491

WATSON Simulation Laboratory
Attn: Larry D'Andrea
University of Waterloo
Waterloo, Ontario N2L3G1
CANADA

Westwork Architects
2403 San Mateo Blvd. NE
Albuquerque, NM

Arthur T. White
6411 Valley Circle Terr.
Canoga Park, CA 91307

A. N. Williams and Associates
Attn: A. Nash Williams
P. O. Box 492
Bonsall, CA 92003

Kendall Williams
106 Avila Road
San Mateo, CA 94402

Larry Workenpin
502 Stroop Ave.
Ridgecrest, CA 93555

Windlight Workshop
P. O. Box 548
Santa Cruz, NM 87567

Omar Wood
P. O. Box 8
San Juan Capistrano, CA 92693

World Crafts Foundation
Attn: Hans Guggenheim
401 Park Avenue South
New York, NY 10016

Wright Patterson AFB
Attn: Jack Geis
AFWAL/POOC
Wright Patterson AFB, OH

Wyle Labs (2)
Attn: Dave Christenson
George Meares
7800 Governors Drive West
Huntsville, AL 35807

Zomeworks
Attn: Steve Baer
1221 Edith NE
Albuquerque, NM

Harry Zuckerberg
MS DTS54
Transportation Systems Ctr.
Kendall Square
Cambridge, MA 02142

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