SIMPLIFIED DESIGN METHODS
FOR PHOTOVOLTAIC SYSTEMS

BY

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ABSTRACT

The objective of this research is to develop an accurate and simple method for analyzing photovoltaic system performance. This is accomplished by examining three aspects affecting system performance.

1. Array output
2. Excess energy (above the instantaneous demand)
3. Battery effects

A method is devised for predicting the monthly average photovoltaic array efficiency using system parameters and monthly average meteorological data. Then monthly average photovoltaic array output is simply the product of the efficiency and the incident radiation. Results obtained using this method are found to agree with detailed computer simulation results within a standard deviation of ±1.5%.

Excess energy must be either dissipated, fed back into the utility grid or stored in a battery. A method is developed for determining the amount of energy dissipated or fed back into the utility grid. The monthly average performance of these systems can then be calculated. Values of monthly average performance obtained from this method compare with computer simulation results within a standard deviation of ±2.0%.

Finally, a method is described which can be used to approximate the effects of battery storage on system performance.

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TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF FIGURES

LIST OF FIGURES
(Continued)

LIST OF TABLES

NOMENCLATURE*

A - Array area

A_c - Total cell area

Be - Effective battery storage capacity

C_p - Number of battery cells in parallel

C_s - Number of battery cells in series

f - Monthly average fraction of the load supplied by the photovoltaic array

f_B - Usable fraction of battery storage

f_{BL} - Monthly average fractional battery losses

G_c - Critical radiation level

$\overline{G}_c$ - Monthly average critical radiation

G_n - Radiation at noon on the average day of the month

G_T - Instantaneous radiation incident upon a tilted surface

H - Daily radiation incident upon a horizontal surface

H_o - Daily extraterrestrial radiation on incident upon a horizontal surface

H_T - Daily radiation incident upon a tilted surface

$\overline{H}_T^+$ - Monthly average daily radiation on a tilted surface during the hours when the incident radiation upon the tilted surface is greater than the average critical level.

K_T - Ratio of daily radiation to extraterrestrial radiation on a horizontal surface

MN - Month

N - Number of days in a month

N_c - number of hours in a month during which the radiation incident upon the tilted surface is greater than the critical level

P_f - Cell packing factor

Q - Battery state of charge

Q_m - Battery capacity

Q_{DEL} - Energy deliverable to the load

Q_E - Array output

Q_L - Load demand

Q_{UL} - Energy to or from an auxiliary source (i.e. utility grid)

QB - Energy to or from battery storage

QB_L - Battery losses

QD_A - Energy dissipated in a photovoltaic system with battery storage

QD_o - Energy dissipated in a photovoltaic system with no battery storage

$r_{t,n}$ - The fraction of the daily radiation incident upon a horizontal surface during an hour entered about noon on the average day of the month

$\overline{R}$ - Ratio of monthly total radiation: incident upon a tilted surface to that on a horizontal surface

R_L - Array load resistance

R_n - Ratio of radiation at noon on a tilted surface to that on a horizontal surface for an average day of the month

S - Array tilt

T_a - Ambient temperature

T_c - Cell temperature when the cell efficiency is zero

T_{CELL} - Instantaneous cell temperature

T_R - Reference temperature for cell reference fficiency

U_{L_o} - Array loss coefficient

V_{oc} - Open circuit voltage

X_c - Dimensionless critical radiation level

α - Cell absorptance

β_R - Temperature coefficient of solar cell efficiency

$\overline{\phi}$ - Monthly average collector utilizability

$\emptyset$ - Latitude

η - Instantaneous array efficiency

$\overline{\eta}$ - Monthly average array efficiency

$\overline{\eta}^+$ - Monthly average daily array efficiency during those hours when the radiation on the tilted surface is greater than the critical level

η_a - Instantaneous array efficiency at ambient temperature

η_I - Inverter efficiency

η_v - Voltage regulator efficiency

η_R - Reference array efficiency at temperature T_R

η_R' - Reference cell efficiency at temperature T_R

η_{R_o} - Reference array efficiency at $T_{CELL} = 0°C$

$\bar{\eta}_s$ - Monthly average system (i.e. power conditioning equipment) efficiency

τ - Array cover transmittance

$\bar{\tau}$ - Monthly average array cover transmittance

$\overline{\tau\alpha}$ - Monthly average transmittance-absorptance product

ω_s - Sunrise hour angle

ω_s' - Collector surface hour angle

$\int_M$ - Integral over a month

$\int_{N_c}$ - Integral over N_c hours

If not otherwise defined, a "—" over any symbol indicated a monthly average daily value

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* This list contains most of the nomenclature used in this thesis. Additional symbols are defined locally.

1. INTRODUCTION

1.1 Overview

In a short period of time, photovoltaic arrays will be used to generate electrical energy that will be economically competitive with conventional utility generated electricity. When this time arrives, the successful design of photovoltaic systems will depend on the quality and availability of system design procedures. This research has as its objective the development of an accurate and simple design method for analyzing photovoltaic system performance.

The photovoltaic system configuration shown in Figure 1-1 is representative of the photovoltaic systems studied. The solar radiation incident on the photovoltaic array is partially absorbed and converted into d.c. power. The amount of power generated will depend on the concentration and total amount of solar radiation, the total solar cell area and the radiation to electrical energy conversion efficiency.

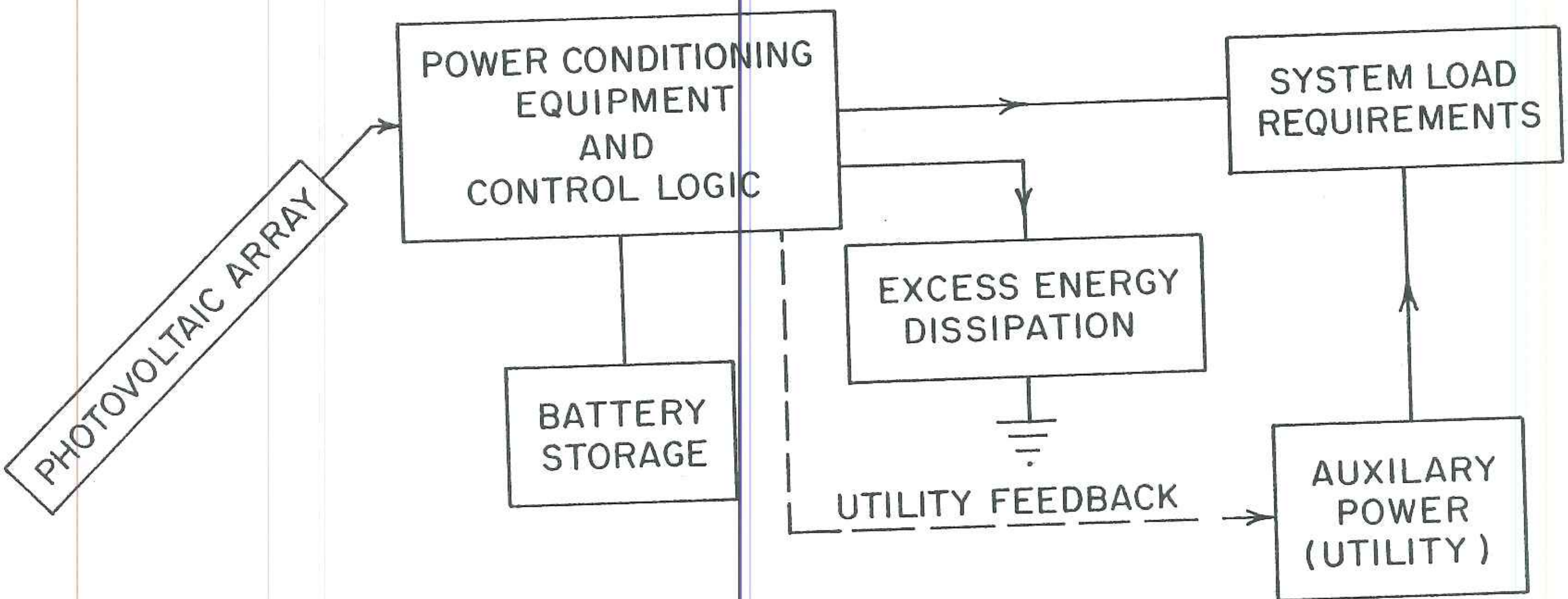


Figure 1-1 Schematic of a Photovoltaic System

The photovoltaic array output power must be properly conditioned and distributed to the various system components. A specific set of control instructions will determine where the array output is sent. For example, in most systems, if the load requirement is greater than the array output power, the control strategy is to deliver all the array output power to the load. On the other hand, if the available array output power is greater than the load requirement, the excess energy may be stored in a battery for use at another time. As an alternative to battery storage, the excess energy may be fed back into the utility grid. If utility feedback and battery storage capabilities are not available, then the excess energy must be dissipated. In any case, any energy required by the load which is not supplied by the array output must be supplied from the auxiliary source, usually a utility grid.

The overall system performance will depend on the specifications of the various system components. The task of a system designer is to determine an optimal system design by comparing alternative system configurations and component specifications. When evaluating system performance two possible approaches are available. The first method utilizes detailed computer simulation models and hourly meteorological data to determine hourly system performance. Long-term system performance is determined by summing the hourly results obtained from the computer simulation.

The use of detailed computer simulation models requires a great deal of time, expertise and expense. Alternatively, simplified design methods can offer the designer a rapid and simple procedure to determine monthly average system performance (using only monthly average meteorological data). The results obtained from simplified design methods compare favorably with detailed computer analyses. This research presents a simplified design method which can be used by the designer to effectively compare alternative system designs. For convenience, the entire design method is organized in a simple computer program called, "PV-DESIGN".

1.2 Literature Survey

The use of simplified design methods for analyzing photovoltaic system performance is a relatively new field. Photovoltaic system analysis has traditionally been accomplished using complicated computer simulations. A series of "Conceptual Design and Systems Analysis of Photovoltaic Power Systems" studies were undertaken by Westinghouse Electric Corporation[1], General Electric Co.[2] and Spectrolab, Inc.[3] The primary objective of each of these reports was to provide conceptual design and systems analysis information for three sizes of terrestrial photovoltaic systems, intended for application to a single family residence, a central station power plant and an on-site intermediate system (shopping center and a commercial retrofit). In addition, these reports examine the financial, environmental, legal and institutional issues related to the actual implementation of these photovoltaic systems.

Generalized computer simulation models for photovoltaic system components have been developed by Evans, et al[4] at Arizona State University under a Sandia Laboratories contract. These simulation models can be used to perform hour by hour calculations to evaluate photovoltaic system performance.

This research utilizes the computer models formulated by Evans and solar engineering concepts to develop simplified design methods. These simplified design methods can be used to determine the monthly average photovoltaic system performance.

1.3 Photovoltaic System Configurations

1.3.1 Common System Components

The design procedures developed in later chapters can be used to determine the long-term average performance of several photovoltaic system configurations. Certain system components will be common to all photovolatic systems examined in this research.

A flat plate photovoltaic array is used to generate d.c. electrical energy. A device called a maximum power tracker is used to maximize the array output power. This device monitors the array output and adjusts the load resistance, R_L, to produce a load line that intersects the characteristic I-V (current-voltage) output curves at the maximum power point. Figure 1-2 shows an array output characteristic I-V curve. The load resistance determines the slope of the load line (i.e., $1/R_L$ = slope). The intersection of this load line and the I-V curve determines the array output voltage and array output current. The largest voltage-current product defines the maximum power point (the area of the rectangle shown in Figure 1-2 is maximized). Other possible power conditioning equipment includes an energy flow control unit, a voltage regulator and a dc/ac inverter. The control unit simply directs the flow of energy from the photovoltaic array to the various system components depending on the control logic specified. The control unit will vary from system to system depending on the number of system components and the complexity of the control logic. Once the energy path is determined, the electrical energy must be conditioned so it can most effectively be used by the receiving system component. The voltage regulator will control the voltage output to the various system components. In changing the array output voltage, the voltage regulator reduces the array output power according to the regulator's rated efficiency, η_V. If the system load requirement is for a.c. power, then an inverter is used to convert d.c. array output. Some photovoltaic systems have the capability of delivering excess power into the utility grid. This "utility feedback" arrangement utilizes an inverter along with other

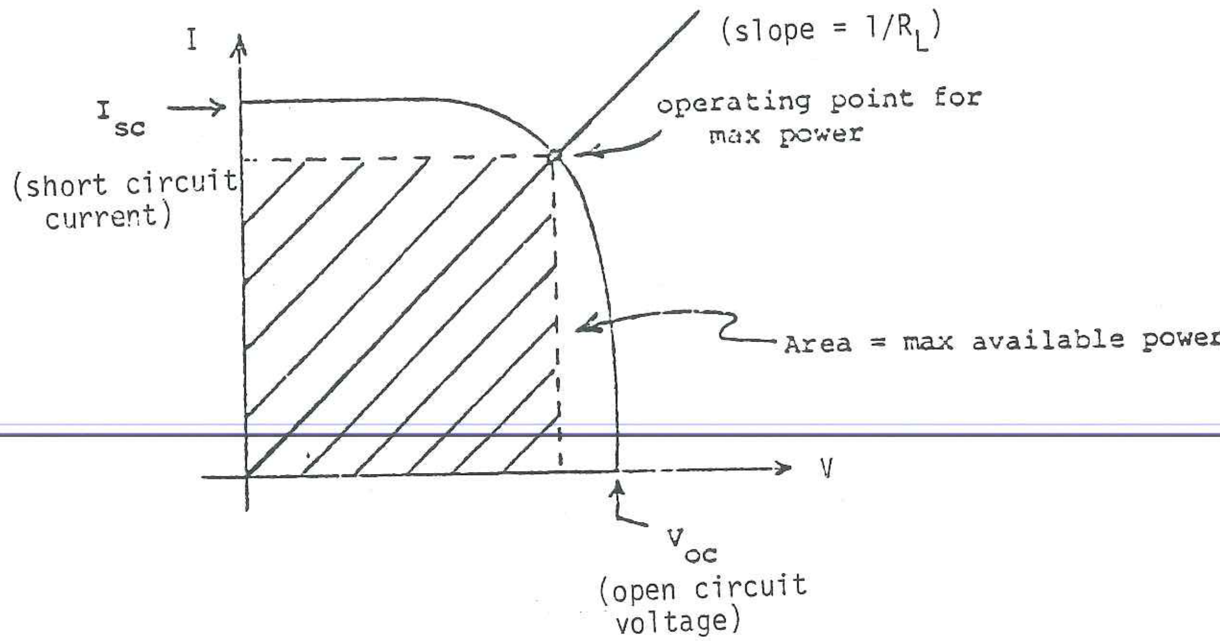


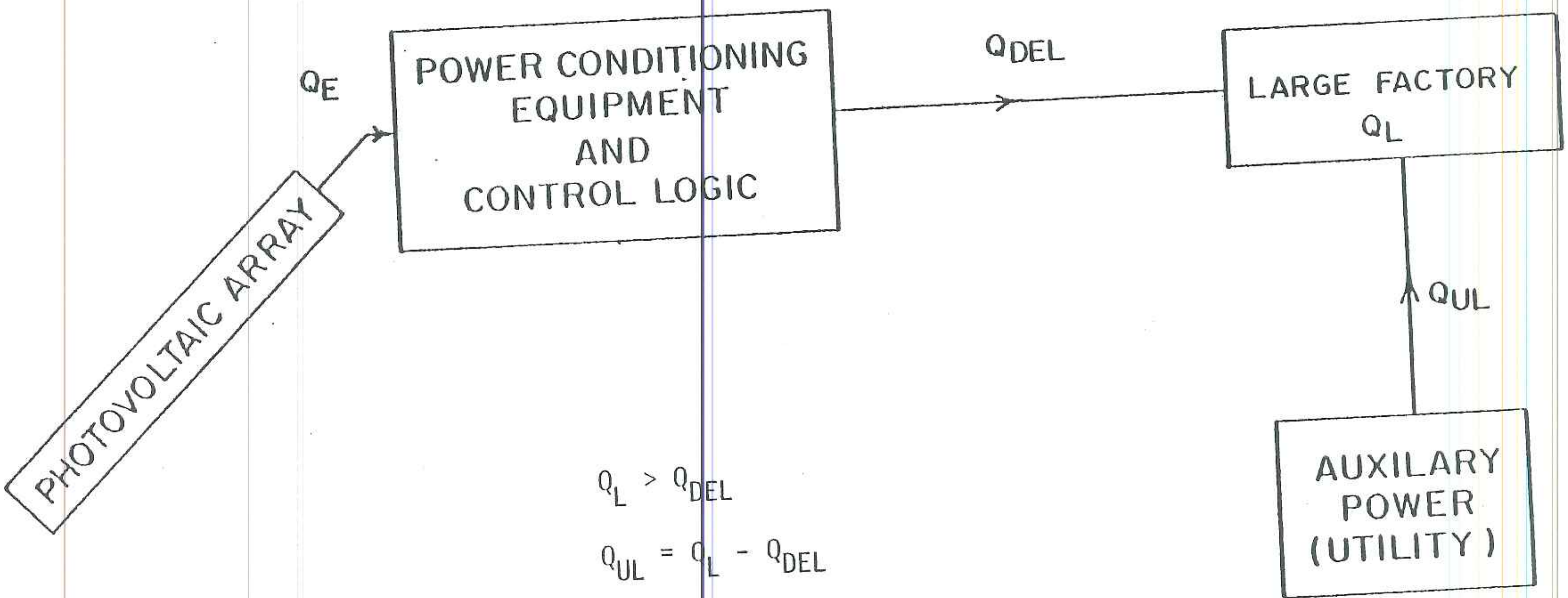
Figure 1-2 Characteristic I-V Output Curves for a Photovoltaic Array Showing the Load Line and Maximum Power Point

power conditioning equipment so that the array output will match the utility power in the grid. The inverter also has a rated efficiency, η_I, determined by the electrical losses involved in d.c. to a.c. power conversion. Both the regulator and inverter (if applicable) efficiencies must be considered when determining photovoltaic system performance.

1.3.2 Photovoltaic Systems - The Load Requirements Always Exceed the Array Output

If the instantaneous array output power, Q_E, is always less than the instantaneous load requirements, Q_L, all the energy generated will be immediately delivered to the load. For example, in Figure 1-3 a photovoltaic array is utilized to supplement the energy needs of a large factory. In this case, the array is sized so that all energy generated is immediately used in the factory. The difference between the instantaneous load requirement and the available array output power is supplied to the factory from the utility company (Q_{UL}, is considered positive for energy from the utility and negative for energy fed back into the grid).

The total array output power delivered to the load in Figure 1-3 is the product of the instantaneous array output and the efficiency of the power conditioning equipment. The array output that can be delivered to the load, Q_{DEL}, is defined in equation 1-1.



$$Q_L > Q_{DEL}$$

$$Q_{UL} = Q_L - Q_{DEL}$$

Figure 1-3 Schematic of a Photovoltaic System in Which No Energy is Dissipated

$$Q_{DEL} = \eta_V \eta_I Q_E \tag{1-1}$$

Since the system shown in Figure 1-3 utilizes all the energy that can be delivered, the monthly fraction of the load supplied, f, by the array can be calculated by integrating the instantaneous values of Q_{DEL} over a month and dividing by the total monthly load.

$$f = \frac{\int_M \eta_V \eta_I Q_E \, dt}{\int_M Q_L \, dt} \tag{1-2}$$

It is assumed that the product of the efficiency factors η_V and η_I can be replaced by a monthly average system efficiency, $\bar{\eta}_S$. Then equation (1-2) can be rewritten as:

$$f = \frac{\bar{\eta}_S \bar{Q}_E}{\bar{Q}_L} \tag{1-3}$$

where $\bar{Q}_E$ and $\bar{Q}_L$ are monthly average daily values. The calculation of the solar fraction defined in equation (1-3) is discussed in Chapter 3.

1.3.3 Photovoltaic Systems - No Storage

Unlike the load requirements discussed in the last section, the energy available to the load is often greater than the load demand. Under these conditions, the excess energy must either be stored, dissipated or fed back into the utility grid. If no battery storage or utility feedback arrangements are available, the excess energy, QD_o (where the subscript indicates the energy is dissipated with no storage) must be dissipated. An example of this type of photovoltaic system is shown in Figure 1-4. The load is represented by a dual-stage compressor. The array is sized so that the energy generated can supply the maximum load requirements. If the compressor is off or running at less than maximum capacity the excess energy generated by the array will be dissipated. At times when the array is not generating enough power to meet the load, the deficit is supplied by the utility. The energy flow strategy is shown below the figure. The array output power delivered to the load is determined by equation (1-4).

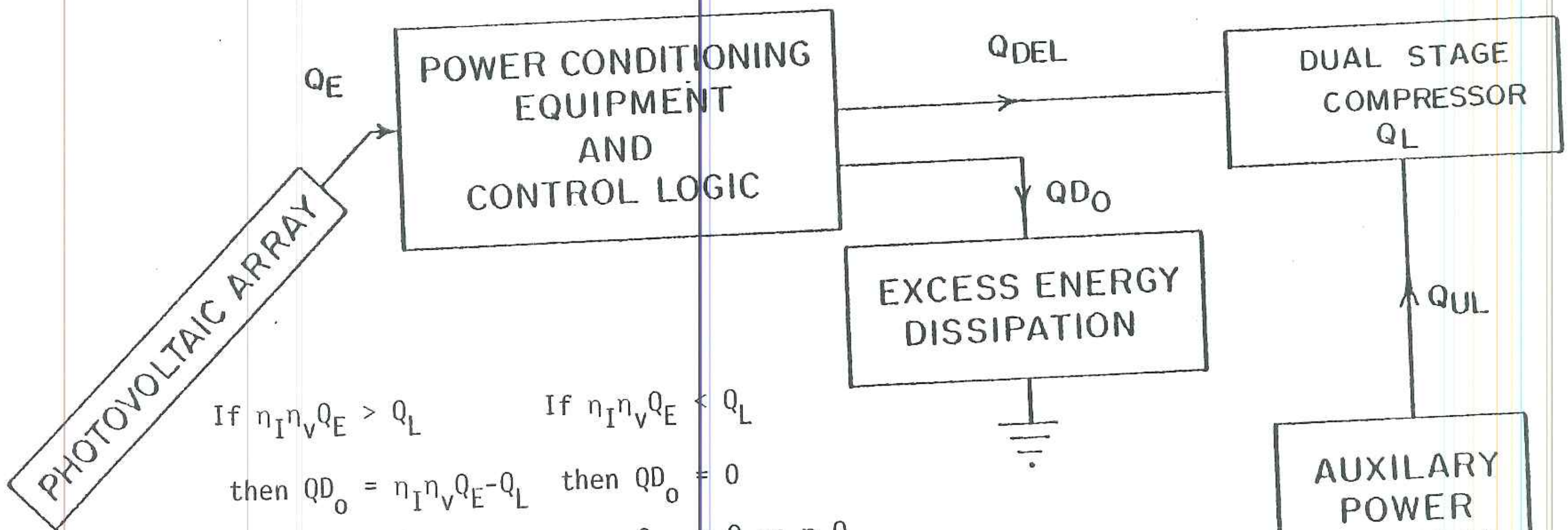
$$Q_{DEL} = \eta_V \eta_I Q_E - QD_o \tag{1-4}$$

The monthly fraction of the system load delivered by the photovoltaic array is defined by equation 1-5.

$$f = \frac{\int_M (\eta_V \eta_I Q_E - QD_o)\, dt}{\int_M Q_L\, dt} \tag{1-5}$$

Again assuming the product $\eta_V \eta_I$ can be replaced by a monthly average system efficiency $\bar{\eta}_S$, equation (1-5) can be rewritten as

$$f = \frac{\bar{\eta}_S \bar{Q}_E - \overline{QD}_o}{\bar{Q}_L} \tag{1-6}$$



If $\eta_I \eta_v Q_E > Q_L$

then $QD_o = \eta_I \eta_v Q_E - Q_L$

$Q_{UL} = 0$

$Q_{DEL} = Q_L$

If $\eta_I \eta_v Q_E < Q_L$

then $QD_o = 0$

$Q_{UL} = Q_L - \eta_I \eta_v Q_E$

$Q_{DEL} = \eta_I \eta_v Q_E$

Figure 1-4 Schematic of a Photovoltaic System in Which All Excess Energy is Dissipated

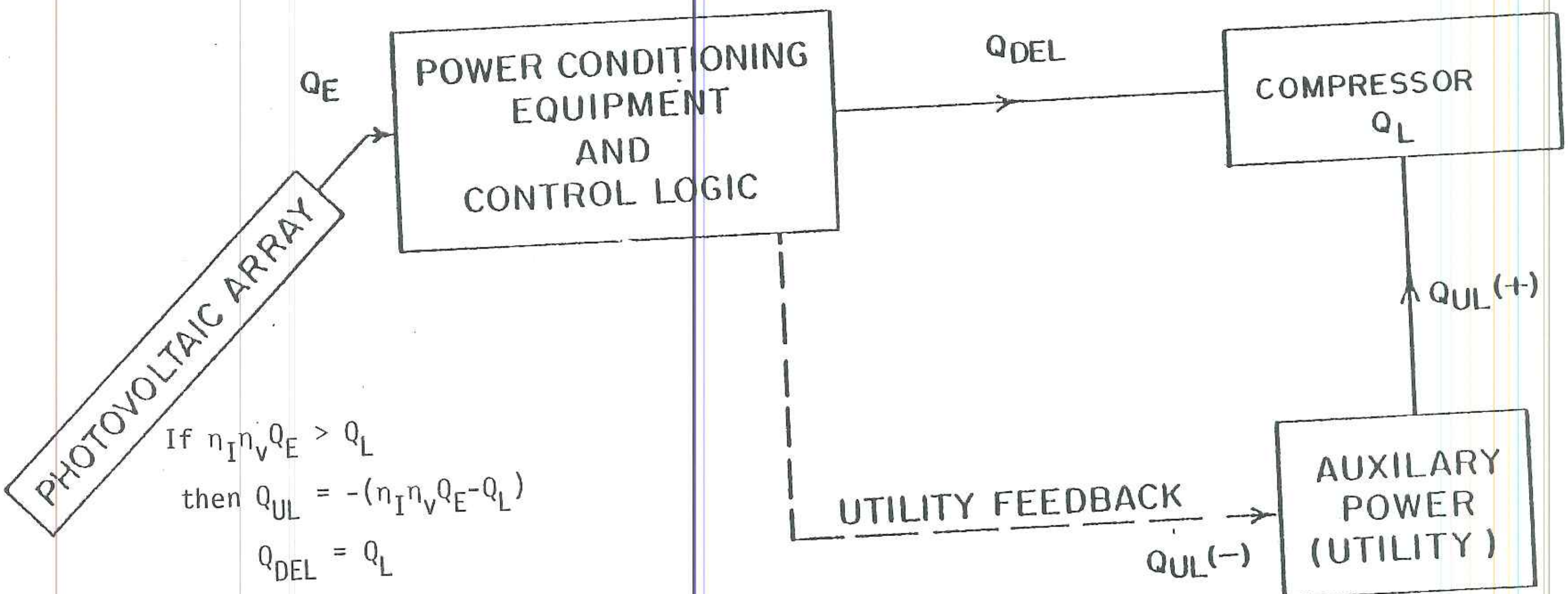
If arrangements are made for the excess energy to be fed back into the utility grid, as shown in Figure 1-5, the amount of energy sent to the utility is identical to QD_0. Assuming that the system efficiency is identical for energy sent to the load or to the utility, the solar fraction for the system in Figure 1-5 is given by equation (1-6). The excess energy, $\overline{QD}_0$ is sold to the utility company.

The evaluation of monthly average performance of the systems shown in Figures 1-4 and 1-5 is discussed in Chapter 4.

1.3.4 Photovoltaic Systems - With Battery Storage

In many instances, battery storage is used to increase system performance and reduce auxiliary energy consumption. Also, battery storage may be required in locations where no auxiliary energy sources are available. These "stand alone" photovoltaic systems are being used in remote rural areas to power such things as pumps, buoys, communication equipment and railroad signals.

Regardless of the reasons for the addition of battery storage, the result is that some of the excess energy (which would have been dissipated if no storage were available) is stored in a battery for later use. When the battery is fully charged, excess energy will be dissipated or fed back into the utility grid (if applicable). The amount of energy dissipated in a system with battery storage, QD_A



If $\eta_I \eta_v Q_E > Q_L$

then $Q_{UL} = -(\eta_I \eta_v Q_E - Q_L)$

$Q_{DEL} = Q_L$

If $Q_L > \eta_I \eta_v Q_E$

then $Q_{UL} = Q_L - \eta_I \eta_v Q_E$

$Q_{DEL} = \eta_I \eta_v Q_E$

Figure 1-5 Schematic of a Photovoltaic System in Which All Excess Energy is Fed Back to the Utility Grid (the subscript indicates actual energy dissipated), should be substantially less than QD_o to warrant the additional expense of battery storage (in exception are locations where battery storage is required for stand alone systems).

The photovoltaic system shown in Figure 1-6 is identical to the system in Figure 1-4, except that a storage battery is included. The storage battery is charged by the array and discharged by the load. A sample of the energy flow strategy that might be used in this type of system is given in Table 1-1. The energy to or from the battery, QB, is positive during charging and negative while discharging. In addition an amount of energy, QB_L is lost due to battery internal resistance and battery gassing. The electrical energy lost is changed into thermal energy and dissipated into the environment.

The total array output power delivered to the load (including the energy that comes indirectly from the array, i.e. from the battery) is defined by equation (1-7).

$$Q_{DEL} = \frac{\eta_V \, \eta_I \, Q_E - QD_A - QB_L}{Q_L} \tag{1-7}$$

Integrating over a month and substituting monthly average efficiency and daily values the monthly solar fraction is defined by equation (1-8).

$$f = \frac{\overline{\eta}_S \, \overline{Q}_E - \overline{QD}_A - \overline{QB}_L}{\overline{Q}_L} \tag{1-8}$$

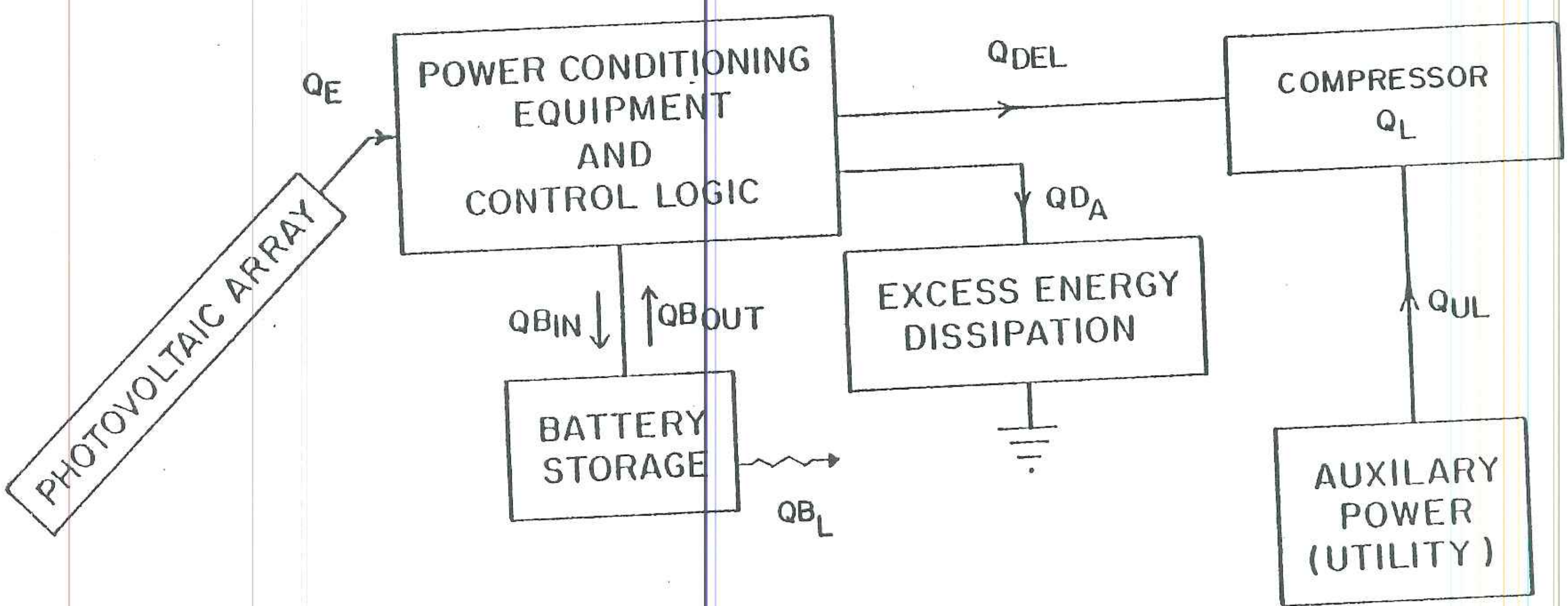


Figure 1-6 Schematic of a Photovoltaic System With Battery Storage

The prediction of monthly average performance of photovoltaic systems with battery storage is discussed in Chapter 5.

IF	THEN
$\eta_I\eta_v Q_E > Q_L$ (here γ = 1 if the battery can accept the excess energy otherwise γ = 0)	$Q_{UL} = 0$ $QB_{IN} = \gamma\,(\eta_I\eta_v Q_E - Q_L)$ $Q_{DA} = (1-\gamma)(\eta_I\eta_v Q_E - Q_L)$ $Q_{DEL} = Q_L$
$\eta_I\eta_v Q_E < Q_L$ (here γ = 1 if the battery can supply the energy deficit otherwise γ = 0)	$Q_{UL} = (1-\gamma)(Q_L - \eta_I\eta_v Q_E)$ $QB_{OUT} = -\gamma\,(Q_L - \eta_I\eta_v Q_E)$ $QD_A = 0$ $Q_{DEL} = \eta_I\eta_v Q_E + QB_{OUT}$

Table 1-1

Energy Flow Strategy for a Photovoltaic System With Battery Storage

2. COMPUTER SIMULATION MODELS

2.1 Introduction

Computer simulation models are available for predicting short-term and long-term photovoltaic system performance.[4] These models require hourly meteorological data and various array and system parameters as inputs. The results of these computer simulation models provide accurate predictions of actual system performance. The results of any simplified design methods for photovoltaic systems are then checked using computer simulation models for identical systems. In addition, results from computer simulation models often reveal certain correlations which can be useful in developing simplified design methods.

The computer simulation model used in this research is a TRNSYS[5] compatible computer modeling package for hybrid photovoltaic/thermal systems developed by Arizona State University. The "Combined Photovoltaic/Thermal Systems Studies"[4] describes the array, regulator/inverter and battery models. These models can be used to evaluate the performance of flat-plate, concentrating and combined (photovoltaic/thermal) photovoltaic arrays.

Appendix I contains complete program listings of the components discussed in the following sections. Complete descriptions of these simulation models can be found in reference 4.

2.2 Photovoltaic Array Models

The photovoltaic array models described in reference 4 were developed primarily for combined photovoltaic/thermal systems. However, these models can also be used to study flat-plate photovoltaic arrays with no thermal energy collection. The various modes of operation in this model represent several levels of complexity. Mode 1 of the array models assumes all array parameters (see parameter list, Appendix I) are constant throughout the simulation. For the purpose of developing simplified design methods, this computationally simple mode of operation will be sufficient. As an additional reference for checking the accuracy of the simplified design method developed, more complicated modes of operation are available. These modes of operation are able to calculate time-dependent array parameters, and utilize actual solar cell test results (using 20x, 40x and 100x concentrator cells) to predict array performance.

The evaluation of the array performance in mode 1 assumes that equation (2-1) can be used to predict array efficiency.

$$\eta = \eta_R \, (1 - \beta_R \, (T_{CELL} - T_R)) \qquad (2\text{-}1)$$

In this equation, η_R is the reference array efficiency, the product of the cell packing factor, P_f (the ratio of cell area, A_c, and array area, A) and η_R', the reference cell efficiency. The reference array efficiency is determined at a cell temperature, T_R, and a concentration of 1 KW/m^2. β_R is the temperature coefficient of efficiency and is determined for material properties at a concentration of 1 KW/m^2 (β_R is not significantly temperature sensitive for the range of cell temperatures that occur in flat plate collectors). Typical values of β_R are: silicon, β_R = .0037/°C, galium arsenide, β_R = .0025/°C.[6] Figure 2-1 shows the relationship between the array parameters η_R, β_R and T_R. In this figure, η_a is the array efficiency when T_{CELL} is equal to T_a (the ambient temperature), and T_c is the cell temperature when the array efficiency is zero. The assumption used in equation (2-1) (i.e., the array efficiency is a linear function of cell temperature), has been validated using experimental data (see reference 7).

Once the array efficiency, η, is determined, the electrical array output, Q_E, can be determined using equation (2-2):

$$Q_E = \eta A \tau G_T \tag{2-2}$$

where G_T is the instantaneous radiation on the array surface and τ is the cover transmittance (if applicable). The absorption, α, of the cells is incorporated in η_R (or η_a).

Combining equation (2-1) and (2-2) the expression for Q_E becomes:

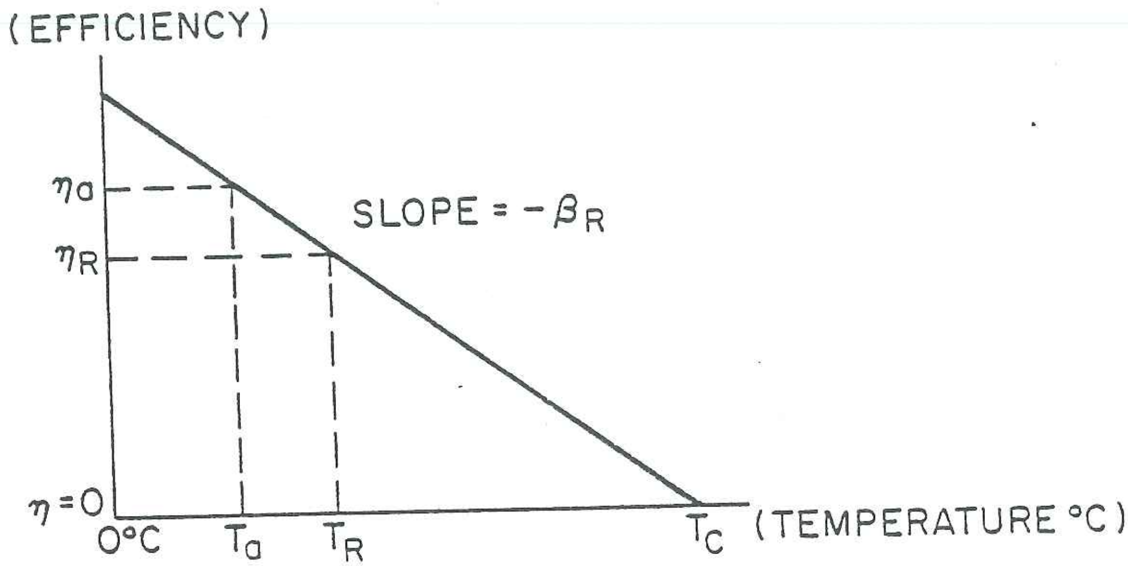


Figure 2-1 The Relationship Between Array Parameters (η_R, β_R, T_R)

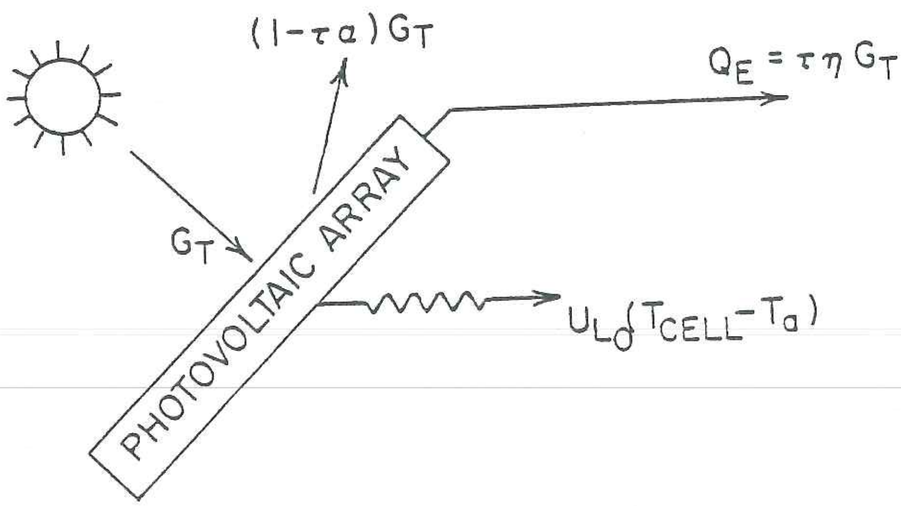


Figure 2-2 Energy Balance on a Photovoltaic Array

$$Q_E = G_T \tau A \eta_R (1 - \beta_R (T_{CELL} - T_R)). \quad (2\text{-}3)$$

An energy balance on the array in Figure 2-2 results in:

$$G_T \tau \alpha = U_{L_o} (T_{CELL} - T_a) + G_T \tau \eta_R (1 - \beta_R (T_{CELL} - T_R)) \quad (2\text{-}4)$$

where U_{L_o} is the thermal loss coefficient of the array.

Combining equations (2-3) and (2-4), the following expression can be used to calculate Q_E without having to evaluate the cell temperature.

$$Q_E = G_T \tau \eta_a A \left[\frac{U_{L_o}(T_c - T_a) - G_T \tau \alpha}{U_{L_o}(T_c - T_a) - G_T \tau \eta_a}\right] \quad (2\text{-}5)$$

T_c and η_a ($\eta_a = \eta_R (1 - \beta_R(T_a - T_r))$) are described in Figure 2-1. This equation is used in the collector model, along with hourly meteorological data to calculate the array output. The system parameters that must be supplied as inputs are P_F, η_R' (the cell reference efficiency), T_R, β_R, τ, α and U_{L_o}. These parameters are constant throughout the period of simulation.

2.3 Regulator/Inverter Models

The regulator/inverter models are used to simulate the conditioning of the array output power. Included in these models is a set of control logic used to determine energy flow paths. Examples of necessary control decisions may include: "Should energy be sent to the battery?", "Is the battery fully charged?"and "Can excess energy be delivered to the utility grid?". A complete description of the various control decisions can be found under "Logic Description" in reference 4.

The inverter portion of this model is required in systems with a.c. loads or in systems with utility feedback capabilities. The inverter model simply multiplies the d.c. input by a conversion efficiency (η_I) to obtain the quantity of a.c. power available to the load. Limitations can be placed on the inverter capacity, however inverters used in this research are considered to be capable of converting all d.c. power delivered.

The regulator model multiplies the incoming energy by a voltage regulator efficiency (η_V) to determine the regulator output. In both the regulator and inverter models the efficiency factors are supplied by the user.

Mode 2 of this model performs the necessary control operations for the photovoltaic systems examined in this research.

2.4 Storage Battery Models

The lead-acid storage battery models in reference 4 were designed to be used in conjunction with the photovoltaic array models and the regulator/inverter models. The various modes of operation determine the battery state of charge, Q, depending on charge and discharge rates. Mode 1 is useful to model an ideal battery with no internal losses. However, this mode does not calculate output voltage or current.

Mode 2, like the other more complicated modes, utilizes formulas relating battery voltage, V, current, I (+ charging, - dischargin), and state of charge, Q. Mode 2 incorporates formulas devised by Shepard.[8]

The rated battery cell capacity, Q_m (in AMP-HRS) is determined by the user and the open circuit voltage of each cell is set at 2.18 volts (nominal voltage - 2V). Then any number of cell units may be placed in series (C_s) or in parallel (C_p) to obtain the required storage output characteristics.

Typical battery parameters used in this research are defined in Table 2-1.

For charging (I > 0) the Shepard formula is:

$$V = e_{qd} - g_d H + I r_{qd} \left(1 + \frac{m_d H}{Q_d/Q_m - H}\right) \qquad (2\text{-}7)$$

and for discharging (I < 0)

$$V = e_{qc} - g_c H + I r_{qc} \left(1 + \frac{m_c H}{Q_c/Q_m - H}\right) \qquad (2\text{-}8)$$

where H is the uncharged fraction of the battery ($H = 1 - Q/Q_m$). When the current is zero the voltage is determined by the following equations:

$$V = V_{oc} - (g_d + g_c) \frac{H}{2} \qquad (2\text{-}9)$$

TABLE 2-1[1]

Parameter	Definition	Value
e_{qc}	open circuit voltages at full	2.25V
e_{qd}	charge (charge and discharge)	2.10V
g_c	small-valued coefficients of	.08
g_d	$H=(1-Q/Q_m)$ in voltage - current-	.08
	state of charge formulas	
m_c	cell type parameters which	.864
m_d	determine the shapes of the	1.0
	I-V-Q characteristics	
r_{qc}	internal resistance at	$3.0/Q_m\Omega$
r_{qd}	full charge	Ω
V_c	cutoff voltage on charge	2.4V
	(to eliminate electrolyte gassing)	
e_d	parameters used in the	1.8V
r_d	calculation of low voltage	$.0024\Omega$
	cutoff ($V_d = e_d - \|I\| r_d$)	
Q_C	cell capacity parameters	$-.035\ Q_m$
Q_D	on charge and discharge	$Q_m/.85$

[1]Definitions from reference 4

where $V_{oc} = \frac{1}{2} (e_{qd} + e_{qc})$.

V_{oc} is the open circuit voltage. An example of the resulting I-V-Q relation is shown in Figure 2-3 for I = 0, ± 5, ± 50 and Q_m = 250 AMP-HRS.

Since the voltage is calculated for charging and discharging currents this model effectively predicts the voltage drop associated with internal battery resistance and battery gassing.

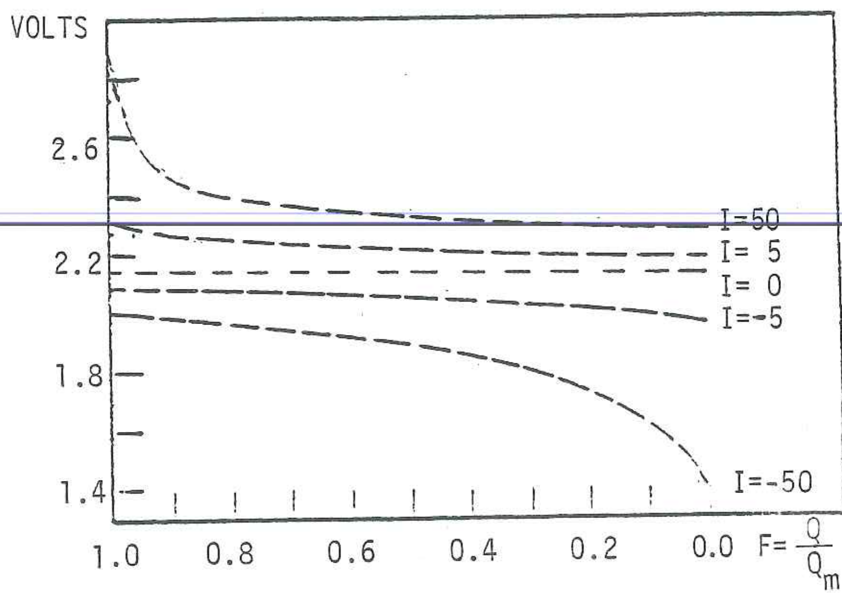


Figure 2-3 I-V-Q Characteristics for a 250 amp-hr. Battery (as derived using the Shepard equations)[4]

3. PREDICTION OF MONTHLY AVERAGE ARRAY EFFICIENCY

3.1 Introduction

The use of TRNSYS(5) in conjunction with the simulation models described in Chapter 2 requires hourly meteorological data, extensive computer capabilities along with user expertise and significant expense. On the other hand, design methods offer a quick and easy way to estimate the performance of alternative designs. Results obtained from the simplified design methods developed in this chapter compare to computer simulation results within an acceptable standard deviation (accuracy of predictions are given in section 3-4). If a more accurate analysis is required, the computer simulation models are available. The next three chapters describe a computationally simple method for predicting the long-term average performance of photovoltaic systems.

In this chapter a method is developed for evaluating monthly average photovoltaic array efficiency. Using this efficiency and monthly meteorological data, the monthly average electrical output can be calculated. The fraction of the load supplied by the array for the system configuration described in section 1.3.2 can then be determined.

Results obtained from this method are compared with results obtained from the TRNSYS simulation program using the models described in Chapter 2.

3.2 Determining the Monthly Average Efficiency - $\bar{\eta}$

The instantaneous energy generated is the product of the array efficiency, η_R, the array cover transmittance, τ, the array area, A, and the insolation on the array, G_T.

$$Q_E = \eta \tau A \, G_T \tag{3-1}$$

On a monthly average basis, the electrical energy produced by the array can be expressed as the product of the monthly average array efficiency, $\bar{\eta}$, the monthly average daily radiation incident on the array, $\bar{H}_T$, the number of days in the month, N, the array area, A, and the average array cover transmittance $\bar{\tau}$.

$$N\bar{Q}_E = \bar{\eta} \, \bar{H}_T \, N \, A \, \bar{\tau} \tag{3-2}$$

where $\bar{Q}_E$ is the monthly average daily output. An expression for $\bar{\eta}$ can be obtained as follows.

The instantaneous efficiency of a maximum power tracking flat-plate photovoltaic array can be calculated using equation (2-1). Given η_R, β_R and T_R, a reference efficiency, η_{R_0} at T_R = 0°C can be defined. In this case, equation (2-1) simplifies to:

$$\eta = \eta_{R_0} \, (1 - \beta_R \, T_{CELL}) \tag{3-3}$$

Solving for T_{CELL} in equation (3-3) and substituting this expression into equation (2-4), the following equation for η can be found.

$$\eta = \frac{\eta_{Ro}\ \beta_R\ \tau\ \alpha\ G_T - U_{Lo}\ \eta_{Ro} + U_{Lo}\ T_a\ \beta_R\ \eta_{Ro}}{\tau\ G_T\ \eta_{Ro}\ \beta_R - U_{Lo}} \tag{3-4}$$

This equation can be simplified if the following inequality is valid:

$$U_{Lo} >> \tau\ G_T\ \eta_{Ro}\ \beta_R \tag{3-5}$$

Maximum values for the variables on the right side of this inequality are given in Table 3-1, along with a minimum value of U_{Lo}. For these worst case conditions, the inequality is a ratio of almost ten-to-one.

Parameter	Maximum Value	Practical Values
η_{Ro}	.20	<.18
β_R	.004	<.004
τ	1	<1
G_{SC}	1353 W/m^2 (Solar Constant)	<1353 W/m^2
	Minimum Value	
U_{Lo}	≈ 10 W/m^2	> 15 W/m^2

Table 3-1

Array Parameters

The minimum value of U_{L_o} is derived by considering only radiation and free convection losses. More realistic values for these parameters results in at least a twenty-to-one inequality. Accepting this inequality, equation (3-5) reduces to:

$$\eta = \eta_{R_o} \left(1 - \beta_R T_a - \frac{\beta_R \tau\alpha G_T}{U_{L_o}}\right) \qquad (3\text{-}6)$$

Equation (3-6) can be used to calculate the instantaneous efficiency without calculating the cell temperature. However, using this equation to predict long-term average performance still requires hour by hour calculations using hourly meteorological data.

The next step is to obtain an expression for $\bar{\eta}$, such that equation (3-2), along with monthly average meteorological data and array parameters can be used to predict the monthly average daily array electrical energy produced. Multiplying the instantaneous array efficiency in equation (3-7) by the instantaneous insolation, and integrating over the month yields the following:

$$\int_M \eta G_T dt = \eta_{R_o} \int_M G_T dt - \eta_{R_o} \beta_R \int_M T_a G_T dt - \frac{\eta_{R_o} \beta_R}{U_{L_o}} \int_M \tau\alpha G_T^2 dt \qquad (3\text{-}8)$$

The integral on the left can simply be written as the product of the monthly average efficiency, and the monthly average daily radiation, and the number of days in the month. The integral involving the ambient temperature can be replaced by the product of the monthly average radiation-weighted ambient temperature, $\overline{T}_a'$, and $\overline{H}_T N$. Using the results obtained from TRNSYS simulations, it was determined that $\overline{T}_a'$ could be replaced by average ambient temperature, $\overline{T}_a$. The first integral on the right is simply $N\overline{H}_T$.

The final integral can be simplified as follows. First $\tau\alpha$ may be removed from under the integral sign if it is replaced by the average transmittance-absorptance product $\overline{\tau\alpha}$ (see reference 9). Equation (3-7) has been reduced to:

$$\overline{\eta} = \eta_{R_O} - \eta_{R_O}\, \beta_R \overline{T}_a - \frac{\eta_{R_O} \beta_R \overline{\tau\alpha}}{U_{Lo}\, N} \frac{\int_M G_T^2 dt}{\overline{H}_T} \tag{3-9}$$

Defining a dimensionless variable, V, such that:

$$V = \frac{\int_M G_T^2\, dt}{\overline{H}_T^2} \tag{3-10}$$

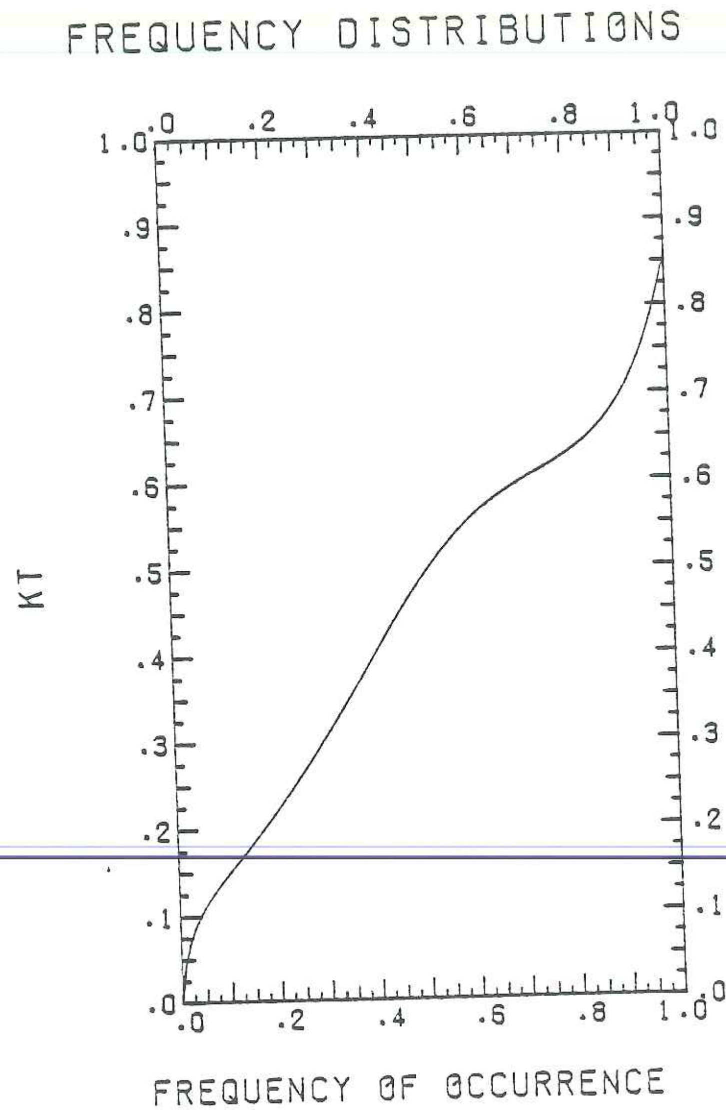
finally reduces equation (3-7) to:

$$\overline{\eta} = \eta_{R_O} \left(1 - \beta_R \overline{T}_a' - \frac{\beta_R \overline{\tau\alpha}\, V \overline{H}_T}{N\, U_{L_O}}\right) \tag{3-11}$$

This equation gives the monthly average efficiency in terms of array parameters, monthly average meteorological data, and two meteorological variables, $\overline{T}_a'$ and V.

At this point, a means of estimating monthly average values of V without using hourly meteorological data is needed. Tables containing long-term monthly average values of V have been developed. The ratio of monthly average daily radiation to extraterrestrial radiation on a horizontal surface, $\overline{K}_T$, is a key variable in calculating long-term monthly average values of V. To calculate $\overline{K}_T$, the monthly average daily radiation on a horizontal surface, $\overline{H}$, must be determined: then the extraterrestrial radiation, $\overline{H}_o$, can be calculated using equations in reference 10. Liu and Jordan[11] have found that the daily distribution of radiation throughout a month (i.e. the number of good and bad days) is directly related to $\overline{K}_T$. Using values of $\overline{K}_T$ between .3 and .7 Liu and Jordan have developed frequency distributions of the K_Ts (the ratio of daily radiation, H, to daily extraterrestrial radiation, H_o, on a horizontal surface) during a month as a function of $\overline{K}_T$. For example, Figure 3-1 shows a frequency distribution for $\overline{K}_T = 0.45$. If a month has thirty days, this frequency distribution is divided into thirty equidistant points (along the X-axis). The thirty values of K_T are listed below the figure. To simplify calculations, Cole[12] has developed correlations for these frequency distributions (for $\overline{K}_T$ between .3 and .7).

The daily total radiation on a horizontal surface, H, can be divided into hourly portions using relationships developed by Liu and Jordan.[11] A similar set of curves determines the hourly diffuse radiation. Using the work of Hottel and Woertz,[13] R_b, the ratio of beam radiation on a tilted surface to that on a horizontal surface can be determined. Using this information, Liu and Jordan[14]



K_Ts

0.062	0.208	0.352	0.504	0.595	0.658
0.109	0.234	0.385	0.528	0.606	0.681
0.138	0.261	0.417	0.549	0.616	0.713
0.161	0.290	0.448	0.567	0.628	0.756
0.184	0.321	0.477	0.582	0.641	0.819

Figure 3-1 Frequency Distribution of K_Ts for $\overline{K}_T$=.45

predict the hourly radiation on a tilted surface. A complete explanation of this process can be found in reference 10.

To determine monthly average values of V, each month is assumed to have thirty days. Then thirty values of K_T are determined using the correlations developed by Cole.[12] For all hours of each day the average hourly radiation is calculated. Hourly radiation is squared and summed over the thirty day period. At the same time monthly average daily radiation is determined. Then equation (3-10) is used to calculate monthly average values of V. This entire process is outlined in Figure 3-2. A complete listing of the computer program which performs these operations can be found in Appendix II.

Table 3-2 (a-e) contains long-term monthly average values of V for latitudes Ø, between 20° and 55°, collector slopes, S, S = Ø, S = 90° Ø ± 20° and for values of $\overline{K}_T$ between .3 and .7.

The following key variables were used to find a correlation for predicting monthly average values of V. The ratio $\overline{R}/R_n$ as used by Klein[15] is a geometry factor which incorporates the effects of collector tilt, latitude and time of year to describe the shape of the monthly average daily radiation curve. Here $\overline{R}$ is the ratio of the monthly total radiation on a tilted surface to that on a horizontal surface, and R_n is the ratio of radiation at noon to that on a horizontal surface for an average day of the month. Stated simply, $\overline{R}$ is a measure of the total area enclosed by the radiation curve and R_n is a measure of the height of that curve. The calculation of

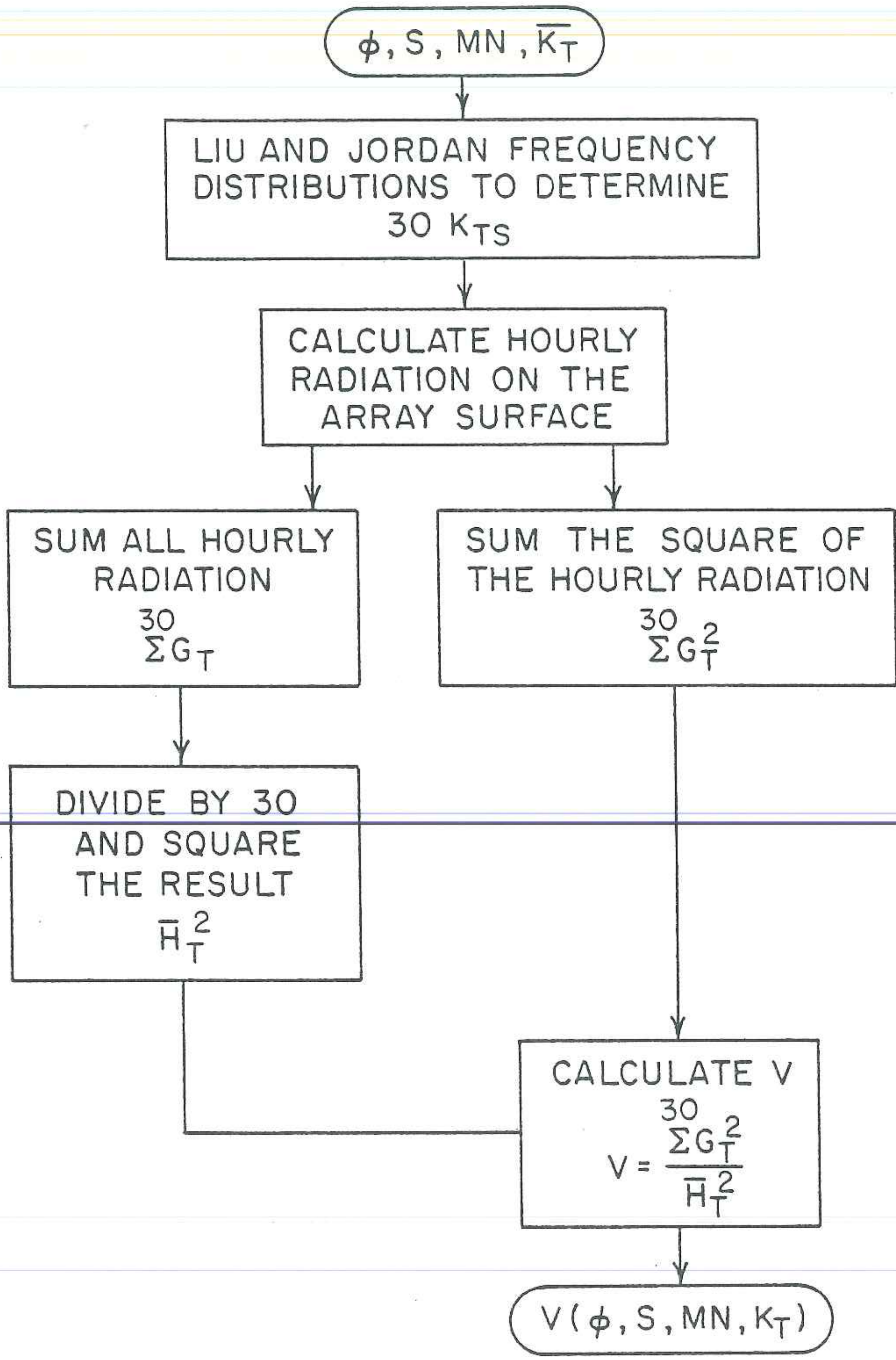


Figure 3-2 Schematic of the Analysis Used to Calculate Monthly Average Values of V

VALUES OF V FOR KTBAR=0.30

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(LATITUDE-TILT)= 20.0												
25	5.54	5.27	4.98	4.69	4.48	4.38	4.42	4.60	4.86	5.17	5.46	5.62
30	5.83	5.46	5.06	4.69	4.43	4.30	4.36	4.58	4.91	5.32	5.74	5.96
35	6.22	5.69	5.17	4.71	4.38	4.24	4.30	4.57	4.98	5.51	6.07	6.38
40	6.71	5.99	5.31	4.74	4.35	4.18	4.25	4.57	5.07	5.75	6.50	6.95
45	7.37	6.36	5.49	4.78	4.32	4.12	4.21	4.58	5.19	6.04	7.07	7.72
50	8.28	6.85	5.70	4.84	4.29	4.06	4.16	4.60	5.33	6.43	7.84	8.84
55	9.65	7.50	5.98	4.92	4.27	4.00	4.12	4.62	5.51	6.91	8.95	10.59
(LATITUDE-TILT)= 0.0												
25	5.86	5.51	5.13	4.78	4.52	4.40	4.46	4.67	4.99	5.38	5.77	5.98
30	6.21	5.74	5.25	4.81	4.49	4.35	4.41	4.67	5.07	5.56	6.08	6.36
35	6.64	6.00	5.38	4.85	4.47	4.30	4.37	4.68	5.16	5.79	6.46	6.85
40	7.19	6.34	5.55	4.90	4.45	4.25	4.34	4.70	5.28	6.06	6.94	7.47
45	7.90	6.75	5.76	4.97	4.44	4.21	4.31	4.74	5.42	6.39	7.56	8.29
50	8.84	7.28	6.01	5.06	4.44	4.17	4.29	4.78	5.60	6.81	8.37	9.44
55	10.21	7.96	6.31	5.16	4.43	4.13	4.26	4.83	5.81	7.32	9.50	11.19
(LATITUDE-TILT)=-20.0												
25	6.09	5.66	5.21	4.79	4.47	4.32	4.39	4.66	5.04	5.50	5.97	6.22
30	6.47	5.91	5.34	4.84	4.46	4.28	4.36	4.67	5.14	5.71	6.32	6.65
35	6.94	6.21	5.51	4.90	4.45	4.25	4.34	4.70	5.26	5.97	6.73	7.17
40	7.52	6.58	5.70	4.98	4.45	4.22	4.32	4.75	5.40	6.27	7.24	7.82
45	8.26	7.02	5.93	5.07	4.46	4.19	4.31	4.80	5.57	6.62	7.89	8.67
50	9.21	7.57	6.21	5.18	4.48	4.17	4.30	4.87	5.77	7.06	8.71	9.83
55	10.57	8.26	6.53	5.31	4.49	4.14	4.29	4.95	6.01	7.60	9.84	11.56
VERTICAL												
25	6.20	5.59	4.92	4.28	3.67	3.44	3.53	4.02	4.68	5.36	6.03	6.39
30	6.65	5.93	5.17	4.46	3.82	3.53	3.65	4.19	4.90	5.67	6.46	6.88
35	7.17	6.30	5.43	4.64	3.96	3.65	3.79	4.36	5.12	6.00	6.93	7.44
40	7.78	6.72	5.70	4.82	4.10	3.76	3.91	4.52	5.35	6.35	7.47	8.11
45	8.51	7.18	5.98	5.00	4.23	3.87	4.03	4.67	5.58	6.75	8.12	8.95
50	9.43	7.73	6.29	5.17	4.33	3.95	4.12	4.81	5.83	7.20	8.92	10.07
55	10.74	8.40	6.62	5.34	4.42	4.01	4.19	4.94	6.08	7.72	10.01	11.73

Table 3-2a Monthly Average Values of V for $\overline{K}_T$ = .3

VALUES OF V FOR KTBAR=0.40

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(LATITUDE-TILT)= 20.0												
25	4.79	4.57	4.33	4.09	3.91	3.83	3.87	4.01	4.23	4.49	4.73	4.86
30	4.99	4.70	4.38	4.09	3.87	3.77	3.82	4.00	4.26	4.59	4.91	5.08
35	5.24	4.85	4.45	4.10	3.84	3.72	3.77	3.98	4.31	4.71	5.13	5.36
40	5.56	5.04	4.54	4.11	3.81	3.67	3.73	3.98	4.36	4.86	5.40	5.72
45	5.97	5.26	4.64	4.13	3.78	3.63	3.69	3.98	4.43	5.04	5.75	6.20
50	6.51	5.56	4.77	4.16	3.75	3.58	3.65	3.98	4.51	5.27	6.22	6.88
55	7.33	5.93	4.92	4.20	3.72	3.52	3.61	3.99	4.61	5.55	6.88	7.96
(LATITUDE-TILT)= 0.0												
25	4.92	4.68	4.42	4.18	3.99	3.90	3.94	4.10	4.32	4.59	4.85	5.00
30	5.14	4.82	4.49	4.19	3.96	3.86	3.90	4.09	4.37	4.70	5.05	5.24
35	5.41	4.99	4.57	4.21	3.94	3.81	3.87	4.09	4.42	4.84	5.29	5.54
40	5.74	5.19	4.67	4.24	3.92	3.78	3.84	4.10	4.49	5.00	5.58	5.92
45	6.16	5.43	4.79	4.28	3.91	3.74	3.81	4.11	4.57	5.20	5.94	6.41
50	6.72	5.73	4.93	4.32	3.89	3.70	3.79	4.13	4.67	5.43	6.41	7.10
55	7.53	6.11	5.09	4.37	3.88	3.66	3.75	4.15	4.78	5.71	7.07	8.16
(LATITUDE-TILT)=-20.0												
25	5.00	4.73	4.46	4.21	4.00	3.90	3.94	4.12	4.36	4.64	4.92	5.08
30	5.23	4.89	4.54	4.23	3.98	3.86	3.91	4.13	4.42	4.76	5.14	5.34
35	5.51	5.07	4.64	4.27	3.97	3.83	3.89	4.14	4.49	4.91	5.38	5.65
40	5.86	5.28	4.75	4.31	3.96	3.80	3.87	4.16	4.57	5.09	5.68	6.04
45	6.28	5.53	4.88	4.36	3.96	3.77	3.86	4.19	4.66	5.29	6.05	6.54
50	6.84	5.83	5.02	4.42	3.96	3.74	3.84	4.22	4.78	5.53	6.53	7.22
55	7.64	6.21	5.19	4.49	3.96	3.71	3.82	4.26	4.90	5.81	7.18	8.28
VERTICAL												
25	4.96	4.62	4.26	3.90	3.38	3.14	3.24	3.69	4.15	4.49	4.87	5.07
30	5.24	4.83	4.42	4.03	3.52	3.25	3.37	3.83	4.29	4.68	5.13	5.37
35	5.55	5.05	4.57	4.15	3.65	3.37	3.50	3.95	4.42	4.88	5.41	5.71
40	5.92	5.30	4.73	4.26	3.75	3.48	3.60	4.06	4.55	5.09	5.73	6.11
45	6.35	5.56	4.89	4.36	3.84	3.56	3.69	4.15	4.68	5.31	6.11	6.61
50	6.89	5.87	5.05	4.45	3.90	3.61	3.74	4.22	4.81	5.56	6.58	7.29
55	7.69	6.24	5.22	4.53	3.94	3.63	3.77	4.28	4.94	5.84	7.23	8.33

Table 3-2b Monthly Average Values of V for $\overline{K}_T = .4$

VALUES OF V FOR KTBAR=0.50

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(LATITUDE-TILT)= 20.0												
25	4.27	4.08	3.88	3.67	3.52	3.45	3.48	3.61	3.80	4.01	4.22	4.33
30	4.41	4.17	3.91	3.67	3.49	3.40	3.44	3.59	3.81	4.08	4.35	4.49
35	4.59	4.27	3.96	3.67	3.46	3.36	3.40	3.58	3.84	4.17	4.50	4.68
40	4.81	4.40	4.01	3.68	3.43	3.32	3.37	3.57	3.87	4.27	4.69	4.94
45	5.09	4.55	4.08	3.68	3.40	3.28	3.33	3.56	3.91	4.38	4.93	5.27
50	5.47	4.75	4.16	3.70	3.38	3.24	3.30	3.56	3.96	4.53	5.25	5.75
55	6.04	5.00	4.25	3.71	3.35	3.19	3.26	3.55	4.02	4.71	5.70	6.52
(LATITUDE-TILT)= 0.0												
25	4.30	4.12	3.93	3.75	3.62	3.55	3.58	3.70	3.86	4.05	4.25	4.35
30	4.45	4.22	3.97	3.76	3.59	3.51	3.55	3.69	3.88	4.13	4.38	4.52
35	4.63	4.32	4.03	3.77	3.57	3.47	3.52	3.68	3.92	4.22	4.54	4.73
40	4.86	4.46	4.09	3.78	3.55	3.44	3.49	3.68	3.96	4.32	4.74	4.99
45	5.15	4.61	4.16	3.80	3.53	3.41	3.46	3.68	4.01	4.45	4.99	5.33
50	5.53	4.81	4.24	3.82	3.51	3.37	3.43	3.69	4.07	4.60	5.31	5.81
55	6.11	5.05	4.33	3.85	3.49	3.33	3.40	3.69	4.13	4.77	5.76	6.59
(LATITUDE-TILT)=-20.0												
25	4.30	4.12	3.95	3.80	3.67	3.60	3.63	3.74	3.89	4.06	4.25	4.36
30	4.46	4.23	4.00	3.81	3.65	3.56	3.60	3.74	3.92	4.14	4.40	4.54
35	4.65	4.34	4.06	3.83	3.63	3.53	3.58	3.75	3.96	4.24	4.56	4.75
40	4.89	4.48	4.12	3.85	3.62	3.50	3.56	3.76	4.01	4.35	4.76	5.02
45	5.18	4.64	4.20	3.88	3.61	3.47	3.53	3.77	4.07	4.47	5.01	5.36
50	5.56	4.83	4.29	3.91	3.60	3.44	3.51	3.78	4.13	4.63	5.33	5.85
55	6.14	5.08	4.38	3.95	3.59	3.40	3.49	3.80	4.20	4.80	5.79	6.62
VERTICAL												
25	4.20	3.99	3.81	3.64	3.20	2.96	3.06	3.49	3.77	3.92	4.14	4.27
30	4.40	4.14	3.91	3.73	3.34	3.08	3.20	3.59	3.86	4.05	4.33	4.48
35	4.62	4.28	4.01	3.80	3.44	3.20	3.31	3.67	3.94	4.18	4.52	4.72
40	4.87	4.45	4.10	3.86	3.51	3.29	3.40	3.74	4.02	4.32	4.74	5.01
45	5.18	4.62	4.20	3.91	3.56	3.35	3.45	3.78	4.09	4.46	5.01	5.37
50	5.57	4.83	4.29	3.96	3.59	3.37	3.47	3.82	4.16	4.62	5.34	5.86
55	6.15	5.08	4.39	4.00	3.60	3.37	3.48	3.84	4.23	4.80	5.80	6.63

Table 3-2c Monthly Average Values of V for $\bar{K}_T$ = .5

VALUES OF V FOR KTBAR=0.60

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(LATITUDE-TILT)= 20.0												
25	4.05	3.88	3.69	3.51	3.36	3.30	3.33	3.44	3.62	3.82	4.01	4.11
30	4.16	3.95	3.72	3.50	3.34	3.26	3.30	3.43	3.63	3.87	4.11	4.23
35	4.30	4.03	3.75	3.50	3.31	3.23	3.27	3.42	3.65	3.93	4.22	4.38
40	4.47	4.13	3.79	3.50	3.29	3.19	3.24	3.41	3.67	4.01	4.37	4.58
45	4.69	4.24	3.84	3.51	3.27	3.16	3.21	3.40	3.70	4.09	4.56	4.85
50	5.00	4.38	3.89	3.51	3.24	3.12	3.18	3.39	3.73	4.20	4.81	5.24
55	5.47	4.57	3.95	3.52	3.22	3.08	3.14	3.39	3.77	4.33	5.18	5.88
(LATITUDE-TILT)= 0.0												
25	4.02	3.87	3.72	3.59	3.48	3.43	3.45	3.54	3.67	3.82	3.98	4.06
30	4.14	3.95	3.75	3.59	3.46	3.40	3.43	3.54	3.69	3.88	4.09	4.20
35	4.28	4.03	3.79	3.60	3.44	3.37	3.40	3.53	3.71	3.95	4.21	4.36
40	4.46	4.13	3.83	3.60	3.42	3.34	3.38	3.53	3.74	4.02	4.36	4.57
45	4.69	4.24	3.88	3.61	3.41	3.31	3.35	3.53	3.77	4.11	4.55	4.84
50	5.00	4.39	3.94	3.63	3.39	3.27	3.33	3.53	3.81	4.22	4.81	5.24
55	5.48	4.58	4.00	3.64	3.37	3.24	3.30	3.52	3.85	4.35	5.18	5.89
(LATITUDE-TILT)=-20.0												
25	3.98	3.85	3.73	3.65	3.57	3.52	3.54	3.61	3.69	3.81	3.94	4.03
30	4.11	3.93	3.77	3.65	3.55	3.49	3.52	3.61	3.72	3.87	4.06	4.17
35	4.26	4.01	3.81	3.67	3.53	3.46	3.49	3.61	3.75	3.94	4.19	4.34
40	4.45	4.12	3.85	3.68	3.52	3.43	3.47	3.62	3.78	4.02	4.34	4.55
45	4.68	4.24	3.90	3.70	3.51	3.40	3.45	3.62	3.82	4.11	4.54	4.84
50	4.99	4.39	3.96	3.72	3.49	3.37	3.43	3.63	3.86	4.22	4.80	5.24
55	5.48	4.58	4.02	3.74	3.48	3.34	3.40	3.63	3.90	4.35	5.18	5.90
VERTICAL												
25	3.85	3.70	3.61	3.59	3.19	2.92	3.03	3.47	3.63	3.66	3.81	3.91
30	4.01	3.82	3.69	3.65	3.34	3.07	3.20	3.56	3.69	3.76	3.96	4.08
35	4.19	3.94	3.76	3.70	3.43	3.21	3.32	3.62	3.75	3.86	4.12	4.28
40	4.40	4.07	3.83	3.73	3.47	3.30	3.39	3.66	3.80	3.96	4.29	4.51
45	4.65	4.20	3.89	3.76	3.52	3.34	3.43	3.68	3.84	4.07	4.51	4.81
50	4.98	4.36	3.96	3.78	3.53	3.35	3.44	3.69	3.89	4.20	4.78	5.23
55	5.47	4.56	4.02	3.79	3.51	3.34	3.42	3.69	3.93	4.33	5.17	5.89

Table 3-2d Monthly Average Values of V for $\overline{K}_T = .6$

VALUES OF V FOR KTBAR=0.70

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(LATITUDE-TILT)= 20.0												
25	3.72	3.57	3.40	3.24	3.11	3.05	3.08	3.18	3.34	3.51	3.68	3.76
30	3.78	3.61	3.41	3.23	3.09	3.02	3.05	3.17	3.34	3.54	3.74	3.84
35	3.87	3.65	3.43	3.22	3.07	2.99	3.03	3.15	3.34	3.57	3.81	3.94
40	3.98	3.71	3.44	3.22	3.04	2.97	3.00	3.14	3.35	3.61	3.90	4.07
45	4.13	3.77	3.46	3.21	3.02	2.93	2.97	3.13	3.36	3.66	4.02	4.25
50	4.34	3.86	3.48	3.20	2.99	2.90	2.94	3.11	3.37	3.72	4.19	4.53
55	4.69	3.98	3.51	3.19	2.97	2.86	2.91	3.09	3.38	3.79	4.45	5.02
(LATITUDE-TILT)= 0.0												
25	3.61	3.50	3.40	3.32	3.24	3.21	3.23	3.29	3.36	3.47	3.58	3.64
30	3.68	3.55	3.41	3.31	3.22	3.18	3.20	3.27	3.37	3.50	3.65	3.73
35	3.78	3.59	3.43	3.30	3.20	3.15	3.17	3.26	3.38	3.53	3.72	3.84
40	3.90	3.65	3.45	3.30	3.18	3.12	3.15	3.25	3.38	3.58	3.82	3.98
45	4.06	3.72	3.47	3.30	3.16	3.09	3.12	3.24	3.39	3.62	3.95	4.18
50	4.28	3.81	3.49	3.29	3.13	3.06	3.09	3.23	3.40	3.69	4.13	4.47
55	4.64	3.94	3.51	3.29	3.11	3.02	3.06	3.21	3.42	3.76	4.41	4.98
(LATITUDE-TILT)=-20.0												
25	3.53	3.45	3.39	3.38	3.36	3.35	3.36	3.38	3.39	3.42	3.50	3.56
30	3.61	3.50	3.41	3.38	3.34	3.32	3.33	3.37	3.39	3.46	3.58	3.66
35	3.72	3.54	3.42	3.38	3.32	3.29	3.30	3.36	3.40	3.50	3.66	3.77
40	3.85	3.61	3.44	3.37	3.30	3.25	3.28	3.35	3.41	3.54	3.77	3.92
45	4.01	3.68	3.46	3.37	3.28	3.22	3.25	3.34	3.42	3.59	3.91	4.13
50	4.24	3.78	3.48	3.37	3.25	3.18	3.22	3.32	3.43	3.65	4.09	4.44
55	4.62	3.91	3.51	3.37	3.22	3.14	3.18	3.31	3.45	3.73	4.38	4.96
VERTICAL												
25	3.37	3.29	3.32	3.48	3.19	2.91	3.03	3.43	3.40	3.28	3.34	3.40
30	3.48	3.37	3.35	3.49	3.32	3.08	3.20	3.47	3.42	3.34	3.45	3.53
35	3.62	3.45	3.38	3.48	3.37	3.20	3.29	3.47	3.43	3.41	3.56	3.67
40	3.77	3.53	3.41	3.48	3.38	3.25	3.32	3.46	3.44	3.47	3.69	3.85
45	3.96	3.62	3.44	3.46	3.37	3.25	3.31	3.44	3.45	3.54	3.85	4.08
50	4.21	3.74	3.47	3.45	3.33	3.23	3.28	3.41	3.46	3.62	4.05	4.41
55	4.60	3.88	3.50	3.42	3.29	3.18	3.23	3.38	3.47	3.71	4.35	4.94

Table 3-2e Monthly Average Values of V for $\overline{K}_T$ = .7

$\overline{R}$ and R_n is explained in reference 15.

As a measure of the width of the monthly average radiation curve, the sunrise hour angle, ω_s, is directly related to day length. However, for beam radiation, the collector surface hour angle, ω_s', is related to the length of time the beam radiation strikes the collector. Equations for calculating ω_s and ω_s' can be found in reference 10. These variables, along with $\overline{K}_T$ were found to correlate with V in the following manner.

$$V = A \cdot RW^2 + B \cdot RW + C \tag{3-12}$$

$$RW = \frac{\overline{R}/R_n}{((\omega_s' \cdot 1.548 \cdot \overline{K}_T)) + ((1 - 1.548 \cdot \overline{K}_T) \cdot \omega_s))}$$

$$A = 15.197\ \overline{K}_T^{\,2} - 12.347\ \overline{K}_T + 1.004$$

$$B = -2.371\ \overline{K}_T^{\,2} - 12.22\ \overline{K}_T + 12.689$$

$$C = 2.547\ \overline{K}_T^{\,2} + 1.542\ \overline{K}_T - .732$$

Figure 3-3 contains a plot of V as a function of RW for the values of Ø, S, $\overline{K}_T$ in Table 3-1. The solid lines drawn in this figure are the curves determined by the correlation for V (for $\overline{K}_T$ = .3, .4, .5, .6, .7). The correlation can be used interchangeably with Table 3-1.

3.3 Example Calculation - $\overline{Q}_E$

As an example of the procedure developed in section 3-2 the performance of a photovoltaic array during January in Madison, Wisconsin, will be calculated. Table 3-3 contains the array parameters and meteorological data available for January in Madison. Using this information, equation (3-11) reduces to: $\overline{\eta}$ = .124 - .00186 V.

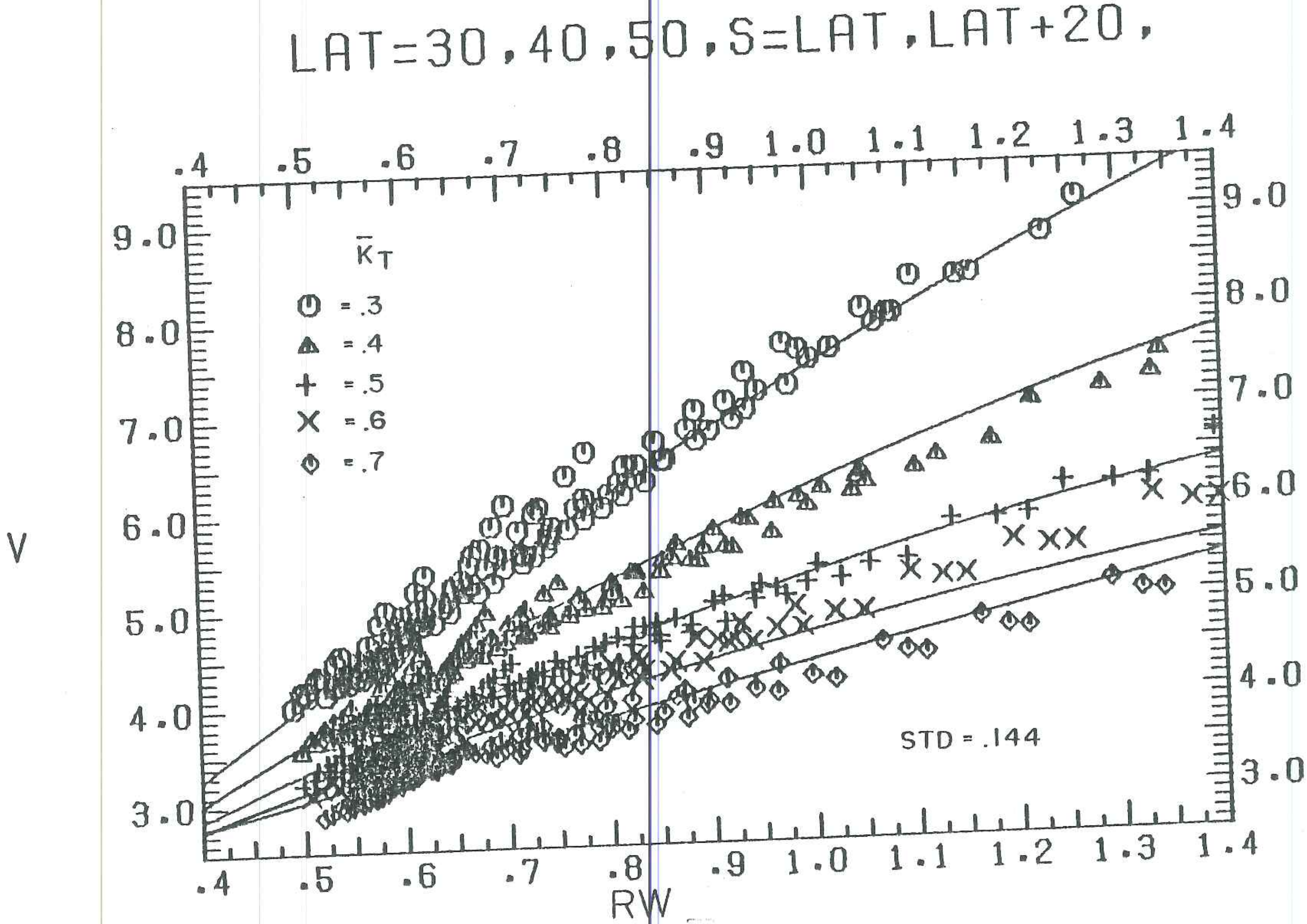


Figure 3-3 Comparison of Monthly Average Values of V (correlation-table)

For the latitude, slope, month and $\overline{K}_T$ for this problem, V can be determined from Table 3-1; however, interpolation with respect to latitude and $\overline{K}_T$ is necessary.

Array Parameter	Value
ϕ	43.13°
S	23.13°
A	$1m^2$
U_{Lo}	20 W/m^2-°C
$\overline{\tau\alpha}$ (τ = 1 no cover)	.95
η_{R_o}	.12
β_R	.004/°C

Meteorological Variable	Value
$\overline{T}_a$	-8.4°C
$\overline{H}_T$	2.52KWH/m^2-day
$\overline{K}_T$	.45

Table 3-3

System Parameters

For January with $\emptyset - S = 20°$

$$V(\overline{K}_T = .4, \emptyset = 40°) = 5.56$$

$$V(\overline{K}_T = .4, \emptyset = 45°) = 5.97$$

then $$V(\overline{K}_T = .4, \emptyset = 43.13) = 5.82$$

Similarly

$$V(\overline{K}_T = .5, \emptyset = 40°) = 4.81$$

$$V(\overline{K}_T = .5, \emptyset = 45°) = 5.09$$

then $$V(\overline{K}_T = .5, \emptyset = 43.13°) = 4.99$$

Interpolating with respect to $\overline{K}_T$;

$$V(\overline{K}_T = .45, \emptyset = 43.13) = 5.41$$

Alternatively, V could have been determined using equation (3-11).

For this problem

$$\overline{R} = 1.53$$

$$R_n = 1.34$$

$$\omega_s = \omega_s' = 1.21 \text{ radians}$$

and for $\overline{K}_T = .45$

$$RW = .944$$

$$A = -1.47$$

$$B = 6.71$$

$$C = .478$$

finally $V(\overline{K}_T = .45, \phi = 43.13, S = 23.13) = 5.50$

The resulting monthly average efficiency in either case is

$$\bar{\eta} \approx .114$$

The total energy produced by the array is given by equation (3-2) here

$$N\overline{Q}_E = A\bar{\eta}\ \overline{H}_T\ N\bar{\tau}$$
$$= 8.90\ \text{KWH}$$

The actual electrical energy that can be delivered to the load will be the product of $\overline{Q}_E$ and the monthly average system efficiency factor $\bar{\eta}_s$.

3.4 Accuracy of Predictions

The accuracy in using equation (3-11) to predict $\bar{\eta}$ will depend on the accuracy of the approximations

1) $\tau\ G_T \eta_{R_o}\ \beta_R << U_{L_o}$
2) $\overline{T}_a' \approx \overline{T}_a$
3) $V\ (\phi, S, \overline{K}_T, MN)$ can be determined using long-term values (Table 3-1).

The comparison of TRNSYS simulations and this design method (relying on the three assumptions) for predicting $\bar{\eta}$ is shown in Figure 3-4. The locations and range of array parameters used in these comparisons are given in Table 3-4. The diagonal line in

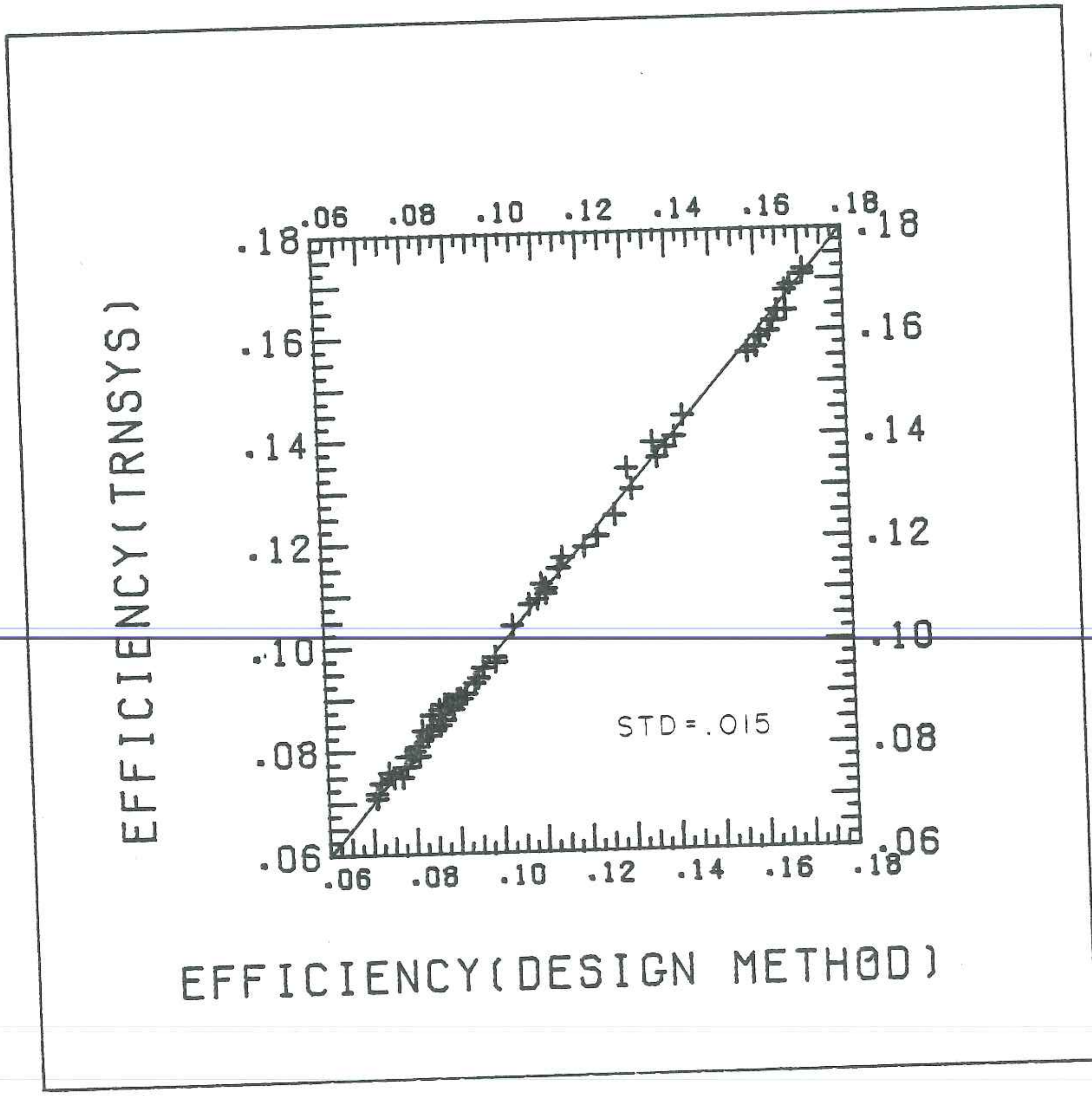


Figure 3-4 Comparison of Monthly Average Efficiency (TRNSYS-design method)

Table 3-4

System Parameters (Figure 3-4)

Parameter	Range
Efficiency (T_R = 0°C)	$.08 < \eta_{R_o} < .18$
Temp. vs. Efficiency Coefficient	$.0025/°C \le \beta_R \le .004/°C$
Thermal Loss Coefficient	$.014 \frac{KW}{m^2-°C} < U_{Lo} < .042 \frac{KW}{m^2-°C}$
Cover Transmittance	$.88 < \tau \le 1$
Absorptance	$.85 < \alpha < 1$
Collector Tilt	$-20° < (\emptyset - S) < 20°$

Locations

Albuquerque, New Mexico

Ely, Nevada

Madison, Wisconsin

Seattle, Washington

Nashville, Tennessee

Cape Hatteras, North Carolina

Bismarck, North Dakota

Figure 3-4 represents perfect agreement between simulations and the predicted values. The standard deviation between the simulated and predicted values is less than 1.5% of the monthly average efficiency. This agreement between simulation and predicted values is quite good.

3.5 Conclusions

The monthly average array efficiency calculated in this chapter can be used to predict the maximum monthly average daily array output, $\bar{Q}_E$. In order to evaluate system performance, an estimation of the average system efficiency must be known (the product of the monthly average regulator and inverter efficiencies is one estimate). The solar fraction of the total energy delivered to the load, $\mathcal{f}$, for the type of photovoltaic system described in section 1.3.2 is calculated using equation (3-13).

$$\mathcal{f} = \frac{\bar{Q}_E \, \bar{\eta}_S}{\bar{Q}_L} \qquad (3\text{-}13)$$

In a photovoltaic system where all the energy generated is not immediately utilized, more information is needed to determine the solar fraction. These systems will be discussed in the following chapters.

4. PREDICTION OF MONTHLY AVERAGE PERFORMANCE - SYSTEMS WITH NO STORAGE

4.1 Introduction

The instantaneous electrical output from a photovolatic array may exceed the energy required by the load. The excess energy produced by the array must be stored for use at another time, sold to the utility or dissipated. An accurate prediction of the amount of energy which must be dissipated in a system having no storage will be essential to the analysis of all photovoltaic systems where excess energy is produced.

In this study, only twenty-four hour constant load patterns have been considered. It is quite possible to extend this work so that non-constant load patterns can be examined.

4.2 Prediction of the Non-Utilizable Energy, QD_o

The instantaneous energy generated by a photovoltaic array is defined in equation (3-1). In a system with no storage or utility feedback capabilities, the energy dissipated can be defined by equation (4-1).

$$QD_o = [\bar{\eta}_s Q_E - Q_L]^+ \qquad (4\text{-}1)$$

Here the superscript "+" indicates that only positive values are considered. Substituting for Q_E from equation (2-2) and integrating over a month, equation (4-1) becomes:

$$N\overline{QD}_o = \int_M [\overline{\eta}_s \tau G_T \eta A - Q_L]^+ dt \qquad (4\text{-}2)$$

which can be rewritten as

$$N\overline{QD}_o = \int_M \overline{\eta}_s A \eta \tau [G_T - \frac{Q_L}{A\eta\tau\overline{\eta}_s}]^+ dt \qquad (4\text{-}3)$$

A maximum radiation level or critical radiation level can be defined such that all radiation above G_c is non-utilizable (i.e. in excess of the load)

$$G_c = \frac{Q_L}{A\eta\tau\overline{\eta}_s} \qquad (4\text{-}4)$$

then equation (4-3) becomes:

$$N\overline{QD}_o = A\overline{\eta}_s \int_M \tau \eta [G_T - G_c]^+ dt \qquad (4\text{-}5)$$

which is equivalent to:

$$N\overline{QD}_o = A\overline{\eta}_s \int_M \overline{H}_T \eta \tau \frac{[G_T - G_c]^+}{\overline{H}_T} dt \qquad (4\text{-}6)$$

equation (4-6) becomes:

$$N\overline{QD}_o = A \overline{H}_T N \overline{\eta}^+ \overline{\phi} \overline{\tau} \overline{\eta}_s \qquad (4\text{-}7)$$

where $\overline{\phi}$ is the fraction of the monthly total radiation which is above the critical level, G_c;

$$\overline{\phi} = \frac{1}{N} \int_M \frac{[G_T - G_c]^+}{\overline{H}_T} dt \qquad (4\text{-}8)$$

and $\overline{\eta}^{+}$ is a radiation weighted monthly average efficiency during those hours when the radiation G_T exceeds the critical level G_c.

The monthly average fraction, $\overline{\phi}$, has been used by Klein[15] to estimate the monthly average performance of solar thermal collectors. In solar thermal calculations, $\overline{\phi}$ refers to the utilizable fraction of the incident solar energy. Klein, extending the results of Whiller,[16] and Liu and Jordon,[14] has correlated $\overline{\phi}$ as a function of three meteorological variables: $\overline{K}_T$, $\overline{R}/R_n$ and X_c. The correlation is given in equation 4-9:

$$\overline{\phi} = \exp\left((A + B\,(R_n/\overline{R}))(X_c + (X_c^{\,2})\right) \qquad (4\text{-}9)$$

where $A = 2.943 - 9.271\,\overline{K}_T + 4.0315\,\overline{K}_T^{\,2}$

$B = -4.345 + 8.853\,\overline{K}_T - 3.602\,\overline{K}_T^{\,2}$

$C = -0.170 - 0.3058\,\overline{K}_T + 2.936\,\overline{K}_T^{\,2}$

The variables $\overline{K}_T$ and $\overline{R}/R_n$ have been discussed in section 3-2. X_c is a dimensionless critical radiation ratio, defined as the critical level G_c, divided by the radiation at noon, G_n, for the average day of the month. G_n can be calculated using methods developed in reference 15.

To determine $\overline{\phi}$, it is necessary that the critical level be constant throughout the month. In actuality, the critical level will vary since the efficiency, and the cover transmittance are not constant. An average critical level, $\overline{G}_c$ can be calculated using the monthly average efficiency and a monthly average transmittance as shown in equation (4-10).

$$\overline{G}_c = \frac{Q_L}{\overline{\eta}\,\overline{\tau}\,A\,\overline{\eta}_s} \tag{4-10}$$

The efficiency, $\overline{\eta}^+$, can be calculated using techniques similar to those prescribed to determine $\overline{\eta}$.

Specifically,

$$\overline{\eta}^+ = \eta_{R_o}\left(1 - \frac{\beta_R \int_{N_c} T_a\, G_T\, dt}{\int_{N_c} G_T\, dt} - \frac{\beta_R}{U_{L_o} N}\,\frac{\int_{N_c} \tau\alpha\, G_T^2\, dt}{\int_{N_c} G_T\, dt}\right) \tag{4-11}$$

where N_c is the set of all times when the radiation on the array is greater than the critical level. The integral, $\int_{N_c} G_T\, dt$, can be replaced by the product of the monthly average daily radiation during N_c, $\overline{H}_T^+$, and the number of days in the month. The integral containing ambient temperature is equal to the product of $N\overline{H}_T^+$ and the radiation-weighted ambient temperature during N_c, $\overline{T}_a''$. It has been found that a reasonable approximation of $\overline{T}_a''$ is the monthly average ambient temperature, $\overline{T}_a$. Defining

$$V^+ = \frac{\int_{N_c} G_T^2\, dt}{\overline{H}_T^+\,\overline{H}_T} \tag{4-12}$$

equation (4-12) reduces to:

$$\overline{\eta}^{+} = \eta_R \left(1 - \beta_R \overline{T}_a - \frac{\beta_R \overline{\tau\alpha}}{U_{L_o} N} V^{+} \overline{H}_T\right) \qquad (4\text{-}13)$$

Again, $\tau\alpha$ has been replaced by the monthly average product $\overline{\tau\alpha}$. This equation is in the same form as equation (3-10) for $\overline{\eta}$. However, V^{+} differs from V, because V^{+} is also a function of the monthly average critical level.

Monthly average values of V^{+} can be predicted using procedures similar to those used to calculate V. Once again all months are assumed to have thirty days. The radiation during each hour of each day is calculated. Each hour the radiation G_T is checked to see if it is less than the monthly average critical level $\overline{G}_c$. If so, that hour's radiation is not included in the set of hours N_c. A flow diagram of the process is shown in Figure 4-1. Appendix III contains a complete listing of the computer program used to calculate V^{+}. A set of graphs generated by this program are also in Appendix III. These graphs can be used to determine monthly average values of V^{+} for ϕ = 30°, 40°, 50° and slope, s = ϕ, $\phi \pm 20°$ and $\overline{K}_T$ between .4 and .7 for all values of $\overline{G}_c$.

Figure 4-2 shows the values of V^{+} for an array in Madison, Wisconsin ($\overline{K}_T$ = .45, ϕ = 43.13, S = 23.13) during January. Figure 4-3 shows the corresponding values of $\overline{\eta}^{+}$ (using the meteorological data and array parameters from Table 3-1). When the critical level is zero, all hours of radiation are considered and

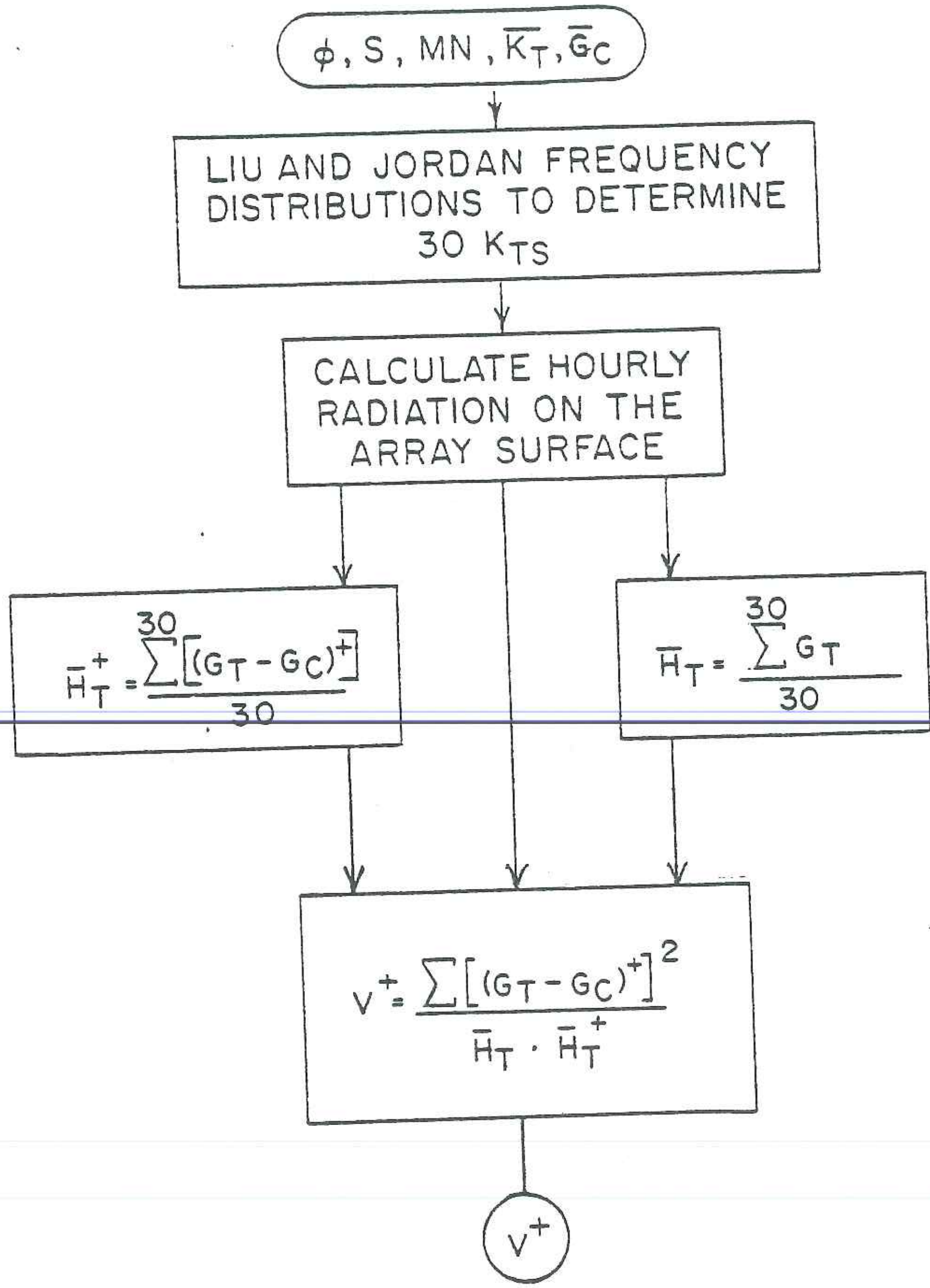


Figure 4-1 Schematic of the Analysis Used to Calculate Monthly Average Values of V^+

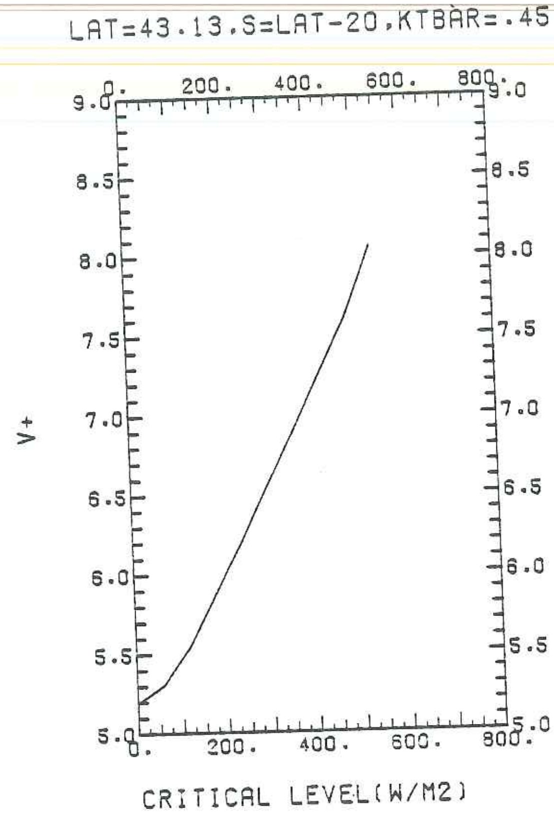


Figure 4-2 Comparison of V^+ and Critical Radiation Levels

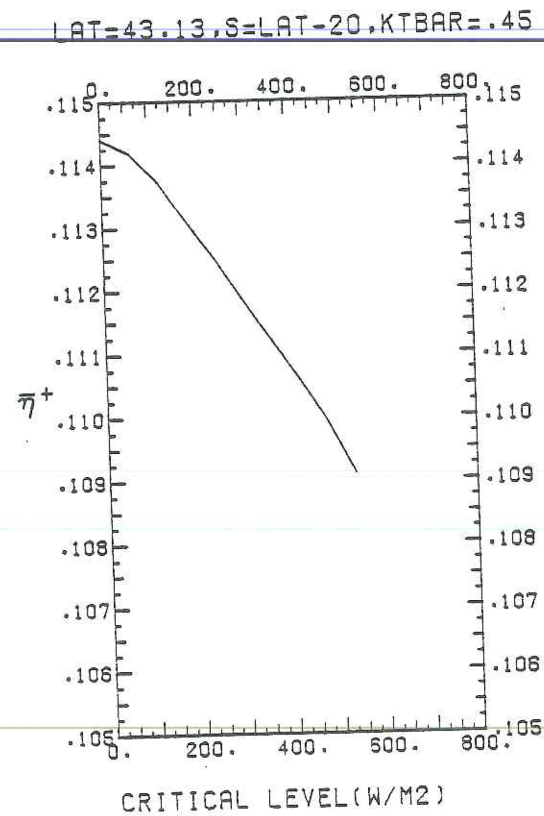


Figure 4-3 Comparison of $\bar{\eta}^+$ and Critical Radiation Levels

$\bar{\eta}^+ = \bar{\eta}$ (here $\bar{\eta}^+ = \bar{\eta} \simeq .114$) as the critical level increases, the array efficiency, $\bar{\eta}^+$, decreases. Physically, the higher critical level means that only larger values of insolation are considered (as the critical level increases, the amount and period of time that energy is dissipated decreases) when calculating $\bar{\eta}^+$. As the level of insolation increases the average cell temperature, $\bar{T}_{CELL}$, also increases, causing the decrease in $\bar{\eta}^+$.

The monthly average daily energy dissipated can be calculated, using the graphs in Appendix III for determining V^+, equation (4-13) to find $\bar{\eta}^+$, equation (4-9) to calculate $\bar{\phi}$ and finally equation (4-7) is used to determine $\overline{QD}_o$.

A correlation for the function V^+ has not as yet been determined. However, there is a correlation for V. If the assumption:

$$\bar{\eta}^+ \simeq \bar{\eta} \tag{4-14}$$

is valid, then equation (4-7) becomes:

$$N\,\overline{QD}_o = AN\,\bar{\eta}\,\bar{\phi}\,\bar{H}_T\,\bar{\tau}\,\bar{\eta}_s \tag{4-15}$$

Since $\bar{\eta}^+$ is always less than or equal to $\bar{\eta}$, equation (4-15) will tend to overpredict the monthly average dissipated energy. The percentage by which $\overline{QD}_o$ is overpredicted will depend on the monthly average critical level, $\bar{G}_c$, the array parameters, and the accuracy of the $\bar{\phi}$ correlation. Section 4-4 will discuss the accuracy of the $\overline{\eta}^{+} \simeq \overline{\eta}$ approximation.

These procedures for calculating $\overline{QD}_o$ are demonstrated in an example calculation in the next section.

4.3 Example Calculation - $\overline{QD}_o$

$\overline{QD}_o$ will be calculated for a photovoltaic system in Madison, Wisconsin during January (using the array parameters and meteorological data given in Table 3-1). Two constant load levels will be examined, namely:

$$Q_{L1} = 14 \text{ W}$$
$$Q_{L2} = 28 \text{ W}$$

Subscripts will be used to distinguish between the two loads.

<u>Step 1</u> Calculate $\overline{\eta}$

From section 3.3 $\overline{\eta} = .114$

<u>Step 2</u> Calculate $\overline{G}_c$

Assuming an overall system efficiency of 90% ($\eta_V = .95$, $\eta_I = .95$) the monthly average critical levels are:

$$\overline{G}_{c_1} = .137 \text{ KW/m}^2$$
$$\overline{G}_{c_2} = .273 \text{ KW/m}^2$$

<u>Step 3</u> Calculate $\overline{\phi}$

$$X_c = \frac{\overline{G}_c}{\overline{G}_n} = \frac{\overline{G}_c}{r_{t,n} R_n \overline{H}}$$

where $r_{t,n}$ is the ratio of the radiation at noon to the daily total radiation for the average day of the month ($r_{t,n}$ can be determined from equations or graphs in reference 10). For this example:

$\overline{H}_T = 2.52\ KWH/m^2\text{-day}$

$r_{t,n} = .180$

$R_N = 1.34$

$\overline{R} = 1.53$

$\overline{H} = 1.65\ KWH/m^2\text{-day}$

then

$X_{c1} = .343$

$X_{c2} = .686$

Finally using the correlation for $\overline{\phi}$ (with $\overline{K}_T = .45$)

$$\overline{\phi}_1 = .595$$

$$\overline{\phi}_2 = .323$$

Step 4 Calculate $\overline{NQD}_o$

A) Using the $\overline{\eta}^+ \simeq \overline{\eta}$ approximation, equation 4-15 predicts:

$$\overline{NQD}_{o1} = 4.77\ KWH$$

$$\overline{NQD}_{o2} = 2.59\ KWH$$

B) Determine $\overline{\eta}^+$ from Figure 4-3 (or by finding V^+ from the graphs in Appendix III and using equation (4-13) to calculate $\overline{\eta}^+$).

$$\overline{\eta}^+_1 = .113$$

$$\overline{\eta}^+_2 = .112$$

Using equation (4-7)

$$\overline{NQD}_{o_1} = 4.73 \text{ KWH}$$

$$\overline{NQD}_{o_2} = 2.53 \text{ KWH}$$

In this example the difference between the two methods for determining $\overline{QD}_o$ is less than .5% of the total monthly load.

4.4 Accuracy of Predictions

Figures 4-4 (a-c) shows comparisons between TRNSYS results and the simplified design method using the different assumptions described in Table 4-1. The amount of energy dissipated is divided by the monthly load for dimensionless comparisons. The locations and array parameters used in these comparisons are listed in Table 4-2. In each of these figures the diagonal line represents perfect agreement between TRNSYS and the design method.

Figure 4-4 reveals that the comparisons between TRNSYS values and design method values (calculating actual $\overline{\eta}^+$ and $\overline{\phi}$) are quite good. Using the $\overline{\eta}^+ \simeq \overline{\eta}$ approximation, the accuracy of predictions is slightly reduced and the design method tends to overpredict the TRNSYS results (this is expected since $\overline{\eta} \geq \overline{\eta}^+$). Finally, Figure 4-4c shows the change in accuracy caused by using long-term average values of $\overline{\phi}$. Since the $\overline{\phi}$ correlation calculates long-term averages, actual $\overline{\phi}$s for a specific month may differ from the $\overline{\phi}$ calculated using the correlation by as much as 10%. Also it has been

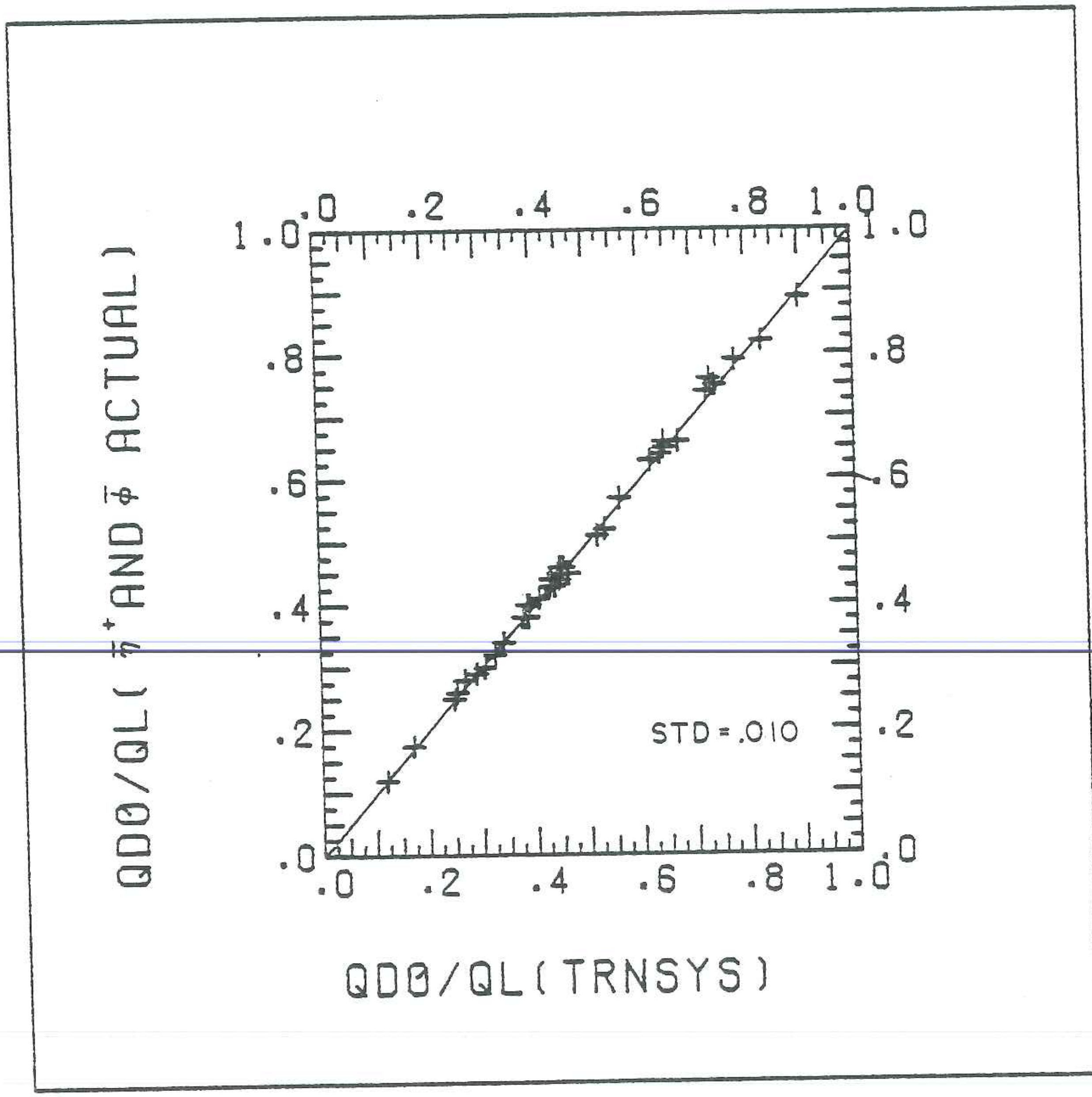


Figure 4-4 a Comparisons of $\overline{QD}_o/\overline{Q}_L$ (TRNSYS - $\bar{\eta}^+$ and $\bar{\phi}$ Actual)

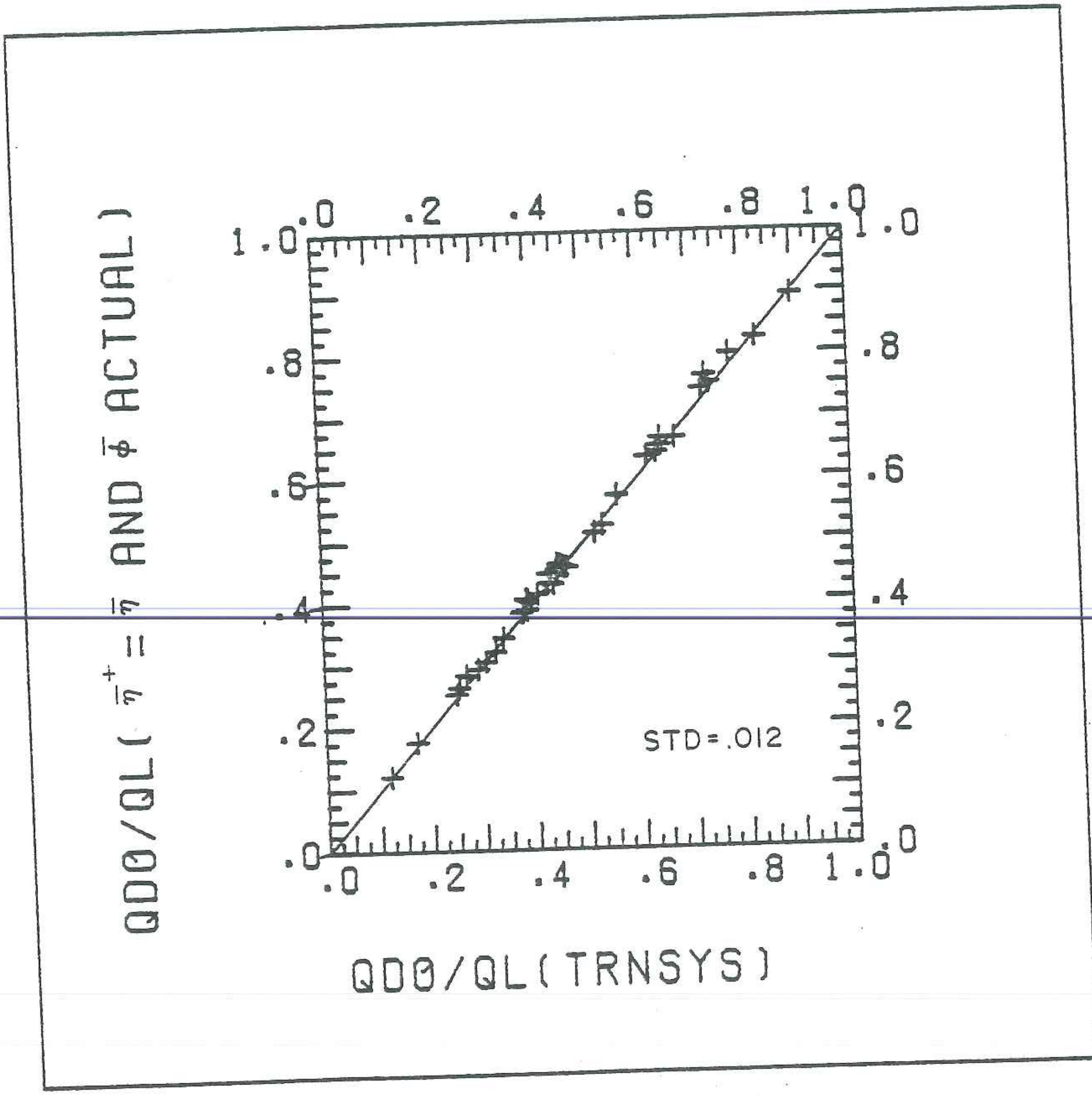


Figure 4-4 b Comparisons of $\overline{QD}_o/\overline{Q}_L$ (TRNSYS - $\overline{\eta}^+ = \overline{\eta}$ & $\overline{\phi}$ Actual)

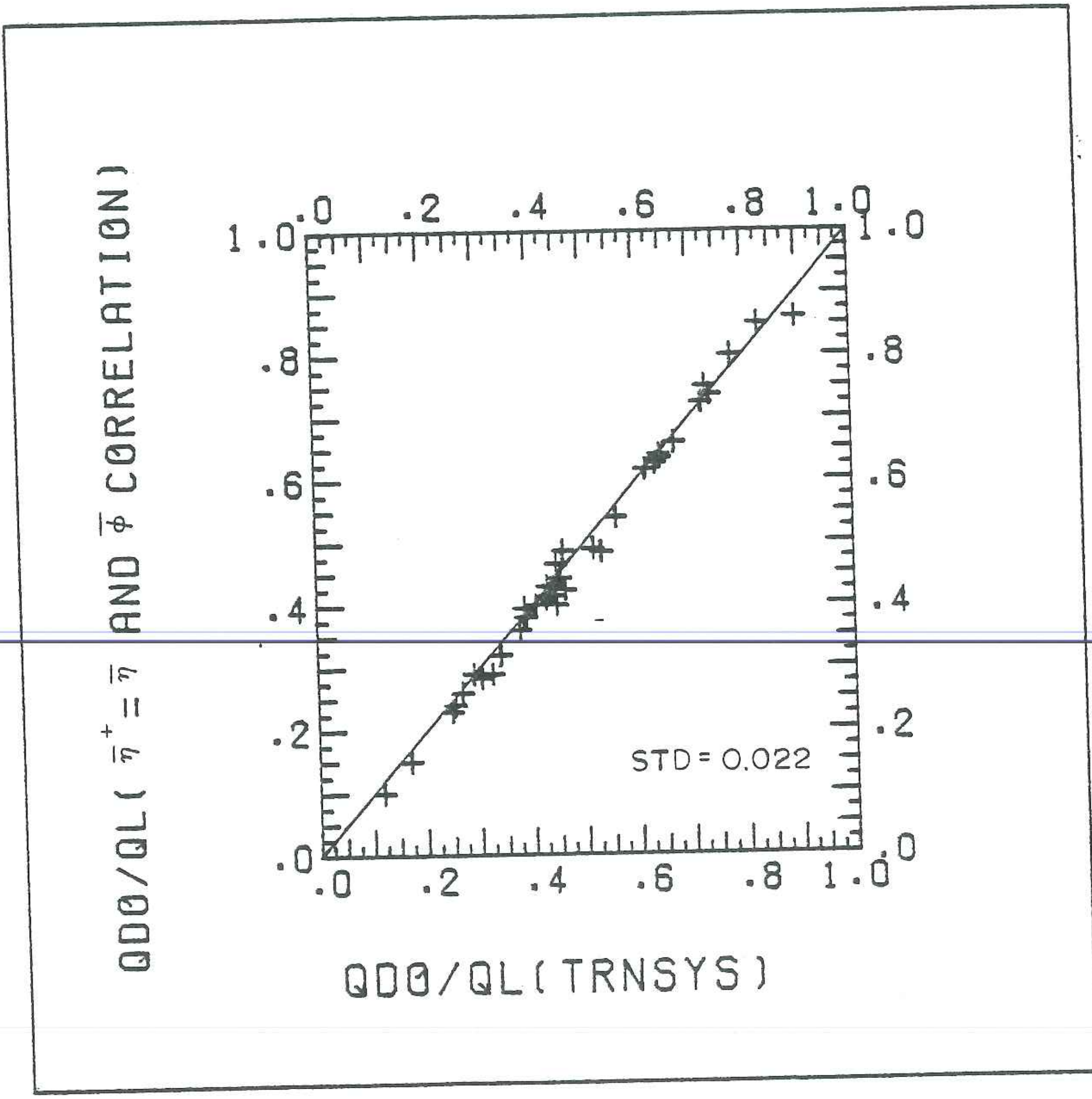


Figure 4-4 c Comparisons of $\overline{QD}_o/\overline{Q}_L$ (TRNSYS - $\bar{\eta}^+$ and $\bar{\phi}$ Actual)

Table 4-1

System Parameters (Figure 4-4 a-c)

Parameter	Range
Efficiency (T_R = 0°C)	$.08 < \eta_{R_o} < .18$
Temp. vs. Efficiency Coefficient	$.0025/°C \leq \beta_R \leq .004/°C$
Thermal Loss Coefficient	$.014 \frac{KW}{m^2-°C} < U_{Lo} < .042 \frac{KW}{m^2-°C}$
Cover Transmittance	$.88 < \tau \leq 1$
Absorptance	$.85 < \alpha < 1$
Collector Tilt	$-20° < (\emptyset - S) < 20°$
No Storage Dissipation - Load Ratio	$\overline{QD}_o/\overline{Q}_L < 1.2$

Locations

Albuquerque, New Mexico	Madison, Wisconsin

determined that the existing $\overline{\phi}$ correlation has a tendency to underpredict the actual $\overline{\phi}$.[17] The amount that $\overline{\phi}$ is underpredicted will depend on time of year and critical level (i.e., the $\overline{\phi}$ correlation underpredicts by the greatest amount at high critical levels during the winter). Presently a new $\overline{\phi}$ correlation is being developed at the Solar Energy Laboratory, University of Wisconsin.[17]

Figure 4-5 shows a comparison between TRNSYS results and those obtained from the design method (using the $\overline{\eta}^{+} \simeq \overline{\eta}$ approximation and the $\overline{\phi}$ correlation) for all the locations and range of array parameters listed in Table 3-4. The agreement between TRNSYS values and predicted values is quite good.

4.5 Conclusions

Once $\overline{QD}_o$ has been determined, the solar fraction may be calculated for two more types of system configurations, specifically those configurations described in section 1.3.3. In a system with no storage capabilities

$$f = \frac{\overline{\eta}_s \overline{Q}_E - \overline{QD}_o}{\overline{Q}_L} \tag{4-16}$$

if the excess energy is fed back to the utility grid

$$\overline{Q}_{UL} = \overline{QD}_o \tag{4-17}$$

The degrading effects of no storage or utility feedback capabilities on overall system performance can be seen by

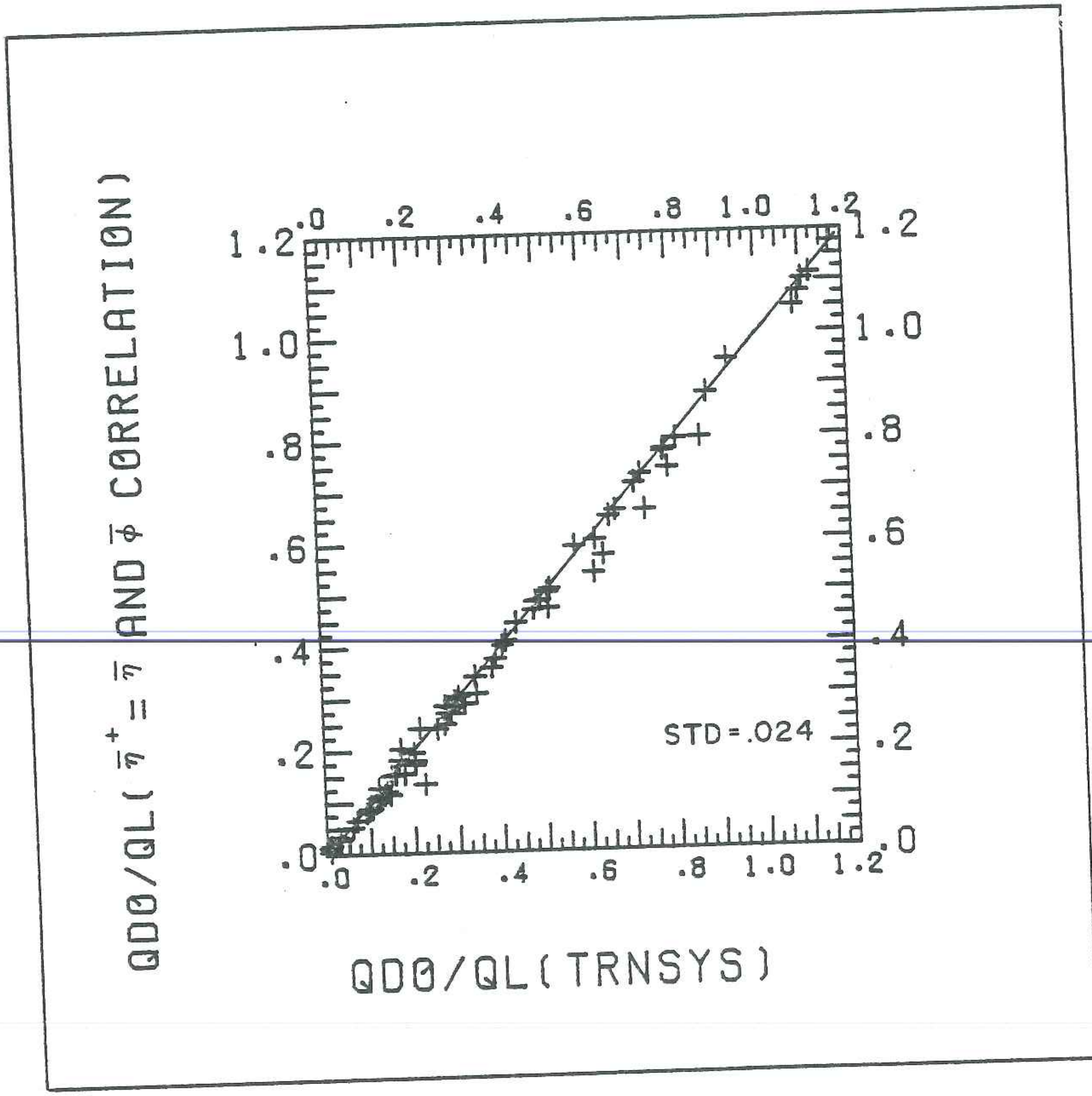


Figure 4-5 Comparisons of $\overline{QD}_0$ (TRNSYS - $\bar{\phi}$ correlation and $\bar{\eta}^+ \simeq \eta$ approximation)

comparing solar fractions for systems with no storage and systems described in section 1.3.2. For the example calculation in section 4.3:

$$f_1 = .31$$

$$f_2 = .26$$

if all the energy generated could have been utilized the monthly solar fractions would have been

$$f = \frac{\bar{\eta}_s \bar{Q}_E}{\bar{Q}_L} \qquad (4\text{-}18)$$

and for this example

$$f_1 = .77$$

$$f_2 = .38$$

If the excess energy can be sold to the utility, overall system performance will be improved.

5. PREDICTIONS OF MONTHLY AVERAGE PERFORMANCE - BATTERY STORAGE SYSTEMS

5.1 Introduction

Battery storage is important in photovolataic systems for two reasons: the addition of battery storage may substantially improve overall system performance and is often required in locations where no other auxilary power supply is available (e.g. buoys at sea, communication systems in mountainous locations, etc.). Battery storage also has two main disadvantages: cost and maintenance.

In this chapter a method is presented which can be used to estimate the amount of energy actually dissipated, QD_A, in a system with battery storage. The energy available to the load Q_{DEL} can be determined using equation (5-1).

$$Q_{DEL} = \eta_s Q_E - QD_A - QB_L \tag{5-1}$$

Here Q_{BL} is the energy lost in the battery due to internal battery losses and electrolyte gassing. Estimation of battery losses will be discussed in section 5.3.

5.2 Predicting the Actual Energy Dissipated - QD_A

An energy balance on the battery in Figure 5-1 gives the following relations between monthly average daily values:

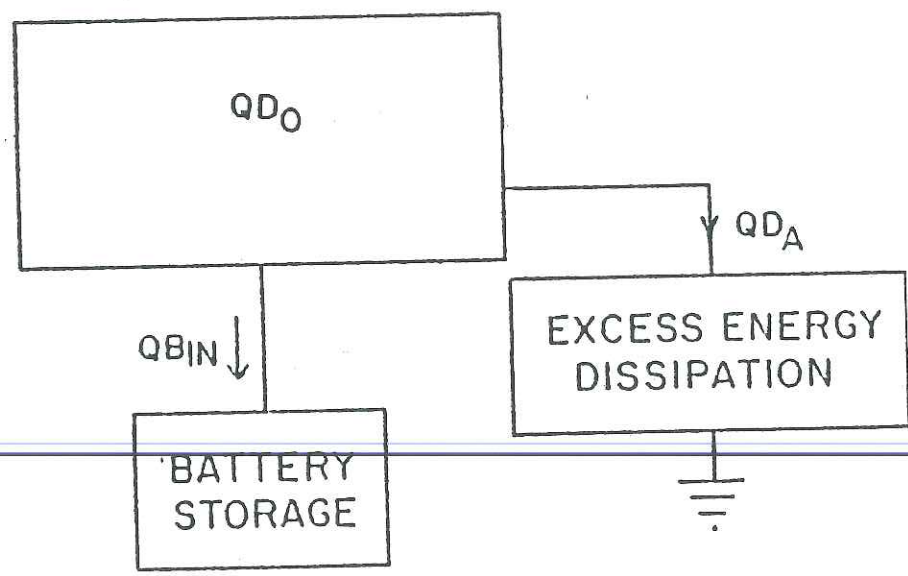


Figure 5-1 Schematic of Energy Flow for Battery Storage

$$\overline{QD}_A = \overline{QD}_o - \overline{QB}_{IN} \qquad (5\text{-}2a)$$

In this equation, the monthly average daily energy which is dissipated is related to the amount of energy that would have been dissipated if there were no storage ($\overline{QD}_o$) and the total amount of energy sent to the battery ($\overline{QB}_{IN}$). The quantity $\overline{QD}_o$ can be calculated using procedures developed in section 4-2. The amount of energy sent to the battery cannot (as yet) be calculated directly. However, it has been shown empirically to be related to the effective battery storage capacity and the total amount of energy available to the battery (i.e. $\overline{QD}_o$). Using the results of TRNSYS simulations a relationship between three dimensionless ratios, $\overline{QD}_A/\overline{Q}_L$, $\overline{QD}_o/\overline{Q}_L$ and $Be/\overline{Q}_L$ has been developed. Figure 5-2 shows this relationship which was developed using the locations and array parameters listed in Table 5-2. The battery cell model used in the TRNSYS simulations was discussed in section 2-4 and additional battery parameters used are listed in Table 5-2. The monthly data points shown in Figure 5-1 are for several daily storage-load fractions ($Be/\overline{Q}_L$ = .25, .5, .75, 1.0, 3.0). The diagonal line represents the no storage case. Several conclusions can be drawn from this figure:

1. In a particular photovoltaic system as the storage-load ratio increases the relative change in $\overline{QD}_A$ decreases (i.e., above a

Table 5-1

System Parameters (Figure 5-2)

Parameter	Range
Efficiency (T_R = 0°C)	$.08 < \eta_{R_o} < .18$
Temp. vs. Efficiency Coefficient	$.0025/°C \leq \beta_R \leq .004/°C$
Thermal Loss Coefficient	$.014 \frac{KW}{m^2-°C} < U_{Lo} < .042 \frac{KW}{m^2-°C}$
Cover Transmittance	$.88 < \tau \leq 1$
Absorptance	$.85 < \alpha < 1$
Collector Tilt	$-20° < (\emptyset - S) < 20°$
No Storage Dissipation - Load Ratio	$\overline{QD}_o/\overline{Q}_L < 1.2$
Storage - Load Ratio	$Be/\overline{Q}_L < .5$

Locations

Albuquerque, New Mexico	Ely, Nevada
Madison, Wisconsin	Nashville, Tennessee

Table 5-2

Battery Parameters (Figure 5-2)

Parameter	Definition	Value
V_{oc}	open circuit voltage	2.18 V
F_D	minimum fractional state of charge	.2
F_C	maximum fractional state of charge	.9
f_B	usable fraction F_C-F_D	.7
C_s	cells in series	56

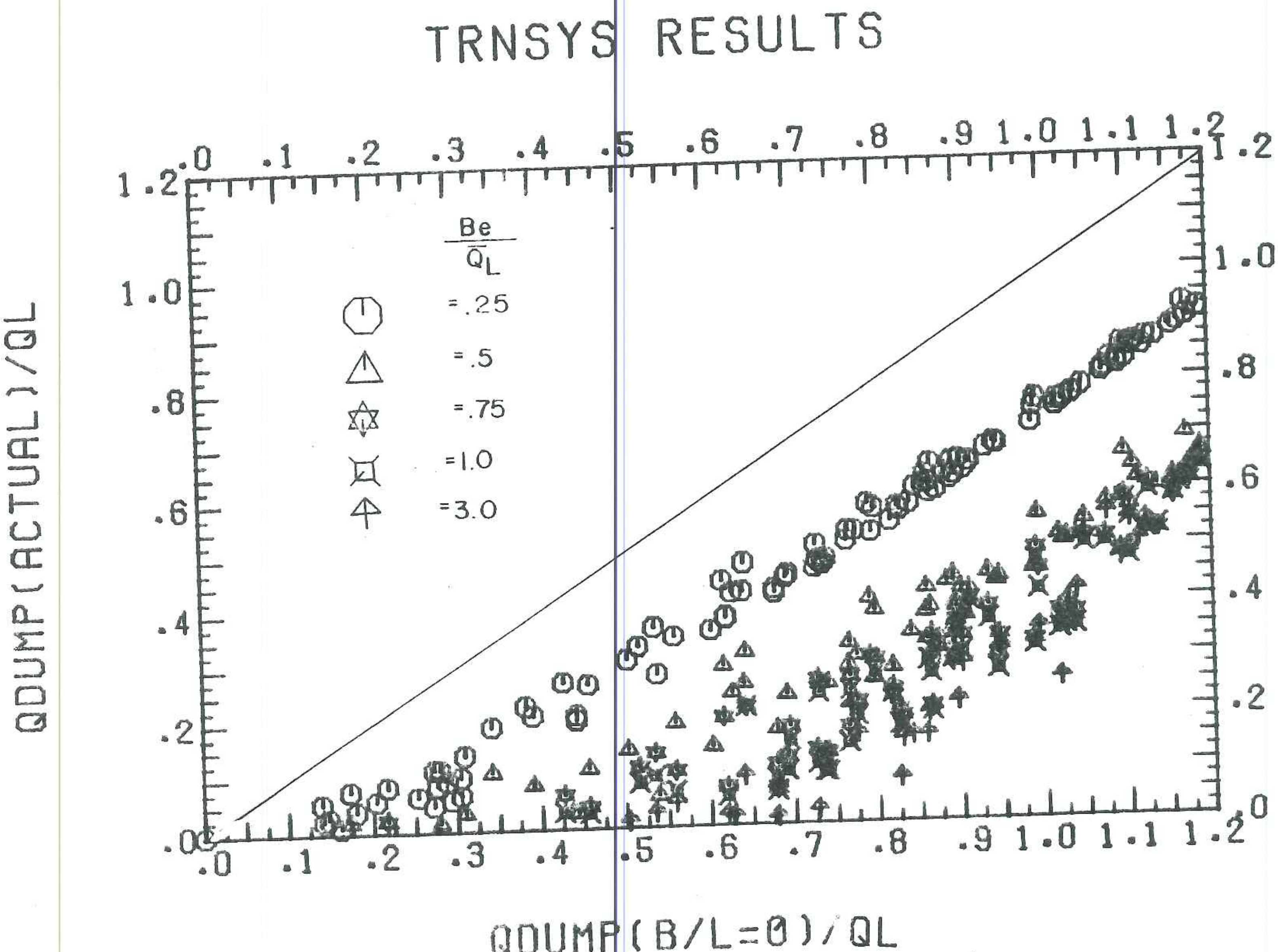


Figure 5-2 Comparisons of $\overline{QD}_A/\overline{Q}_L$ (TRNSYS Results)

certain capacity the effects of increasing storage are minimal).

2) When all excess energy can be stored, the ratio $\overline{QD}_A/\overline{Q}_L$ is zero while $\overline{QD}_o/\overline{Q}_L$ may be non-zero.

3) As the ratio $\overline{QD}_o/\overline{Q}_L$ becomes large ($\overline{QD}_o/\overline{Q}_L > .75$) the larger battery sizes dissipate the same amount of energy.

4) This relationship works well at low storage-load ratios (i.e. $Be/\overline{Q}_L$ is small enough so there is no carryover from day to day) and not as well at larger ratios. One explanation for this is that the effects of day-to-day storage (energy) carryover are not included in this relation.

Using the results of Figure 5-2 the following correlation for $\overline{QD}_A/\overline{Q}_L$ has been developed. Defining

$$XDO = \overline{QD}_o/\overline{Q}_L$$

$$YDA = \overline{QD}_A/\overline{Q}_L$$

then if:

$Be/\overline{Q}_L = 0.0$

$$YDA - XDO \qquad (5\text{-}3a)$$

$Be/\overline{Q}_L = .25$

$$YDA = .094 \cdot XDO^2 + .766 \cdot XDO - .12 \qquad (5\text{-}3b)$$

$Be/\overline{Q}_L = .5$

$$YDA = .281 \cdot XDO^2 + .314 \cdot XDO - .10 \qquad (5\text{-}3c)$$

$Be/\overline{Q}_L = .75$

$$YDA = .576 \cdot XDO^2 - .147 \cdot XDO - .013 \qquad (5\text{-}3d)$$

$B_e/\overline{Q}_L$ - 1.0

$$YDA = .69 \cdot XDO^2 - .305 \cdot XDA + .012 \qquad (5\text{-}3e)$$

$Be/\overline{Q}_L$ = 3.0

$$YDA = .686 \cdot XDO^2 - .16 \cdot XDO - .147 \qquad (5\text{-}3f)$$

The curves generated from equations (5-3a-f) are shown in Figure 5-3.

The effective battery storage capacity can be estimated as:

$$Be = Q_m V_{oc} f_B \qquad (5\text{-}4)$$

where f_B is the usable fraction of the battery (often limitations are put on the battery charge and discharge levels to prolong the battery lifetime).

Once the quantities $\overline{QD}_o/\overline{Q}_L$ and $Be/\overline{Q}_L$ have been determined, equations (5-3a-f) can be used to estimate the actual monthly average daily dissipated energy. Linear interpolation can be used to calculate values of $\overline{QD}_A/\overline{Q}_L$ for other storage-load ratios (i.e. $0 \leq Be/\overline{Q}_L < 3.0$).

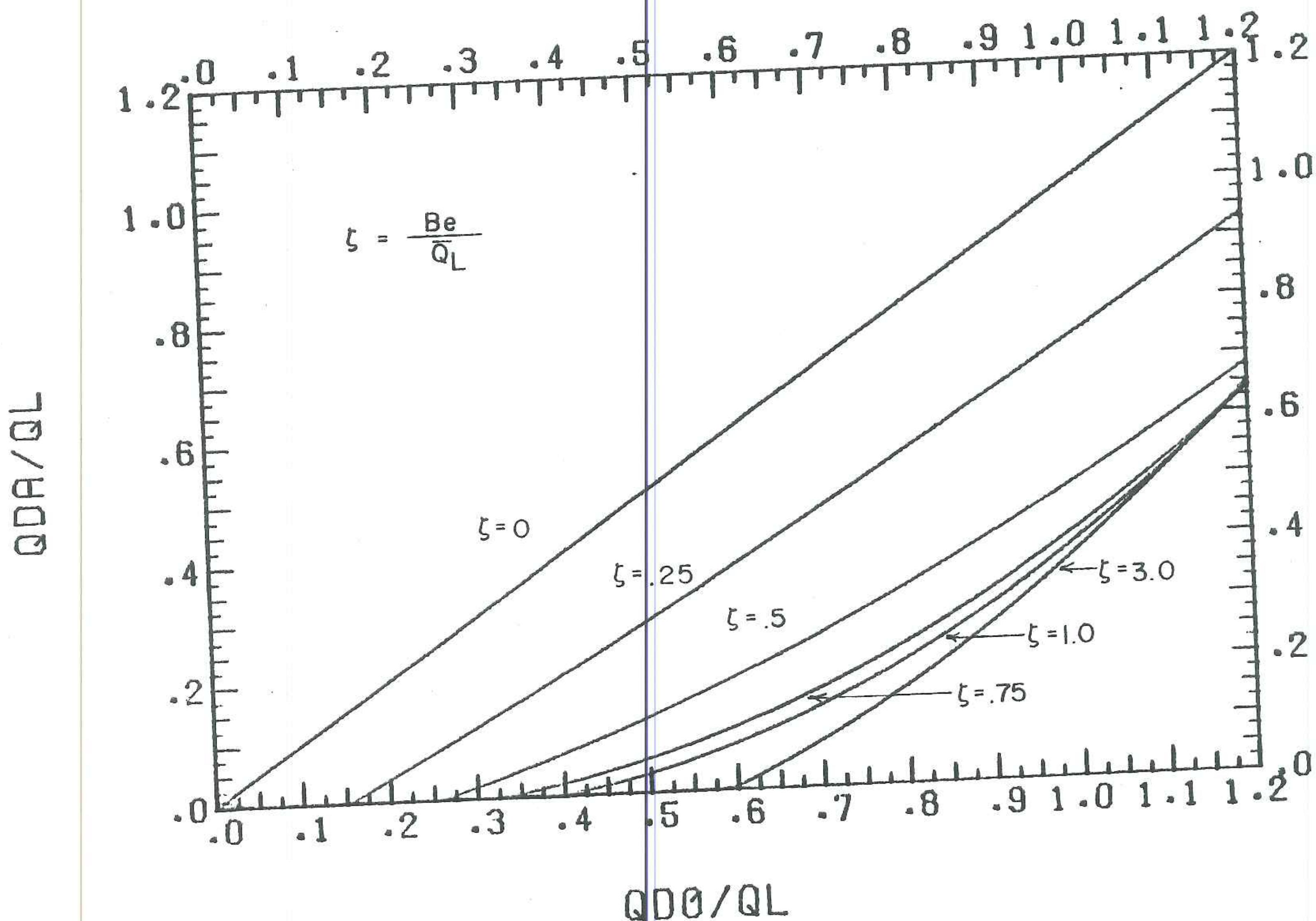


Figure 5-3 Comparisons of $\overline{QD}_A/\overline{Q}_L$ (Correlation)

It is important to note that equations (5-3 a-f) refer to a specific battery storage system. The accuracy of these curves for all types of battery systems has not been examined (altering f_B and C_s have been seen to have little effect on these curves). However, using TRNSYS and the simulation models described in Chapter 2, similar relations can be developed for any type of battery storage system.

The accuracy in determining the actual amount of energy dissipated will directly effect the accuracy of predictions of overall system performance. The prediction of overall performance for systems using battery storage will be discussed in section 5-5.

5.3. Battery Losses - QB_L

The internal resistance of a battery (and the losses due to electrolyte gassing) varies with battery state of charge, voltage and current. Therefore, it is difficult to formulate a reliable method to predict the long-term fractional battery losses. The monthly average fractional battery losses, f_{B_L}, is defined as:

$$f_{B_L} = 1 - \frac{\overline{QB}_{OUT}}{\overline{QB}_{IN}} \qquad (5\text{-}5)$$

where $\overline{QB}_{OUT}$ is the energy sent to the load from the battery.

The battery losses represent a small fraction of the total energy delivered to the load. Therefore, a moderate error in f_{BL}

will not have a large effect on the prediction of monthly average system performance (for example, see section 5-4).

As a guide to choosing a value of f_{B_L}, results of the monthly simulations used to generate Figure 5-1 were examined. In these simulations, the average value of f_{B_L} was .14 with a standard deviation of $\pm$ .02. For a specific photovaltaic system, as the battery capacity increases, the fractional battery losses will generally decrease. This is because the voltage drop (i.e., internal battery losses) between charging and discharging currents becomes smaller as the battery capacity (Q_m) increases (see equation (2-7) and (2-8)).

Once the fractional battery losses are known, then $\overline{QB}_L$ can be determined using equation (5-6).

$$\overline{QB}_L = f_{B_L} (\overline{QD}_o - \overline{QD}_A) \qquad (5\text{-}6)$$

5.4 Example Calculation - System Performance With Battery Storage

The results of the previous example problems (section 3.3, 4.3) and the methods presented in the previous section are used to predict the monthly average performance of a photovoltaic system with battery storage (in Madison, Wisconsin during January). The battery cell used is described by the parameters in Table 2-1 and Table 5-1. The battery capacity (Q_m) is 100 amp - hrs.

The effective battery storage can be calculated using equation (5-4) yielding:

$$B_e/\bar{Q}_{L1} = .46$$

$$B_e/\bar{Q}_{L2} = .23$$

and from the results of section 4.3:

$$\frac{\overline{QD}_{o1}}{\bar{Q}_{L1}} = .46$$

$$\frac{\overline{QD}_{o2}}{\overline{QL}_2} = .12$$

Using equations (5-3a-d) or Figure 5-2:

$$\overline{QD}_A/\overline{QL}\ (\overline{QD}_o/\overline{QL} = .46,\ Be/\overline{QL} = .46) = .13$$

$$\overline{QD}_A/\overline{QL}\ (\overline{QD}_o/\overline{QL} = .12,\ Be/\overline{QL} = .23) = 0.0$$

Multiplying these values by the monthly average daily loads:

$$N\overline{QD}_{A_1} = 1.35 \text{ KWH}$$

$$N\overline{QD}_{A_2} = 0.0$$

The monthly average daily total energy sent to the load is given by equation (5-7).

$$\bar{Q}_{DEL} = (\bar{\eta}_s\bar{Q}_E - \overline{QD}_o) + (1 - f_{B_L}) \cdot (\overline{QD}_o - \overline{QD}_A) \qquad (5\text{-}7)$$

Assuming the fractional battery losses are approximately .14 then:

$$N\overline{Q}_{DEL_1} = 6.2 \text{ KWH}$$

and $$N\overline{Q}_{DEL_2} = 7.7 \text{ KWH}$$

The fraction of the load supplied by the photovoltaic array is:

$$\delta = \frac{\overline{Q}_{DEL}}{\overline{Q}_L} \quad (5\text{-}8)$$

and for this example:

$$\delta_1 = .60$$

$$\delta_2 = .37$$

The overall system performance has increased significantly in comparison with the performance of the same system with no storage (see section 4.3).

As an example of the sensitivity of the results with respect to changes in f_{BL}, if f_{BL} were chosen to be .1 (instead of .14) then:

$$\delta_1 = .61$$

$$\delta_2 = .37$$

The error caused by a greater than 25% change in f_{BL} is small in either case.

5.5 Accuracy of Predictions

Table 5-3 lists the standard deviation between the $\overline{QD}_A$ correlation (Figure 5-3) and the actual data points (Figure 5-2) used to derive these correlations.

Table 5-3
Standard Deviation in Predicting $\overline{QD}_A/\overline{Q}_L$ (monthly)

$Be/\overline{Q}_L$	STD
.25	.022
.5	.039
.75	.053
1.0	.052
3.0	.059

The standard deviation increases significantly as the storage-load ratio increases. Therefore the accuracy in predicting $\overline{QD}_A$ is best at low storage-load ratios (i.e. when the storage-load ratio is small enough that there is no carryover from day to day). Also, the accuracy of yearly predictions is considerably better than monthly predictions. This is because the inaccuracies in the $\overline{QD}_A$-correlation tend to balance out when yearly totals are examined. Figure 5-4 shows a comparison of monthly TRNSYS results and predicted values of the fraction of the load supplied by a photovoltaic system with battery storage (for $Be/\overline{Q}_L \leq .5$). The comparison of yearly results is shown in Figure 5-5. The monthly fraction by solar is defined by equations (5-7) and (5-8). The locations and range of parameters for this comparison are listed in Table 5-4. The diagonal line in either figure represents perfect agreement between simulation results and predicted

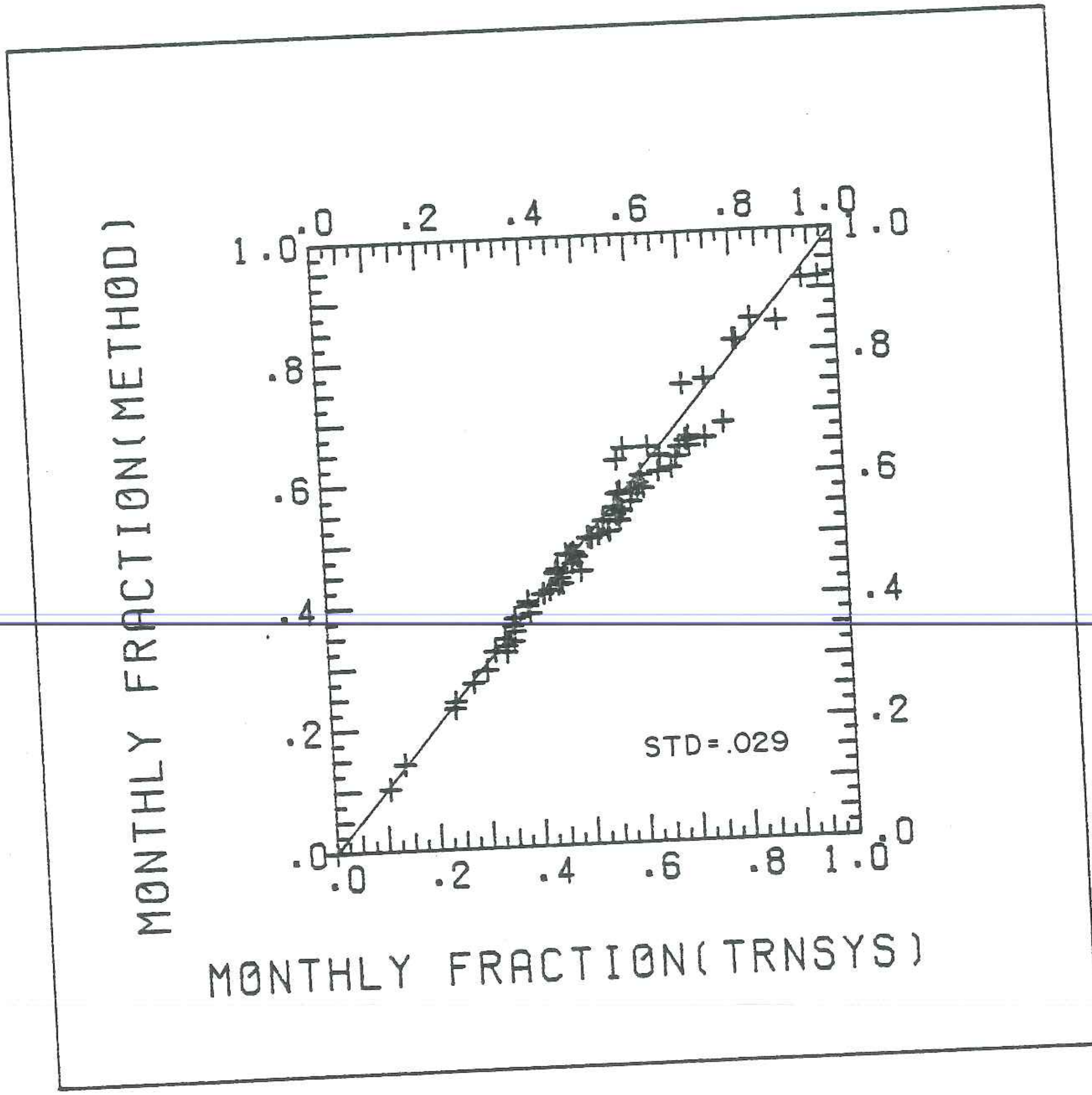


Figure 5-4 Comparisons of Monthly Average Photovoltaic System Performance for Systems With Battery Storage

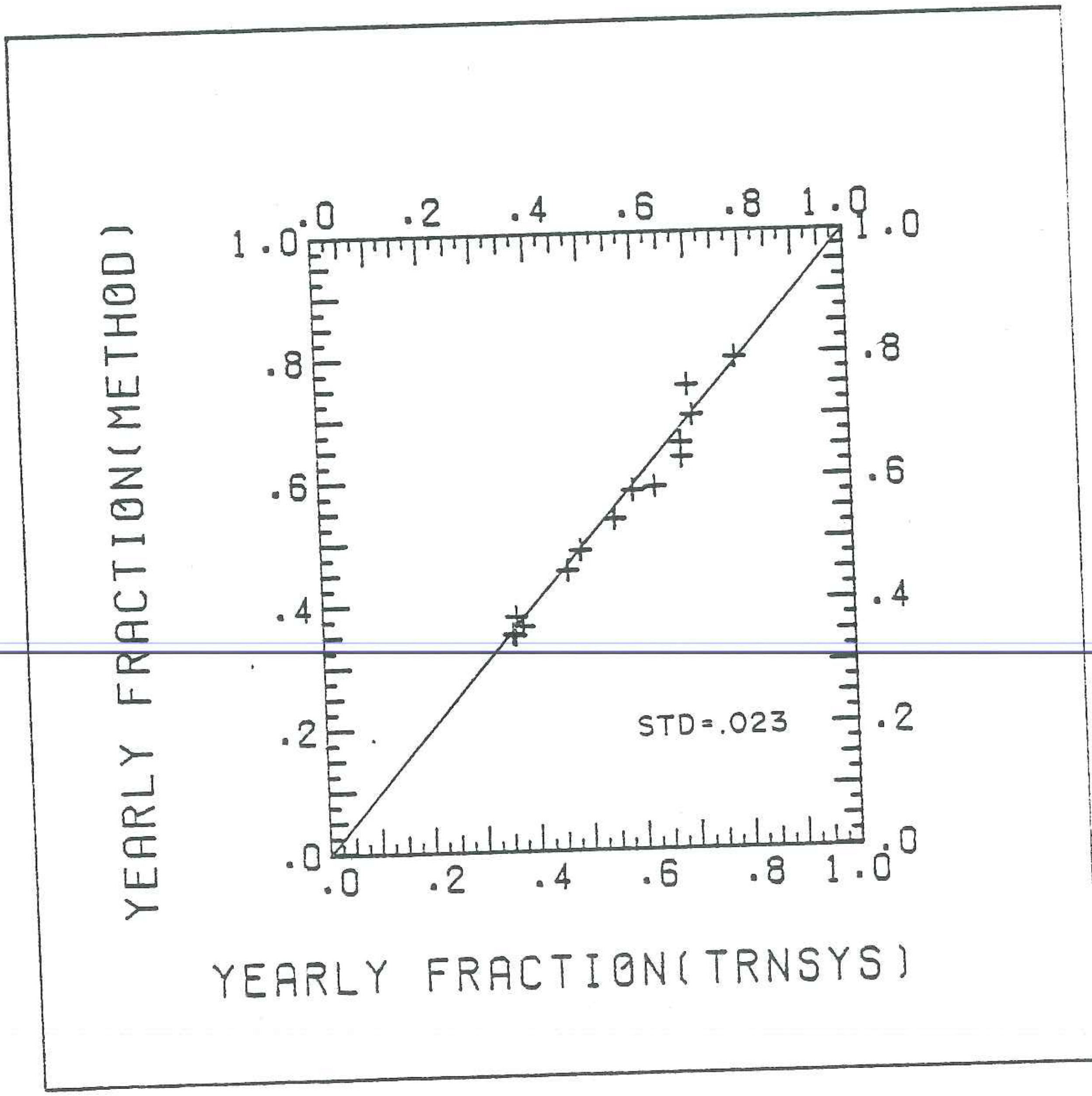


Figure 5-5 Comparisons of Yearly Photovoltaic System Performance for Systems With Battery Storage

Table 5-4

System Parameters (Figures 5-4 and 5-5)

Parameter	Range
Efficiency (T_R = 0°C)	$.08 < \eta_{R_o} < .18$
Temp. vs. Efficiency Coefficient	$.0025/°C \leq \beta_R \leq .004/°C$
Thermal Loss Coefficient	$.014 \frac{KW}{m^2\text{-}°C} < U_{Lo} < .042 \frac{KW}{m^2\text{-}°C}$
Cover Transmittance	$.88 < \tau \leq 1$
Absorptance	$.85 < \alpha < 1$
Collector Tilt	$-20° < (\emptyset - S) < 20°$
No Storage Dissipation - Load Ratio	$\overline{QD}_o/\overline{Q}_L < 1.2$
Storage - Load Ratio	$Be/\overline{Q}_L < .5$

Locations

Seattle, Washington	Cape Hatteras, North Carolina
Bismarck, North Dakota	

values. The accuracy shown in these figures is quite good. However, greater accuracy could have been achieved by determining relations for other storage-load ratios (i.e. $Be/\overline{Q}_L$ = .125, .375). Then linear interpolation between values of $Be/\overline{Q}_L$ would more accurately predict $\overline{QD}_A/\overline{Q}_L$ (it can be seen that $\overline{QD}_A/\overline{Q}_L$ is not a linear function with respect to $Be/\overline{Q}_L$, however linear interpolation between closer values of $Be/\overline{Q}_L$ will result in better accuracy in predicting the actual amount of energy dissipated).

6. CONCLUSIONS

6.1 Summary

The design methods developed in the previous chapters can be used to determine the monthly average performance of a photovoltaic system in which

1) All energy generated is instantaneously utilizable (i.e. the load requirements are always greater than the array output)

2) Energy in excess of the load is

   a) dissipated

   b) fed back into the utility grid

   c) stored for use at another time

The accuracy of these procedures is shown to be quite good for the range of system parameters examined. In addition the sample calculations performed in the text demonstrate the simplicity of these design procedures.

These design methods are combined with FCHART[18] subroutines into an interactive computer program for predicting photovoltaic system performance. This program, "PV-DESIGN", can be used to analyze the system configurations described in section 1-3. In addition, it is possible to perform economic analyses and array area optimization. Appendix IV contains sample output and a complete program listing.

6.2 Recommendations

The development and utilization of simplified design methods for analyzing photovoltaic system performance is a relatively new a-proach. Some suggestions for future research are as follows:

1) Concentrating Arrays - The methods presented in section 3-2 should be generalized so that they can be used to determine the monthly average efficiency of concentrating photovoltaic arrays.

2) Non-constant Load Distributions - The analyses carried out in Chapters 4 and 5 are based on a constant load distribution. These design methods must be altered so to include any load distribution.

3) Battery Storage - A great deal more work must be done to better understand the behavior of battery storage in photovoltaic systems. A more generalized approach is needed to extend the method presented here to a wider range of systems.

4) Sensitivity Studies - The effects of varying array parameters and different system component specifications need to be examined. The effects of various control strategies on system performance is not well understood.

APPENDIX I - Photovoltaic Array, Regulator/Inverter, Battery Models[4]

```
C
      SUBROUTINE TYPE1(TIME,XIN,OUT,T,DTDT,PAR,INFO)
      REAL IC,K1,K2
      DIMENSION PAR(35),XIN(10),OUT(20),INFO(9)
C.
C.    THIS COMPONENT SIMULATES THE THERMAL PERFORMANCE OF A
C.    FLAT-PLATE SOLAR COLLECTOR USING THE MODEL DEVELOPED BY
C.    HOTTEL, WHILLIER, AND BLISS.
C.
C.    HR       - TOTAL RADIATION INCIDENT ON THE TILTED COLLECTOR SURFACE
C.    S        - SOLAR ENERGY ABSORBED BY THE SURFACE OF THE ABSORBER
C.             - FOR THE CASE OF THE CONCENTRATING PV/THERMAL COLLECTOR
C.             - SOLAR ENERGY INCIDENT ON THE ABSORBER
C.    SINC     - SOLAR ENERGY INCIDENT ON THE ABSORBER
C.    QU       - THE USEFUL ENERGY COLLECTION RATE PER UNIT AREA
C.    A        - COLLECTOR AREA
C.    FP       - (F-PRIME)  COLLECTOR GEOMETRY EFFICIENCY FACTOR
C.    UL       - OVERALL ENERGY LOSS COEFFICIENT
C.    TA       - AMBIENT TEMPERATURE
C.    TIN      - INLET FLUID TEMPERATURE
C.    TOUT     - OUTLET FLUID TEMPERATURE
C.    TM       - MEAN FLUID TEMPERATURE
C.    FLWRT    - COLLECTOR FLUID FLOWRATE
C.    CPF      - THERMAL CAPACITANCE OF THE COLLECTOR FLUID
C.    TAUALF - THE PRODUCT OF THE TRANSMITTANCE OF THE GLASS
C.    NOTE THAT DIFFUSE RADIATION IS TREATED AS IF IT STRIKES THE
C.    COLLECTOR SURFACE AT 60 DEGREES.
C.             AND THE ABSORPTANCE OF THE COLLECTOR PLATE SURFACE.
C.
C.
C.
C.    THIS PROGRAM HAS EIGHT MODES OF OPERATION AS DETERMINED BY
C.    THE VALUE OF MODE.
C.         IF MODE=1,5,7 UL AND TAUALF ARE CONSTANTS
C.         IF MODE=2,4,6,8  UL IS CALCULATED AS A FUNCTION OF*
C.
C.    NG       - THE NUMBER OF GLASS COVERS
C.    EP       - THE THERMAL EMITTANCE OF THE COLLECTOR PLATE SURFACE
C.    UBE      - THE CONTRIBUTION TO UL DUE TO BOTTOM AND EDGE
C.               LOSSES (KJ/HR-M2-C)
C.    ANGLE    - THE TILT OF THE COLLECTOR WITH RESPECT TO HORIZONTAL
C.    WIND     -  THE WINDSPEED (M/SEC)
C.
C.         IF MODE=3,4  TAUALF IS CALCULATED AS A FUNCTION OF*
C.
C.    THETA1 - THE ANGLE OF INCIDENCE OF RADIATION ON THE COLLECTOR
C.    ALF      - THE ABSORPTANCE OF THE COLLECTOR PLATE SURFACE (CONSTANT)
C.    XKL      - PRODUCT OF THE EXTINCTION COEFFICIENT AND THE
C.               THICKNESS OF EACH GLASS COVER
C.    REFIND - THE REFRACTIVE INDEX OF THE GLASS
C.    HBT      - THE INSTANTANEOUS BEAM RADIATION ON THE COLLECTOR SURFACE
C.    HDT      - THE INSTANTANEOUS DIFFUSE RADIATION ON THE COLLECTOR SURFACT
C.
C.         IF MODE=5,6,7,8  A COMBINED (PHOTOVOLTAIC-THERMAL)
C.              COLLECTOR IS SIMULATED
C.              MODE=5,6 ASSUMES CELLS ARE OPERATED AT PEAK POWER
C.              MODE=6,7 ASSUMES THE VOLTAGE ON THE ARRAY IS FIXED EXTERNALL
C.
Y          -APERTURE AREA TO ABSORBER AREA(GEOMETRICAL CONCENTRATION
C.    AR          RATIO) FOR USE IN CONCENTRATING COLLECTORS
C.                APPROPRIATE FIN EFFICIENCY
C.    FE         -BACK LOSS COEFFICIENT
C.    UB         -THERMAL CONDUCTANCE BETWEEN CELLS AND ABSORBER
C.    CB         -FILM COEFFICIENT BETWEEN FLUID AND ABSORBER
C.    UF
```

```
C.   UT        -TOP LOSS COEFFICIENT FOR MODES 5 AND 7
C.
C.      MODES 1 THRU 4 HAVE BEEN MODIFIED TO ALLOW SIMULATION OF
C.          FLAT PLATE COMBINED COLLECTORS AS DEVELOPED BY
C.          FLORSCHUETZ (SHARING THE SUN JOINT SOLAR CONFERENCE
C.          PROCEEDINGS, VOL. 6, P.79-92, WINNIPEG (1976)
C.   THE FOLLOWING  PARAMETERS ARE REQUIRED IN ADDITION
C.          TO THE ORIGINAL ONES REQUIRED IN MODES 1 THRU 4
C.   BR        -TEMPERATURE COEFFICIENT OF THE CELLS
C.   TR        -A REFERENCE EFFICIENCY WHERE THE CELL EFFICIENCY IS
C.            KNOWN--- THE CELL EFFICIENCY IS ENTERED AS XIN(5,6,7,8)
C.              IN MODE 1,2,3,4 RESPECTIVELY
C.   CELLPF    -THE RATIO OF CELL AREA TO ABSORBER AREA
      COMMON /LUNITS/ LUR,LUW,IFORM
      DIMENSION ATR(3),BTR(3),CTR(3),TAU040(3)
      DATA EG/0.88/,PI/3.1415927/,SB/5.678E-08/
      DATA ATR/-2.9868,-1.4214,-0.74816/
      DATA BTR/-3.7360,-5.7356,-6.5262/
      DATA CTR/4.3541,5.7723,6.3769/
      DATA TAU040/0.92,0.845,0.785/
      DATA IUNIT/0/,REFIND/1.526/,NPP/0/,AR/1./,UBE/0./
      INFO7=INFO(7)
      IF (INFO(7).GE.0) GO TO 100
      INFO(9)=0
      INFO(6) =12
      MODE=PAR(1)
      IF (MODE.EQ.1) CALL TYPECK(1,INFO,5,10,0)
      IF (MODE.EQ.2) CALL TYPECK(1,INFO,6,13,0)
      IF (MODE.EQ.3) CALL TYPECK(1,INFO,7,11,0)
      IF (MODE.EQ.4) CALL TYPECK(1,INFO,8,13,0)
      IF (MODE.EQ.5) CALL TYPECK(1,INFO,4,31,0)
      IF (MODE.EQ.6) CALL TYPECK(1,INFO,6,32,0)
      IF (MODE.EQ.7) CALL TYPECK(1,INFO,5,31,0)
      IF (MODE.EQ.8) CALL TYPECK(1,INFO,7,32,0)
      IF (MODE.GE.1.AND.MODE.LE.8) GO TO 100
      CALL TYPECK(4,INFO,0,0,0)
      RETURN
  100 CONTINUE
      ITER=0
      IF (INFO(1).EQ.IUNIT) GO TO 71
      IUNIT=INFO(1)
      MODE=PAR(1)
      A=PAR(2)
      FP=PAR(3)
C   PAR(3) IS REDEFINED BELOW IF MODE.GE.5
      CPF=PAR(4)
      ALF=PAR(5)
      GO TO (21,22,23,24,25,25,25,25),MODE
   21 UL=PAR(6)
      TAU=PAR(7)
      BR = PAR(8)
      TR = PAR(9)
      CELLPF = PAR(10)
      TAUALF=TAU*ALF
      GO TO 71
   22 XNG=PAR(6)
      EP=PAR(7)
      UBE=PAR(8)
      ANGLE=PAR(9)
      TAU=PAR(10)
      BR = PAR(11)
      TR = PAR(12)
      CELLPF = PAR(13)
      NG=XNG
```

```
      TAUALF=TAU*ALF
      GO TO 71
   23 XNG=PAR(6)
      UL=PAR(7)
      XKL=PAR(8)
      BR = PAR(9)
      TR = PAR(10)
      CELLPF = PAR(11)
      NG=XNG
      GO TO 78
   24 XNG=PAR(6)
      EP=PAR(7)
      UBE=PAR(8)
      ANGLE=PAR(9)
      XKL=PAR(10)
      BR = PAR(11)
      TR = PAR(12)
      CELLPF = PAR(13)
      UL = 0.
      NG=XNG
      GO TO 78
   25      IP=MOD(MODE-5,2)+12
      AR=PAR(3)
      IF(MODE.GE.7) NPP=1
      FE=PAR(6)
      UB=PAR(7)
      CB=PAR(8)
      UF=PAR(9)
      UF=UF*(1.+FE)
      IF(CB.LT.1.E-5)  CALL TYPECK(4,INFO,0,0,0)
      TAU=PAR(10)
      TAUALF=TAU*ALF
      GO TO (71,71,78,78,79,80,79,80), MODE
   79 UT=PAR(11)
      GO TO 71
   80 XNG=PAR(11)
      EP=PAR(12)
      GO TO 71
   78 CONTINUE
      TAU60=EXP(-1.21453*XNG*XKL)*(1.-EXP((ATR(NG)+
     1   (BTR(NG)+CTR(NG)*0.5)*0.5)*0.5))
C.  TAU60 IS THE TRANSMITTANCE OF THE GLASS COVER SYSTEM AT AN
C.  INCIDENCE ANGLE OF 60 DEGREES, AS ASSUMED FOR DIFFUSE RADIATION
C.  SEE HOTTEL AND WOERTZ
   71 CONTINUE
      TIN=XIN(1)
      FLWRT=XIN(2)
      TA=XIN(3)
      IF(MODE.GE.5) GO TO 710
      TC = TR+1./BR
      BA = 1./(TC - TA)
  710 GO TO (31,32,33,34,35,36,37,38),MODE
   31 CONTINUE
      UL = PAR(6)
      HR=XIN(4)
      ETAR = XIN(5)*CELLPF
      ETAA = ETAR*(1.-BR*(TA - TR))
      UL = UL - TAU*HR*ETAA*BA
      GO TO 72
   32 HR=XIN(4)
      WIND=XIN(5)
      ETAR = XIN(6)*CELLPF
      ETAA = ETAR*(1.-BR*(TA - TR))
      GO TO 73
```

```
   33 HBT=XIN(4)
      HDT=XIN(5)
      UL = PAR(6)
      THETA1=XIN(6)
      ETAR = XIN(7)*CELLPF
      ETAA = ETAR*(1.-BR*(TA - TR))
      GO TO 83
C
   35 HR=XIN(4)
      ICT=1
      GO TO 172
   36 HR=XIN(4)
      WIND=XIN(5)
      TILT=XIN(6)
      GO TO 73
   37 HR=XIN(4)
      V=XIN(5)
      ICT=1
      GO TO 172
   38 HR=XIN(4)
      WIND=XIN(5)
      V=XIN(6)
      TILT=XIN(7)
      GO TO 73
   34 HBT=XIN(4)
      HDT=XIN(5)
      THETA1=XIN(6)
      WIND=XIN(7)
      ETAR = XIN(8)*CELLPF
      ETAA = ETAR*(1.-BR*(TA - TR))
   83 CONTINUE
C.
      HR=HBT+HDT
      TAU=0.0
      IF (THETA1.GT.85.) GO TO 96
      IF (HR.LE.1.0E-10) GO TO 96
      THETA1=THETA1*2.*PI/360.0
      COSTH1=COS(THETA1)
      THETA2=ASIN(SIN(THETA1)/REFIND)
      COSTH2=COS(THETA2)
      TAU=TAU040(NG)
      IF (COSTH1.GE.0.766) GO TO 86
      TAU=1.0-EXP((ATR(NG)+(BTR(NG)+CTR(NG)*COSTH1)*COSTH1)*COSTH1)
   86 CONTINUE
      TAU=HBT/HR*TAU*EXP(-XNG*XKL/COSTH2)
      TAU=TAU+HDT/HR*TAU60
C.
C.
   96 CONTINUE
      TAUALF=ALF*TAU
      UL = UL - TAU*HR*ETAA*BA
C.
      GO TO (72,73,72,73,172,73,172,73),MODE
   73 CONTINUE
      ICT=0
      HWIND=5.7+3.8*WIND
       TM=TIN
   74 CONTINUE
      IF(ITER.EQ.0) ICT=ICT+1
      IF (ICT.GT.2) GO TO 97
       TMC=TM+273.15
       TAC=TA+273.15
       IF (TMC.LE.TAC) TMC=TAC+1.0
       F=(1.0-0.04*HWIND+5.0E-04*HWIND*HWIND)*(1.0+0.091*XNG)
```

```
      IF(XNG.LT..5) F = 1.
      C=365.9*(1.0-0.00883*ANGLE+0.0001298*ANGLE*ANGLE)
       STF1=C/TMC*((TMC-TAC)/(XNG+F))**0.33
       STF1=XNG/STF1+1.0/HWIND
       STF1=1.0/STF1
       STF2=1.0/(EP+0.05*XNG*(1.0-EP))+(2.*XNG+F-1.)/EG-XNG
       STF2=SB*(TMC*TMC+TAC*TAC)*(TMC+TAC)/STF2
       UL=(STF1+STF2)*3.6+UBE
      IF(MODE.GE.5)  GO TO 172
      UL = UL - TAU*HR*ETAA*BA
C  UT WILL BE SET EQUAL TO  UL FOR MODES 6 & 8
C.
C.  UL IS CALCULATED USING THE RELATION OF KLEIN
C.
      GO TO 72
  172 S=HR*TAUALF*AR
      SINC=S/ALF
      IF(MODE.EQ.6.OR.MODE.EQ.8) UT=UL
      DENOM=UT*(CB+UF) + CB*UF
      K1=CB/DENOM
      IF(ICT.NE.1) GO TO 173
      TP=K1*(S-UT*(TIN-TA))+TIN
      TCELLR=UF*(TP-TIN)/CB+TP
      IF(FLWRT.LT.1.E-5)TCELLR=(S+TA*(UT+CB*UB/(CB+UB)))/
     1(UT+CB-CB**2/(CB+UB))
      TCELL=TCELLR
  173 CONTINUE
C
      TEMP=TCELL
      IF(MODE.EQ.5.OR.MODE.EQ.6) TEMP=TCELLR
      CALL SOLCEL(TCELLR,TEMP,SINC,PR,BETA,IC,V,ITER,NPP,INFO7,A,AR,
     1MODE,PAR(IP))
   75 K2=1.+K1*PR*BETA*(CB+UF)/CB
        IF(S.LT.1.E-4) PRS=0
        IF(S.GT.1.E-5) PRS=PR/S
      FP=UF*K1*(1.-PRS*(1.+BETA*(TA-TCELLR)))/K2
      ULAB=UF*K1*(UT+PR*BETA)/(K2*FP)
      UL=ULAB/AR
      ULO=UT/AR
   72 CONTINUE
      IF (FLWRT-1.E-5) 4,4,3
    3 CONTINUE
      FR=FLWRT*CPF*(1.0-EXP(-FP*UL*A/(FLWRT*CPF)))/(A*UL)
      HRT = HR*(1. - ETAA/ALF)
      IF(MODE.GE.5) HRT=HR
      QU = FR*(HRT*TAUALF - UL*(TIN - TA))
      QE = TAU*HR*ETAA*(1.-BA*(FR*(TIN - TA) + (TAUALF*HRT
     1/UL)*(1. - FR)))
      IF(MODE.LE.4) GO TO 796
      QE=PR*(1.+BETA*(TCELL-TCELLR))/AR
  796  CONTINUE
      TOUT=QU/FLWRT*A/CPF+TIN
       GO TO 5
    4 QU=0.0
      IF(MODE.LE.4)  GO TO 41
      QE=PR/AR
      TCELLR=(S-PR+TA*(UT+CB*UB/(CB+UB)))/
     1(UT+CB-CB**2/(CB+UB))
      TCELL=TCELLR
      TEMP=TCELL
      TOUT=TCELL*(1.-UB/(UB+CB))+TA*UB/(UB+CB)
      FLWRT=0.
      GO TO 6
   41 CONTINUE
```

```
      ULO = UL + TAU*HR*ETAA*BA
      QE = TAU*HR*ETAA*(ULO - TAUALF*HR*BA)/UL
   42 FLWRT=0.0
      TOUT = (TAUALF*HR - QE)/ULO + TA
    5 CONTINUE
      TM=(TIN+TOUT)/2.0
       IF(MODE.GE.5) GO TO 45
      TCELL = TM
      IF(HR.LE.1.E-5.AND.MODE.LE.4) GO TO 900
      TCELL = TC - (QE/(TAU*HR*ETAR))*(TC - TR)
      IF(MODE.LE.4) GO TO 900
   45 TP=QU*AR/UF+TIN
      TCELLR=UF*(TP-TIN)/CB+TP
      TPR = QU*AR/UF + TM
      TCELL =    UF*(TPR-TM)/CB+TPR
      TM=TCELL
      TEMP=TCELL
      IF(MODE.EQ.5.OR.MODE.EQ.6) TEMP=TCELLR
    6 CONTINUE
      PRSAVE=PR
      BETAS=BETA
      ITER=1
      CALL SOLCEL(TCELLR,TEMP,SINC,PR,BETA,IC,V,ITER,NPP,INFO7,A,AR,
     1MODE,PAR(IP))
       IF(PR.LT.1.E-5.AND.PRSAVE.LT.1.E-5) GO TO 800
       IF(PR.LT.1.E-5) GO TO 802
       IF(ABS((PR-PRSAVE)/PR).GT.0.05) GO TO 802
       IF(ABS((PR-PRSAVE)/PR).GT.0.05) GO TO 802
       IF(BETA.LT.1.E-5.AND.BETAS.LT.1.E-5) GO TO 801
  800  IF(BETA.LT.1.E-5.AND.BETAS.LT.1.E-5) GO TO 801
       IF(BETA.LT.1.E-5) GO TO 802
       IF(ABS((BETA-BETAS)/BETA).GT.0.05) GO TO 802
  801  ITER=0
  802  CONTINUE
       IF(MODE.EQ.5.OR.MODE.EQ.7) GO TO 171
      IF(ITER.GT.0) GO TO 74
      GO TO 900.
  171 CONTINUE
      ICT=ICT+1
      IF(ITER.GT.0) GO TO 75
      IF(ICT.LE.2) GO TO 75
  900 CONTINUE
      GO TO (97,74,97,74,97,74,97,74),MODE
   97 CONTINUE
      OUT(1)=TOUT
      OUT(2)=FLWRT
      OUT(3)=QU*A
      OUT(4)=UL
      OUT(5)=TAUALF
C          CORRECTION FOR QE.LT.0.0
         IF(QE.LT.0.0) QE=0.0
      OUT(6) = QE*A
      OUT(7) = TCELL
      OUT(8) = ULO
      OUT(9)=0.
      OUT(10)=0.
      OUT(11)=0.
      OUT(12)=0.
      GO TO (1000,1000,1000,1000,1001,1001,1001,1001), MODE
 1001 OUT(4)=ULO
      OUT(8)=UL
      OUT(9)=V
       IF(V.GT..001) GO TO 55
       OUT(10)=0.0
       GO TO 56
   55 OUT(10)=QE*A/(V*3.6)
```

```
   56 OUT(11)=TCELLR
      OUT(12)=ITER
 1000 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TYPE35(T,XIN,OUT,E,DEDT,PAR,INFO)
      DIMENSION PAR(10),XIN(11),OUT(10),INFO(9)
      REAL IBCH
      DATA NSTK/3/
C
C  THIS COMPONENT SIMULATES THE PERFORMANCE OF A POWER REGULATOR
C  AND INVERTER.  IT OPERATES IN CONJUNCTION WITH A SOLAR CELL
C  ARRAY, STORAGE BATTERY, AND LOAD.
C
C  PA = POWER FROM ARRAY
C  PD = POWER DEMANDED BY LOAD
C  PL = (+) POWER SENT TO LOAD FROM ARRAY AND BATTERY,
C       (-) POWER SENT TO BATTERY FROM UTILITY
C  PLMAX = CAPACITY OF INVERTER - ENTERED AS OUTPUT LIMIT, THEN CONVERTE
C  INVERTER INPUT (DC TO AC) LIMIT
C  PU = POWER SUPPLIED BY OR FED BACK TO UTILITY
C  PB = POWER TO OR FROM BATTERY (+ CHARGE, - DISCHARGE)
C  PBMAX,PBMIN = MAXIMUM INPUT (CHARGE), MINIMUM OUTPUT (DISCHARGE)
C  PC = ALLOWED CHARGE RATE WHEN BATTERY NEARLY FULLY CHARGED
C  F = FRACTIONAL STATE OF CHARGE (1.0=FULL CHARGE)
C  FC,FC,FB,FBCH = LIMITS ON F FOR CHARGING, DISCHARGING, BEGINNING
C  OF DISCHARGE AFTER CHARGE, AND CHARGING FROM UTILITY.
C  V = VOLTAGE
C  VC,VD = MAXIMUM BATTERY VOLTAGE (CHARGE), MINIMUM VOLTAGE (DISCHARGE)
C  TR = TIME OF DAY
C  T1,T2 = TIMES OF DAY BETWEEN WHICH BATTERY SHOULD BE CHARGED AT RATE
C  PBCH.  SET T1=T2 IF THIS OPTION NOT DESIRED.
C  IBCH = CURRENT FOR UTILITY CHARGING. (THIS MUST INCLUDE MULT. BY
C  NO. OF BATTERY CELLS IN SERIES AND IN PARALLEL.)
C  EFF1,EFF2,EFF3 = EFFICIENCIES OF REGULATOR, INVERTER (DC TO AC), AND
C  INVERTER (AC TO DC)
C  NBIAS,NFULL,NMARK,NCHAR = FLAGS SET FOR SIGN OF PB, FULLY CHARGED
C  STATE, CONTINUATION OF CHARGING, UTILITY CHARGING
C  NCT,NBATT,NSTK = PREVENT OSCILLATIONS IN CERTAIN CIRCUMSTANCES (SEE
C  COMMENTS BEFORE STATEMENT 70)
C
C  THE REGULATOR/INVERTER CAN OPERATE IN ONE OF FOUR MODES:
C  MODE 0 - NO BATTERY, ARRAY OUTPUT SENT TO LOAD AND POSSIBLY FED BACK
C           TO UTILITY
C  MODE 1 - BATTERY CHARGE AND DISCHARGE LIMITED BY F ONLY.  OPERATES
C           WITH MODE 1 OF BATTERY
C  MODE 2 - CHARGE AND DISCHARGE CONTROLLED BY F AND V.  ALSO LIMITS
C           OF PBMAX, PBMIN, AND PC.  V COMPUTED FROM PB IN MODE 2 OF BA
C  MODE 3 - AFTER UNREG CONCEPT IN GE REPORT.  SAME AS MODE 2, BUT NOW H
C           CURRENTS INSTEAD OF POWERS, 'P' REALLY MEANS 'I.'  V CALCULA
C           FROM IB IN MODES 3 OR 4 OF BATTERY, EQUALS V OF ARRAY.
C           ITERATION REQUIRED TO SATISFY KIRCHOFF'S LAW FOR CURRENTS.
C
C
C
      IF (INFO(7).GE.0) GO TO 12
      INFO(9)=0
      MODE=PAR(1)
      INFO(6)=3
      IF (MODE.EQ.1.OR.MODE.EQ.2) INFO(6)=5
      IF (MODE.EQ.3) INFO(6)=10
      IF (MODE.EQ.0) CALL TYPECK(1,INFO,2,2,0)
      IF (MODE.EQ.1) CALL TYPECK(1,INFO,3,7,0)
      IF (MODE.EQ.2) CALL TYPECK(1,INFO,11,10,0)
      IF (MODE.EQ.3) CALL TYPECK(1,INFO,11,10,0)
      IF (MODE.EQ.0.OR.MODE.EQ.1.OR.MODE.EQ.2.OR.MODE.EQ.3) GO TO 10
      CALL TYPECK(4,INFO,0,0,0)
      RETURN
10    CONTINUE
```

```
C
C    SET PARAMETERS
       EFF1=PAR(2)
       IF (MODE.EQ.0) GO TO 12
       EFF2=PAR(3)
       FC=PAR(4)
       FD=PAR(5)
       FB=PAR(6)
       PLMAX=PAR(7)/EFF2
       IF (MODE.EQ.1) GO TO 12
       EFF3=PAR(8)
       IBCH=PAR(9)
       FBCH=PAR(10)
 12    CONTINUE
       NCT=NCT+1
       IF (INFO(7).NE.0) GO TO 14
       TR=AMOD(T/24.,1.)*24.
       NFULL=0
       NMARK=0
       NCHAR=0
       NCT=1
       NBATT=0
C
C    SET INPUTS
 14    PA=XIN(1)
       IF (PA.LT.0.) PA=0.
       PD=XIN(2)
       IF (MODE.EQ.0) GO TO 16
       F=XIN(3)
       IF (MODE.EQ.1) GO TO 16
       V=XIN(4)
       PBMAX=XIN(5)
       PBMIN=XIN(6)
       VD=XIN(7)
       VC=XIN(8)
       PC=XIN(9)
       T1=XIN(10)
       T2=XIN(11)
       PBCH=IBCH*V*3.6
C
C    IN MODE 3, CONVERT POWERS TO CURRENTS
C    AT THIS POINT, PA IS IN AMPS, BUT PAR(7), PC, PD,
C    PBMAX, PBMIN, AND PBCH ARE IN KJ/HR.
       IF (MODE.NE.3) GO TO 16
       PLMAX=PAR(7)/EFF2/V/3.6
       PC=PC/V/3.6
       PD=PD/V/3.6
       PBMAX=PBMAX/V/3.6
       PBMIN=PBMIN/V/3.6
       PBCH=PBCH/V/3.6
 16    CONTINUE
C
       PA=PA*EFF1
       IF (MODE.EQ.0) GO TO 58
C    CHECK IF BATTERY CHARGING FROM UTILITY IS CALLED FOR
       IF (NCHAR.EQ.1) GO TO 22
       IF (MODE.EQ.1 .OR. F.GE.FBCH .OR. NFULL.EQ.1) GO TO 17
       IF (TR.GE.T1 .AND. TR.LT.T2) GO TO 21
       IF (T1.LE.T2) GO TO 17
       IF (TR.GE.T2 .AND. TR.LT.T1) GO TO 17
 21    NCHAR=1
 22    PB=PBCH
       IF (PA.LT.PB) GO TO 23
C    PL IS POSITIVE
```

```
      PL=PA-PB
      IF (PL.GT.PD/EFF2) PL=PD/EFF2
      IF (PL.GT.PLMAX) PL=PLMAX
      PR=PA-PB-PL
      GO TO 30
C  PL IS NEGATIVE
23    PL=(PA-PB)/EFF3
      IF (-PL*EFF3.GT.PLMAX*EFF2) PL=-PLMAX*EFF2/EFF3
      PB=PA-PL*EFF3
      PR=0.
      IF (VC-V.GT..001) GO TO 60
      IF (PB.LE.PC) GO TO 60
      IF (PA.GE.PC) GO TO 31
      PL=(PA-PC)/EFF3
      IF (-PL*EFF3.GT.PLMAX*EFF2) PL=-PLMAX*EFF2/EFF3
      PB=PA-PL*EFF3
      GO TO 60
C
17    NBIAS=0
      IF (ABS(PB).GT.1.E-5) NBIAS=PB/ABS(PB)
C
C  TEST F VS. FD, FC, AND FB AND FOR NSTICK CONDITION (SEE COMMENTS BEFO
      IF(NBATT.EQ.1) GO TO 70
      IF (F.LE.FD.OR.NMARK.EQ.1) GO TO 29
      IF (F.GE.FC.OR.NFULL.EQ.1) GO TO 39
      IF (F.LT.FB.AND.NBIAS.GE.0) GO TO 29
C
C  TEST DEMAND VS. ARRAY POWER, WITH BATTERY PARTIALLY CHARGED
      IF (PD/EFF2.GT.PA) GO TO 18
C
C  PARTIAL CHARGE
      PL=PD/EFF2
      IF (PL.GT.PLMAX) PL=PLMAX
      PB=PA-PL
      PR=0.
      IF (MODE.GE.2) GO TO 30
      GO TO 60
C
18    IF (MODE.EQ.1) GO TO 50
C  IN MODES 2 AND 3, TEST V VS. VD
      IF (V.LE.VD) GO TO 29
      GO TO 50
C
C  TOTAL CHARGE
29    NMARK=1
      PB=PA
      PL=0.
      PR=0.
      IF (MODE.EQ.1) GO TO 60
C
C  IN MODES 2 AND 3, TEST V VS. VC
30    IF (VC-V .GT. .001) GO TO 35
C
C  SLOW CHARGE
      IF (PB.LE.PC) GO TO 60
31    PL=PA-PC
      IF (PL.GT.PD/EFF2) PL=PD/EFF2
      IF (PL.GT.PLMAX) PL=PLMAX
      PR=PA-PL-PC
      PB=PC
      GO TO 60
C
C  IN MODES 2 AND 3, TEST PB VS. PBMAX
35    IF (PB.LE.PBMAX) GO TO 60
```

```
      PB=PBMAX
C  NOW TEST PL TO SEE IF WE CAME FROM TOTAL CHARGE OR PARTIAL
C  CHARGE SEGMENTS
      IF (PL.LT.1.E-5) GO TO 36
      PR=PA-PL-PB
      GO TO 60
36    PL=PA-PB
      IF (PL.GT.PD/EFF2) PL=PD/EFF2
      IF (PL.GT.PLMAX) PL=PLMAX
      PR=PA-PB-PL
      GO TO 60
C
C  TEST DEMAND VS. ARRAY POWER, WITH BATTERY FULLY CHARGED
39    NFULL=1
      IF (PD/EFF2.GT.PA) GO TO 50
      PB=0.
      PL=PD/EFF2
      IF (PL.GT.PLMAX) PL=PLMAX
      PR=PA-PL
      GO TO 60
C
C  DISCHARGE
50    PL=PD/EFF2
      IF (PL.GT.PLMAX) PL=PLMAX
      PB=PA-PL
      IF (PB.LE.0.) GO TO 51
      PB=0.
      PR=PA-PL
      GO TO 60
51    PR=0.
      IF (MODE.EQ.1) GO TO 60
C
C  IN MODES 2 AND 3, TEST PB VS. PBMIN
      IF (PB.LT.PBMIN) PB=PBMIN
      PL=PA-PB
      GO TO 60
C
C  MODE 0
58    PL=PA
      IF (PL.GT.PD) PL=PD
      PU=PD-PA
      OUT(1)=PA/EFF1
      OUT(2)=PL
      OUT(3)=PU
      RETURN
C
60    PU=PD-PL*EFF2
      IF (PL.LT.0.) PU=PD-PL
      IF(PU.LT.1.E-5) PU=0.
      IF(MODE.EQ.3) GO TO 64
      OUT(1)=PA/EFF1
      OUT(2)=PB
      OUT(3)=PL*EFF2
      IF (PL.LT.0.) OUT(3)=PL
      OUT(4)=PR
      OUT(5)=PU
      RETURN
64    OUT(1)=PA/EFF1*V*3.6
      OUT(2)=PB*V*3.6
      OUT(3)=PL*EFF2*V*3.6
      IF (PL.LT.0.) OUT(3)=PL*V*3.6
      OUT(4)=PR*V*3.6
      OUT(5)=PU*V*3.6
      OUT(6)=PA/EFF1
```

```
      OUT(7)=PB
      OUT(8)=PL*EFF2
      IF (PL.LT.0.) OUT(8)=PL
      OUT(9)=PR
      OUT(10)=PU
      IF(NCT.LT.NSTK) GO TO 62
      IF(NBATT.EQ.1) GO TO 62
      IF(PB.LT.-0.001.AND.PBSTOR.GT.-0.001) GO TO 70
      IF(PB.LT.-0.001.AND.PBSTOR.LT.-0.001) GO TO 70
      IF(PB.GT.-0.001.AND.PBSTOR.GT.0.001) GO TO 70
      IF(PB.LT.0.001.AND.PBSTOR.LT.0.001) GO TO 70
      IF(PB.GT.0.001.AND.PBSTOR.LT.0.001)
C   THE FOLLOWING IS A STABILIZING INFLUENCE
C   TO OFFSET THE DIVERGING DIFFERENCE
C   BETWEEN THE BATTERY CHARGE/DISCHARGE CURVES
C   AND THE SOLAR CELL I-V CURVES
      OUT(7)=(PB+PBSTOR)/2.
 62   PBSTOR=OUT(7)
      RETURN
C  THIS IS AN NSTICK TO PREVENT OSCILLATIONS BETWEEN COLLECTOR,
C  BATTERY, AND REG/INV (IN MODE 3) WHICH CAN BE CAUSED BY
C  COLLECTOR OUTPUTS THAT ARE NOT TOO MUCH ABOVE THE DEMAND.
C  TO CHANGE THE NUMBER OF ITERATIONS THAT ARE PERMITTED BEFORE
C  STICKING, CHANGE THE VALUE OF NSTK IN THE DATA STATEMENT.
 70   NBATT=1
      PB=0.
      IF(PD/EFF2.GT.PA) GO TO 72
      PL=PD/EFF2
      IF(PL.GT.PLMAX) PL=PLMAX
      PR=PA-PL
      GO TO 60
 72   PL=PA
      PR=0.
      GO TO 60
      END
```

```
C
      SUBROUTINE TYPE30(T,XIN,OUT,Q,DQDT,PAR,INFO)
      DIMENSION PAR(8),XIN(1),OUT(11),Q(1),DQDT(1),INFO(9)
      REAL IQ,MC,MD,K1,I1,IQMAX,IQMIN,IC,IC1,ICTOL
      DATA ESC/2.25/,ESD/2.10/,GC/.08/,GD/.08/,MC/.864/,MD/1./
      DATA ED/1.8/,RD/2.4E-3/,VC/2.4/
      DATA I1/2.5/,K1/29.3/
C
C     THIS COMPONENT SIMULATES THE PERFORMANCE OF A LEAD-ACID
C     STORAGE BATTERY.  IT IS DESIGNED TO OPERATE IN CONJUNCTION
C     WITH A SOLAR CELL ARRAY AND REGULATOR.
C
C     Q = STATE OF CHARGE (MODE 1 - WATT HRS, MODES 2,3,4 - AMP HRS)
C     QM = RATED CAPACITY OF CELL
C     QC,QD = CAPACITY PARAMETERS ON CHARGE, DISCHARGE
C     F = FRACTIONAL STATE OF CHARGE = Q/QM (1.0 IS FULL CHARGE)
C     CP,CS = NUMBER OF CELLS IN PARALLEL, SERIES
C     P = POWER (THE 3.6 FACTOR CONVERTS KJ/HR TO WATTS ON INPUT AND VICE
C     OUTPUT)
C     IQ = CURRENT
C     IQMAX,IQMIN = MAXIMUM CURRENT (CHARGE), MINIMUM CURRENT (DISCHARGE)
C     V = VOLTAGE
C     VC,IC = CUTOFF VOLTAGE ON CHARGE, CURRENT CORRESPONDING TO VC
C     ICTOL,VTOL = PARAMETERS FOR ITERATIVE CALCULATIONS, MODES 3 AND 5
C     VD = CUTOFF VOLTAGE ON DISCHARGE
C     ED,RD = DATA USED TO CALCULATE VD
C     VDI = DIODE VOLTAGE FROM Z-P MODEL, USED IN MODE 4 ONLY
C     VOC = OPEN CIRCUIT VOLTAGE AT FULL CHARGE
C     ESC,ESD = EXTRAPOLATED OPEN CIRCUIT VOLTAGES
C     GC,GD = COEFFICIENTS OF (1-F)IN V FORMULAS
C     RSC,RSD = INTERNAL RESISTANCES AT FULL CHARGE
C     MC,MD = CELL TYPE PARAMETERS WHICH DETERMINE THE SHAPES OF THE
C     I-V-Q CHARACTERISTICS
C
C     THE BATTERY CAN OPERATE IN ONE OF FIVE MODES:
C     MODE 1 - DISCHARGE RATE IS DETERMINED BY A POWER EFFICIENCY FACTOR
C     MODE 2 - THE I-V-Q FORMULA IS BASED UPON THE SHEPHERD MODEL, WITH
C     IQ AND V CALCULATED FROM P. MODES 2 AND 3 ARE PEAK-POWER MODES.
C     MODE 3 - SAME AS MODE 2, BUT USING MODEL RECOMMENDED IN THE BEST
C     REPORT (THE HYMAN MODEL).  IT IS THE SHEPHERD MODEL MODIFIED BY
C     THE ADDITION OF A ZIMMERMAN-PETERSEN DIODE IN BOTH THE CHARGE AND
C     DISCHARGE EQUIVALENT CIRCUITS.
C     MODE 4 - SHEPHERD MODEL, BUT WITH P AND V CALCULATED FROM IQ. THIS
C     AND MODE 5 ARE CLAMPED-VOLTAGE MODES.
C     MODE 5 - SAME AS MODE 4, BUT USING HYMAN MODEL
C
      IF (INFO(7).GE.0) GO TO 90
      INFO(9)=1
      MODE=PAR(1)
      INFO(6)=11
      IF (MODE.EQ.1) INFO(6)=4
      IF (MODE.EQ.1) CALL TYPECK(1,INFO,1,5,-1)
      IF (MODE.EQ.2 .OR. MODE.EQ.4) CALL TYPECK(1,INFO,1,7,-1)
      IF (MODE.EQ.3 .OR. MODE.EQ.5) CALL TYPECK(1,INFO,1,8,-1)
      IF (MODE.GE.1 .AND. MODE.LE.5) GO TO 70
      CALL TYPECK(4,INFO,0,0,0)
      RETURN
70    NDER=INFO(5)
      IF (NDER.EQ.1) GO TO 80
      CALL TYPECK(5,INFO,0,0,0)
      RETURN
80    CONTINUE
C
```

```
C     SET PARAMETERS.
        QM=PAR(2)
        CP=PAR(3)
        CS=PAR(4)
        EFF=PAR(5)
        IF (MODE.EQ.1) GO TO 90
        IQMAX=PAR(6)
        IQMIN=PAR(7)
        IF (MODE.NE.3 .AND. MODE.NE.5) GO TO 82
        ICTOL=PAR(8)
 82     QC=-.035*QM
        QD=QM/.85
        RSC=3./QM
        RSD=.5/QM
C
 90     CONTINUE
        IF (MODE.GE.4) GO TO 88
        P=XIN(1)
        P=P/3.6/(CP*CS)
        GO TO 89
 88     IQ=XIN(1)
        IQ=IQ/CP
 89     IF (MODE.GE.2) GO TO 100
C
C     MODE 1
        IF (P.LE.0.) DQDT(1)=P
        IF (P.GT.0.) DQDT(1)=P*EFF
        GO TO 120
C
 100    CONTINUE
        F=Q(1)/QM
        H=1.-F
        GO TO (120,101,96,97,110), MODE
C
 101    CONTINUE
C     MODE 2
        IC=(VC-ESC+GC*H)/RSC/(1.+MC*H/(QC/QM-H))
        IF (ABS(P).GT.1.E-5) GO TO 92
        VOC=(ESC+ESD)/2.
        V=VOC - (GC+GD)*H/2.
        IQ=P/V
        GO TO 95
 92     IF (P.LT.0.) GO TO 93
        A=RSC*(1.+MC*H/(QC/QM-H))
        B=ESC-GC*H
        GO TO 94
 93     A=RSD*(1.+MD*H/(QD/QM-H))
        B=ESD-GD*H
 94     C=-P
        IQ=(-B+SQRT(B**2 - 4.*A*C))/(2.*A)
        IF (IQ.GT.IQMAX) IQ=IQMAX
        IF (IQ.LT.IQMIN) IQ=IQMIN
        V=B + IQ*A
        IF (V.LE.VC) GO TO 91
        V=VC
        IQ=IC
 91     P=IQ*V
 95     IF (IQ.LE.0.) DQDT(1)=IQ
        IF (IQ.GT.0.) DQDT(1)=IQ*EFF
        VMIN=ESD-GD*H+IQMIN*RSD*(1.+MD*H/(QD/QM-H))
        VMAX=ESC-GC*H+IQMAX*RSC*(1.+MC*H/(QC/QM-H))
        GO TO 120
C
 96     CONTINUE
```

```
C     MODE 3
         VOC=(ESC+ESD)/2.
         VDIMAX=1./K1*ALOG(IQMAX/I1+1.)
         VMAX=VOC+VDIMAX-GC*H+IQMAX*RSC*(1.+MC*H/(QC/QM-H))
         VDIMIN=1./K1*ALOG(-IQMIN/I1+1.)
         VMIN=VOC-VDIMIN-GD*H+IQMIN*RSD*(1.+MD*H/(QD/QM-H))
         IF (ABS(P).GT.1.E-5) GO TO 132
         V=VOC-(GC+GD)*H/2.
         IQ=P/V
         GO TO 139
 132     IF (P.LT.0.) GO TO 135
         V=2.2
         VTOL=ICTOL
 133     V1=V
         IQ=P/V1
         VDI=1./K1*ALOG(IQ/I1+1.)
         V=VOC+VDI-GC*H+IQ*RSC*(1.+MC*H/(QC/QM-H))
         IF (ABS(V1-V).GT.VTOL) GO TO 133
         IF (IQ.LT.IQMAX) GO TO 138
         IQ=IQMAX
         V=VMAX
 138     IF (V.LE.VC) GO TO 140
         V=VC
         IC=50.
 134     IC1=IC
         VDI=1./K1*ALOG(IC1/I1+1.)
         IC=(VC-VOC-VDI+GD*H)/RSC/(1.+MC*H/(QC/QM-H))
         IF (ABS(IC1-IC).GT.ICTOL) GO TO 134
         IQ=IC
         GO TO 140
 135     V=2.1
         VTOL=ICTOL
 136     V1=V
         IQ=P/V1
         VDI=1./K1*ALOG(-IQ/I1+1.)
         V=VOC-VDI-GD*H+IQ*RSD*(1.+MD*H/(QD/QM-H))
         IF (ABS(V1-V).GT.VTOL) GO TO 136
         IF (IQ.GT.IQMIN) GO TO 139
         IQ=IQMIN
         V=VMIN
 139     IF(IQ.LE.0.) DQDT(1)=IQ
 140     IF(IQ.GT.0.) DQDT(1)=IQ*EFF
         P=IQ*V
         GO TO 120
C
 97      CONTINUE
C     MODE 4
         IC=(VC-ESC+GC*H)/RSC/(1.+MC*H/(QC/QM-H))
         IF (ABS(IQ).GT.1.E-5) GO TO 102
         VOC=(ESC+ESD)/2.
         V=VOC -(GC+GD)*H/2.
         GO TO 104
 102     IF (IQ.LT.0.) GO TO 103
         IF (IQ.GT.IQMAX) IQ=IQMAX
         V=ESC-GC*H+IQ*RSC*(1.+MC*H/(QC/QM-H))
         IF (V.LE.VC) GO TO 105
         V=VC
         IQ=IC
         GO TO 105
 103     IF (IQ.LT.IQMIN) IQ=IQMIN
         V=ESD-GD*H+IQ*RSD*(1.+MD*H/(QD/QM-H))
 104     IF (IQ.LE.0.) DQDT(1)=IQ
 105     IF (IQ.GT.0.) DQDT(1)=IQ*EFF
         VMAX=ESC-GC*H+IQMAX*RSC*(1.+MC*H/(QC/QM-H))
```

```
      VMIN=ESD-GD*H+IQMIN*RSD*(1.+MD*H/(QD/QM-H))
      P=IQ*V
      GO TO 120
C
110   CONTINUE
C   MODE 5
      VOC=(ESC+ESD)/2.
      IF (ABS(IQ).GT.1.E-5) GO TO 112
      V=VOC - (GC+GD)*H/2.
      GO TO 114
112   IF (IQ.LT.0.) GO TO 113
      IF (IQ.GT.IQMAX) IQ=IQMAX
      VDI=1./K1*ALOG(IQ/I1+1.)
      V=VOC+VDI-GC*H+IQ*RSC*(1.+MC*H/(QC/QM-H))
      IF (V.LE.VC) GO TO 115
      V=VC
      IC=50.
122   IC1=IC
      VDI=1./K1*ALOG(IC1/I1+1.)
      IC=(VC-VOC-VDI+GC*H)/RSC/(1.+MC*H/(QC/QM-H))
      IF (ABS(IC1-IC) .GT. ICTOL) GO TO 122
123   IQ=IC
      GO TO 115
113   IF (IQ.LT.IQMIN) IQ=IQMIN
      VDI=1./K1*ALOG(-IQ/I1+1.)
      V=VOC-VDI-GD*H+IQ*RSD*(1.+MD*H/(QD/QM-H))
114   IF (IQ.LE.0.) DQDT(1)=IQ
115   IF (IQ.GT.0.) DQDT(1)=IQ*EFF
      P=IQ*V
      VDIMAX=1./K1*ALOG(IQMAX/I1+1.)
      VMAX=VOC+VDIMAX-GC*H+IQMAX*RSC*(1.+MC*H/(QC/QM-H))
      VDIMIN=1./K1*ALOG(-IQMIN/I1+1.)
      VMIN=VOC-VDIMIN-GD*H+IQMIN*RSD*(1.+MD*H/(QD/QM-H))
120   CONTINUE
C
      OUT(1)=Q(1)
      OUT(2)=Q(1)/QM
      OUT(3)=P*CP*CS*3.6
      OUT(4)=0.
      IF (P.GT.0.) OUT(4)=(1.-EFF)*P*CP*CS*3.6
      IF (MODE.EQ.1) GO TO 130
      OUT(5)=IQ*CP
      OUT(6)=V*CS
      PMAX=VMAX*IQMAX
      OUT(7)=PMAX*CP*CS*3.6
      PMIN=VMIN*IQMIN
      OUT(8)=PMIN*CP*CS*3.6
      VD=ED-ABS(IQ)*RD
      OUT(9)=VD*CS
      OUT(10)=VC*CS
      PC=IC*VC
      OUT(11)=PC*CP*CS*3.6
130   RETURN
      END
```

APPENDIX II

```
C      ******************************************
C      *  THIS PROGRAM WILL CALCULATE VALUES OF V  *
C      *  FOR VALUES OF KTBAR BETWEEN .3 AND .7    *
C      ******************************************
        DIMENSION COEF(5,5)
        DIMENSION XKT(100,5),SQR(100,5)
        DIMENSION HT(100),V(100,5),RHT(100,5)
        DIMENSION DAILY(12,5)
        DIMENSION RAD(100,40)
        COMMON /MT/DELT,HINC,IPR
        COMMON /DT/ SLOPE,ALAT,AZMTH,RHO,SC,GO,WSPR
        COMMON /DRF/ADRF,BDRF,CDRF
        DATA COEF/1.5222,5.38682,-19.0553,25.37202,-12.10546,
     1   0.3071,8.84065,-28.45748,37.01945,-16.58585,
     2   0.11382,5.66517,-17.42259,23.99726,-11.19355,
     3   0.07104,3.7203,-10.42775,15.03488,-7.34399,
     4   0.0192,1.9276,-2.89291,4.73631,-2.69085/
        HINC=0.2
        IPR=1
        WRITE(-,599)
599     FORMAT(1H1)
        READ(-,-) NBINS
C       HERE THE NUMBER OF BINS IS SET TO 30 DAYS
        NBINS=30
C       THE GROUND REFLECTANCE RHO IS SET EQUAL TO 0.2
        RHO=0.2
        ADRF=.294
        BDRF=.1445
        CDRF=4.97
        DO 10 KT=1,5
        C1=COEF(1,KT)
        C2=COEF(2,KT)
        C3=COEF(3,KT)
        C4=COEF(4,KT)
        C5=COEF(5,KT)
        DP=1.0/NBINS
        P=-DP/2.
        DO 10 J=1,NBINS
        P=P+DP
        XKT(J,KT)=P/(C1+C2*P+C3*P*P+C4*P**3+C5*P**4)
C.    THIS FIT OF THE LIU AND JORDAN DISTRIBUTION CURVES IS FROM
C.    R. COLE,'LONG-TERM AVERAGE PERFORMANCE PREDICTIONS FOR CPC'S",
C.    PROCEEDINGS OF THE AMERICAN SECTION OF I.S.E.S.,ORLANDO
C.    FLORIDA, (1977), P36-6
10      CONTINUE
        READ(-,-) DELT
C       THE TIMESTEP DELT IS SET TO 0.25
        DELT=0.25
        READ(-,-) AZMTH
C       THE AZMITH ANGLE IS SET EQUAL TO ZERO
        AZMTH=0.0
        READ(-,-) ALAT,SLOPE
        SD=0.
        SC=4871.
        IDELT=24/DELT+0.01
        WRITE(-,2) DELT,SLOPE,ALAT,AZMTH,RHO,SC,ADRF,BDRF,CDRF
2       FORMAT(1H1,9(F9.4,2X)/)
C       THE VALUES OF V WILL BE CALCULATED FOR KTBAR BETWEEN .3 AND .7
        DO 31 KT=1,5
        XKTB=(KT+2.)/10.
        WRITE(-,678) XKTB
678     FORMAT(//53X,'KTBAR=',F4.2)
        DO 30 MN=1,12
```

```
      DAILY(MN,KT)=0.0
      SQR(MN,KT)=0.0
      DO 40 ID=1,NBINS
      CALL QRD(XKT(ID,KT),MN,HT)
      DO 40 IH=1,IDELT
      RAD(IH,ID)=HT(IH)
      DAILY(MN,KT)=DAILY(MN,KT)+HT(IH)
40    CONTINUE
      DAILY(MN,KT)=DAILY(MN,KT)/NBINS*DELT
      DO 70 ID=1,NBINS
      DO 70 IH=1,IDELT
      SQR(MN,KT)=RAD(IH,ID)**2+SQR(MN,KT)
70    CONTINUE
      SQR(MN,KT)=SQR(MN,KT)*DELT
      V(MN,KT)=SQR(MN,KT)/DAILY(MN,KT)**2
      RHT(MN,KT)=SQR(MN,KT)/DAILY(MN,KT)
50    CONTINUE
      WRITE(-,-) MN,V(MN,KT)
30    CONTINUE
31    CONTINUE
      END
```

```
C          ****************************************
C          *  USE THIS PROGRAM TO CALCULATE HOURLY  *
C          *     RADIATION ON A TILTED SURFACE       *
C          ****************************************
      SUBROUTINE QRD(XKT,MN,HR)
        DIMENSION DAYS(12)
C.    THIS ROUTINE WILL ESTIMATE THE BEAM,DIFFUSE AND TOTAL RADIATION
C.    ON A HORIZONTAL AND TILTED SURFACE FROM THE DAILY TOTAL
C.    RADIATION ON A HORIZONTAL SURFACE USING THE RELATIONSHIPS OF
C.    LIU AND JORDAN.     SOLAR ENERGY IV-3, 1960
C.
C.
C.      ALAT   -  THE LATITUDE
C.      SLOPE  -  THE SLOPE OF THE COLLECTOR SURFACE WITH RESPECT TO
C.                THE HORIZONTAL
C.      AZMTH  -  THE AZIMUTH OR ORIENTATION ANGLE
C.      DAY1   -  THE DAY AT WHICH SIMULATION IS STARTED (USED TO
C.                CALCULATE THE SOLAR DECLINATION)
C.      SC     -  THE SOLAR CONSTANT
C.      RHO    -  THE GROUND REFLECTIVITY
C.      IOPT   -  AN INTEGER OF VALUE 1,2,3 OR FOUR WHICH DETERMINES
C.                THE MANNER IN WHICH DIFFUSE RADIATION IS TO BE TREATED
C.
C.
C.     IOPT=1   THE SINGLE INPUT (XIN(1)) IS THE TOTAL RADIATION ON A
C.              HORIZONTAL SURFACE.  IT WILL BE TREATED AS IF IT WERE
C.              ALL BEAM RADIATION
C.
C.     IOPT=2   THE SINGLE INPUT (XIN(1)) IS THE TOTAL RADIATION ON A
C.              HORIZONTAL SURFACE.  THE BEAM AND DIFFUSE RADIATION
C.              COMPONENTS WILL BE CALCULATED FROM RELATIONSHIPS GIVEN
C.              IN LIU AND JORDAN (SOLAR ENERGY IV-3 1960)
C.              THE DIFFUSE COMPONENT IS TAKEN TO BE UNIFORMILY DISTRIBUTED
C.
C.     IOPT=3   SIMILAR TO IOPT=2 EXCEPT THAT THE DIFFUSE COMPONENT IS TO
C.              BE CORRECTED BY A FACTOR (1+COS(SLOPE))/2 AS GIVEN IN
C.              LIU AND JORDAN.  IN ADDITION, THE CONTRIBUTION FOR
C.              GROUND REFLECTANCE IS INCLUDED.  (SEE LIU AND JORDAN)
C.
C.
        DIMENSION HR(400)
       COMMON /MT/ DELT
       COMMON /DT/ SLOPE,ALAT,AZMTH,RHO,SC,HSS,GO,WSPR
        COMMON /DRF/ ADRF,BDRF,CDRF
       DATA SCALE/41.868/,FIVNIN/0.5555555555556/,REFIND/1.526/
       DATA IUNIT/0/,RDCONV/0.0174533/,PI/3.1415927/
        DATA DAYS/17.,47.,75.,105.,135.,162.,198.,228.,258.,288.,
     1   318.,344./
C.
C.
        IOPT=3
        HINC=0.25
       IDELT=1.001/DELT
       COSLAT=COS(ALAT*RDCONV)
       SINLAT=SIN(ALAT*RDCONV)
       TANLAT=SINLAT/COSLAT
       COSAZM=COS(AZMTH*RDCONV)
       SINAZM=SIN(AZMTH*RDCONV)
       COSSLP=COS(SLOPE*RDCONV)
       SINSLP=SIN(SLOPE*RDCONV)
       RD=(1.0+COSSLP)/2.
       RR=(1.0-COSSLP)/2.0*RHO
        DAY=DAYS(MN)
       DECL=23.45*SIN((284.+DAY)/365.*PI*2.)
```

```
      COSDEC=COS(DECL*RDCONV)
      SINDEC=SIN(DECL*RDCONV)
      TANDEC=SINDEC/COSDEC
      ECC=1.0+0.033*COS(2.0*PI*DAY/365.)
C.  ECC IS THE ECCENTRICITY CORRECTION FACTOR FOR THE SOLAR CONSTANT
      SHR=ACOS(-TANDEC*TANLAT)
       WS2=ACOS(-TAN((ALAT-SLOPE)*RDCONV)*TANDEC)
       WSPR=MIN(SHR,WS2)
      SINSHR=SIN(SHR)
      COSSHR=COS(SHR)
       A=0.409+0.5016*SIN(SHR-1.047)
       B=0.6609-0.4767*SIN(SHR-1.047)
C.  SHR IS THE SUNSET HOUR ANGLE
      HSS=24.0/PI*SHR
      SRSS=HSS/2.0-HINC
       WSRSS=SRSS*PI/12.
      COSTZ=COSLAT*COSDEC*COS(WSRSS)+SINLAT*SINDEC
      COSTT=SINDEC*SINLAT*COSSLP-SINDEC*COSLAT*SINSLP*COSAZM
     1  +COSDEC*COSLAT*COSSLP*COS(WSRSS)+COSDEC*SINLAT
     2 *SINSLP*COSAZM*COS(WSRSS)+COSDEC*SINSLP*SINAZM*SIN(WSRSS)
       RBSS=COSTT/COSTZ
       IF (RBSS.LE.0.00) RBSS=0.0
C.  HSS IS THE HOURS FROM SUNRISE TO SUNSET
      G0=24.0/PI*ECC*SC*(COSLAT*COSDEC*SINSHR+SHR*SINLAT*SINDEC)
C.  GO IS THE DAILY EXTERRESTRIAL RADIATION ON A HORIZONTAL SURFACE
      GT=G0*XKT
C.  XKT IS THE DAILY CLOUDINESS INDEX
       IF(XKT.GT.0.75) GO TO 555
      DRD=1.0045+0.04349*XKT-3.5227*XKT**2+2.6313*XKT**3
        GO TO 556
555   DRD=0.166
556   IF (DRD.GT.1.0) DRD=1.0
C.  THIS FUNCTION FORM FOR DAILY DIFFUSE RATIO IS DUE TO BRUNO
      GD=DRD*GT
C.
C.  GD IS THE DAILY DIFFUSE RADIATION ON A HORIZONTAL SURFACE.
C.
C.
       ILOOP=24*IDELT
       DO 17 K=1,ILOOP
       HR(K)=0.
       TCHK=IABS(ILOOP/2-K)*DELT
       IF (TCHK.GT.HSS/2.) GO TO 17
       COSHR=COS((K-ILOOP/2)*15.0*DELT*RDCONV)
       SINHR=SIN((K-ILOOP/2)*15.0*DELT*RDCONV)
      HD=GD*PI/24.0*(COSHR-COSSHR)/(SINSHR-SHR*COSSHR)
       RDIF=HD/GD
       RATIO=RDIF*(A+B*COSHR)
      IF (HD.LE.0.0) HD=0.0
C.  HD IS THE AVERAGE (HOURLY) DIFFUSE RADIATION ON A HORIZONTAL
C.  SURFACE  (LIU AND JORDAN'S RELATIONSHIP)
C.
      HT=GT*RATIO
       IF (HT.GT.0.0) GO TO 602
       HT=0.0
       HR(K)=0.0
       GO TO 17
602    CONTINUE
       HD=AMIN1(HD,HT)
C.  HT IS THE HOURLY TOTAL RADIATION ON A HORIZONTAL SURFACE
      HB=HT-HD
      IF (HB.LE.0.0) HB=0.0
C.  HB IS THE HOURLY BEAM RADIATION ON A HORIZONTAL SURFACE
      RB=RBSS
```

```
      IF (TCHK.GT.SRSS) GO TO 511
C.  IF TIME OF DAY IS NOT WITHIN HINC HOURS OF SUNRISE OR SUNSET, RB=RBS
      COSTZ=COSLAT*COSDEC*COSHR+SINLAT*SINDEC
      IF (COSTZ.LE.0.0) GO TO 511
C.  COSTZ IS THE COSINE OF THE ANGLE OF BEAM RADIATION INCIDENT
C.  ON A HORIZONTAL SURFACE
C.
      COSTT=SINDEC*SINLAT*COSSLP-SINDEC*COSLAT*SINSLP*COSAZM
     1  +COSDEC*COSLAT*COSSLP*COSHR+COSDEC*SINLAT
     2 *SINSLP*COSAZM*COSHR+COSDEC*SINSLP*SINAZM*SINHR
C.  COSTT IS THE COSINE OF THE ANGLE OF INCIDENT RADIATION
C.  RADIATION (THETA) ON THE TILTED SURFACE
      RB=COSTT/COSTZ
      IF (RB.LE.0.0) RB=RBSS
511   GO TO (51,52,53),IOPT
   51 CONTINUE
C.  INCOMING RADIATION IS TREATED AS IF IT WERE ALL BEAM
      HR(K)=HT*RB
      GO TO 17
   52 CONTINUE
C.  DIFFUSE IS UNIFORMILY DISTRIBUTED
      HBT=HB*RB
      HR(K)=HBT+HD
      GO TO 17
   53 CONTINUE
C.  TILT FACTOR FOR DIFFUSE AND GROUND RADIATION
      HBT=HB*RB
      HDT=HD*RD+HT*RR
      HR(K)=HBT+HDT
   17 CONTINUE
      END
```

APPENDIX III

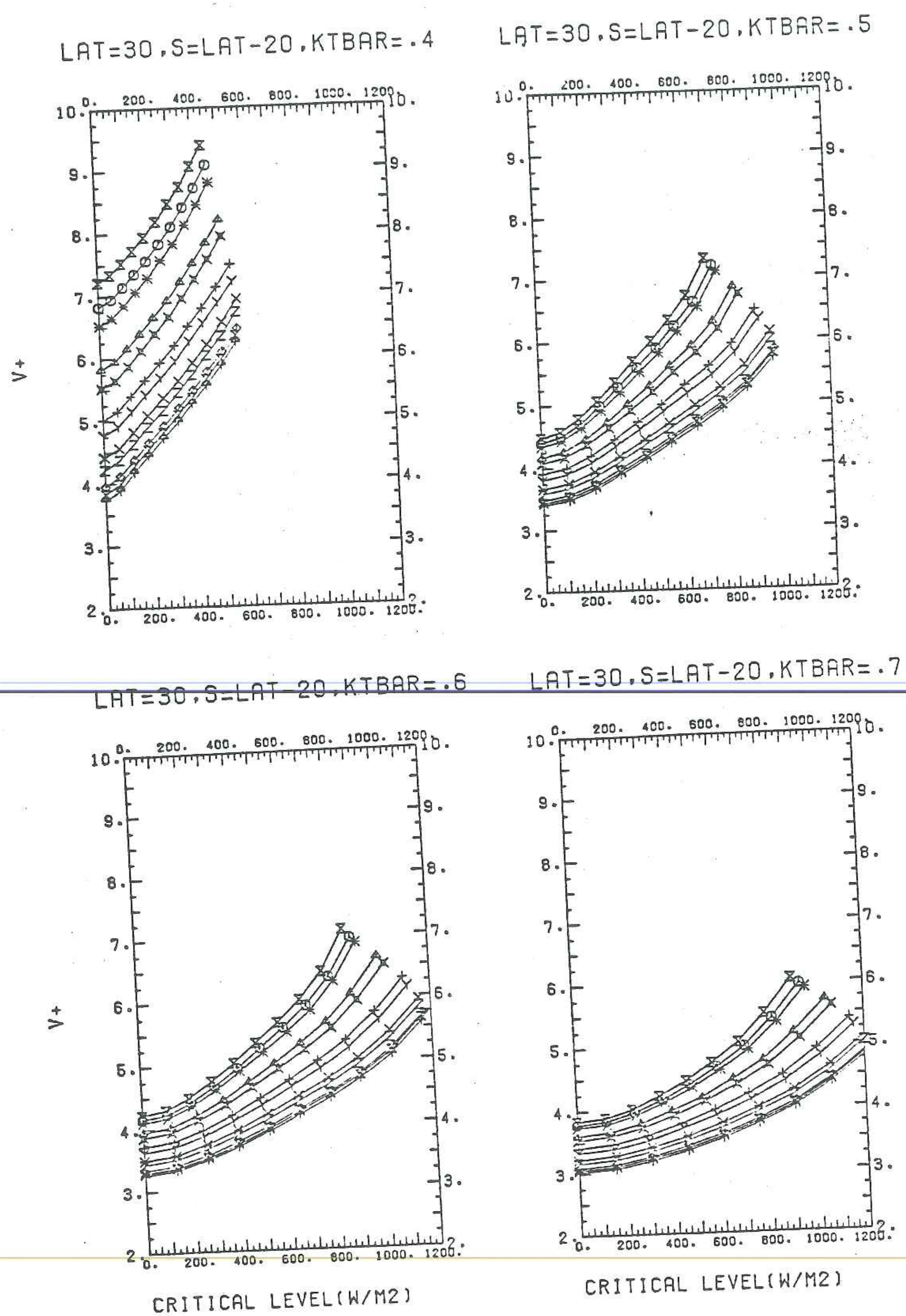
```
C              ****************************************
C              *  THIS PROGRAM WILL CALCULATE VALUES  *
C              *     OF V+ FOR VALUES OF KTBAR BETWEEN *
C              *           .3 AND .7                  *
C              ****************************************
      DIMENSION COEF(5,5)
      DIMENSION XKT(100,5),V2(11,12,5)
      DIMENSION AVG(11),STDEV(11),TORAD(11,12,5)
      DIMENSION HT(100)
      DIMENSION DAILY(12,5)
      DIMENSION CLINC(12,5)
      DIMENSION RAD(100,40)
      COMMON /MT/DELT,HINC
      COMMON /DT/ SLOPE,ALAT,AZMTH,RHO,SC,HSS,GO
      COMMON /DRF/ADRF,BDRF,CDRF
      DATA COEF/1.5222,5.38682,-19.0553,25.37202,-12.10546,
     1  0.3071,8.84065,-28.45748,37.01945,-16.58585,
     2  0.11382,5.66517,-17.42259,23.99726,-11.19355,
     3  0.07104,3.7203,-10.42775,15.03488,-7.34399,
     4  0.0192,1.9276,-2.89291,4.73631,-2.69085/
      HINC=0.2
      WRITE(-,599)
599   FORMAT(1H1)
      NBINS=30
C     READ(-,-) RHO
      RHO=.2
C     READ(-,-) ADRF,BDRF,CDRF
      ADRF=.294
      BDRF=.1445
      CDRF=4.97
      DO 10 KT=1,5
      C1=COEF(1,KT)
      C2=COEF(2,KT)
      C3=COEF(3,KT)
      C4=COEF(4,KT)
      C5=COEF(5,KT)
      DP=1.0/NBINS
      P=-DP/2.
      DO 10 J=1,NBINS
      P=P+DP
      XKT(J,KT)=P/(C1+C2*P+C3*P*P+C4*P**3+C5*P**4)
C.  THIS FIT OF THE LIU AND JORDAN DISTRIBUTION CURVES IS FROM
C.  R. COLE,'LONG-TERM AVERAGE PERFORMANCE PREDICTIONS FOR CPC'S",
C.  PROCEEDINGS OF THE AMERICAN SECTION OF I.S.E.S.,ORLANDO
C.  FLORIDA, (1977), P36-6
10    CONTINUE
C     READ(-,-,END=99) CLR,DELT
      CLR=.15
      DELT=.25
1     CONTINUE
      SD=0.
      READ(-,-,END=99) ALAT,IB
      AZMTH=0.0
      SC=4871.
      IDELT=24/DELT+0.01
      DO 37 IT=1,IB
      SLOPE=ALAT+(IT-2)*20.
      WRITE(-,2) CLR,DELT,SLOPE,ALAT,AZMTH,RHO,SC,ADRF,BDRF,CDRF
2     FORMAT(1H1,10(F9.4,2X)/)
      DO 31 IKT=1,5
      XKTB=(KT+2.)/10.
      WRITE(-,678) XKTB
678   FORMAT(//53X,'KTBAR=',F4.2)
      WRITE(1,-) XKTB
      DO 77 IC=1,10
77    AVG(IC)=0.0
      DO 30 MN=1,12
```

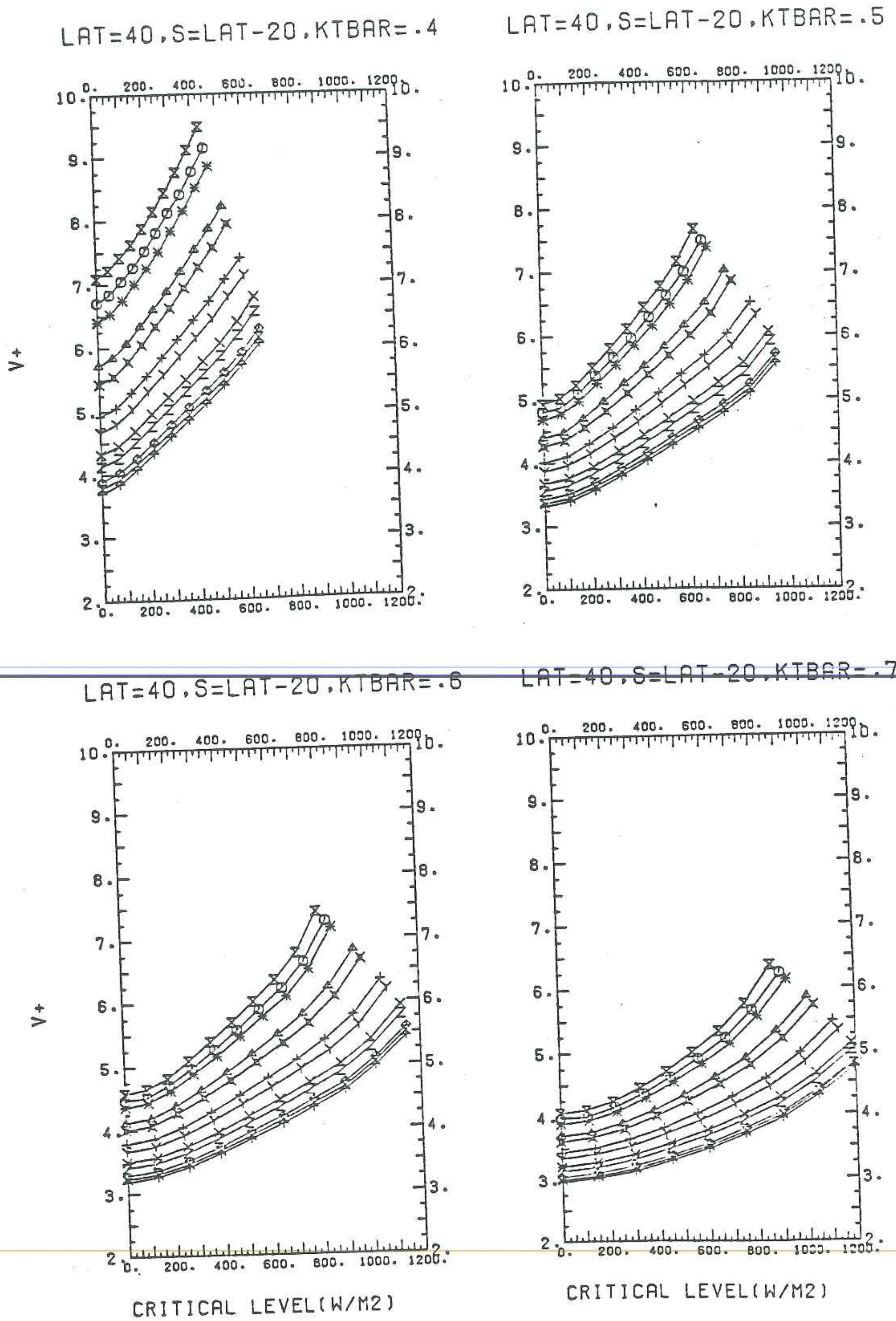
```
      DAILY(MN,KT)=0.0
      DO 40 ID=1,NBINS
      CALL QRD(XKT(ID,KT),MN,HT)
      DO 40 IH=1,IDELT
      RAD(IH,ID)=HT(IH)
      DAILY(MN,KT)=DAILY(MN,KT)+HT(IH)
 40   CONTINUE
      DAILY(MN,KT)=DAILY(MN,KT)/NBINS*DELT
      CLINC(MN,KT)=CLR*ANORM(XKTB,MN,ALAT,SLOPE,DAILY(MN,KT),R)
      CL=CLINC(MN,KT)
      CL1=CLR
      DO 50 IC=1,10
      V2(IC,MN,KT)=0.
      IF(IC.EQ.1) CL=0.0
      TORAD(IC,MN,KT)=0.0
      DO 70 ID=1,NBINS
      DO 70 IH=1,IDELT
      IF(RAD(IH,ID).LT.CL) GO TO 70
      V2(IC,MN,KT)=V2(IC,MN,KT)+RAD(IH,ID)**2
      TORAD(IC,MN,KT)=TORAD(IC,MN,KT)+RAD(IH,ID)
 70   CONTINUE
      TORAD(IC,MN,KT)=TORAD(IC,MN,KT)/NBINS*DELT
      V2(IC,MN,KT)=V2(IC,MN,KT)*DELT
      IF(TORAD(IC,MN,KT).GT..01) GO TO 80
      V2(IC,MN,KT)=0.0
      GO TO 85
 80   V2(IC,MN,KT)=V2(IC,MN,KT)/(TORAD(IC,MN,KT)*DAILY(MN,KT))
 85   CONTINUE
      AVG(IC)=AVG(IC)+V2(IC,MN,KT)
      CL=CL+CLINC(MN,KT)
      CL1=CL1+CLR
 50   CONTINUE
      WRITE(10,7) MN,GO,DAILY(MN,KT),CLINC(MN,KT)
     1   ,(V2(IC,MN,KT),IC=1,10)
 7    FORMAT(2X,I2,1X,F6.0,2X,F6.0,2X,F6.0,10(F7.4,1X))
 30   CONTINUE
      DO 78 IC=1,10
 78   AVG(IC)=AVG(IC)/12.
      WRITE(-,59)
 59   FORMAT(/)
      WRITE(-,8) (AVG(IC),IC=1,10)
 8    FORMAT(41X,10(F7.4,1X))
      DO 75 IC=1,10
      SUM=0.
      DO 76 MN=1,12
      SUM=SUM+(AVG(IC)-V2(IC,MN,KT))**2
 76   CONTINUE
      STDEV(IC)=SQRT(SUM/11.)
 75   CONTINUE
      WRITE(-,8) (STDEV(IC),IC=1,10)
 31   CONTINUE
 37   CONTINUE
      GO TO 1
 99   CONTINUE
      STOP
      FUNCTION ANORM (XKT,MN,ALAT,SLOPE,HT,R)
      DIMENSION DAYS(12)
      DATA SCALE/41.868/,FIVNIN/0.5555555555556/,REFIND/1.526/
      DATA RHO/0.2/
      DATA IUNIT/0/,RDCONV/0.017453293/,PI/3.1415927/
      DATA SC/4871./
      DATA DAYS/17.,47.,75.,105.,135.,162.,198.,228.,258.,288.,
     1   318.,344./
C.
      HOUR=0.0
      COSLAT=COS(ALAT*RDCONV)
      SINLAT=SIN(ALAT*RDCONV)
      TANLAT=SINLAT/COSLAT
```

```
C.
      DAY=DAYS(MN)
      DECL=23.45*SIN((284.+DAY)/365.*PI*2.)
      COSDEC=COS(DECL*RDCONV)
      SINDEC=SIN(DECL*RDCONV)
      TANDEC=SINDEC/COSDEC
      ECC=1.0+0.033*COS(2.0*PI*DAY/365.)
      COSSLP=COS(SLOPE*RDCONV)
      SINSLP=SIN(SLOPE*RDCONV)
      RD=(1.0+COSSLP)/2.
      RR=(1.0-COSSLP)/2.0*RHO
      SINPMS=SIN((ALAT-SLOPE)*RDCONV)
      COSPMS=COS((ALAT-SLOPE)*RDCONV)
      TANPMS=SINPMS/COSPMS
      WS=ACOS(-TANDEC*TANLAT)
      COSWS=COS(WS)
      SINWS=SIN(WS)
      HSSH=24.0/PI*WS
      SHRT=ACOS(-TANDEC*TANPMS)
      SHR=AMIN1(WS,SHRT)
      HSS=24.0/PI*SHR
C.
      DRD=ADRF+BDRF*SIN(CDRF*XKT)/XKT
      IF (DRD.GE.1.0) DRD=1.0
C.   THE FORM OF THIS FIT FOR THE DAILY DIFFUSE RADIATION FRACTION
C.   IS FROM BRUNO, SOLAR ENERGY, VOL. 20, PP.97-100
      SINHNN=SIN(HOUR*15.*RDCONV)
      COSHNN=COS(HOUR*15.0*RDCONV)
      RDIF=PI/24.*(COSHNN-COSWS)/(SINWS-WS*COSWS)
      A=0.4090+0.5016*SIN(WS-1.047)
      B=0.6609-0.4767*SIN(WS-1.047)
      RT=RDIF*(A+B*COSHNN)
C.   THIS FORM FOR RT IS FROM ARI RABL, PERSONAL COMMUNICATION
      COSTZ=COSLAT*COSDEC*COSHNN+SINLAT*SINDEC
      COSTT=COSPMS*COSDEC*COSHNN+SINPMS*SINDEC
      RB=COSTT/COSTZ
      R=RB*(1.-RDIF/RT*DRD)+DRD*RDIF/RT*RD+RR
      G0=24.0/PI*ECC*SC*(COSLAT*COSDEC*SINWS+WS*SINLAT*SINDEC)
C.   GO IS THE DAILY EXTERRESTRIAL RADIATION ON A HORIZONTAL SURFACE
      ANORM=RT*R*G0*XKT
      RETURN
      END
```

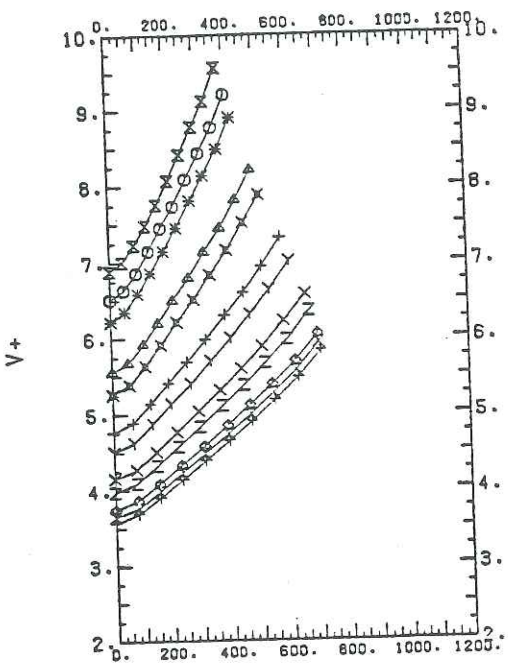
SYMBOL LIST

	January
	February
	March
	April
	May
	June
	July
	August
	September
	October
	November
	December

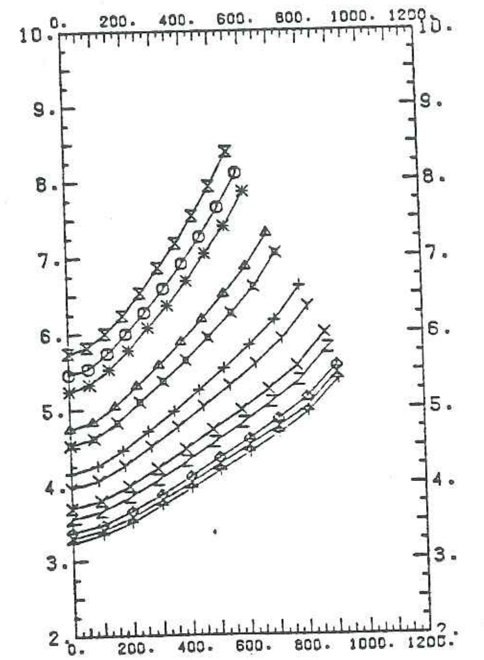

LAT=30,S=LAT-20,KTBAR=.4
LAT=30,S=LAT-20,KTBAR=.5
LAT=30,S=LAT-20,KTBAR=.6
LAT=30,S=LAT-20,KTBAR=.7
V+
CRITICAL LEVEL(W/M2)
CRITICAL LEVEL(W/M2)


LAT=40,S=LAT-20,KTBAR=.4
LAT=40,S=LAT-20,KTBAR=.5
LAT=40,S=LAT-20,KTBAR=.6
LAT=40,S=LAT-20,KTBAR=.7
V+
V+
CRITICAL LEVEL(W/M2)
CRITICAL LEVEL(W/M2)

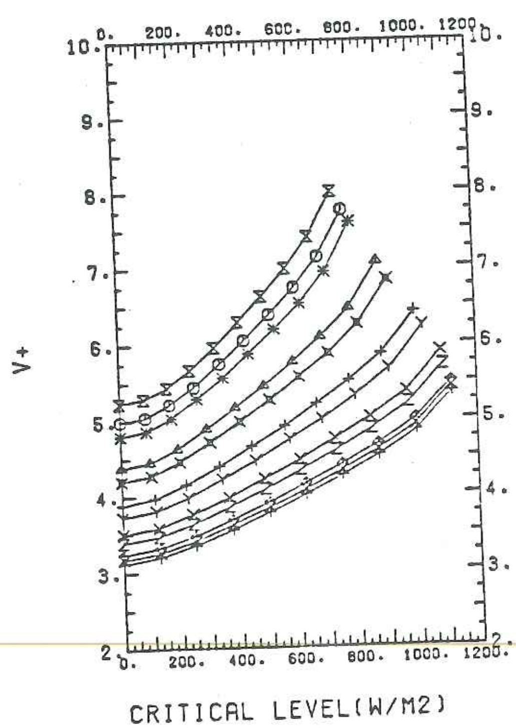
LAT=50,S=LAT-20,KTBAR=.4



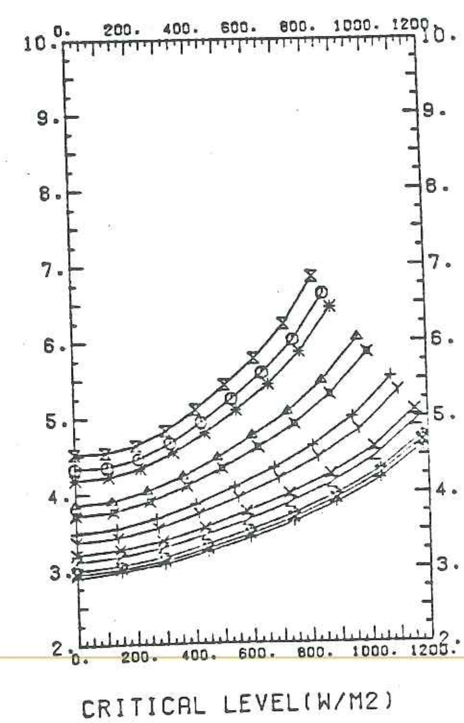
LAT=50,S=LAT-20,KTBAR=.5



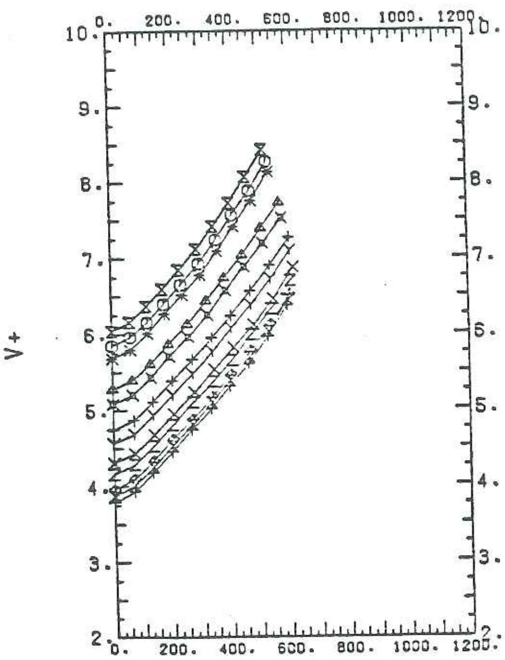
LAT=50,S=LAT-20,KTBAR=.6



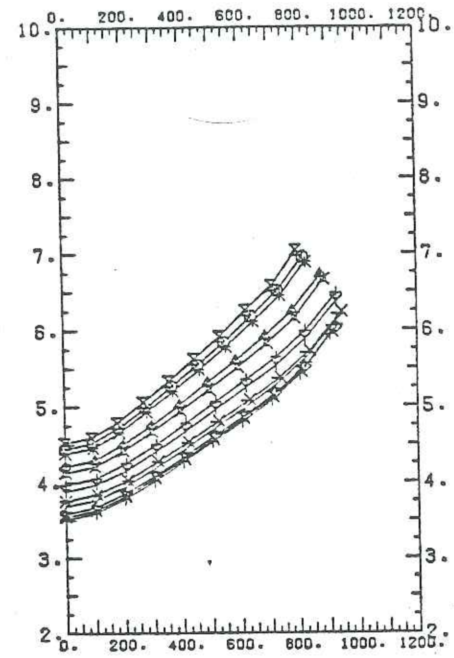
LAT=50,S=LAT-20,KTBAR=.7



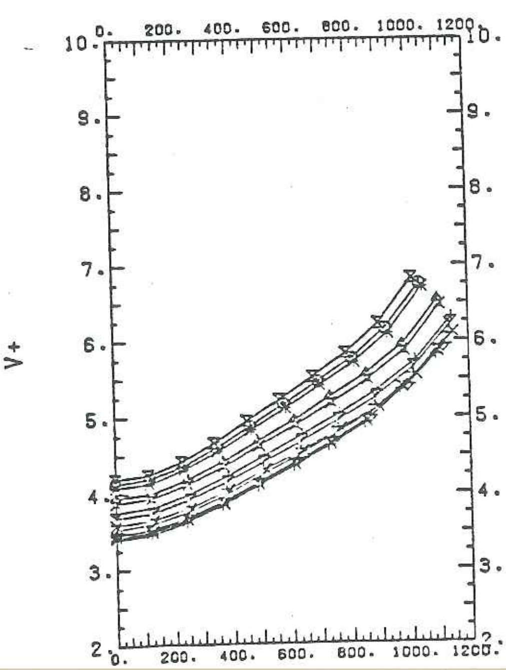
LAT=30,S=LAT,KTBAR=.4



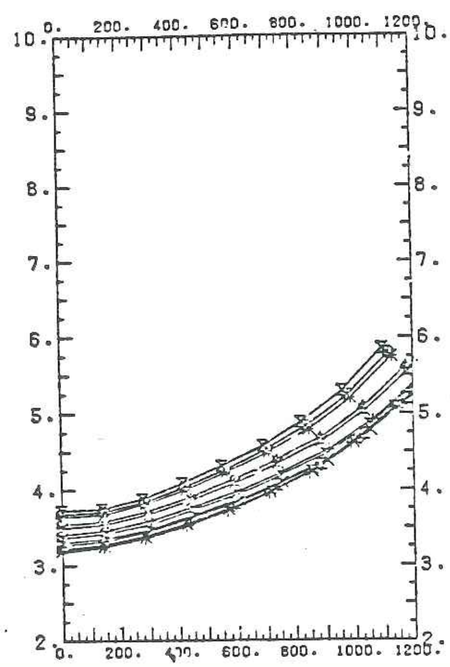
LAT=30,S=LAT,KTBAR=.5



LAT=30,S=LAT,KTBAR=.6

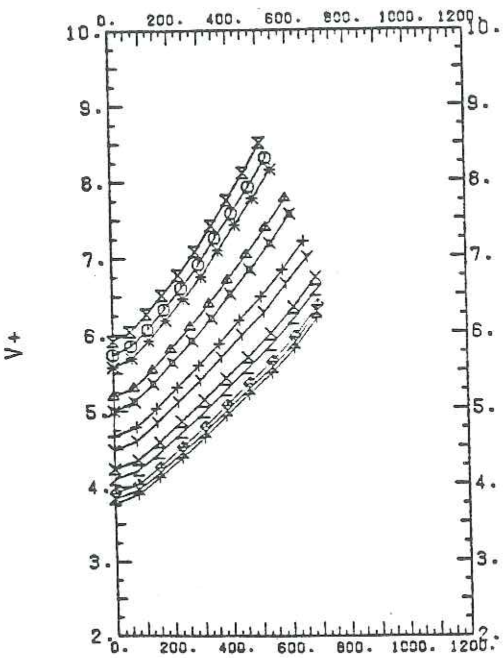


LAT=30,S=LAT,KTBAR=.7

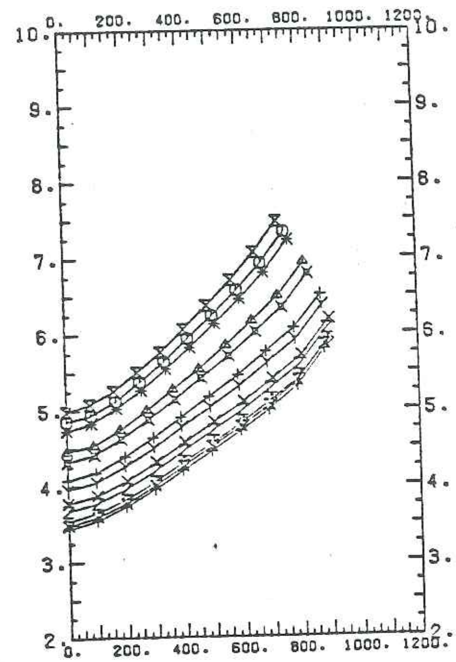


CRITICAL LEVEL(W/M2)

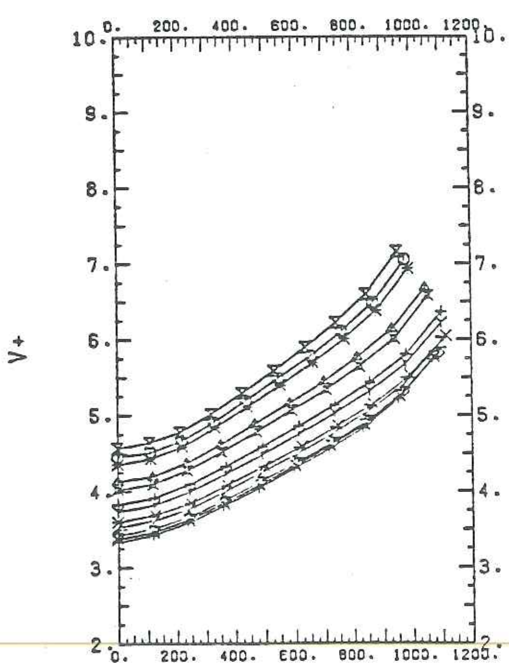
LAT=40,S=LAT,KTBAR=.4



LAT=40,S=LAT,KTBAR=.5

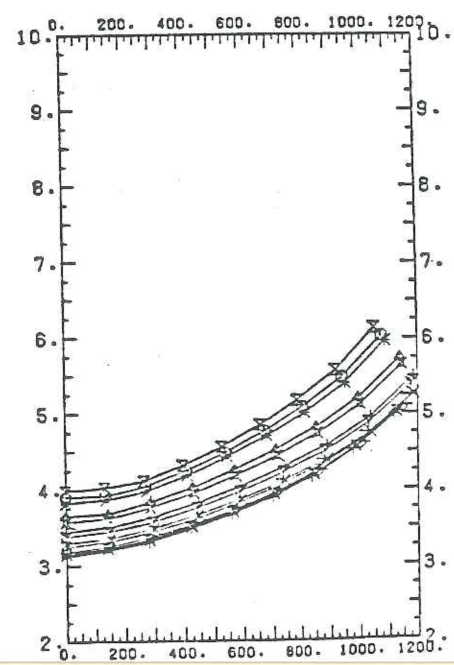


LAT=40,S=LAT,KTBAR=.6



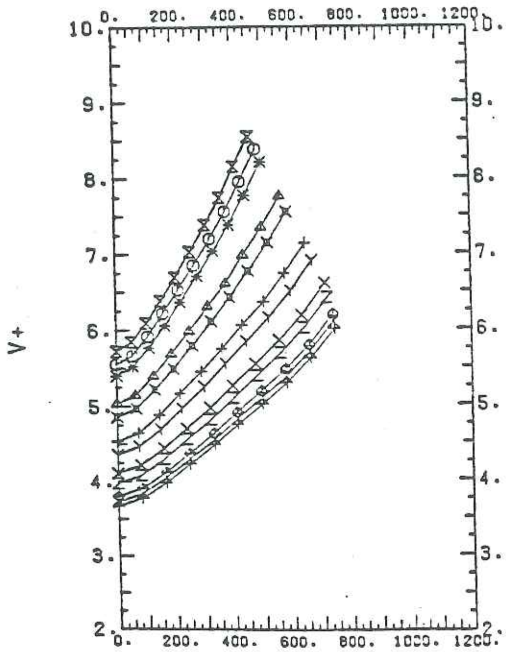
CRITICAL LEVEL(W/M2)

LAT=40,S=LAT,KTBAR=.7

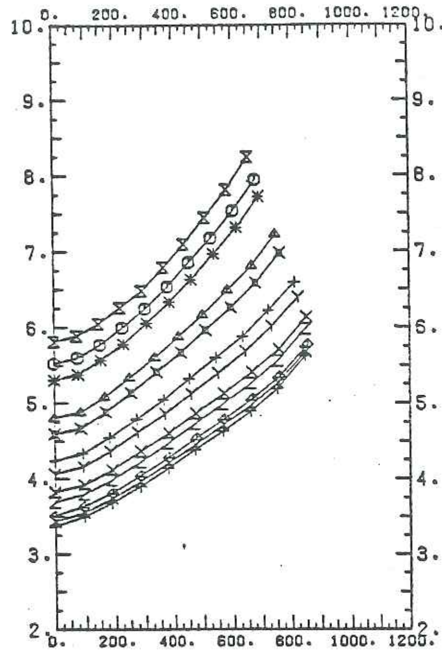


CRITICAL LEVEL(W/M2)

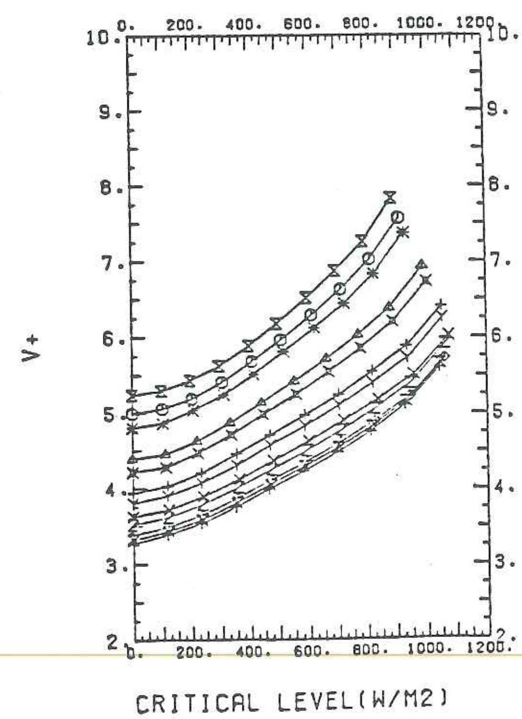
LAT=50,S=LAT,KTBAR=.4



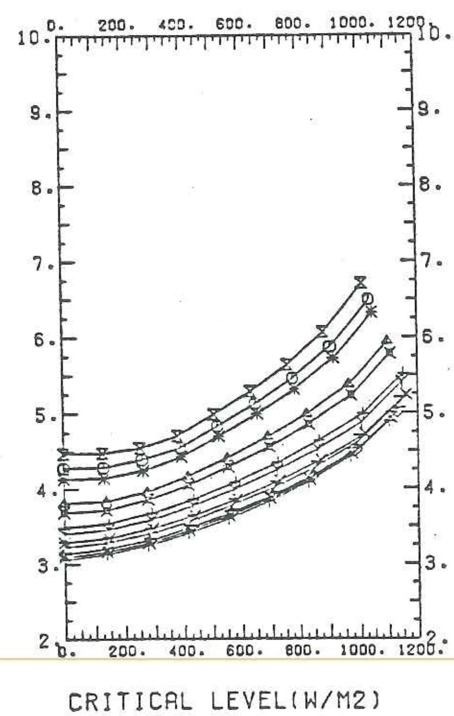
LAT=50,S=LAT,KTBAR=.5

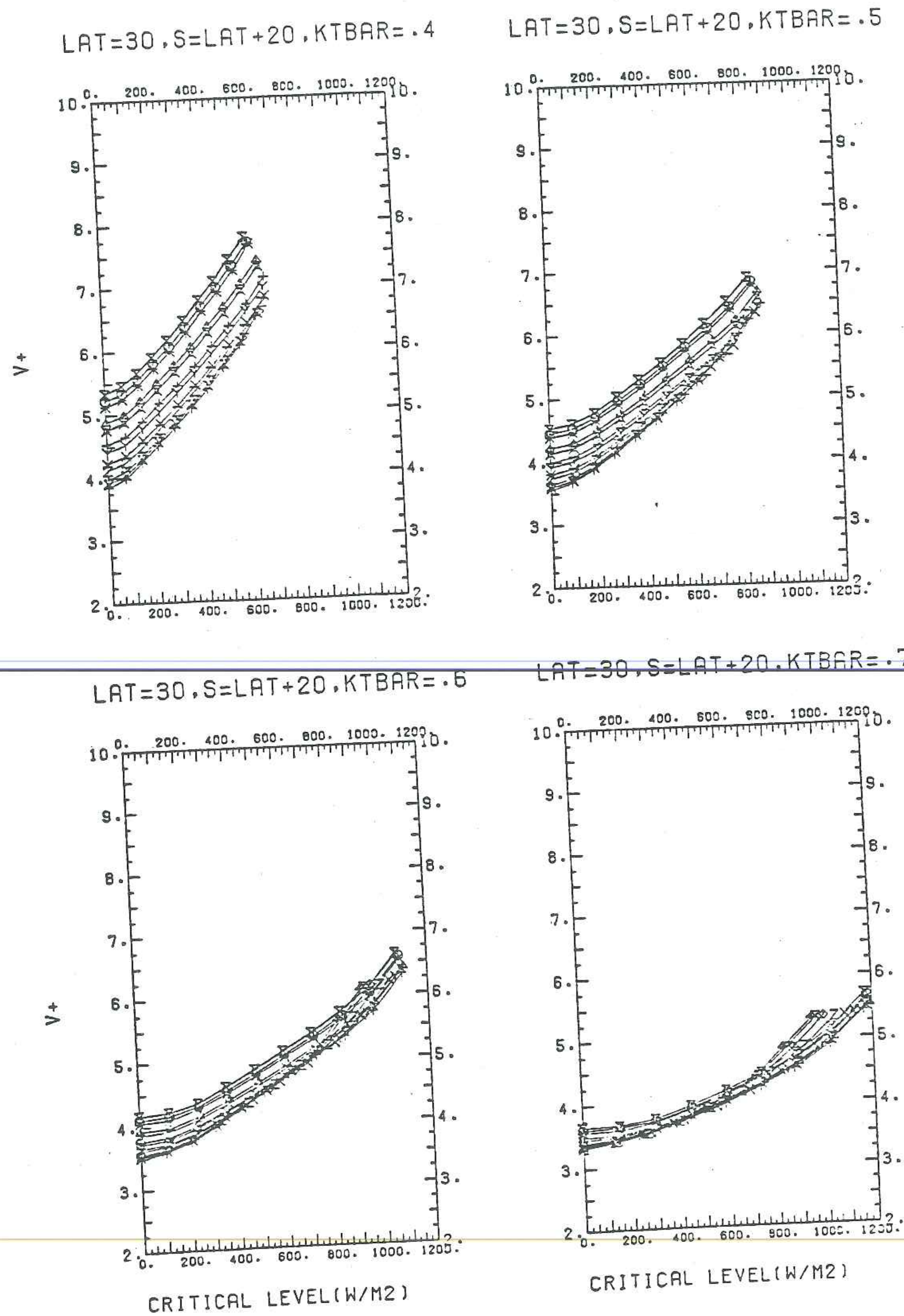


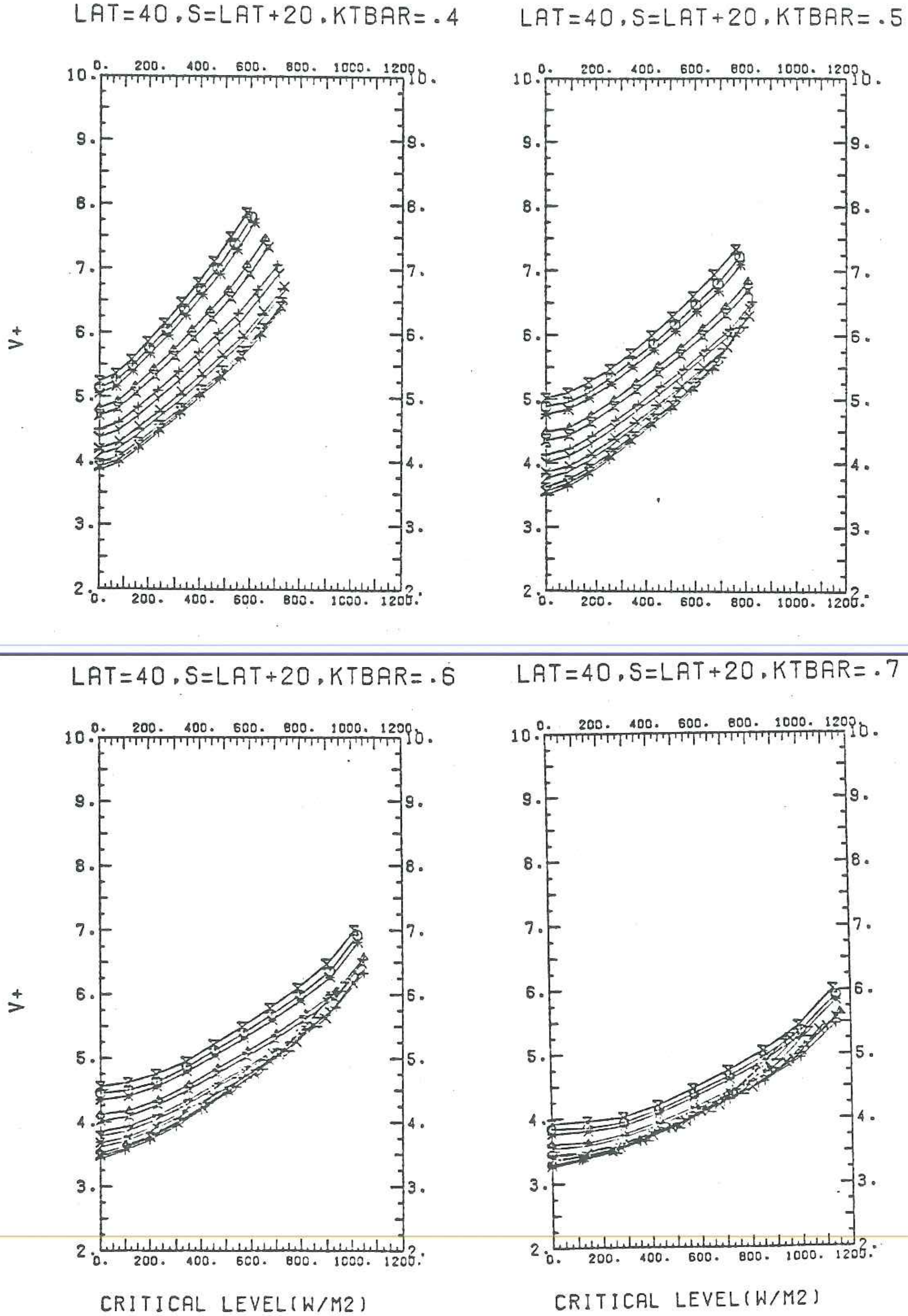
LAT=50,S=LAT,KTBAR=.6

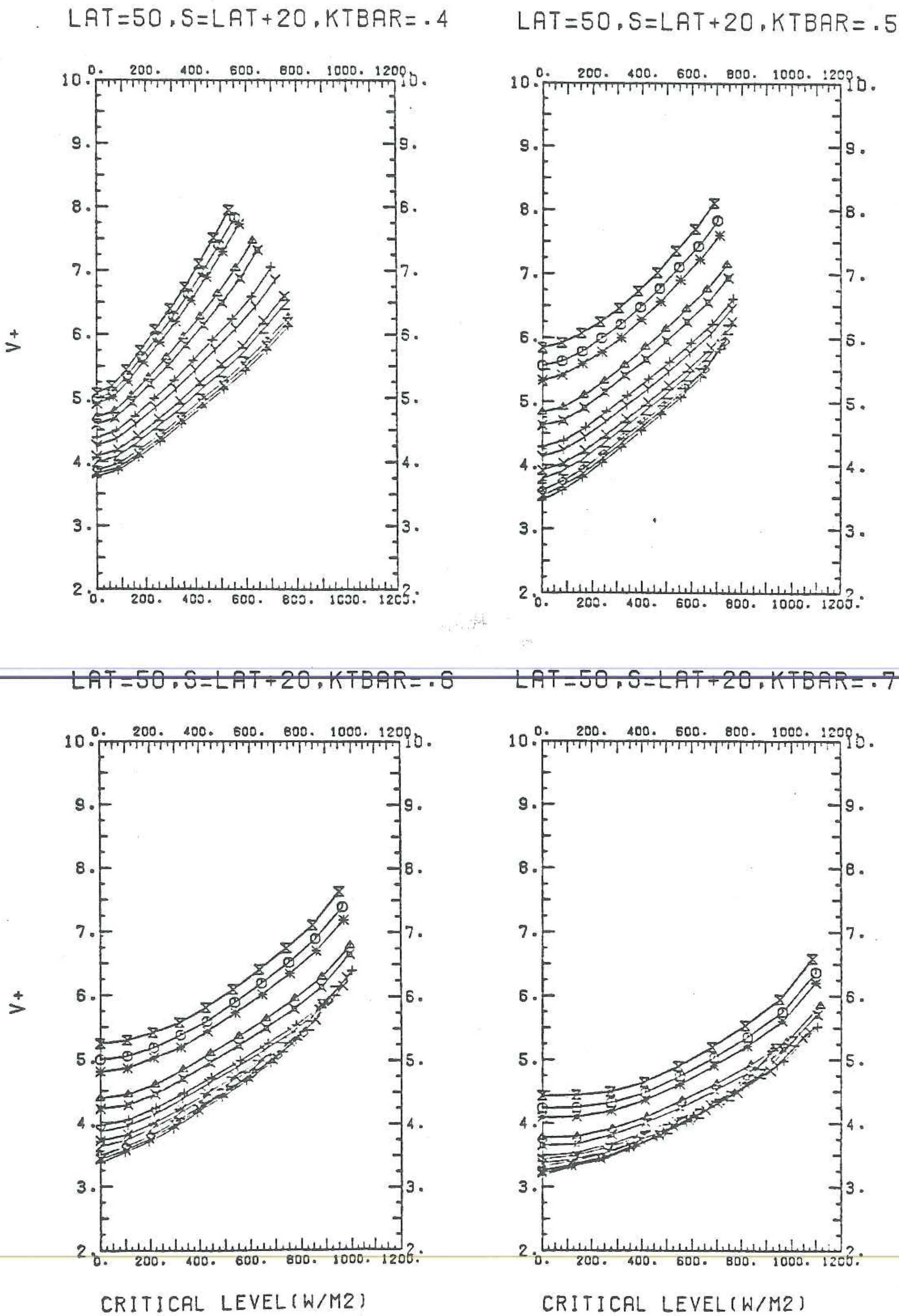


LAT=50,S=LAT,KTBAR=.7




LAT=30,S=LAT+20,KTBAR=.4
LAT=30,S=LAT+20,KTBAR=.5
LAT=30,S=LAT+20,KTBAR=.6
LAT=30,S=LAT+20,KTBAR=.7
V+
CRITICAL LEVEL(W/M2)
0. 200. 400. 600. 800. 1000. 1200.
2. 3. 4. 5. 6. 7. 8. 9. 10.


LAT=40,S=LAT+20,KTBAR=.4
LAT=40,S=LAT+20,KTBAR=.5
LAT=40,S=LAT+20,KTBAR=.6
LAT=40,S=LAT+20,KTBAR=.7
V+
CRITICAL LEVEL(W/M2)
0. 200. 400. 600. 800. 1000. 1200.
2. 3. 4. 5. 6. 7. 8. 9. 10.


LAT=50,S=LAT+20,KTBAR=.4
LAT=50,S=LAT+20,KTBAR=.5
LAT=50,S=LAT+20,KTBAR=.6
LAT=50,S=LAT+20,KTBAR=.7
V+
V+
CRITICAL LEVEL(W/M2)
CRITICAL LEVEL(W/M2)

APPENDIX IV - Sample Output

CODE	VARIABLE DESCRIPTION	VALUE	UNITS
1	NO STOR.=1,UTL FDBK=2,STOR.=3,BAT.&UTL.=4	3.000	
2	REFERENCE EFFICIENCY AT 1 SUN,TA=0 DEG. C.	.120	
3	TEMPERATURE VS. EFF BR. (.004 FOR SI)	.004	
4	COLLECTOR AREA...........................	1.000	M2
5	TAU-ALPHA PRODUCT(NORMAL INCIDENCE)..	.950	
6	AVERAGE UL	.020	KW/C-M-M2
7	INCIDENCE ANGLE MODIFIER (ZERO IF NOT AVAIL.)	.000	
8	NUMBER OF TRANSPARENT COVERS................	.000	
9	COLLECTOR SLOPE.............................	23.130	DEGREES
10	AZIMUTH ANGLE (E.G. SOUTH=0, WEST=90)........	.000	DEGREES
11	EFFECTIVE STORAGE CAPACITY..................	.153	KWH
12	CONSTANT LOAD...............................	.336	KWH/DAY
13	FRACTIONAL BATTERY LOSSES...................	.150	
14	OVERALL SYSTEM EFFICIENCY(DIST.,REG.,DC/AC)..	.900	
15	BATTERY CHARGING EFFICIENCY.................	1.000	
16	UTILITY FDBACK/UTILITY COSTS PRICE RATIO....	1.000	
17	CITY CALL NUMBER............................	3.000	
18	ELECTRICAL PRINT OUT BY MONTH=1, BY YEAR=2...	1.000	
19	ECONOMIC ANALYSIS ? YES=1, NO=2..............	2.000	

TYPE IN CODE NUMBER AND NEW VALUE

R

WHAT IS THE COLLECTOR MODULE SIZE(FT2 OR M2)?

1

MADISON WI 43.13

****ELECTRIC ANALYSIS DESIGN METHOD****

TIME	PERCENT SOLAR	INCIDENT SOLAR (KWH)	TOTAL LOAD (KWH)	EFFMAX	ELEC MAX (KWH)	ELEC SUPP (KWH)	ELEC DUMP(BE=0) (KWH)	BATT LOSS (KWH)	ELEC DUMP (KWH)	AMBIENT TEMP (C)
JAN	57.6	7.52+01	1.04+01	.114	7.72+00	6.00+00	4.57+00	5.02-01	1.22+00	-8.0
FEB	68.7	9.49+01	9.41+00	.110	9.44+00	6.46+00	6.12+00	5.54-01	2.42+00	-6.0
MAR	78.6	1.43+02	1.04+01	.108	1.38+01	8.19+00	9.59+00	7.05-01	4.89+00	-2.0
APR	79.3	1.38+02	1.01+01	.102	1.27+01	7.99+00	8.48+00	6.62-01	4.07+00	9.0
MAY	84.3	1.65+02	1.04+01	.099	1.47+01	8.78+00	9.92+00	7.12-01	5.17+00	15.0
JUN	86.2	1.70+02	1.01+01	.096	1.47+01	8.69+00	9.92+00	6.95-01	5.29+00	20.0
JUL	86.4	1.82+02	1.04+01	.095	1.56+01	9.00+00	1.07+01	7.25-01	5.84+00	22.0
AUG	84.4	1.77+02	1.04+01	.096	1.53+01	8.79+00	1.06+01	7.24-01	5.77+00	20.0
SEP	78.5	1.44+02	1.01+01	.098	1.27+01	7.92+00	8.57+00	6.64-01	4.14+00	17.0
OCT	68.0	1.07+02	1.04+01	.104	1.00+01	7.09+00	6.31+00	5.93-01	3.38+00	10.0
NOV	53.8	6.67+01	1.01+01	.110	6.59+00	5.43+00	3.66+00	4.39-01	7.27-01	2.0
DEC	47.8	5.53+01	1.04+01	.114	5.67+00	4.98+00	2.95+00	3.99-01	2.94-01	-4.0

YEAR	FRACT	SOLAR	QLOAD	QMAX	QDEL	QDUMP(BE=0)	BATLOSS	QD(ACTUAL)
YR	72.8	1.52+03	1.23+02	1.39+02	8.93+01	9.13+01	7.37+00	4.22+01

APPENDIX IV - Computer Listings*

```
C..SUBPROGRAM CALC PERFORMS THE SOLAR SYSTEM ELECTRIC ANALYSIS BASED ON
C..THE EMPIRICAL FCHART EQUATIONS FOR STANDARD SYSTEMS. CALC CALLS RBAR
C..WHICH, WITH THE HELP OF TAUALF, ESTIMATES RADIATION ON THE COLLECTOR
C..SURFACE GIVEN DATA ON THE HORIZONTAL. ECON IS CALLED TO PERFORM A LIFE
C..CYCLE COST ANALYSIS WHICH CAN BE USED TO OPTIMIZE COLLECTOR AREA.
      SUBROUTINE CALC(XLIST,XLOAD,RHO,IU,DELTAC)
      DIMENSION MONTHL(12),RHO(12),XLIST(46),XLOAD(12),F(12)
      DIMENSION QDA(12),QLOSS(12),TAU(12)
      DIMENSION R1(12),RT(12),WSP(12),XKT(12),DAYS(12)
      DIMENSION CRIT(12),XC(12),QDMON(12),QDL(12)
      DIMENSION H(12),S(12),QDO(12),PHI(12),TAMB(12)
      DIMENSION ICITY(6),NERR(24),QMAX(12),EFFMAX(12),RB(12),WS(12)
      COMMON /LUNITS/LUR,LUW,DATAR
      COMMON /UTIL/QDQUYR,MODE1
      DATA YEAR/3HYR /
      DATA DAYS/31.,28.,31.,30.,31.,30.,31.,31.,30.,31.,30.,31./
      DATA MONTHL/3HJAN,3HFEB,3HMAR,3HAPR,3HMAY,3HJUN,3HJUL,3HAUG,
     13HSEP,3HOCT,3HNOV,3HDEC/
C..INTERNALIZE ALL NEEDED PARAMETERS FROM XLIST.
      MODE1=IFIX(XLIST(1)+.001)
      TNR=XLIST(2)
      BR=XLIST(3)
      AC=XLIST(4)
      PTA=XLIST(5)
      UL=XLIST(6)
      AIM=XLIST(7)
      NG=IFIX(XLIST(8)+.001)
      SLOPE=XLIST(9)
      AZMTH=XLIST(10)
      STOR=XLIST(11)
      XLD=XLIST(12)
      PERC=XLIST(13)
      ACDC=XLIST(14)
      EFFBAT=XLIST(15)
      CPA=XLIST(16)
      ICCN=IFIX(XLIST(17)+.001)
      IPRT=IFIX(XLIST(18)+.001)
      IECON=IFIX(XLIST(19)+.001)
      LOPMZ=IFIX(XLIST(20)+.001)
      ADCOST=XLIST(23)
      CCOST=XLIST(24)
C..VERIFY THAT ALL PARAMETERS USED ARE REASONABLE
      DO 1 J=1,24
1     NERR(J)=1
      IF(MODE1.LT.1.OR.MODE1.GT.4) NERR(1)=2
      IF(TNR.LT.0.0.OR.TNR.GT..22) NERR(2)=2
      IF(BR.LT.0.0005.OR.BR.GT.0.01) NERR(3)=2
      IF(AC.LT.0.0) NERR(4)=2
      IF(PTA.LT.0.0.OR.PTA.GT.1.0) NERR(5)=2
      IF(UL.LT..01.OR.UL.GT.1.0) NERR(6)=2
      IF(AIM.LT.0.0) NERR(7)=2
      IF(NG.LT.0.OR.NG.GT.3) NERR(8)=2
      IF(SLOPE.LT.0..OR.SLOPE.GT.90.) NERR(9)=2
      IF(AZMTH.LT.-180..OR.AZMTH.GT.180.) NERR(10)=2
      RATIO=STOR/XLD
      IF(RATIO.GT.3.0) NERR(11)=2
      IF(XLD.LT.0.0) NERR(12)=2
      IF(SYSV.LT.0.0) NERR(13)=2
      IF(ACDC.LT.0.0.OR.ACDC.GT.1.0) NERR(14)=2
      IF(EFFBAT.LT.0.0.OR.EFFBAT.GT.1.0) NERR(15)=2
      IF(CPA.LT.0.0.OR.CPA.GT.2.0) NERR(16)=2
      IF(IPRT.NE.1.AND.IPRT.NE.2) NERR(18)=2
      IF(IECON.NE.1.AND.IECON.NE.2) NERR(19)=2
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      IF(LOPMZ.NE.1.AND.LOPMZ.NE.2) NERR(20)=2
      IF(ADCOST.LT.0.) NERR(23)=2
      IF(CCOST.LT.0.) NERR(24)=2
4     IRET=0
      DO 6 J=1,24
      IGO=NERR(J)
      GO TO(6,5),IGO
5     WRITE(LUW,525) J
      IRET=1
6     CONTINUE
      IF(IRET.EQ.1) RETURN
C..FETCH DATA FOR THE DESIRED LOCATION.
      IFILE=0
      ISTYPE=1
      CALL CYREAD(ICCN,ICITY,XLATTI,IERR,IFILE)
      CALL DATAIN(ICCN,IFILE,H,ISTYPE)
      CALL DATAIN(ICCN,IFILE,TAMB,3)
C..SET CONSTANTS FOR S.I. UNITS.
      SCONV=1./3600.
      TM=1.
      TA=0.
      XCONV=1.
C..PRINT ELECTRIC OUTPUT HEADING OF LOCATION AND LATITUDE.
7     WRITE(LUW,515) (ICITY(J),J=1,6),XLATTI
      DO 9 J=1,12
      RB(J)=RBAR(J,XLATTI,SLOPE,AZMTH,H(J),RHO(J),NG,AIM,TARAT,
     1XKT(J),R1(J),RT(J),WS(J),WSP(J),TAU(J))
      S(J)=H(J)*RB(J)
      S(J)=S(J)*SCONV
C..ISTYPE=1 FOR HORIZONTAL SOLAR DATA, 2 FOR COLLECTOR SURFACE DATA.
C..TARAT IS THE RATIO OF THE AVERAGE TRANSMITTANCE-ABSORPTANCE
C..PRODUCT TO THAT AT NORMAL INCIDENCE
      RBW=R1(J)/(WSP(J)*1.548*XKT(J)+(1-1.548*XKT(J))*WS(J))
      AA=15.197*XKT(J)**2-12.347*XKT(J)+1.004
      BB=(-2.371*XKT(J)**2-12.22*XKT(J)+12.689)
      CC=(2.547*XKT(J)**2+1.542*XKT(J)-0.732)
      TAMB(J)=TAMB(J)*TM+TA
      V=AA*RBW**2+BB*RBW+CC
      EFFMAX(J)=TNR*(1-BR/UL*S(J)*TARAT*PTA/DAYS(J)*V-BR*TAMB(J))
      QDL(J)=XLD*DAYS(J)
9     CONTINUE
C..USE GOLDEN SECTION SEARCH TO FIND OPTIMUM COLLECTOR AREA.
      IOPMUM=0
      IF(LOPMZ.EQ.2) IOPMUM=1
      AREA=AC
      IF(IECON.EQ.2.OR.LOPMZ.EQ.2) GO TO 15
      BOUND1=0.
      JKL=1
      IF(XLATTI.LT.0.) JKL=7
      BOUND2=3.3*XLD/EFFMAX(JKL)/S(JKL)
      GOLD=(SQRT(5.)-1.)/2.
      REGION=BOUND2-BOUND1
      ICOUNT=1
      AREA=BOUND2-REGION*GOLD
      GO TO 15
10    ACOLD=AREA
      PWOLD=PW
      AREA=BOUND1+REGION*GOLD
      ICOUNT=2
      GO TO 15
11    IF(BDNEW.GT.ACOLD) GO TO 14
      AREA=BDNEW+REGION*GOLD
      GO TO 15
14    AREA=BDNEW-REGION*GOLD
```

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15    TOTLYR=0.
      QUYR=0.
      IF(IOPMUM.NE.1.OR.LOPMZ.EQ.2) GO TO 17
C..OPTIMIZE ON AN AREA WHICH IS AN INTEGER MULTIPLE OF COLLECTOR MODULE S
IZE
      PANELS=AREA/DELTAC
      IPANEL=IFIX(PANELS)
      IF(PANELS.GT.(FLOAT(IPANEL)+.5))IPANEL=IPANEL+1
      AREA=DELTAC*FLOAT(IPANEL)
17    CONTINUE
      DO 25 J=1,12
C     THIS SECTION INCLUDES ALL AREA DEPENDENT CALCULATIONS
      QMAX(J)=EFFMAX(J)*AREA*S(J)*DAYS(J)*TAU(J)*ACDC
      CRIT(J)=QDL(J)/(AREA*EFFMAX(J)*ACDC*24*TAU(J)*DAYS(J))
      PHI(J)=PHIBAR(J,XKT(J),R1(J),RT(J),H(J),RB(J),XC(J),CRIT(J))
      QDO(J)=PHI(J)*S(J)*AREA*EFFMAX(J)*DAYS(J)*ACDC*TAU(J)
      IF(QDO(J).LT..01) QDO(J)=0.0
      GO TO(300,310,320,320),MODE1
300   QDMON(J)=(QMAX(J)-QDO(J))
      EXTRA=0.0
      IF(QDMON(J).GT.QDL(J)) EXTRA=QDMON(J)-QDL(J)
      IF(QDMON(J).GT.QDL(J)) QDMON(J)=QDL(J)
      F(J)=QDMON(J)/(QDL(J))
      QUYR=QDMON(J)+QUYR
      QDA(J)=QDO(J)+EXTRA
      GO TO 25
310   QDMON(J)=((QMAX(J)-QDO(J)))
      IF(QDMON(J).LT.QDL(J)) GO TO 315
      QDA(J)=-QDO(J)-(QDMON(J)-QDL(J))
      QDMON(J)=QDL(J)
      GO TO 317
315   QDA(J)=-QDO(J)
317   QUYR=QUYR+QDMON(J)
      QDQUYR=ABS(QDA(J))*CPA+QDMON(J)+QDQUYR
      F(J)=QDMON(J)/(QDL(J))
      GO TO 25
320   IF(QDO(J).LT..01) GO TO 323
      XDA=QDO(J)/(QDL(J))
      BE=STOR/XLD
      QDA(J)=QDACT1(XDA,BE)*QDL(J)
323   IF(QDO(J).LT..01) QDA(J)=0.0
      IF(QDA(J).LT..001) QDA(J)=0.0
      IF(QDA(J).GT.QDO(J)) QDA(J)=QDO(J)
      QLOSS(J)=PERC*(QDO(J)-QDA(J))*EFFBAT
      QDMON(J)=((QMAX(J)-QDO(J))+((QDO(J)-QDA(J))*EFFBAT)-QLOSS(J))
      IF(QDMON(J).LT.QDL(J)) GO TO 325
      QDA(J)=QDA(J)+(QDMON(J)-QDL(J))
      QDMON(J)=QDL(J)
325   F(J)=QDMON(J)/(QDL(J))
      QUYR=QUYR+QDMON(J)
      QDQUYR=ABS(QDA(J))*CPA+QDMON(J)+QDQUYR
      IF(MODE1.EQ.4) QDA(J)=-QDA(J)
25    CONTINUE
      TOTLYR=XLD*365
      OPAREA=AREA
      FYR=QUYR/TOTLYR
      ORGINV=AREA*ADCOST+CCOST
      IF(IOPMUM.EQ.1) XLIST(4)=AREA
      IF(IECON.EQ.2.OR.IOPMUM.EQ.1)GO TO 35
C..CALL ECON TO EVALUATE ECONOMICS OF PROJECT WITH CURRENT COLLECTOR AREA
      CALL ECON(IOPMUM,XLIST,ORGINV,TOTLYR,FYR,PWSOL,IERR,IU)
      IF(IERR.EQ.1) RETURN
      PW=PWSOL
      IF(ICOUNT.EQ.1) GO TO 10
```

```
      REGION=REGION*GOLD
      IF(REGION.LT.1.0) IOPMUM=1
      BDNEW=AREA
      IF(PWOLD.LT.PW) GO TO 11
      BDNEW=ACOLD
      ACOLD=AREA
      PWOLD=PW
      GO TO 11
C..PRINT OUT ELECTRIC ANALYSIS RESULTS
35    WRITE(LUW,520)
      WRITE(LUW,500)
      IF (IU.EQ.1) WRITE(LUW,501)
      SOLYR=0.
      QMAXYR=0.
      QLSYR=0.
      QDAYR=0.
      QDOYR=0.
      QDAYR=0.
      QDMYR=0.
      TYR=0.
      DO 40 J=1,12
      S(J)=S(J)*OPAREA*DAYS(J)
      SOLYR=SOLYR+S(J)
      QDAYR=QDAYR+QDA(J)
      QDMYR=QDMYR+QDMON(J)
      QMAXYR=QMAXYR+QMAX(J)
      QLSYR=QLSYR+QLOSS(J)
      QDOYR=QDOYR+QDO(J)
      F(J)=F(J)*100.
      IF(IPRT.EQ.2) GO TO 40
      WRITE(LUW,505) MONTHL(J),F(J),S(J),QDL(J),EFFMAX(J),QMAX(J),
     1QDMON(J),QDO(J),QLOSS(J), QDA(J),TAMB(J)
40    CONTINUE
      TYR=TOTLYR
      FYR=FYR*100.
      WRITE(LUW,530)
      WRITE(LUW,510) YEAR,FYR,SOLYR,TYR,QMAXYR,QDMYR,QDOYR,QLSYR,QDAYR
      IF(IECON.EQ.2) GO TO 45
      FYR=FYR/100.
C..CALL ECON ONE LAST TIME FOR PRINT OUT
      CALL ECON(IOPMUM,XLIST,ORGINV,TOTLYR,FYR,PWSOL,IERR,IU)
45    CONTINUE
500   FORMAT('  TIME PERCENT INCIDENT TOTAL  EFFMAX   ELEC   ELEC   ELEC
     1      BATT   ELEC     AMBIENT',/
     18X,'SOLAR    SOLAR   LOAD              MAX    SUPP  DUMP(BE=0) LOSS
     1 DUMP       TEMP')
501   FORMAT(17X,'(KWH)  (KWH)           (KWH)   (KWH)  (KWH)    (KWH)  (
     1KWH)          (C)')
505   FORMAT(2X,A3,F7.1,1PE10.2,1PE9.2,0PF6.3,5(1PE8.2),2X,0PF6.1)
510   FORMAT(2X,A3,F7.1,1PE10.2,6(1X,1PE9.2))
515   FORMAT(1X,6A3,F8.2)
520   FORMAT(/,' ****ELECTRIC ANALYSIS  DESIGN METHOD****')
525   FORMAT(' THE VALUE OF PARAMETER #',I4
     1,' IS OUT OF RANGE.')
530   FORMAT(2X,'YEAR   FRACT   SOLAR    QLOAD      QMAX     QDEL   QDUM
     1P(BE=0) BATLOSS  QD(ACTUAL) ')
      RETURN
      FUNCTION QDACT1(XDA,BE)
      DIMENSION Y(6),B(6)
      Y(1)=XDA
11    Y(2)=.0937*XDA**2+.766*XDA-.12
12    Y(3)=.281*XDA**2+.314*XDA-.1
13    Y(4)=.576*XDA**2-.147*XDA-.0132
14    Y(5)=.69*XDA**2-.305*XDA+.012
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15    Y(6)=.686*XDA**2-.16*XDA-.147
      B(1)=0.0
      B(2)=.25
      B(3)=.5
      B(4)=.75
      B(5)=1.0
      B(6)=3.0
      IF(BE.LT.B(2).AND.BE.GE.B(1)) N=1
      IF(BE.LT.B(3).AND.BE.GE.B(2)) N=2
      IF(BE.LT.B(4).AND.BE.GE.B(3)) N=3
      IF(BE.LT.B(5).AND.BE.GE.B(4)) N=4
      NM=N+1
      QDACT1=Y(N)+((B(N)-BE)/(B(NM)-B(N)))*(Y(N)-Y(NM))
      IF(QDACT1.LT.0.0) QDACT1=0.0
      RETURN
      END
```

```
        FUNCTION PHIBAR(J,XKT,R1,RT,H,RBAR,XC,CRIT)
C       *****************************************
C       * THIS PROGRAM WILL CALCULATE PHIBAR     *
C       * USING THE CORRELATION DEVELOPED BY KLEIN*
C       *****************************************
        RO=RBAR/R1
        XC=3600*CRIT/RT/H/RO
        A=2.943-9.271*XKT+4.0315*XKT*XKT
        B=-4.345+8.853*XKT-3.602*XKT*XKT
        C=-0.170-0.3058*XKT+2.936*XKT*XKT
        PHIBAR=EXP((A+B/R1)*(XC+C*XC*XC))
        RETURN
        END
```

*The remaining subroutines may be obtained from a complete listing of the FCHART[18] program.

BIBLIOGRAPHY

1. P. F. Pittman, "Conceptual Design and Systems Analysis of Photovoltaic Power Systems", Westinghouse Electric Corp., Pittsburgh, PA, 1977.

2. A. Kirpich, "Conceptual Design and Systems Analysis of Photovoltaic Power Systems", General Electric Co., Philadelphia, PA, 1977.

3. Spectrolab, Inc., "Conceptual Design on Systems Analysis of Photovoltaic Power Systems", Sylmar, CA, 1977.

4. D. L. Evans, W. A. Facinelli, R. T. Otterbein, "Combined Photovoltaic/Thermal System Studies", SAND 78-7031.

5. TRNSYS - A Transient Simulation Program, Engineering Experiment Station Report 38, Solar Energy Laboratory, University of Wisconsin-Madison.

6. D. L. Evans and L. W. Florchuetz, "Terrestrial Concentrating Photovoltaic System Studies", Solar Energy 20, p. 37 (1978).

7. Jet Propulsion Laboratory, "A Solar Cell Array Design Handbook", Vol. II, Report #JPL SP 43-38, 1976.

8. C. M. Shepherd, "Design of Primary and Secondary Cells II. An Equation Describing Battery Discharge", Journal of Electrochemical Society, 112, 657 (1965).

9. S. A. Klein, "Calculation of the Monthly-Average Transmittance-Absorptance Product", Solar Energy, 23, p. 547-551 (1979).

10. J. A. Duffie, W. A. Beckman, "Solar Energy Thermal Processes", John Wiley and Sons (1974).

11. B. Y. H. Liu, R. C. Jordan, "The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation", Solar Energy, 4, No. 3 (1960).

12. R. J. Cole "Long-Term Average Performance Predictions for CPC's", Proceeding of the American Section of I.S.E.S., Orlando, FL, p. 36 (1977).

13. H. C. Hottel, B. B. Woertz, "Performance of Flat-Plate Solar-Heat Collectors", Trans. ASME 64, 91 (1942).

14. B. Y. H. Liu and R. C. Jordan, "The Long-Term Average Performance of Flat-Plate Solar Energy Collectors", Solar Energy, 7, 53 (1963).

15. S. A. Klein, "Calculation of Flat-Plate Collector Utilizability", Solar Energy, 22, 393 (1978).

16. A. Whiller, "Solar Energy Collection and Its Utilization For House Heating", Ph.D. Thesis, M.I.T., Cambridge, MA (1953).

17. J. C. Theilacker, "Improvements in the Utilizability Relationships", Proceeding I.S.E.S. Meeting, Phoenix, AZ (1980).

18. FCHART - An Interactive Program for Designing Solar Heating Systems, Engineering Experiment Station Report 49-3, Solar Energy Laboratory, University of Wisconsin (1978).